

STUDIES OF THE DYNAMIC COMPRESSIBILITY OF WATER-SATURATED FIBER NETWORKS

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ABSTRACT

The dynamic compressibility of water-saturated fiber networks was investigated. Two types of experiments were performed: (1) Compression behavior was investigated by exerting a defined stress pulse onto a fiber network; (2) Expansion behavior was investigated through the sudden relief of an applied stress to a fiber network. All experiments were performed at three temperatures (23°C, 50°C, and 80°C). The webs used in this study had a grammage of 30 g/m² and were produced from either softwood bleached kraft or thermomechanical pulp. Roll-nip-like stress pulses were applied to the webs. The length of the stress pulse ranged between 20 ms and 200 s, and the peak stress varied from 5 to 20 MPa. Compression behavior was evaluated in terms of the work required to compress the fiber network and in terms of stress-strain relationships. Expansion behavior was characterized in terms of the time-dependent strain increase and the strain obtained after 300 s. The qualitative compression behavior was found to be similar under all process conditions investigated. A large reduction in strain was observed during the stress pulse, with the minimum strain obtained between the peak stress and the end of the stress pulse. No significant expansion was observed as long as stress was applied to the network. However, a rapid and considerable expansion was observed after the end of the stress pulse. Higher peak stresses, higher temperatures, and longer stress pulses led to a larger deformation of the web. The stress-strain relationship was approximated quantitatively by a power-law function. The effects of temperature and pulse length were accounted for by shifting the stress-strain curve horizontally by means of a shift factor. The time-dependent expansion was quantitatively approximated by an exponential function.

INTRODUCTION

The extent of web deformation during wet pressing has a large influence on the final dryness of the web. Thus, knowledge of the dynamic compressibility of the fiber network is important. Previous investigations can be divided into two groups.

In the first group, the evaluation is based on the comparison of web dryness before and after the wet-pressing event, e.g., Wahlström (1), Sweet (2), Nilsson and Larsson (3), Schiel (4), Andersson and Back (5), Francik and Busker (6), and McDonald and Kerekes (7). Some qualitative information can be derived regarding the dynamic compressibility of the network. A higher web dryness and possibly web compaction was obtained for higher peak stresses, longer compaction times, and higher operating temperatures.

In the second group, the web thickness is directly measured during a dynamic compression, e.g., Asklöf *et al.* (8), Chang (9), Ceckler *et al.* (10), Carlsson and Lindström (11), Ellis (12), Jantunen (13), Burton and Sprague (14), Burns *et al.* (15), El-Hosseiny (16), and Szikla (17). Although giving much more information regarding the deformation of the *web* during the compression, conclusions concerning the behavior of the *network* have to be drawn with care. Web stratification and/or the interaction with the contacting material can influence the results considerably (14, 17–20). In order to avoid a flow inside the fiber network and consequent stratification, Ellis (12) and later Szikla (17) used unsaturated wet webs. However, they found contradicting results. Szikla observed, in contrast to Ellis, a stress-rate dependency in the compression behavior. Szikla relates this phenomenon to the flow of water within and out of the fiber wall. This influence has been mentioned also by others (18, 21, 22) and is supported by the fact that a considerable amount of water is pressed out of the fiber wall at the compression levels obtained in wet pressing (23, 24). However, using unsaturated webs has the disadvantage that the network compressibility might have already changed due to the increased dryness. Given the interaction between the fiber wall material and the water, the dynamic compressibility of the network should therefore be investigated under saturated conditions.

The dynamic *expansion* behavior of wet webs has received little attention despite its important role in conjunction with rewetting (25–27). In dynamic compression experiments, little or no web expansion was observed *during* the stress pulse (11, 15, 16). Observation of expansion *after* a wet-pressing event is reported only by Qviller (28). For different initial saturation degrees, he observed the largest final expansion for completely saturated webs. However, Qviller did not describe the dynamics of the expansion behavior. The dynamic expansion behavior of initially dry, precompressed fiber webs is reported by Skowronski *et al.* (29) and Mantanis *et al.* (30). Upon contact with water, the webs expand rapidly or, when confined, rapidly develop stress up to 60 kPa. Fiber swelling and the release of built-in stresses are given as driving mechanisms. Because of the known time-dependent phenomena in water–fiber interaction, these results can give qualitative information regarding the behavior of initially wet webs.

Given the little amount of information available on the dynamic compressibility of the fiber network, the objective of this work was to investigate it during and after a dynamic compression.

EQUIPMENT

The compression device shown in **Figure 1** was used in this study. This device is described in a paper by Vomhoff and Norman (31). A water-saturated web was compressed between a smooth solid surface and a solid surface equipped with 1-mm-wide bars separated by 1-mm-wide grooves. The web thickness was measured using a displacement transducer located in the center of the bottom plate. An in-plane water flow was generated when the web was compressed, causing the water to flow into the grooves. In order to perform experiments at elevated temperatures, a metal plate with a circular flow channel was placed under the bottom plate. Water of a defined temperature flowed through the channel, keeping the bottom plate at a set

temperature. During the experiments, the web was completely immersed in tap water, and web saturation was assumed.

