EFFECTS OF HEATING, DRYING AND STRAINING ON THE RELAXATION AND TENSILE PROPERTIES OF WET PAPER

by
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Preface

Abstract

   Producers, converters and printers of paper try to maximize the production and minimize the waste. The runnability of paper web plays an important role when the efficiency of processes is improved. This investigation was here focused on evaluating in-plane viscoelastic strength properties of paper when miming the conditions typical of the paper machine press and dryer section. In order to study the effects of refining, straining, heating and drying on wet paper strength properties, new test methods were developed. The advantage of these methods was to produce more realistic laboratory data for evaluating the runnability of wet paper web in the paper machine and that of dry paper web in the converting and printing processes.

   Measurement of the residual tension in a tension relaxation test is essential for describing the runnability of a pulp furnish in the paper machine. In addition to this, several parameters are needed to describe the runnability of wet and dry paper web. The tension-strain behavior of wet paper and web handling in the paper machine determines to large extent the runnability potential of dry paper. Wet web draws during drying influence the tension-strain properties of dry web that govern the dry web runnability.

   In wood containing printing paper grades (NEWS, LWC, SC) the runnability potential of mechanical pulps (TMP, PGW) is very good compared with that of chemical reinforcement pulps. The effect of addition of bleached softwood reinforcement pulp on the tension-strain properties of mechanical-pulp-based furnish is different for dry and wet paper. Generally, in mechanical-pulp-based furnishes, bleached softwood reinforcement pulp is not able to improve the tensile stiffness of wet paper. However, the reinforcement ability of bleached softwood kraft pulp in wet paper depends on the strength properties of the mechanical pulp there.

   Heating has a strong negative influence on the strength and relaxation properties of wet paper. Decrease of its tensile stiffness can be explained by softening of polymers in the cell wall of fibers. The observed temperature-accelerated relaxation in wet paper seems to be analogous to the moisture-accelerated creep phenomenon in dry paper. Elevated temperatures used in the paper machine have a strong influence on the wet web tensile behavior, e.g. in the transfer from the press to the dryer section, as the tensile stiffness is decreased and increasing tension relaxation of the wet web.

   This work raises some fundamental aspects in the complex subject of the paper web runnability, and aim to provide tools for the controlling the wet web tension-strain behavior, and ensuring properties of the end product.

Keywords Drying, filler content, heating, jet/wire speed ratio, refining, relaxation rate, residual tension, runnability, tensile strength, tensile stiffness, wet paper

List of publications

I. Kouko, J., Retulainen, E. and Kekko, P. (2014): Straining and relaxation properties of wet paper during heating, Mech. Time-Depend. Mater. 18, 697-719.

II. Kouko, J., Kekko, P. and Retulainen, E. (2014): Influence of straining during wet pressing and drying on strength properties of paper, Nord. Pulp Paper Res. J. 29, 453-461.

III. Kouko, J., Kekko, P. and Retulainen, E. (2014): Influence of filler content, jet/wire speed ratio and straining during drying on strength properties of paper, Nord. Pulp Paper Res. J. 29, 700-710.

IV. Kouko, J., Kekko, P., Liimatainen, H., Saari, T. and Kurki, M. (2006): Wet runnability of fibre furnish for magazine papers, Paperi Puu 88, 169-174.

The author of this Thesis is the principal author of all papers. All the calculations have been performed by the author. The author has performed all the measurements in the papers I and IV and significantly contributed to the execution and supervised all the measurements in the papers II and III. The author has significantly contributed to development of the measuring and analysis methods related to the two tensile testers.

RELATED SUPPORTING PUBLICATIONS

V. Kurki, M., Kouko, J., Kekko, P. and Saari, T. (2004): Laboratory Scale Measurement Procedure of Paper Machine Wet Web Runnability: Part 1, Paperi Puu 86, 256-262.

VI. Kouko, J., Salminen, K. and Kurki, M. (2007): Laboratory scale measurement procedure for the runnability of a wet web on a paper machine: Part 2, Paperi Puu 89, 424-430.

VII. Lappalainen, T. and Kouko, J. (2011): Determination of local strains and breaking behaviour of wet paper using high-speed camera, Nord. Pulp Paper Res. J. 26, 288-296.

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List of symbols

a_i	A constant
c	Specific heat of a dry paper
CR_i	Contribution ratio
e	Emission factor
F_0	Value of a statistical F-test
h	Heat transfer coefficient of free convention
L	Half a thickness of a wet paper before a test
m	Mass
m_{cp}	Added mass coefficient
R	Tension relaxation rate
$R_\%$	Relaxation percentage
R_{web}	Radius of web curvature
S	Tensile stiffness
S_i	Tensile stiffness of a sheet with low bonding
S_0	Tensile stiffness of a well-bonded sheet
SS_i	Sum of squares
t	Time
T	Tension
T_c	A constant for tension
T_0	Initial tension of relaxation
T_{Res}	Residual tension
TS	Tensile strength
v	Velocity of web
X, Y, Z	Cartesian coordinates
W_{adh}	Adhesion energy
β	Take-off angle
ε	Engineering strain
θ	Temperature of a paper
θ_i	Initial temperature of a paper
θ_∞	Temperature of moving air at a paper surface
θ_{sur}	Temperature of surrounding air
ρ	Density of a wet paper sample
σ	Stefan-Boltzmann coefficient
Φ	Efficiency factor
Δp	Average pressure difference
ΔW_E	Recoverable elastic energy
ΔW_H	Hysteresis work

List of abbreviations

ANOVA	Analysis of Variance
BSK	Bleached softwood Kraft
EBS	Elastic breaking strain
ECF	Elementally chlorine free
IR	Infrared
LC	Lumped capacitance
LWC	Lightweight coated
MD	Machine direction
NEWS	News paper
PGW	Pressure groundwood
PID	Proportional-integral-derivative
RH	Relative humidity
SC	Super calendered
TMP	Thermomechanical pulp

1 Introduction

During the past centuries since its invention, paper has had an enormous role in the development of science and communication between the people in the world. Yet, nowadays paper is losing its importance as information carrier, but its other uses are still growing. It is obvious that paper will be produced for a long time in the future. Already, the first handmade paper making processes utilized its principal stages, which include: beating of natural fibers, fiber, draining fine fiber suspension through a cloth or screen, pressing and drying [Lindberg 2000]. Modern industrial papermaking is an advanced complicated process, but however the basic operations are the same [Paulapuro 2000, Norman, Söderberg 2001, Norman 2000, Lumiainen 2000, Sundholm 1999, Kuhasalo *et al.* 2000].

Essence of the papermaking process is removal of water in the paper machine. Consistency of the paper making furnish, which enters the forming section of the paper machine is typically between 0.2-1.0% [Kuhasalo *et al.* 2000]. Further, when the stock consistency increases to around 20% in the forming section, furnish can still be defined as fluid, but it has also measurable mechanical strength properties like a solid web [Kerekes 2006, Bousfield 2008, Derakhshandeh 2011, Lyne, Gallay 1954a, Lyne, Gallay 1954b, Brecht, Erfurt 1959, Barnet, Harvey 1980a, Barnet, Harvey 1980b, Seth *et al.* 1982, Pikulik 1997, Kuhasalo *et al.* 2000, de Oliveira *et al.* 2009]. At a 40-50% solids content, the strength of wet paper web is already sufficient so as to pass short distances without a support of fabric or cylinder in a modern high speed paper machine [Paulapuro 2000, Kiiskinen *et al.* 2000, Kurki *et al.* 2000].

The physics of continuous materials with both solid and fluid characteristics is called rheology [Findley *et al.* 1989, Owens, Phillips 2002, Lakes 2009]. Paper is such a material and more particularly, it can be considered as a viscoelastic material [Steenberg 1947, Steenberg 2006, Niskanen 1998, Mäkelä, Östlund 2003, Coffin 2005, Coffin 2009, Sorvari 2009]. Viscoelasticity of a wet paper web viscoelasticity is relevant for the runnability of a modern paper making process, because of the finite deformations at short times in the press and dryer sections of the paper machine [Findley *et al.* 1989, Jantunen 1985, Kurki *et al.* 2000, Mäkelä 2007, Lakes 2009]. Tension in a wet and dry paper web is non-linearly proportional to its strain, and depends of the strain rate [Steenberg 1947, Andersson, Sjöberg 1953, Göttsching 1970, Hauptmann 1977, Niskanen 1998]. Strain in paper is not completely recoverable once the tensile load is removed, part of the recovery is time-dependent and part is non-recoverable [Skowronski, Robertson 1986, Lakes 2009]. Viscoelastic materials exhibit characteristic responses: tensile creep, tension relaxation and tensile stiffness depend on the strain rate, hysteresis occurs in cyclic loading leading to dissipation of mechanical energy, and acoustic waves experience attenuation [Lakes 2009]. Viscoelastic materials are typically sensitive to temperature changes [Lakes 2009]. These phenomena govern the tensile behavior of paper web in the papermaking, converting and printing processes [Craven 1962, Okushima 1977, Haslach, Abdullahi 1995, Habeger, Coffin 2000, Coffin 2005,

Kekko *et al.* 2009, Retulainen, Salminen 2009]. The tension-strain behavior of wet paper is described in Fig. 1.
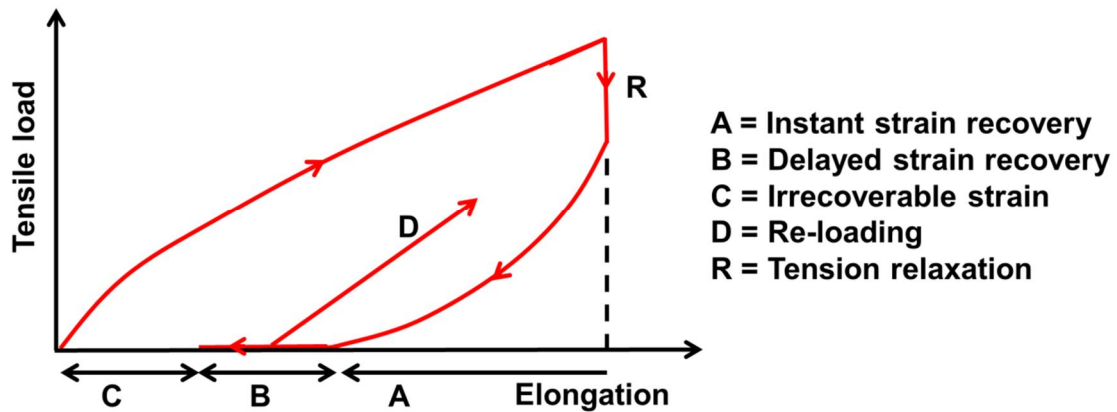

Figure 1. A schematic description of the viscoelastic tension-strain behavior of wet paper in a uniaxial tensile test (which displays the hysteresis effect).

Understanding of viscoelasticity of a wet web would enables improvement of web runnability in the paper machine. Good runnability is defined as a continuous machine operation with a minimum break frequency while the productivity of the machine and amount of waste are maintained at a desirable level [Roisum 1990a]. High speeds require an extremely high runnability of the web both in the press and dryer sections. Runnability problems may arise from different factors [Roisum 1990b, Deng *et al.* 2007, Salminen *et al.* 2010, Ora 2012]. A key to runnability of the wet web in the paper machine is the ability of the web to maintain a sufficient tension under different draw sequences in the various sub-processes [Pikulik 1997, Publication IV]. In a modern paper machine stabilizing systems which create a vacuum, e.g. suction rolls and blow boxes, are essential for the runnability of the wet web [Leimu 2008, Juppi 2010, Kurki *et al.* 2010]. However, a wet web is insensitive to even large defects [Ora 2012].

Advanced modeling is commonly used for estimating or solving problematic situations in complex processes such as ones that occur in the paper machine. Also, multi-variant analysis methods are useful optimization tools. However, atomic or molecular models are incapable of evaluating the viscoelastic response [Lakes 2009]. Unquestionably, material models of the wet web behavior require properly tailored measurements, because conditions for a web in the paper machine are far from standardized laboratory conditions. Some of the conditions, e.g. fast strain rate of open draws and elevated temperatures of wet paper, are also difficult to mimic in the laboratory.

The most challenging area for wet web runnability is the first open draw between the press and dryer sections and the first opening gaps of the cylinder dryer. Runnability of a wet web in the paper machine is significantly affected by furnish, web tension, relaxation phenomena, solids content of the web, machine speed and geometry, use of supporting fabrics and other web runnability stabilizing systems, to mention a few [Mardon, Short 1971, Ionides *et al.* 1977, Kuhasalo *et al.* 2000, Leimu 2008, Edwardsson, Uesaka 2009, Pakarinen *et al.* 2010]. However, a wet paper web gradually

transforms into a dry paper web during the wet pressing and drying stages. Mechanical properties and structure of the web evolve constantly during the papermaking process enhancing also the runnability [Heikkilä, Paltakari 2010, Kiiskinen *et al.* 2000].

Runnability of a dry paper web is essential in all the converting processes, where the unwinding/winding step is included. Uesaka *et al.* have performed a comprehensive field investigation of the factors which control the breaks of a dry paper web in the printing process [Uesaka *et al.* 2001, Uesaka 2005]. Majority of the web breaks are caused by tension variations and web strength variations in the printing process. The paper strength properties, which control the runnability of the printing process are MD tensile strength, MD strain at break and the uniformity of tensile strength. One of the objectives of this Thesis was to investigate effects of some papermaking process parameters, especially the effect of press and dryer section draws, on the strength properties of paper, which control the runnability of the printing process.

This Thesis is aimed to clarify the reinforcement potential of various mechanical pulps and softwood kraft pulp in SC and LWC type furnishes as well as its influence on the wet web runnability. Rheology of wet paper as a solid material was considered under the conditions that simulate the paper machine process. Papermaking process was mimicked via tensile, relaxation and multi-stage straining tests during heating and drying at high speeds. Influence of activation and bonding of the fiber network on some viscoelastic phenomena are also discussed (for activation and bonding of the fiber network, see for example [Lobben 1975, Retulainen 1997, Vainio 2007]. One of the targets was to observe the rheological time-dependent tension-strain behavior of wet paper, since it plays a key role in the web transfer from the press to the dryer section. Effect of heating on the relaxation behavior of wet web, in particular, is a poorly known phenomenon. A better understanding of the effects of heating and drying on wet paper have practical significance, as then commonly happen in paper and board machines.

1.1   Development of fast tensile test methods for wet paper at VTT

Production speeds and efficiency of the fastest paper machines have continuously increased over the past century [Schlegel 2001, Diesen 2007, Kurki *et al.* 2010, Publications V-VI]. The major developments have been based on more stable and better-controlled processes and an efficient utilization of raw materials [Kuhasalo *et al.* 2000, Lindberg 2000, Juppi 2010].

One of the most critical areas in runnability is the first draw in the press-to-dryer-section area [Kuhasalo *et al.* 2000]. At that point the paper web is typically at a 40-50% solids content and its strength is only 10-15% of that in dry paper [Kurki *et al.* 2010]. Traditionally, the press-to-dryer-section transfer "runnability turbulence" is handled by adjusting the speed difference between the press and dryer sections. However, increasing machine speeds increase the needed web tension and strain in an open draw (see Fig. 2) [Kuhasalo *et al.* 2000, Juppi 2006, Edwardsson, Uesaka 2009].
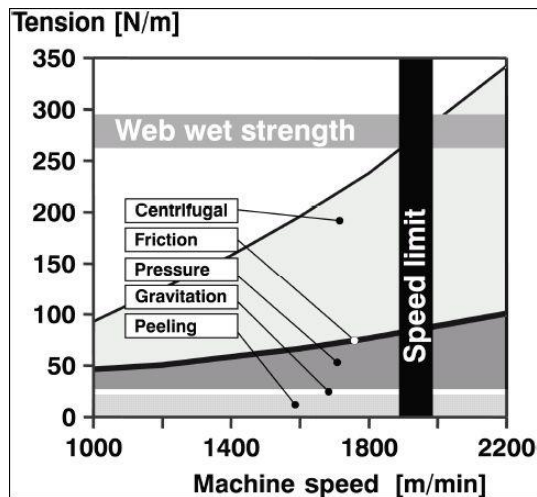
Figure 2. Schematic presentation of tension components that affect the wet pressed paper web during the press-to-dryer transfer [Kuhasalo *et al.* 2000].

Paper machines speeds have exceeded 1500 m/min in the 1990s. It was found that with that straining of wet web started gradually to lose its power to develop adequate web tension for runnability, and breaking strain of paper became a limiting factor [Ilvespää 1998, Edwardsson, Uesaka 2009]. Constructional developments were introduced in order to circumvent the difficulties, e.g. reduction of length and locations of open draws with single felting [Kuhasalo *et al.* 2000]. The fastest paper machines of all major printing paper grades (SC, LWC, NEWS and copy paper) have exceeded running speed of 2000 m/min in the mid 2010's.

In the mid 1990s, Valmet and VTT initiated the development of test methods for the wet web runnability. The strain rate in wet web draws of the paper machine, which is considerably higher than in standard laboratory testing, was one of the original ideas behind this. At that moment, there were a few published studies related to fast tensile properties of paper, and the related strain rates, sample solids content, etc. [Mardon *et al.* 1975]. Additionally, methods were neither consistent nor realistic for a simulation of the press and dryer sections of the paper machine. Moreover, there was lack of knowledge related to strength properties of wet paper in more general. Another objective was to study the effect of high velocity on the web tension without breakage of paper as it happens in a paper machine draw. Relaxation (or creep) test provides more reliable data than tensile test (with a constant strain rate) in the case of viscoelastic materials, because the effect of time is isolated from any nonlinearity [Lakes 2009].

Two fast tensile test rigs known as the Impact tester [for a more detailed description see Publications V-VI] and the C-Impact tester were developed. These two testing devices and relevant testing procedures have improved by the contribution of several people at VTT and Valmet (Metso Paper) during the past 20 years. Scope of research was not restricted only to the viscoelastic properties of paper, but also covered the furnish properties, fillers, chemicals and effects of drying and heating on the strength properties of wet and dry paper, and the in-plane dimensional stability [Kekko 2000, Retulainen, Salminen 2009, Sorvari 2009, Miettinen 2009, Lipponen 2010, Salminen 2010, Oksanen 2012, Erkkilä 2013].

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1.2 Objectives of the study

The objective of the work was to clarify the behavior of a wet paper web as a solid material in conditions that simulate the paper machine process and influence the conditions of wet and dry web runnability. In this study, tension relaxation as well as the influence of heating on the viscoelastic behavior of paper, were studied extensively. The effect of multi-stage straining during drying on the tensile properties of paper were also investigated. Effects of several furnish and papermaking process related factors (e.g., reinforcement pulp content and refining, filler content and jet/wire speed ratio) on the strength properties of dry paper were thoroughly studied.

Influence of papermaking chemicals on the results was not in the focus of this Thesis, but they were used in a typical manner in sample forming at a pilot paper machine. Printability of paper (optical properties, smoothness, air and oil permeability) is not considered in this Thesis, though it is important for the end product quality. However, some quality properties are reported in Publication IV.

1.3 Research questions

The primary research questions were as follows:

- What are the effects of temperature changes on the tension-strain and relaxation behavior of wet paper?
- What are the roles of mechanical pulp and chemical reinforcement pulp in the reinforcing of a wet paper web at a 40-55% solids content?
- How draws in the paper machine affect the runnability potential of a dry web in converting and printing processes?
- Which of the mechanical properties of paper control the runnability of a wet and dry web?
- What is the optimal combination of the papermaking related factors studied, e.g. wet web draws, filler content, jet/wire speed ratio and furnish composition for achieving the best possible runnability of a wet and dry web for a wood-containing printing paper?
- To what extent the papermaking operations studied affect bonding and activation of the fiber network?

2   Materials and methods

2.1   Impact tester

In Publication IV, the Impact, a fast strain rate tensile tester, was used for the tensile and relaxation testing of paper in the laboratory (see Fig. 3 A) [Kurki *et al.* 1999, Publications V-VI]. The Impact tester can create an average elongation speed of 1.0 m/s. This means that for the paper sample with span of 100 mm the strain rate was 1000%/s, and the time consumed for creating a displacement of 1 mm was 1 ms. Elongation speed of the Impact tester was approximately 3000 times faster than in standard tensile test methods (see for example ISO 5270:1998). High elongation speed combined with motion towards a target displacement was achieved by a high acceleration that caused a harmful dynamical force. Damping of the disturbance without losing accuracy was essential for a successful measurement. Measurement accuracy and disturbances were controlled by the special structure of the Impact tester [Kurki *et al.* 1999].

