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EXTENSIBLE PAPER BY THE DOUBLE-ROLL COMPACTING PROCESS

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Synopsis—After a review of the development of extensible papers, a description of the double-roll compacting process and its variables is given. Its principal feature is the venturi section formed in the nip between a rubber and a steel roll, between which the paper web passes in a semi-dry state. On running the rubber roll more slowly than the steel roll, the web will shrink in the machine-direction. Experiments on a pilot machine showed an increase in the compacting effect with increasing nip pressure and speed difference, though with certain limitations. When considering nip width and peripheral speed difference as primary variables, however, linear relationships with the paper properties were found. The nip width will vary with the nip pressure and rubber thickness and hardness.

The mechanism of double-roll compacting is considered to involve tangential forces, which move the rubber towards the back side of the nip, where it contracts, thereby shrinking the web. The structure of the resulting extensible paper was examined by photomicrographs of surface and cross-sections, by measuring the thickness changes on stretching and by load elongation measurements. The fibres appear curved after the compacting operation. This will result in the breaking of bonds when stretching the paper and in an ultimate breaking load lower than for flat kraft. The total rupture energy, however, is considerably higher.

An apparent increase in the rubber roll diameter on increasing nip pressure was observed. This will cause a decrease in the mean speed difference at the nip. At a limited set speed difference, the rubber roll was found to change from being driven to be driving on increasing the nip pressure. In an appendix, the nip width and the slip have been treated theoretically as well as experimentally.

Introduction

THE importance of high stretch in a kraft paper has been demonstrated by several investigators, correlating field performance[1, 2] or drop tests[3] of paper sacks to paper properties. Before this experimental evidence was obtained, papermakers had for half a century endeavoured to impart higher stretch to their papers, as shown in the patent literature.[4–7] Creping from a Yankee cylinder is known to give a higher stretch without substantially improving the paper strength; creping from the last wet press was developed in Germany for sack paper. The corresponding patent[8] does not cover the creping process, but the converting of paper with 5–18 per cent machine-direction stretch to sacks. In a more recent method of creping, the Duostress process,[9] a paper web is creped from a drying cylinder at a moisture content of 30–40 per cent, subsequently crinkling it in the machine-direction to improve the sheet stiffness in the machine-direction.

Other patents of interest in this area are Lemberg[4] and a Swiss patent [12] translated as follows—'The moist paper web is put in contact with at least one elastic surface, which during the time of contact changes its dimensions, whereby the paper web follows those changes.' An early application of textile shrinkage machinery[10] was for sanitary paper.[11]

To achieve an improved stretch, but maintaining an essentially smooth surface for better printing quality, additional lengthwise compacting processes were developed. The compressive shrinkage machinery was commercially adapted to paper in 1957 by Cluett in co-operation with West Virginia Paper Co. That development used a rubber blanket for the elastic surface, whereas a compactor with the rubber fixed to a roll was put in production by Scott Paper Co. Both are licensed by Clupak Inc. The paper produced has to meet certain specifications to be marketed under the Clupak trade mark.

Both the blanket and the double-roll compactor can be regarded as a venturi section, consisting of two hard surfaces into which an elastic material like rubber is fed together with the moist paper web. The elastic material is stretched before the nip and will contract after it. The paper web will follow the contracting rubber surface and slip against the hard surface.

The venturi section is shown in Fig. 1. For wrinkle-free operation, a certain draw has to be maintained on running the web into the press and a positive draw must be kept up on the back side of the press. As the paper web becomes shorter in the nip, the draw there must be negative, as indicated in the figure—the paper is progressively shrunk. The exact mathematical form of the region with negative draw is not known. Its extension must, however, be influenced by the nip pressure, the nature of the materials facing the web, the web moisture content, the draws on both sides of the press, etc.

The products made by the two compacting processes and the shrinking mechanism in the venturi section are essentially equal as has been described in a previous paper.[14] In the present paper, the discussion will therefore be concentrated on the double-roll compactor, which is considered to have operational advantages. Some of the results obtained may, however, have a more general interest for other press applications in papermaking. The studies were made on a 50 cm wide experimental unit (see Appendix 1) in a joint research effort of Billerud AB, M. Peterson & Sön A/S and Uddeholm AB. Experience from their commercial units has also been considered.

