INFLUENCE OF HEATING ON TENSILE AND RELAXATION BEHAVIOR OF WET PAPER

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ABSTRACT

The influence of increasing temperature on the strength and relaxation of wet never-dried paper was studied using C-IMPACT, a tensile tester equipped with a special heating chamber. The heating device formed a small climate chamber around the paper sample and raised the temperature of the paper to the target temperature of 30-70 degree Celsius within a couple of seconds. The heating chamber made fast heating possible without detectable moisture loss. The tests were performed only in the machine direction of the paper samples.

The results showed that temperature had a significant influence on the straining, relaxation and re-straining behavior of wet paper. Increasing temperature decreased the tensile strength and stiffness of wet paper, but did not affect strain at break. However, due to mechanical conditioning, tensile stiffness in the re-straining of wet paper depended only marginally on temperature.

Increasing temperature strongly increased the apparent relaxation rate. In this study, the apparent tension relaxation rate was obtained by fitting a log-linear function to the relaxation data. The initial 2 seconds of tension relaxation were omitted from the curve fitting because in the other case (pre-straining) heating started after 1 second of relaxation. The data between 2 and 4 seconds was used for the analysis. Depending on the temperature, 30-70% of initial tension was lost during the first 4 s. The observed short time scale phenomena in wet paper have practical significance for fiber webs dried under tension in paper machines. Most of the observed changes due to increased temperature seem to originate from the properties of wet fibers and, especially, from the softening of fiber wall material.

Temperature has strong influence on wet paper tensile behavior at temperatures used in industrial processes. The results clearly show that effects of temperature on wet paper occur relatively fast. Temperature should therefore be taken into account in studies related to processes involving variable temperature conditions, in the same manner as dryness in the case of variable moisture content of wet paper.

NOMENCLATURE

CD	Cross web direction
GW	Stone groundwood pulp
IR	Infrared
LC	Lumped capacitance
MD	Machine direction, i.e. along direction of travel
NIR	Near infrared
LWC	Lightweight coated paper
PGW	Pressure groundwood pulp
TMP	Thermomechanical pulp
c	Specific heat of dry paper
h	Heat transfer coefficient of free convention
L	Half of thickness of wet paper before test
R	Tension relaxation rate
T, T_c	Tension of paper
t	Time
θ, θ_i	Temperature of paper
θ_∞	Temperature of moving air
θ_{sur}	Temperature of surrounding air
X, Y, Z	Cartesian coordinates
ε	Emission factor
ρ	Density of wet paper sample
σ	Stefan-Boltzmann coefficient
σ_0	Initial tension of relaxation
σ_∞	Asymptotic tension of relaxation after infinite time

INTRODUCTION

The runnability of a wet paper web in a paper machine is affected by furnish composition, tension, relaxation and dryness of the web, among other parameters [1, 2, 3]. A large part of the water in the paper web is removed by thermally induced evaporation, the rate of which is strongly influenced by temperature. At certain positions on a modern paper machine the wet paper web is heated and its temperature is increased without evaporation of water. There are, however, only a few studies showing the effect of temperature on the mechanical properties of the wet web [4]. This is mainly due to difficulties in handling wet paper and controlling its temperature without changing the moisture content. In this paper, the effect of heating on wet paper properties is studied at constant moisture content.

The effects of temperature and moisture on paper properties depend on the softening temperatures (glass transition point) of the main components of wood (lignin, hemicellulose and cellulose). In the case of lignin, the softening temperature depends on the wood species and varies over wide range [5]. The softening temperature for moist native lignin is about 110 deg C, but for partially sulfonated or oxidized lignin it ranges from 70 deg C to 90 deg C, whereas moist hemicellulose has been estimated to have a softening temperature of below 0 deg C [6]. The softening temperature of cellulose is higher than that of hemicellulose, although amorphous cellulose at 50% dryness has a softening temperature as low as room temperature. In very moist conditions, the softening of cellulose dominates in all papers [6]. Wet paper at dryness below 60% contains a substantial amount of free water within and between fibers [7]. The effect of temperature on the viscosity and surface tension of water is well known [8].

Andersson and Berkyto [9] studied the strength properties of dry newspaper and kraft paper samples in the machine and cross machine directions. The effect of moisture was virtually eliminated from their study, as relative humidity was kept close to zero. Stress was found to have an exactly linear dependency over a wide over a wide temperature range from -50 deg C to 150 deg C. Benson [10] and Andersson and Berkyto [9] also reported that tensile strength and tensile stiffness are inversely proportional to temperature. Moisture acts as a softener, and softening increases with temperature [10]. Benson [10] re-analyzed the data of Andersson and Berkyto [9] and showed that the average loss in tensile strength of kraft when increasing the temperature from 15.5 to 48.9 deg C was 12% at RH 0%, which corresponds to about 21% at RH 50% and RH 65%.

According to Setterholm [11], the elastic modulus of dry paper decreases when the temperature is increased, but at the same time, the equilibrium moisture content is reduced. Jantunen [12] studied dry sheets made of TMP, PGW and GW mixed with 12.5% chemical pulp, and found that with rising temperature and relative humidity the dynamic tensile stiffness of wet paper was significantly diminished. According to the experimental results of de Ruvo et al. [13], the relative change in elastic modulus with temperature is about 2×10^{-3} K^{-1}. The corresponding estimate of Batten and Nissan [14] was 2.4×10^{-3} K^{-1}. Haslach and Abdullahi [15] proposed that temperature-accelerated creep has the same underlying mechanism as moisture-accelerated creep.

