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COMPRESSION BEHAVIOUR OF FIBRE MATS IN WET PRESSING

Z. Szikla* and H. Paulapuro
The Finnish Pulp and Paper Research Institute, P.O. Box 136,
SF-00101 Helsinki, Finland

*Now with: Research Institute of the Paper Industry,
Duna Str. 57, H-1215 Budapest, Hungary

ABSTRACT

The dynamic compression behaviour of the wet fibre mat is the key factor to understanding the mechanisms of wet pressing. At present this behaviour is imperfectly understood. The main reason for this may be the lack of suitable measuring equipment. To fill this gap, laboratory devices (press simulators) were built at the Finnish Pulp and Paper Research Institute. The simulators permit controlled pressing to be performed within a wide speed range, the fastest pressure rise being equivalent to that encountered in the presses of the fastest paper machines. The web thickness and the hydraulic pressure created in the web during pressing can be measured accurately. Papers with grammages of 50 and 100 g/m^2 and with various furnish compositions were tested with these devices.

The results show that when compression is fast and the pressure evenly distributed, most of the compression force is consumed by the movement of water in the web. Up to a highly dense state the mechanical stiffness is very low. The association of fibre and water does not lend itself to easy compressibility. The replacement of water with hydrocarbons resulted in a dramatic increase in web compressibility. Alcohol replacement also had a similar, though less pronounced, effect. The binding of water to the fibre material seemed to affect compression at least as much as did viscosity.

Of the raw material properties studied, the particle size distribution, fibre stiffness and type of fibre (either mechanical or chemical) all affected web compressibility. Grammage and sheet structure also proved to be important in this respect. The magnitude of the effects often depends very much on the water content of the web and on the speed of compression. The effects of the above-mentioned and some other parameters on web compression are discussed in detail and explanatory mechanisms are proposed.

INTRODUCTION

The main lines of our present understanding of the mechanisms of the dynamic compression behaviour of paper webs were drawn by Wahlström (1, 2, 3). According to his widely accepted theory the compressive pressure applied is balanced by two clearly separate components, one arising from the stiffness of the structure and the other from the flow of water. In compliance with this theory, the total pressure can be divided into structural and hydraulic components. The sum of the structural and hydraulic pressures in the z-direction is constant and equivalent to the pressure applied at this point.

Much work has been done to study the dynamic compression behaviour of the paper web (e.g. 4, 5, 6, 7, 8, 9 and 10), but most of the tests have been carried out with a much slower compression speed than is normal in paper machines. Because the phenomenon is highly time-dependent, the adaptation of the available information in practice is often difficult.

First Chang (7) and later groups of scientists at the University of Maine at Orono (11) and at the Swedish Pulp and Paper Research Institute (12) made attempts to measure the hydraulic pressure in the boundary layer between the paper web and the impermeable pressing surface. But again it is difficult to apply their results to conditions prevailing in paper machines either because of the great difference in the conditions or because of the limited accuracy of the measurements.

Mathematical modelling of the phenomenon has also been attempted (13, 14), but as the physical laws governing the phenomenon are known incompletely, the assumptions may lead to significant errors.

Our approach to the subject was first to develop the equipment to simulate wet pressing under the type of conditions prevailing in paper machines.

Using this equipment we then studied the behaviour of the paper web under various pressing conditions with the following aims:

- to find the optimum conditions for given pressing situations
- to obtain basic information about the compressibility of the paper web.

EXPERIMENTAL

The tests were carried out using the two press simulators at the Finnish Pulp and Paper Research Institute (15). One is a Wahren-Zotterman type simulator, which creates short sine pulses with a dwell time of 1-5 ms. This simulator is equipped with load and displacement transducers. Using the displacement transducer the thickness of the paper can be measured during pressing with an accuracy of ± 2-3 μm. In the other simulator the pressing force is created by a hydraulic actuator. The only limitation of this device is in the speed; the shape of the pulse can be varied over a wide range. The shortest period in which the load can be increased from 0 to maximum (i.e. 50 kN) is 3 ms, and the minimum dwell time of the pulse is 5 ms. In addition to the load and displacement transducers, the hydraulic simulator is also equipped with a pressure sensor to measure the hydraulic pressure being developed in the paper web. The hydraulic pressure created in papers with low grammage can also be recorded: measurements with 42 g/m^2 newsprint have been made as a matter of routine. The time difference derived from the equipment between the hydraulic pressure and the load signals can be determined and set to zero. As our study showed (15) the systematic error of our hydraulic pressure measurement is smaller than 15%.

Two types of test were carried out. In one set of tests only the load and the thickness of the paper were monitored, while the other tests also included the hydraulic pressure. The reason for this arrangement was that the desired accuracy could be obtained only using special procedures, which were different for thickness and hydraulic pressure measurements. Additionally, two different levels of compression speed were used, one being close to the speeds characteristic of pressing in modern paper machines, and the other significantly slower. In the compressibility tests the pressure was increased from 0 to 10 MPa in 1.5 or 15 ms and in the tests measuring also the hydraulic pressure the pressure was raised from 0 to 4 MPa in 3 or 15 ms. In a paper machine with roll presses the pressure increases from 0 to 4-10 MPa in 1-1.5 ms if the running speed is around 20 m/s. The slower and lower pressure compressions used in hydraulic pressure tests were due to the limitations of our hydraulic simulator.

Paper samples with grammages of 50 and 100 g/m^2 were made of never dried pulps in a laboratory sheet mould (SCAN C26:76). The properties of the different furnishes used are listed in Table 1.

After the sheets had been made, the moisture ratio of the web was set to the desired ingoing level by gentle pressing between blotting papers.

The thickness values obtained in the compressibility tests were converted into moisture ratio values assuming the sheet to be saturated. Thereafter the following formula was fitted to the moisture ratio-pressure data derived:

$$P = a\,(MR)^b, \quad \text{where} \qquad (1)$$

P = pressure, MPa
MR = moisture ratio at pressure P, g H_2O/g fibre
a and b are constants.

The formula could be fitted to the data with a confidence of around 98%.

Pulp	Length-weighted average fibre length, mm	CSF ml	WRV g H_2O/g fibre
UBPK, unbeaten and dried	-	-	1.24
UBPK, unbeaten	1.74	650	1.81
UBPK, beaten 1 [1]	1.68	470	2.00
UBPK, beaten 2 [1]	1.63	310	2.15
UBPK, beaten 3 [1]	2.01	480	2.08
UBPK, beaten 3, R 35 fraction [2]	2.41	650	1.86
UBPK, beaten 3, R 20 fraction [2]	2.69	675	1.80
Spruce PGW 1	0.89	145	1.47
Spruce PGW 2	0.82	102	1.58
Spruce PGW 3	0.88	75	1.81

1) Valley beater
2) Bauer McNett

Table 1. Properties of the pulps tested.

UBPK = unbleached pine kraft
Pine = Scots pine
Spruce = Norway spruce

RESULTS

Effect of Moisture Content of Web

Moisture content had a very pronounced effect on the dynamic compressibility of the web (Figs. 1 and 2). Below saturation point the resistance to compression was not detectable up to a relatively high density.

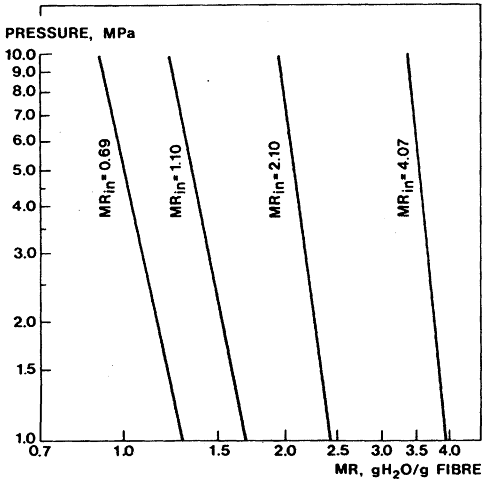

Fig. 1. Effect of moisture content on the dynamic compression of a chemical pulp sheet. Unbleached pine kraft, CSF 475 ml, 100 g/m^2. Compression time 1.5 ms.