A)   **B)**
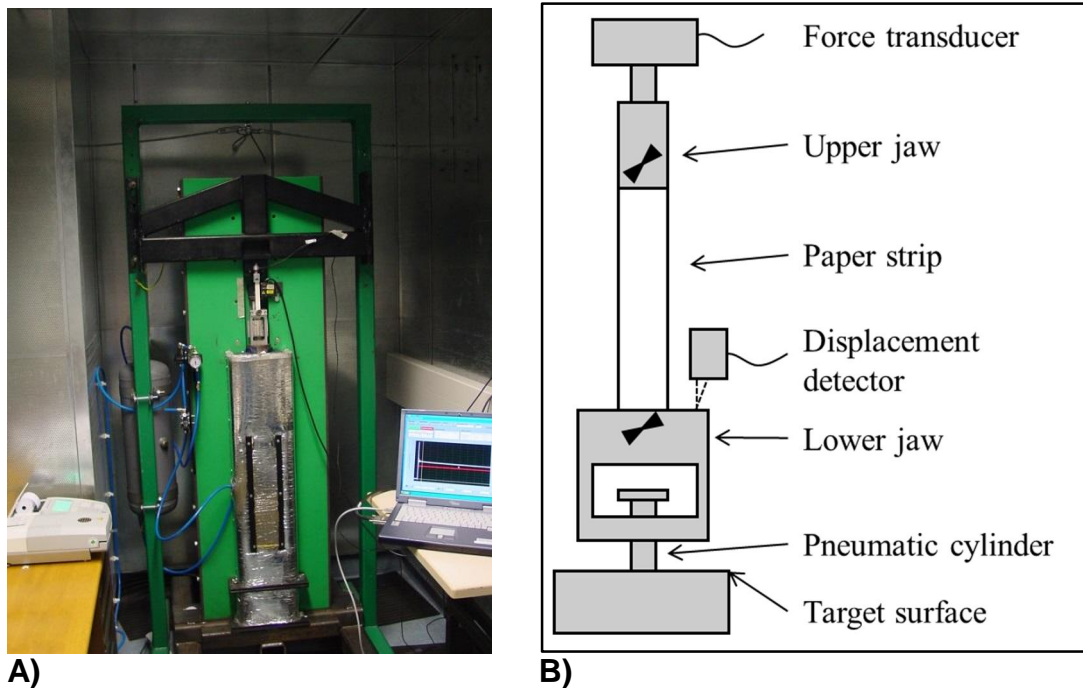
Figure 3. A) The Impact tester, a computer for data recording and Mettler Toledo HR73 infrared dryer for a solids content measurement, B) a schematic description of the Impact tester with the following main components: Laser for strain detecting, force transducer, pneumatic cylinder and target surface for sample straining.

A paper sample was clamped in the Impact between two jaws (see Fig. 3 B). A piezoelectric force sensor was located above the upper jaw. The lower jaw moved creating thus an elongation that was measured with a laser distance sensor. The motion of the lower jaw was generated by a pneumatic cylinder that enabled a one-way motion to the desired distance. The desired elongation could be adjusted by determining the gap between the lower jaw and the target surface. Span length of the sample could be in a range of 50-250 mm.

The maximum sampling frequency in data acquisition for all measuring components was 20 kHz, and it was always used in tensile tests. In tension relaxation tests that frequency was 0.5-4 kHz.

Using the Impact tester in tensile and relaxation tests, 11-12 repetitions were performed at each solids content level. The solids content of the samples was measured using a Mettler Toledo HR73 infrared dryer. Solids content were then given as an averages over 4-6 paper samples. Measurements were performed in standard laboratory conditions, *i.e.* RH 50% and temperature 23 °C.

2.2   C-Impact tester

In Publications I-III, the C-Impact, another fast strain rate tensile tester, was used in laboratory trials. A force sensor was located above the upper jaw and an electromagnetic actuator below the lower jaw (see Figs 4 and 6). Displacement of the lower jaw was measured with a laser distance sensor. The solids content of the samples was measured with an optical moisture analyzer, which was based on the near-infrared technology. Temperature of the samples was measured with two infrared (IR) temperature detectors. The maximum sampling frequency in data acquisition for all measuring components was 5 kHz (100 Hz in the moisture analyzer).

Accuracy of the solids content data was sensitive to calibration and depended on the paper grade. After calibration, accuracy of the on-line measurement was typically about ±2 % units. Reliability of the solids content calibration was double checked with Mettler Toledo HR73 moisture analyzer.

The C-Impact test equipment together with data recording were operated by a computer. PID control of the actuator caused a small unavoidable error in the motion. The criteria for tuning the PID control were, firstly, a constant 1 mm/s displacement rate (error less than 2%) in a range of 10 to 90% of the target displacement. Secondly, a stable target position without oscillation (a short period of damped oscillations was allowed immediately after reaching the target position). Thirdly, the overshoot of displacement was less than 2% for a displacement rate of 1 mm/s. The motion that actuator performed was very repeatable, and, therefore, the differences measured between the samples were not caused by the actuator.

2.2.1   Electric heating chamber

In Publication I, a special electric heating device was attached to the tensile tester (shown in Fig. 4). The heating device formed a small climate chamber, which was able to heat the samples to a target temperature of 30-70 °C within a couple of seconds (see Fig. 5). Temperature of the heating chamber could be adjusted with an accuracy of one degree Celsius. The electric heating device was operated by a computer.
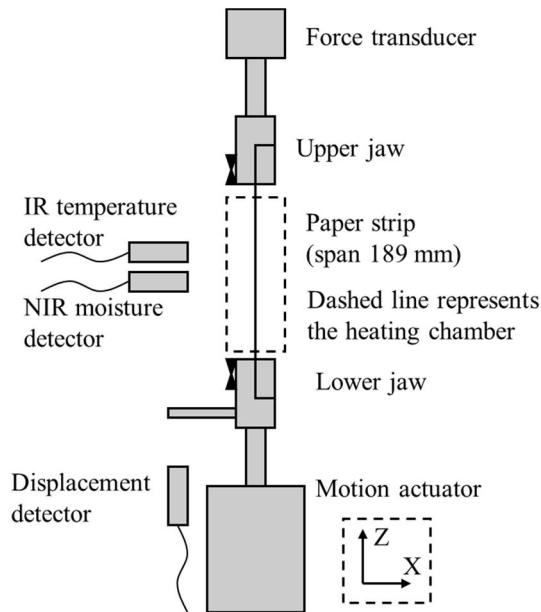
Figure 4. A schematic presentation of the C-Impact tester with the following main components: IR-sensor, moisture detector (based on the NIR technique), laser for strain detection, force transducer, motion actuator for sample straining, and heating chamber shown in the heating position (dashed line). Figure is from Publication I.
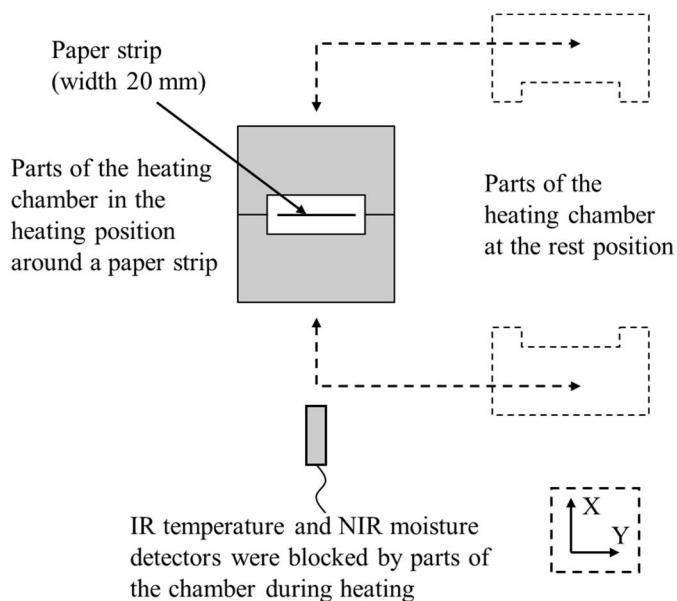
Figure 5. A schematic presentation (from the top down) of the heating chamber elements around the sample during heating, and their rest positions. Figure is from Publication I.

The time for heating and evaporation of water from the press-dry sample was minimized by minimizing the volume of the heating chamber. Dimensions of the heating chamber around the paper sample were 2.35 mm × 24.30 mm × 178 mm (X × Y × Z, respectively in Figs 4 and 5). Sample length was 189 mm and width 20 mm. Sample accounted for 3-5% of the chamber volume. The relative humidity of the air in the heating chamber was estimated by Wagner and Pruß (2002). For the used temperatures, paper grammages and solids content values used (Publication I), the

maximum increase in the solids content of paper was two percentage units. In the case of one-sided heating, moisture and temperature gradients were detected in the thickness direction of paper [Batchelor *et al.* 2004, Keränen *et al.* 2009]. However, in this study these gradients were not determined in detail. Tension and strain of the sample could be measured during heating, because the heating chamber was not in mechanical contact with it.

2.2.2   Electric drying unit

 In Publications II and III, a special electric drying unit was attached to the tensile tester, and used for laboratory scale trials (see Fig. 6).
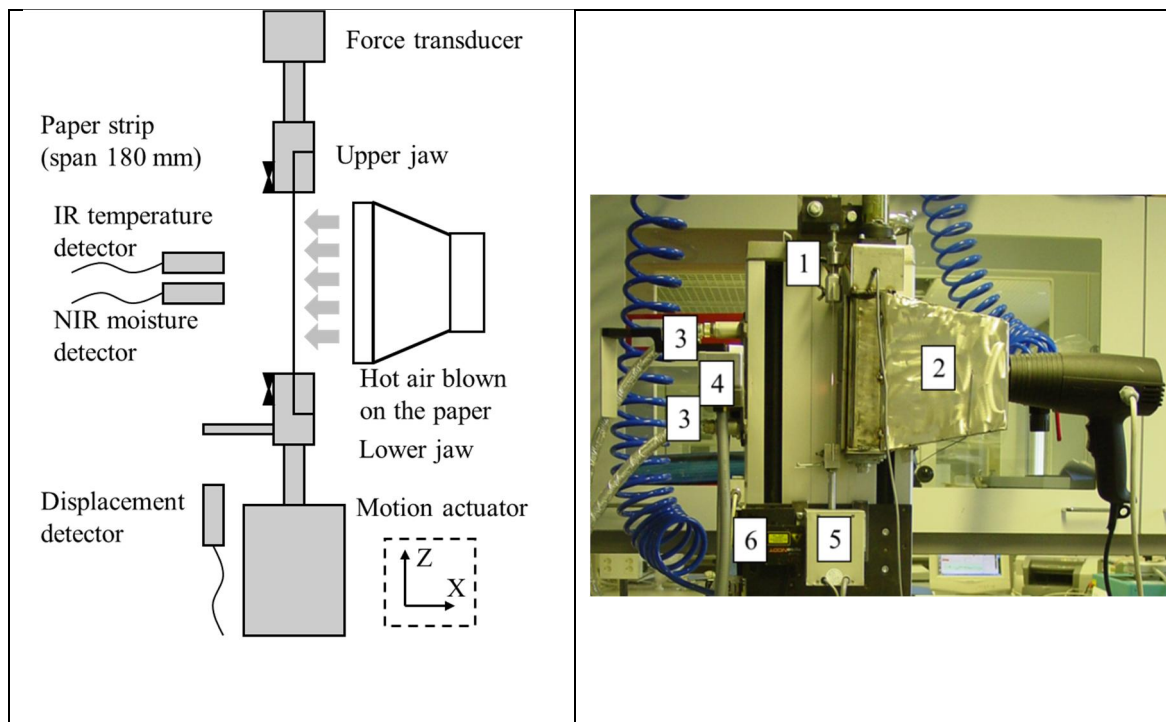
Figure 6. Main components of the C-Impact tester: 1) force sensor, 2) dryer unit, 3) IR temperature sensors (2 pc.), PIRMA moisture sensor (Near Infrared technique), 5) actuator, 6) strain sensor. Paper strip was attached in the jaws between 1) and 5). Control units for the actuator, temperature of the drying air and flow rate and data logging are not shown in this figure. Figure is from Publication II.

  Air at a temperature of 95 °C was blown onto one side of the paper strip using the drying unit attached to the tester. One-sided drying of the C-Impact mimics a modern single felted drying section and has an advantage of enabling solids content and temperature measurements of the paper samples during drying. This method has also some drawbacks, e.g. one-sided drying causes moisture and tension profiles in the thickness direction of the samples [Batchelor *et al.* 2004, Keränen *et al.* 2009]. Because the cross directional tensions of the samples were uncontrolled, samples typically developed a curl during drying. Length of the sample was 180 mm and width 20 mm. The main components of the C-Impact tester used for the measurements are shown in Fig. 6.

2.3   Paper samples

In Publications I-III, fine-paper, lightweight coated (LWC) base-paper and super calendered (SC) paper samples were taken press-dry after the wet press section from a pilot paper machine (Valmet (Metso Paper), Jyväskylä, Finland). The SC paper furnish was composed of a mixture of thermo mechanical (~80% of the fiber raw material) and softwood chemical pulp (~20% of the fiber raw material) and hydrous kaolin as a filler (~25% of the raw material). The LWC-base-papers were made of a mixture of TMP (Norway spruce) and BSK (Norway spruce and Scots pine). The fine-papers were made of a mixture of hardwood (birch) and BSK.

In Publication IV, samples were press-dry and dried laboratory handsheets. In this study were investigated Nordic LWC type TMP and two Nordic pressure groundwood pulps (PGW) of the LWC and SC types. These mechanical pulps were blended with BSK. The mechanical pulps examined were decker pulps from Finnish paper mills. The BSK used was ECF bleached reinforcement pulp for LWC grades. The BSK pulp was refined with a Valley laboratory beater. According to Lumiainen (2000), Hollander beater produces a gentle refining and quite a uniform fiber treatment.

All the press-dry paper samples were stored hermetically in a cold storage at 6°C. The hermetically sealed samples were allowed to warm up to room temperature before testing, but no other conditioning was used. These paper samples are described in more detail in Publications I-IV.

2.4   Tension-strain curve

2.4.1   Tensile stiffness

Young's modulus, also known as the tensile modulus or elastic modulus, is a measure of the in-plane stiffness of an elastic material. Young's modulus determines the amount of strain that a stress causes in the material. However, thickness of a compressive material, such as wet paper, can be difficult to determine accurately. Thickness measurement can be avoided using the tensile stiffness as a characterizing material quantity.

In solid mechanics, slope of the stress-strain curve at any point is called the tangent modulus. Tangent modulus of the initial, linear portion of a stress-strain curve is called Young's modulus. It can be experimentally determined from the slope of a stress-strain curve of the material as given by a tensile test on it.

Wet paper is not an ideally elastic material and there may not be an initial linear part in the stress-strain curve. In this Thesis, tensile stiffness was defined as a tangential stiffness. Tangential stiffness was calculated as the maximum slope of the tension–strain curve (see Fig. 7). Mathematically, tensile stiffness is the first-order derivative of a fitted equation. The equation used for fitting the tension-strain curves was given by

$$\mathbf{T}(\varepsilon) = \sum_{i=0}^{4} a_i \varepsilon^i + a_5 \, \mathbf{arctan}(\varepsilon) \quad [N/m], \qquad (1)$$

where T is tension, ε is strain (percentage in units) and a_i is a constant. The first order derivative of Eq. 1, *i.e.* tangential stiffness is given by

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$$S(\varepsilon) = 0.1 \left(\sum_{i=1}^{4} a_i i \varepsilon^{i-1} + a_5 \frac{1}{1+\varepsilon^2} \right) \ [kN/m]. \qquad (2)$$

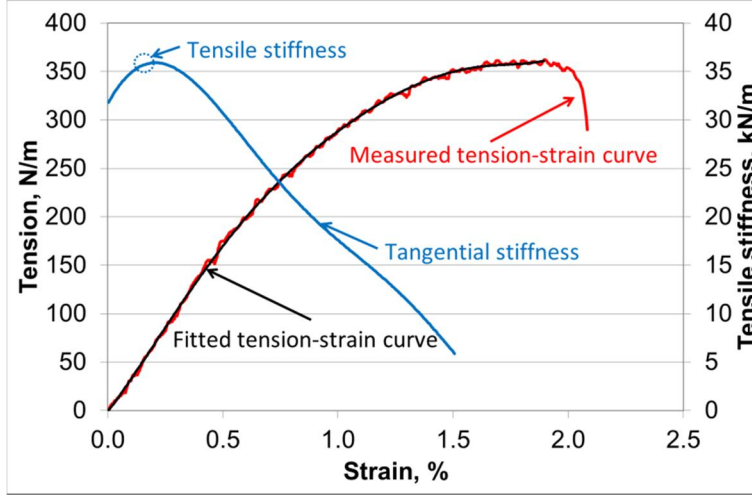The maximum of S(ε) is defined as tensile stiffness and it is denoted simply by S.

Figure 7. Tension-strain and tangential stiffness curves of SC paper, 36 g/m^2, 53% solids content, MD, strain rate 4.8 %/s. Ratio of measurement frequency to strain rate was 500 1/%.

Suitability of Eq. 2 for curve fitting depends on the ratio of measurement frequency to strain rate. A suitable ratio seems to be in a range of 100-500. Low measurement frequency in comparison with strain rate decreases the accuracy of tensile stiffness. On the other hand, an unnecessarily high frequency increases the time taken by data fitting without any improvement in the accuracy. Measurement accuracy depends on the detector used for measuring the strain. Ratio of strain rate to measurement frequency gives a theoretical maximum for the accuracy of strain measurement in a tensile test with a constant strain rate. For the Impact tester, the ratio of measurement frequency to strain rate in a tensile test was 20 1/%. For the C-Impact tester this ratio varied between 100 1/% and 500 1/%. A low ratio in the Impact tester led to simplification of Eq. 2. Reduction of higher order polynomials improved the variance of repeated measurements.

2.4.2 Efficiency factor

Efficiency factor has been used to describe the efficiency of stress transfer between fibers in a paper sheet [Seth, Page 1981]. Efficiency factor has been used to describe changes in the inter- and intra-fiber effects on the shape of the tension–strain curve [Seth, Page 1981, Coffin 2005, Coffin 2012]. In Publications II and III, efficiency factors were determined for the tension-strain curves of dry paper samples. Efficiency factor was now defined such that:

$$\Phi = S_i / S_0 , \qquad (3)$$

where S_i is tensile stiffness of a sheet with the lower ability for fiber network activation and S_0 is the tensile stiffness of a sheet with the higher ability to fiber

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network activation (see Lobben (1975) for activation). In this study, S_0 was actually obtained from the sample that had the highest tensile stiffness, *i.e.* the sample with a high level of draws in all draw locations. The corresponding efficiency factor was 1.0. For other samples S_i and the efficiency factor were lower. In this study, efficiency factor represents a kind of relative efficiency of the samples. It gives an estimate, if the draws cause changes in the fiber network activation (strain hardening).

2.4.3 Elastic breaking strain

Elastic breaking strain (EBS) has been used to describe the in-plane bonding properties of paper, e.g. the shear strength of bonds [Niskanen, Kärenlampi 1998, Tanaka *et al.* 2001, Hiltunen 2003, Vainio 2007, Hiltunen, Paulapuro 2011]. Uesaka, Ferahi 1999, have used EBS as one of the key factors, which describes the pressroom runnability of a dry paper web,

$$EBS\left[\%\right] = TS/S \times 100\% \ , \qquad\qquad (4)$$

where S is the tensile stiffness and TS is the tensile strength. In this study, the elastic breaking strain represents the in-plane inter-fiber bonding in the samples. Role of the fiber bonding in paper properties has been described in detail by Retulainen (1997).

2.4.4 Determination of strain at break for wet paper

Determination of strain at break for wet paper may not be a straightforward task. The strain that corresponds to the maximum tension of paper is defined as the strain at break (*i.e.* stretch). However, a wet paper sample may have quite a long plateau around the level of maximum tension (see Fig. 8). Shape of the tension-strain-curve of wet paper is always more rounded before breaking than that of dry paper. For instance, a handsheet with a solids content below 50%, which contains a significant amount of mechanical pulp fibers, may have a plateau that is as long as 5-6 % units of the strain (see Fig. 8). It seems that, the filler content and fiber orientation in the direction of testing typically reduce the length of a possible plateau.