Variables of the double-roll compactor

Fig. 1 is taken as a starting point for the analysis. The nip width is at work considered to consist of two regions—the first one *AB*, being locked and not

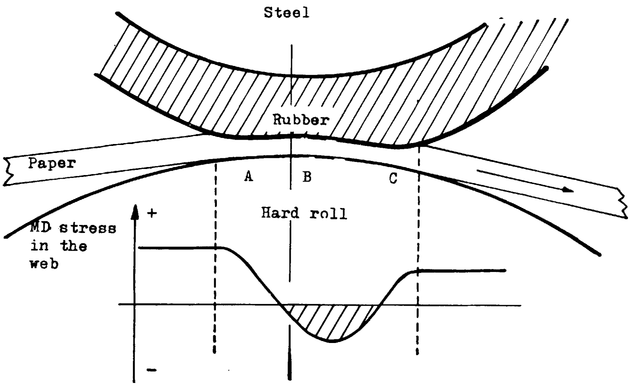


Fig. 1—The pressure nip schematically represented as a venturi section

allowing slippage; in the following region *BC*, where the draw is negative, shrinkage will occur. The width of the two zones will be influenced by—

1. Roll speed difference.
2. Nip pressure.
3. Rubber thickness.
4. Rubber hardness.
5. Friction forces between steel roll and paper.

At a given equipment set-up, the main variables should thus be the pressure and the speed difference applied. This was checked on a virgin wet web of Scots pine kraft paper, formed on an experimental Swedish machine.(15)

The paper was dried to 40, 35 and 30 per cent moisture content and reeled in this wet state. Normal flat kraft paper was also run from the same stock and dried to 5 per cent moisture content. The beating was set to give a TAPPI porosity of 20 or 30 sec, tested on the dried paper. The sheet basis weight was about 70 g/m^2. The compacting was done within a week, both with the virgin wet webs and with the dried paper after rewetting to the same moisture levels.

Three speed differences were used—6.7, 9.3 and 11.9 per cent, calculated from the roll peripheries with no pressure applied. The machine speed was 23 m/min and the web was subsequently dried to 6.0 ± 0.5 per cent moisture. Seven pressure levels were used for each speed difference. The draw after the press was kept at 0 or 3 kgf/m.

Fig. 2 shows the machine-direction stretch of one of the papers as a function of the pressure, using the speed difference as parameter. The stretch increased with pressure and speed difference. At the low level of speed difference, however, a maximum in stretch was obtained at a pressure of about 10 kgf/cm. This graph shows in principle the effect of the main variables, but tells little about the mechanism of the process, which will now be considered.

Since each roll is driven at a constant number of revolutions, giving different peripheral speeds, slippage must occur somewhere. The mean value of the speed difference at the nip could be one of the main factors governing the

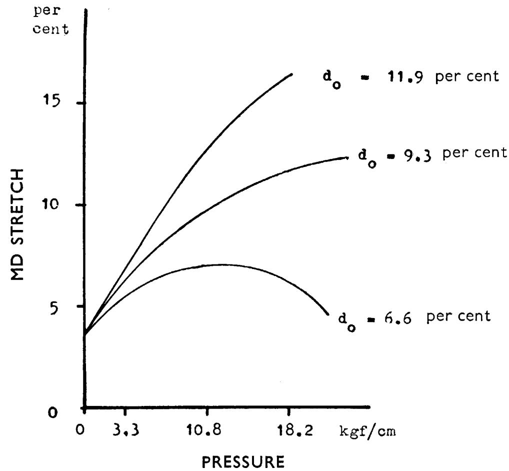


Fig. 2—Results of MD stretch plotted against linear pressure with the speed difference as parameter from a test run with virgin wet (35 per cent moist) paper web

process (Appendix 2). The roll pressure applied perpendicularly to the web cannot be directly responsible for the lengthwise compaction. The nip width was considered instead to be one of the primary factors in the compacting mechanism, which are influenced by the pressure. The paper properties were therefore plotted against the product of nip width and mean speed difference (Fig. 3). The nip width was determined in separate experiments, at zero speed and varying pressure, by using a heat-sensitive paper (Appendix 2). The paper properties tested were breaking length, stretch and rupture energy. They were determined on 15 mm × 100 mm paper strips at a rate of elongation of 30 mm/min. The rupture energy was referred to a basis weight of 100 g/m^2 throughout (in analogy to the tear factor) to obtain comparative figures for paper of varying substances caused by the compaction.