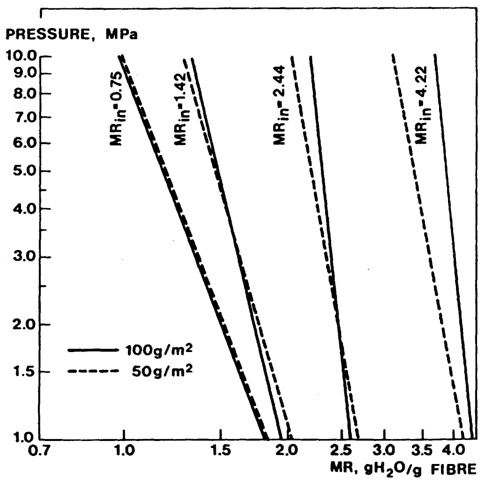

Fig. 2. Effect of moisture content on the dynamic compression of a mechanical pulp sheet. Pressure groundwood, CSF 75 ml. Compression time 1.5 ms.

Pulp	CSF	Fast pressing (10 MPa in 1.5 ms)			Slow pressing (10 MPa in 15 ms)		
		Compr. press. at void volume (cm^3/g)			Compr. press. at void volume (cm^3/g)		
		2.0	1.5	1.0	2.0	1.5	1.0
			MPa			MPa	
PGW	145	0.5	1.8	10.0	0.5	1.4	5.5
PGW	102	0.5	1.7	10.0	0.7	1.8	6.0
PGW	75	0.7	2.0	10.0	0.4	1.1	4.5
Unbl. pine kraft	650	0.3	1.3	10.0	0.5	1.1	3.7
Unbl. pine kraft	470	0.1	0.4	5.5	0.1	0.5	3.7
Unbl. pine kraft	310	0.0	0.2	3.7	0.1	0.3	0.2

Table 2. Pressures needed to compress sheets to certain void volumes when moisture content was low (0.7 g H_2O/g fibre)

As shown in Table 2, when paper sheets with low moisture ratio (0.7 g H_2O/g fibre) were compressed, the resistance to compression started to appear only at a void volume of 1.5-2.0 cm^3/g. (Assuming a saturated sheet, this is equivalent to a moisture ratio of 1.5-2.0 g H_2O/g fibre.) The hydraulic pressure measured on the side of the impermeable pressing surface was also affected greatly by the moisture content (Figs. 3, 4 and 5). A high hydraulic pressure was discernible in all tests in which the compression speed was fast (compressive pressure raised from 0 to 6 MPa in 3 ms). This was also the case with 50 g/m^2 sheets. As a rule, the maximum hydraulic pressure coincided in the tests with maximum total pressure, the time differences between the maximums in most cases being less than ± 0.3 ms. The direction of the small time differences seemed to be similar to the ones stated previously by Carlsson (16), but the differences were much smaller.

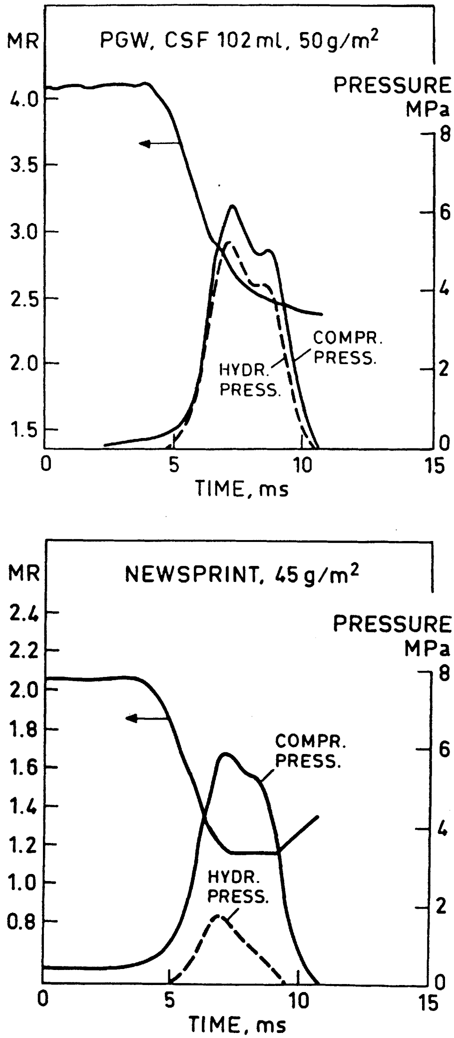

Fig. 3. Typical results obtained in the hydraulic pressure measuring test.

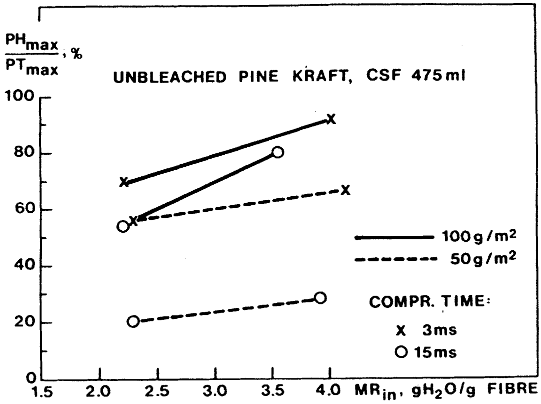

Fig. 4. Effect of moisture content, grammage and speed of compression on the hydraulic pressure in a chemical pulp sheet.

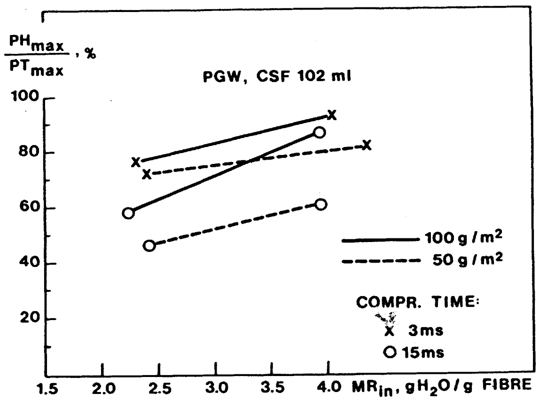

Fig. 5. Effect of moisture content, grammage and speed of compression on the hydraulic pressure in a mechanical pulp sheet.

Effect of Beating Chemical Pulps, and Freeness of Mechanical Pulps

Beating also had a significant effect on the dynamic compression of chemical pulps (Fig. 6), and the effect was greatly dependent on the moisture content. When the moisture ratio was high, beating increased the resistance to dynamic compression, but reduced it when the water content was low (0.7 g H_2O/g fibre) and no water removal occurred during pressing. Drying had a very pronounced influence on the compression behaviour: the dynamic compression of sheets made of unbeaten fibres which were then dried and rewetted was almost independent of the moisture content.

