LAPPEENRANTA
UNIVERSITY OF TECHNOLOGY

Irina Rauvanto

THE INTRINSIC MECHANISMS OF SOFTWOOD FIBER DAMAGE IN BROWN STOCK FIBER LINE UNIT OPERATIONS

Thesis for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in Auditorium of the Student Union House at Lappeenranta University of Technology, Lappeenranta, Finland on the 14th of May, 2010 at noon.

Acta Universitatis
Lappeenrantaensis
385

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ISBN 978-952-214-923-7
ISBN 978-952-214-924-4 (PDF)
ISSN 1456-4491
Lappeenrannan teknillinen yliopisto
Digipaino 2010

ABSTRACT

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The intrinsic mechanisms of softwood fiber damage in brown stock fiber line unit operations
Lappeenranta 2010
62 p.
Acta Universitatis Lappeenrantaensis 385
Diss. Lappeenranta University of Technology

ISBN 978-952-214-923-7, ISBN 978-952-214-924-4 (PDF), ISSN 1456-4491

The effects of pulp processing on softwood fiber properties strongly influence the properties of wet and dry paper webs. Pulp strength delivery studies have provided observations that much of the strength potential of long fibered pulp is lost during brown stock fiber line operations where the pulp is merely washed and transferred to the subsequent processing stages.

The objective of this work was to study the intrinsic mechanisms which may cause fiber damage in the different unit operations of modern softwood brown stock processing. The work was conducted by studying the effects of industrial machinery on pulp properties with some actions of unit operations simulated in laboratory scale devices under controlled conditions. An optical imaging system was created and used to study the orientation of fibers in the internal flows during pulp fluidization in mixers and the passage of fibers through the screen openings during screening. The qualitative changes in fibers were evaluated with existing and standardized techniques.

The results showed that each process stage has its characteristic effects on fiber properties: Pulp washing and mat formation in displacement washers introduced fiber deformations especially if the fibers entering the stage were intact, but it did not decrease the pulp strength properties. However, storage chests and pulp transfer after displacement washers contributed to strength deterioration. Pulp screening proved to be quite gentle, having the potential of slightly evening out fiber deformations from very deformed pulps and vice versa inflicting a marginal increase in the deformation indices if the fibers were previously intact. Pulp mixing in fluidizing industrial mixers did not have detrimental effects on pulp strength and had the potential of slightly evening out the deformations, provided that the intensity of fluidization was high enough to allow fiber orientation with the flow and that the time of mixing was short. The chemical and mechanical actions of oxygen delignification had two distinct effects on pulp properties: chemical treatment clearly reduced pulp strength with and without mechanical treatment, and the mechanical actions of process machinery introduced more conformability to pulp fibers, but did not clearly contribute to a further decrease in pulp strength. The chemical composition of fibers entering the oxygen stage was also found to affect the susceptibility of fibers to damage during oxygen delignification. Fibers with the smallest content of xylan were found to be more prone to irreversible deformations accompanied with a lower tensile strength of the pulp. Fibers poor in glucomannan exhibited a lower fiber strength while wet after oxygen delignification as compared to the reference pulp. Pulps with the smallest lignin content on the other hand exhibited improved strength properties as compared to the references.

Keywords: softwood, fiber damage, pulp strength, oxygen delignification, fluidization, screening
UDC 676.1 : 676.032 : 676.017.4

PREFACE

This work was carried out within the Fiber Treatment Project in 2003 to 2005 and within the Advanced Fiber Treatment project in 2005 to 2008. The projects were financed by the National Technology Agency of Finland and industrial partners UPM-Kymmene Oyj, Stora Enso Oyj, Sunila Oy, Oy Metsä-Botnia Ab, Andritz Oy and Sulzer Pumps Oy. Although this work was intended to be purely academic by nature, it turned out to be more of an engineering piece of work due to the nature of the subject and more so due to the close interaction with the industrial processes.

During this long journey, I have received much help from different people working for the pulp and paper industry. I would like to acknowledge the contribution of all, too many to mention here, who have in some way participated in my work. Especially I would like to thank our steering board members for their endless interest in these projects: Mr Esa Hassinen, Dr Tom Hultholm and Mr Niklas Keskinen from UPM-Kymmene Oyj, Dr Kari Kovasin from Oy Metsä-Botnia Ab, Mr Veikko Jokela and Olli Timonen from Stora Enso Oyj, Mr Juha Piipponen and Ari Haakana from Sunila Oy, Mr Janne Vehmaa and Tech. Lic. Olavi Pikka from Andritz Oy, and Mr Reijo Vesala from Sulzer Pumps Oy.

I have also had the opportunity to work with very skilled professionals, of whom I would like to mention Dr Jaakko Pere from VTT and our French colleagues from EFPG, with whom I had the opportunity to work during my stay in France, Grenoble: Dr Raphael Passas, Dr Christine Chirat and Dr Dominic Lachenal. My acknowledgements also go to Dr Leif Robertsén and Dr Olli Joutsimo for reviewing my thesis. I would also like to honor the memory of Professor Chad Bennington from the University of British Columbia. Dr Bennington was supposed to be my opponent, but passed away suddenly and all too early.

Special thanks are due to Dr Sergey Malkov, whose encouragement and friendship I will always cherish, and Ms Salla Husu whose contribution during the Advanced Fiber Treatment Project was indispensable.

My warmest acknowledgments go to my supervising professors; Professor Kaj Henricson, Professor Hannu Manner and Professor Isko Kajanto. Kaj – your work as my advisor has probably not been the easiest one. Thank you for your patience, flexibility, support and guidance not only work-related but in life generally.

I also wish to thank the Walter Ahlström Foundation, Finnish Paper Engineers Association, Lauri and Lahja Hotinen Foundation, Lappeenranta University of Technology and the City of Kotka for the scholarships I received in 2003 to 2009.

At last but not least my loving thanks go to my family for their encouragement and support. Special thanks to Toni for cooking, cleaning and taking care of our boys – while mum was working.

Siuntio,
Irina Rauvanto

CONTENTS

LIST OF PUBLICATIONS

The thesis consists of a theoretical introduction, summary of four publications listed below, and additional previously unpublished experimental work.

I. Rauvanto I., Passas R., Henricson K., Fiber damage in unbleached reinforcement pulp - The phenomena in industrial softwood kraft pulps, published in Paperi ja Puu (4) 239-246 (2006)

II. Rauvanto I., Pere J., Henricson K., Fiber damage in unbleached reinforcement pulp - The effect of hemicelluloses and lignin on the susceptibility of fibers to damage during oxygen delignification, published in Nordic Pulp Paper Res. J., 21(3) 238-335, (2006)

III. Rauvanto I., Rasa M., Henricson K., Fiber damage in unbleached reinforcement pulp - Studies on the effects of MC fluidization, published in JPPS 34(2) (2008)

IV. Rauvanto I., Henricson K., Fiber damage in oxygen delignification - mechanical and chemical interactions, accepted for publication in JPPS 35(1) (2009)

AUTHOR'S CONTRIBUTION TO THE WORK PRESENTED IN THE LISTED PUBLICATIONS

I. Experimental planning and analysis of the results; manuscript

II. Main part of the experimental planning and analysis of the results; manuscript

III. Experimental planning and carrying out of the on-site simulation tests with DMX and analysis of the results; manuscript

IV. Experimental planning, industrial study work and analysis of the results, manuscript

OTHER RELEVANT PUBLICATIONS

Rauvanto I., The effect of oxygen delignification on fiber properties in kraft pulp production - A review, Lappeenranta University of Technology, Finland, Report 146, 2003, 26 p.

Rauvanto I. and Henricson K., Fiber damage in softwood kraft pulping - What is it and how can it be defined, EFPG days 2004, April 2004 Grenoble, France

Rauvanto I. and Henricson K., Softwood fiber technology - How to get better fiber quality out of your process, PulPaper 2004, June 2004 Helsinki

Rauvanto I. and Henricson K., Studies on MC-fluidization - mill-scale conditions in a new laboratory tester, TAPPI Technical Fall Conference, November 2004 Atlanta, USA

Rauvanto I., Characterization of industrial softwood fiber damage and a new testing method for pulp fluidization, WURC International Seminar, 21.9.2005, Uppsala, Sweden

Rauvanto I. and Henricson K., Softwood fiber damage - the role of slow mixing and rapid fluidization during brown stock operations, Ekmandagarna, Stockholm, Sweden 30.1.-1.2.2006

Rauvanto I., Henricson K., Fiber damage in oxygen delignification: Mechanical and chemical interactions, International Pulp Bleaching Conference, June 3 2008, Quebec, Canada

ABBREVIATIONS

DD	Drum Displacer® washer
DMX	Dynamic Medium Consistency Mixer – laboratory scale mixing tester
FSP	Fiber saturation point
HC	High consistency
LC	Low consistency
MC	Medium consistency
SEM	Scanning Electron Microscopy
ZST	Zero span strength
WZST	Wet (rewetted) zero span strength

1 INTRODUCTION

1.1 Background

Softwood kraft pulps are used for reinforcement purposes in paper and board production due to their superior strength properties as compared to mechanical and semimechanical pulps as well as hardwood kraft pulps (Annergren et al. 1962). Softwood fibers are complicated biocomposite structures with an extremely good weight-to-strength ratio. The use of reinforcement pulp in paper production increases the strength of the paper which is important not only in paper production but also in the following converting processes.

The strength of softwood pulp is determined by the quality of wood raw material and fiber length and chemical and mechanical treatments taking place during pulp processing. Pulp strength builds up roughly of three factors; single fiber strength, fiber-fiber bond strength per unit area, and the total fiber-fiber bonded area (Page 1969). Changes in any of the factors affect the total strength outcome.

According to many studies, the good strength potential of the raw material is lost during pulp processing due to numerous factors, such as carbohydrate dissolution during cooking and bleaching operations, strength loss caused by unspecific radical reactions and fiber damage occurring due to the pressure changes, and introduction of mechanical energy to high consistency pulps during fiber line operations (Hill et al. 1950, Green 1962, Hartler 1963, De Grâce et al. 1976, Tikka et al. 2001, MacLeod et al. 1980 and 1995, Pihlava 1998, Kibblewhite 1974, Joutsimo 2004).

The effects of brown stock processing on pulp and fiber properties have gained a lot of attention from softwood kraft pulp producers due to only partially explicable deterioration of pulp strength properties prior to pulp bleaching sequences (MacLeod 1987, MacLeod et al. 1987, Green 1962, De Grâce et al. 1976, MacLeod et al. 1995, Tikka et al. 2001, Pihlava 1998). If expressed as strength delivery numbers, the brown stock usually falls in the range of 70-85%, and the bleached pulp falls in the range of 60-75% (MacLeod et al. 1995, Tikka et al. 2001, Pihlava 1998). According to these studies, the loss of pulp strength is caused by fiber damage resulting from chemical and mechanical treatments during brown stock processing.

Fiber damage caused by the mechanical actions of mill machinery has been recognized and studied as a phenomenon only for a decade or so. The prerequisite for measuring fiber damage has been an estimated difference in the pulp strength of industrially processed and laboratory treated pulps originating from the same raw material or an estimated loss of strength potential of softwood in industrial processes. A number of good studies have been conducted quite recently to show where and how fiber strength deteriorates, by authors such as MacLeod, Ellis, Allison, Seth, Tikka, Sundquist, Cyr, Bennington, Fahlèn, Mohlin Ulla-Britt, Pihlava, Savolainen, Ander and Joutsimo. However, studies on the alteration of fiber morphology during pulp processing or due to specific mechanical treatments such as refining go way back in history, for this authors such as Page, Seth, De Grace, Gurnagul, Kibblewhite, Hartler etc. have to be acknowledged. So the phenomenon is not new, but the way to look at it is.

Authors such as Bennington, Seth, Ellis and Allison have provided us with good understanding of what happens to pulps during mechanical treatments in mixing and fluidization and how the

introduction of energy to pulp is reflected in fiber properties. Authors such as Mohlin Ulla-Britt, Fahlèn Jesper and Joutsimo Olli have also presented good studies attempting to unambiguously explain the structural changes in the fiber cell wall that can be identified as fiber damage. The variety and good coverage of the field provided by these studies makes it possible to place the phenomena in the industrial scale and with additional studies to provide new guidelines for the design and operation of softwood fiber lines.

1.2 Objectives of the thesis

The objective of this work was to study the intrinsic mechanisms which may cause fiber damage in the different unit operations of modern softwood brown stock processing. The work presented was for a large part conducted with industrial pulp and industrial machinery with some actions of unit operations simulated and studied in laboratory scale devices. An optical imaging system was created during this work and used to study the orientation of fibers in the internal flows during pulp fluidization in mixers and the passage of fibers through the screen openings during screening.

The changes in fibers were evaluated with existing and standardized techniques that in previous studies have been proven to show the relevant changes in the fiber structure and properties. The approach of combining industrial references with targeted laboratory simulations was selected for the following reasons: due to the poor comparability of laboratory scale studies to actual performance of industrial machinery and due to the evaluation of these results in the light of previous knowledge in order to provide conclusive, unambiguous evidence on the effects of industrial processes.

The previously tested and rather precise analysis methodology studying industrial pulps and processes contains a conscious risk that industrial pulps originating from different raw materials and produced in different processes, as well as being heterogenic by nature within the batch, may introduce high variability in the results and in the worst scenario even produce inconsistent results. The risk was, however, justified as in practice the applicability of the results obtained from industrial studies is better than those from laboratory scale studies when designing new fiber lines and processes or optimizing old ones. Thus it outweighed the potentially better repeatability of laboratory studies. To minimize the variability, special attention was paid to the number of variables being minimized, studies in industrial fiber lines being done at steady state conditions, and all comparisons in one study being performed on the same pulp batch and pulp grade.

2 THEORETICAL CONSIDERATIONS

2.1 Fiber as a composite structure – the roles of different components in the structure

Softwood fibers are typical representatives of biological composite structures, where each of the components serves its purpose and usually nothing is useless. The development of the cell wall composition is governed by the genes and growing conditions of the tree. Pulp processing uses chemical and mechanical means to alter the structure of native wood fibers to attain the desired properties, with specificity demands on the physical properties constantly increasing. Luckily, modern technology allows very specific and targeted treatments at high volumes, and the outcome in general is very good. However, mechanical and chemical treatments tend to affect the structure of the fibers on several levels, and for this reason it is important to understand the structure of the fiber cell wall and the functions of its components. As Fengel put it simply in his work: “One of the most striking properties of the wood components, from the analytical point of view, is their intimate mixing with one another within the cell wall. Consequently one cannot be separated quantitatively without incurring changes to others.” Thus understanding of the fiber structure is essential to the understanding of fiber damage.

Native softwood cells are chemically heterogeneous and built up of a polymeric matrix of carbohydrates, mainly cellulose and hemicelluloses (glucomannan and glucuronoxylan), lignin and extractives. Softwood contains 40% to 45% of cellulose, 25% to 30% of hemicelluloses and 25% to 30% of lignin in the dry solids. Each of these components has its characteristic function in the wood cell.