The calculated linear regression coefficients for the relationships shown

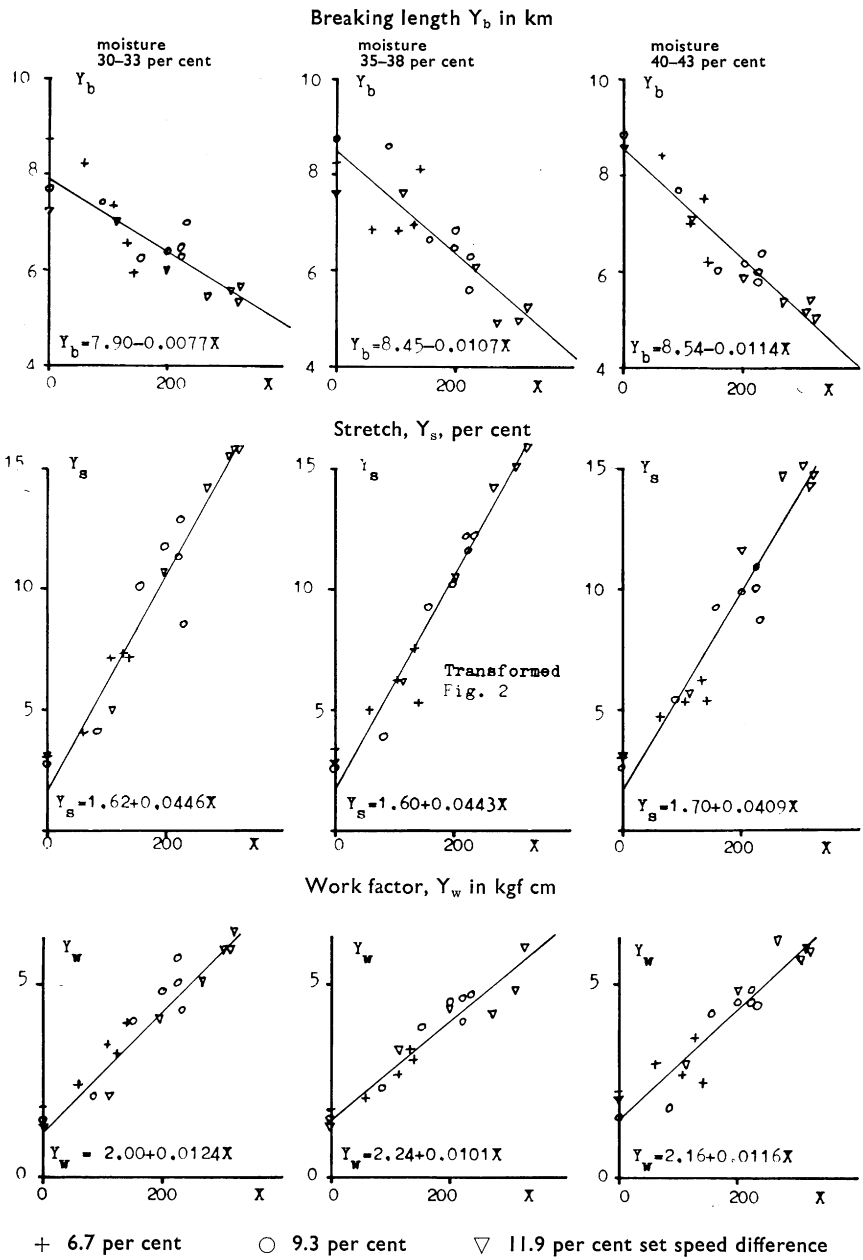


Fig. 3—Results from test runs with virgin wet kraft paper, 70 g/m²—paper properties *Y* in the machine-direction graphed against the product *X* of the mean speed difference in the nip and the nip width: rubber roll diameter 415 mm, 50° Shore; steel roll diameter 600 mm, speed 23 m/min

in Fig. 3 have been given in Table 1, using the general equation—

$$Y_i = A_i + B_i \cdot X$$

where Y_i denotes the paper property and X the product of nip width and mean speed difference. The following observations can be made—