Repeatability of strain at break measurements is significantly decreased in the case the tension-strain curve has plateau. Additionally, strain at break as determined by its definition, can significantly differ from the actual strain at the point, where break actually occurs. In this Thesis, a complementary concept is used for determining strain at break of wet paper. It is defined as the strain at 90% tension of the maximum on the descending side of the tension (see Fig. 8).
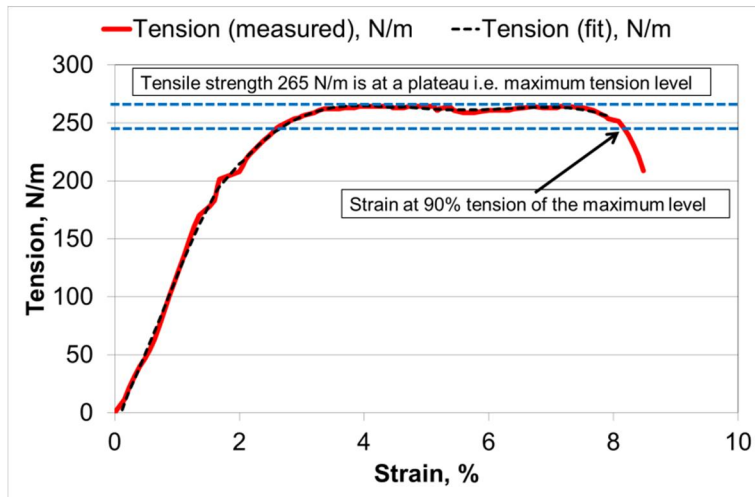
Figure 8. The tension-strain curve of a handsheet sample, which contained 60% PGW and 40% BSK at 33% solids content, 60 g/m^2 dry grammage and 1000 %/s strain rate. Ratio of measurement frequency to strain rate was 20 1/%.

2.5   Tension relaxation in wet web runnability

2.5.1   Importance of tension relaxation and residual tension in wet web runnability

Residual tension of a wet web in a tension relaxation test is considered to be an important parameter that describes its runnability in the press and dryer sections of the paper machine. Importance of this parameter becomes evident from Fig. 9. Tensile strength of the wet web in the press-to-dryer-section transfer area is only 10-15% of the strength of a dry web. However, web transfer needs to occur undisturbed even at this low level of strength. Viscoelastic (especially tension preservation) properties determine the tension response of the web. At higher speeds external forces (aerodynamic, centripetal, etc. forces as presented in Eq. 4 and Fig. 2) demand an increased tension, which in turn increases the role of mechanical properties of the furnish in runnability [Pakarinen, Kurki 1995].
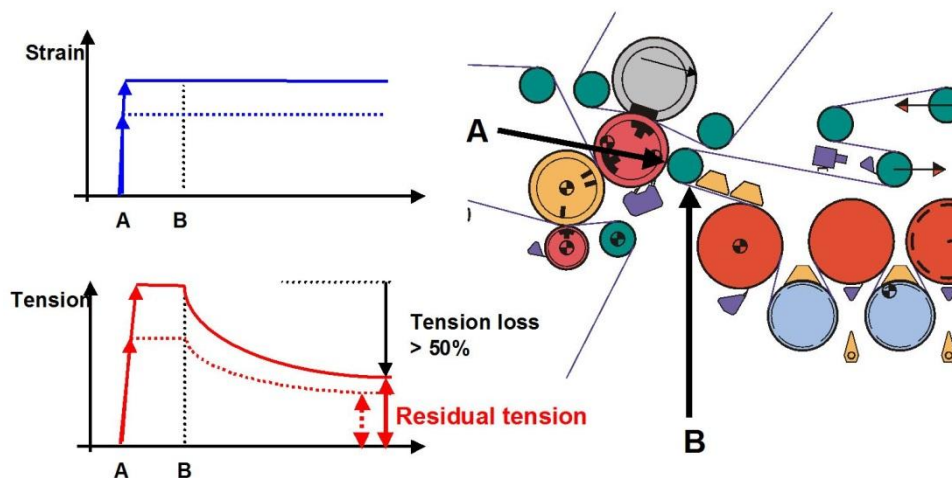

Figure 9. A schematic presentation of a drop in the tension of a stretched, wet pressed paper web during the press-to-dryer transfer. Figure is from Publication V.

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According to Kurki *et al.* (2010), web tension in an adhesive open draw can be expressed in the form

$$T = \Delta \bar{p}\, R_{web} + (m + m_{cp})\, v^2 + W_{adh}/(1 - \cos\beta), \tag{4}$$

where Δp is the average pressure difference between the upper and lower sides of the web, R_{web} is the radius of web curvature, m is mass, m_{cp} is an added mass coefficient, v is velocity of the web, W_{adh} is the adhesion energy and β is the take-off angle. Under stable production rate conditions both the average pressure difference Δp and the centrifugal force component $(m + m_{cp})v^2$ remain constant. Shape of the paper web (local web radius R and peeling angle β) can thus be controlled either through web tension (T) or by stabilizing the negative pressure (for the latter see Publication IV, Fig. 19).

According to Kurki *et al.* (2010), a reduction in grammage of paper increases the strain in an adhesive open draw. High machine speed, limited wet web strength and low grammage of paper increase the probability of break, *i.e.* decrease the runnability (see Fig. 2). At high machine speeds effective water removal, effective technical solutions for runnability and material components of the furnish are essential for a good runnability [Kurki *et al.* 2010].

2.5.2 Relaxation rate and relaxation percentage

The relaxation rate of dry paper has been studied by Craven (1962) and Kubát *et al.* (1963) and recently that of wet paper by Kekko *et al.* (2009). Craven (1962) found that the relaxation rate of dry paper depends only on the initial load and relaxation rates for a wide range of materials (dry paper, polymers, crystals, composites, etc.). They fall within a small range (Kubát 1965), and relaxation tension as a function of time is given by

$$T(t) = T_c - R \log(t), \tag{5}$$

where T is tension, t is time, T_c is a constant and R is the relaxation rate of the tension. In Publications I and III, an apparent relaxation rate of the tension was obtained by fitting relaxation data by Eq. 5. The asymptotic part of the relaxation curve of the tension was fitted by using a logarithmic time. The initial 2 seconds of tension relaxation was omitted, so as to enable compatibility with results in Publications I-III, otherwise for the given time period, the relaxation data was apparently linear in that time scale (see Fig. 10).
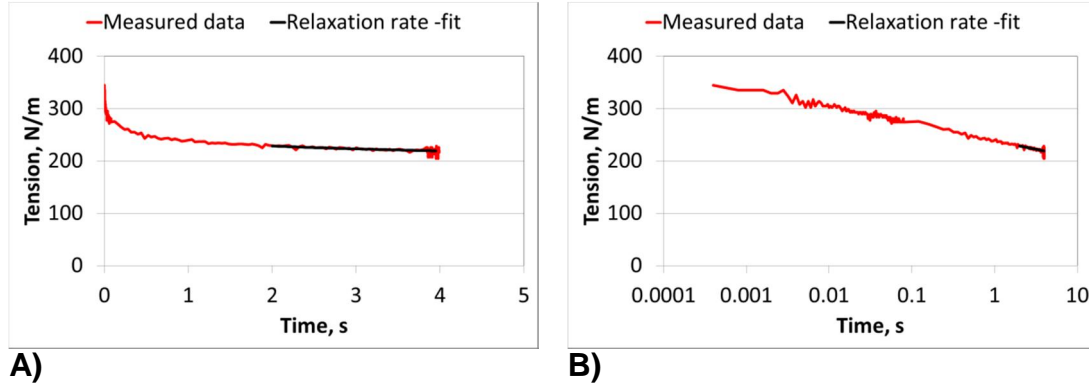
Figure 10. A) A tension relaxation curve together with a fit in a linear time scale, B) the same curves in a log-linear scale.

It is evident from the Fig. 10 that relaxation of the initial tension occurs rapidly, especially in the case of wet paper. This short time scale can cause technical difficulties in the measurements, but has a considerable practical significance for wet webs in the paper machine. Some of the difficulties are related to recording of tension relaxation in short time scales. They can be avoided using the following expression:

$$R_{\%} = (T_0 - T_{\text{Re}s})/T_0 \times 100\% \quad , \tag{6}$$

where $R_{\%}$ is the relaxation percentage, T_0 is the initial maximum tension and T_{Res} is the residual tension after a given time. The advantage of relaxation percentage is in the inclusion of both the initial and the asymptotic logarithmic time dependence of tension relaxation. Relaxation percentage of a wet paper has been found to decrease with an increasing strain level, and to increase with an increasing strain rate [Publication VI, Salminen 2010]. Jantunen (1985) has shown relaxation percentage to decrease with an increasing solids content and increase with an increasing strain level in contrast with the results reported by Salminen (2010) and in Publication VI. The concept of relaxation percentage was used in Publication I.

2.6 Lumped capacitance method for temperature evaluation

In Publication I, a special electrical heating device was used in the C-Impact tester (see Figs 4 and 5). Temperature and solids content of the paper were measured with IR-detectors before and after heating. Paper temperature could not be measured during the heating phase as the heating chamber obscured the field of view of the IR-detector (see Fig. 5). Wet paper cools rapidly once the heating is released due to evaporation. Temperature of the paper at the moment of opening the heating chamber was therefore evaluated using the Lumped Capacitance (LC) method, which gave an estimate for temperature of the paper at the end of the heating phase [Incropera, DeWitt 2002],

$$\int_{\theta_i}^{\theta} d\theta = \theta(t) - \theta_i = -\frac{1}{\rho cL} \int_0^t \left[h(\theta - \theta_\infty) + e\sigma(\theta^4 - \theta^4_{\text{sur}}) \right] dt \quad , \tag{7}$$

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where θ is the temperature of the paper, θ_i is its initial temperature, θ_∞ is the temperature of moving air at the paper surface after opening the chamber (at 23 °C), θ_{sur} is the temperature of the surrounding air (heat sink at 23 °C), t is time, ρ is the density of the (wet paper) sample, L is a half of the thickness of the sample before the test, c is the specific heat of dry paper (1340 kJ/kgK) [Kiiskinen *et al.* 1998], h is the heat transfer coefficient of free convention (values for free convection are between 2-25 W/m^{2}K), e is the emission factor for paper and water (0.95) and σ is the Stefan-Boltzmann coefficient (5.67×10^{-8} W/m^{2}K^4). The specific heat of dry paper was used as it is the only available experimentally determined value and because the effect of bound water on the specific heat of wet paper is not known. Equation 7 was solved by numerical integration. The minimal change in paper thickness due to straining [Göttsching, Baumgarten 1973] was ignored.

The fourth-order terms in Eq. 7 describe the heat loss due to radiation, and the first-order term the heat loss due to convection from paper to air. Heat loss due to evaporation was ignored, as the temperature gradient between the paper and air was assumed to be negligible. The effect of evaporation was assumed to be negligible compared to the two former terms [Heikkilä, Paltakari 2010]. This finding was also supported empirically, as evaporation was found to increase the solids content of the fine-paper samples only when the temperature of the chamber was 125 °C.

Temperature of the paper at the moment of opening the chamber was evaluated by fitting the LC equation to the cooling data measured with the IR-detector and extrapolating back to the time of opening. The estimated paper temperature at the chamber temperature of 110 °C is shown in Fig. 11.
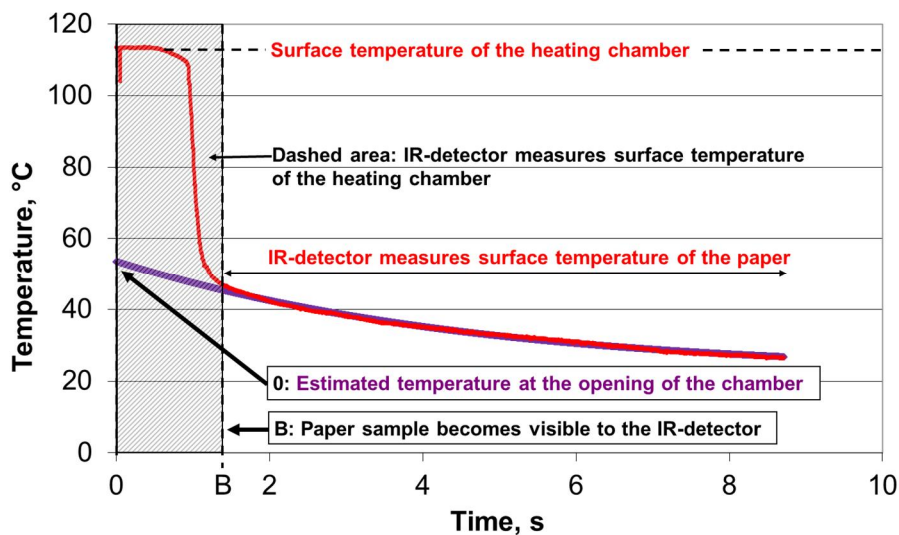
Figure 11. Evaluation of the temperature of LWC-base-paper #1 at the time of opening (A) the chamber. Paper becomes visible to the IR-detector at time B. It was heated in the chamber at 110 °C. Figure is from Publication I.

2.7 Method for conducting press and dryer section draws

Paper was pressed at four (Publication II) and three (Publication III) locations in the press section of a pilot paper machine. However, it was strained only at the latter two

(Publication II) and the last (Publication III) location, namely the first and second press section draws. Wet web straining was one of the process parameters analyzed in this study. Generally, the purpose of wet web straining in a press section is to ensure runnability in the press section and in the beginning of the dryer section. Samples taken for laboratory tests were strained at three stages simulating the drying section draws. Laboratory test set-up used in these studies is introduced in Sec. 2.2.2.
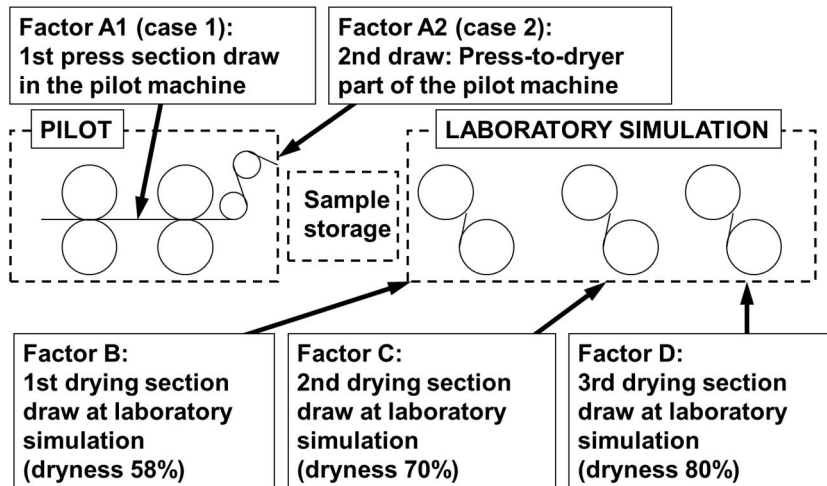

Figure 12. A schematic illustration of the draws performed in the press section of a pilot paper machine and the dryer section draws simulated by the laboratory tensile tester. Figure is from Publication II.

In Publication II, paper samples were strained at two locations in the press section, as shown in Fig. 12. The solids content of paper after the 1st location was 55-56% and after the 2nd location 57%. Paper samples were dried using the C-IMPACT tensile tester. The drying section draws were performed at three different solids contents to mimic paper machine condition. A more detailed description of the press and dryer section draws can be found in Publication II.

In Publication III a similar procedure was used as in Publication II. Instead of press section draws, effects of filler content and the jet/wire speed ratio was studied in combination with dryer section draws. A more detailed description of the used parameters can be found in Publication III.

2.8 Methods for statistical analysis

In Publications II-IV, the trials were organized so that the factorial analysis of variance (ANOVA) method could be used in the analysis of the results. In Publications II and III, the four independent variables had three or four distinct values. Three of the factors were fixed as three drying section draws in the C-Impact laboratory tensile tester. In Publication II, the fourth factor was the press section draw in a pilot paper machine. In Publication III, the fourth factor was either the filler content of the sample or jet/wire speed ratio of a pilot paper machine. The effects of the various factors (independent variables) on the dependent variables (e.g. tensile stiffness) were tested by four test repeats. In Publication IV, the full factorial design had three factors with three distinct values. Three of the factors were fixed as the pulp type (qualitative factor), BSK

refining degree measured as CSF and BSK content of the furnishes. The effects of the factors on the dependent variables were tested by five (dry paper residual tension) and ten (all the other tests) test repeats.

Evaluation of the data included seven steps: 1) sum of squares, 2) degrees of freedom, 3) mean squares, 4) F-ratio, 5) looking up the critical value of F_0 (P-value), 6) contribution ratio and 7) plots of averages. 95% confidence levels that are given in the figures, were calculated using exactly the same method as for the plots of averages in the figures. Instead of calculating averages, the 95% confidences were calculated. The final step, choosing the optimal parameters, needs also quality properties of paper (e.g. porosity, light scattering, etc.).

Calculation of steps 1–4 was performed according to Montgomery (1997). The P-value of step 5 was obtained using the FDIST function of MS Excel, and the contribution ratio CR_i of step 6 was obtained in accordance with Frigon and Mathews (1997). A more detailed description of the method is given in Publication II.

The percentage of contribution ratio CR_i (also known as R^2) is a quotient of the sum of squares of the factors and the total sum of squares. The contribution ratio of unexplained variance measures the unexplained or residual variability of the data. The contribution ratio of factors is given by

$$CR_{Factor} = \frac{SS_{Factor}}{SS_T} . \tag{8}$$

The degrees of freedom of the 3^3 full factorial design (for data of Publication IV) in the cases of five and ten repeats are tabulated in Table 1.

Table 1. Degree of freedom for sources of variation for five and ten repeats (Publication IV).

	Degree of freedom (5 repeats)	Degree of freedom (10 repeats)
Main factors (A, B, C)	2	2
Two-factor interactions (AB, AC)	4	4
Three-factor interactions (ABC)	8	8
Error	108	243
Total	134	269

3 Viscoelastic behavior of paper

This Section reports findings related to important features of the viscoelastic behavior of wet paper. Results are related to experimental methods and findings to the runnability of paper web in the papermaking process. The residual tension of wet web is shown to have a significant role in describing the runnability of wet web in the paper machine. Additionally, results help to understand the reasons for temperature changes that influence the tensile behavior of the wet web tensile in the paper machine.

3.1   Effect of temperature on tensile behavior of wet paper

Temperature has a significant influence on the shape of the straining–relaxation–re-straining cycle of wet paper. Press-dry fine-paper and LWC-base-paper samples from a pilot paper machine were heated in a specially constructed heating chamber (described in Sec. 2.2.1). Heating of the wet paper was conducted without a noticeable increase in its solids content. Ranges of the temperatures and solids contents studied correspond to those found in the press and dryer sections of the paper machines.

Increased temperature decreases the tensile strength and stiffness of wet paper, but has practically no effect on the strain at break (see Fig. 13). The fine-paper and LWC-base-paper samples studied show the same relative change in their tensile strength per unit temperature -4.7×10^{-3} °C^{-1}. Relative change in the tensile stiffness (modulus of elasticity) was -7.7×10^{-3} °C^{-1} for both of the paper samples. Change of the relative tensile stiffness of wet paper due to temperature change was approximately 4 times higher than for the paper made of BSK [de Ruvo *et al.* 1973, Caulfield 1986]. Therefore, the effect of temperature on tensile strength and tensile stiffness seems to be stronger at lower solids content levels. Relative changes in the tensile strength and tensile stiffness were in accordance with the 1%/°C value reported for wet paper [Back, Andersson 1992].

In practice, strain in a wet web is caused by a speed difference between driving groups. Rarely the speed is lowered immediately after being raised, and therefore a tension-relaxation phase follows the straining phase. Figure 14 illustrates the influence of heating on the straining–relaxation–de-straining cycle of fine-paper. The apparent plastic region of the wet papers examined was almost linear, as shown in Fig. 14. The higher the temperature, the lower the tension at a given strain and after the following relaxation phase. If the de-straining phase is ignored, Fig. 17 can be considered to represent the effect of temperature change on the wet web behavior in the first open draw at the press or dryer section of the paper machine. The effect of increased temperature on web tension has to be compensated by an increasing draw.
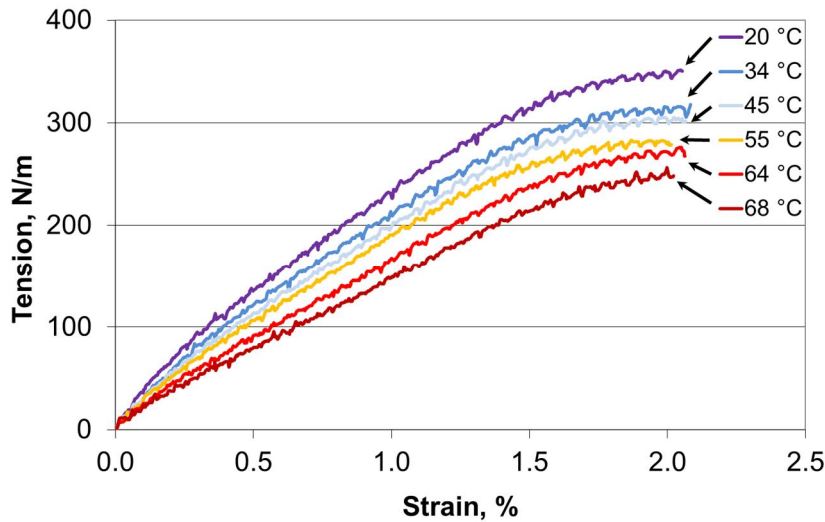
Figure 13. Typical tension-strain-curves for LWC-base-paper samples at 58% solids content and for different temperatures. The curves shown are medians of 5 tests at each temperature and the strain at break value represents the average of 5 tests. Figure is from Publication I.
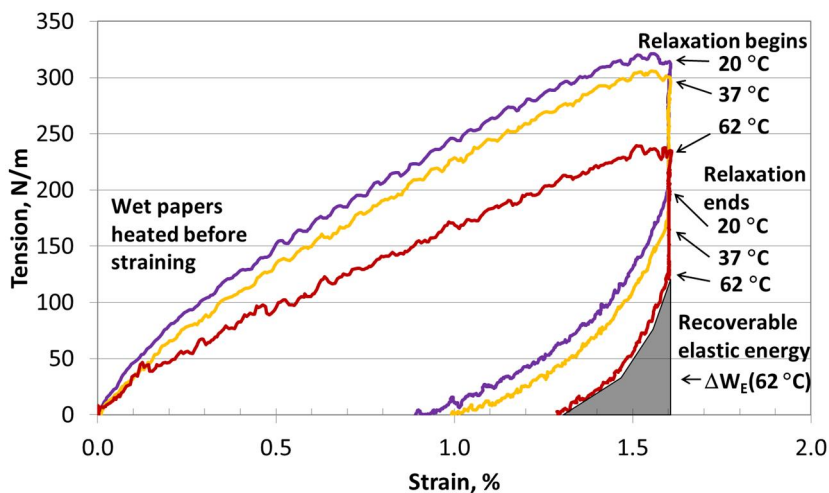

Figure 14. Straining–relaxation–de-straining cycles for never-dried fine-paper samples at 56% solids content for different temperatures after pre-heating. Heating started 8 s before the straining phase. The strain rate was 13%/s and the de-strain rate was 4%/s. Relaxation time was 12 s. Figure is from Publication I.

