Characteristics of out-of-plane rheological behaviour of paper

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ABSTRACT

Paper experiences z -directional compressive strains in several papermaking and converting processes. The rheological response of paper generally depends on the humidity, temperature, structure and composition of paper. In this experimental study the dynamic strain behaviour of paper under z-directional compressive forces was investigated using a novel custom made laboratory testing rig.

Laboratory hand sheets with same basis weights but different raw material composition were used. Compressive stress level and dwell time were main external variables. The applied dwell times ranged from a few milliseconds to several hundred milliseconds. The stress levels were varied from a few megapascals to tens of megapascals. The temperature and moisture of the samples were constant. The plastic, elastic and creep components of strain caused by increasing stress and dwell time were determined and analysed. The results show that the logarithmic strain varied non-linearly with increasing stress level. The plastic deformation was causing the increase of the logarithmic strain. The increasing dwell time at constant stress caused also non-linear increase in strain. This was due to both increase in plastic component and decrease in the elastic component. The results also revealed significant differences between mechanical and chemical pulp samples in both time and stress-dependent behaviour of strain probably due to the difference in the network structure. Large deformations occurred already in short time-scales.

BACKGROUND

In papermaking and converting processes paper is subject to stresses in out-of plane direction. Typically wet pressing, size pressing, calendering, reeling, winding, printing and cutting operations cause considerable dynamic out-of-plane stresses and deformations in paper. It is important to understand the resulting thickness change, the contact area between paper and the cylinder surface and the final irreversible deformation and how they depend on the shape and extent of the press pulse, and on the temperature – humidity conditions. Paper structure is one factor determining the compressive deformation of paper. Structure is changed by the furnish composition and wet stretching/drying history and material distribution in z-direction.

The effects of main external variables on paper compressibility has been recognized for several decades[1,2,3,4]. However, there are still some shortcomings in the present knowledge. First of all, most of the studies are made using static or quasi-static compression pulses, which are outside the time-scales of industrial processes. Fewer studies are made near process time-scales. The effects of conditioning of paper samples, i.e. elevations in temperature and moisture content, on compressibility are not fully examined as well. The reason for these shortcomings has been in the limited capacities of the experimental set-ups.

In this study, the objective was to determine basic reological characteristics of paper under compressive stresses during short times scale. The interest was in examining how handsheets made of pure pulp components differ in compressibility behaviour when stress magnitude and stress dwell time are varied. The compressibility of pulp mixes and the effect of elevated moisture content will be the subject of further studies.

MATERIALS

Handsheets were made from mechanical and chemical pulp according to SCAN-C 26:76 apart from the following exception: the normal drying plates were replaced by blotters in order to avoid two sidedness created by conventional drying plates. This method allows the hand sheets to shrink modestly during drying.

The pulps used were obtained from Finnish pulp mills. Chemical pulp was Aki Botnia pine bleached sulphate softwood pulp from Äänekoski mill beaten to 500 ml CSF with a Valley laboratory hollander. Mechanical pulp was unbleached softwood SC TMP pulp with 50 CSF from Jämsänkoski mill. The handsheet grammage was 60-g/m^2 and average thicknesses of chemical and mechanical pulp sheets were 105 m and 150 m, respectively. Conventional tests were conducted under standard climate (23 ^oC and 50% RH). Some relevant handsheet properties are listed in Table 1.

TESTING EQUIPMENT AND METHOD

A dynamic compression test rig with press platens was used in the measurements. The tester is called AKTU and it is developed in the laboratory of VTT Processes in Jyväskylä[5]. The basic idea behind this device is similar to that of a typical uniaxial compression tester. The material to be examined is placed between two press plates under a certain initial preload. A compression pulse is applied to the sample and the resulting compressive force and deformation are measured at the same time. The force is measured above the sample with a quartz crystal force gauge and the compressive pressure is specified as the force divided by the surface area of the sample. Compressive deformation is measured with three eddy-current distance sensors and is defined as the average change in distance between the press platens. The tester is capable of producing controlled pressure loading pulses with duration about 1 millisecond and dynamic force up to 5 kN, depending on required speed and displacement. Moreover, testing conditions (temperature and humidity) can be varied by using a climate chamber. The temperature in the climate chamber can be adjusted from 20°C to 80°C and moisture from 5% RH to 60-90% RH, the upper limit depending on the temperature. A computer with special data acquisition software and a data acquisition board is used for recording the measurements. The experimental equipment is shown in Figure 1.