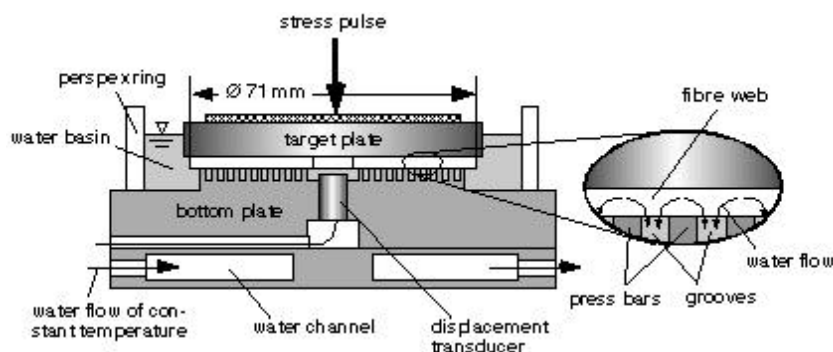


Figure 1. Compression device with water heating.

The compression and expansion behaviors were investigated separately. Compression behavior was evaluated by exerting a roll-nip-like stress pulse onto the web. Expansion behavior was investigated by precompressing the web to a defined thickness. This compression level was held for 60 s to establish a quasi-equilibrium condition prior to the expansion. The stress on the web was then removed instantaneously (less than 6 ms), and the web thickness was recorded as a function of time for 300 s. Both experimental procedures were performed in a computer-controlled hydraulic press. Prior to the experiments, the webs were placed onto the immersed bars of the bottom plate. The target plate was then placed on top of the web, causing a small compression stress of 2.2 kPa due to the weight of the target plate (386 ± 1 g).

PARAMETERS

The experimental conditions used in both the compression and expansion experiments are summarized in **Table I**. Experiments were performed using both slightly beaten softwood bleached kraft pulp (SBK) webs and thermomechanical pulp (TMP) webs. The webs had a grammage of approximately 30 g/m^2 . All experiments were carried out at three temperatures: 23°C , 50°C , and 80°C . The stress pulse was calculated using Eq. 1.

The initial modified strains $\delta_{m, \text{init}}$ in the expansion experiments were set to 0.5, 1, and 1.5, which correspond to web drynesses of 70%, 47%, and 30%, respectively. (See discussion under the heading “Evaluation” for a definition of the modified strain δ_m and its conversion to dryness.) Web expansion was recorded for 300 s after relief of the stress.

Common parameters	Pulp type	Slightly beaten softwood bleached kraft (SBK), 22.3°SR Thermomechanical pulp (TMP), 160 mL CSF
	Web grammage Temperature ($\pm 2^\circ\text{C}$)	30 g/m ² 23°C, 50°C, 80°C
Compression	Stress pulse	$\sigma_a(t) = \sigma_{\max} \cdot \sin^2(\pi \cdot t / t_p)$ (1) (approximate roll-nip pulse, see Figure 6)
	Peak stress ($\sigma_{\max}$) Pulse length (t_p)	5, 10, 20 MPa SBK: 20 ms, 200 ms, 2 s, and quasistatic (200 s) TMP: 20 ms, 100 ms, 200 ms, 2 s, and quasistatic (200 s)
Expansion	Initial strain ($\delta_{m,\text{init}}$)	0.5, 1.0, and 1.5
	Length of observation	300 s after relief of stress
*All experiments were duplicated.		

Table 1. Parameters for the compression and expansion experiments*.

Test sheets were made on a Finnish laboratory sheet former. Four circular webs with a diameter of 71 mm were punched out from each laboratory sheet, of which one was used for grammage determination. The other webs were stored in plastic bags in a refrigerator until they were used in experiments.

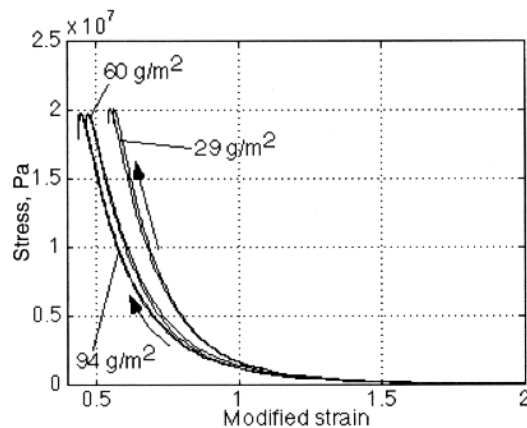


Figure 2. Stress–strain behavior of SBK webs at different grammages for quasistatic pulses (200 s); results of duplicate measurements (for definition of strain, see “Evaluation” section).

The influence of sheet grammage on the quasistatic compression behavior was investigated in preliminary experiments. Stress–strain relationships for SBK webs of three different grammages are shown in **Figure 2**. To obtain the same degree of compaction, webs with a lower grammage had to be compressed with a higher stress. This grammage-dependent effect decreases with increasing grammage. A grammage of 30 g/m² was chosen for use in the experiments due to its higher in-plane permeability. In addition, a boundary effect due to lateral spreading of the applied stress at the bar edges was assumed to be smaller with thinner webs. This assumption should result in a better-defined compressed area. However, when quantitatively interpreting the stress–strain relationship, this grammage dependency has to be kept in mind.

EVALUATION

A modified strain δ_m was defined. Due to the high deformability of the web at low loads, it was difficult to obtain a reproducible measurement of the initial web thickness when the target plate had been placed onto the web. The thickness h_0 of a completely compressed web without pores was therefore used as a reference thickness. This was calculated as the quotient of fiber material density ρ_f and grammage w . Fiber material densities of 1550 kg/m^3 and 1460 kg/m^3 , respectively, were used for SBK and TMP (23). The modified strain δ_m at a given web thickness h was calculated using Eq. 2:

$$\delta_m = \ln\left(\frac{h}{h_0}\right) = \ln\left(\frac{h \cdot \rho_f}{w}\right) \quad (2)$$

Because modified strain is an unfamiliar quantity for papermakers, a conversion to dryness is given in **Figure 3**. Complete web saturation was assumed for the results in Figure 3.