When paper was heated after straining to a given level (pre-straining), relaxation rate accelerated as the temperature was increased. Figure 15 illustrates the influence of heating of fine-paper on its relaxation and de-straining phases. Tension after the relaxation phase decreased with increased temperature. The amount of dissipated mechanical energy was increased during the hysteresis loop due to increase of temperature. Energies related to a straining cycle are discussed in detail in Publication I.
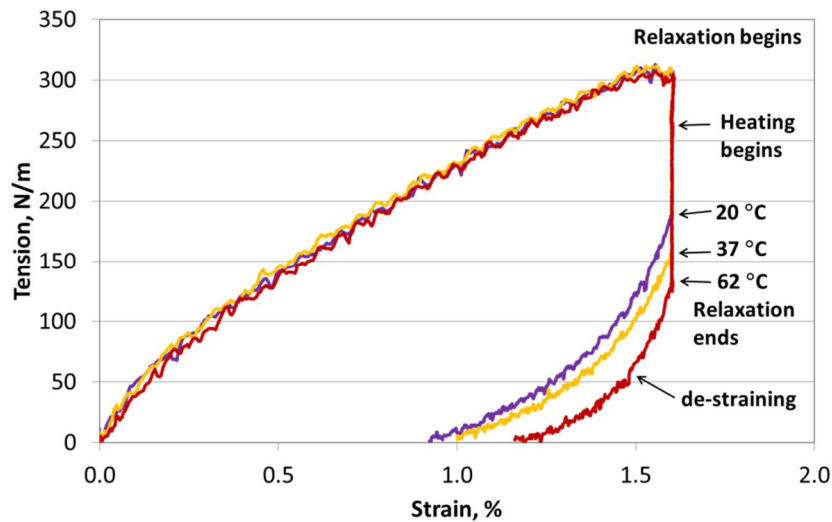
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Figure 15. Straining–relaxation–de-straining cycles of never-dried fine-paper samples at 56% solids content and for different temperatures. Heating was started during the relaxation phase. The straining phase was performed at 20 °C. The strain rate was 13%/s and the de-strain rate was 4%/s. Relaxation time was 18 s. Figure is from Publication I.

   Results indicate that the effect of temperature on the tensile behavior of wet paper occur relatively fast. Temperature has a major impact on the tensile stiffness of wet paper, which originates most probably from the material properties of fiber-wall softening. Elevated temperature is always employed in industrial papermaking and thus has a strong influence on the tensile behavior of wet web. Influence of temperature has not been typically considered in studies related to wet paper. However, temperature should be taken into account in studies related to processes, which involve variable temperature conditions, in the same manner as solids content in the case of variable moisture content of wet paper.

3.2   Effect of mechanical conditioning on the tensile behavior of wet paper

   Mechanical conditioning (tensile straining) causes irrecoverable changes to the structure and tension-strain behavior of paper. In Fig. 16, the initial linear region in the re-straining phase of wet paper is increased in comparison to the first straining cycle. The apparent linear elastic region ends when tension in the re-straining curve approaches that of the initial curve. Behavior is similar to that observed in dry paper (for example [Coffin 2009]). In the case of 2% initial straining shown in Fig. 16, the apparent linear elastic region of re-straining was about 0.7%.These results indicate that in a straining–relaxation–re-straining cycle some activation of fibers takes place (see Lobben 1975 for activation). The initial slope in the re-straining of a wet paper was weakly influenced by temperature (see Fig. 17), while the initial straining was influenced by temperature (see Figs 13 and 14). The tension-strain curve of Fig. 17 indicates that significance of fiber bonds with respect to the tensile behavior of wet paper was probably small, and that there were a sufficient amount of bonds of adequate strength. Activation of fibers at a high temperature may be more effective, and the number of active fibers would compensate for the decreased stiffness of fibers at an

elevated temperature. Straightening of fibers leads to a reduction in the non-linear behavior, as shown in Fig. 17. Baum *et al.* (1984) have actually found indication by direct observation of fibers straightening during wet straining at 35-40% solids content. Decrease of viscosity and surface tension of water with increasing temperature may also have an important role in the strength development of a wet fiber network.
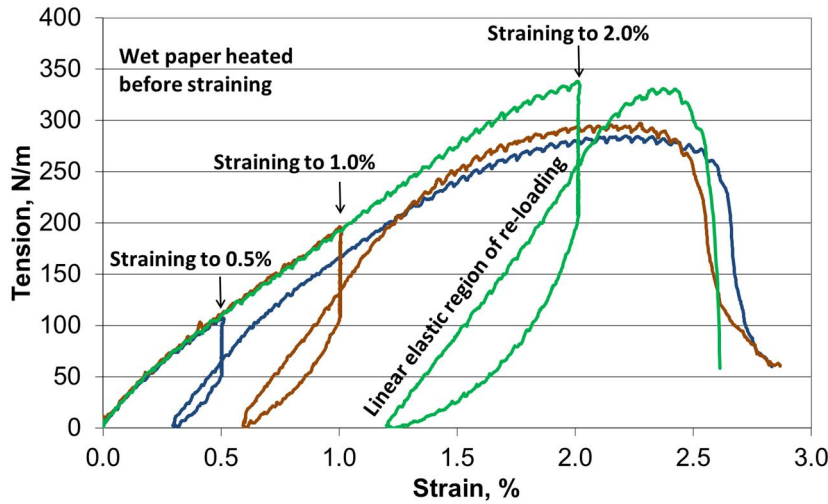

Figure 16. Straining–relaxation–de-straining–re-straining cycles for never-dried heated LWC-base-paper samples at 58% solids content and at 45 °C. Heating was started 6 s before the first straining cycle. The strain and de-strain rates were 5.3%/s. Recovery times before re-straining were 0.1, 0.2 and 0.4 s at prescribed strains of 0.5, 1.0 and 2.0%, respectively. Figure is from Publication I.
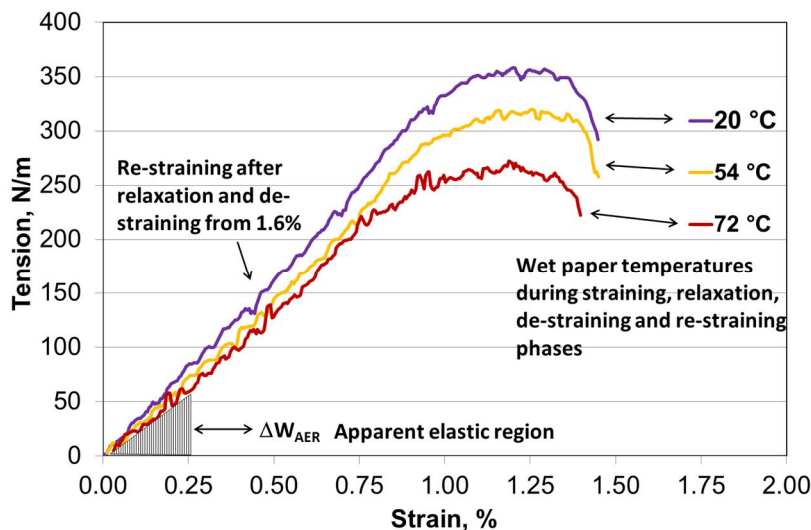
Figure 17. Tension-strain-curves in re-straining of never-dried LWC-base-paper samples at 53% solids content for different temperatures. Heating was started 3 s before the first straining cycle (not shown in this figure) to a 1.6% strain at a strain rate of 13%/s, and a de-strain rate of 4%/s. Recovery time before re-straining was 0.1 s. Figure is from Publication I.

In supporting Publication VII, local strains were measured in wet LWC-paper strips using a digital image-correlation method. Breaking behavior was estimated by a single-

phase tensile test (common tensile strength test) and by a three-phase tensile test (including a relaxation phase between two straining phases). In the single-phase tensile test, paper fracture started at a zone, where the largest local difference between the strains of the two paper edges was detected. Results show that the relaxation phase has a significant effect on the breaking behavior of wet paper strips. In the three-phase tensile test, paper fracture started at a zone with the largest local strain. Relaxation phase seems to even out the local strain variation in paper, which is significant for mechanical conditioning. This indicates also that local strain and tension variations in a wet paper web, which are generated in the press and dryer section draws, may even out in the dryer section.

3.3   Effect of straining on the temperature of wet paper

Straining leads to reversible elastic and irreversible plastic deformations, both in dry and wet paper. Temperature of a dry paper has been shown to decrease during straining in the elastic region (heat is absorbed) and to increase in the plastic region [Ebeling 1973, Yamauchi, Murakami 1993, Dumbleton *et al.* 1973, Hyll *et al.* 2012].

In Publication I, the work of straining was divided into a hysteresis work (ΔW_H) and a recoverable elastic energy (ΔW_E). Hysteresis work was defined as the work lost in the straining–relaxation–de-straining cycle of wet paper. Recoverable elastic energy was defined as the work recovered during the de-straining phase. Detailed considerations related to the mechanical work and heat that wet paper experiences during a straining cycle are presented in Publication I.

Results indicate that the hysteresis work of the wet papers examined correspond to a 1-22 mK temperature change. This suggests that temperature changes in wet paper induced by straining play no role in practice.

The mechanical straining work of the re-straining phase was used for estimation of the linear thermal-expansion coefficient of wet paper. Estimation method which was based on the comprehensive study of heat during straining by Ebeling (1970), is presented in Publication I. Effect of the thermal expansion of fibers and wet paper on the relaxation rate seemed to be small, but not negligible. The linear thermal-expansion coefficient of wet paper in the machine direction was estimated to be about $2.7\text{-}6.7 \times 10^{-6}$ °C^{-1}. Influence of the solids content on the linear thermal expansion-coefficient of paper was relatively small. The result is in line with values reported for dry paper [Kubát *et al.* 1969, Ebeling 1973].

3.4   Relaxation rate of wet paper

Relaxation rate of wet paper can be used to describe the wet web behavior in the press-to-dryer-section transfer of the paper machine. Results of Publication I show that increasing temperature accelerates the apparent tension relaxation of paper. The relaxation rates observed in wet paper were considerably higher than those reported for dry paper [Craven 1962, Kubát *et al.* 1963]. The results of Publication III show the effect of three papermaking-process parameters, e.g., filler content, jet/wire speed ratio, and press section draws, on the apparent relaxation rate. The method used for relaxation rate measurements was described in Sec. 2.5.2.

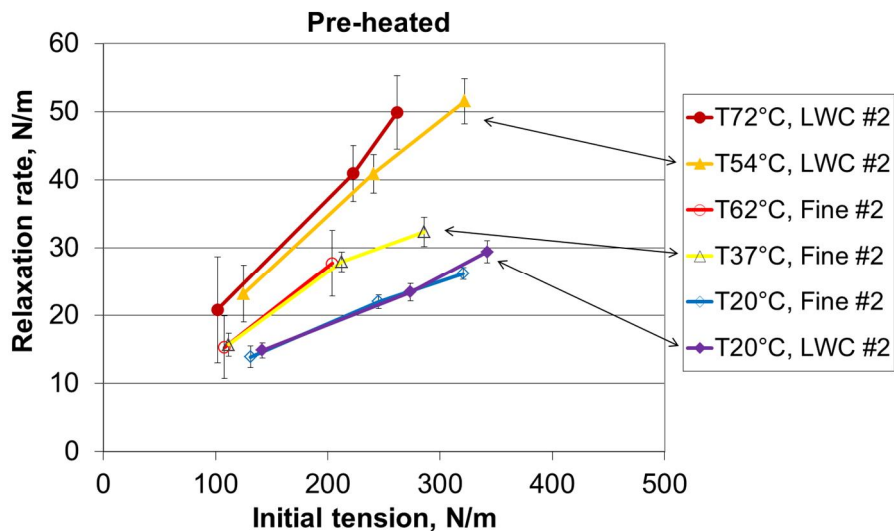Figure 18. Apparent rates of tension relaxation pre-heated fine-paper samples at 56% solids content and LWC-base-paper samples at 53% solids content for different temperatures. Pre-heating means heating was started before straining. Figure is from Publication I.
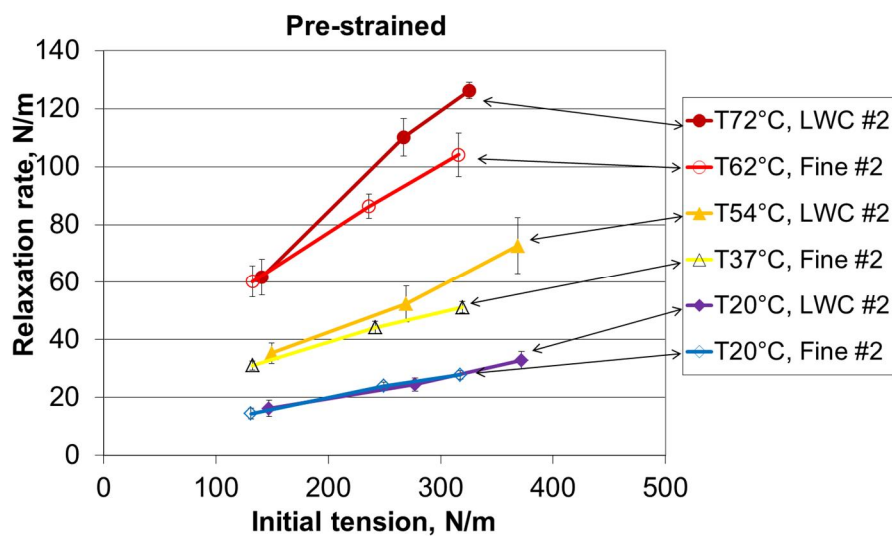

Figure 19. Apparent rates of tension relaxation in the pre-strained case for fine-paper samples at 56% solids content and LWC-base-paper samples at 53% solids content for different temperatures. Pre-straining means straining by 0.5%, 1.1%, and 1.6% before commencing the heating. Figure is from Publication I.

The apparent relaxation rate of wet paper was sensitive to temperature and depended linearly on the initial tension (see Figs 18 and 19). Relaxation rates were further accelerated if heating of paper started during the relaxation phase (see Fig. 19). This seems to be analogous to the moisture-accelerated creep phenomenon for dry paper. It has been recently proposed that cause of the moisture-accelerated creep is an uneven stress distribution and consequent concentrations of stress [Habeger, Coffin 2000, Alfthan *et al.* 2002]. Analogously, an uneven stress distribution and concentrations of stress may also be the origin of temperature-accelerated relaxation and creep [Haslach, Abdullahi 1995, Green 2003]. Although the temperature and moisture gradients in the

wet samples were small in the temperatures studied, they may still be significant. Temperature and moisture gradients may cause uneven stress distributions between fibers and within the fiber walls. A gradual but uneven loss of fiber stiffness under tension may cause stress concentrations and lead to an accelerated relaxation, especially in the case of pre-straining.

The role of inter-fiber bonds in the elastic modulus, tensile creep behavior and in the nonlinearity of stress-strain curve of dry paper is relatively small [Seth, Page 1981, DeMaio, Patterson 2006]. Simulations performed on wet paper suggest that the strength of fiber-fiber contacts only quantitatively affect the strain at break value, while the general shape of the stress-strain curve is the same [Borodulina *et al.* 2012]. Based on this the influence of elevated temperature and moisture on the tensile, creep and relaxation behavior of paper was primarily explained by the fiber properties, whereas fiber bonding played a minor role.

The apparent rate of tension relaxation of wet paper, for varying jet/wire speed ratio and press-section draws (results shown in Publication III) depended only on the initial tension. In the varied filler content case, the apparent rate of tension relaxation of wet paper depended on the filler content and initial tension (see Fig. 20).
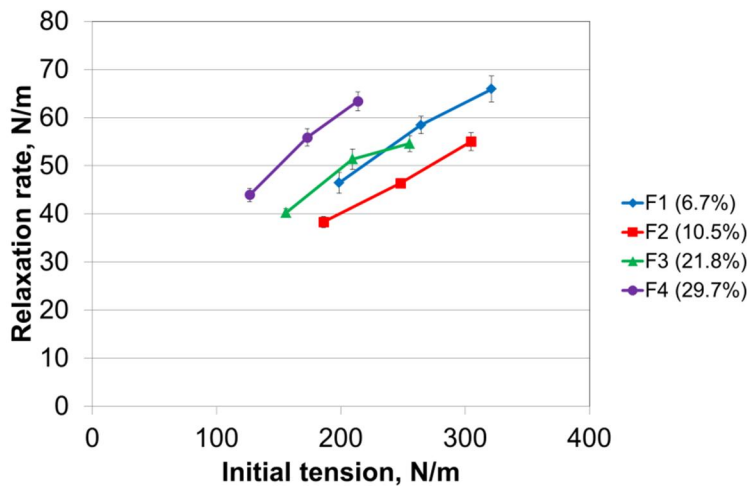

Figure 20. Effect of initial tension on the apparent rate of tension relaxation of SC paper for different filler contents (F1-F4) and solids contents of 51-57%. Straining by 0.6%, 0.9% and 1.2% was performed at a strain rate of 5.6 %/s. Slopes of the curves were between 0.141-0.224. Figure is from Publication III.

An increase in the filler content from 6.7% to 10.5% decreased the apparent tension relaxation rate by 15% and the initial tension by 6%, and increased the solids content slightly from 50% to 52%. This indicates that a filler content of less than 10% may improve the wet web runnability of a SC-type furnish. Generally, an increased solids content leads to an increase in the initial tension and relaxation rate increases with a constant slope. An increase in the filler content from 10.5% to 29.7% increased the apparent rate of tension relaxation and decreased the initial tension, although the solids content also increased. In the varied filler content case, the apparent rate of tension relaxation of wet paper depended both on the initial tension and filler content (see Fig.

20). Filler displaces the fiber material and reduces the relative bonded area that carries the load, which in turn increases the relaxation rate.

Relaxation percentage (described in Sec. 2.5.2) provides an overview of the total tension loss due to relaxation. Examination of such a short-time-scale phenomenon is important for understanding the viscoelastic behavior of a wet web in the paper machine. Relaxation percentage was determined after 4 seconds of relaxation in Publication I. It decreased slightly with a decreasing initial tension (*i.e.*, initial strain) and dependence got stronger for increasing temperature (see Publication I). In supporting Publication VI, relaxation percentage was also found to decrease with increasing initial strain for a wet fine-paper furnish. It approximately doubled for increasing the strain rate from 1 %/s to 100 %/s [Publication VI]. The total loss of tension due to relaxation during the first tenths of a second is strongly underestimated, if only the apparent relaxation rate is used for describing the amount of relaxation.