Cellulose

Cellulose is a polydispersed linear homopolysaccharide consisting of D-glucose residues bound together by β (1,4) glucosidic linkages, and having a strong tendency for intramolecular and intermolecular hydrogen bonding. Within the plant cell wall, the molecular chains of cellulose are arranged in systems at various levels of magnitude, i.e. microfibrils and macrofibrils and fibril aggregates. The cell wall itself can be regarded as the highest-level system. The smallest units are termed “elementary fibrils” and are about 30 Å in diameter (Fengel 1970). These elementary fibrils are densely packed into higher units, about 120 Å in diameter, and are very stiff structures. The interfaces between the elementary fibrils are formed by less ordered cellulose chains and by hemicellulose chains. From the fibril-forming properties of isolated hemicelluloses, it is concluded that these molecules are oriented in the direction of the cellulose fibrils within the cell wall (Heyn 1977, Fengel 1970). The next higher-level system is represented by the microfibrils which are built up of 120 Å fibrils, and arranged in a layer specific angle. Microfibril units can be easily split into 120 Å units by alkali treatment, as the interfaces are assumed to consist mainly of hemicelluloses. The movement of water, i.e. swelling and shrinking of the cell wall, occurs mainly in these interfaces. The microfibrils in turn are surrounded by hemicelluloses and lignin (Fengel 1970).

Scallan and Tigerström suggested a model for fibrillar arrangement (figure 1) combining previous observations of cell wall component arrangements (Scallan 1974, Page 1976, Fengel 1970, Scallan and Tigerström 1992), where cellulose microfibrils provide the skeleton of the fiber cell wall by

periodically attaching to each other by hydrogen bonds, and pores afforded by the cellulose structure are filled with ligno-hemicellulose.

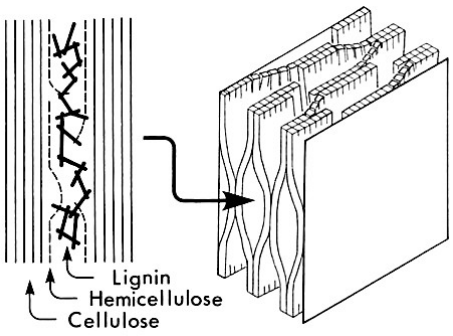


Figure 1. A model of the ultrastructure of the cell wall (Scallan 1974, Page 1976, Scallan and Tigerström 1992)

According to Page et al., cellulose fibrils are the sole tensile-load-bearing elements and hemicellulose and lignin serve as the matrix that transfers the stress under shear from fibril to fibril (Page, Seth, El-Hosseiny, 1985).

Lignin

Lignin is an amorphous, highly-branched polymer which acts as a cross-linking agent within the cell wall. Lignin is built up of phenylpropanoid units; p-coumaryl alcohol, coniferyl alcohol and sinapyl alcohol (Sjöström 1993). The major part of lignin is located in the middle lamella (ML) and primary layer (P) of the fiber cell wall, where it acts as a binder between wood cells, and limits the penetration of water into the wood cells. Figure 2 presents a model of fiber structure suggested by Fengel and Wegener, a very similar presented earlier by Lagergren et al., and Côtè (Fengel et al., 1989, Côtè 1967, Lagergren et al. 1957).

During kraft cooking, practically all of the lignin in the middle lamella and most of the lignin in the primary wall is dissolved so that the lignin yield after softwood kraft pulping is usually between 5 and 10% (Molin 2002), and the remaining lignin is located in the secondary tangential layers of the cell wall, where it imparts rigidity to the cell wall (Stone et al. 1971, Alén 2002).

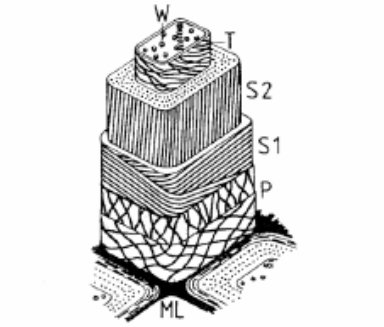


Figure 2. Schematic drawing of Norway spruce (Picea abies) wall layering, showing microfibril orientation and relative size of the different layers. Key: ML = middle lamella, P = primary wall, S1 = outer layer of the secondary wall, S2 = middle layer of the secondary wall, T (or S3) = inner layer of the secondary wall, and W = warty layer.

Hemicellulose

The primary hemicellulose components in softwood are galactoglucomannans (glucomannan) and arabinoglucuronoxylan (xylan). Glucomannan comprises two-thirds and xylan about one-third of the total hemicellulose content (Timell 1967). According to Salmèn and Olsson, glucomannan is more closely associated with the cellulosic fibril surfaces than xylan, and xylan on the other hand is more associated with lignin (figure 3); however, they may not be fully independently distributed (Salmèn and Olsson 1998, Åkerholm and Salmén, 2003, Fahlèn 2005).

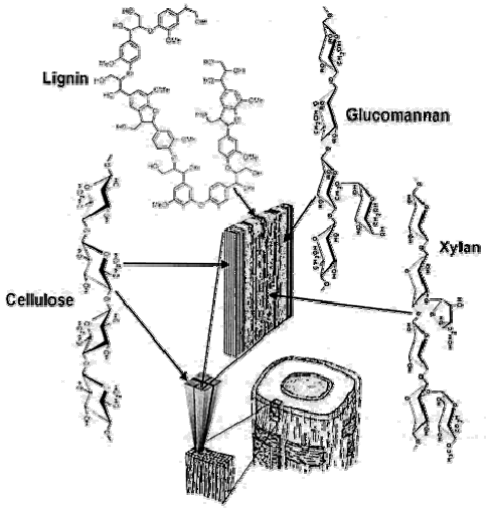


Figure 3. A schematic illustration of hemicellulose-lignin distribution within cellulosic fibril pores (Åkerholm and Salmén, 2003)

Hemicelluloses regulate the water content in the fiber cell, and their ability to retain water is a requirement for the elasticity of the cell wall and fibers. In a kraft pulping process, the structure of hemicellulose is modified extensively and the acetyl groups of hemicelluloses are completely removed. In softwood, a larger fraction of the glucomannans than that of xylan is removed during pulping, and the residual glucomannan in the fibers is very stable against dissolution and degradation (Annergren et al. 1962, Sjöström 1997, Rättö et al. 1993).

Attempts by various authors have been made to explain the role of the hemicellulose content for fiber strength. Leopold and McIntosh suggested that the removal of hemicellulose results in inadequate adhesion between cellulose fibrils, and that a linear correlation exists between fiber strength and xylan-based hemicellulose content, but not so much with glucomannan (Leopold et al. 1961). Spiegelberg suggested that when flexible hemicellulose-cellulose bonds are replaced by more rigid cellulose-cellulose bonds, the strength of a fiber decreases due to poor stress distribution (Spiegelberg 1966). Page et al. confirmed the theory later, and suggested that in fibers with over 80% content of α-cellulose, fiber strength in pulping is decreased through the elimination of the stress-equalizing matrix, i.e. hemicellulose-lignin matrix (Leopold et al. 1961, Page 1989, Suurnäkki et al. 2003, Schönberg et al. 2001). Annergren et al. showed in 1962 that the increasing content of hemicelluloses increases tensile strength but decreases tear strength. Oksanen et al. suggested that xylan and glucomannan play a very crucial role in fiber hornification during drying. Hornification can be clearly observed as deteriorated fiber properties: decrease in sheet density and tensile strength, and increase in fiber stiffness, all of which demonstrate the loss of fiber swelling and pore volume and bonding capacity. Extensive removal of xylan and glucomannan located in the fiber pores and interfibrillar spaces resulted in the significant hornification of fibers during drying (Oksanen et al. 1997).

Suurnäkki et al. discovered that the location and type of hemicelluloses clearly affect the bonding properties of ECF-bleached softwood kraft pulp. According to their study, the amount of surface hemicellulose affects the bonding ability whereas the bonding strength is more affected by the total amount and composition of hemicelluloses in fibers. In the case of xylan, also the charge plays an important role: the more anionic the charge of surface xylans and the higher the content of surface xylans, the more they improve the bonding ability (Suurnäkki et al. 2001, and 1996). In their work, Suurnäkki et al. even suggest that the surface hemicellulose content and acidity could be modified by chemical, enzymatic and chemo-enzymatic methods to improve the fiber bonding ability. Fiber surface charge can also be modified during kraft cooking; according to Andreasson 2003 and Laine 1996, pulps with higher yields display higher fiber charge values due to the higher content of acidic groups.

However, according to Annergren, as early as in 1962, and practical observations in industrial processes, regardless of the explanations and laboratory findings, a weaker pulp is obtained by increasing the carbohydrate yield above “normal”.

2.2 Definitions of fiber damage

Fiber damage as a term has been problematic due to the fact that it holds within it a variety of structural changes causing different outcomes in pulp properties. The terminology of structural

changes also adds up the complexity, as the same terms are used to describe similar structural alterations which may nevertheless be caused by different treatments and thus result in different outcomes in fiber properties.

Based on previous studies, fiber damage can be summed up and divided into three main categories: The loosening and breakage of the fiber wall structure, which is seen as changes in the ability of the fiber cell wall to retain water, delamellation and changes in porosity profile; changes in the three-dimensional fiber form, i.e. fiber deformations characterized as fiber curl, kink, dislocations and alterations in fiber crimping, and broken fibers; and changes in the fiber surface, i.e. increased or decreased surface fibrillation and crack formation. Usually all of the above changes are present simultaneously in industrially produced pulps.

2.2.1 Fiber deformations

Fiber deformations have been studied by a good number of scientists: Hägglund, Kilper, Robinson, Wardrop, Forgacs, Green, Iwasaki, Hartler, Page, De Grâce, Hill, Kibblewhite, Jones, Kallmes, Corte, Helle, Jordan. The first attempt to computerize the measurement of fiber curl in wood fibers was made by Graminski and Kirch.

Page et al. (1985) provided a good general definition for fiber deformations in a survey on fiber deformations; that it is simply a deviation from the original form of the fiber. Fiber deformations are the most easily detectable and measurable form of fiber damage and they are mainly caused by the mechanical actions of pulp processing. Fiber deformations can be categorized into four clearly different deformation types: curl, kink, dislocations and microcompressions (Page et al. 1985). Figure 4 presents SEM images collected within this work presenting all of the above mentioned deformation types with an addition of a twisted fiber, which can only be detected with an SEM microscope.

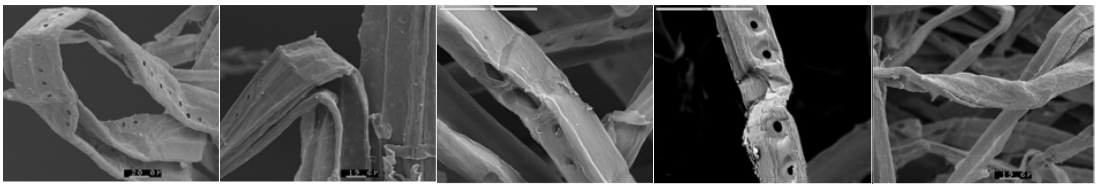


Figure 4. SEM images of different fiber deformation types in softwood pulp

Fiber curl and kinks can be rather easily quantified as indices in pulp as they are easy to detect and measure with optical image analyzers. Automated optical analyzers allow analyses to be performed on a good quantity of fibers which makes the results reliable and repeatable. Quantification of both curl and kink is based on different methods of calculation depending on the analyzer.

Fiber curl and kink are usually distinguished from each other by the lack or presence of an angle at the point of discontinuity. If a clear angle is not present the deformation is defined as a curl and can be quantified. There are several quantification equations but the one provided by Page and Jordan

where the curl index is a relationship of fiber contour length and the longest dimension (end to end length) has been more extensively used. The calculation of fiber kink uses more complex equations, and the mathematics behind this index varies depending on the analyzer. In this work studying the development of fiber curl and kink was emphasized as it is clearly a phenomenon that can be avoided with proper technical solutions, and thanks to automated analyzers these changes in fibers can be reliably measured from a good quantity of fibers.

The quantification of dislocations (also termed nodes in some studies) and microcompressions has not been automated yet, and is usually a tedious, subjective analysis done on a small quantity of fibers with a light microscope. According to Robinson, dislocations can be seen as bright, linear regions in the fiber wall when viewed under polarized light, figure 5. The observed lines presumably relate to the structural changes in the S_1 layer and even greater structural changes like the separation of the S_1 and S_2 layers, i.e. delamellation, and following buckling and folding of the fiber cell wall (Keith et al. 1968). Microcompressions are a type of dislocations, where a deformity in the fiber cell wall can also be observed in the transverse direction (figure 4).

Most scientists believe that there is a correlation between dislocations and ray crossings, and that weak planes and most discontinuities occur preferentially near ray pit fields (Forgacs 1961, Page et al. 1967, Dinwoodie 1968, Keith 1971). Areas of weakness are also found close to the tracheids' ends, where the cells often deviate from their vertical alignment and are heavily pitted (Keith 1971). When fibers are subjected to axial stresses even at low consistencies, dislocations and microcompressions will develop into kinks (Page et al. 1985). Forgacs and Frölander suggested that dislocations make fibers more flexible and sensitive to chemical attack with an accompanying improvement in the binding capacity (Forgacs 1961, Frölander 1969). Similar observations have been made by Hakanen et al. 1995 and Savolainen 2003, who also proposed that dislocated regions increase polysaccharide degradation by enhanced diffusion of harmful radicals into dislocated and disarranged segments of the fiber cell wall.

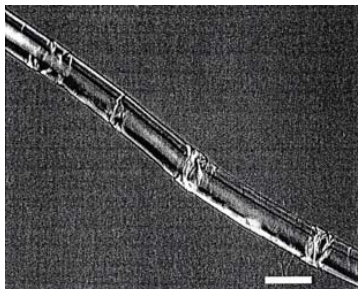


Figure 5. Dislocation areas across the width of a spruce fiber (scale bar = 40 μm) (Robinson 1920)

Fibers of different origin have different susceptibilities to deform. In their survey on fiber deformations, Page et al. (1985) suggested, based on the gathered observation of several scientists, that chemical treatments do affect the susceptibilities of fibers to deform. Apparently fibers with the highest α-cellulose content and low-yield pulps are more prone to deform, while on the other hand fibers from different wood species, but similar in properties, if treated in exactly the same manner deform equally.

2.2.2 The effects of fiber deformations on pulp properties

Fiber deformations affect the physical properties of the fiber network in a paper sheet. According to Page et al. (1980 and 1985), fiber dislocations enhance paper sheet strain, and curl and kink further increase the sheet strain, figure 6.