1. The increase in stretch was lower for the highest web moisture content than for the other two moisture levels, whereas the rupture energy was less dependent on the moisture level of the compacting operation.
2. Beating did not significantly influence the relationship in the range studied.
3. Basically, the same conclusions could be drawn from experiments with rewetted paper as with virgin wet webs, the former being easier to prepare.
4. The compaction always led to a decrease in tensile strength, but an increase in stretch and rupture energy. This applies to machine-direction (MD) properties. Some decrease in tensile strength was experienced for the cross-direction (CD) properties, which was compensated by a slight increase in stretch, leaving the rupture energy nearly unchanged. Since the working width was only 50 cm, the observations on CD properties must be judged with caution.

TABLE 1—REGRESSION COEFFICIENTS A_i AND B_i IN THE LINEAR RELATION $Y_i = A_i + XB_i$ BETWEEN PAPER PROPERTY Y_i AND THE PRODUCT X OF NIP WIDTH AND MEAN SPEED DIFFERENCE

	Moisture content, per cent	*Air permeability, sec*	*Breaking length, km*		*Stretch, per cent*		*Work factor, kgf cm*	
			A_b	$B_b \times 10^4$	A_s	$B_s \times 10^4$	A_w	$B_w \times 10^4$
Web unstressed after the compacting press	VW 31	30	7.90	−77	1.62	446	2.00	124
	VW 35	30	8.45	−107	1.60	443	2.24	101
	VW 42	27	8.54	−114	1.70	409	2.16	116
	VW 35	16	7.84	−94	1.87	412	2.06	108
	RW 31	30	7.71	−75	1.50	402	1.91	81
	RW 35	30	8.17	−115	1.17	337	2.03	70
	RW 42	27	8.16	−105	1.44	294	1.95	67
	Mean of standard error	VW	0.12	−13	0.32	35	0.10	10
		RW	0.09	−8	0.33	26	0.09	6
Web stress 3 kgf/m after the compacting press	VW 31	30	7.88	−60	1.06	288	1.94	97
	VW 35	30	8.64	−84	1.46	313	1.89	103
	VW 42	27	9.00	−102	1.08	247	1.75	84
	VW 35	16	8.15	−77	1.06	292	1.57	97
	RW 31	30	7.85	−58	1.54	253	1.78	65
	RW 35	30	8.49	−97	1.62	153	1.62	62
	RW 42	27	8.84	−106	1.53	122	1.82	30
	Mean of standard error	VW	0.12	12	0.22	25	0.10	10
		RW	0.16	15	0.23	23	10.13	13

VW = Virgin wet web RW = Rewetted web

The influence of the rubber thickness was studied, using rewetted paper with a substance of 70 g/m^2, 35 per cent moisture content and 12 per cent set speed difference. The rubber roll had a core of 32.0 cm diameter and an initial rubber thickness of 4.5 cm. After each run, some rubber was ground off, leaving progressively a thickness of 3.4 cm, 2.4 cm and 1.3 cm. Then with varying nip pressure, the paper properties were found to be related to the nip width and speed difference as before. A linear relationship was obtained when plotting the properties against the product of mean speed difference and the square root of the nip pressure (Fig. 4). The latter factor has been found to be proportional to the nip width (Appendix 2). As some pressure is needed to create a locked region, the results at zero pressure are indefinite. The linear relationship will start instead at a higher pressure, here 3 kgf/cm. Thus, at least at a machine speed of 23 m/min, the rubber thickness did not influence the relationship, which corroborated the assumption of nip width as a primary variable.