3.5 Correlation between residual tension and runnability of the paper machine

Correlation between the residual tension and runnability of the paper machine is shown in Fig. 21 (from Publication IV). The higher is the residual tension of furnish (measured after 0.475 s relaxation at a 1% strain with the Impact tester) the lower is the relative vacuum of the web stabilization component in the first dryer group of a pilot paper machine. Correlation emphasizes the importance of knowing the wet residual tension of the basic furnish, and confirms the hypothesis of Sec. 2.5.1.
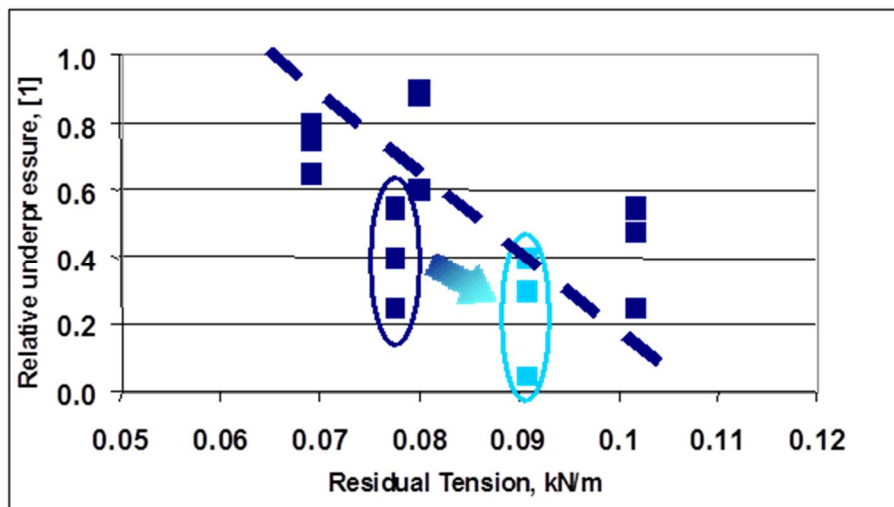
Figure 21. Correlation between the measured residual tension of pulp and the stabilizing runnability component (negative pressure) in the first dryer group (pilot machine). Machine speed, draws, grammage, solids content after wet pressing and fiber orientation were kept identical. Arrow and lighter dots mark the effect of reduction of BSK from 45% to 15% in TMP base. Figure is from Publication IV.

The correlation of Fig. 21 means that a furnish with a higher residual tension has better runnability, because it requires less vacuum of stabilizing the runnability. If the solids content and residual tension of the wet web are unfavorable for runnability, it is possible to improve the runnability by increasing the web tension (by drawing). Another option is to prevent an unstable web behavior in the first dryer group by using power of

the stabilizing component [Leimu 2008]. However, use of the wet web draw is limited in high-speed paper machines [Edwardsson, Uesaka 2009].

Residual tension has a linear correlation with the tensile strength (supporting Publication VI). Correlation between the tensile strength of dry paper and residual tension has typically less variation from linearity than the corresponding correlation for wet paper. The apparent correlation depends strongly on the pulp type and strain rate, and therefore tensile strength cannot be used as a reliable indicator of the residual tension.

4 Influence of process parameters on the runnability of wet and dry paper web

This Section emphasizes the importance of process parameters for the tensile and relaxation properties of paper. It connects experimental methods in the laboratory with certain parameters in commercial paper machines, *i.e.*, the runnability of a wet and dry paper web in papermaking, converting and printing processes.

4.1 Mechanical pulp, BSK content and refining intensity of BSK

The parameters studied in this Section are fixed before web is formed in the forming section of the paper machine. A detailed description of the materials and results can be found in Publication IV and of the measurement methods in supporting Publication V. The key results were re-plotted at a 45% solids content.

The primary reason for the use of mechanical pulp is basically economic. Certain optical and other printability-related properties are also major reasons for using mechanical pulp in SC and LWC paper grades [Heikkurinen, Leskelä 1999]. Mechanical pulp is commonly used also in board grades that have today growth potential in the global market in contrast with the wood containing printing paper grades [Pöyry 2013]. In fact, there is no clear definition between paperboard and paper, but usually paperboards are heavier than 150 grammage with some exceptions [Kiviranta 2000].

This Section (from Publication IV) emphasizes the importance of knowing the tensile and relaxation properties of the basic furnish of wet paper for the wet web runnability. Our findings show clear differences between the residual tension (relaxation) of wet paper and the tensile strength of dry paper. Our results indicate that a higher fiber length of the mechanical pulp may be one factor that improves the runnability of a mechanical-pulp-based furnish. Increase of BSK content in the furnish improves the strength properties of a dry mechanical-pulp-based paper (tensile strength, strain at break, tensile stiffness, residual tension, tear index, T.E.A). Mechanical properties with an exception of strain at break and tear index, can be improved by refining BSK to a higher freeness level. Additionally, the all above-mentioned strength properties of the dry basic furnish, except for the strain at break and tear index, benefit from a high refining degree of BSK. Our results are in line with conclusions of Lehto (2011), *i.e.*, the reinforcement ability of mechanical pulp fibers for a dry paper is lower than that of chemical pulp fibers. However, one of the cornerstones in this Thesis is to establish that the strength properties of dry paper are not capable of representing the runnability potential of a wet web.

The wet residual tension is one the most important parameters describing the wet web runnability in the paper machine. Increase of BSK content generally decreases the wet residual tension (see Fig. 22 B), and does not improve the wet tensile stiffness (see Fig. 23 B). There are minor differences in the influence of BSK content on furnishes based on different mechanical pulps (see Publication IV). PGW1 furnish has the lowest tensile stiffness and residual tension, and may slightly benefit from addition of BSK. It is

obvious that the tensile strength (see Fig. 24 B) of wet mechanical-pulp-based furnishes is improved by an increase in the BSK content. This finding indicates that BSK may be beneficial for the wet web runnability if the wet web draw is very high, *i.e.*, close to breaking. A high refining degree of BSK is favorable for the tensile strength and tensile stiffness of a wet web, however it does not improve the strain at break (see Fig. 26). The results of Publication IV show that solids content of the mechanical-pulp-based furnishes is generally improved by an increase of BSK content, because of the lower freeness of BSK. However, the lower is the freeness of BSK, the less can BSK improve the water removal of a mechanical-pulp-based furnish. Thus, the amount and refining degree of BSK should be selected in each case separately with respect to wet web runnability. Even though BSK does not necessarily improve the wet web runnability, this is still required for maintaining the strength of dry paper in converting operations such as coating and printing. The reinforcement ability of mechanical pulp for the wet web runnability is generally better than that of chemical pulp. The reinforcement ability of BSK for the wet web runnability in the cases of a hardwood-based furnish may be totally different from that of a mechanical-pulp-based furnishes.

A)　　　　　　　　　　　　　　　　**B)**
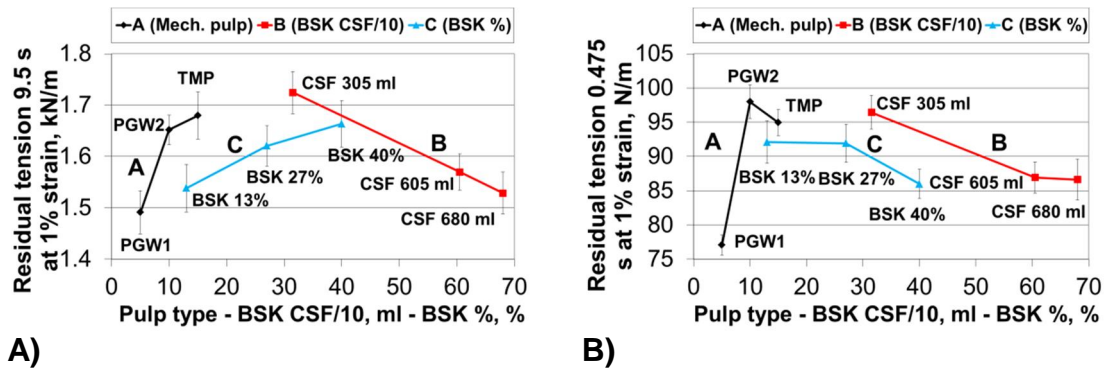
Figure 22. Residual tensions of A) dry paper samples after 9.5 s at a 1% strain, B) wet paper samples at 45% solids content after 0.475 s at 1% strain. Handsheet grammage 60 g/m^2, strain rate 1000 %/s.
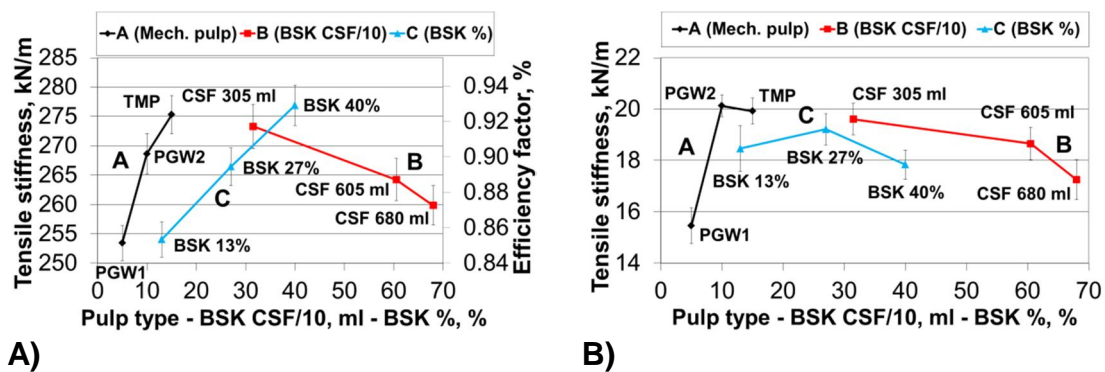

A)　　　　　　　　　　　　　　　　**B)**

Figure 23. Tensile stiffnesses of A) dry paper samples with the corresponding efficiency factors and B) wet paper samples at 45% solids content. Grammage of handsheets 60 g/m^2, strain rate 1000 %/s.
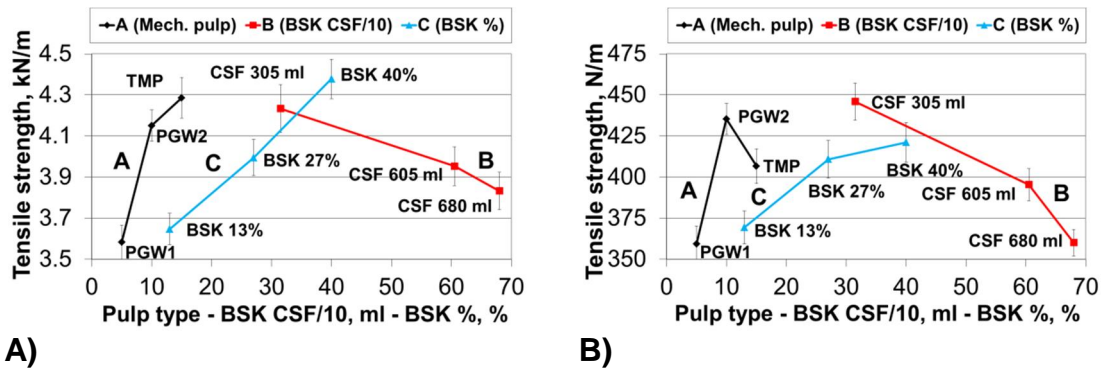
Figure 24. Tensile strengths of A) dry paper samples and B) wet paper samples at 45% solids content. Grammage of handsheets 60 g/m², strain rate 1000 %/s.

The MD tensile strength, MD stain at break, elastic breaking strain (for definition see 2.4.3) and strength uniformity (modulus of a 2-paramter Weibull) are the most important paper-strength properties controlling the runnability of paper in the pressroom (Uesaka *et al.* 2001). According to Uesaka *et al.* (2001), fracture toughness is a valid parameter for estimating the dry-web runnability, when the failure of paper is driven by macro-size cracks (*i.e.* disorder length is >> 1-2 mm). However, the runnability of a coating process may partially depend on different parameters. According to Liimatainen *et al.* (2003), T.E.A. is a suitable quantitative indicator for the runnability of dry paper web in the converting operations.

Examples of the tear index of dry paper are shown in Fig. 25 A. Despite the fact that tear index does not predict consistently web breaks in the pressrooms [Uesaka *et al.* 2001], it is, however, believed to indicate the runnability of the coating process. On the other hand, tear index can be used for benchmarking the analysis method used, because the effects of BSK content and the refining degree of BSK on the tear strength of wood-containing paper are generally well-known.
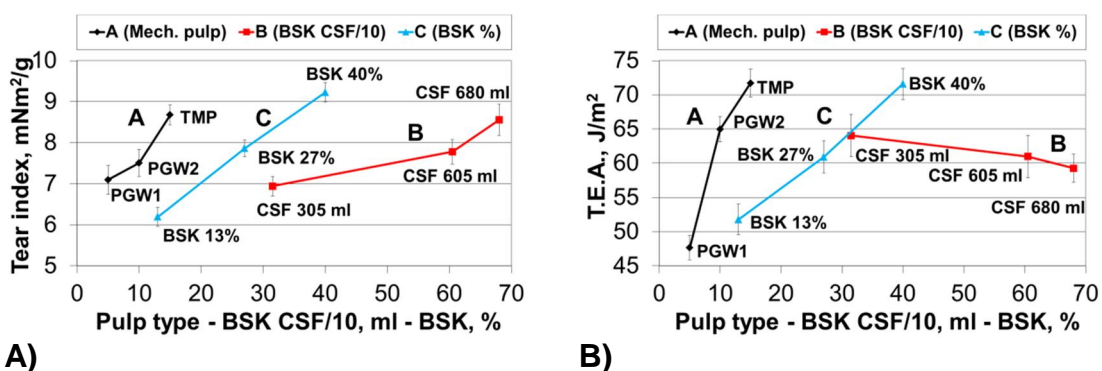
Figure 25. A) Tear indexes and B) T.E.A. of dry laboratory handsheets. Grammage of handsheets 60 g/m².

Strain at break of a paper at 45% solids content is inversely proportional to the fiber length of its furnish (see Fig. 26 and Publication IV). Addition of BSK reduces the strain at break of a PGW1-based furnish and improves the strain at break of a TMP-based furnish (see Publication IV). Strain at break (see Fig. 26 A) and strain at 90%

tension (see Fig. 27 A) of dry paper are within 0.1% percentage points (for the definition of strain at 90% tension see Sec. 2.4.4). In the case of wet paper, difference between the strain at break (see Fig. 26 B) and strain at 90% tension (see Fig. 27 B) is 1.5-1.8% percentage points. This indicates that LWC type wet basic furnishes have a long plateau at the level of maximum tension. This plateau has a significant influence on the possible straining potential in the press-to-drying-section web transfer.
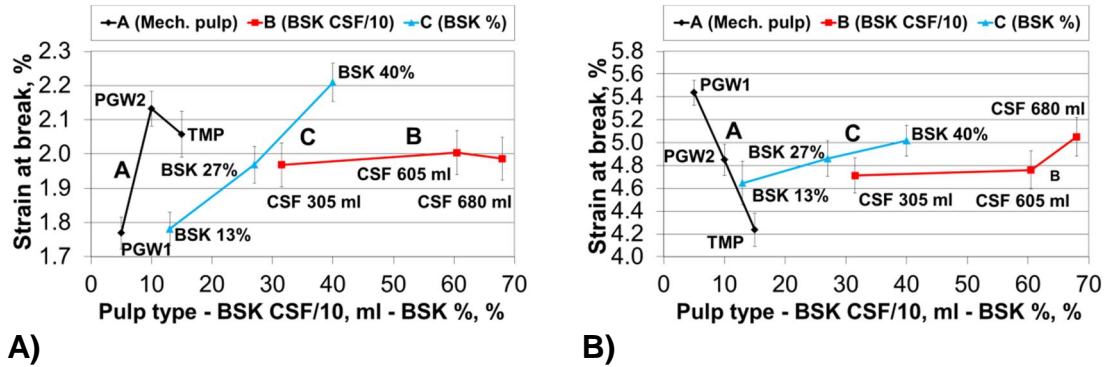

Figure 26. Strain at breaks of A) dry paper samples and B) wet paper samples at 45% solids content. Grammage of handsheets 60 g/m², strain rate 1000 %/s.
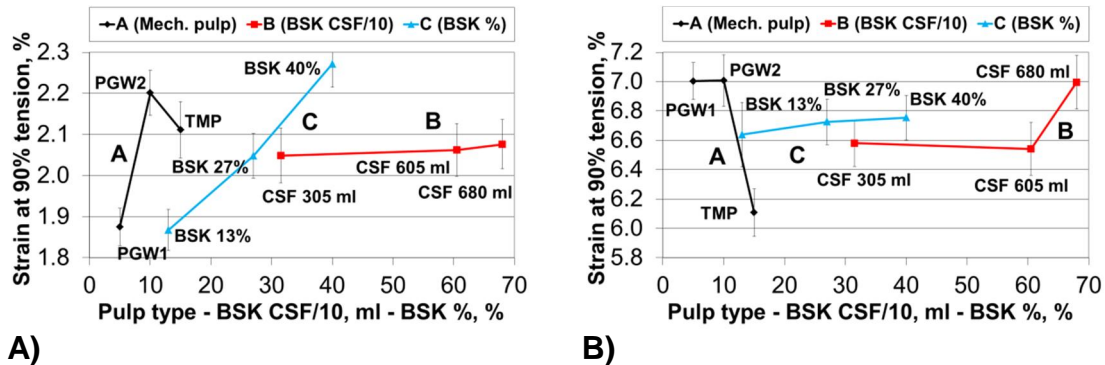
Figure 27. Strains at 90% tension of the maximum tension of A) dry paper samples and B) wet paper samples at 45% solids content. Handsheets grammage 60 g/m², strain rate 1000 %/s.

Statistical contribution ratios for dry and wet paper-strength properties are shown in Table 2 and 3. These contribution ratios show that the type of the mechanical pulp used is the major factor that affects wet paper and the residual tension of dry paper. BSK content is important for the strength properties of dry paper especially for the tear index.

Table 2. Contribution ratios of main factors (A-C), sum of all cross factors (CF) and unexplained variance (UV) for the dry paper samples.

	A	B	C	CF	UV
Tensile strength	34.9	10.6	33.5	8.0	12.9
Strain at break	25.8	0.2	32.4	5.8	35.8
Tensile stiffness	25.6	9.6	26.7	13.6	24.5
Residual tension after 9.5 s at 1% strain	27.9	28.7	10.9	15.7	16.7
Tear index	16.7	16.2	57.2	7.4	2.5
A = Mechanical pulp type, B = BSK CSF, C = BSK content of furnish					

Table 3. Contribution ratios of main factors (A-C), sum of all cross factors (CF) and unexplained variance (UV) for the wet paper samples at 45% solids content.

	A	B	C	CF	UV
Tensile strength	28.7	36.2	14.5	15.0	5.6
Strain at break	40.8	3.0	3.2	15.0	38.1
Tensile stiffness	39.4	7.9	2.7	16.7	33.2
Residual tension after 0.475 s at 1% strain	48.3	11.8	4.6	12.2	23.2
A = Mechanical pulp type, B = BSK CSF, C = BSK content of furnish					

The tension-strain behavior of dry and wet paper is illustrated with two schematic figures (Figs 28 A and 28 B). The influence of addition of BSK on the tension-strain behavior of mechanical-pulp-based furnishes is clearly different for dry and wet papers. Addition of BSK in to mechanical-pulp-based furnishes improves the tensile stiffness, strain at break and tensile strength of dry paper. In the case of wet paper, addition of BSK improves the tensile strength, and depending on the type of mechanical pulp used, it may either improve or decrease the strain at break. However, BSK is not generally able to improve the tensile stiffness of wet paper for a mechanical-pulp-based furnish. In the case of hardwood-based furnish, the influence of addition of BSK on the tensile properties of wet and dry paper may be positive, *i.e.* schematically Fig. 28 A might represent both cases.
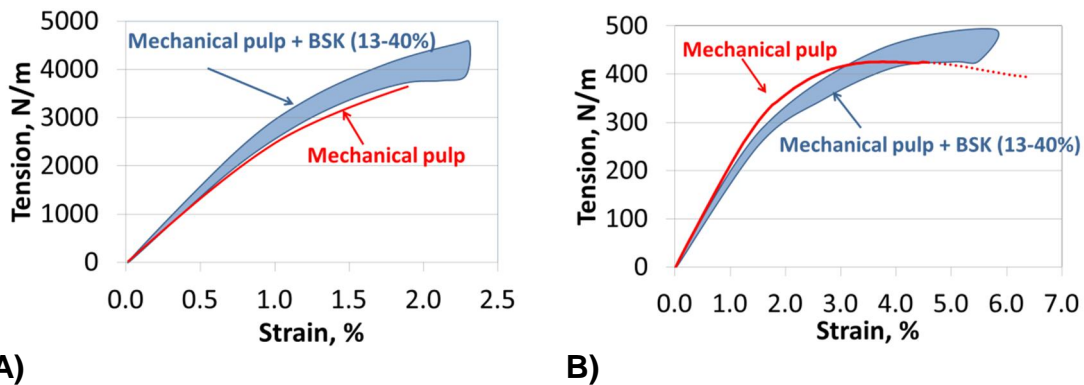
Figure 28. Schematic illustration of the influence of BSK on the tension-strain behavior of A) dry paper and B) wet paper at about 45% solids content based on a mechanical pulp.