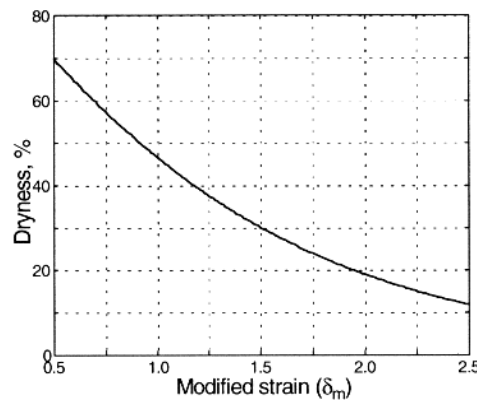


Figure 3. Conversion between modified strain and web dryness for SBK, assuming a complete saturation of the web; fiber material density $\rho_f = 1500 \text{ kg/m}^3$.

For simplicity, “strain” and “modified strain” are used synonymously in the following discussion, unless otherwise stated.

Network compression work

The work $W_{1.0}$ expended on the compression of the network from a start strain of ≈ 2.4 to a strain of 1.0 was calculated to elucidate dynamic effects. The strain of 1.0 was chosen because it was obtained in all experiments. $W_{1.0}$ was calculated as the difference between the work $W_{FL,1.0}$ required for generating the in-plane flow and the work $W_{C,1.0}$ for compressing the fiber network during this compression. However, an evaluation is only reasonable if $W_{FL,1.0}$ amounts to a minor share of $W_{C,1.0}$. $W_{FL,1.0}$ and $W_{C,1.0}$ were calculated according to a method described by Vomhoff and Norman (31). Here, porosity–permeability relationships measured at a temperature of 23°C were used in all experiments (32). The change in viscosity at the different temperatures was accounted for. The quotient of $W_{FL,1.0}$ and $W_{C,1.0}$ was calculated. The results for the stress pulses with a peak stress of 20 MPa are depicted for the SBK and the TMP pulp webs in **Figures 4 and 5**, respectively.

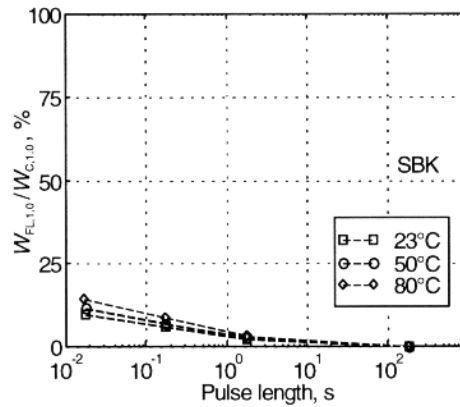


Figure 4. Quotient of the flow-generating work $W_{FL,1.0}$ and the total compression work $W_{C,1.0}$ at three temperatures for compression of SBK webs from a start strain of ≈ 2.4 to a strain of 1 (20-MPa peak stress).

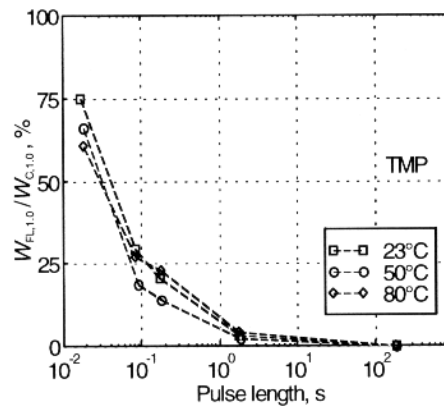


Figure 5. Quotient of the flow-generating work $W_{FL,1.0}$ and the total compression work $W_{C,1.0}$ at three temperatures for compression of TMP webs from a start strain of ≈ 2.4 to a strain of 1 (20-MPa peak stress).

In the case of the SBK webs, the share of $W_{FL,1.0}$ amounted at most to about 10%, as seen in Figure 4. This was considered small and all results could be used for evaluation. However, this situation was different for the TMP pulp webs. Here, the generation of the in-plane flow was as high as 75%, as seen in Figure 5. An arbitrary value of 25% was chosen as a limit for the results to be evaluated in terms of $W_{1.0}$.

Compression behavior

The compression behavior was characterized by the stress–strain relationship. For pulse lengths up to 2 s, a general behavior was found, as seen in **Figure 6**. From the start of the stress pulse, the web was compacted with increasing stress. This compaction continued even after the maximum stress had been applied. The minimum strain was reached after the peak stress, and thereafter the strain remained constant until the end of the stress pulse. A significant and rapid expansion of the web occurred only after the applied stress had been completely removed. The description of the stress–strain relationship focused therefore on the behavior during the first part of the stress pulse (bold line in Figure 6).