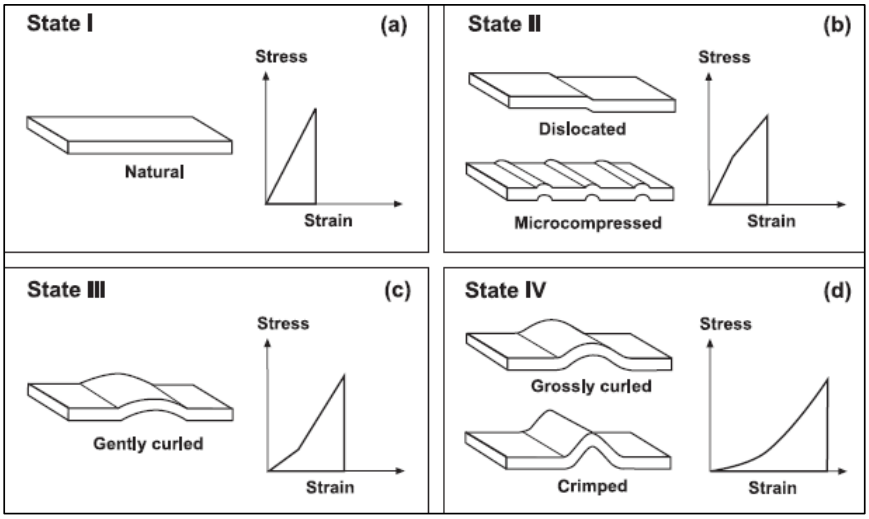


Figure 6. Fiber deformation types and their effects on paper sheet strain (Page et al. 1980)

Fiber curl and kink reduce tensile strength and enhance tear strength. This is caused by the uneven distribution of stress along the length of a curled fiber in a fracture zone, thus transferring larger stresses to the bonds which in breaking consume more energy (Van der Akker 1966). The low tensile index of curly fibers has been explained by low fiber segment activation as suggested by Giertz (1979).

In an older study, Page et al. (1980) also suggested that fiber curl increases the sheet stretch and decreases the elastic modulus. Fiber curl also raises the sheet bulk and porosity, increases light scattering thus improving brightness and opacity, reduces the drainage resistance of pulps, and improves drying (Page et al. 1985, Hill et al. 1950).

Fiber curl and kink can be regarded as secondary and reversible types of deformations as these can be removed with pulp beating (Kibblewhite 1976, Mohlin et al. 1990, Seth 2001). Mohlin et al. defined reversible deformations and irreversible fiber damage. Reversible deformations can be removed with mild PFI beating, as low as a 1,000 revs PFI beating is sufficient to straighten the fibers and return pulp strength properties to the level of pulp with straight fibers. According to Mohlin, when studying irreversible fiber damage, reversible fiber deformations should at first be removed with a PFI mill before the comparison of different pulp samples.

Dislocations reduce fiber stiffness with a slight improvement in the z-directional bonding ability of fibers (Page et al. 1980, Joutsimo 2004). If delamination occurs at the dislocated region and fibers

are heavily dislocated, the z-directional strength will be reduced due to the separation of the structural elements of the fiber cell wall upon stress (Joutsimo 2004). Alongside curl and kink, dislocations also contribute to the reduction in the elastic modulus (Page et al. 1979). Some scientists suggest that dislocated regions also represent weak sites in the fibers and thus contribute to the decrease in single fiber strength (Hartler 1995 and 1969). As the single fiber strength is an important factor in the formation of pulp strength, the overall pulp strength properties will be decreased if fibers are heavily dislocated. Dislocations may be reduced with mild beating, but they cannot be removed in the same manner as curl and kink (Page et el. 1985).

2.2.3 Irreversible fiber damage

Mohlin et al. 1996 presented in their work that irreversible fiber damage could be evaluated as the difference in the zero span tensile index between undamaged and damaged fibers when both are straight, which should either be confirmed before testing or achieved with mild pulp beating.

In 1989, Gurnagul and Page studied the differences in fiber zero span strength when tested as dry (ZST) and rewetted (WZST), and presented that wetting reduces fiber strength more if the fibers have been degraded by chemical or mechanical means than the wetting of intact fibers. The more severe the degradation, the more considerable zero span strength losses can be observed in fibers after rewetting. In this work, the wet zero span test was used consistently to evaluate the extent of irreversible fiber degradation; however, the observations made by Mohlin et al. were applied and the comparison of WZST in different samples was made on PFI beaten pulps.

3 EXPERIMENTAL WORK

3.1 Structure of the experimental work

The main objective of this work was to find the basic mechanisms in industrial brown stock unit operations that lead to fiber damage and deformations. Although fiber strength development along a fiber line has been studied previously, this work was started by collecting new industrial references. The gathered information pinpointed those processes and actions that needed to be studied more thoroughly, thus providing the outline for the study. Figure 7 presents a workflow of the study and the main objectives of the subprojects.

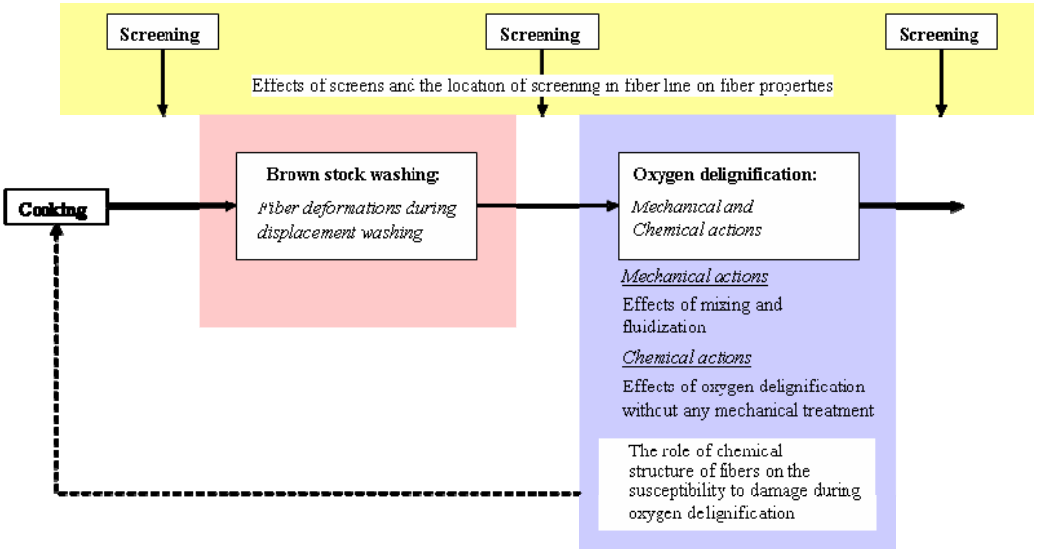


Figure 7. Workflow of the experimental work

Furthermore, previous investigations on fiber damage have shown evidence that pulp treatments after sampling, storage and possible transportation may affect the fiber properties. For this reason a methodology for pulp sampling, treatment and storage was developed in the early stage of this work to ensure good comparability of the results throughout the whole study. The results of the methodology studies are not reported in this thesis.

3.2 Materials and methods

3.2.1 Industrial references

The industrial references on fiber quality and strength development were collected from two similar fiber lines producing softwood kraft pulp from quite similar raw material. Table I presents the process descriptions of the brown stock fiber lines, sampling points and pulp compositions of both

fiber lines. Initially, the industrial references were collected from fiber line B only. The outline and the results of this study are presented in Paper I. Later it was felt that this survey should be complemented with results obtained from another fiber line with a similar pulp composition and somewhat similar process, hence industrial references were also collected from fiber line F. The methods and description of both surveys are presented in detail in this chapter.

The sampling in the industrial fiber lines was always done taking into the consideration the time lags between the process stages, to be able to follow the same pulp batch. The estimation of time lags was done from the production rate, volumes and retention rates of the tanks and reactors. In general, in all of the industrial pulp sampling and analyses presented in this work, the sampling was always conducted when the mills were operating at steady state conditions at nominal daily production. Tables II and III present the process conditions at the time of sampling.

Table I. Process descriptions of Mill B and F, and sampling points

Pulp mill operation consistency Nominal daily production	Brown stock fiber line process description	Sampling points	Pulp composition AVG fiber length
Mill B 10% - 12% ~2000 t/d	– Continuous digester (HiHeat washing) – Atmospheric diffuser – DD washer – Storage tank – O_2 delignification 2 stages – DD washer	1) After blow valve 2) After DD washer 3) After O_2 DD washer	60% pine (Pinus Silvestris) 40% spruce (*Picea Abies*) 2.10 mm
Mill F 8% -10% ~1600 t/d	– Continuous digester – DD washers – Storage tank – Screening – Brown stock washing (Enso filters) – O_2 delignification 2 stages – DD washer	1) After blow valve 2) After blow tank, MC and control valve 3) After DD washers 4) After screening 5) After Enso filters 6) After O_2 delignification	73% pine (*Pinus Silvestris*) 27% spruce (*Picea Abies*) 2.25 mm

Table II. Process conditions during sampling, Mill B (online measurements)

Sampling point	**After blow valve**	**After brown stock washing**	**After oxygen stage washer**
kappa number	26.8	25.4	13.2
Temperature, °C	73	78	97
Pulp consistency, %	~10	~10	~10
Pulp flow rate, liters/second	179	169	178

Table III. Process conditions during sampling, Mill F (online measurements)

Sampling point	After blow valve	After brown stock washing	After oxygen stage washer
kappa number	29	~26-27	~17
Temperature, °C	75.2	~72	~80
Pulp consistency, %	~8	~12	~8
Pulp flow rate, liters/second	150	--	165

After the sampling, the pulp samples were gently washed and stored in cold at ~7% consistency achieved by simply letting the washing water to drain out on a wire. The fines were retained in the pulp by the recirculation of the 0-wash water through the pulp mat. Special attention, in all cases, was paid to avoid all possibly damaging treatments of the samples such as mixing or centrifuging. Before the testing, the pulp samples were screened on a vibrating screen Serla (manufactured by G.A. Serlachius, Mänttä), using screen plates of 1.0 mm and 0.3 mm.

Pulp analyses

The extent of fiber damage was measured by combining fiber form analysis using the automated, optical analyzer FiberExpert from Metso Oy with standardized pulp strength analyses; tensile index (ISO 1924-2), tear index (ISO 1974), wet zero span (ISO 15361) and Scott Bond (TAPPI T 569). The strength analyses were performed from unbeaten and beaten pulp samples. Pulp beating was carried out in a PFI mill in three steps: 1000 revs, 2000 revs and 3000 revs.

In addition to the aforementioned analysis package, some additional analyses were performed on the samples collected from Mill B. Scanning electron microscopy was used to verify fiber morphology analysis results and to evaluate the overall condition of the fibers and pulp, and thermoporosity analysis was used to evaluate the changes in the porosity of fibers. These analyses are described in detail in Paper I.

3.2.2 Brown stock washing

The study was carried out in Mill B and, apart from the dislocation analyses, is previously unpublished. Both of the studied brown stock washers, the atmospheric diffuser and drum displacement washer, are displacement washers.

The atmospheric diffuser can be installed as a single-stage or two-stage washer for washing brown stock. A medium consistency storage tank is located below the washer. Equally spaced concentric screen rings are arranged about a common vertical axis inside the diffuser tank for each washing stage (Dence and Reeve, 1996). Each ring comprises two perforated plates about 5 centimeters apart that form a hollow interior channel for filtrate to flow through. Pulp travels upward between the concentric rings and wash water is introduced into the pulp through distributors located in the annuli. Filtrate is forced to flow through the pulp to the screens where it is extracted. The entire screen assembly undergoes a regular vertical stroking cycle to remove pulp from the surface of the screens and prevent plugging (Dence and Reeve, 1996).

The drum displacement washer is a pressurized, multistage drum washer consisting of a mat formation zone, one to four washing zones, and a discharge zone. A two-stage unit is usually selected for post-oxygen washing and a four-stage unit can be selected for brown stock washing. The drum is surrounded by a casing which is separated into sections by sealing bars that run along the length of the drum (Dence and Reeve, 1996). Pulp enters the forming zone at 6 to 10% consistency and forms a 10 to 12% consistency mat on the drum. The drum passes stationary sealing bars as it rotates. These sealing bars create a separate stationary wash pond for each washing stage. The wash zone remains stationary as the pulp mat rotates through it. Wash water flows counter currently from one washing compartment to the next. Pulp which has passed the final wash zone enters a vacuum zone where the mat consistency is raised to approximately 15% by a vacuum pump. The filtrate removed from the pulp is returned to the previous washing zone and fresh water is added to the final washing stage (Dence and Reeve, 1996).

Pulp samples were collected along the fiber line starting from the blow valve and prior to and after each washer. The possible effects of pumps, screws and agitators were excluded by taking the sample after the feed pumps as close to the washer as was technically possible. The sampling from the atmospheric diffuser was done from the top section of the washer. The samples from the drum displacement washers were taken before the discharge screw. The sampling points along with the conductivity of washing liquors in the washers are presented in table IV.

Table IV. Sampling points and conductivity of washing liquors in Mill B

Process stage	**Conductivity [mS/m]**
Blow valve	--
Brown stock washer 1 (Atmospheric diffuser washer)	~1950
Storage chest and MC pump	--
Brown stock washer 2 (Drum displacement washer)	~1500-1900
Oxygen delignification	--
Post-oxygen washer (Drum displacement washer)	~300-800

Pulp analyses

The applied analyses were fiber deformation analysis with Fiber Expert, dislocation analysis and standardized tensile, tear and Scott-Bond strength measurements from unrefined and PFI-refined unbleached pulps, according to standards ISO 1924-2, ISO 1974, and TAPPI T 569. PFI beating was carried out in three steps, 1000 revs, 2000 revs and 3000 revs.

The estimates of fiber dislocations were made with a light microscope. For each pulp, the projected fiber images were examined and the number of dislocated regions in each fiber was calculated. The degrees of dislocations were classified into the following groups: fibers with no dislocations were classified to class 0, fibers with an increasing amount of dislocations were allocated the respective values 1, 2 and 3, and fibers covered with dislocations were classified to class 4. The degree of dislocation indices comprised the average of the values obtained from 100-200 fibers. The results of the dislocation measurements are also presented in Paper IV.

3.2.3 Fluidization studies – Dynamic Medium Consistency Mixer

The mixing and fluidization experiments were performed in a novel bench scale pulp testing device called DMX (Dynamic Medium Consistency Mixer) as on-site tests in Mill B, figures 8 to 11. The device was connected to a pressurized pipe line prior to the first oxygen stage mixer. The construction and operation of the device as well as the results of the study are presented in detail in Paper III.