The feature shown in Fig. 28 demonstrates that the viscoelastic behavior of wet fiber network differs from that of dry fiber network. During straining of a wet fiber network at 40-50% solids content, fibers may slide. A high specific-surface area of the fiber network due to a high amount of fines and short fibers improves the elongation potential of a wet fiber network. In relaxation, however, movements in the fiber structure seem to be minimal, which is also suggested by simulations of wet fiber networks [Miettinen *et al.* 2009].

4.2   Jet/wire speed ratio

A detailed description of the methods and results of this and the next section can be found in Publication III. Set-up of the laboratory test used in the studies of this and the next two sections is introduced in Sec. 2.2.2 and the method for doing press and dryer section draws in Sec. 2.7.

The minimum of the studied strength properties were close to a jet/wire speed ratio of unity (see Figs 29 and 30). Effect of the first dryer section draw on the tensile strength is shown in these figures with dashed lines. The tensile strength, tensile stiffness and strain at break were improved by a change in the jet/wire speed ratio from unity in any direction. One could expect that change of paper anisotropy would cause the MD tensile stiffness and MD strain at break change in opposite directions. In supporting Publication VI, influence of the jet/wire speed ratio on the residual tension of wet paper and the tensile strength of wet and dry paper was similar with respect to the jet/wire speed ratio, *i.e.* their minima were found to be close to unity. However, effects of the jet/wire speed ratio on the paper properties depend slightly on the former type [Odell, Pakarinen 2001].

A)   **B)**
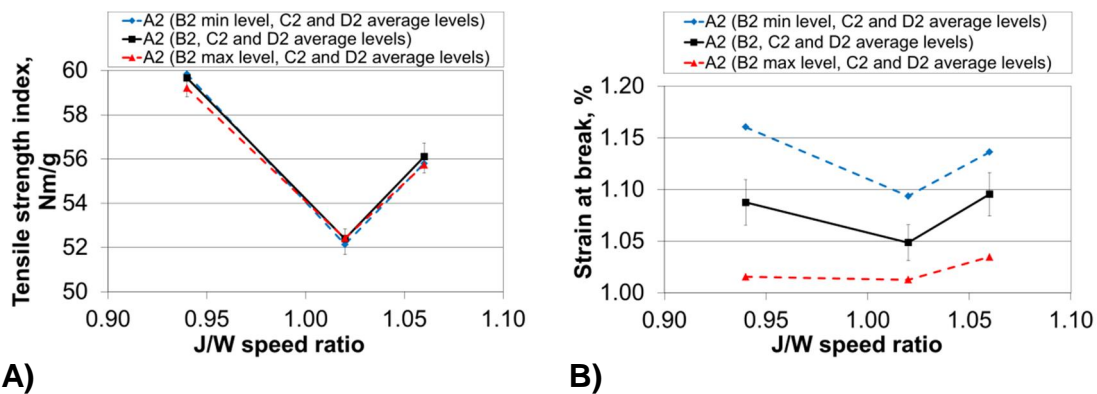
Figure 29. A) Tensile strength index and B) strain at break of dry SC paper samples as a function of the jet/wire speed ratio. Test direction MD, air-dry grammage 42 g/m^2, strain rate 5.6 %/s.
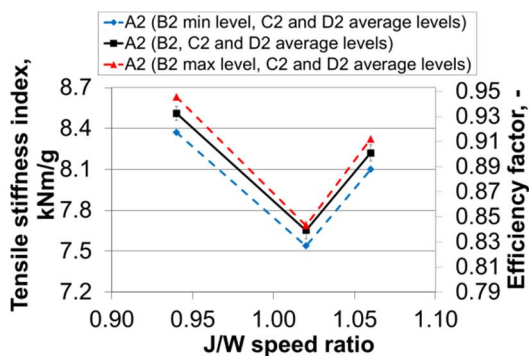

Figure 30. Tensile stiffness index of dry SC paper samples as a function of the jet/wire speed ratio. Test direction MD, air-dry grammage 42 g/m^2, strain rate 5.6 %/s.

4.3   Filler content

Increase in the filler content of paper significantly reduces its drying time (reported in Publication III). The reduced drying time decreases the consumption of drying energy and leads to lower production costs.

Figure 31 and 32 show that an increasing filler content of paper almost linearly correlates with decrease in the tensile strength and stiffness of dry paper. A relatively small addition of filler (by 10% or less) may improve the strain at break of paper. For an addition of filler by more than 10% strain at break is deteriorated. In the tensile properties of dry paper, effect of the filler content dominates the draws performed during drying.

A)   **B)**
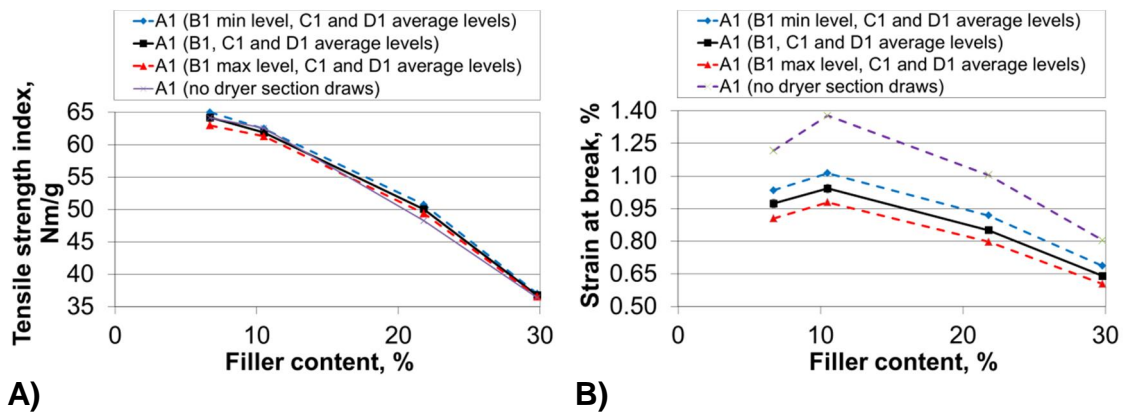
Figure 31. A) Tensile strength index and B) strain at break of dry SC paper samples as a function of the filler content. Test direction MD, air-dry grammage 42 g/m^2, strain rate 5.6 %/s. Influence of dryer section draws on the tensile strength index is shown with dashed lines.

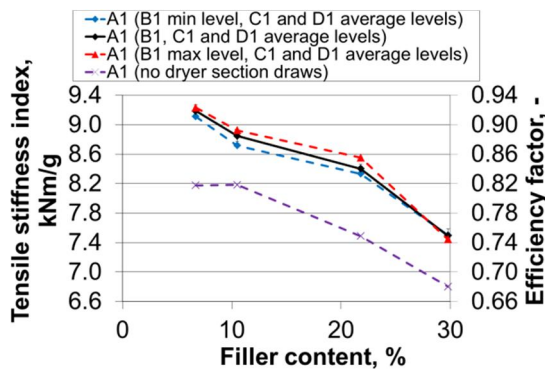Figure 32. Tensile stiffness index of dry SC paper samples as a function of the filler content. Test direction MD, grammage 42 g/m^2, strain rate 5.6 %/s. Influence of dryer section draws on the tensile strength index is shown with dashed lines.

4.4 Draws during wet pressing and drying

A detailed description of the methods and results of this Section can be found in Publication II. The straining history of paper in drying has a significant influence on the drying tension, tensile and elastic properties of paper. Increasing any of the draws after the press rolls and during drying leads to almost a linear decrease in the strain at break of dried paper (see Fig. 33 A). This effect does not depend on the filler content or the jet/wire speed ratio (Publication III). However, increasing all the draws at same time did not decrease linearly the strain at break of dry paper linearly.
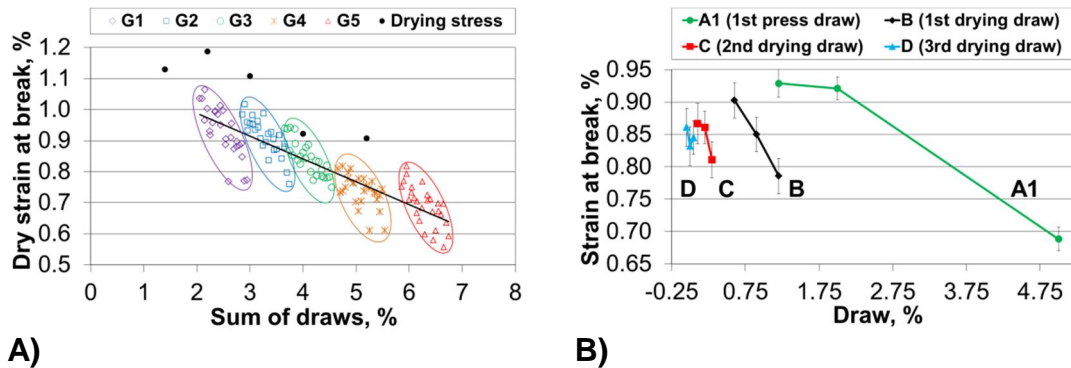

Figure 33. A) Strain at break as a function of sum of press and dryer section draws (G1-G5) and B) strain at break as a function of draws at different stages. Dry SC paper samples in MD, air-dry grammage 54 g/m², filler content 25–26%, jet/wire speed ratio 1.08, strain rate 5.6 %/s.
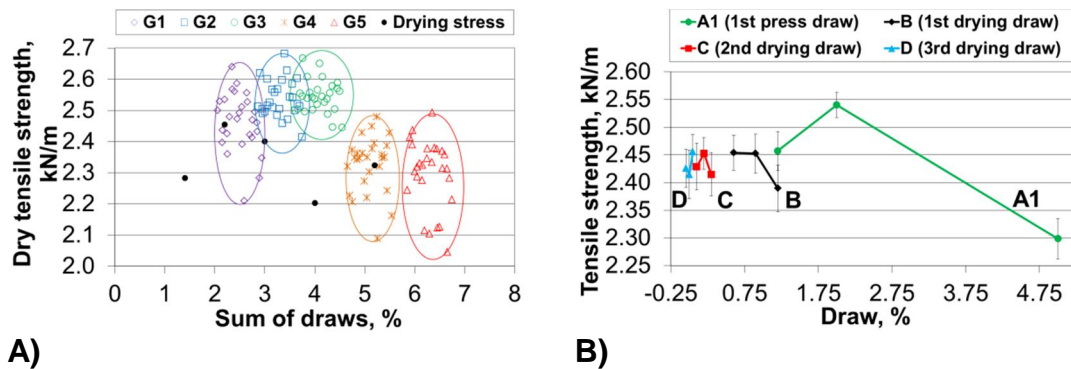
Figure 34. A) Tensile strength as a function of sum of press and dryer section draws (G1-G5) and B) tensile strength as a function of draws at different stages. Dry SC paper samples in MD, air-dry grammage 54 g/m², filler content 25–26%, jet/wire speed ratio 1.08, strain rate 5.6 %/s.

The critical sum of draws decreasing the tensile strength is most likely about 4% (see Fig. 34 A), which is in line with results of Schulz (1961). The tensile stiffness is increased considerably (*i.e.* by 15-20%) by straining in the press section and during drying (See Fig. 35). The solids content of paper during the draws significantly influences the development of tensile stiffness. However, according to Wahlström *et al.* (2000), at which shrinkage or wet straining it takes place is not critical to tensile stiffness, only the total shrinkage or wet strain is. However, that is not in accordance with the results shown in Fig. 35.

Figure 35. A) Tensile stiffness as a function of sum of press and dryer section draws (G1-G5) and B) tensile stiffness as a function of draws at different stages. Dry SC paper samples in MD, air-dry grammage 54 g/m², filler content 25–26%, jet/wire speed ratio 1.08, strain rate 5.6 %/s.
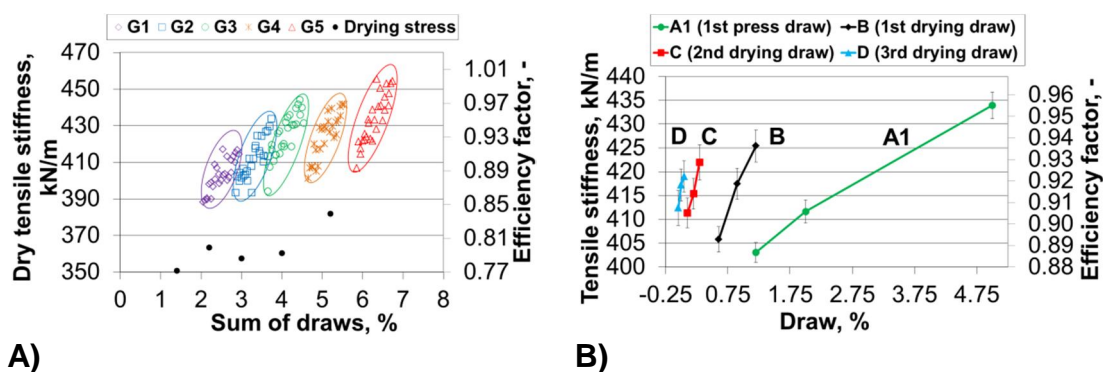
Phenomena at the latter part of the drying section are important. According to Retulainen *et al.* (2006), major part of the final drying stress is caused key the removal of the last 4-6% of moisture.

Draws in drying reduce the strain at break of dry paper, but on the other hand, they do increase the tensile stiffness. Effect of low draws in the press section on the tensile stiffness of dry paper can be compensated by increased straining during drying. This study proposes that it is reasonable to ensure runnability of paper machine by applying draws only up to a certain limit which is well below the critical sum of draws. Otherwise, paper quality (e.g. roughness, oil absorption) and strength properties (e.g. internal bond strength (Scott Bond) and tear index) will suffer [Juppi, Kaihovirta 2002].

4.5   Solids content after wet pressing

Results of this Section are not included in Publications I-IV, but the method is similar to the one used in Publications II and III. The laboratory test set-up used in the studies of this Section is introduced in Sec. 2.2.2.

The initial solids content before drying and draws has a significant influence on the tensile stiffness (Fig. 37 A) and tensile strength (Fig. 36 A) of dry paper. A decreasing effect of the dryer section draws on the strain at break (Fig. 36 B) is the same as the one observed in previous sections. A higher solids content before dryer section draws improves the strength properties of dry paper when the dryer section draws are constant. A local tensile stiffness (in MD) variation may develop from a cross directional moisture variation in combination with dryer section draws.
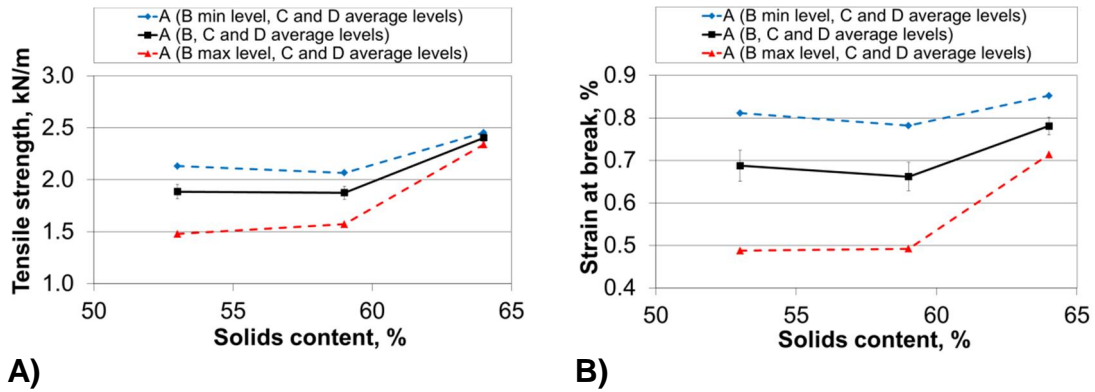
Figure 36. A) Tensile strength and B) strain at break of dry SC paper samples as a function of the initial solids content and dryer section draws. Test direction MD, grammage 42 g/m^2, strain rate 5.6 %/s.
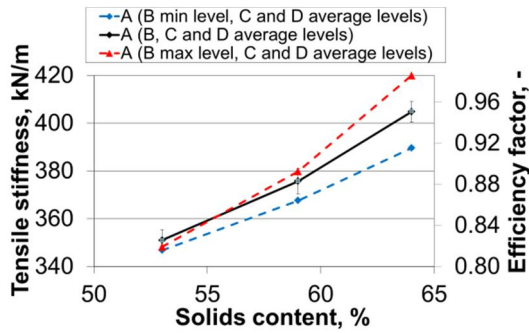
Figure 37. Tensile stiffness index of dry SC paper samples as a function of the initial solids content and dryer section draws. Test direction MD, grammage 42 g/m^2, strain rate 5.6 %/s.

Table 4. Contribution ratios of main factors (A-D), sum of all cross factors (CF) and unexplained variance (UV) for the dry paper samples.

	A	B	C	CF	UV
Tensile strength	46.7	26.1	0.6	0.1	16.3
Strain at break	11.5	49.4	2.6	0.1	19.1
Tensile stiffness	51.0	4.5	2.1	0.5	18.8

A = Solids content after wet pressing, B = 1st drying draw,
C = 2nd drying draw, D = 3rd drying draw

5   Influence of inter-fiber effects on tensile behavior of dry paper

This Section discusses the influence of several process parameters on bonding and activation of the fiber network in dry paper. Results help to understand of the development of the strength properties of dry paper, which affect the runnability of dry web. In this Thesis, bonding properties of the fiber network were estimated using the elastic breaking strain (EBS) concept (see Sec. 2.4.3), while activation of the fiber network was estimated using the efficiency factor concept (see Sec. 2.4.2).

5.1   Bonding in the fiber network of dry paper

The concept of elastic braking strain (EBS) is used to represent the effect of studied factors on the inter-fiber bonding. Increase in the BSK content of paper and freeness (refining) of BSK increase EBS, which indicates that bonding (*i.e.* shear stiffness of inter-fiber bonds) is increased in mechanical pulp furnishes (see Fig. 38). Increase in BSK freeness by refining increases fiber swelling and improves fiber flexibility, which however may not be responsible for a better bonding ability of mechanical and chemical pulp blends (Retulainen 1997). According to the results of Retulainen and Salminen (2009) and Corson and Lobben (1979), it seems that even small amounts of chemical pulp fines may be very effective for increasing the bonding properties of wet and dry wood-containing paper. In this context, it is also worth noting that strengthening mechanisms of fines and starch, which is commonly used to increase the strength of dry paper, are clearly different [Retulainen 1997].The results shown in Fig. 38 indicate that a TMP furnish has a better bonding ability (EBS) than the two studied PGW furnishes. The studied TMP had longer fibers, which are typically more fibrillated, but a lower fines content than the two PGWs (see Publication IV). Character of the fines fraction and more fibrillated fibers may be one explanation for the higher EBS of TMP in comparison with PGW.
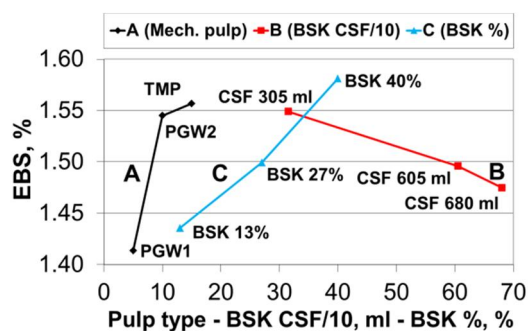
Figure 38. Elastic breaking strain of handsheet samples.

Fig. 39 A indicates that a relatively small amount (10% or less) of fillers does not at all influence the inter-fiber bonding. A higher filler content (above 10%) decreases EBS rapidly. Increasing jet/wire speed ratio decreases EBS, which indicates decrease of inter-fiber bonding (Fig. 39 B). However, jet/wire speed ratio should be kept as a scaling variable with respect to the EBS similar to idea of Seth and Page (1981) for

elastic modulus. Dryer section draws can be used to compensate a change of EBS only to a very limited extent.

According to Tanaka *et al.* (2001), changes of the filler content and refining of BSK in a TMP-based furnish had opposite effects on the tensile stiffness and EBS. However, addition of filler does not change the swelling of fibers whereas refining does. The results in Figs 38, 39 A and 39 B are basically consistent with the results of Tanaka *et al.* (2001).