The effect of temperature on wet web strength properties has been extensively studied by Back and Andersson [4], who found that increased temperature produced a relative drop in tensile strength and tensile stiffness of about 1%/K. Temperature increase also reduced the strain at break (stretch) of bleached reinforcement kraft pulp. The relaxation rates of dry papers has been studied by Craven [16] as well as Kubát et al. [17], and wet paper by Kekko et al. [18]. Tension relaxation as a function of time has been described using Equation {1}:

$$T(t) = T_c - R\log(t) \qquad \{1\}$$

where T is tension, t time, T_c constant and R the tension relaxation rate. Craven [16] found that the relaxation rate of dry paper depended only on the initial load. The relaxation rates of a wide range of materials; dry paper, polymers, crystals, composites, etc., fall within a narrow range [19]. Relaxation rates of dry paper with and without certain typical papermaking polymers have been shown to increase with increasing temperature and humidity [20]. Wet paper tension relaxation rate has been reported to depend on dryness, orientation angle and paper grade. Chemical pulp based papers have a higher relaxation rate at any initial load compared to mechanical pulp based grades [18]. According to Htun [21], increased drying temperature increases the relaxation rate and decreases the drying stress and specific elastic modulus of dry paper when the drying time is kept constant [21].

The objective of this study was to measure the influence of heating on the strength and relaxation properties of wet paper. The effect of heating on relaxation behavior, in particular, is poorly known phenomenon. A better understanding of the effects of heating on wet paper has practical significance, as in paper machines the wet web is subject to considerable temperature increases within short time scales.

EXPERIMENTAL

Materials

The paper samples were never-dried fine paper and LWC base paper samples taken after the wet press section of a pilot paper machine (Metso Paper, Jyväskylä, Finland). All samples were produced on the pilot paper machine. The tests were performed only in the machine direction (MD) of the paper samples. The LWC base paper was made of a mixture of thermomechanical and softwood chemical pulp. The fine paper was made of a mixture of hardwood and softwood chemical pulps. The properties of the test samples are given in Tables 1 and 2.

Material property		LWC #2
Grammage (dry), g/m^2	45	41
Grammage (wet), g/m^2	68	68
Density (wet), kg/m^3	670	849
Thickness (wet), µm	101	80
Filler content, %	12.1	6.3
MD/CD –tensile ratio (dry)	4.06	3.46
MD tensile strain (dry), %	1.55	1.24
Initial dryness, %	58	53

Table 1 – Some mechanical properties of the studied LWC base paper samples.

Material property	Fine paper #1	Fine paper #2
Grammage (dry), g/m^2	68	65
Grammage (wet), g/m^2	151	107
Density (wet), kg/m^3	982	918
Thickness (wet), µm	154	116
Filler content, %	23.5	12
MD/CD –tensile ratio (dry)	1.9	1.87
MD tensile strain (dry), %	1.52	1.83
Initial dryness, %	43	56

Table 2 – Some mechanical properties of the studied fine paper samples.

Test Rig and Heating Chamber

A C-Impact fast strain rate tensile tester was used for the laboratory trials (see Figure 1) [22]. A special electrical heating device was developed and attached to the tensile tester (shown in Figure 2). The heating device formed a small climate chamber around the paper sample and raised the temperature of the paper to the target temperature of 30-70 degree Celsius within a couple of seconds. The temperature of the heating chamber could be adjusted to an accuracy of one degree Celsius (measured in Kelvin). The temperature of the heating device was controlled with a thermocouple and an Omron E5CN temperature controller.

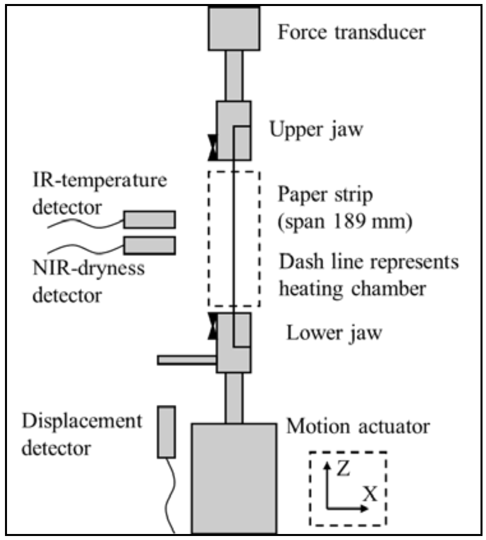

Figure 1 – Schematic description of the C-Impact tester with following main components: IR-sensor, dryness detector (based on NIR technique), laser for strain detecting, force transducer, motion actuator for sample straining, and heating chamber shown in the heating position (dash line).

Making the chamber volume as small as possible around the sample minimized the heating time and the evaporation of water from the press-dry paper. The volume dimensions around the paper sample were 2.35 mm × 24.30 mm × 178 mm (respectively X × Y × Z in Figures 1 and 2). The sample length was 189 mm and width 20 mm. The paper sample accounted for 3-5% of the chamber volume. The relative humidity of the air in the heating chamber was estimated according to Wagner and Pruß [23]. With the used temperatures and the paper grammage and dryness values given in Table 1 and 2, the maximum dryness increase of the paper was two percentage points. In the case of one-sided heating, moisture and temperature gradients in the paper thickness direction were detected [24, 25]. However, in this study these gradients were not determined in detail. The tension and strain of the paper could be measured during heating because the heating chamber was not in mechanical contact with the paper sample.