Table 1. Basic properties of tested hand sheet samples.

Property		Chemical pulp	Mechanical pulp
Caliber/sheet	µm	105	150
Density	kg/m^3	571	400
Basis Weight	g/m^2	60	60
Paper moisture at 50% RH	%	91.1	89.9
PPS roughness	µm	8.4	7.7

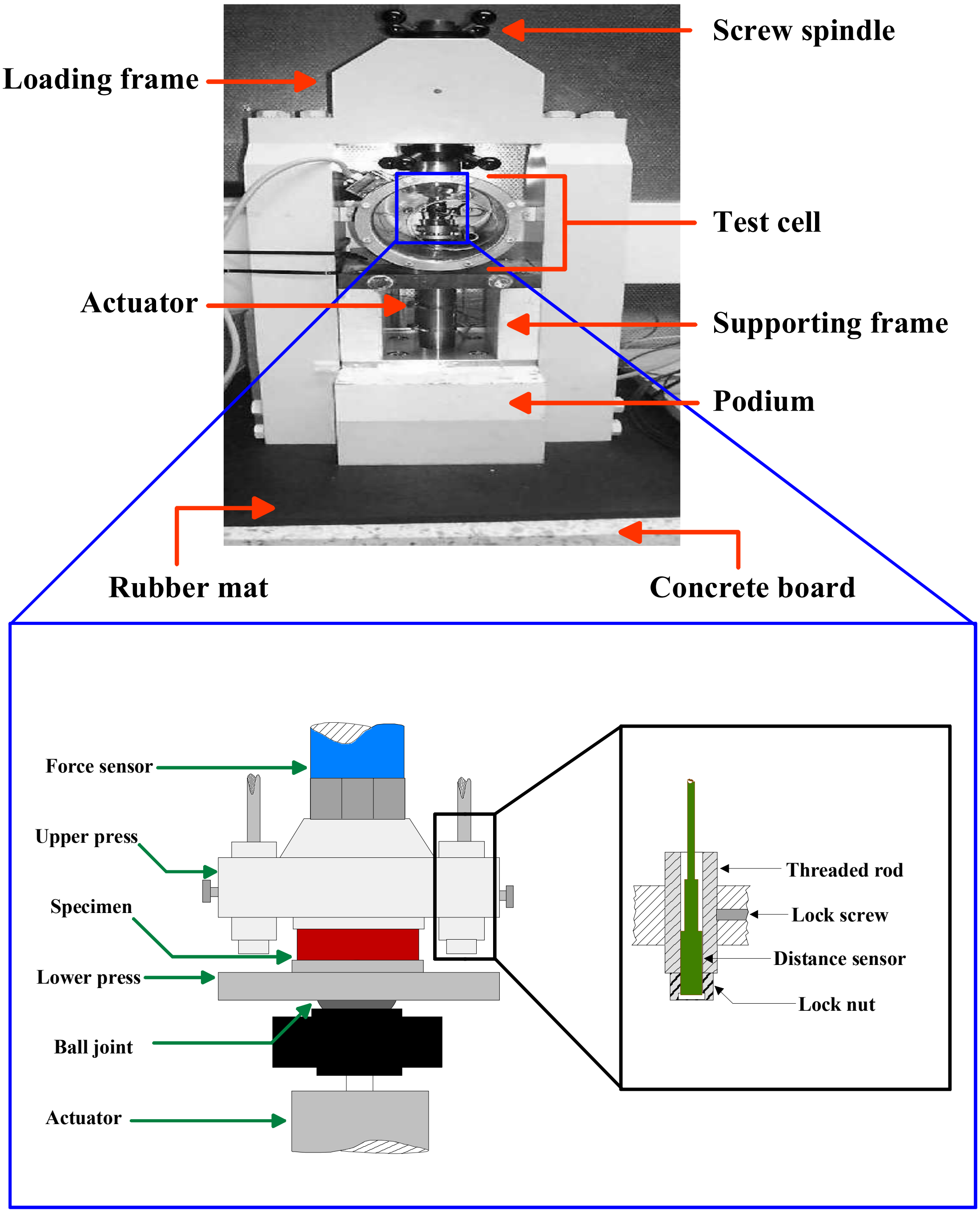

Figure 1. General view of the test rig (upper figure) and detailed side view of the test cell area (expanded view).

EXPERIMENTS

Compression tests were made on one sample sheet using single rectangular shaped stress pulse with constant rise rate. Both pulse dwell time and stress level were changed independently. Dwell time was varied from 4 to 512 ms under given 10 MPa stress and stress level was increased from 2MPa to the highest level, while the 128 ms dwell time was kept constant. The highest stress levels were 36 MPa for mechanical pulp and 49 MPa for chemical pulp determined by the limited force-motion relation of the actuator. The round pressing area had 10 mm diameter. Static preload of 100 kPa was used to make sure that there is a good initial contact between the sample and the press plates right from the beginning. Tests were repeated five or more times for every trial point and the shown results are averages of those measurements. In addition, the effect of machine compliance under load was eliminated from the results.

DATA ANALYSIS

Force (F), compressive deformation (Δl) and time (t) data are recorded in compression tests. The compression stress, σ applied to the sample is calculated from the compression force and nominal area under compression (A). Absolute compressive deformation can be used to describe the response of material to applied stress, but it is dependent on material dimensions, especially thickness. Strain, on the other hand, is a property of material itself independent of dimensions and is therefore preferred for comparison of different samples. The logarithmic or true strain ε of sample caused by applied stress is defined through the equation: $\varepsilon = -\ln(l/l_o)$, where l and l_o are current and initial thicknesses of