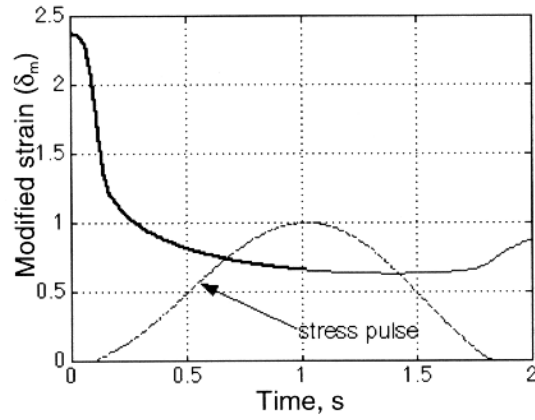


Figure 6. Example of modified strain as a function of time for SBK; bold curve designates the range used for evaluation; dashed curve designates the normalized stress pulse (2-s pulse, 20-MPa peak stress, 23°C).

The stress–strain relationship for the results given in Figure 6 is depicted in **Figure 7**. It was observed that the distance between the stress–strain curves at the different temperatures and pulse lengths was approximately constant over the entire stress range. An overlapping of the curves could be obtained by shifting the curves horizontally using a strain-shift $\delta_{m,shift}$. The network deformation $\delta_{m,total}$ could therefore be approximated by Eq. 3:

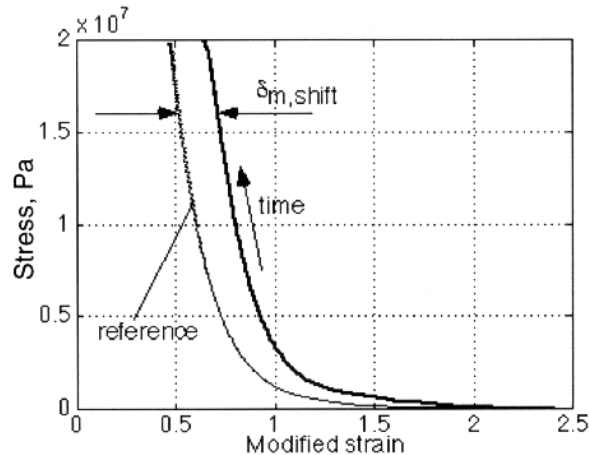


Figure 7. Result of Figure 6 presented in the stress–strain diagram together with the appropriate reference curve; $\delta_{m,shift}$ designates the distance to the reference curve.

$$\delta_{m,total} = \delta_{m,ref} + \delta_{m,shift} = \frac{1}{\log(c_2)} \cdot \log\left(\frac{\sigma_a}{c_1}\right) + \delta_{m,shift} \quad (3)$$

The deformation of the reference strain curve $\delta_{m,ref}$ was described by a power-law function of the applied stress σ_a . For the different peak stresses, the lowest values of δ_m were obtained for the quasistatic pulses at 80°C for both TMP and SBK. These curves were therefore chosen as reference curves. The mean difference between a measured curve and the corresponding

reference curve was calculated. The strain-shift $\delta_{m,shift}$ was calculated by averaging the values obtained for different peak stresses at one temperature and one pulse length.

This evaluation was performed only on results where the flow-generating work $W_{FL,\sigma_{max}}$ amounted to less than 25% of total performed work $W_{C,\sigma_{max}}$ for the compression up to the peak stress. Therefore, the results for the 20-ms pulses with the TMP webs could not be used for evaluation.

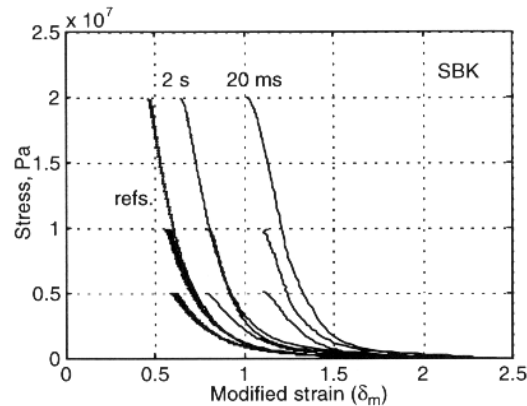


Figure 8. Example of stress–strain behavior in SBK webs at different peak stresses (5, 10, 20 MPa) for two pulse lengths (2 s, 20 ms) at 23°C; reference curves depict stress–strain behavior for 200-s press pulse at 80°C.

An example of the determination of the shift factors for SBK webs is given in **Figure 8**. The stress–strain curves for SBK pulp webs at 23°C at different peak stresses (5, 10, 20 MPa) and pulse lengths (20 ms, 2 s) are given along with the corresponding reference curves. The differences between the reference curves and the average values (dashed line) are depicted in **Figure 9**. The differences varied at low stresses but became fairly constant for higher stresses. The strain-shift $\delta_{m,shift}$ for a given pair of temperature and pulse length was calculated by averaging the values obtained for the three peak stresses.

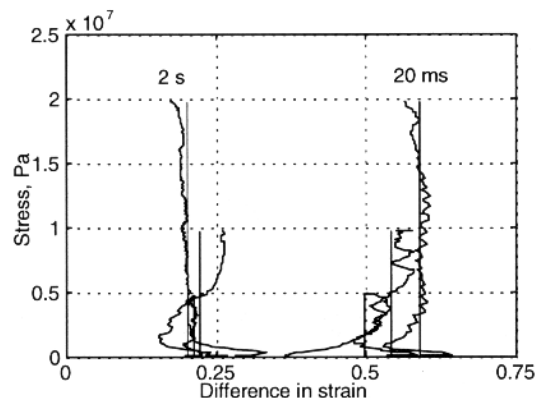


Figure 9. Calculated differences from the reference curves as a function of stress for the results of Figure 8 and their average values (vertical lines).