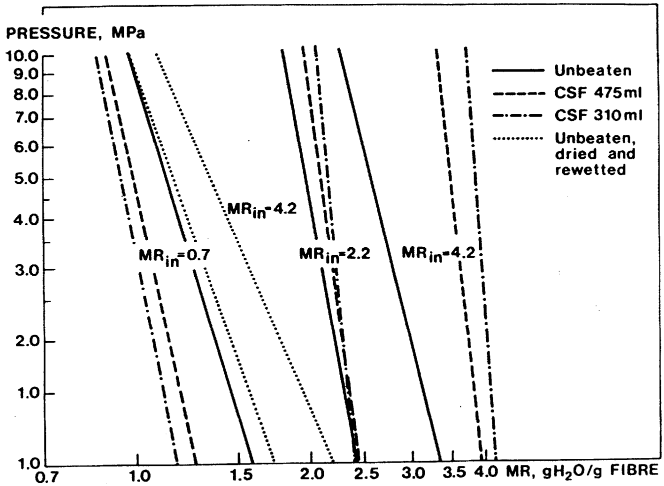

Fig. 6. Effect of beating of chemical pulp on the dynamic compression of the sheet. Unbleached pine kraft, 100 g/m². Compression time 1.5 ms.

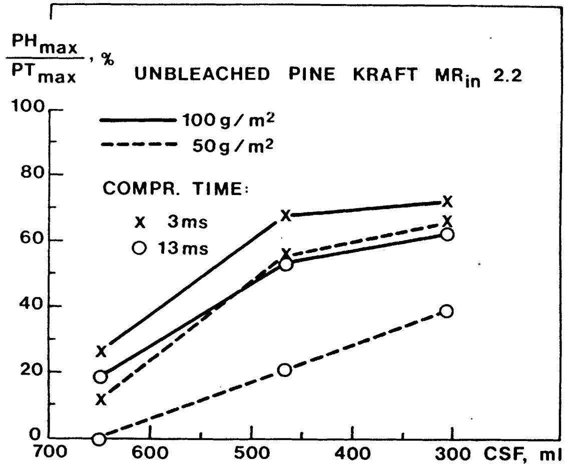

Fig. 7. Effect of beating of chemical pulp on the hydraulic pressure in the sheet.

Beating increased the hydraulic pressure created in the web (Fig. 7).

The effect of the freeness of mechanical pulp was studied in the range of 75-145 ml, which is typical of printing papers. In this range freeness did not affect the dynamic compression behaviour.

Effect of Fibre Stiffness

To study the effect of fibre stiffness, sheets containing 27% stainless steel fibres and 73% unbleached pine kraft pulp were made. (The proportions were calculated by weight.) The properties of the stainless steel fibres were as follows:

- diameter 12 µm
- length 3 mm
- stiffness $2x10^{-10}$ Nm^2

For comparison, the stiffness of unbeaten softwood kraft fibres has been measured to be 5x 10^{-12} Nm^2 (17). In the sheet-making procedure great care was taken to keep the fines in the structure; circulating white water was used and the retention was frequently monitored. This effort was obviously successful, as the water retention values of the 100% wood pulp sheets and sheets containing 27% metal fibres were the same.

As Fig. 8 shows, fibre stiffness had a pronounced effect on dynamic compression at low moisture content: stiffer fibres displayed higher resistance to compression. As the moisture content increased, the effect of fibre stiffness gradually decreased. At the initial moisture ratio of 4.2 both sheets performed approximately according to the same compression curve.

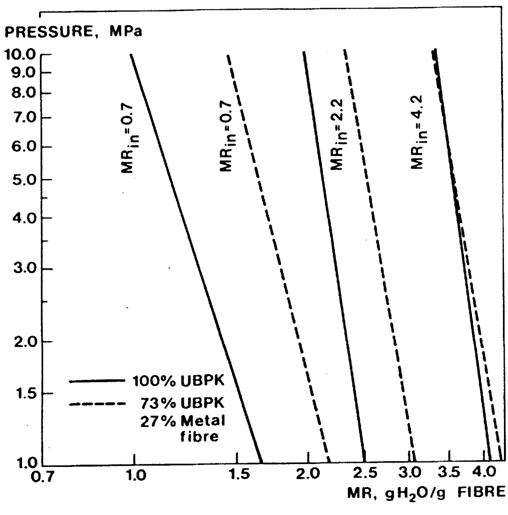

Fig. 8. Effect of fibre stiffness on the dynamic compression of the sheet. Unbleached pine kraft, CSF 475 ml, 100 g/m^2. Compression time 1.5 ms.

The hydraulic pressure in the web containing metal fibres was lower than that in the 100% wood pulp web at both initial moisture ratio values (2.2 and 3.5) studied (Fig. 9). The difference was somewhat smaller at higher moisture content.

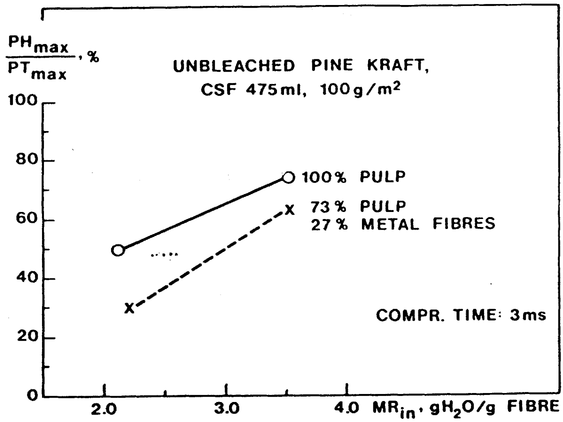

Fig. 9. Effect of fibre stiffness on the hydraulic pressure in the sheet.

Effect of Particle Size

To study the effect of particle size, sheets were made from the different fractions of softwood unbleached kraft pulp:

- the whole pulp, CSF 480 ml, WRV 2.08 g H_2O/g fibre,
- the R35 fraction (85% of the whole pulp), CSF 650 ml, WRV 1.86 g H_2O/g fibre,
- the R20 fraction (70% of the whole pulp), CSF 675 ml, WRV 1.80 g H_2O/g fibre.

The fractionation was carried out using a Bauer McNett apparatus.

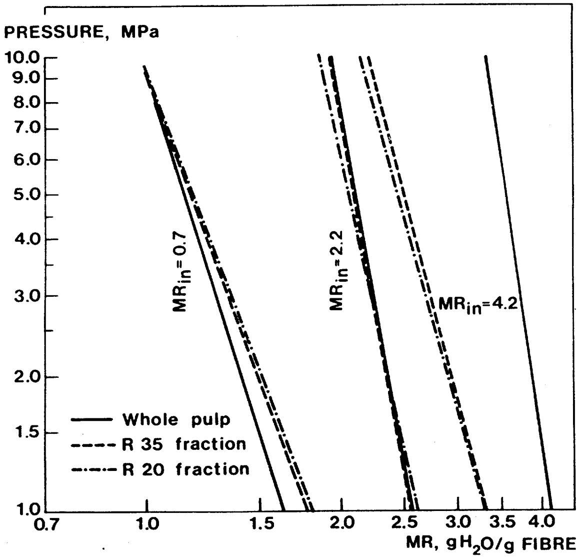

Fig. 10. Effect of particle size on the dynamic compression of the sheet. Unbleached pine kraft, 100 g/m^2. Compression time 1.5 ms.

When the moisture content was high, the removal of the finest 15% of the particles greatly reduced the resistance to dynamic compression (Fig. 10). Removal of the next 15% of fines had no further effect on compression. The compression curves of the sheets of the R35 and R20 fractions were very similar at all moisture contents despite the difference observed in hydraulic pressures (Fig. 11). The fines extraction slightly increased the compression resistance when the moisture ratio was low (0.7).