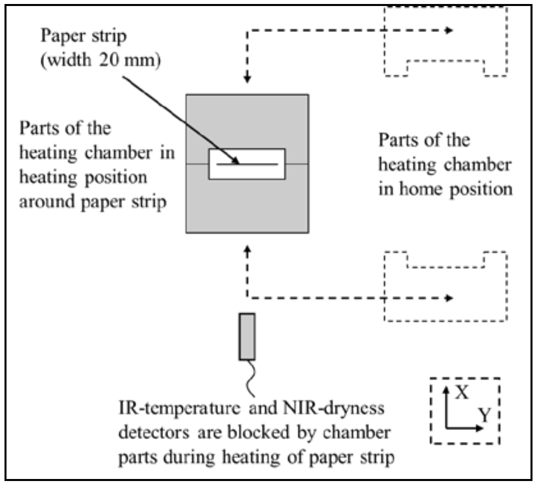

Figure 2 – Schematic figure (top–down) of the heating chamber elements around the sample during heating, and the movement path of elements to the home position.

The temperature and dryness of the paper were measured with IR-detectors before and after heating. The temperature could not be observed during heating due to obstruction by the heating chamber. As a reference, temperature measurement was performed with press-dry bleached birch kraft pulp handsheets in which K-type thermocouples were embedded. The temperature of the paper during heating is shown in Figure 3. Typical target temperatures of the heating chamber were 20 deg C, 60 deg C, 80 deg C, 100 deg C, 110 deg C and 125 deg C.

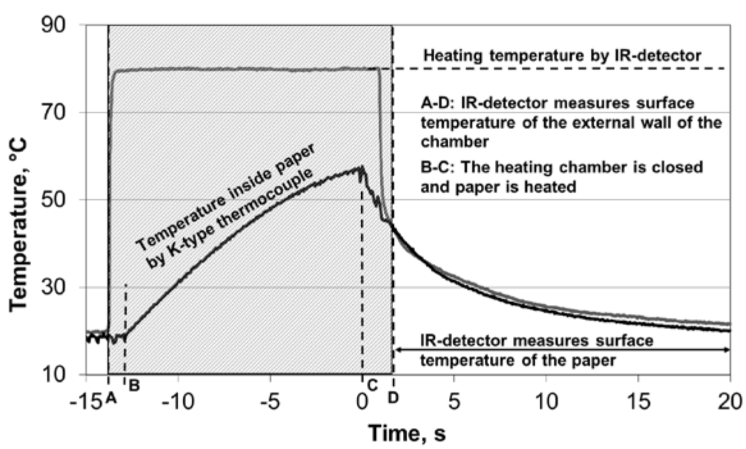

Figure 3 – K-type thermocouple embedded in a 60 g/m^2 handsheet of 100% chemical birch pulp at 55% dryness. The surface temperature of the heating chamber was 80 deg C. The paper was not visible to the IR-detector during time A-D, and the heating chamber was closed around the paper during time B-C.

Methods

In this study, the apparent tension relaxation rate was obtained by fitting Equation {1} to the relaxation data. The initial 2 seconds of tension relaxation were omitted from the curve fitting because in the other case (pre-straining) heating started after 1 second of relaxation. The data between 2 and 4 seconds was used for the analysis, as shown in Figures 6 and 7. For the time period in question, the relaxation data appeared to be a log linear function of time. In the literature, Equation {1} is typically used to determine stress, but for the purposes of the present study stress was substituted for tension. Therefore, R was selected to describe the apparent tension relaxation rate instead of the original F describing the stress relaxation rate.

The paper temperature could not be measured during the heating phase as the heating chamber obscured the field of view of the IR-detector (as shown in Figure 2). The wet paper sample cooled rapidly once the heating chamber was opened due to evaporation. The temperature of the paper at the moment of opening the heating chamber was therefore evaluated using the Lumped Capacitance (LC) method, which gave a temperature estimate for the paper at the end of the heating phase [26].

$$\int_{\theta_i}^{\theta} d\theta = \theta(t) - \theta_i = -\frac{1}{\rho c L}\int_0^t \left[h(\theta - \theta_\infty) + \varepsilon\sigma(\theta^4 - \theta_{sur}^4)\right]dt$$

In Equation {2}, θ is the temperature of the paper, θ_i the initial temperature of the paper, θ_∞ the temperature of moving air at the paper surface after opening the chamber (at 23 deg C), θ_{sur} is the temperature of the surrounding air (heat sink at 23 deg C), t is time, ρ the density of the wet paper sample, L half the thickness of the wet paper before the test, c the specific heat of dry paper (1340 kJ/kgK) [27], h the heat transfer coefficient of free convention (values for free convection are between 2-25 W/m^2K), ε the emission factor for paper and water (0.95) and σ the Stefan-Boltzmann coefficient (5.67×10^{-8} W/m^2K^4). The specific heat value 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 {2} was solved by numerical integration. The minimal change in paper thickness due to straining [28] was ignored.

The fourth-order terms in Equation {2} describe the heat loss due to radiation, and the first-order term the heat loss due to convection from the paper to air. Heat loss due to evaporation was ignored, as the temperature gradient between the paper and air was assumed to be small. The effect of evaporation was thus assumed to be negligible compared to the two former terms [29]. This was also supported empirically, as evaporation was found to change the dryness of fine paper samples only when the temperature of chamber was 125 deg C. This temperature was not included in the results.