The use of the strain-shift $\delta_{m,shift}$ was practical, since the influence of temperature and pulse length could be characterized by a single parameter. The approximation of the stress–strain behavior using Eq. 3 was good. For all stress–strain relationships, the average relative deviation between approximated and measured values was found to be less than 10%. The results offer a reasonably accurate quantitative description of the stress–strain relationship at different conditions. The regression analysis of the reference curves is given in the Appendix to this paper.

Expansion behavior

It must be emphasized that the measured dynamic web expansion represents the slowest network expansion possible. A faster network expansion could have been retarded by a flow in the fiber network. In contrast to the compression experiments, the expansion forces inside the network could not be measured. Thus it was not possible to compare the flow-generating forces with the expansion forces.

The following equation was used to approximate the recorded web expansion after relief of the stress:

$$\delta_m(t) = \delta_{m,init} + \Delta\delta_m \cdot \left(1 - e^{-\frac{c_r}{\Delta\delta_m}t}\right) \quad (4)$$

$$\text{with: } \Delta\delta_m = \delta_{m,300} - \delta_{m,init} \quad (5)$$

The term $\delta_{m,init}$ designates the initial strain, and $\Delta\delta_m$ designates the total strain increase during the experiment. As seen in Eq. 5, $\Delta\delta_m$ is defined as the difference between the strain after 300 s, $\delta_{m,300}$, and the initial strain, $\delta_{m,init}$. The expansion rate c_r was calculated using the value of elapsed time necessary for 25% of the total strain increase $\Delta\delta_m$ to be achieved.

Equation 4 approximated the expansion behavior well. For every experiment, the average relative deviation between approximated and experimental values was calculated. It was less than 10% for all expansion curves.

RESULTS AND DISCUSSION

Network compression work

Temperature and pulse length had a significant influence on the work W expended on network compression. **Figure 10** depicts $W_{1.0}$ required to perform a compression of SBK webs from a starting strain of approximately 2.4 to a strain of 1. The required work increased considerably with decreasing pulse length. Higher temperatures reduced the required amount of work. The same behavior was found qualitatively for TMP, as seen in **Figure 11**.

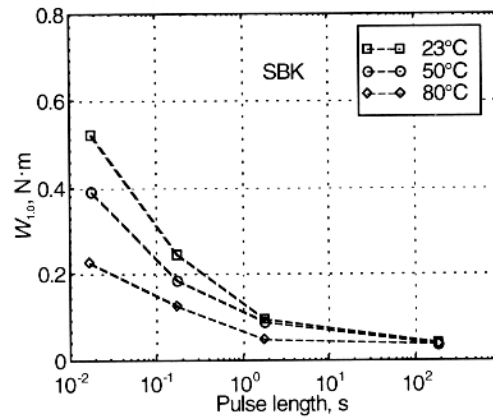


Figure 10. Network compression work $W_{1.0}$ for SBK as a function of pulse length and temperature for a compression from a start strain of ≈ 2.4 to a strain of 1 (20-MPa peak stress).

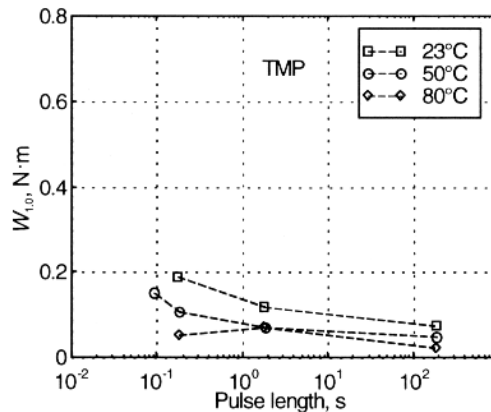


Figure 11. Network compression work $W_{1.0}$ for TMP as a function of pulse length and temperature for a compression from a start strain of ≈ 2.4 to a strain of 1 (20-MPa peak stress).

The influence of the temperature can be explained by the change in viscosity of water and the temperature-dependent behavior of the polymeric fiber material.

The results were divided by the viscosity of water in order to estimate the relevance of the water flow inside and outside the fibers. These results are presented in **Figures 12** and **13** for SBK and TMP, respectively. For both pulps, the relative differences of the compression work were reduced. This indicates that water movement inside the pulp fibers affected the dynamic compressibility of the fiber network. For the TMP web at 80°C and a pulse length of 2 s, the value was unusually high. We have no explanation for this anomaly.

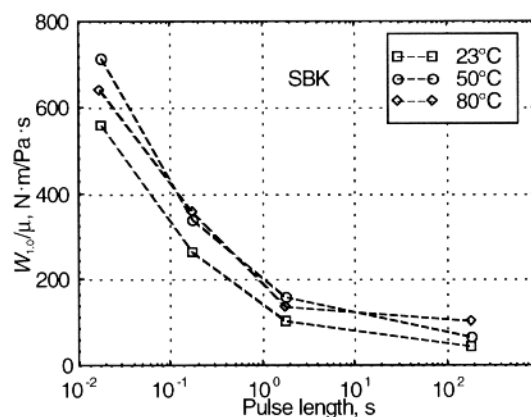


Figure 12. SBK results depicted in Figure 10 normalized by the appropriate viscosity of water.