In the same sense, the rubber hardness should also be reflected in the nip width and a soft rubber roll was found to be more efficient in compacting, although for durability a hardness of 45–55° Shore has been found suitable.

The previously described trials were performed with an electrically heated steel roll, the surface of which was only turned and not polished. The distance between the grooves was 0.3 mm and their depth about 0.05 mm. With a polished steel roll, difficulties were experienced in the compacting of moist webs, particularly with hard rubber rolls. The web tended to stick to the steel cylinder, in a similar way as to a Yankee. When running with cold rolls, the moistest web slipped on the polished surface, the excess water acting as a lubricant. The grooves of the rougher roll may serve as receivers of this excess water and make the process less sensitive to moisture variations in the web. They can also be made coarse enough to give an embossing effect along with the compacting, which might possibly increase the paper MD stiffness.

The experience referred to is contrary to the statement(16) that the steel roll should preferably be chromium-plated to allow the web to slip easily. With the grooved roll, not only kraft paper, but also greaseproof paper, magazine paper and newsprint were easily compacted, using either a rubber roll or a blanket against it.

Conclusions about the mechanism of the double-roll compactor

OWING to friction between the hard and the soft roll, tangential forces will deform the soft roll, the surface of which will be stretched on one side and compacted on the other. The nip can be divided into regions, where the surface speed of the soft roll is positive, zero or negative relative to the hard roll. On double-roll compacting, it is believed that, on the entering side of the

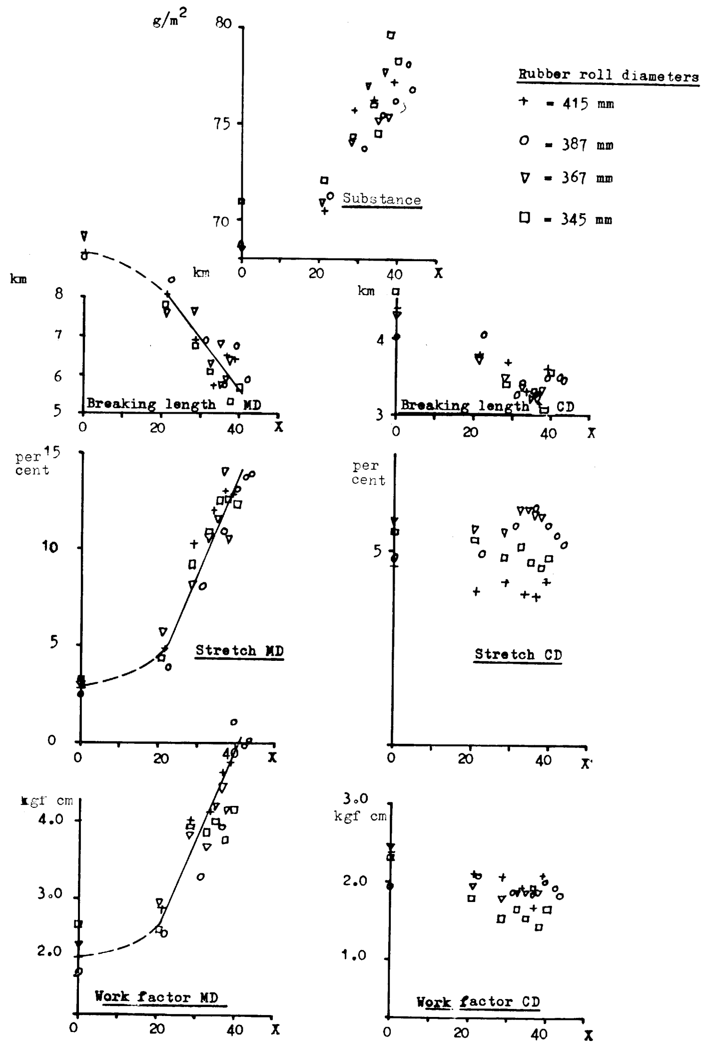


Fig. 4—Results from test runs with one rubber roll, the rubber thickness being varied by grinding—rewetted kraft paper originally of 70 g/m² used; steel roll speed about 23 m/min and set speed difference 12 per cent: paper properties are graphed against the product *X* of the mean speed difference and the square root of the linear pressure

nip, a region with zero difference is found and, on the back side, the rubber will move at varying rate in the opposite direction to the steel roll.