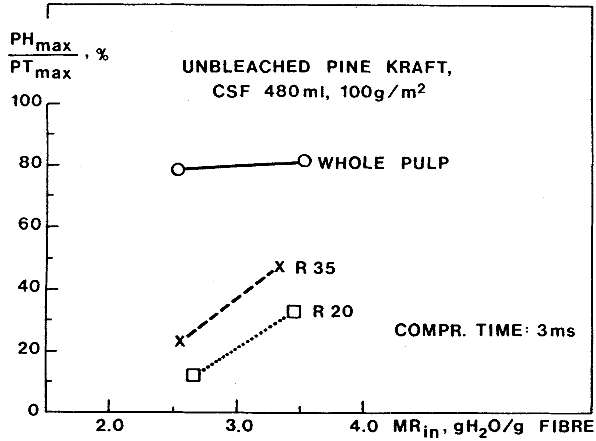

Fig. 11. Effect of particle size on the hydraulic pressure in sheets made of different pulp fractions.

The hydraulic pressure was significantly affected by the finest 15% of the particles, but a notable effect was also discernible when a further 15% of small particles was removed (Fig. 11).

Effect of Speed of Compression

The effect of the speed of compression was studied using three different speeds:

- in some tests the pressure was raised from 0 to 10 MPa in either 1.5 or 15 ms, during which the thickness of the sheet was continuously measured,
- in other tests the pressure was raised to a certain level in 1 s and kept there for 25 s before the thickness of the sheet was measured. Five different pressure levels were used: 0.5, 1.0, 2.0, 4.0 and 10 MPa. This type of compression is later called "static compression".

In the first type of test three different initial moisture ratios (4.2, 2.2 and 0.7) were used, but in the "static compressions" only the initial moisture ratio of 4.2 was used.

The chemical and mechanical pulps responded to changes in the speed of compression in a very similar way (Figs. 12 and 13). A higher compression speed always resulted in a higher resistance to dynamic compression. The effect was influenced by the moisture content of the sheets, being more pronounced at higher moisture content, although it was still clearly observable at the lowest moisture content studied. There was a dramatic difference between dynamic and static compressions.

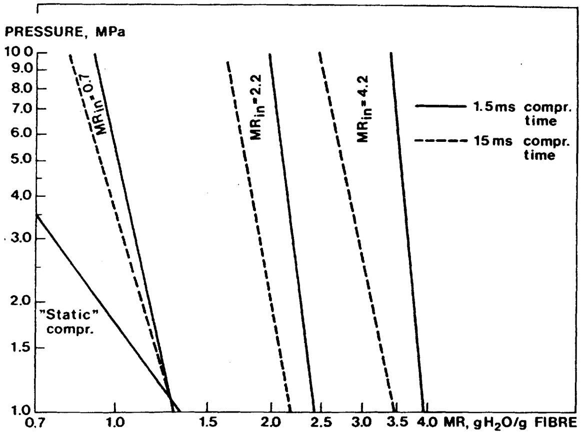

Fig. 12. Effect of speed of compression on the compressibility of the sheet. Unbleached pine kraft, CSF 475 ml, 100 g/m^2.

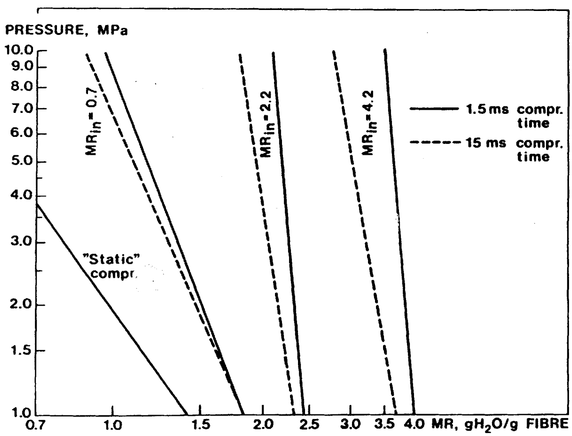

Fig. 13. Effect of speed of compression on the compressibility of the sheet. Pressure groundwood, CSF 102 ml, 100 g/m^2.

The effects of the factors studied are summarized in Table 3.

	High MR Resistance to compr.	High MR Hydr. pressure	Medium MR Resistance to compr.	Medium MR Hydr. pressure	Low MR Resistance to compr.
Increase in beating of chemical pulp (from 650 to 310 ml)	+++	++	+	++	-
Decrease in freeness of mechanical pulp (from 145 to 75 ml)	(+)	(+)	0	+	0
Increase in fibre stiffness (by 27% metal fibres)	0	-	++	--	+++
Decrease in fines content (by removal of 15% of the finest particles)	---	--	0	---	+
Increase in grammage (from 50 to 100 g/m^2)	+	++	+	+	0
Increase in speed of compression (from 1.5 to 15 ms compr. time)	++	+	++	++	+

Table 3. Effects of different factors on resistance to compression and hydraulic pressure

Effect of Properties of the Fluid in the Web on Compression

Because the presence of water had such a decisive effect on the dynamic compressibility of the sheet, it was desirable to have a clearer picture about the role of water properties in determining compressibility. It is generally assumed that the flow in the web during wet pressing can be described by Darcy's formula, and accordingly the only property of the water explicitly affecting the flow is its viscosity. To obtain experimental evidence of this, the viscosity of the fluid was changed over a wide range:

- by altering the temperature,
- by replacing the water by a series of Dextran solutions and
- by replacing the water by alcohols and hydrocarbons.

All these methods have their own advantages and disadvantages. Changing the temperature is a simple procedure, but the viscosity range so covered is narrow and at the same time other properties such as adsorption forces, water structure and surface tension also change. Using polymers, viscosity can be altered over a wide range. If the polymer is inactive, the fibre-water interaction may remain unaffected; overall, the fluid may keep its water-like behaviour. The disadvantage of using polymers is that replacing the water by a polymer solution is a laborious and time-consuming process in which the sample can be easily damaged; also, the large polymer molecules cannot penetrate into all pores. Hence the viscosity of the fluid is not constant throughout the structure. Various other compounds are also suitable for achieving a significant change in viscosity. Furthermore, it is a simple matter to replace water by other compounds. The fluid-fibre interaction may, however, be different for each compound, and this may have a significant effect on compressibility.

Dextrans were chosen as polymer because they are well known in paper science, and as they have been shown to be chemically and physically inactive towards fibre (18). Furthermore, it is also known what portion of the pore volume of the fibre network is not accessible by Dextran of a certain molecular size (19, 20). Dextran T10 and T2000 were used in the tests; T10 has a molecular weight of 11200 and a molecular diameter in water of 5 nm. The corresponding values for T2000 are $2x10^6$ and 56 nm. After the fluid change the amount of water not replaced by Dextran molecules was measured and found to be 0.5 ± 0.3 g H_2O/g fibre for T10 and 1.1 ± 0.5 g H_2O/g fibre for T2000. These values are reasonably close to those found in the literature (19, 20). This result shows that in the procedure used all the water located in pores bigger than the Dextran molecules was replaced by Dextran solution.

Before pressing the sheets were handled in such a way that their fluid content did not fall below 4 cm^3 fluid/g fibre. Thus the creation of surface tension forces, which tend to change the fibre structure, was avoided. A light microscope study of well fibrillated fibres (bleached pine kraft, CSF 310 ml) did not show any change in fibre structure caused by different fluids. (The adhesion of the solid surfaces depends on the thickness and the structure of the fluid layer adsorbed onto the solid surfaces (21). The more lyophilic the surface is, the smaller is the adhesion. The adhesion of hydrophilic materials may be increased by fluids with dehydration properties. Accordingly, the adhesion between the surfaces of the fibre material was probably smallest in water and highest in hydrocarbons. The higher adhesion might have led to the closing of some pores. However, this effect has not been studied in connection with wood fibres and is assumed to be negligible in our case.)