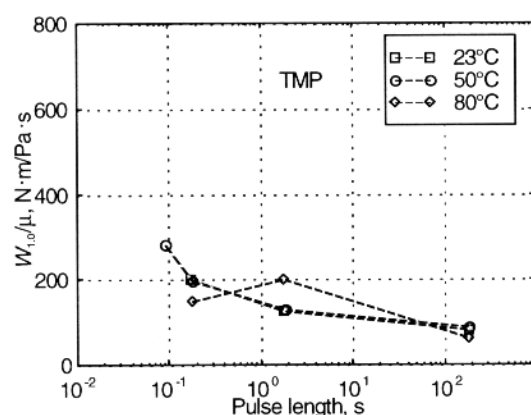


Figure 13. TMP results depicted in Figure 11 normalized by the appropriate viscosity of water.

Compression behavior

The compression behavior varied significantly with experimental conditions. Results of the duplicated experiments for extremely different conditions are depicted in **Figure 14**. The obtained modified strain was strongly dependent on both pulse length and temperature. For pulses up to 2 s, the minimum strain was observed after the peak stress had been reached. No significant expansion during the pulse was observed except for the 200-s-long pulses (Figure 14). Here, the larger amount of expansion when the applied stress was reduced during the second part of the stress pulse can be ascribed to the fact that lower modified-strain values were obtained during the quasistatic stress pulses.

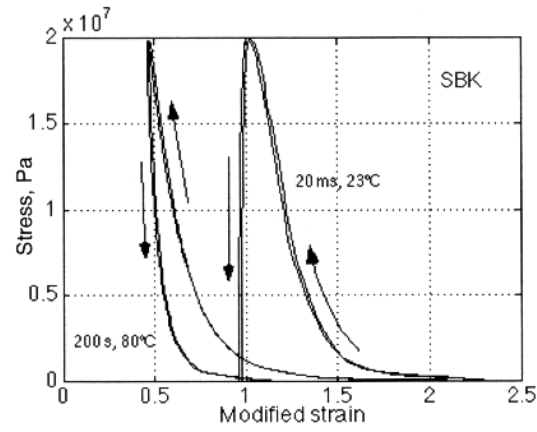


Figure 14. Stress-strain relationship for SBK webs subjected to 20-MPa press pulse at the highest and lowest combinations of time and temperature.

The calculated strain-shifts for SBK and TMP are summarized in **Figures 15** and **16**, respectively. For both pulps, the shifts varied considerably with pulse length and temperature. The fiber network became stiffer — i.e., the strain-shift $\delta_{m,shift}$ became larger — for shorter pulses and decreasing temperatures. The influence of temperature was larger for TMP over the entire range of pulse length.

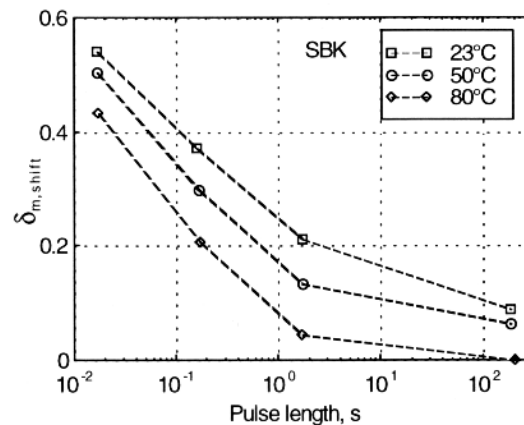


Figure 15. Strain-shift $\delta_{m,shift}$ as a function of pulse length for SBK at three temperatures.

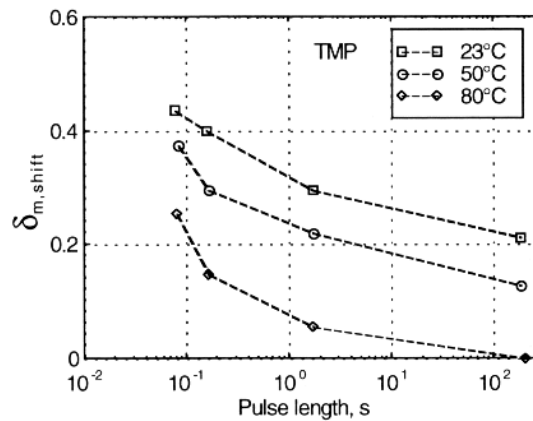


Figure 16. Strain-shift $\delta_{m,shift}$ as a function of pulse length for TMP at three temperatures.

Expansion behavior

The expansion occurred rapidly, as seen in **Figure 17**. The thickness $\delta_{m,300}$ was approached within a few seconds. Under most conditions, the mechanical pulp web expanded faster than the chemical pulp web. A sigmoidal shape of the expansion curve was observed for SBK, as seen in Figure 17. The lower expansion rates right at the beginning could have been caused by an expansion delay due to water flow in the fiber network or inside the fibers wall. The exponential function used approximated the results reasonably well. The repeatability of the experiment was good, with the results of the duplicated experiments nearly overlapping.

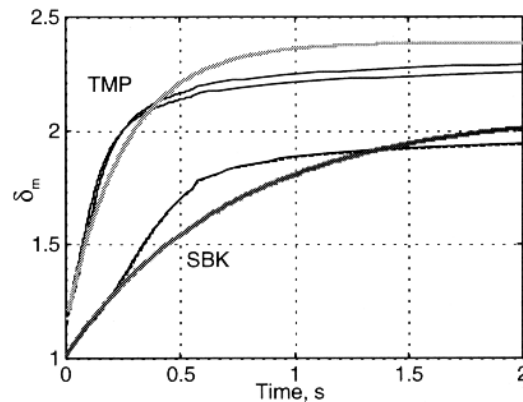


Figure 17. Expansion of mechanical and chemical pulp webs at 23°C from an initial strain of 1 (black lines: duplicated experimental results; colored lines: calculated results).