The temperature of the paper at the moment of opening the chamber was evaluated by fitting the LC equation {2} to the cooling data measured with the IR-detector and extrapolating back to the time of opening. Figure 4 shows the estimated paper temperature at a chamber temperature of 110 deg C.

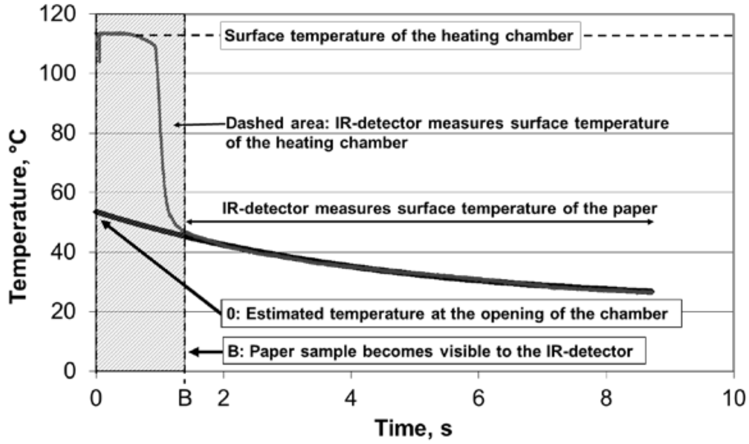

Figure 4 – Evaluation of the temperature of LWC base paper #1 at the time of opening. The paper was heated in the chamber at 110 deg C.

The straining, de-straining and re-straining rates of the fine paper #1 and LWC base paper #1 samples were 5.3%/s. In the case of the tensile tests of fine paper #1 and LWC base paper #1, heating was started 10 seconds and 6 seconds before straining (hereafter 'pre-heating'), respectively. The duration of pre-heating was increased in line with increasing grammage of the paper samples. In the case of the relaxation tests, the test procedure included a straining–relaxation–de-straining cycle. The initial tension of the relaxation phase was varied by using three prescribed strain levels, 0.5%, 1.0% and 2.0%. The duration of the relaxation phase was 5 and 15 seconds for the two heating types, respectively, during which heating was performed in the same manner as in the tensile test (pre-heating) or started 1 second after straining and continued for 8 seconds (hereafter 'pre-straining'), respectively. The de-straining phase was followed by a final re-straining until rupture.

The strain rates of the fine paper #2 samples at strain levels 0.5%, 1.1% and 1.6% were 4%/s, 8%/s and 13%/s. The strain rates of the LWC base paper #2 samples at strain levels 0.5%, 1.1% and 1.6% were 9%/s, 22%/s and 32%/s. A constant straining time was used, because in practical applications wet web strain is by a speed difference between drive groups of short lengths. Heating of fine paper #2 and LWC base paper #2 was started 8 seconds and 3 seconds before straining (pre-heating), respectively. The duration of pre-heating was increased in line with increasing grammage of the paper samples. In the pre-straining case, heating was started 1 second after straining and continued until the end of the test (pre-straining). The test procedure included a straining–relaxation–de-straining cycle. The duration of the relaxation phase of the fine paper #2 samples in the pre-heating case was 12 seconds and in pre-straining case 18 seconds. The duration of the relaxation phase of the LWC base paper #2 samples in the pre-heating case was 4 seconds and in pre-straining case 6 seconds. The duration of the relaxation phase loosely followed the inverse of typical machine speeds used for the studied paper grades. The de-straining and re-straining rates were 4%/s for the fine paper #2 sample and 9%/s for the LWC base paper #2 sample. The de-straining and re-straining rates were constant to enable comparability of recoverable elastic properties (in the de-straining phase) and tensile testing (in the re-straining phase). Tensile testing was not performed with the fine paper #2 or LWC base paper #2 samples.

RESULTS

Influence of Heating on Tension and Tensile Behavior of Wet Paper

The tension–strain curves of the LWC base paper #1 sample at 58% dryness at different paper temperatures are illustrated in Figure 5. The average tensile strength, strain at break and tensile stiffness values for the fine paper #1 and LWC #1 samples are given in Table 3.

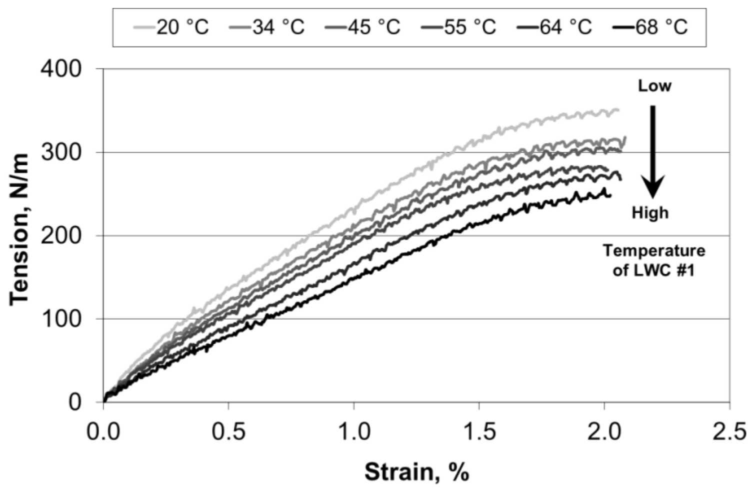

Figure 5 – Typical tensile curves for LWC base paper #1 samples at 58% dryness and at different paper temperatures. The curves shown are medians of 5 tests at each temperature and the strain at break value represents the average of 5 tests.