The sheets were made of bleached pine kraft pulp with a CSF of 475 ml and a WRV of 1.52 g H_2O/g fibre. The grammage was 100 g/m^2. Bleached pulp was chosen to avoid chemical reactions between the fibres and the different compounds.

The surplus of fluid (over 4 cm^3 fluid/g fibre) was first removed from the sheets by slow pressing; the test was then carried out using the pulse shown in Fig. 14. The thickness of the paper was recorded during the pulse and the total fluid removal (dMR) was determined by weighing. The thickness measurement was used to confirm the outgoing fluid content. The results are shown in Table 4.

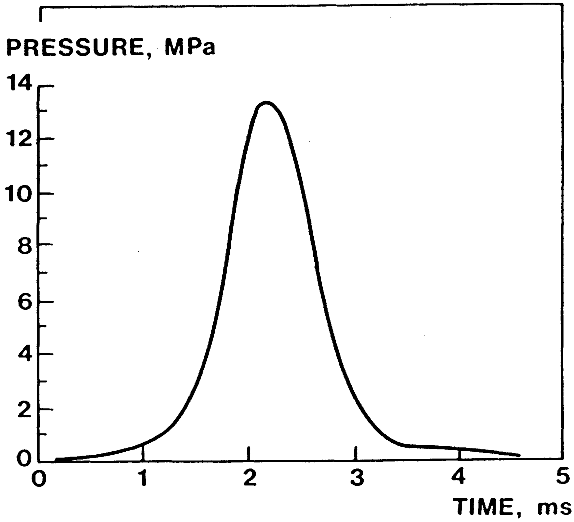

Fig. 14. Press pulse used in tests studying the effect of fluid properties.

Fluid	Viscosity mPa s	MRin cm^3/g	MRout cm^3/g	dMR cm^3/g
Distilled water	0.94	3.49	2.89	0.60
5% Dextran T10 in water	1.45	3.27	2.83	0.44
2.5% Dextran T2000 in water	3.67	3.48	2.89	0.59
5% Dextran T10 in water	1.45	3.55	2.90	0.65
0.7% Dextran T2000 in water	1.45	3.81	3.07	0.74
Distilled water at 23 °C	0.94	3.57	2.54	1.03
1.1% Dextran T2000 at 60 °C	0.92	3.50	2.34	1.16
1.1% Dextran T2000 at 23 °C	1.88	3.57	2.64	0.93
Distilled water	0.94	3.74	2.78	0.96
Methyl alcohol CH_3OH	0.60	4.03	2.50	1.53
Ethyl alcohol C_2H_5OH	1.20	4.07	2.77	1.30
Butyl alcohol C_4H_9OH	2.95	4.16	3.01	1.15
Heptane C_7H_{16}	0.41	4.27	1.35	2.92
Pentadecane $C_{15}H_{32}$	2.81	3.76	1.69	2.07

Table 4. Effect of fluid viscosity on fluid removal from the web

All the important factors affecting fluid removal were kept constant only within the groups separated from each other by spacing in Table 4. Thus the results can only be compared within the groups. Obviously, owing to the numerous phases of sample preparation, the scatter of the results was greater than in our other tests. A statistically significant distinction with 95% confidence can be made if the difference between dMR:s is greater than 0.1.

The differences in fluid removal between the various webs were smaller than the differences in the viscosity of the fluids in the webs. For example, the amount of methyl alcohol removed was only 33% more than that of butyl alcohol, although the viscosity of methyl alcohol is one-fifth of that of butyl alcohol. In another case the viscosity was reduced to one-half by increasing the temperature, but this increased water removal by only 25%. The change in viscosity in pores larger than 56 nm did not significantly affect water removal. Major differences were discernible between the various fluids, i.e. between water, alcohols and hydrocarbons. At the same viscosity the amount of alcohol removed was about 60% and the amount of hydrocarbon about 180% higher than that of water.

DISCUSSION

It is necessary to start the discussion by defining hydraulic and structural pressures as we understand them:

- Hydraulic pressure is the pressure created in the interfibre channels of the structure due to flow resistance. Hydraulic pressure is a true pressure and was measured in our tests in the boundary layer between the impermeable pressing surface and the web.

- Structural pressure is the difference between total and hydraulic pressures. Structural pressure is not the response of fibre structure alone to compression, but the response of a fibre-water association. The water in this association is equivalent to the bound water, and the water is in this respect bound if the forces acting on it are unable to separate it from the structure. The behaviour of the fibre-water association may also be affected by the proportion of water. Structural pressure is the sum of three factors: one arises from the mechanical stiffness of the fibre structure, one from the flow resistance inside the fibres and one from the forces needed to break the bonds between water and fibre material. Accordingly the pressure created by mechanical stiffness may differ significantly from the structural pressure. A maximum value of the pressure created by mechanical stiffness can be obtained by measuring the compressibility of the unsaturated web. On the other hand, measuring the structural pressure may be a very difficult task - in fact there is at present no known method for carrying out this measurement.

Something must also be said about the quantitative application of our results in practical situations. The tests were made using smooth and even pressing surfaces, and most of the pressure variations probably arose from the inhomogeneity of the paper web. In paper machine press sections the pressure is very unevenly distributed due to the many nonuniformities of the felts and the pressing surfaces. The uniformity of pressure may have a significant effect on the pressure arising at a given average density from the mechanical stiffness of the fibres and also on the magnitude of structural pressure at a given average density. The less uniform the pressure, the lower the average density at which a given resistance develops in the web. Thus the mechanical compression resistances developing in paper machine press sections may be higher than our test results at the same average density.

Mechanical Stiffness of the Web

As mentioned above, a rough estimate of the pressure created by mechanical stiffness is the pressure needed to compress the unsaturated web. In our study, at void volumes higher than about 1.0 cm^3/g this is the pressure needed to compress webs with a moisture ratio of 0.7. As the results show, the mechanical stiffness of the web is small up to a relatively high density, calculated in void volume to about 1.2-1.5 cm^3/g, but when the compression is continued further, stiffness rises quickly to high values (Figs. 1 and 2 and Table 2). The mechanical stiffnesses of the mechanical pulps and the unbeaten chemical pulps were about the same. The beating of chemical pulps greatly reduced their stiffness (Fig. 6), but the removal of fines affected it only slightly (Fig. 10). Thus the effect of beating on the mechanical stiffness of a sheet is primarily due to the increase in comformability and/or decrease in stiffness of single fibres.

Within the variation range relevant to practice, the mechanical stiffness of paper webs had no notable effect on compressibility down to a void volume of about 1.2-1.5 cm^3/g.

The compression resistance of the web was greatly affected by the speed of compression, even in cases when water removal did not occur (Figs. 12 and 13). In the case of "static" compression, for example, a void volume of 1 cm^3/g was achieved with a pressure of 2 MPa. For the same void volume a pressure of 9 MPa was needed when compression was fast, as in modern paper machines. This result confirms the viscoelastic nature of the mechanical stiffness, and also indicates that in the density range relevant to wet pressing, the elastic component of the mechanical stiffness is small.

Movement of Water Inside the Web

In our experience, down to a moisture ratio of about 1.2-1.5, the resistance to dynamic compression develops in the paper web mainly because water is relocated with respect to the fibres. The movement of water (or fluid) had only a minor effect on compression in the following cases:

- when the web was made of Dacron fibres (380 g/m^2 sheets were made of Dacron fibres with a diameter of 12 µm and a length of 3 mm),
- when unbeaten and dried chemical softwood fibres were used and
- when the water in the sheet was replaced by hydrocarbons.