For SBK webs, the modified strain after 300 s ($\delta_{m,300}$) depended largely on the initial strain, as seen in **Figure 18**. Clearly, the level of compression prior to stress relief determined the extent of web expansion after 300 s. For TMP webs, the dependency on the initial strain was much less pronounced, but the TMP webs expanded to a much greater extent than the SBK webs, as seen in **Figure 19**. Temperature also affected web expansion, with lower $\delta_{m,300}$ values observed at higher temperatures for both SBK and TMP webs.

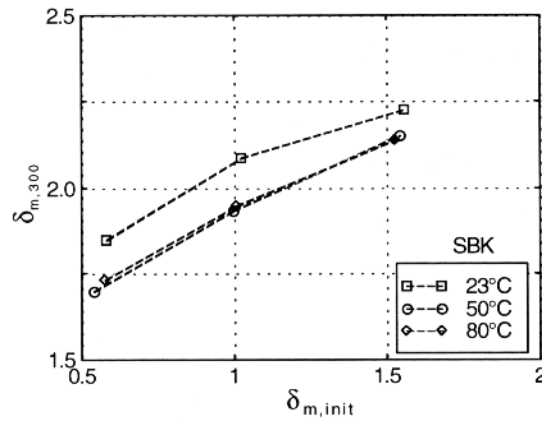


Figure 18. Strain measured after 300 s as a function of initial strain for SBK at three temperatures.

The occurrence of wet hornification — the closure of fiber pores due to mechanical compression — could explain the large dependency on the initial strain, especially in the case of the chemical pulp (33). At lower initial strains prior to the expansion, more pores would be expected to be closed irreversibly, thus reducing the amount of thickness recovery. No explanation can be given for the influence of the temperature.

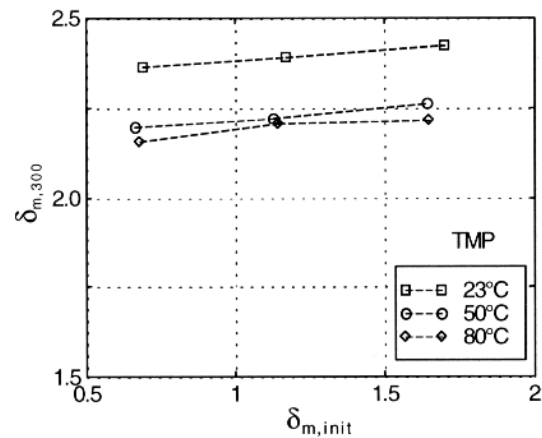


Figure 19. Strain measured after 300 s as a function of initial strain for TMP at three temperatures.

The dynamic expansion behavior of the SBK and TMP webs, expressed in terms of the expansion rate c_r , is depicted in **Figures 20** and **21**, respectively. For SBK, the expansion rate was significantly dependent on the initial strain, particularly at higher initial strains. The lower expansion rates at lower initial strain could be explained by a retarding mechanism caused by closed pores both between and inside the fibers prior to the expansion. The expansion rate increased somewhat when the temperature was increased from 23°C to 50°C. A further temperature increase did not have any effect.

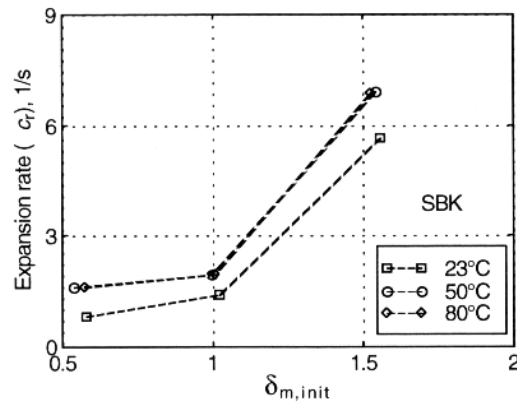


Figure 20. Expansion rate c_r of SBK as a function of initial strain at three temperatures.

The results obtained for TMP were somewhat contradictory. The initial strain appeared to influence the expansion rate only at a temperature of 23°C. However, at both 50°C and 80°C, the expansion rate was independent of the initial strain. No clear trend was observed for the influence of the temperature on the expansion rate of the TMP webs.

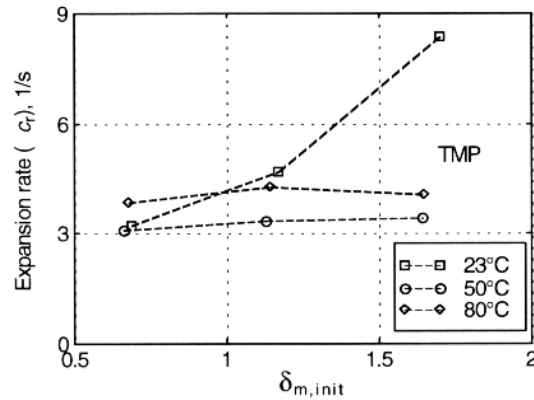


Figure 21. Expansion rate c_r of TMP as a function of initial strain at three temperatures.

In general, for initial strains below one, considerably higher expansion rates were obtained for TMP in comparison with SBK.