A)   **B)**
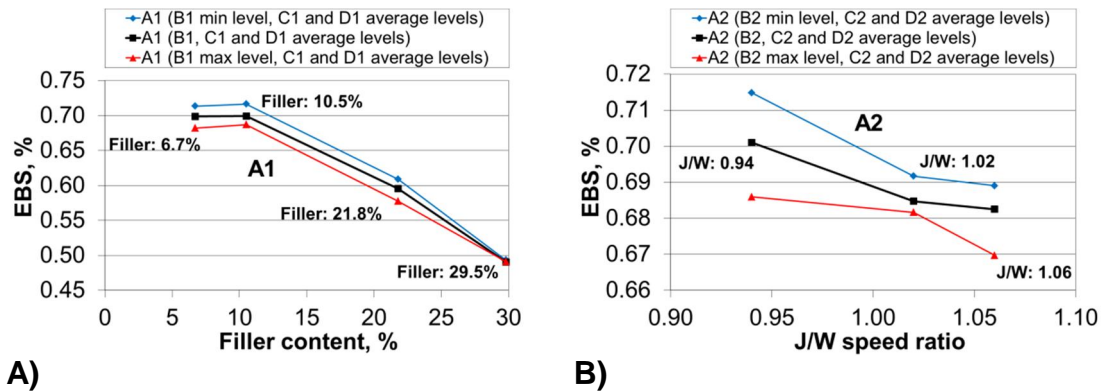
Figure 39. A) Elastic breaking strain of SC paper in MD for a varying filler content and B) elastic breaking strain of SC paper samples in MD for a varying jet/wire speed ratio.

Figures 39 A and 39 B indicate that increase of press and dryer section draws reduces the inter-fiber bonding. Dryer section draws increase the tensile stiffness, whereas tensile strength is then decreased (see Figs 34 and 35). A restrained drying of a fiber network causes shrinkage of bonded fiber segments, and free fiber segments to dry under load [Retulainen 1997]. When a dry fiber network is strained, both bonded areas and free fiber segments are ready to bear load, which may appear here as an apparently decreased bonding (EBS). For an increasing sum of draws, most likely around 4%, de-bonding of the activated fiber network becomes critical for the tensile strength. The contribution ratios of the factors, interactions and unexplained variance with respect to the results are shown in Table 5.

A)   **B)**

Figure 40. A) Elastic breaking strain (A1 is 1st press draw), B) Elastic breaking strain (A2 is 2nd press draw) of dry SC paper samples as a function of press and dryer section draws. Test direction MD.

Table 5. Contribution ratios of main the factors (A-D), sum of all cross factors (CF) and unexplained variance (UV) for varying the 1st draw (A1) and the 2nd draw (A2) in the press section.

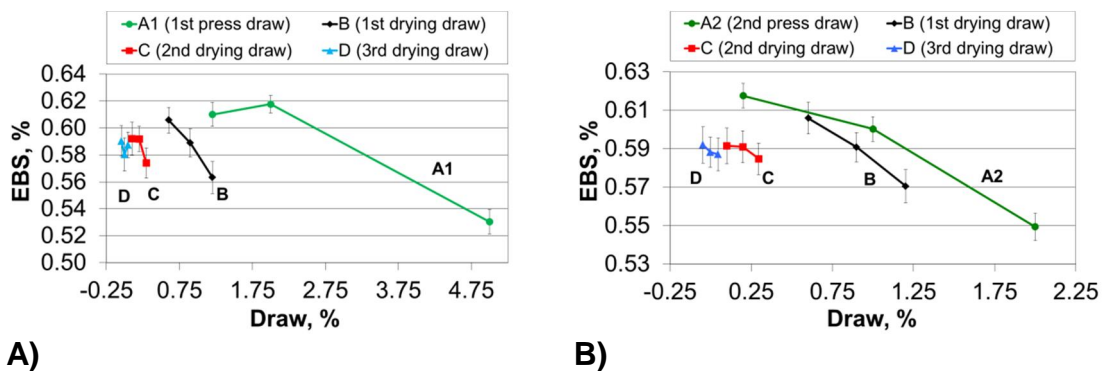|	A	B	C	CF	UV
Elastic breaking strain (EBS) (A1)	45.1	8.9	2.1	0.5	11.0
Elastic breaking strain (EBS) (A2)	40.6	10.2	0.5	0.2	11.9

A1 = 1st press draw, A2 = 2nd press draw,
B = 1st drying draw, C = 2nd drying draw, D = 3rd drying draw

In Fig. 41, the solids content after wet pressing and scaling of the solids content of dryer section draws has remarkable influence on EBS. Results show that influence of wet web straining on EBS decreases with increasing solids content. For lower solids content (drying starts from 53% solids content) the magnitude of dryer section draws (see the difference between min and max levels with respect to solids content in Fig. 41) has a three-fold higher influence on EBS than for high solids content (drying starts from a level of 64%). Results indicate that extensive dryer section draws at a low solids content may deteriorate the inter-fiber bonding compared with the same draws performed at a high solids content. This finding may have practical significance in controlling the internal bond strength of dry paper.
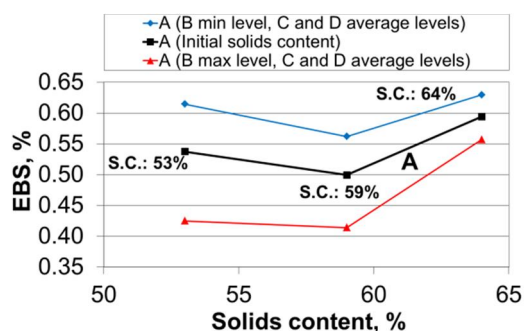
Figure 41. Elastic breaking strain of dry LWC-base-paper in MD.

5.2 Influence of intra- and inter-fiber effects on the shape of tensile behavior of dry paper

It is widely known that, increase in the filler content of paper reduces its strength properties. However, in Publication III, a relatively small amount of fillers (10% or less) did not significantly change the shape of the tension-strain curve scaled with the efficiency factor (see Fig. 42 A). When the filler content was higher (20% or more), the strength and strain at break of paper were deteriorated. This was detected by an impaired scaling of tensile curves with the efficiency factor.

Filler may act in two different ways by reducing the bonding and activation of the fiber network, which reduces the evenness of tension transfer within paper web. This is actually reported to be nearly completely opposite to the effect of refining, but the effect of swelling is absent [Tanaka et al. 2001].
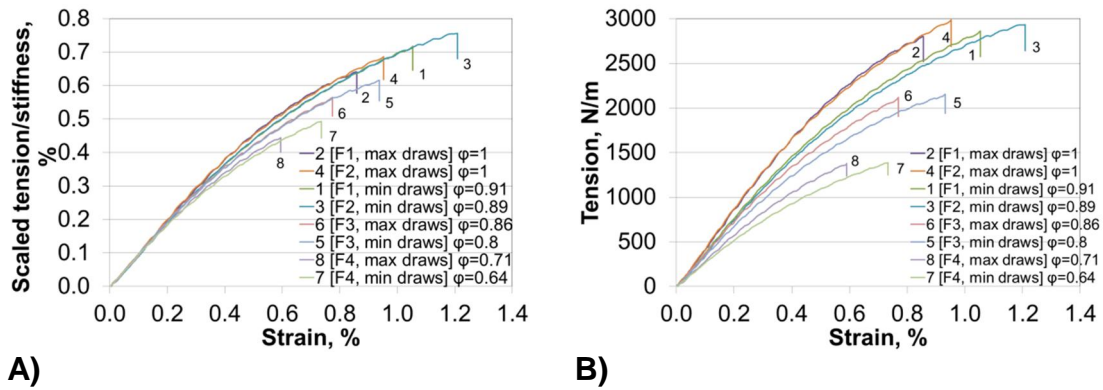
Figure 42. Transposed scaled tension-strain curves of dry paper for the dryer section draws ('min' and 'max') described in Publication III. F1-F4 stand for different filler contents (F1: 6.7%, F2: 10.5%, F3: 21.8% and F4: 29.7%).

Differences between the transposed curves for a varying filler content (see Fig. 42 A) indicate that a reduced bonded area between fibers may change the activation of bonded and free fiber segments during drying. The efficiency factor is also influenced during drying due to straining as the reduced EBS (apparent bonding) indicates in Figs 40 A and 40 B. This finding is in line with that of Seth and Page (1981). Borodulina *et al.* (2012) simulated the effect of the number of bonds on the efficiency factor for a given thickness, and found that reduction of the number of bonds by 25% and 50% dropped the efficiency factor to 0.98 and 0.9, respectively. The relative number of bonds presented by Borodulina *et al.* (2012) can be plotted against efficiency factor and used as a guideline. Using results of Borodulina *et al.* (2012) as a guideline, the number of bonds may have decreased by about 50-60% for a filler content of 22% (see F3, max draws in Fig. 42 A) and the reduction in the number of bonds may have been about 60-80% for a filler content of 30% (see F4, max draws in Fig. 42 A).

In the case of varying jet/wire speed ratio, the transposed tension-strain curves did not form a single curve (Fig. 43 A). It appears that the jet/wire speed ratio that influences the average fiber orientation has some impact on the shape of the tensile-strain curve and on the way the active material bears the load.
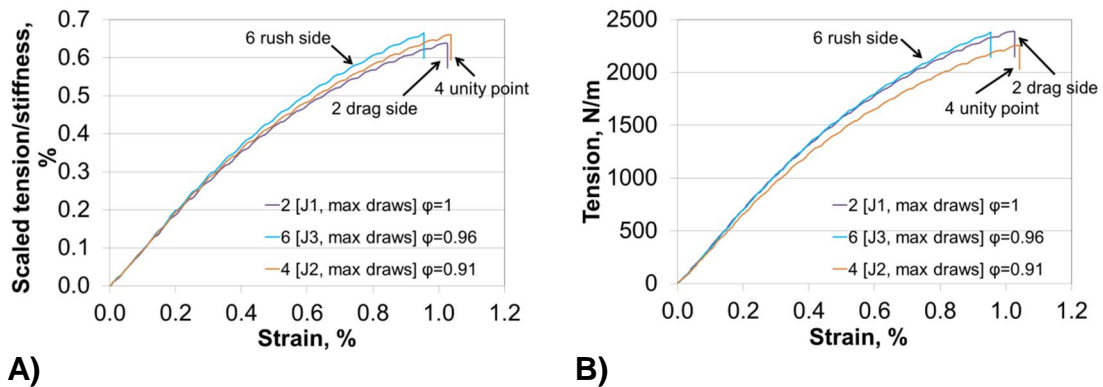

Figure 43. Transposed scaled tension-strain curves of dry paper for the dryer section draws ('min' and 'max') described in Publication III. J1-J3 stand for different jet/wire speed ratios (J1: 0.94, J2: 1.02 and J3: 1.06).

Draws in wet pressing and drying have a clear influence on the tension-strain curves of dry paper (see Fig. 44 B), but curves scaled with the efficiency factor could be superimposed to a single curve (see Fig. 44 A). This results was confirmed by the results shown in Fig. 42, where the tension-strain curves superimposed only in the case when the strain history was changed ('max' and 'min' indicate different draw levels in Figs 42-44, a detailed description of the draws is given in Publications II and III).
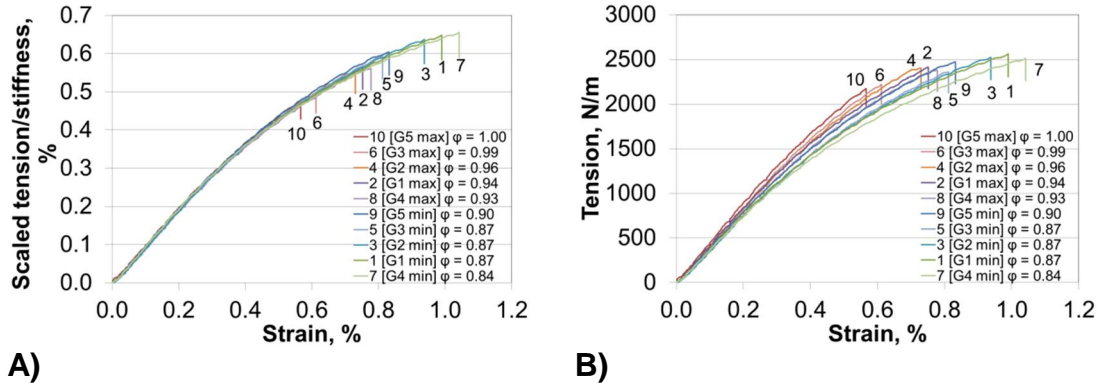
Figure 44. Transposed scaled tension-strain curves of dry paper for the dryer section draws ('min' and 'max') described in Publication II. G1-G5 stand for sums of different press section draws (G1: 1.4%, G2: 2.2%, G3: 3.0%, G4: 4.0% and G5: 5.2%).

The result in Fig. 44 A shows that the main effect of all draws is on the efficiency factor, and on the amount of active material bearing the load. The general deformation behavior and way of loading of the active material remain the same. However, the amount of active material (*i.e.* efficiency factor) changes, and the elongation potential and point of final fracture are changed. Changes in the elongation potential of paper caused by the draws may be explained by a decrease in the elongation potential at the fiber level, but not by changes in bonding. Dryer section draws increase shrinkage of the bonded fiber segments, and enhance free fiber segments to dry under load. Both processes improve the fiber network activation. In Figs 42 A and 44 A the efficiency factors forms two groups according to the 'Min' and 'Max' combinations of the dryer section draw. On the other hand, the effect of straining on the network activation is not permanent unless it becomes fixed during drying.

6 Conclusions

This Thesis describes parameters that govern the runnability of wet and dry web in the paper machine. The primary objective was to investigate the rheological (time-dependent tension-strain) behavior of wet paper, since it controls web transfer from the press to the dryer section. Special emphasis was given to tension relaxation of paper.

An additional objective of this study was to evaluate the influence of heating on the viscoelastic behavior of paper. The effect of multi-stage straining in drying on the tensile properties of dry paper was also investigated. Outcome for the runnability of a dry paper web in converting and printing processes was estimated. Effects of certain furnishes and process related factors in papermaking (e.g. reinforcement pulp content and refining, filler content and jet/wire speed ratio) on the strength properties of dry paper were as well determined.

The primary research questions were as follows:

1. What are the effects of temperature changes on the tension-strain and the relaxation behavior of wet paper?
2. What are the roles of mechanical pulp and chemical reinforcement pulp in reinforcing of a wet paper web at a 40-55% solids content?
3. How draws in the paper machine affect the runnability potential of a dry web in converting and printing processes?
4. Which of the mechanical properties of paper control the runnability of a wet and dry web?
5. What is the optimal combination of the papermaking related factors studied, e.g. wet web draws, filler content, jet/wire speed ratio and furnish composition, for achieving the best possible runnability of a wet and dry web for a wood-containing printing paper?
6. To what extent the papermaking operations studied affect bonding and activation of the fiber network?

Based on the results the following conclusions could be made:

1. Heating deteriorates the strength and relaxation properties of wet paper. Effects of temperature on the viscoelastic properties of wet paper take place in a few tenths of a second. Temperature has a major impact on the tensile stiffness and tensile strength, whereas the strain at break of wet paper is not sensitive to temperature changes. Influence of temperature on the tensile stiffness of wet paper originates most probably from the tensile properties of the fiber wall. Reduction of adhesion in the fiber-fiber contacts due to increased temperature plays a minor role in the tensile behavior in re-straining of wet paper samples. Furthermore, structural reorganization of the fiber network is an unlikely response to an increased temperature. The observed temperature-accelerated relaxation in wet paper seems to be analogous to the moisture-accelerated creep phenomenon in dry paper. Increase of temperature increases the relaxation rate of wet paper, but increasing temperature during relaxation seems to accelerate its relaxation even more. This behavior has not been

before reported for wet paper. Temperatures and temperature changes that occur in industrial processes have a strong influence on the tensile and relaxation behavior of wet web, e.g. in the press section and in the beginning of the dryer section of the paper machine.

2. In wood-containing printing papers the ability of a mechanical pulp to improve the runnability of wet web is bigger than that of a chemical reinforcement pulp. Influence of the bleached softwood reinforcement pulp (BSK) on the strength properties of a mechanical-pulp-based furnish is clearly different for a dry and wet paper. BSK improves the water removal of a wet furnish at forming and press section and the strength properties of dry paper. Conversely, the ability of BSK to improve the strength properties of wet paper depends on the properties of the mechanical pulp. Results indicate that addition of BSK is not able to improve the runnability of a mechanical based furnish at the typical draw levels of the press and dryer section. Conversely, at relatively high draw levels close to web breaking, BSK may improve the runnability of a wet web, which in turn means that the optimal strain at break and tensile strength for the dry web runnability cannot be reached. However, the reinforcement ability of BSK for the wet web runnability in the case of a hardwood-based fine-paper furnishes may be totally different from that of a mechanical-pulp-based furnish.

3. Draws in drying of wet paper have a significant influence on the strength properties of dry paper that dictate the dry web runnability. The strain at break of dry paper decreases drastically, whereas the tensile stiffness increases significantly with increasing draws during drying. On the other hand, results indicate that the critical sum of draws decreasing the tensile strength is about 4% for the draws performed in the press and dryer section. The higher is the solids content after wet pressing in which straining takes place the better are the strength properties of dry paper. The positive effect of draws in the press section and in the beginning of the dryer section on the tensile stiffness of dry paper can be reached by straining the paper web at a later stage of drying with a minor expense of the strain at break. Strength properties of the wet web together with the used web handling operations in the paper machine determine the runnability potential of a dry paper web in converting. The results of this work can also be used when cross directional web profiles are estimated. For example variations in the local strength properties of dry paper originate partly from deviations in the local moisture and filler content, which are strengthened by the dryer section draws.

4. Results indicate that the residual tension in a tension relaxation test is the key measurement for describing the runnability potential of a pulp furnish in the paper machine. The residual tension of furnishes that were measured in the laboratory correlated with vacuum of a stabilizing runnability component in the dryer section of a pilot paper machine. The tensile strength, tensile stiffness and strain at break values of the wet web furnish provide complementary information for the wet web runnability. In the case of dry paper the importance of the residual tension for runnability has not been proved. The relative amount of relaxation in dry paper is significantly lower than in wet paper. According to literature, the strain at break and

tensile strength of dry paper correlate with web breaks in the printing machine, whereas tear index plays a minor role. Based on these assumptions, the runnability of a wet and dry paper web should be described with different strength variables.

5. The high average length of mechanical pulp fibers may be an indicator of a better wet and dry web runnability. The main purpose of the chemical reinforcement pulp in a mechanical-pulp-based furnish is to improve the strength properties and runnability. The optimal content of chemical reinforcement pulp in a mechanical-pulp-based furnish depends on several factors, but first of all it depends on the properties of the mechanical pulp. Increasing the reinforcement pulp content improves the tensile strength and strain at break of dry paper, but may be detrimental to the residual tension of the wet web furnish in a typical case when the wet mechanical pulp has a superior residual tension. However, refining of the chemical pulp is generally beneficial for the both residual tension of wet pulp furnish and tensile strength of dry paper, but has only a minor influence on the strain at break of dry paper, which plays a major role in control of the wet and dry web runnability. Conversely, higher degree of refining of chemical pulp decreases water removal of furnish, which is one advantage of the use of chemical pulp in mechanical-pulp-based furnishes. High solids content after wet pressing is not only beneficial for the consumption of drying energy, but leads to lower dryer section draws, which improves the strain at break and several other important strength and quality properties of dry paper. For high solids content the dryer section draws that are needed to ensure the web runnability are less detrimental for the strength properties of dry paper. Fillers are used in wood-containing printing papers due to product quality and economic reasons, though it generally worsens all strength properties and runnability of paper. The deteriorating influence of fillers cannot be compensated by any means in a large scale, but in a small scale compensation also dryer section draws can be used. However, for a low filler content of less than 10%, fillers may slightly improve the wet web relaxation and the strain at break of dry paper. The optimal jet/wire speed ratio for the strength properties of paper is either on the drag of rush side, not at unity. The purpose of press and dryer section draws is to secure the wet web runnability. Relatively speaking, low press and dryer section draws lead generally to optimal strength properties of dry paper. Need of the press and dryer section draws is determined by the location and extent of draws, mechanical web stabilizing systems for runnability, speed of the paper machine and wet web properties such as the solids content and viscoelastic behavior of wet paper.

6. Furnish related factors, e.g. type of the mechanical pulp, the content and the refining level of chemical pulp and filler content, have a major influence on bonding of the fiber network. Increasing press and dryer section draws decrease the apparent bonding of the fiber network, but its influence is minor compared to those of the furnish related factors. Increasing filler content decreases ability of the active fiber network to bear load. A reduced bonded area between fibers may reduce the inter-fiber bonding but increase the activation free fiber segments during drying. Varying the jet/wire speed ratio, which influences the average fiber orientation, has a small impact on the shape of the tensile-strain curve and on the way the active material

bears the load. Dryer section draws do not change the general deformation behavior, and the way of loading of the active material remains the same. However, the amount of active material (*i.e.* efficiency factor) changes, and the elongation potential and point of final fracture. Changes in the elongation potential of paper caused by the draws may be explained by a decrease in the elongation potential at the fiber level, but not by changes in bonding.