In the cases listed above, the effect of fluid content on compressibility had almost completely disappeared, i.e. the dynamic compression curves for sheets with the initial moisture ratios of 0.7 and 4.2 were very similar (Fig. 6). One interpretation of the behaviour of sheets containing hydrocarbons will be discussed later in this paper. Common features of the Dacron and unbeaten dried fibre sheets were that their fibres were unfibrillated and unswelled and that they contained only a small amount of fines. (The WRV of unbeaten dried UBPK pulp was about the same as the WRV of PGW pulp!) The removal of the finest particles from a beaten pulp also significantly reduced its resistance to dynamic compression during water removal (Fig. 10), but this effect was much smaller than those listed above. The difference between sheets made from fractionated pulp and those made from unbeaten dried pulp shows the effect of fibrillation and swelling. These results indicate that the difficulty in achieving compression is at least partly due to the fibrillated structure of the fibres, the existence of fines and swelling of the fibre material.

Theoretically, a high mechanical stiffness could improve compressibility at high moisture contents, because high stiffness makes the creation of the z-direction density gradient more difficult, and most of the flow resistance may develop in the densest layers of the sheet. But as the results with sheets containing metal fibres show (Fig. 8), the attainment of this kind of situation is difficult; despite the unusually high increase in mechanical stiffness, the compression of the web was no easier at a moisture ratio of 4.0.

It is interesting to note that the water retention value correlated with the compressibility inside the same pulp, e.g. inside unbleached pine kraft. But when mechanical pulp was compared with chemical pulp, the correlation between WRV and compressibility disappeared. In the procedure used to measure WRV, the driving force for water removal is the centrifugal force, which creates a pressure difference across the fibre mat. Compared to the situation in wet pressing, the magnitude of this pressure difference is smaller and the dwell time longer. Obviously, during measurement of WRV, all the water which is bound to the fibre material with a force higher than the centrifugal force remains in the fibre mat. The amount of retained water is not affected by the distance the water has to travel to get out of the mat. The binding force is affected by adsorption and capillary forces. The capillary pressure (p) can be estimated by the following formula:

$$p = (2 \gamma \cos \Phi)/r, \text{ where} \qquad (2)$$

γ = surface tension
Φ = contact angle
r = radius of capillary

The flow through capillaries (V), which in turn must correlate with compression, can be described using Poiseuille's formula:

$$V = (\pi p r^4)/(8 l \eta), \text{ where} \qquad (3)$$

p = pressure difference over the capillary
r = radius of capillary
l = length of capillary
η = viscosity of water

Thus a significant part of the water retention value may be inversely proportional to the size of the pores, and may be unaffected by the distance of the flow. In dynamic compression the flow basically depends on the fourth power of pore size and is inversely proportional to the distance of the flow. For example, the WRV may be high if the web contains a lot of small pores, but compression may still be easy if at the same time the distance of flow is short.

Another interesting observation in connection with WRV was that around the moisture ratio equivalent to WRV, no change in the compression behaviour was discernible. At this point the size of pores changes considerably, by 1-2 orders of magnitude, and the flow resistance is greatly dependent on the size of pores. If most of the work was consumed by counteracting the flow resistance, then, despite the inhomogeneity typical of the paper web, the change in behaviour would be expected here.

The similar behaviour of pulps PGW 1 and "UBPK beaten 2" also supports the observation that very different structures may yield the same end result. Unbleached kraft pulp was probably difficult to compress because of pronounced swelling, whereas PGW was difficult to compress because of its small particle size.

In the study of the effect of water properties, the test conditions were chosen so that the compression would have been controlled - as is at present understood - by the flow resistance in the interfibre channels. If the flow in the web is described by Darcy's equation, significant differences in water removal would have been obtained in accordance with the differences in viscosity. This, however, was not the case. Higher viscosity resulted in less water removal only in cases where the change was made within the same type of fluid, e.g. alcohols. It is concluded, therefore, that fluid properties other than viscosity must also have a significant effect on the compression of the paper web. Comparing the compression of sheets containing water, alcohol and hydrocarbon showed that the effect of the type of fluid was more significant than that of viscosity. At the same viscosity the amount of alcohol removed was 60% higher than that of water and the amount of hydrocarbon 180% higher. The replacement of water by other fluids was carried out in such a way as to preserve the pore structure of the web, thus preventing structural changes from being the main source of the differences. Mechanical stiffness was significantly affected by the change of fluid (Fig. 15), but, as the sheets strengthened by metal fibres showed, stiffness had only a minor effect on compression when the fluid content was high.

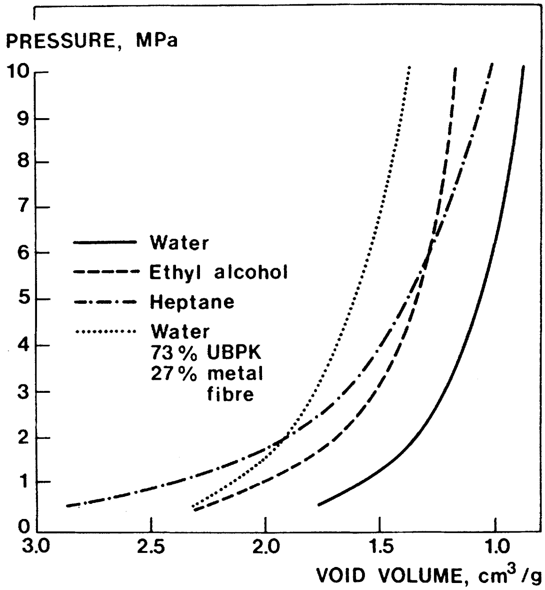

Fig. 15. Compression of sheets containing different fluids. Ingoing fluid ratio 0.7 cm^3 fluid/g fibre. Bleached pine kraft, CSF 475 ml, 100 g/m^2. Compression time 1.5 ms.

There are essential differences in the interactions between the fibre material and the various fluids. According to the latest measurement published, 1 g of fibre is able to limit the mobility of 2.2-2.9 g of water (22). Of this amount about 1.2-2.0 g (18, 19 and 20) is accommodated in pores smaller than 56 nm. Because the surface tension of water is high and the surfaces of fibres (and fibrils too) are hydrophilic (23), high capillary pressure may develop in such pores if they are filled with water and if water-air interfaces exist. (Because compression is fast, part of the air is probably unable to leave the web and water-air interfaces exist in wet pressing.) The amount of water bound with Van der Waals forces to the fibre surfaces is approx. 0.4 g/g fibre (24 and 25). Some of the bindings (probably Van der Waals forces and also some of the capillary forces) may resist the forces acting in wet pressing, thus reducing the area available to the flow. Other bindings break, and this is responsible for some of the work consumed during wet pressing. The presence of alcohol in the sheet instead of water means less solvation of the fibre surfaces and smaller capillary forces, while Van der Waals forces and the surface tension are smaller. (An indication of the magnitude of Van der Waals forces is the relative permittivity of the material, which for water, alcohols and hydrocarbons is 80, 18-33 and 2,respectively.) The loosening of the association continues further with hydrocarbons as Van der Waals forces are even weaker than those in webs with alcohols and the fibre surfaces are lyophobic. The surface tension of hydrocarbons is similar to that of alcohols.

From this, the differences in fibre-fluid interactions would seem to be the most likely reason for the very different compression behaviour of sheets containing different fluids.