In order to apply the expansion measurement to a wet-pressing event, the experimental results depicted in Figure 17 were converted into dryness, as seen in **Figure 22**. A rapid dryness decrease can be observed for both pulps, with a faster decrease for the TMP pulp. However, the results in Figure 22 should only be taken as rough estimates, as it was assumed that all pores inside the network were filled with water. This might not be the case during wet pressing. Nevertheless, Figure 22 corroborates the commonly known experience of papermakers that the web can rapidly absorb water after the stress pulse in a press nip.

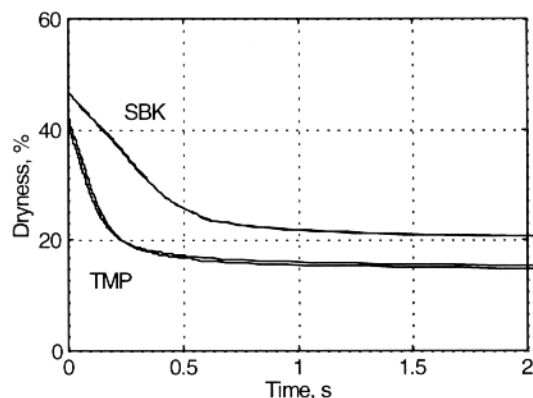


Figure 22. Dryness as a function of time calculated from the experimental results depicted in Figure 17 (23°C; complete saturation of the web was assumed).

SUMMARY AND CONCLUSIONS

The dynamic compressibility of saturated fiber networks was investigated. Compressed by a roll-nip-like stress pulse, the following qualitative behavior was found: A considerable reduction in web thickness occurred during the first part of the stress pulse when the stress was increased. The compaction continued even beyond the peak stress, although at a much lower rate. The minimum thickness was obtained between the peak stress and the end of the pulse. After achieving the minimum thickness, almost no expansion occurred for short pulses. However, a considerable and rapid expansion was observed as soon as the stress was removed from the web. Fiber networks made from mechanical and chemical pulps behaved qualitatively similarly.

The behavior during the compression pulse was evaluated as stress-strain relationships. A significant reduction in strain was found only during the first part of the stress pulse. It was quantitatively approximated by a power-law relationship. The softening influence of an increasing pulse length or an increasing temperature was accounted for by shifting the curve horizontally toward lower strains. The dynamic expansion behavior, investigated in separate experiments, was approximated by an exponential function. Both quantitative approximations described the measured behavior well and can be used to model the wet-pressing process.

The following conclusions were drawn. No considerable amount of energy is stored in the wet fiber network during a dynamic compression. Thus reabsorption of water caused by web expansion is not possible as long as the stress applied to the web is within a range relevant for wet pressing. However, after relief of the applied stress, a reabsorption can occur due to the rapid expansion observed.

APPENDIX: REGRESSION ANALYSIS OF THE REFERENCE EXPERIMENTS

The experimental results were fitted to the following function (Eq. 6) by the least-squares method.

$$\sigma_a = c_1 \cdot c_2^{\delta_{m,ref}} \quad (6)$$

Pulp and pressing conditions			c_1 , Pa	c_2 , (dimensionless)	r^2 , %
SBK	5 MPa	80°C	5.56×10^7	1.76×10^{-2}	99.6
	10 MPa	80°C	1.12×10^8	1.26×10^{-2}	99.4
	20 MPa	80°C	1.48×10^8	1.11×10^{-2}	98.6
TMP	5 MPa	80°C	5.67×10^7	2.02×10^{-2}	97.4
	10 MPa	80°C	8.57×10^7	1.15×10^{-2}	98.3
	20 MPa	80°C	1.39×10^8	8.04×10^{-3}	98.2

Table II. Regression results for the reference experiment.

NOMENCLATURE

A	Compression area, m ²
c_r	Expansion rate, 1/s
c_1	Regression coefficient in the reference stress–strain correlations, N/m ²
c_2	Regression coefficient in the reference stress–strain correlations (dimensionless)
h	Thickness of the web, m
h_0	Reference thickness, equivalent to the thickness of a poreless web, m
w	Grammage of the web, kg/m ²
W	Network compression work, N·m
$W_{1.0}$	Work expended on network compression to a modified strain of 1.0, N·m
W_C	Compression work, N·m
$W_{C,1.0}$	Compression work for a compression to a modified strain of 1.0, N·m
$W_{C,\sigma_{max}}$	Compression work for the compression up to σ_{max} , N·m
W_{FL}	Work required for generating in-plane flow, N·m
$W_{FL,1.0}$	Work required for generating in-plane flow for compression to a modified strain of 1.0, N·m
$W_{FL,\sigma_{max}}$	Work required for generating the in-plane flow for a compression up to σ_{max} , N·m
δ_m	Modified strain (dimensionless)
$\delta_{m,init}$	Initial modified strain in expansion experiments (dimensionless)
$\delta_{m,total}$	Total modified strain during a compression (dimensionless)
$\delta_{m,ref}$	Reference modified strain as a function of stress (dimensionless)
$\delta_{m,shift}$	Horizontal strain-shift in modified strain (dimensionless)
$\delta_{m,300}$	Modified strain 300 s after the stress release (dimensionless)
$\Delta\delta_m$	Total increase in modified strain during the expansion (dimensionless)
σ_a	Applied stress during stress pulse, N/m ²
σ_{max}	Peak stress of the stress pulse, N/m ²

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