sample. Because the sample weight is not affected by the compression process and there is no essential variations in plane directional dimensions during compression in the case of paper, the change in sample thickness is in practise equal to the change of sample density and therefore the strain can also be expressed as: $\varepsilon = -\ln(\rho_o/\rho)$, where ρ and ρ_o are current and initial density of sample. The logarithms are negative valued due to thickness reduction (and density increase) and the minus signs have been added because the convenience of using positive values.

In the analysis, the total strain ε_t is divided into subcomponents including instant elastic strain ε_i and creep strain ε_c which are obtained from rising part of the strain curve and to elastic ε_e and plastic strain ε_p found from the post peak or decaying part of the strain curve. The delayed elastic (viscoelastic) component is not separated from the total strain but it is included in elastic strain. Different strain components are located by utilising the peaks of first derivate of strain. The components are linked to each other by following equations: $\varepsilon_t = \varepsilon_i + \varepsilon_c$, $\varepsilon_t = \varepsilon_e + \varepsilon_p$.

A logarithmic function $\varepsilon = a + b\ln(x)^c$, (where x is time or stress) with three free parameters a, b and c was fitted to strain-time and strain-stress data. Parameter values of the function were evaluated using Matlab based fitting program. As can be seen from the results, this function describes well the strain-time and strain-stress behaviour in the measured range. However, logarithm has a negative infinite value at the origin, which gives a non-physical value for strain at zero time and stress. This is the main drawback of using a logarithmic function.

RESULTS

The experimental results are shown in figures 2 and 3. The values of the fitted parameters in the logarithmic function and the coefficients of determination are listed in table 2. All the plots are presented in log-linear format.