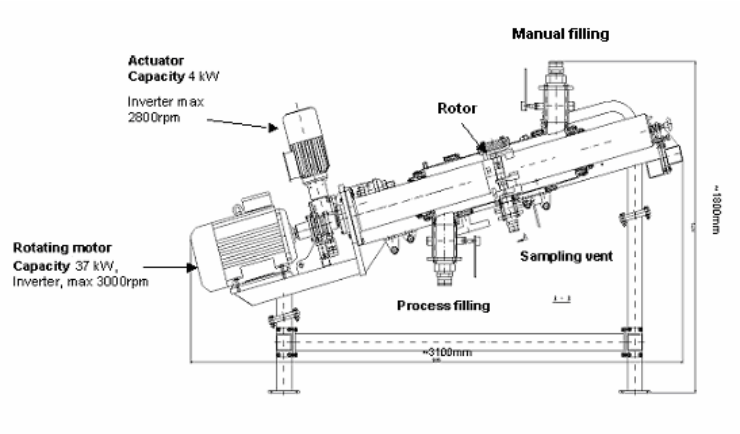


Figure 8. DMX, side view

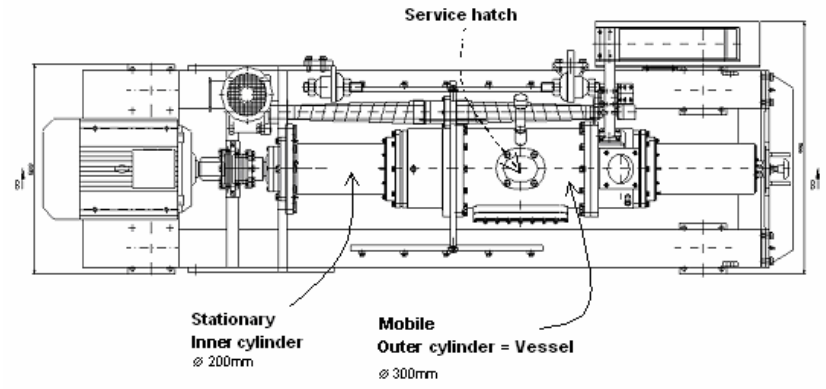


Figure 9. DMX, view from above

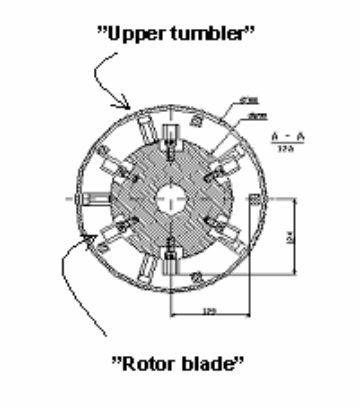


Figure 10. DMX, diagram of rotating assembly

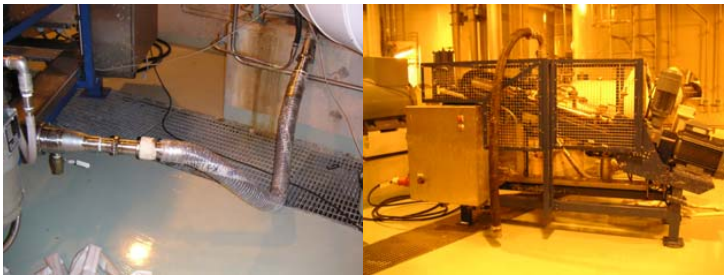


Figure 11. Connection of DMX to the pressurized pipe line prior to the oxygen mixer AM40 in Mill B

The pulp in this study was of the same quality as in the industrial reference study, a mixture comprising 60% of pine (Pinus silvestris) and 40% of spruce (Picea abies). A total of four trials are reported in Paper III. Three of the trials (TR1 - TR3) were performed with pulp with an average fiber length of ~2.15 mm, and the fourth trial (TR4) was a repetition of TR1 with pulp with an average fiber length of ~2.26 mm. The length of the fibers was varied by different relationships of log chips and sawmill chips.

Trials TR1 and TR4 aimed to study the effects of fluidization on pulp properties with different fiber lengths, trial TR2 aimed to study the effects of fluidization time, and trial TR3 aimed to study the effects of very intense fluidization on fiber morphology. Each trial comprised five reciprocating motions (i.e. five sequences) and one non-treated reference sample taken after feeding the pulp into the device; hence a total of six samples were produced in one trial. Before starting the trials, it was made sure that pulp feeding into the device does not affect the fiber properties.

The results of on-site trials with the DMX were compared not only to each other but also to the industrial mixing in AM40 mixer from Andritz. Due to the heterogenic nature of industrial pulp and variations between different pulp batches, an industrial reference was taken in each of the trials. The

industrial references were sampled before and after the oxygen stage mixer, with oxygen addition, and one sample (TR1/Ref.1) also without oxygen addition.

The mixer in question has a rotor speed of 1000 rpm, which corresponds to a circumferential speed of approximately 15-20 m/s. The treatment conditions, fluidization times, and intensities in industrial mixing and DMX trials are presented in more detail in table V.

Table V. Fluidization times and intensities in DMX during on-site trials, and conditions in industrial mixer

Test run	**Ref. 1 - Ref. 4**	**TR1 and TR4**	**TR2**	**TR3**
Equipment	Ind. mixer	DMX	DMX	DMX
Mixer speed, rpm	1000	1299	1299	2650
Circumferential velocity, m/s	15-20	~17.0	~17.0	~34.7
Pulp flow rate, liters/second	180	~10	~5	~10
Fluidization time, s	0.02-0.3*	~0.4**	~0.8**	~0.4**
Power dissipation, MW/m^3	1-5*	~2**	~2**	~10**
Energy, MJ/kg	~0.002-0.02*	~0.007**	~0.014**	~0.041**
Pulp consistency, %	10.2	10	10.4	10
Temperature, ºC	85	85	84	83
pH	10.8	10.8	10.8	10.3

*) Dence C.W., Reeve D.W., Pulp Bleaching, Principles and Practice, Tappi Press, Atlanta, 1996 pp. 562.
**) Corresponds to one treatment! Due to reciprocating motion, the actual energy dissipation is twice the figure in the table.

3.2.4 Chemical and mechanical interactions in oxygen delignification

The objective of this study was to investigate what types of changes mechanical actions of MC processing and chemical actions of oxygen and their possible synergy induce in softwood kraft pulp during two-stage industrial oxygen delignification. The study was a combination of an industrial unit operation survey done in Mill B and a specific laboratory scale study.

Laboratory scale oxygen delignification was done in a bomb autoclave in a manner which would inflict as minimum mechanical damage to the fibers as possible, while the chemical treatment was adjusted to be as close to the industrial one as possible, figure 12. The study is presented in detail in Paper IV.

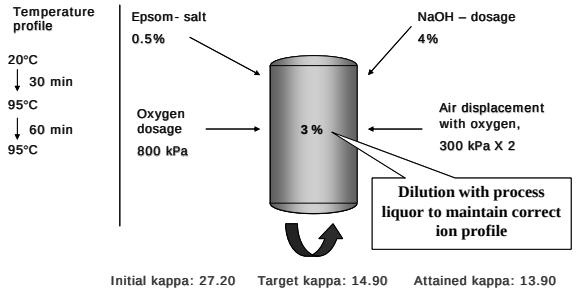


Figure 12. Laboratory scale oxygen delignification in a rotating bomb autoclave

3.2.5 Effects of chemical components on the susceptibility of fibers to damage

The objective of this study was to investigate the role of hemicelluloses, namely xylan, glucomannan and lignin, on the susceptibility of fibers to damage during oxygen delignification. The study was conducted by using targeted enzymatic treatments that enabled controlled modification of the lignin and hemicellulose content in the fiber cell wall prior to laboratory oxygen delignification. The pulp originated from the feed stream to oxygen delignification from Mill F. The changes in fiber properties were evaluated by analyzing fiber deformations and pulp strength properties. The study is presented in detail in Paper II.

3.2.6 Pulp screening

The aim of this work was to investigate the effects of pulp screening on softwood fiber properties when screening is done with similar equipment at different points of the fiber line. The studied screening locations were screening after pulp washing (washed brown pulp, Mill A), screening right after cooking prior to pulp washing (unwashed brown pulp, Mill C) and screening after washing and oxygen delignification (washed and oxygen-delignified pulp, Mill B).

The pulp produced in these lines was softwood kraft pulp with different fractions of pine and spruce. In Mill C, knot removal is done on unwashed pulp and screening is done after pulp washing with a wash press, in Mill B knot removal and screening are done on washed and oxygen delignified pulp, and in Mill A knot removal and screening are done on washed but unbleached pulp. In all three fiber lines the screening equipment was similar in construction and operation.

Pulp sampling

Pulp samples were collected in each fiber line from four process points: feed to knot screen, knot screen accept, feed to primary screen, and primary screen accept. The time lags between the sampling points were estimated from the production rates, volumes and retention rates of the tanks

and reactors. The flow rates, pulp consistency in the feed flows, knot screen hole and primary screen slot sizes are indicated in table VI.

Table VI Flow rates and pulp consistencies in studied screening operations in Mills A, B and C

Sampling points (Mill A, B, C)	**Mill A**	**Mill B**	**Mill C**
Feed consistency to knot screen	3.30%	4.16%	2.60%
Feed volume to knot screen	233.6 l/s	505 l/s	531 l/s
Knot screen hole size	10 mm	10 mm	9 mm
Feed consistency to primary screen	2.80%	3.02%	3.40%
Feed volume to primary screen	521.1 l/s	721 l/s	535 l/s
Primary screen slot size	0.25 mm	0.27 mm	0.27 mm

Pulp analyses

The applied analyses were fiber deformation analyses with Fiber Expert for all samples and dislocation calculation for the samples from Mill A and B.

3.2.7 Optical observations

Optical observations (Fiber Optics) of the pulp flow were done to complement the numerical data obtained in the fluidization and screening studies. The technique enables the observation of single fibers inside the suspension while wet and in motion and is applicable to fiber behavior studies in a variety of process units, such as washers, screens, pumps, pipes etc. (Rasa 2004).

In the fluidization study, Fiber Optics was used to show the flow of the fibers in the pulp suspension in the proximity to the mixer blades in the DMX. The imaging was done through the optics installed in the service hatch (located in the middle of the moving vessel of the DMX, figures 9 and 13). The test arrangement is presented in detail in Paper III.

For the screening study, the observations of fiber behavior during the active passage through the screen plate openings made by Mr Rasa in 2004 were used as such to provide explanations for the results. The optics were installed in a pilot scale screening device from Andritz Oy (Rasa, 2004).

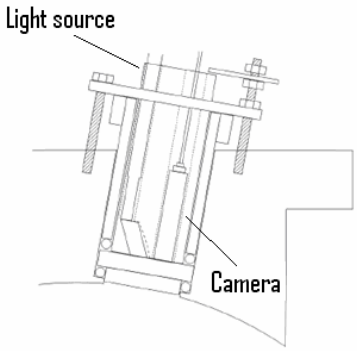


Figure 13. Placement of the CCD camera and the light source in the service hatch

For the fiber optics study, the DMX was filled with repulped, bleached commercial pulp. Before the filling, a handful of fibers were dyed with black textile color and mixed evenly into the bleached pulp suspension. The mixing trials were performed at 3, 6, 9 and 12% consistencies at different mixing intensities. The data from the fiber optics trials was collected as video images, which were further processed with Matlab and a photo editing program (Rasa 2004).

4 RESULTS AND DISCUSSION

The results of this work are presented and discussed in this section. Some of the results represent previously unpublished data and are presented here in detail. The parts of the work that have been published previously are presented as a summary and as main conclusions in this section and in more detail in the relevant publication.

4.1 Changes in fiber properties along brown stock fiber line – industrial references

The industrial references study served as a zero study that pinpointed the process stages that needed to be studied more thoroughly and also showed what kinds of physical changes are to be expected in the pulp and fibers when moving along the brown stock fiber line. The changes in fibers and pulp properties were studied as absolute changes, not in strength delivery numbers.

The results of the industrial survey in Mill B are presented in detail in Paper I, and the results of the survey in Mill F are previously unpublished material and presented in detail in this section.

Mill B

The survey in Mill B showed that fibers were quite intact after the blow valve, which was seen as a lack of deformation, intact fiber surface and superior strength properties. The SEM images confirmed the quantitative information on the condition of fibers (figure 14). The structure and morphology of fibers began to change as early as after brown stock washing: fiber deformations increased (figure 15), cell wall porosity increased (figure 16), and the strength properties were altered (figures 18 to 21). Oxygen delignification further promoted fiber deformations and an increase in porosity and also added to the changes to the chemical structure of the fiber cell with relevant consequences on pulp strength properties. The changes in the fiber structure after the main process stages were well reflected in pulp strength properties, e.g. the tear strength of washed and oxygen-delignified pulps as a function of density did not differ from each other substantially but were quite different when compared to freshly-cooked pulp, figure 20. Unbeaten tensile strength and sheet density clearly dropped in both samples taken along the fiber line consistently with the increase in deformation indices as suggested by Page et al. in 1985.

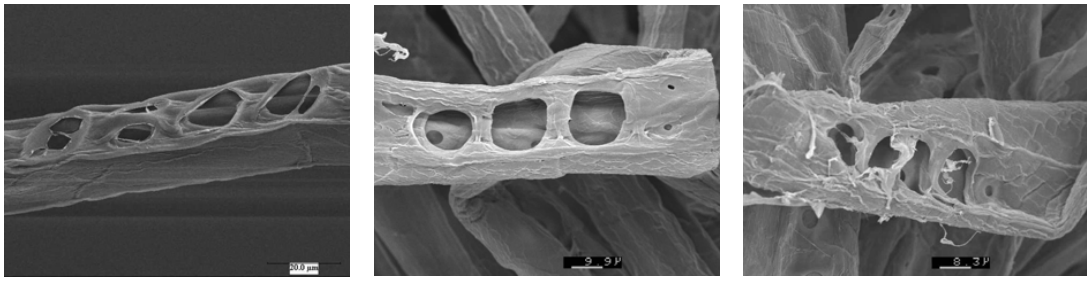
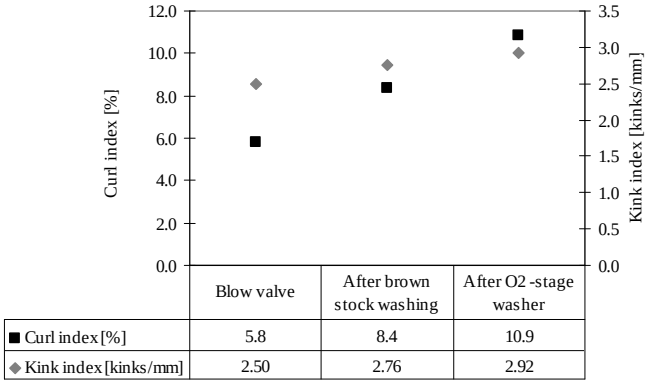


Figure 14. SEM images of pulp samples from Mill B (in order of appearance: fiber from blow valve sample, fiber after brown stock washing, fiber after O_2 stage)



	Blow valve	After brown stock washing	After O2 -stage washer
■ Curl index [%]	5.8	8.4	10.9
◆ Kink index [kinks/mm]	2.50	2.76	2.92

Figure 15. Changes in fiber deformation indices along brown stock fiber line in Mill B, measured with FiberExpert, (LSD Curl index: 1% unit, kink index 0.20 kinks/mm)

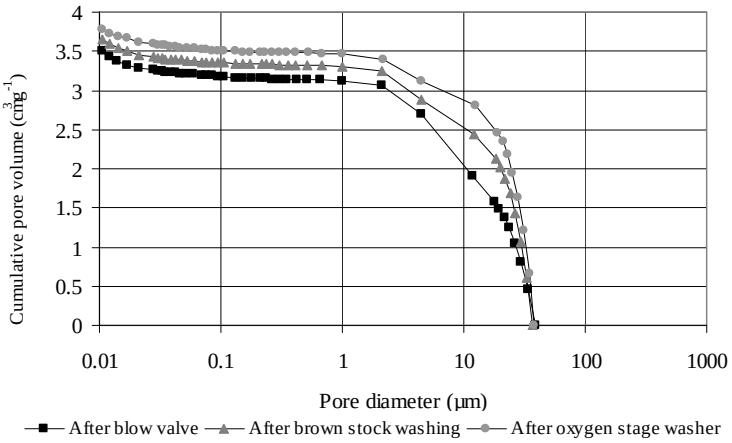


Figure 16. Pore diameter distributions of fibers from brown stock fiber line in Mill B (cumulative pore volume is in the range from 0 to 4 cm^3g^{-1})

The increase in cell wall porosity is explained by the removal of interstitial material. During kraft cooking nearly 50% of the wood material is dissolved causing the fibrils to aggregate into bigger units creating pores in the fiber cell wall as proposed by several scientists (Stone and Scallan 1968, Maloney 2000, Fahlen 2005). Figure 17 presents an example on the formation of fibril aggregates and cell wall cavities as proposed by Fahlén in his work in 2005. The material dissolved during cooking mainly goes into the cooking solution and some of it remains in the fiber cell wall. The remaining dissolved material must be removed in the subsequent pulp washing operations to ensure

an effective bleaching of pulp. The removal of the remaining dissolved material during washing results in the further aggregation of fibrils and formation of cavities in the cell wall, as well as a slight reduction in the pulp kappa number. The mechanical actions in the washing stages may promote the increase in porosity.