Increasing temperature had a lowering effect on tensile stiffness and strength. Strain at break, in contrast, seemed to be essentially independent of temperature. The fine paper #1 and LWC #1 samples showed the same relative change in tensile strength per unit temperature $-4.7 \times 10^{-3}\ K^{-1}$. The relative change in strain at break was less than $-1 \times 10^{-3}\ K^{-1}$, in other words, strain at break decreases from 2% to 1.9% when the temperature increases from 20 deg C to 70 deg C. The relative change in tensile stiffness (modulus of elasticity) was $-7.7 \times 10^{-3}\ K^{-1}$ for both the fine paper #1 and LWC #1 samples despite the fact that the samples had different dryness, filler content and MD/CD tensile ratios. The relative tensile stiffness change of the wet paper due to the temperature change was approximately 4 times higher than the results reported for dry bleached sulfate paper [13, 30]. The relative change in tensile strength and tensile stiffness were in accordance with the 1%/K value reported for wet paper [4]. The effect of temperature on tensile strength and tensile stiffness seems to be stronger at lower dryness levels. The decrease in tensile strength and tensile stiffness due to increased temperature may be caused by the softening of fibers, weakening of inter-fiber bonds, or reorganization of the fiber network. Fiber softening offers a likely explanation for the observed phenomena. Similarly to dry paper, a reduction or weakening of inter-fiber bonding would reduce strain at break, but the shape of the stress-strain curve, excluding its very end, would remain constant [31, 32]. Structural reorganization of the fiber network, on the other hand, is an unlikely response to increased temperature.

Test point	Tensile strength, N/m	Strain at break, %	Tensile stiffness, kN/m
Fine #1, at 20 deg C	137.3	2.28	11.5
Fine #1, at 29 deg C	125.5	2.21	10.9
Fine #1, at 38 deg C	113.3	2.20	8.5
Fine #1, at 46 deg C	117.8	2.26	9.4
Fine #1, at 54 deg C	115.5	2.15	8.5
LWC #1, at 20 deg C	347.2	2.05	31.5
LWC #1, at 34 deg C	309.8	2.08	25.7
LWC #1, at 45 deg C	303.8	2.06	24.1
LWC #1, at 55 deg C	282.2	2.01	22.2
LWC #1, at 64 deg C	277.3	2.06	20.8
LWC #1, at 68 deg C	256.8	2.02	18.4

Table 3 – Some mechanical properties of fine paper #1 samples in MD at 43% dryness and LWC base paper #1 samples at 58% dryness. Coefficient of variation within 5 test repeats for tensile strength and strain at break were approximately 4% and for tensile stiffness approximately 8%.

Influence of Heating on Tension Relaxation of Wet Paper

Two kinds of relaxation tests were performed: pre-heating and pre-straining. In pre-heating, heating was started before straining was commenced (see Figure 6). In pre-straining, straining to a prescribed strain level was performed before heating was commenced during the relaxation phase (see Figure 7).

In the pre-heating case increasing temperature decreased the maximum tension reached at the target strain (see Figure 6) as a result of decreased tensile stiffness due to heating. Starting heating of the wet paper during tension relaxation phase (pre-straining) increased the relaxation rate (Figure 7). Moisture gradients are likely to have occurred inside the wet paper sample during heating, but in the pre-heating tests, these gradients will probably have leveled off before straining started.

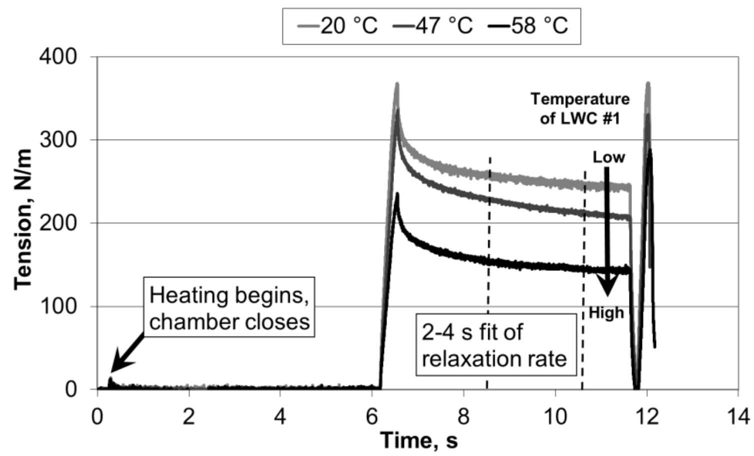

Figure 6 – Straining LWC base paper #1 samples at 58% dryness to 2% strain, followed by a relaxation phase. Heating of the sample started 6 s before straining and continued during the relaxation phase (pre-heating case). Paper temperatures are given.