Bibliography

Alfthan, J., Gudmundson, P. and Östlund, S. (2002): A micro-mechanical model for mechano-sorptive creep in paper, J. Pulp Paper Sci. 28, 98–104.

Andersson, O. and Sjöberg, L. (1953): Tensile studies of paper at different rates of elongation, Svensk papperstidning 56, 615–624.

Back, E.L. and Andersson, L.I. (1992): The effect of temperature on wet web strength properties, Pan-Pacific pulp and paper technology vol. B, 141-150.

Barnet, A. and Harvey, D.M. (1980a): Wet web characteristics and relation to wet end draws, Part I – Lab studies demonstrating factors that influence wet web properties, Pulp Paper Canada 81, T302-T305.

Barnet, A. and Harvey, D.M. (1980b): Wet web characteristics and relation to wet end draws, Part II – Wet behavior in the press section of an experimental papermachine, Pulp Paper Canada 81, T306-T310.

Batchelor, W.J., Wu, Z. and Johnston, R.E. (2004): Measurement of z-direction moisture transport and shrinkage in the drying of paper, Appita J. 57, 107-111.

Baum, G.A., Pers, K., Shepard, D.R. and Ave'Lallemant, T.R. (1984): Wet straining of paper, Tappi 67, 100-104.

Borodulina, S., Kulachenko, A., Galland S. and Nygårds, M. (2012): Stress-strain curve of paper revisited, Nord. Pulp Paper Res. J. 27, 318-328.

Bousfield, D.W. (2008): Rheological issues in the paper industry, Rheology Reviews 6, 47-70.

Brecht, W. and Erfurt, H. (1959): Wet-web strength of mechanical and chemical pulps in different form composition, Tappi 42, 959-968.

Caulfield, D. (1986): Effect of moisture and temperature on the mechanical properties of paper, in: Perkins, R.W., Mark, R.E., Thorpe, J.L. (Eds.), Solid mechanics advances in paper related industries, Proceedings of National Science Foundation workshop, Syracuse University, 50-62.

Coffin, D.W. (2005): The creep response of paper, in: I'Anson, S.J. (Ed.), Advances in paper science and technology, Trans. XIIIth Fund. Res. Symp. Cambridge, pp. 651–747.

Coffin, D.W. (2009): Developing a deeper understanding of the constitutive behavior of paper, in: I'Anson, S.J. (Ed.), Advances in Pulp And Paper Research, Trans. XIVth Fund. Res. Symp. Oxford, pp. 841–875.

Coffin, D.W. (2012): Use of the efficiency factor to account for previous straining on the tensile behavior of paper, Nord. Pulp Paper Res. J. 27, 305-312.

Corson, S. and Lobben, T. (1979): On the influence of fines on wet web strength, Int. Paper Physics Conf., pp. 115-121.

Craven, B.D. (1962): Stress Relaxation and Work Hardening in Paper, Appita 16, 57–70.

DeMaio, A. and Patterson, T. (2006): Influence of bonding on the tensile creep behavior of paper in a cyclic humidity environment, Mech. Time-Dep. Mat. 10, 17–33.

Deng, N.X., Ferahi, M. and Uesaka, T. (2007): Pressroom runnability: A comprehensive analysis of pressroom and mill databases, Pulp Paper Canada 108, T39-T42.

de Oliveira, M.H., Tejado, A. and van de Ven, T.G.M. (2009): Effects of fillers on the wet web strength of paper, Nord. Pulp Paper Res. J. 24, 141-147.

de Ruvo, A., Lundberg, R., Martin-Löf, S. and Söremark, C. (1973): Influence of temperature and humidity on the elastic and expansional properties of paper and the constituent fiber, in: Bolam, F. (Ed.), The Fundamental Properties of Paper Related to its Uses, Trans. Vth Fund. Res. Symp. Cambridge, pp. 785–806.

Derakhshandeh, B., Kerekes, R.J., Hatzikiriakos, S.G. and Bennington, C.P.J. (2011): Rheology of pulp fibre suspensions: A critical review, Chem. eng. sci. 66, 3460-3470.

Diesen, M. (2007): Main characteristics of the global pulp and paper industry, in: Diesen, M. (Ed.), Economics of the pulp and paper industry, Second edition, Paperi ja Puu Oy, Helsinki. pp. 10-17.

Dumbleton, D.P., Kringstad, K.P. and Söremark, C. (1973): Temperature Profiles in Paper during Straining. Svensk papperstidning 76, 521–528.

Ebeling, K. (1970): Distribution of Energy Consumption During Straining of Paper. Ph.D. Thesis, Lawrence University Appleton, Wisconsin, USA.

Ebeling, K.I. (1973): Distribution of energy consumption during the straining of paper, in: Bolam, F. (Ed.), The Fundamental Properties of Paper Related to its Uses, Trans. Vth Fund. Res. Symp. Cambridge, pp. 305–335.

Edwardsson, S. and Uesaka, T. (2009): System dynamics of the Open-Draw With Web Adhesion: Particle Approach, J. Appl. Mech. 77, 021009-1-021009-11.

Findley, W.N., Lai, J.S. and Onaran, K. (1989): Creep and relaxation of nonlinear viscoelastic materials, Dover publications, 400 p.

Frigon, N.L. and Mathews, D. (1997): Guide to experimental design, John Wiley & Sons, Inc., 342 p.

Green, C. (2003): A view of accelerated creep and residual strain: Accelerating creep by heating, Int. Paper Physics conf., Victoria, Canada, pp. 297-301.

Göttsching, L. (1970): Das Festigkeitsverhalten von Papier unter statischer dynamischer Beanspruchung, Teil I, Papper Trä 52, 535-554.

Göttsching, L. and Baumgarten, H.L. (1973): Triaxial deformation of paper under tensile load, in: Bolam, F. (Ed.), The Fundamental Properties of Paper Related to its Uses, Trans. Vth Fund. Res. Symp. Cambridge, pp. 227–249.

Habeger, C.C. and Coffin, D.W. (2000): The role of stress concentrations in accelerated creep and sorption-induced physical aging, J. Pulp Paper Sci. 26, 145–157.

Haslach, H.W. and Abdullahi, Z. (1995): Thermally cycled creep of paper. Mechanics of Cellulosic Materials, AMD Vol. 209, MD Vol. 60, R.W. Perkins (ed.), ASME, New York, 13-22.

Hauptmann, E.G. and Cutshall, K.A. (1977): Dynamic mechanical properties of wet paper web, Tappi 60(10), 106-108.

Heikkilä, P. and Paltakari, J. (2010): Fundamentals of paper drying, in: Karlsson, M. (Ed.), Papermaking Part 2, Drying, second edition, Paperi ja Puu Oy, Helsinki. pp. 40-77.

Heikkurinen, A. and Leskelä, L. (1999): The character and properties of mechanical pulps, In: Mechanical pulping, ch. 15, Fapet Oy, Helsinki, Finland, pp. 394-413.

Hiltunen, E. (2003): On the beating of reinforcement pulp, Doctoral Thesis, Helsinki University of Technology, Department of Forest Products Technology, Espoo, Finland.

Hiltunen, E. and Paulapuro, H. (2011): Effect of long-fibred reinforcement pulp on mechanical properties of short fibred-based paper, O Papel 72(8), 42-48.

Hyll, C., Vomhoff, H. and Nygårds, M. (2012): Analysis of the plastic and elastic energy during the deformation and rupture of a paper sample using thermography, Nord. Pulp Paper Res. J. 27, 329-334.

Ilvespää, H. (1998): Challenging the speed potential, Valmet Paper Technology Days, Jyväskylä, Finland, pp. 63-71.

Incropera, F.P. and DeWitt, D.P. (2002): Fundamentals of heat and mass transfer, Fifth Edition, John Wiley & Sons.

Ionides, G.N., Jackson, M., Smith, M.K. and Forgacs, O.L. (1977): Factors influencing the strength properties of wet-webs, in: Trans. VIth Fund. Res. Symp. Oxford, pp. 357-374.

Jantunen, J. (1985): Visco-elastic properties of wet webs under dynamic conditions, in: Punton, V. (Ed.), Papermaking Raw Materials, Trans. VIIIth Fund. Res. Symp. Oxford, pp. 133–162.

Juppi, K. and Kaihovirta, J. (2002): The effect of the dryer section on the paper quality, 88th Annual meeting, Paptac, Montreal, Canada, pp. B23-B26.

Juppi, K. (2006): Improved runnability and drying capacity through new technology, Metso Paper Technology Days, Finland, pp. 66-75.

Juppi, K. (2010): Multicylinder dryer and drying concepts, In: Paper making part 2, Drying (2nd ed.), Fapet Oy, Helsinki, Finland, pp. 78-125.

Kekko, P. (2000): Paperin elastiset ja plastiset ominaisuudet ja niiden merkitys LWC-paperin tuotantoprosessin hallintaan, Licentiate Thesis, University of Jyväskylä, Jyväskylä, Finland.

Kekko, P., Kouko, J., Retulainen, E. and Timonen, J. (2009): Effects of strain rate on the stress relaxation of wet paper, in: Considine, J.M., Ralph, S.A. (Eds.), Proceedings, Sixth International Symposium: Moisture and Creep Effects on Paper, Board and Containers, Madison, Wisconsin, USA, pp. 49–58.

Kerekes, R.J. (2006): Rheology of fibre suspensions in papermaking: An overview of resent research, Nord. Pulp Paper Res. J. 21, 598-612.

Keränen, J.T., Paaso, J., Timofeev, O. and Kiiskinen, H. (2009): Moisture and temperature measurement of paper in the thickness direction, Appita J. 62, 308-313.

Kiiskinen, H.T., Lyytikäinen, K. and Hämäläinen, J.P. (1998): Specific heats of dry Scandinavian wood pulps, J. Pulp Paper Sci. 24, 219–223.

Kiiskinen, H., Paltakari, J. and Pakarinen, P. (2000): Drying and paper quality, In: Paper making part 2, Drying, Fapet Oy, Helsinki, Finland, pp. 333-368.

Kiviranta, A. (2000): Paperboard grades, In: Paper and board grades, ch 2., Fapet Oy, Helsinki, Finland, pp. 55-74.

Kubát, J., Nyborg, L. and Steenberg, B. (1963): Response of paper to low frequency sinusoidal strain, Svensk papperstidning 66, 754–764.

Kubát, J. (1965): Stress relaxation in solids, Nature 205, 378–379.

Kubát, J., Martin-Löf, S. and Söremark, C. (1969): Thermal Expansivity and Elasticity of Paper and Board, Svensk papperstidning 72, 763–767.

Kuhasalo, A., Niskanen, J., Paltakari, J. and Karlsson, M. (2000): Introduction to paper drying and principles and structure of a dryer section, In: Paper making part 2, Drying, Fapet Oy, Helsinki, Finland, pp. 16-53.

Kurki, M., Kekko, P. and Martikainen, P. (1999): Fast elasticity properties of paper web. Tappi papermakers conference, Atlanta, USA, vol. 2, 411-426.

Kurki, M., Pakarinen, P., Juppi, K. and Martikainen, P. (2000): Web handling, In: Paper making part 2, Drying, Fapet Oy, Helsinki, Finland, pp. 369-431.

Kurki, M., Martikainen, P., Saarikivi, P. and Salminen, K. (2010): Web handling, In: Paper making part 2, Drying (2nd ed.), Fapet Oy, Helsinki, Finland, pp. 484-541.

Lakes, R.S. (2009): Viscoelastic materials, Cambridge University Press, 480 p.

Lehto, J. (2011): Reinforcement ability of mechanical pulp fibres, Doctoral Thesis, Aalto University, Department of forest products technology, Espoo, Finland.

Leimu, J. (2008): Theoretical and experimental investigation of the cylinder dryer opening nip, Doctoral Thesis, Åbo Akademi University, Faculty of technology, Turku, Finland.

Liimatainen, H. Tuominen, R., Heimonen, J. and Jonsson, S. (2003): Furnish Concepts, Metso Paper Technology Days, Lahti, Finland.

Lindberg, N.J. (2000): History of papermaking, In: Papermaking Part 1, Stock Preparation and Wet End, ch 2, Fapet Oy, Helsinki, Finland, pp. 56-71.

Lindqvist, H. (2013): Improvement of wet and dry web properties in papermaking by controlling water and fiber quality, Doctoral Thesis, Åbo Akademi University, Department of chemical engineering, Laboratory of wood and paper chemistry,Turku, Finland.

Lipponen, P. (2010): Elasto-plastic modelling approach for cockling and curling phenomena, Doctoral Thesis, University of Kuopio, Kuopio, Finland.

Lobben, T.H. (1975): The tensile stiffness of paper Part 1, A Model based on activation, Norsk Skogindustri 29, 311-315.

Lumiainen, J. (2000): Refining of chemical pulp, In: Papermaking Part 1, Stock Preparation and Wet End, ch 4., Fapet Oy, Helsinki, Finland, pp. 86-122.

Lyne, L.M. and Gallay, W. (1954a): Measurement of wet web strength, Tappi 37, 694-698.

Lyne, L.M. and Gallay, W. (1954b): Fiber properties and fiber-water relationships in relation to the strength and rheology of wet webs, Tappi 37, 581-596.

Mardon, J. and Short, R.J. (1971): Wet web strength related to papermaking, Part I, Paperi Puu 53, 203-215.

Mardon, J., Kutshall, K., Smook, G., Branion, R. and Michie, I. (1975): Effect of wet-web furnish properties on newsprint runnability, Pulp Paper Canada 76, T153-T166.

Miettinen, P. (2009): Simulations of the structure and rheology of wet webs, Doctoral Thesis, University of Jyväskylä, Jyväskylä, Finland.

Miettinen, P.P.J., Kekko, P. and Kouko, J. (2009): Relaxation of wet paper by simulations and laboratory-scale experiments, Nord. Pulp Paper Res. J. 24, 381-387.

Montgomery, D.C. (1997): Design and analysis of experiments, Fourth edition, John Wiley & Sons, Inc., 720 p.

Mäkelä, P. and Östlund, S. (2003): Orthotropic elastic-plastic material model for paper materials, Int. J. Solids Struct. 40, 5599-5620.

Mäkelä, P. (2007): The effect of moisture ratio and drying restraint on the stress relaxation of paper, Appita annual conference, pp. 169-177.

Niskanen, K. (1998): Rheology and moisture effects, In: Paper physics, ch 8., Fapet Oy, Helsinki, Finland, pp. 260-283.

Niskanen, K. and Kärenlampi, P. (1998): In-plane tensile properties, In: Paper physics, ch 5., Fapet Oy, Helsinki, Finland, pp. 138-191.

Norman, B. (2000): Web forming, In: Papermaking Part 1, Stock Preparation and Wet End, ch 6., Fapet Oy, Helsinki, Finland, pp. 191-250.

Norman, B. and Söderberg, D. (2001): Overview of forming literature 1990-2000, Trans. XIIth Fund. Res. Symp. Oxford, pp. 431–558.

Odell, M. and Pakarinen, P. (2001): The complete fibre orientation control and effects on diverse paper properties, Tappi Papermakers Conference, Proceedings, Cincinnati.

Oksanen, A. (2012): Improving the material efficiency of furnishes in papermaking by stratification and chemical modifications, Doctoral Thesis, University of Jyväskylä, Jyväskylä, Finland.

Okushima, S. (1977): Rheological deformation of paper sheet during straining and stress relaxation, Mokuzai Gakkaishi 23, 666-669.

Ora, M. (2012): The effect of web structure on wet web runnability, Doctoral Thesis, Aalto University, Department of forest products technology, Espoo, Finland.

Owens, R.G. and Phillips, T.N. (2002): Computational rheology, Imperial college press, 417 p.

Pakarinen, P. and Kurki, M. (1995): Development of high-speed paper machines, in: Kinnunen, L. et al. (Eds), High technology in Finland 1995, The Finnish Academics of Technology, Helsinki.

Pakarinen, P., Kiiskinen, H., Kekko, P. and Paltakari, J. (2010): Drying and paper quality, in: Karlsson, M. (Ed.), Papermaking Part 2, Drying, second edition. Paperi ja Puu Oy, Helsinki. pp. 238-295.

Paulapuro, H. (2000): Wet pressing, In: Papermaking Part 1, Stock Preparation and Wet End, ch 8., Fapet Oy, Helsinki, Finland, pp. 284-340.

Pikulik, I.I. (1997): Wet-web properties and their effect on picking and machine runnability, Pulp Paper Canada 98, T487-T491.

Pöyry (2013): World fibre outlook up to 2025 (2012 edition).

Retulainen, E. (1997): The role of fibre bonding in paper properties, Doctoral Thesis, Helsinki University of Technology, Espoo, Finland.

Retulainen, E., Martikainen, P. and Timofeev, O. (2006): Characterization of Mechanical Behavior of Paper And Three-Ply Board During Drying, 60th Annual Appita General Conference, Melbourne Australia, 3-5 April 2006, pp. 105-112.

Retulainen, E. and Salminen, K. (2009): Effect of furnish-related factors on tension and relaxation of wet webs, in: I'Anson, S.J. (Ed.), Advances in Pulp And Paper Research, Trans. XIVth Fund. Res. Symp. Oxford, pp. 1019–1037.

Roisum, D.R. (1990a): Runnability of paper, Part 1: predicting runnability, Tappi 73, 97-101.

Roisum, D.R. (1990b): Runnability of paper, Part 2: troubleshooting web breaks, Tappi 73, 101-106.

Salminen, K., Xiling, Z., Retulainen, E., Martikainen, P., Shiyu, F., MacNeil, D., Peng, J., Xiaohong, L. and Zishan, F. (2010): Analysis of web breaks and stickies in a newsprint mill using recovered paper, Proceedings of 4th ISETPP, pp. 1448-1452.

Salminen, K. (2010): The effects of some furnish and paper structure related factors on wet web tensile and relaxation characteristics, Doctoral Thesis, Lappeenranta University of Technology, Lappeenranta, Finland.

Schlegel, M. (2001): Maschinenbauliche Fortschritte bei der Papierherstellung, Wochenblatt für Papierfabrikation, 129, 555-563.

Schulz, J.H. (1961): The effect of straining during drying on the mechanical and viscoelastic behavior of paper, Tappi 44, 736-741.

Seth, R.J. and Page, D.H. (1981): The stress-strain curve of paper, in: Brander, J. (Ed.), The Role of Fundamental Research in Paper Making, Trans. VIIth Fund. Res. Symp. Cambridge, pp. 421–452.

Seth, R.J., Barbe, J.C., Williams, J.C.R. and Page, D.H. (1982): The strength of wet webs: a new approach, Tappi 65, 135-138.

Skowronski, J. and Robertson, A.A. (1986): The deformation properties of paper: Tensile strain and recovery. J. Pulp Paper Sci. 12, J20–J25.

Sorvari, J. (2009): Modelling methods for viscoelastic constitutive modelling for paper, Doctoral Thesis, University of Kuopio, Kuopio, Finland.

Steenberg, B. (1947): Paper as a viscoelastic body, Svensk Papperstidning 50, 127–140.

Steenberg, B. (2006): Rheomembrances, Annual Trans. Nord. Rheol. Soc., Vol. 14.

Sundholm, J. (1999): What is mechanical pulping? In: Mechanical pulping, ch 2., Fapet Oy, Helsinki, Finland, pp. 16-21.

Tanaka, A., Hiltunen, E., Kettunen, H. and Niskanen, K. (2001): Fracture properties in filled papers, Trans. XIIth Fund. Res. Symp. Oxford, pp. 1403–1421.

Uesaka, T. and Ferahi, M. (1999): Principal factors controlling pressroom breaks, Int. Paper Physics conf., pp. 229-245.

Uesaka, T., Ferahi, M., Hristopoulos, D. Deng, N. and Moss, C. (2001): Factors controlling pressroom runnability of Paper, Trans. XIIth Fund. Res. Symp. Oxford, pp. 1422–1440.

Uesaka, T. (2005): Principal Factors Controlling Web Breaks in Pressrooms: Quantitative evaluation, Appita J. 58, 425-432.

Vainio, A. (2007): Interfibre bonding and fibre activation in paper – Observations on the phenomena and their influence on paper strength properties, Doctoral Thesis, Helsinki University of Technology, Department of Forest Products Technology, Espoo, Finland.

Wagner, W. and Pruß, A. (2002): The IAPWS formulation 1995 for the thermodynamic properties of ordinary water substance for general and scientific use, J. Phys. Chem. Ref. Data 31, 387–535.

Wahlström, T., Fellers, C. and Htun, M. (2000): A Laboratory Method for Biaxial straining of paper during drying, Tappi J. 83(7):75.

Yamauchi, T. and Murakami, K. (1993): Observation of deforming and fracturing process of paper by use of thermography, in: Baker, C.F. (Ed.), Products of papermaking, Trans. Xth Fund. Res. Symp. Oxford, pp. 825–847.