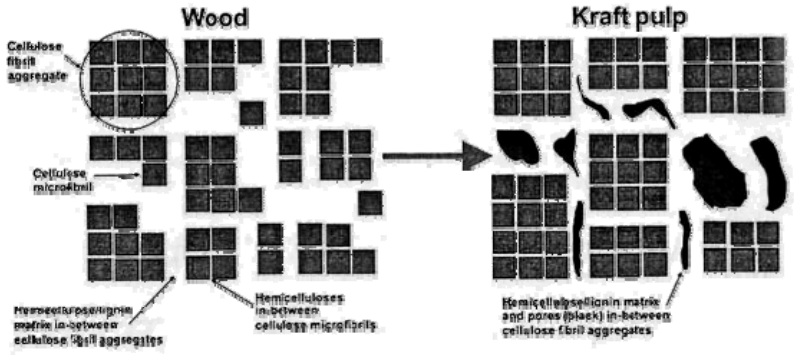


Figure 17. Dissolution of interstitial material from fiber cell wall and formation of cavities, (Fahlén 2005)

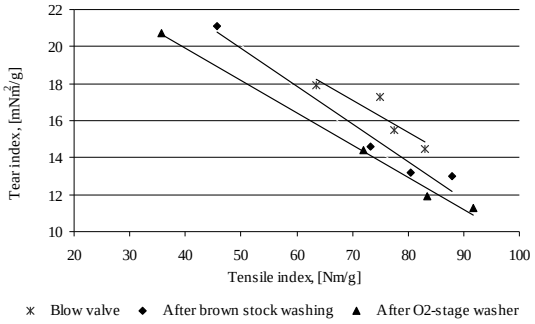


Figure 18. Tear index as a function of tensile index (PFI beating 0, 1000, 2000 and 3000 revs) in pulp samples from Mill B

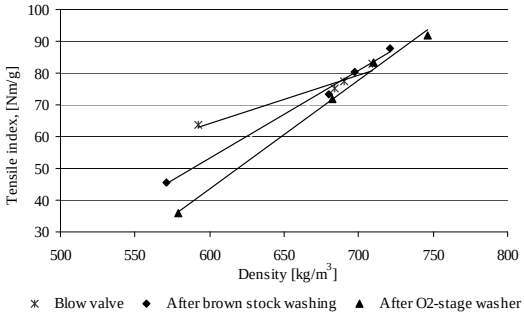


Figure 19. Tensile strength as a function of sheet density (PFI beating 0, 1000, 2000 and 3000 revs), Mill B

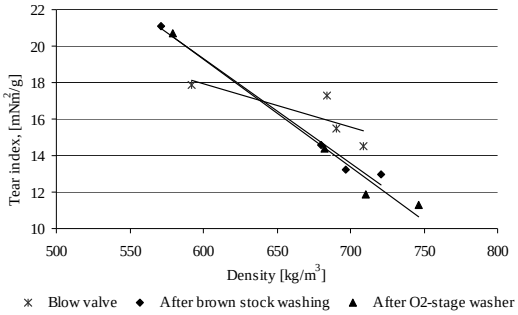


Figure 20. Tear strength as a function of sheet density (PFI beating 0, 1000, 2000 and 3000 revs), Mill B

Chemical modification of the fiber cell wall in the oxygen stage produced pulp with lower WZST (figure 21) even after beating as compared to the two other samples, and higher Scott-Bond (figure 22) in beaten pulps with an accompanying decrease in CSF, probably partially due to the formation of fines and higher drainage resistance caused by the fiber surface peeling also observed in the SEM images.

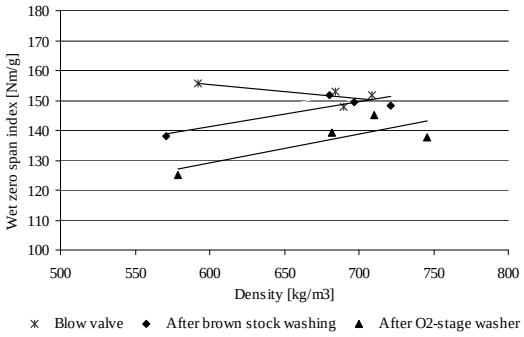


Figure 21. WZSTI as a function of sheet density (PFI beating 0, 1000, 2000 and 3000 revs), Mill B

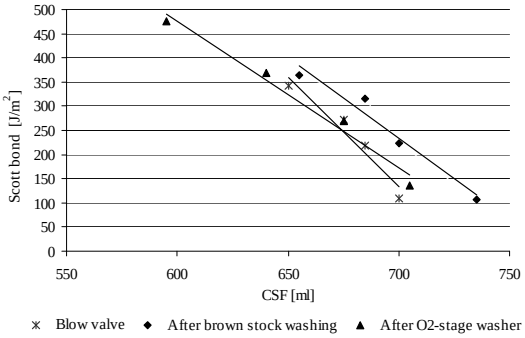
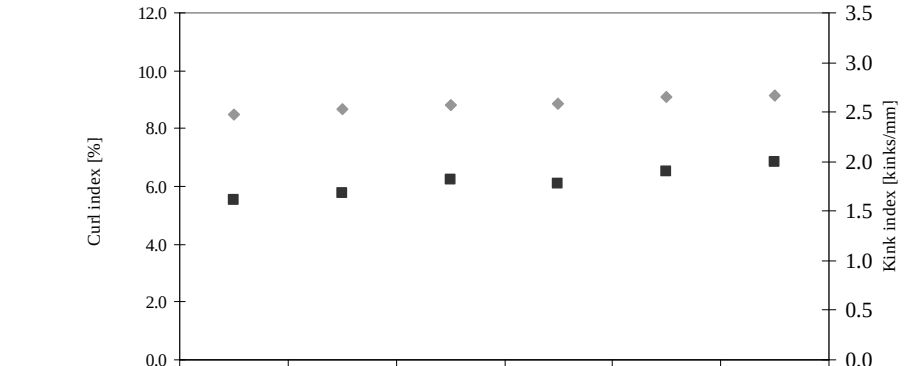


Figure 22. Scott-Bond strength as a function of CSF (PFI beating 0, 1000, 2000 and 3000 revs), Mill B

Mill F

The survey in Mill F showed that the level of fiber deformations after the blow valve was at the same level as in Mill B (figure 23). However, the increase in the deformation indices further along the fiber line in Mill F was quite moderate, and the level of fiber deformations after oxygen delignification was clearly lower, especially with curl index, than in Mill B.



	After the blow valve	After the blow tank, MC and control valve	After DD washers	After screening	After Enso filters	After O2 delignification
■ Curl index [%]	5.6	5.8	6.3	6.1	6.5	6.9
◆ Kink index [kinks/mm]	2.48	2.53	2.58	2.59	2.65	2.67

Figure 23. Changes in fiber deformation indices along the brown stock fiber line in Mill F, measured with FiberExpert, (LSD Curl index: 1% unit, kink index 0.20 kinks/mm)

The strength analyses showed that the initial tear-tensile strength of freshly-cooked pulp in Mill F was slightly lower than that of Mill B (figure 24). However, the decrease in strength along the brown stock fiber line was not as clear in Mill F as in Mill B. As a result, pulp strength in Mill F after oxygen delignification was slightly higher than in Mill B, which was partially caused by higher kappa after the oxygen stage in Mill F.

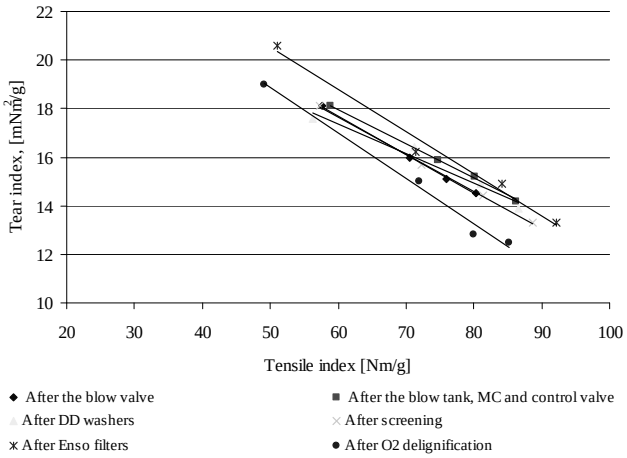


Figure 24. Tear index as a function of tensile index (PFI beating 0, 1000, 2000 and 3000 revs), in pulp samples from Mill F

All pulp samples except for the oxygen stage sample were quite similar with respect to tensile strength (figure 25). The oxygen stage reduced pulp tensile strength in both unbeaten and beaten pulps. Tear strength was affected by processing after pulp washing in Enso Filters and oxygen stage in such a way that tear strength in the unbeaten samples was increased with a decrease following pulp beating in the PFI mill (figure 26).

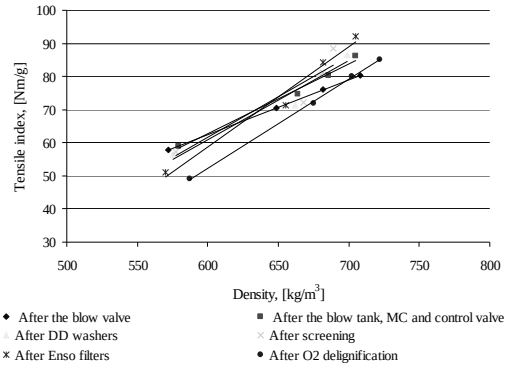


Figure 25. Tensile strength as a function of sheet density (PFI beating 0, 1000, 2000 and 3000 revs), Mill F

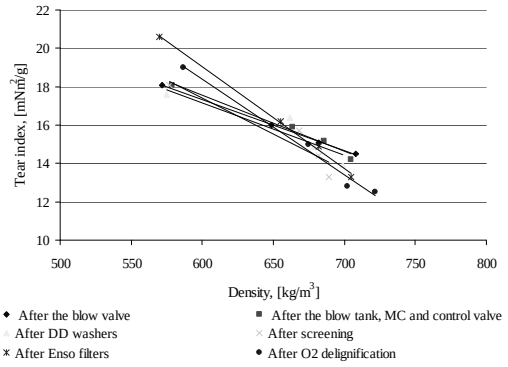


Figure 26. Tear strength as a function of sheet density (PFI beating 0, 1000, 2000 and 3000 revs), Mill F

WZSTI in the pulp samples from Mill F exhibited a similar pattern as was seen in the samples from Mill B. WZSTI decreased in unbeaten samples along the fiber line, but beating in the PFI mill reversed the changes in all samples except for the sample taken after oxygen delignification, where chemical modification of the cell wall took place. Overall, WZSTI was marginally on a higher level in Mill F than in Mill B, probably due to higher kappa.

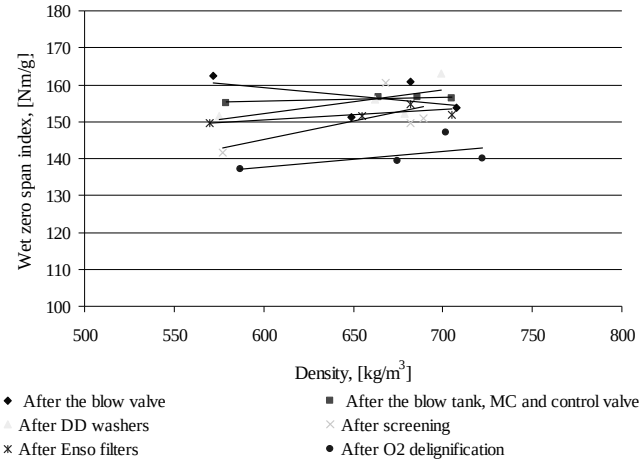
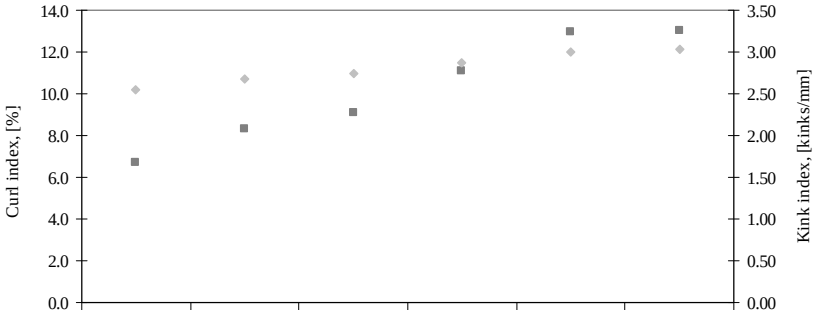


Figure 27. WZSTI as a function of sheet density (PFI beating 0, 1000, 2000 and 3000 revs), Mill F

4.2 Brown stock washing – mill case results

The zero study on the formation of fiber damage in the main brown stock process stages in Mill B gave reason to look more thoroughly into the effects of brown stock washers on pulp and fiber properties. An additional survey on pulp washing effects in Mill B showed that pulp washing in both an atmospheric diffuser and a brown stock DD washer increased fiber curl and slightly also kink (figure 28). However, the post-oxygen delignification DD washer had very little effect on fiber deformations. This indicates that the physical condition of the fibers entering the washer has a considerable effect on the magnitude at which a unit operation can induce fiber deformations.



	Blow valve	Atmospheric diffuser	Storage chest and MC-pump	DD 1 -washer	Oxygen delignification	O2 DD - washer
Curl index, [%]	6.7	8.3	9.1	11.1	13.0	13.1
Kink index, [kinks/mm]	2.56	2.67	2.75	2.87	3.01	3.04

Figure 28. Fiber curl and kink results in Mill B washer survey, measured with Fiber Expert (LSD Curl index: 1% unit, kink index 0.20 kinks/mm)

Generally, with an increase in curl and kink indices in industrial MC processing, an increase in dislocations also takes place. However, the dislocation analysis showed that the degree of dislocations increased rather linearly during brown stock processing, and the increase did not follow the pattern seen with fiber curl and kink indices, table VII. Dislocations are already common in untreated softwood tracheids entering the pulping process, and are also formed during cooking operations which was seen as a 1.4 degree of dislocations after the blow valve, but their amount increases during pulp processing due to axial compression strains on fibers (Green 1962, Stone 1961, Hartler et al. 1969, Allison et al. 1998, Ellis et al. 1997, Ellis et al. 1995). According to Allison and Ellis et al., dislocations develop especially due to medium consistency mixing operations. However, in this study the even increase in dislocations in each process stage suggests that compressive stresses are more or less present at the same magnitude throughout the fiber line. This would suggest that dislocations arise from something more constant like overall pulp handling and flow at 10% consistency in large volumes.