Because the fibre-water interaction seems to have such an important effect on the dynamic compressibility of the paper web and as wet pressing is carried out in practice over a moisture ratio range in which almost all the water is somehow bound to the structure, models of wet pressing should also include the effect of binding. Our experience indicates that a significant proportion of the work done during wet pressing may be consumed by the breaking of fibre-water bonds. Another problem in constructing a model of wet pressing may arise from the fact that not all the water is bound to the structure by the same forces; in fact, the strength of the bonding varies over a wide range (18). A certain bonding strength only resists forces smaller than a certain limit. The smaller the hydraulic pressure drop over a layer of fibres, the higher the amount of water that remains attached to the structure. Consequently the cross-sectional area of the channels available for flow is smaller. By increasing the hydraulic pressure drop (e.g. keeping the impulse constant and increasing the total pressure) some water that previously belonged to the structure becomes detached and the area of the flow channels increases. Ceckler et al. (26) introduced the concept of incipient crushing, which is a macro-scale structural change caused by a large hydraulic pressure drop. The phenomenon explained above is similar to incipient crushing in that it is also a change in the structure of the fibre-water association due to a hydraulic pressure drop. But the change appears on the micro-scale and affects mainly the water part of the association, leaving the fibre structure practically unaffected. In our tests in which the impulse was kept constant, the pressings carried out at higher pressure in most cases gave higher water removal. This effect may be a further indication of the significance of the above mentioned mechanism, i.e. the higher pressure drop probably yielded a larger area for the flow and so increased the permeability. Studies carried out earlier imply that the permeability coefficient is affected only by the density and is independent of the hydraulic pressure drop over the fibre mat (27 and 28). This statement is probably valid under the conditions used in the studies cited, i.e. when the flow is slow, of long duration and steady. But in wet pressing, where the pressure develops explosively and the flow lasts only for 1-2 ms, the behaviour of the fibre-water association may in this respect be significantly different.

If the permeability coefficient during wet pressing is affected not only by the density but also by the hydraulic pressure drop, as our experience implies, then the use of Darcy's formula to describe the flow in the web in this phase of the process becomes extremely complicated.

CONCLUSIONS

Water removal in the press section of paper machines starts at a moisture ratio of about 4.0 and is completed at a moisture ratio of about 1.0. In this process, down to a moisture ratio of about 1.2-1.5 the movement of water in relation to the fibres plays a decisive role in the development of compression resistance. Up to this point the mechanical stiffness of the structure is negligibly small, but increases quickly after that and soon becomes significant. Mechanical stiffness has a visco-elastic nature and the contribution from the elastic component in the density range relevant in wet pressing is small.

As far as mechanical stiffness is negligible, the difficulty of compression is due to the fibrillation and swelling of the fibres, and the existence of fines and water-fibre interaction. In this range, a decrease in bonding forces or simultaneous reductions in fibre surface area and swelling would be the most effective way to reduce dynamic compression resistance. As the measurement of the hydraulic pressure and also the comparison of unbeaten and fractionated pulp sheets indicated, at high moisture contents the interfibre flow consumes most of the work done in pressing. It appears that as the moisture content decreases, the role of intrafibre water movement gradually becomes more important. In the case of beaten chemical pulp with a CSF of 475 ml at a moisture ratio of 2.2, it already has a decisive role. In mechanical pulp sheets the hydraulic pressure remains high up to lower moisture contents, i.e. the importance of intrafibre water movement there appears later.

Indications were obtained that the use of Darcy's formula for describing the flow in the web during wet pressing is more complicated than so far understood:

- despite the decisive role of water movement the effect of viscosity was weak, and in most cases the impulse alone did not determine water removal, which was also affected by the level of pressure,
- the binding of water to the structure seemed to have a significant influence on resistance to dynamic compression.

After Wahlström introduced his wet pressing theory, the pressure in the compressed web was divided into two components: hydraulic and structural pressures. This division was useful and clearly understandable as long as the structural pressure was considered to be purely mechanical and the hydraulic pressure consisted of all the forces necessary to overcome the flow resistances. First Carlsson and coworkers (29) showed that part of the compressing work is consumed by the flow resistance inside the fibres, which evidently belongs to the structural pressure. The present study revealed that fibre-water bonds also play an important role. It is still possible to define structural and hydraulic pressures as earlier in this paper. This division facilitates our understanding of compression behaviour, but the theoretical prediction of the other component - structural pressure - does not seem much simpler than that of the total pressure. The dynamic compressing force is balanced in the paper web by the following factors:

- the flow resistance in the interfibre channels,
- the flow resistance inside the fibres,
- the resistance against the separation of associated water from the fibres and
- the mechanical stiffness of the fibre mat.

This division would also be a possible approach to a systematic analysis of the compression behaviour of the web.

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Transcription of Discussion

COMPRESSION BEHAVIOUR OF FIBRE MATS IN WET PRESSING

Z. Szikla and H. Paulopuro

B. Wahlstrom, Consultant

I have a question regarding the binding forces of water to the cell wall. Obviously, the effect of water on cellulose is a part of that phenomena, and removing water from the fibre wall is a combination of flow resistance and these forces you have talked about. I have difficulty in believing the fact that you can get straight lines of the relationship between press impulse and moisture ratio independent of whether you go from an unsaturated to a saturated condition, unless the same kind of phenomena controls through the whole range. How do you explain that with your model?

Z. Szikla The Finnish Pulp and Paper Research Institute

We cannot really explain this, and were surprised ourselves. It implies that the mechanisms are the same or at least similar. We have thought about it, but cannot find any other reasonable answer to this question.

Prof. B. Steenberg, Royal Institute of Technology

I like your explanation of the chemical relationships between fibres and water. We have in this case a polyelectrolyte, and if you have a flow through a capillary, which is electrically loaded, you get an electrokinetic potential and this prevents flow. I guess that one of the reasons why you get this effect with water, less with alcohol and practically nothing with hydrophobic substance is that you are moving liquid over an electrostatic layer and try to move the ions against each other which sets up a very high streaming potential, and of course prevents the flow. That is the chemical way of describing what you have done.

Dr. J.D. Lindsay, Institute of Paper Science & Technology

In your compression experiments, is the paper sample undergoing compression between two impermeable surfaces or is there a permeable receiver below it?

Z. Szikla

There is a permeable receiver on the other side of the paper.

Dr. J.D. Lindsay

Does the nature of that permeable receiver have much influence on your results?

Z. Szikla

It affects the thickness measured, but this is the subject of some other work, which I do not wish to talk about. It has no effect on the work I have described here.

Dr. J.D. Lindsay

We heard from M. MacGregor about the importance of in plane flows or pressure gradients in the plane. What size were your paper samples, and did you see any evidence of in plane flow or water squirting out of the edges when you reached peak hydraulic pressure?

Z. Szikla

As I remember it, the size of our samples was 70 mm x 70 mm or in some cases 50 mm x 50 mm.

Dr. J.D. Lindsay

Would you get different results with different sizes of disc?

Z. Szikla

Not in this case.

Dr. J.D. Lindsay

So, you do not believe that you saw any evidence of in plane flows which would affect your results?

Z. Szikla

No, I did not.

Zoltan Szikla (Prepared Contribution)

In my prepared contribution I would like to add some information to the discussion around the platen press as a tool of wet press research.

In this respect First I would like to point out that the simulator is not a copy of the real equipment. The simulator fulfils this requirement only if the changes of its outgoing variables resulting from a certain change of the ingoing variables are equivalent to the change of outgoing variables obtained in the simulated equipment by the same action.

In the Finnish Pulp & Paper Research Institute we made extensive research with platen press type simulators. Before the start of the program we studies the water flow behaviour, made some rough calculations and concluded that the main direction of flow is perpendicular to the sheet plain. Then we built our simulators, test them against a paper machine and found good correlation.

Thus we believe that a platen press simulator is a suitable device for wet press studies, if designed and built properly. The platen press simulator is probably not able to simulate the wet pressing process in its entirety at the same time, but it is certainly a useful device to study most of the mechanisms individually. For example, to study the dynamic compression, the effect of press parameters, felt, beating, furnish, chemicals, etc. on water removal or quality.