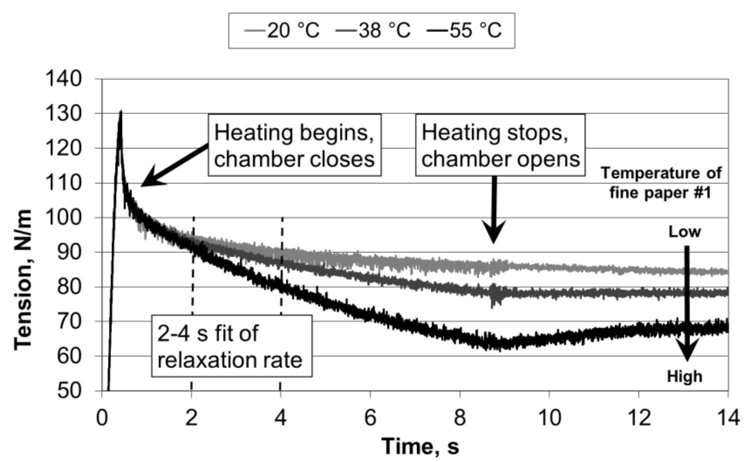

Figure 7 – Straining fine paper #1 samples at 43% dryness to 2% strain, followed by a relaxation phase. During the relaxation phase, the sample was heated for 8 seconds (pre-straining case) - Paper temperatures are given.

Influence of Heating on Apparent Tension Relaxation Rate of Wet Paper

The apparent tension relaxation rates with respect to initial tension are shown in Figures 8 and 9 for fine paper #2 and LWC #2. The apparent tension relaxation rate of wet paper depends linearly on the initial tension (Figures 8 and 9). In the pre-straining case (Figure 9), the slope of the line (slopes 0.073-0.354) was higher and more sensitive to temperature than in the pre-heating case (Figure 9) (slopes 0.060-0.141). In the pre-heating case, the initial tension at the given strain also decreased with increased temperature due to decreased tensile stiffness, as expected. But at constant initial tension the pre-strained samples have still clearly higher relaxation rates. This suggests that there is a mechanism involved that accelerates the relaxation.

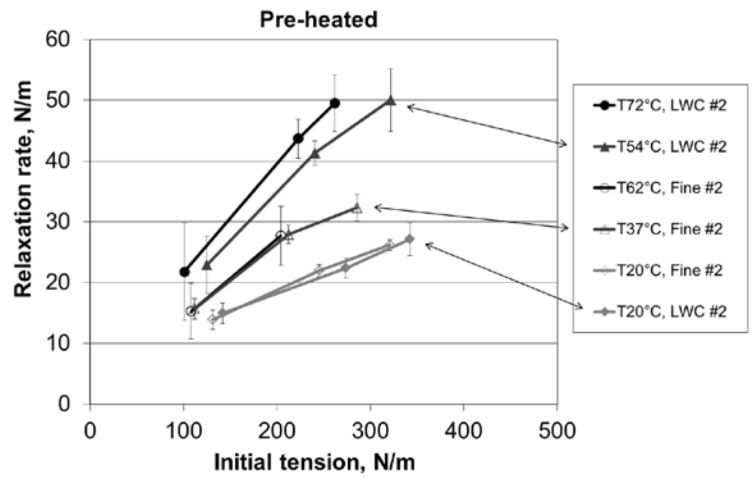

Figure 8 – Apparent tension relaxation rates of pre-heated fine paper #2 samples at 56% dryness and LWC base paper #2 samples at 53% dryness at different temperatures. Pre-heating means heating was started before straining.

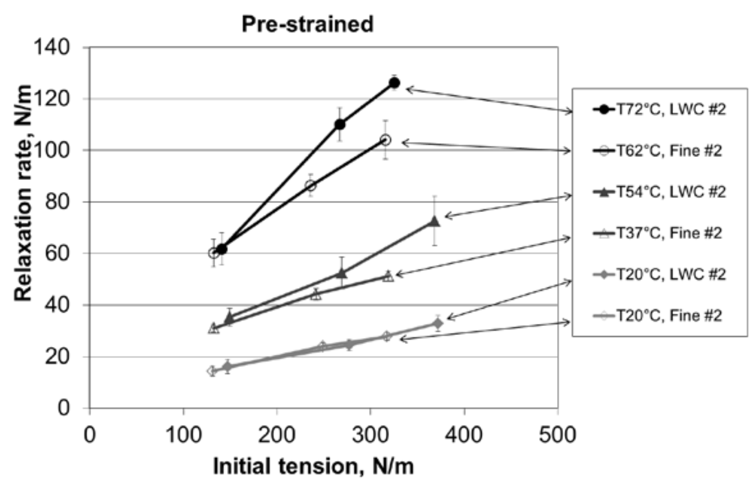

Figure 9 – Apparent tension relaxation rates in the pre-strained case for fine paper #2 samples at 56% dryness and LWC base paper #2 samples at 53% dryness at different temperatures. Pre-straining means straining to 0.5%, 1.1% and 1.6% before commencing heating.

It has been recently proposed that the cause of moisture-accelerated creep is uneven stress distributions and consequent stress concentrations [33, 34]. Analogously, uneven stress distributions and stress concentrations may also be the origin of temperature-accelerated relaxation [15]. Thus, although at the studied temperatures the temperature and moisture gradients in the wet samples were small, they may be significant.

Effect of Heating on the Straining–De-straining Cycle

The studied straining–de-straining cycles contained a relaxation phase. This was because in practical applications wet web strain is caused by a speed difference between drive groups of short lengths. Additionally, changes in elasticity and plasticity are interesting phenomena. Rarely is the speed lowered immediately after being raised.

Heating paper before a straining–relaxation–de-straining cycle reduced the tensile stiffness and de-straining stiffness of the examined wet papers. Figure 10 illustrates the influence of pre-heating on the straining–relaxation–de-straining cycle of fine paper #2. The apparent plastic region of the examined wet papers was typically almost linear, as shown in Figure 10. The higher the temperature, the lower the tension at the prescribed strain and after the following relaxation phase.