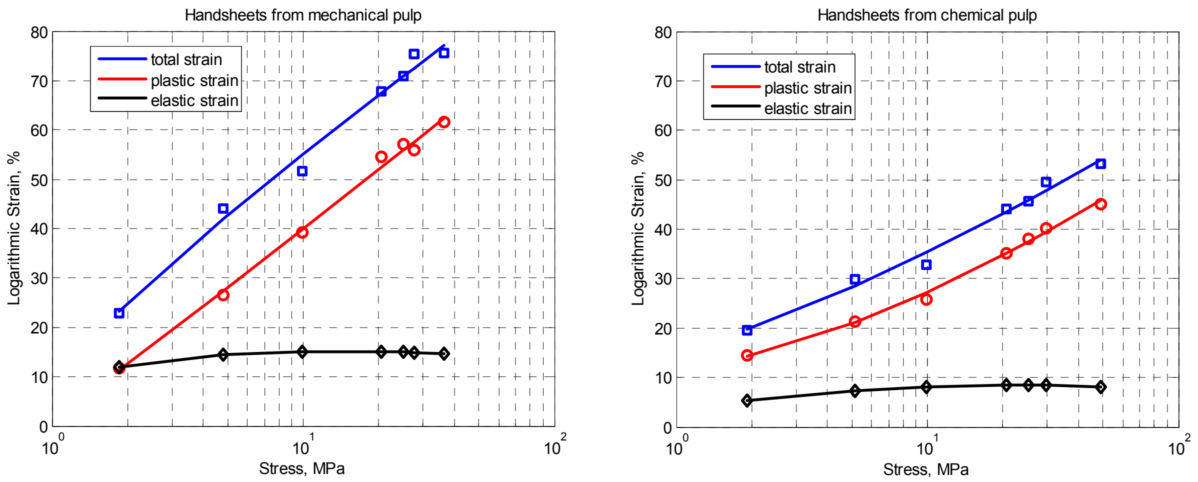

Figure 2. Different strain components versus stress with varying magnitude and constant duration (128 ms) for hand sheets made of chemical (left) and mechanical pulp (right). The solid lines are the predictions of the logarithmic model.

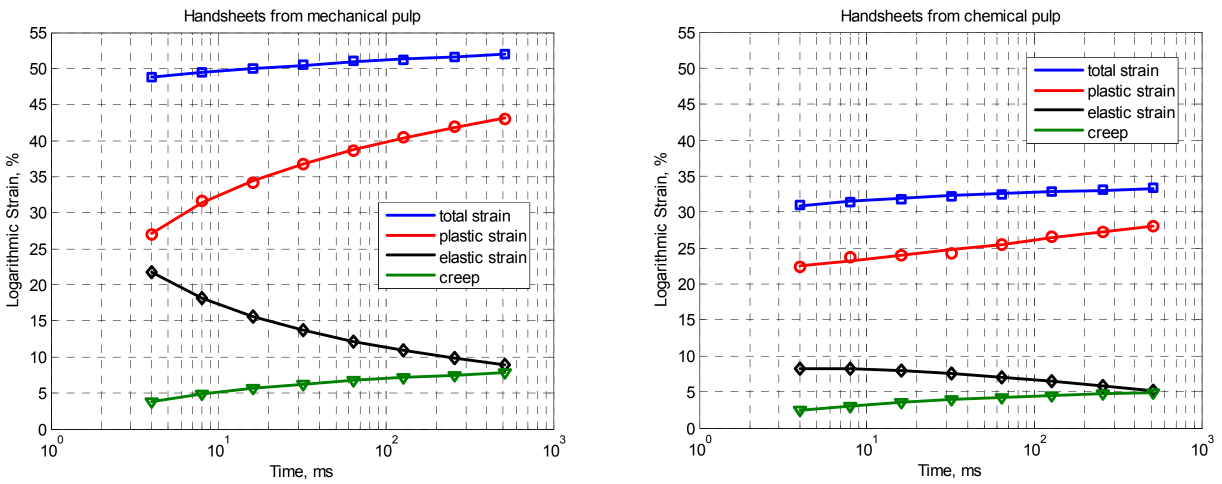

Figure 3. The effect of loading time on strain components under given (10 MPa) stress. The solid lines are the predictions of the logarithmic model.