Table VII. Development of fiber dislocations along the fiber line

Process stage	**Degree of dislocations**
Blow valve	1.4
Brown stock washer 1 (Atmospheric diffuser washer)	1.7
Storage chest and MC pump	2.0
Brown stock washer 2 (Drum displacement washer)	2.2
Oxygen delignification	2.4
Post-oxygen washer (Drum displacement washer)	2.6

Pulp strength analyses showed that despite the increase in deformations, pulp washers did not decrease pulp strength properties at a tensile strength of 70 Nm/g, table VIII. The tear index at tensile 70 Nm/g decreased after the storage chest and MC pump, and further slightly during oxygen delignification. After the oxygen stage, drum displacement washer tear strength shows an ~7% increase back to the level of brown stock drum displacement washer. In general, the observed changes were quite small and varied within the confidence interval.

Table VIII. Pulp strength properties at tensile index 70 Nm/g

Process stage	**Tear index [mNm^2/g]**	**Scott-Bond [J/m^2]**
Blow valve	16.3	182
Brown stock washer 1 (Atmospheric diffuser washer)	17.1	207
Storage chest and MC pump	15.0	211
Brown stock washer 2 (Drum displacement washer)	15.2	217
Oxygen delignification	14.2	293
Post-oxygen washer (Drum displacement washer)	15.4	302

What really showed an interesting change were the Scott-Bond results at tensile 70 Nm/g with an almost linear increase in brown stock samples and a slightly higher increase in oxygen-delignified samples. The Scott-Bond test is very sensitive to fiber conformability and inter-fiber bonding, and less affected by fiber length or fiber strength. Campbell has proposed that pulp refining results in an increase in pulp conformability due to the breakdown of the fiber cell wall into separate lamellas, i.e. delamination. According to Page and De Grâce (1967), curlating, mechanical actions at high consistencies during pulp processing can produce fiber cell wall delamination, which then is further promoted by pulp refining. Keith et al. (1968) suggested that dislocations are localized separations of S_1 and S_2 layers, i.e. one type of delamination, usually occurring in the transverse direction in the fiber cell wall. Page and Seth (1980) also suggested that dislocations unlike fiber curl and kink cannot be removed with pulp beating. In the light of these previous observations, the Scott-Bond results were plotted against the degree of fiber dislocations. The obtained curve, figure 29, shows a good correlation between the degree of dislocations in unrefined pulp and Scott-Bond strength at a tensile index of 70 Nm/g, indicating that a higher degree of dislocations promotes fiber conformability in beaten pulps, an effect that is further promoted if the pulp has gone through oxidative chemical treatment (Forgacs 1961, Frölander et al. 1969).

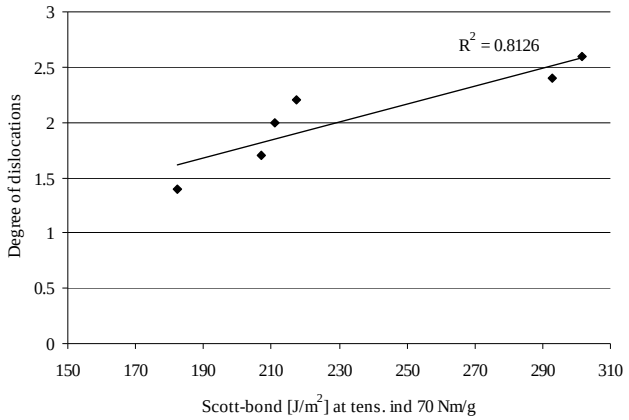


Figure 29. Degree of dislocations as a function of Scott-Bond strength at a tensile index of 70 Nm/g

4.3 The intrinsic mechanisms leading to fiber damage in industrial brown stock unit operations

4.3.1 Predisposition of fibers to damage during oxygen delignification

The results of this study are presented in detail in Paper II. The aim of this study was to provide some new insight into the effects of chemical components xylan, glucomannan and lignin on the susceptibility of fibers to damage during oxygen delignification. The targeted modification of

hemicellulosic components and lignin was carried out using specific enzymes on industrial pulp after which the pulp underwent oxygen delignification in laboratory scale.

This work confirmed the earlier findings that hemicelluloses play an important role as pulp strength promoting components. The results of this work also showed that hemicelluloses have a role in the ability of fibers to resist damage. Specific removal of xylan and glucomannan produced both pulps with a higher level of fiber deformations and also deformations that are more resistant to straightening in a PFI mill than the reference pulp, figure 30 (O Xyl = pulp with reduced xylan content, O Man = pulp with reduced glucomannan content, O Lac = pulp with reduced lignin content). Apparently xylan plays a more important role of the two hemicelluloses as pulps with a reduced xylan content had the highest levels of deformations in unbeaten pulp and pulps in all beating stages.

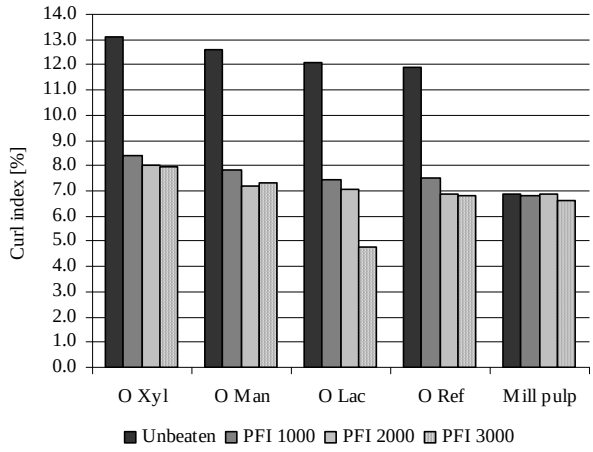


Figure 30. Fiber curl index in the unbeaten and beaten pulp samples (LSD Curl index: 1% unit, kink index 0.20 kinks/mm)

As a matter of interest, the procedure of enzymatic treatment comprising 20 h of mixing produced pulps with a very high curl index, which in turn affected the net forming properties of all treated pulps and a reference pulp as compared to the oxygen-delignified mill sample. Despite the higher curl values of treated pulps, the comparison of pulp strengths indicated that the removal of xylan leads to a reduction in tensile strength as has also been shown in previous studies, figure 31. Possibly the reduction of acidic xylan reduced the charge of fibers thus reducing swelling and fiber flexibility as proposed by Suurnäkki in 2001. According to Laine (1996), a higher fiber charge has a positive effect on the tensile strength of paper web, thus the result seems self-consistent. Since swelling also promotes fiber form stability as has been known in paper physics (Niskanen 2000), a reduction in swelling logically would be expected to produce an opposite effect, which would explain the higher curl index in all beating stages.

The degradation of glucomannan did not have the same effect on the tensile strength as xylan; however, the removal of glucomannan did decrease wet fiber strength measured with WZSTI, figure 32. The result goes well with the theory proposed by Salmén and Olsson (1998) that

glucomannan is more closely associated with the cellulosic fibril surfaces than xylan. Thus the degradation of mannan loosens cellulosic fibrils from their original location after which they do not transmit load as uniformly. The WZSTI of the pulp with a low xylan content was quite similar to the reference sample, with lower values in the unrefined sample and slightly higher after refining. The degradation of lignin produced the lowest WZSTI in the unrefined sample; however, after substantial refining, the laccase-treated pulp had an even higher WZSTI than the mill pulp. Overall, the results suggest that WZSTI is affected more so by the removal of glucomannan, and less by xylan or lignin.

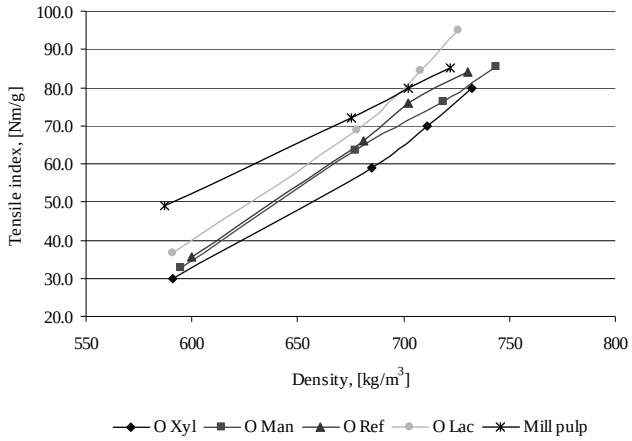


Figure 31. Tensile strength as a function of sheet density

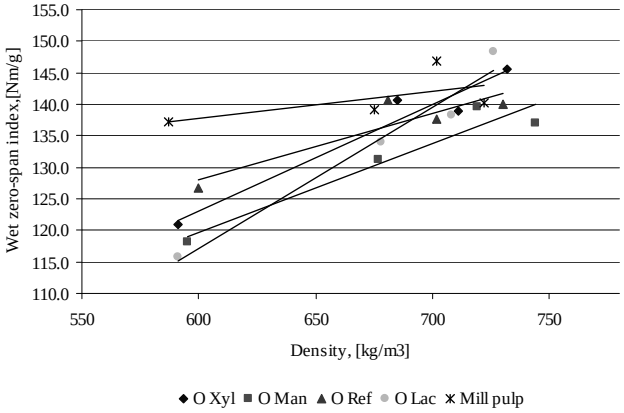


Figure 32. Wet zero span strength as a function of sheet density

The lower initial content of lignin prior to oxygen delignification resulted, after oxygen delignification, in a slight improvement in pulp tear strength properties and beatability even when compared to the mill pulp sample, figure 33. Due to its hydrophobic nature, lignin counteracts fiber

bonding and thus enhanced lignin removal improves paper strength (Annergren et al. 1962). Moreover, the specific removal of lignin increases the relative content of cellulose and hemicellulose in fibers. Since xylan promotes fiber form stability, glucomannan promotes wet fiber strength, and tear-tensile strength properties are attained in the cellulose net, these properties were not lost during the specific degradation of lignin and subsequent oxygen delignification but on the contrary were slightly enhanced due to the increased relative content of these components.

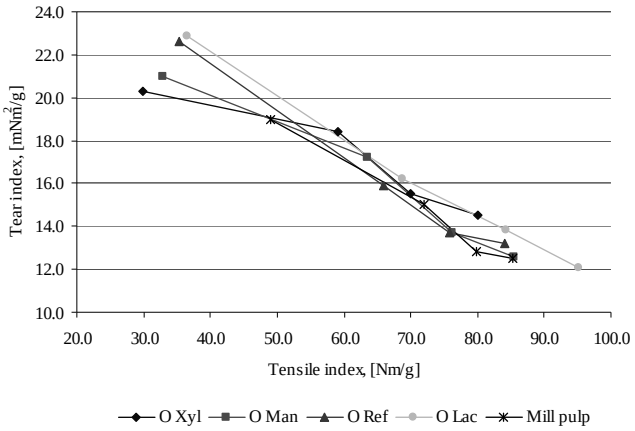


Figure 33. Tear index as a function of tensile index

In the pulping process, it is quite common that both hemicelluloses and lignin are modified to different extents depending on the cooking conditions, thus the chemical composition and ultrastructure of the fiber cell wall vary. Despite close interaction of the cell wall components with each other, there are technical means to increase the relative content of one or few of the components, usually hemicelluloses. Due to the variety of different cooking methods and additional treatments, the possibilities of chemical profile modification with subsequent effects on fiber properties will not be discussed here. It can only be concluded in general that the extent of fiber damage in unit operations is not governed by the process units alone, but also by the different chemical compositions of the fiber cell wall.

4.3.2 Mechanically induced fiber damage in mixing operations

The work presented in this chapter aimed to study the effects of high-intensity fluidization and basic mixing operations on fiber and pulp properties under conditions similar to those in mill processes. The study was conducted as on-site experiments in Mill B. The results of the fluidization study are presented in detail in Paper III and complemented in this thesis with a few references on slow mixing in a storage tank in Mill B.

Fluidization

The fluidization study was based on a new fluidization device, DMX, which enables the performance of laboratory scale studies in actual mill conditions, without the need for any supplementary pulp treatments and transportation prior to the testing. The device was connected to a pressurized pipe line at the mill site and adjusted to study the effects of fluidization on pulp properties with different fiber lengths, and the effects of fluidization time and intensity on fiber morphology. The results were compared to industrial high-intensity fluidization on the same fiber line. The effects of fluidization on the fibers in the proximity to the mixing area were also studied with Fiber Optics.

The trials with the DMX together with the Fiber Optics study showed that when the pulp is fluidized under conditions corresponding to mill scale processes, a fluidizing intensity well above the level where fluidization begins leads to a slight straightening of the fibers, and a fluidizing intensity at a level where fluidization begins may not be enough to produce the straightening effect for all of the fibers in the suspension, and this may still be seen as an increase in fiber deformations.

The DMX tests showed that trials TR1, TR2 and TR4 with a rotor speed of 1299 rpm gradually induced fiber curling and kinking, resulting in more than 1 percentage unit higher fiber curl index after the five sequences, whereas trial TR3 with a higher rotor speed resulted in a marginal decrease (seen as a downward trend, but within 1% variability) in the fiber curl and kink indices (figures 34 and 35). Trial TR2 with a longer residence time seemed to have a slightly higher increase rate of fiber deformations, although the result is mainly indicative due to the normal variation of fiber deformation indices with the same sample. Trials TR1 and TR4 appeared to have the same effects on the fiber deformation indices, i.e. the 0.11 mm difference in fiber length was not reflected in the development of fiber deformations during mixing.

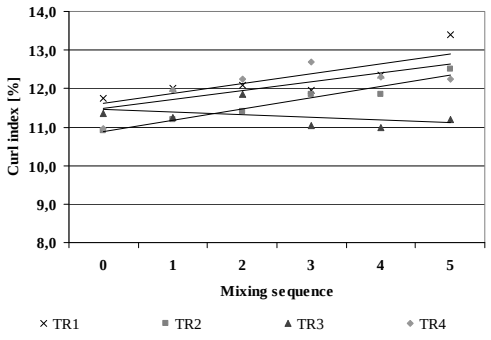


Figure 34. Fiber curl development in DMX mixing trials

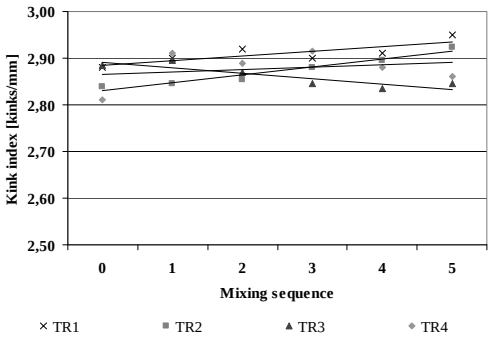


Figure 35. Fiber kink development in DMX mixing trials

The industrial mixer studies and Fiber Optics observations showed that the industrial mixer induces slight straightening of fibers during mixing and does not affect the papermaking properties of fibers, figures 36 to 39.