The non planar shape of pressing is usually highly exaggerated in the drawings made to illustrate the situation in roll presses. We have to remember that the sheet has a thickness of approx. 10^2 µm and the roll diameter is approx. 10^6 µm.

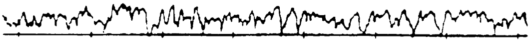
Even in platen presses the problems relating to the measurements are difficult to solve. In connection with the thickness measurement one difficulty comes from the roughness of the permeable material. The paper tries to intrude into the pores if they are too large, and the measured thickness becomes smaller than it is in reality. The roughness of the plate we were using is shown in Fig. 1. In the figure the roughness of standard machine calendered newsprint and some characteristics of the plate are also shown. The effect of roughness was measured and shown in Fig. 2. It indicates, that already a plate with 19µm pores can give false thickness results. The roughness of commercial felts is so high (Fig. 3 and 4) that the measurement of paper thickness using a differencing method is not possible.

In connection with the measurements it is also important to have the capability to detect those time differences which come from the measuring system, (Fig.5).

Despite the difficulties it is possible to measure the hydraulic pressure developed in very thin sheets, eg. in newsprint, (Fig. 6).

Profile of standard newsprint:

Profile of porous plate used in thickness measurement:



Properties of plate:

- absolute filter rating 11 µm (average pore size appr. 7 µm)
- permeability factor $5.4 \times 10^{-12}\ m^2$) (paper $10^{-13} \ldots 10^{-15}\ m^2$)

Fig 1

Effect of roughness of permeable surface on paper thickness measured by differencing method:

Aver. pore size of permeable plate µm	Measured thickness µm
2	76.2
7	78.3
19	68.5

Fig 2

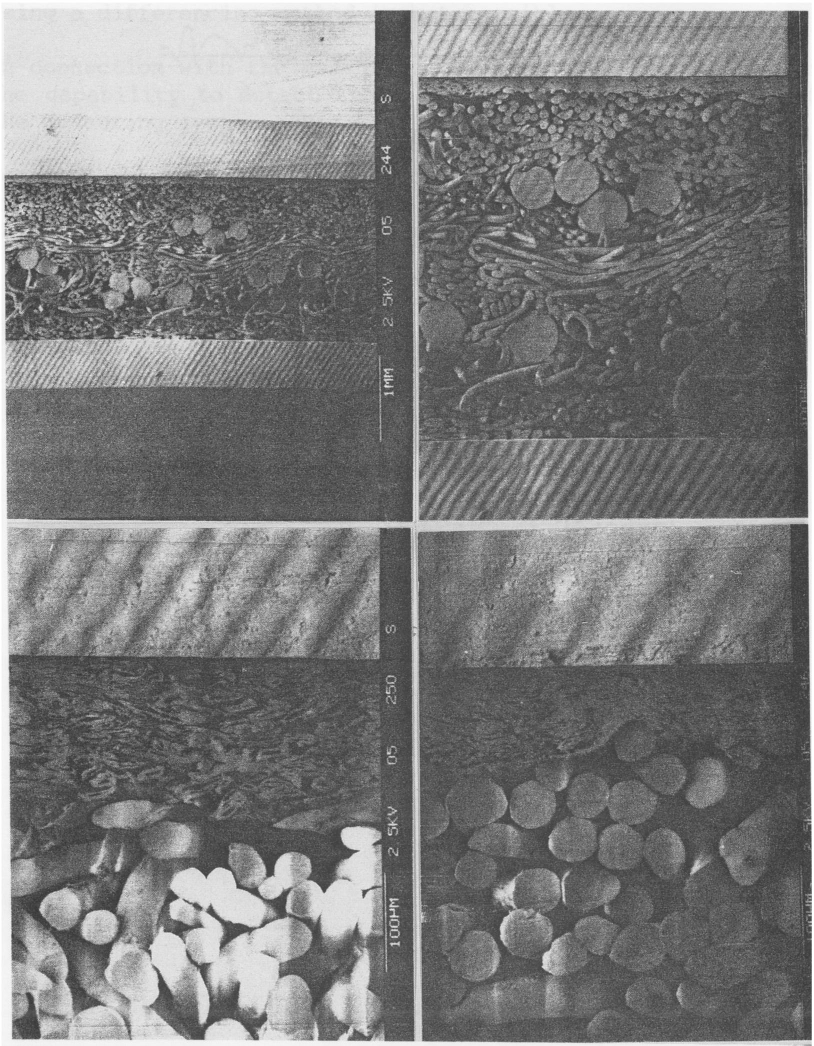


Fig 3

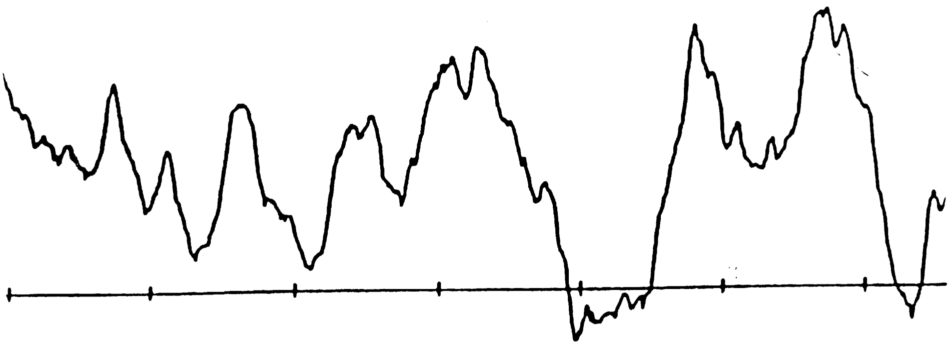


Fig 4

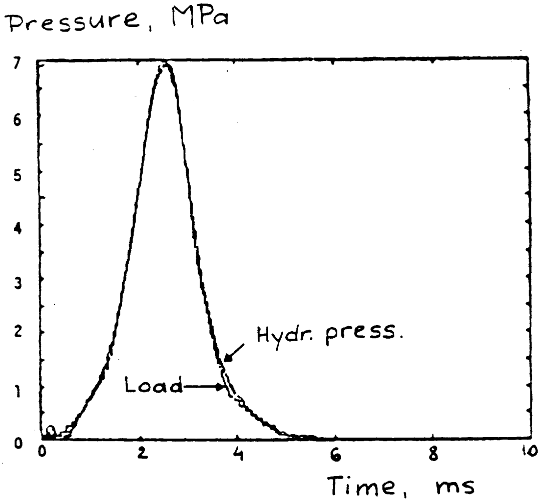
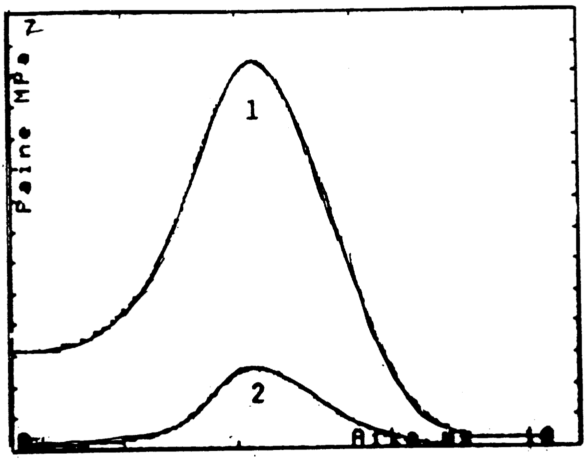


Fig 5

NEWSPRINT 48 g/m^2

MR_{IN} = 1,33

MR_{OUT} = 0,83



1. TOTAL PRESSURE

2. HYDRODYNAMIC PRFSSURE

Fig 6