Increasing compressive stress (Fig 2) causes an apparently linear increase (in log-linear diagram) in the logarithmic strain with both furnishes. The elastic strain stays nearly constant and the increased deformation is mainly due to plastic strain component. The total deformation and the total strain is higher with the mechanical pulp sheets, and also the elastic strain component is higher with mechanical pulp than chemical pulp handsheets.

Increasing holding time at constant stress (Fig 3) increases the total strain almost linearly in log-linear frame. However, the elastic strain is decreased and plastic strain is increased with increasing time but the creep strain is increased very little. This suggests that the creep strain is only partially responsible for the increased plastic strain, but also part of the elastic strain is converted into plastic strain. These changes are greater in short time scale

Table 2. Parameter values of used logarithmic function for different strain components.$^{*)}$

Development of strain components under various stress magnitudes with given dwell time				
Strain component	a	b	c	r^2
total strain, mech.	8.6030	22.4474	0.8737	0.9892
plastic strain, mech.	1.5184	16.2315	1.0344	0.9951
elastic strain, mech.	---	---	---	---
total strain, chem.	15.9671	6.6080	1.2884	0.9851
plastic strain, chem.	12.1989	4.1380	1.5429	0.9951
elastic strain, chem.	---	---	---	---
Development of strain components at various dwell times of given stress magnitude				
total strain, mech.	45.6965	2.6357	0.4744	0.9957
plastic strain, mech.	-437.7703	461.4103	0.0226	0.9993
elastic strain, mech.	---	---	---	---
creep strain, mech.	$-7.0625 \cdot 10^5$	$7.0625 \cdot 10^5$	$3.7445 \cdot 10^{-6}$	0.9537
total strain, chem.	$5.8441 \cdot 10^5$	$-5.8438 \cdot 10^5$	$-2.7195 \cdot 10^{-6}$	0.9749
plastic strain, chem.	21.5210	0.7270	1.2015	0.9797
elastic strain, chem.	---	---	---	---
creep strain, chem.	-8.2798	10.2657	0.1376	0.9806

*) r^2 is a square of Pearson's correlation coefficient. Elastic strain is obtained by subtracting the plastic strain from the total strain. Therefore the data of elastic strain is not fitted to the model and the parameters are missing from the table.

CONCLUSIONS

The results show that the novel compression test equipment is suitable for studying short time scale rheological phenomena of paper. The response of logarithmic strain to increased compressive stress is apparently linear in log-linear scale and it is mainly due to increased plastic deformation. Increasing dwell time under constant stress increases the logarithmic strain also linearly in log-linear scale. On the contrary to the effect of compressive stress, the strain increase in time is due to nonlinear response of plastic and elastic strains.

Under compressive stress mechanical pulp sheets show larger deformations, and also a larger part of this deformation is elastic than with chemical pulp sheets.

ACKNOWLEDGMENTS

The authors wish to thank TEKES for financial support of this work and the staff of VTT processes for preparing the hand sheets. Metsä-Botnia Äänekoski mill and UPM-Kymmene Jämsänkoski mill are acknowledged for providing the pulps for the experiments.

REFERENCES

1. Jackson, M., Ekström, L., "Studies concerning the compressibility of paper", Svensk Papperstidning 67(20):807 (1964).
2. Chapman, D.L.T., Peel, J.D., "Calandering processes and the compressibility of paper, part 1", Paper Technology 10(2):116 (1969).
3. Colley, J., Peel, J.D., "Calandering processes and the compressibility of paper, part 2 - The effects of moisture content and temperature on the compressive creep behaviour of paper", Paper Technology 13(5):350 (1972).
4. Rättö, P.," On the compression properties of paper – implications for calandering", PhD thesis, Department of Paper Technology, KTH, Stockholm, Sweden, 2001.
5. www.paperrc.com.