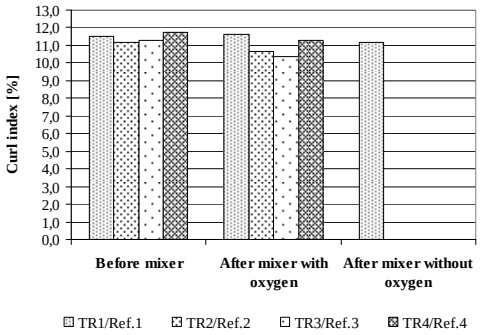


Figure 36. Fiber curl development in AM40 mixer, Mill B

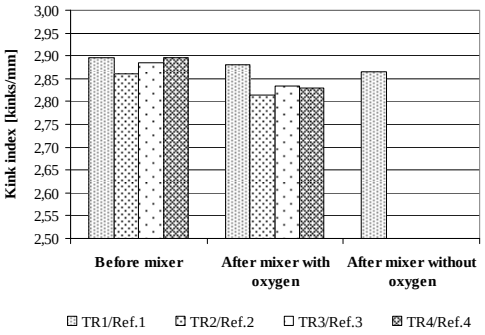


Figure 37. Fiber kink development in AM40 mixer, Mill B

Pulp strength analyses showed that mill pulp experienced rather insignificant changes in the strength properties, table IX. The unrefined tear index, which is very easily increased by fiber deformations (Page et al. 1985), and the tear index at a tensile strength of 70 Nm/g remained at the same level after the mill mixer with a small variation in both directions between the samples. The need for pulp refining to 70 Nm/g tensile index decreased slightly in mixed pulps probably due to oxygen addition, as in the sample TR1/Ref.1 (without oxygen addition) SRE was at the same level after the mill mixer.

Rewetted zero span strength experienced some decrease during oxygen mixing. Again according to Gurnagul and Page, WZST is highly dependant on the strength of the hemicellulose-lignin matrix and cellulose fibrils. Degradation of the matrix by chemical means, such as oxygen, allows fibrils to slide over one another resulting in the reduction of wet fiber strength (Gurnagul et al. 1989). Although in this study the pulp was only in a very short contact with oxygen before sampling and stabilizing the pulp, it nevertheless experienced slight decrease in kappa, indicating that delignification starts immediately once the pulp is in contact with the oxygen. WZST in the sample mixed without oxygen was at the same level as in the unmixed sample.

The Scott-Bond strength, which has previously been found to correlate with an increase in fiber deformations, only showed random variation in this case, indicating that the slight straightening experienced by the fibers did not affect the z-directional strength properties of pulp.

Table IX. Pulp strength properties before mixing and after mixing in AM40 with and without the addition of oxygen

Sample	Kappa	SRE [kWh/t]	Unrefined tear index [mNm^2/g]	Tear index [mNm2/g] at tensile [70 Nm/g]	Rewetted zero-span [Nm/g]	Scott-Bond [J/m^2]
TR1/Ref. 1						
Before mixer	22.2	1427	22.1	15.0	140.6	249
After mixing with oxygen	21.4	1128	20.7	15.1	137.2	260
After mixing without oxygen	22.4	1444	20.4	15.4	139.8	259
TR2/Ref. 2						
Before mixer	24.9	1162	21.8	16.2	143.9	242
After mixing with oxygen	22.5	946	21.4	15.4	138.0	219
TR3/Ref. 3						
Before mixer	24.0	1623	19.7	15.4	141.4	283
After mixing with oxygen	21.3	1581	21.9	14.5	140.7	287
TR4/Ref. 4						
Before mixer	24.9	1654	20.2	15.6	145.0	227
After mixing with oxygen	23.7	1457	21.6	16.8	143.9	231

The results are in line with previous studies carried out by Bennington et al. (1989), where they showed that pulp experiences light beating at energies below 2 MJ/kg. However, in this study the industrial mixer had considerably lower energy dissipation, in the range of 0.002-0.02 MJ/kg. The beating action seen with higher intensities in laboratory studies was not detected in industrial mixing, as confirmed by the strength analyses. The straightening of fibers that took place during industrial mixing is hence more of a hydraulic straightening than a result of the beating action.

It has been suggested that fluidization is the source of fiber damage when processing pulps at MC consistencies. Several studies have shown that fluidization induces fiber damage in softwood pulps, which manifests itself indirectly as increased sheet stretch and decreased tensile strength, and directly as an increased amount of severe microcompressions and higher degree of fiber curl, i.e. fiber deformations (Bennington et al. 1989, Seth et al. 1993, Seth et al. 1995, Ellis et al. 1997, Ellis et al. 1995). According to the fluidizing theory provided by Gullichsen et al. 1981, when pulp is totally fluidized, the flow has flow characteristics corresponding to those of water. According to Bennington et al. (1989), pulp suspensions display a range of fluid-like behavior during fluidization, extending from the motion of flocks relative to one another through to the motion of individual fibers relative to one another. The initiation of motion in a pulp suspension first occurs between flocks. As the applied shear is increased, the relative motion between flocks increases, and with a further increase, the shear flocks themselves are ruptured. Bennington et al. showed in their later work (1991) that at the point of fluidization defined by Gullichsen et al., the flocks could still be observed in the suspension, and fluidization on fiber level did not exist. In the same study Bennington et al. also demonstrated that different chamber geometries in the mixers produced different results.

The work presented in this thesis showed that MC fluidization in mill scale did not produce fiber damage, and the numerical data was explained by the image information obtained with Fiber Optics. With the use of Fiber Optics, it was possible to define the beginning and the end of

fluidization as well as the corresponding mixing intensities by analyzing freeze images. This work is presented in detail in Paper III.

With Fiber Optics it was noted that in the proximity to the mixing area, if the fluidization was sufficient, individual fibers were pulled out of the flocks into the flow resulting in straightening and simultaneous orientation in the direction of the flow. This observation corresponds to the observation made by Bennington et al. 1989 on the latter point of fluidization. Figures 38 and 39 present freeze images from the 12% consistency mixing trials. In figure 38 dyed fibers, seen as black lines, are clearly flocked. However, at a high fluidization intensity the fibers in the proximity to the fluidization area are straightened, oriented with the direction of the flow and after that pass the mixing area rather freely, figure 39.

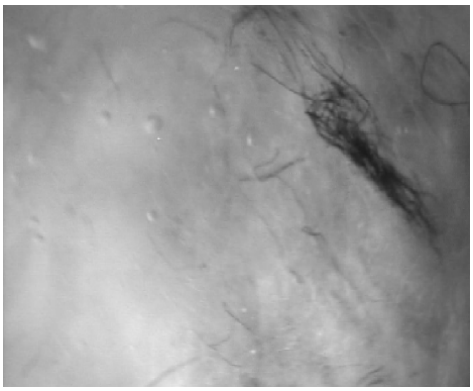


Figure 38. Unmixed pulp

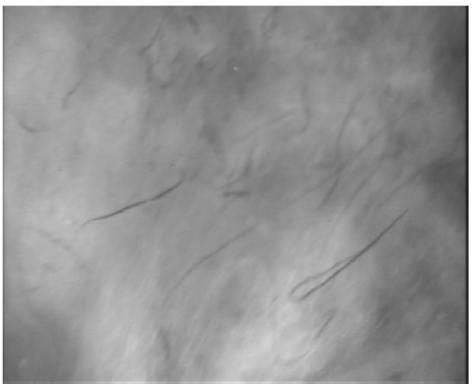


Figure 39. The point where individual fibers are pulled out of the flocks and oriented with the flow

The higher the consistencies, the higher the intensity, i.e. the rotor speed must be used to achieve a fluidization point were fibers are straightened. If the rotor speed is not high enough, only flocks are oriented, but fibers remain curled inside the flocks. The fluidization trials and Fiber Optics study together showed that if fluidization at the fiber level is not achieved, fiber deformations will increase. If the fluidization intensity is high enough, the fluidization on fiber level will result in slight straightening of the previously curled fibers, or the deformation level will remain unchanged.

In industrial mixers, the circumferential speed may vary depending on pulp consistency and flow rates. It is quite usual for industrial mixers to be overdimensioned with respect to the mixing intensity to ensure good mixing in all situations. Based on this study, it can be fairly suggested that fluidization in a well-dimensioned industrial mixer does not induce fiber damage for two reasons: the time during which the fibers are subjected to mixing is very short, and if fluidization on a fiber level is achieved, there will be no fiber deformation in the mixed pulp volume.

4.3.3 Effects of mechanical and chemical interactions in oxygen delignification

This study was conducted in order to separate the different effects of oxygen delignification chemistry and the mechanical actions of two-stage oxygen delignification mill machinery on pulp properties. The results are presented in detail in Paper IV.

The study showed that the mechanical actions of industrial oxygen delignification induced an increase in fiber deformations in the pulp, with the major increase taking place in the second stage of delignification or during pulp discharge from the reactor, figure 40. Again the oxygen mixer was found to slightly reduce the level of deformations in the pulp as was seen in the fluidization study.

Delignification itself did not increase fiber curl, but slightly increased fiber kink as was seen in the laboratory-delignified pulp.

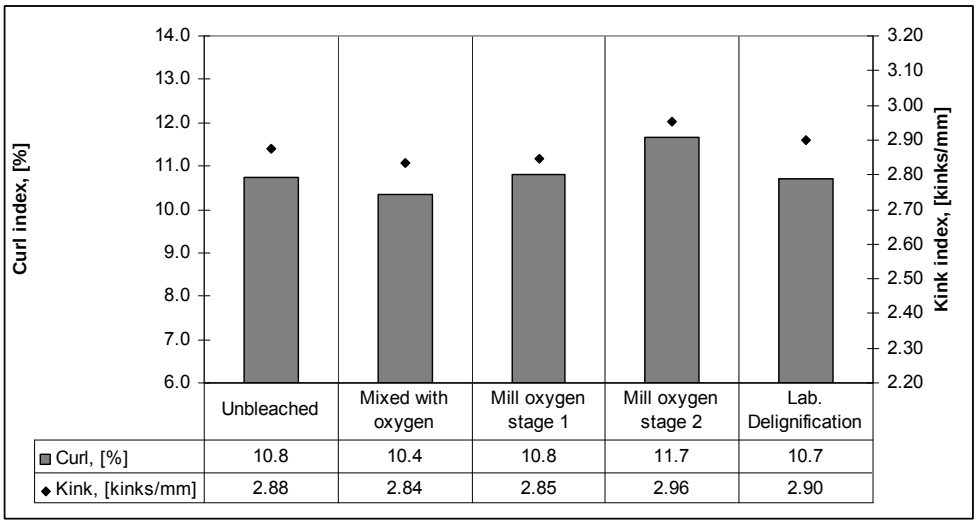


Figure 40. Fiber curl and kink indices, measured with Fiber Expert (LSD Curl index: 1% unit, kink index 0.20 kinks/mm)

Pulp strength properties experienced a surprisingly similar decrease in both laboratory and industrial delignification, which strongly indicates that the decrease in pulp strength in oxygen delignification was due to the chemical modification of the fiber cell wall structure, not to fiber damage caused by the machinery, figures 41 and 42. A clear and nearly identical decrease in tear strength properties after beating in both laboratory-delignified and mill-delignified pulps was observed. The mill-delignified sample exhibited a higher tensile strength than the unbleached and laboratory-delignified sample after an equal amount of beating; e.g. after 1000 revs of PFI beating the tensile indices were 64.1 Nm/g for the unbleached sample, 72.0 Nm/g for the mill-delignified sample and 65.1 Nm/g for the laboratory-delignified sample.

Both laboratory and mill delignification resulted in a similar decrease in WZSTI, consistently with a reduction in kappa numbers as compared to the unbleached sample. Almost identical WZSTI results

in the mill and laboratory samples strongly indicate that the marginal reduction in WZSTI was caused by the removal of interstitial material during oxygen delignification, through the mechanism proposed by Gurnagul and Page (1989).

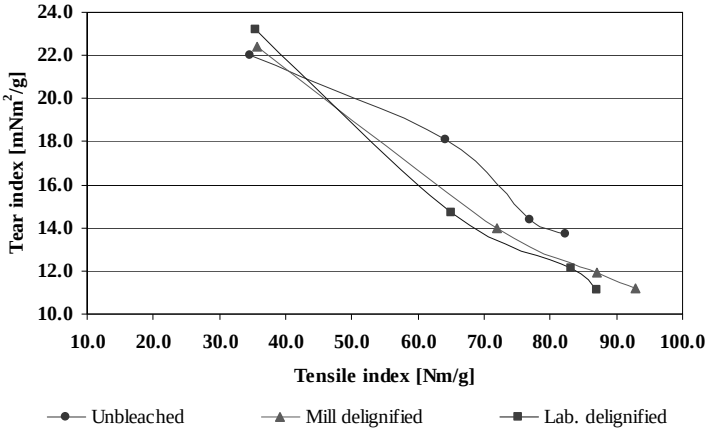


Figure 41. Tear strength as a function of tensile strength in unbleached, mill-delignified and laboratory-delignified pulps

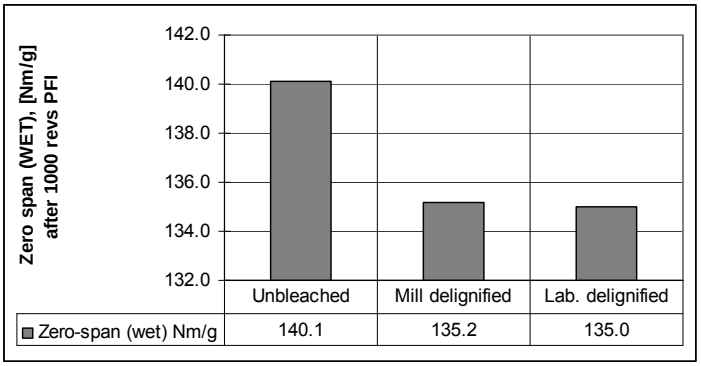


Figure 42. Wet zero span strength in unbleached, mill-delignified and laboratory-delignified pulps

The only difference seen between mill-delignified and laboratory-delignified pulp was that the mill pulp had more conformable fibers, due to the irreversible dislocations as fiber deformations were evened out prior to pulp strength testing. Higher conformability resulted in a larger binding area and consequently higher z-directional strength (measured as Scott-Bond, figure 43) and higher tensile strength after beating in mill-delignified pulps. This observation differs from the results obtained in previous similar studies done by Allison et al. The results of this work suggest that mechanically-induced fiber damage during oxygen delignification is highly dependent on the type of the

machinery, and with correct process solutions it can be minimized. However, strength reduction due to the treatment of the pulp with oxygen is unavoidable even with the gentlest possible mechanical treatment conditions.