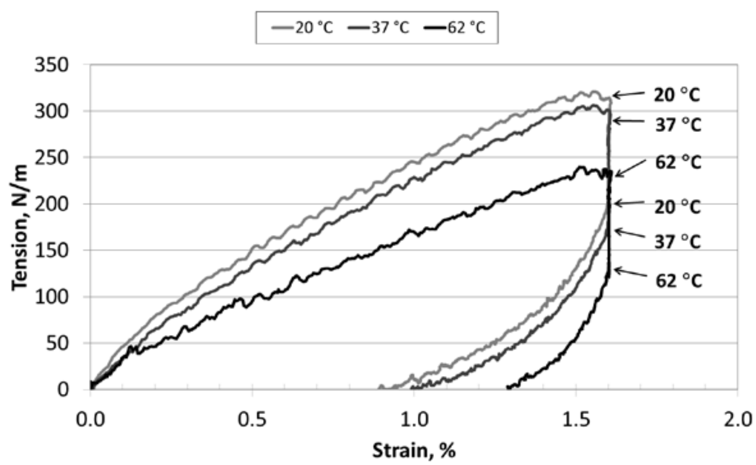

Figure 10 – Straining–relaxation–de-straining cycles for never-dried fine paper #2 samples at 56% dryness at different temperatures after pre-heating. Heating started 8 s before the straining phase. Strain rate was 13%/s and de-strain rate 4%/s. Relaxation time was 12 s.

When the paper was heated after straining to a prescribed level (pre-straining), the relaxation rate accelerated as temperature increased. Figure 11 illustrates the influence of heating of fine paper #2 on the relaxation and de-straining phases. Tension after the relaxation phase was lower with increased temperature. The amount of elastic energy (stored in the paper during straining) recovered during de-straining decreased with increasing temperature.

Figure 11 – Straining–relaxation–de-straining cycle of never-dried fine paper #2 samples at 56% dryness and at different temperatures. Heating was started during the relaxation phase. The straining phase was performed at 20 deg C. Strain rate was 13%/s and de-strain rate 4%/s. Relaxation time was 18 s.

In addition, the recoverable elastic strain of the wet fine paper #2 samples shown in Figures 10 and 11 were almost identical despite the different heating procedures. These findings indicate that the wet fine paper #2 and LWC #2 samples were in a mechanically similar state after the relaxation phase in the two different heating cases. The results clearly show that effects of temperature on wet paper occur relatively fast. Temperature seems to have a major impact on the state, i.e. material properties, of wet paper, such as tensile stiffness, which originates most probably from the material properties of fiber wall. The temperatures used industrial processes have a strong influence on wet paper tensile behavior. Temperature should therefore be taken into account in studies related to processes involving variable temperature conditions, in the same manner as dryness in the case of variable moisture content of wet paper.

Effect of Mechanical Conditioning on Apparent Stiffness in Re-straining

Mechanical conditioning (in this case tensile straining) causes irrecoverable changes to the structure and tensile behavior of wet paper. In the pre-heating case shown in Figure 12, the initial straight line region in the re-straining phase of the wet papers increased compared to the first straining cycle. The initial straight line region, i.e. apparent linear elastic region, ends when the tension in re-straining approaches the tension of the initial curve. The behavior is similar to that typically observed in dry papers [36]. In the case of 2% initial straining, the apparent linear elastic region of re-straining was around 0.7%.

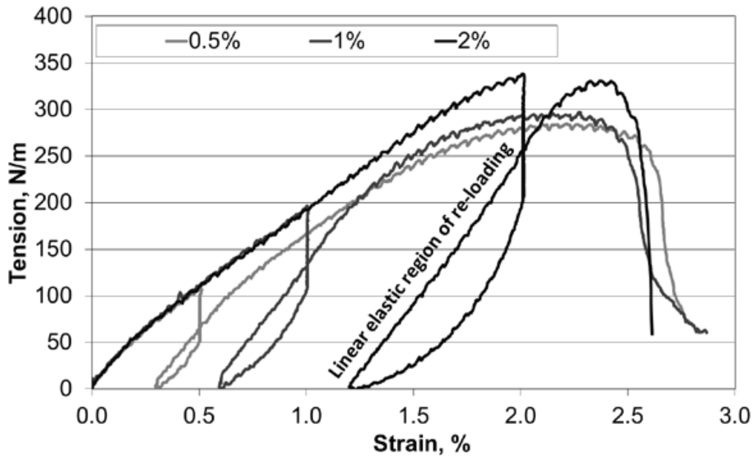

Figure 12 – Straining–relaxation–de-straining–re-straining cycles for never-dried pre-heated LWC base paper #1 samples at 58% dryness and at 45 deg C. Heating was started 6 s before the first straining cycle. Strain and de-strain rates were 5.3%/s. Recovery times before re-straining were 0.1 s, 0.2 s and 0.4 s at prescribed strains of 0.5%, 1.0% and 2.0%, respectively.

Interestingly, the initial slope in the re-straining of wet paper (Figure 13) appeared to depend only marginally on temperature, whereas in initial straining increased temperature decreased the slope significantly (Figure 5 and Figure 11). Increased temperature clearly decreased the tensile strength and slightly decreased the strain at break of wet LWC base paper #2. The activation of fibers at high temperatures may be more effective, and the number of active fibers compensates for the lower stiffness of the fibers at higher temperature.