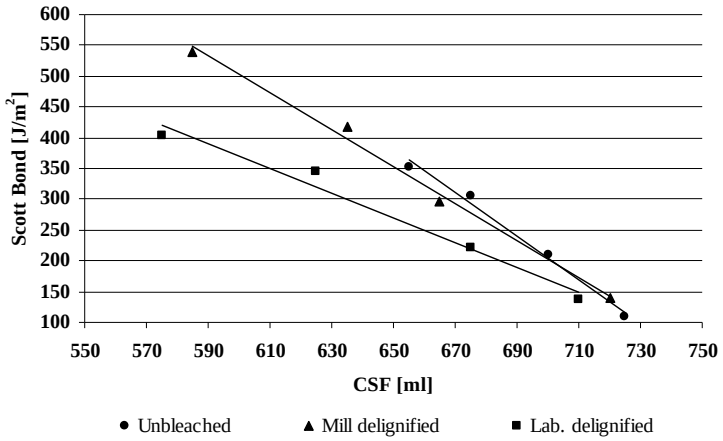


Figure 43. Scott Bond strength as a function of CSF in different beating steps

4.3.4 Effects of screens and location of screening on fiber morphology

The objective of this work was to study the effects of screens and the location of screening on pulp properties. The data presented here is previously unpublished.

All studied cases showed that screening operations, knot removal and primary screening did not increase fiber deformations measured as fiber curl and kink with Fiber Expert, figure 44. The results showed weak signals that screening actually has the potential to slightly straighten the fibers. Some small, arbitrary and statistically insignificant variations in fiber length were observed (figure 45).

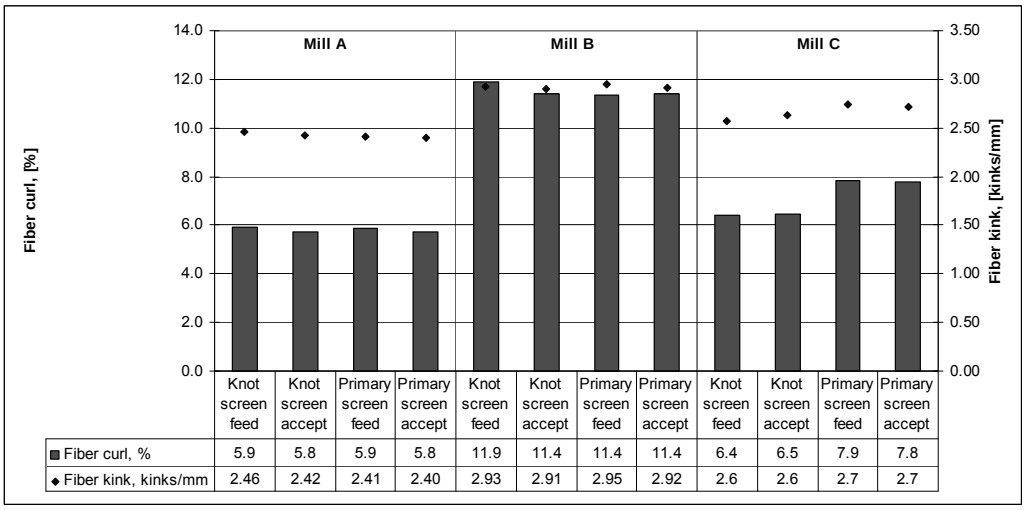


Figure 44. Fiber curl and kink results, measured with Fiber Expert (LSD Curl index: 1% unit, kink index 0.20 kinks/mm)

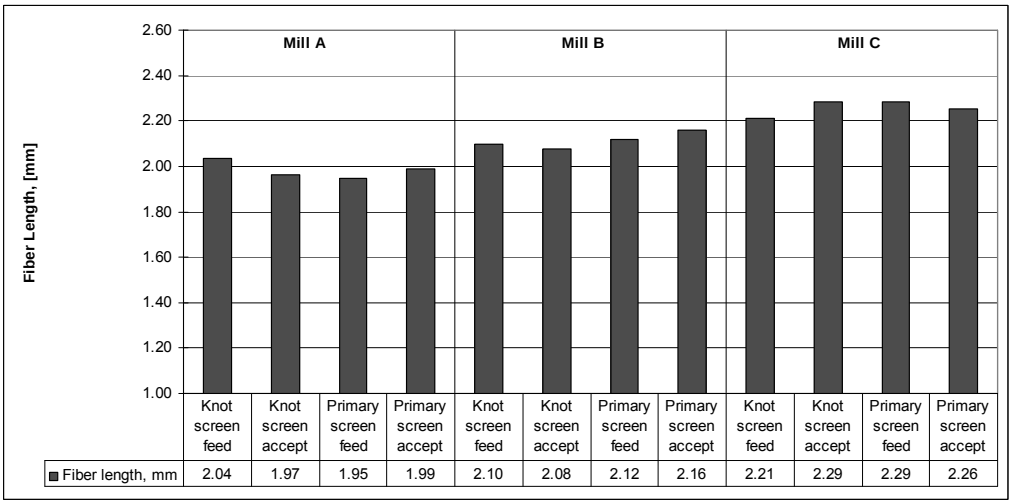
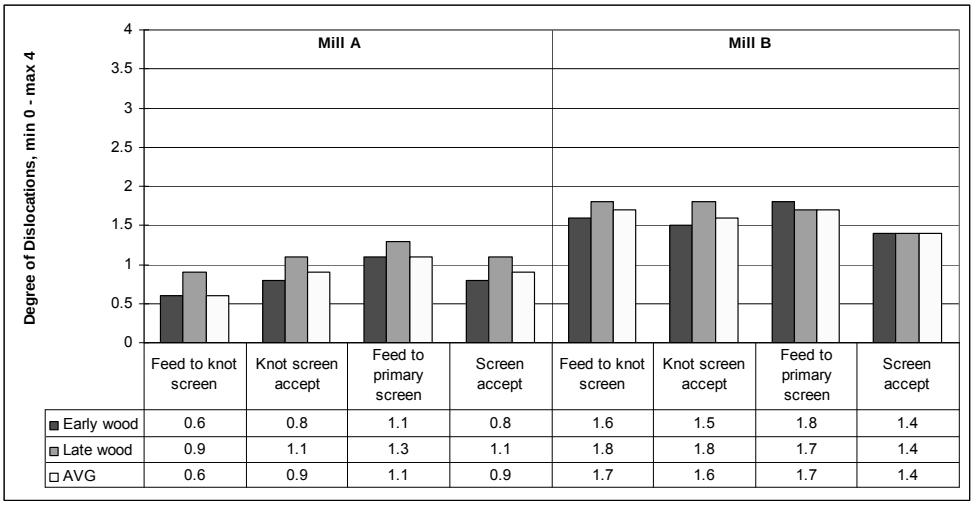


Figure 45. Fiber length, measured with Fiber Expert

A dislocation analysis was performed with a light microscope on 500 fibers. Generally, once a true dislocation (with an accompanying separation of S_1 and S_2 layers) has formed, it is difficult to remove it even with pulp beating. Hence, when moving along the fiber line, the amount of dislocations cannot decrease. If a decrease is observed in a downstream process, it is probably a result of variation or a sample that is not representative enough, or an interpretation mistake. When studying deformed fibers under a light microscope, it was noted that sometimes curled and kinked regions reflected light in a manner that resembled a reflection caused by cell wall dislocation. In the studied cases (Mills A and B), dislocation measurement showed that in Mill A knot removal would

have increased and the primary screen would have decreased the level of dislocations in the pulp (figure 46). The results should be interpreted as follows: the increase in the amount of dislocations is probably true in the knot removal stage; however, a decrease in the level of dislocations in the following screening is unlikely and what is observed is the marginal straightening of curl and kinks. In Mill B where the level of deformations was considerably higher, a decrease in the level of dislocations was observed in all screening stages.



	Feed to knot screen	Knot screen accept	Feed to primary screen	Screen accept	Feed to knot screen	Knot screen accept	Feed to primary screen	Screen accept
Early wood	0.6	0.8	1.1	0.8	1.6	1.5	1.8	1.4
Late wood	0.9	1.1	1.3	1.1	1.8	1.8	1.7	1.4
AVG	0.6	0.9	1.1	0.9	1.7	1.6	1.7	1.4

Figure 46. Degree of dislocations in samples for Mill A and B

The conclusion is that screening may induce dislocations if the fibers to be screened have a low level of deformations when entering the stage. If the fibers entering the screening stage are already heavily deformed, the screening stage has the potential of slight straightening of the deformations, if the orientation of the fibers with the flow is achieved. However, it is unlikely that screening has the potential of evening out truly dislocated regions.

The numerical data on fiber deformation and straightening during screening is supported by optical observations done by Rasa in his thesis in 2004. Rasa studied the passage of fibers through the screening openings with Fiber Optics attached to a screening simulator. The images show that the suction flow has the potential to straighten the fibers. In such a case the fibers in pulp at low consistencies can pass through the screen openings aligned with the flow and be straightened. However, this does not happen in all cases, and some of the fibers pass through the screen plate openings while bent. This may cause different outcomes depending on the original condition of the fibers; if the fibers already contain deformations, the bending will preferably take place at the point of previous bending as the resistance to deformation at this point is lowest, and if the fibers are intact, new deformations will be formed. The image in figure 47 shows both cases.

The results give reason to suggest that screening should preferably be done on already deformed pulp as far at the end of fiber line as is possible. In this way, the screening will only have beneficial effects on fiber morphology.

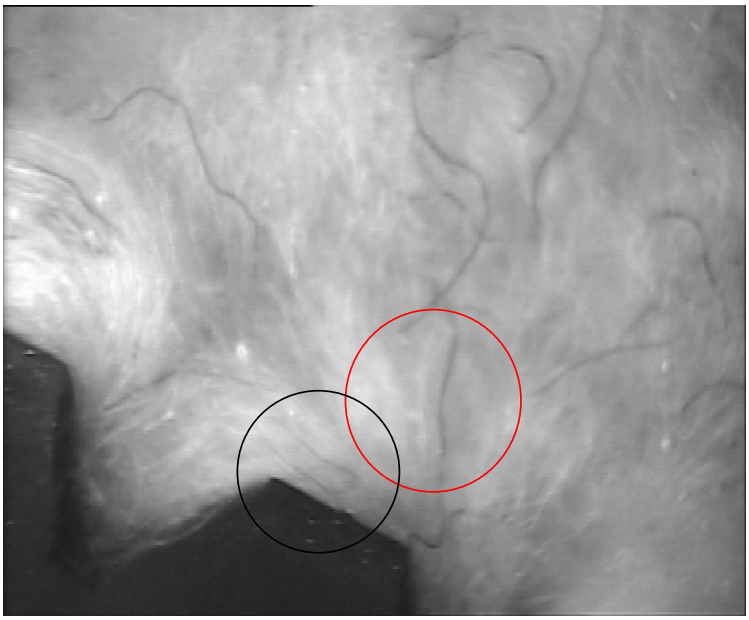


Figure 47. The passage of softwood fibers through the screen plate openings at 4.3 % consistency during screening (Rasa 2004)

5 CONCLUSIONS

The purpose of this work was to study industrial scale fiber damage and, through additional laboratory studies and simulations, to find explanations as to where and why fibers in industrial processes are deformed and loose their strength.

The findings presented here and in relevant publications showed that each process stage has its characteristic effects on fiber properties. Some of the unit operations along the fiber line produced clearly detectable changes in fiber properties such as deformations and pulp strength decrease, while others resulted in merely slight or very slight changes, such as screening and industrial fluidization. Different treatments e.g. mechanical and chemical in a single unit operation also produced distinct changes in the fibers which of course were reflected as a combination in the overall pulp quality, as was seen in the oxygen stage study.

Pulp washing

Pulp washing in displacement washers itself was found not to inflict strength deteriorations in any of the studied washers, although an increase in fiber deformations and conformability was detected. However, subsequent operations in washing stage storage chests and pumping did contribute to strength deterioration. The increase in deformations during washing also depended on the initial condition of the fibers; if the curl was already high, any additional increase in deformation indices was not detected.

Pulp screening

Pulp screening proved to be quite a gentle treatment, although also in this case two possible outcomes were identified depending on the initial condition of the fibers entering screening. If the screening was done right after the cooking stage on intact fibers, the treatment inflicted some increase in deformations. Screening of already deformed fibers after the oxygen stage on the other hand had an opposite effect and showed to slightly even out the deformations. Thus it would seem to be beneficial to place the screening stage as far at the end of the brown stock fiber line as possible, if deformations are to be avoided or if the fiber line processes very long fibers.

Pulp mixing and fluidization

Pulp mixing in a fluidizing industrial mixer was found to slightly even out the deformations. However, laboratory simulations and previous studies showed that the mixing time and intensity have a crucial effect on whether the fibers will experience deformation or straightening during mixing operations. In rotating mixers, the intensity of mixing must reach a point where single fibers are oriented with the flow and are allowed to flow freely, and the active passage through the mixing chamber must only last for a fraction of a second. If the fluidization and mixing are done keeping these two guidelines in mind, the treatment will not have detrimental effects on pulp properties.

Oxygen delignification

Several studies have previously shown that oxygen delignification is detrimental to pulp strength properties due to both chemical and mechanical actions. This work confirmed that the chemical treatment of pulp with oxygen reduces fiber strength and is unavoidable due to the alteration of the fiber cell wall structure. However, the mechanical actions of mill scale machinery in two-stage oxygen delignification did not clearly contribute to a further deterioration of pulp strength, but merely increased the amount of irreversible dislocations in fibers and thus increased fiber conformability. Increased conformability was found to be reflected as a higher z-directional strength and tensile strength after the beating of mill-delignified pulps.

The chemical composition of the fibers entering the oxygen stage was also found to affect the susceptibility of fibers to damage during oxygen delignification. Fibers poor in hemicelluloses have the smallest resistance to mechanically-induced deformation and will also develop deformations that are quite resistant to straightening during beating. The higher level of deformations in beaten market pulp alone will have a negative impact on the tear-tensile strength. Besides the effect of hemicellulose on fiber form stability, xylan and glucomannan were also found to contribute to different strength properties in the pulp: pulp with a lower xylan content had a lower tensile strength and pulp with a lower glucomannan content exhibited decreased fiber strength while wet. The different effects of these hemicelluloses on fiber properties result from the different location of these components in the cell wall with respect to the cellulose fibrils. Pulps that had experienced specific removal of lignin prior to oxygen delignification exhibited slightly improved strength properties and beatability as compared to the oxygen-delignified mill reference pulp.

Concluding remarks – industrial fiber damage

In the end, it is nearly impossible to unambiguously explain industrial fiber damage – so complex and multifaceted phenomenon it is. If we return to the original definition of fiber damage which was investigated as the difference in quality between laboratory and industrial scale pulps, we see that the approach is problematic as in practice it is nearly impossible to fully simulate industrial conditions in laboratory scale and vice versa due to the huge scale differences. At the same time, it is good to point out that while the volumes in the industrial scale increase as compared to the laboratory ones, the size of the fibers remains constant, so the implications of e.g. mixing a pulp batch in a 30 l tank are quite different from those obtained by mixing pulp in a 3000 t tank. So the problem actually is the scale and the comparison of laboratory pulps to industrial ones would in this case be useless, and will only provide us with the information on how well things could be. To the aforementioned, it must also be pointed out that laboratory scale fiber treatments can produce fibers with damage that has not been detected in industrial pulps, which of course does not have any significant value to the evaluation of the performance of industrial unit operations.

If, instead, we look at the absolute changes in the fibers, such as deformations and strength loss, it is easier for a single fiber line to identify which of the changes are undesired yet unavoidable and which can be tolerated if not even avoided. In the end, this is a question of the end product quality and purpose of use: what some producers will consider being damage, others in fact will consider to be a desired feature.

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