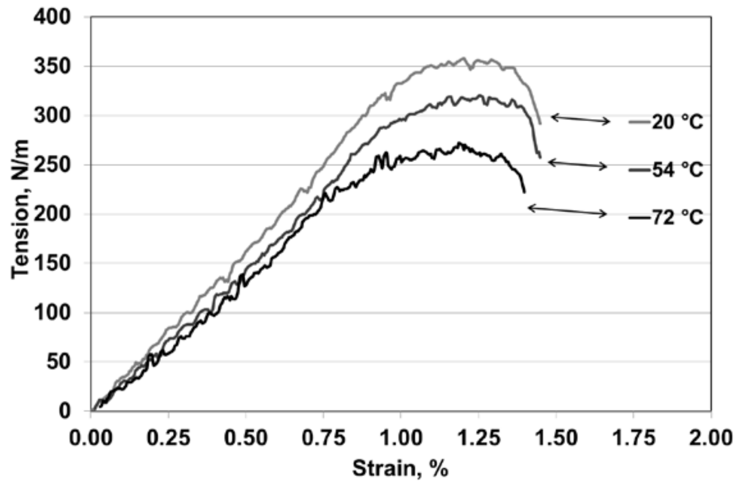

Figure 13 – Tension-strain-curves in re-straining of never-dried LWC base paper #2 samples at 53% dryness at different temperatures. Heating was started 3 s before the first straining cycle to 1.6% strain at a strain rate of 13%/s and de-strain rate of 4%/s. Recovery time before re-straining was 0.1 s.

DISCUSSION

Differences between Tension Relaxation Rates of Wet and Dry Paper

The reported tension relaxation rates in the literature are for dry paper, and the reported values are higher because the relaxation rate depends on the initial tension [16, 17, 37]. Difficulty in comparing the tension relaxation rates of wet and dry paper arises also from the different time ranges studied. The tension relaxation of dry paper can be measured for hundreds of hours, compared to only a few seconds in the case of wet paper. This is due to practical problems involved in maintaining constant dryness. The initial (maximum) tension of relaxation and asymptotic tension are related to the relaxation rate [38]. The relaxation rate obeys linear behavior according to Equation {3}, which is valid for many materials [19]:

$$R \approx 0.1(\sigma_0 - \sigma_\infty) \qquad \{3\}$$

where R is the tension relaxation rate as in Equation {1}, σ_0 initial tension of relaxation, and σ_∞ an asymptotic tension that the samples would reach after infinite time [39]. According to Robertson [20], the tension relaxation rate R of dry paper increases with increasing temperature and humidity. However, the effect of temperature on the relaxation rate of wet paper tension is not known.

The effect of temperature on Equation {3} for wet paper was examined more closely. The asymptotic tension σ_∞ was obtained by extrapolating the relaxation rate to zero using the data shown in Figure 8 and Figure 9. The constants for Equation {3} are given in Table 4. Both ratios of the wet paper samples are increased with increasing temperature. The ratios for wet paper are only partly consistent with the results reported in the literature for dry paper and many other materials [37]. In the pre-straining case, the inconsistency is mainly due to increase of temperature during the relaxation phase.

Test point	Pre-strained $R/(\sigma_0 - \sigma_\infty)$	Pre-heated $R/(\sigma_0 - \sigma_\infty)$
Fine paper #2 at 20 deg C,	0.073	0.065
Fine paper #2 at 37 deg C,	0.109	0.097
Fine paper #2 at 62 deg C,	0.240	0.129
LWC #2 at 20 deg C	0.074	0.060
LWC #2 at 54 deg C	0.170	0.139
LWC #2 at 72 deg C	0.354	0.175

Table 4 – Effect of the temperature on $R/(\sigma_0 - \sigma_\infty)$ –ratio of the wet paper samples

The obtained asymptotic tensions, σ_∞, of the wet paper samples were negative with zero relaxation rate at all temperatures. The apparent negative asymptotic tension indicates that, due to the high inelastic and time-dependent nature of the wet paper, the approximation of linearity used in Equation {3} is no longer applicable. However, the apparent negative asymptotic tension leads to the assumption that tension relaxation in wet paper occurs always when the tension is non-zero.

CONCLUSIONS

The results presented here show that temperature has significant influence on the shape of the straining–relaxation–re-straining cycle of wet paper. Never-dried fine paper and LWC base paper samples were heated in a specially constructed heating chamber. Heating of the wet papers was conducted at virtually constant dryness.

Increased temperature decreases the strength and stiffness of wet paper but has no effect on strain at break. The effect of temperature on tensile strength and tensile stiffness seems to be stronger at lower dryness levels. Increased temperature strongly increases the apparent relaxation rate. The observed relaxation rates in wet paper are considerably higher than those reported for dry paper.

Relaxation rates are further accelerated if heating of the paper is started during the relaxation phase. This seems to be analogous to the moisture-accelerated creep phenomenon for dry paper. Minor temperature and moisture gradients are probably responsible for this.

The results indicate that in a straining–relaxation–re-straining cycle some activation of fibers takes place. The initial slope in the re-straining of wet paper depends only marginally on temperature, whereas in initial straining the effect of temperature is clearly stronger. Activation of fibers at high temperature may be more effective, and the number of active fibers compensates for the lower stiffness of fibers at higher temperature. Examination of short time scale phenomena is important for understanding the behavior of wet webs in paper machines.

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