When the set speed difference is increased, the zero difference region—where the paper is locked between two equally moving surfaces—will decrease. At a certain difference, the locked surface will be too small to maintain the draw into the press, the other variables being constant. No compaction will then take place and the paper will slip against both rolls (for the pilot plant press, this critical set speed difference was found to be about 18 per cent).

The rubber moving towards the nip centre will push the paper against the locked area. Thus, compaction of the web will take place when the rubber moves back to its original position at the roll core. The hot steel roll will exert less friction, possibly because of Leidenfrost phenomena lubricating the contact with the paper web. When using a slightly grooved steel roll, an essentially flat paper surface will finish up in hills and in being creped in the grooves, where the pressure in the z-direction is too low to prevent crinkles appearing.

The width of the two regions together with the mean speed difference at the nip will determine the compaction process. The mean speed difference can be calculated from the set speed difference and the apparent increase in rubber roll diameter.

Full-scale operation

THE process was found to follow the same rules on full-scale trials as in the laboratory. With set speed difference of 9.6 per cent, the MD stretch increased from 7.9 to 9.6 per cent; the MD stretch increased from 7.9 to 9.5 to 11.3 per cent when the pressure was increased from 18 to 20 to 22 kgf/cm. As in the pilot plant case, a too-polished surface caused difficulties and a too-dry web at compacting gave rise to crinkles in the paper.

It has also been possible to calculate directly the necessary power consumption in full-scale operation from test runs in pilot plant trials, but these results will be reported elsewhere.

A new element for pilot operation is introduced when the width of the web increases—that is, the variation in paper properties across the machine. On increasing the draw after the compacting press, but maintaining the speed difference between the drying sections and the press, the mean CD stretch was increased. This increase will mostly be found on the edges, causing an increase in variation across the machine width. Generally, however, a slight improvement in CD stretch followed the lengthwise compaction.

Structure and properties of compacted papers

THE surface structure of some typical lengthwise compacted papers are demonstrated in Fig. 5. For comparison, one normal flat kraft, one wet-creped kraft, one blanket-compacted and one roll-compacted kraft are shown.

The photographs were taken in oblique light. Whereas the surface of the first paper appears essentially smooth and that of the creped paper has a marked crinkled structure, the two compacted papers represent an intermediate structure, with little difference between the two processes. It should be pointed out that considerable variations in the surface structure of compacted papers occur because of process variations. A drier web has been found to give a paper with a more pronounced surface structure after compaction (Fig. 6).

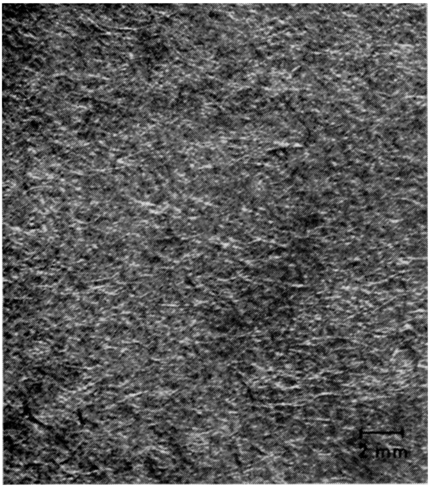
The fibre arrangement in the *z*-direction is clearly demonstrated by cross-sections cut in the machine-direction (Fig. 7). The same papers were studied. Flat kraft paper is characterised by almost straight fibres arranged in parallel, in contrast to the rough and occasionally broken structure of the creped paper. The two compacted papers display a structure of fibres curved in the *z*-direction. With the naked eye, however, the surfaces may be judged as essentially smooth.

Evidence for the internal structure of compacted papers are the changes in thickness shown on stretching. It is well known that a normal flat kraft paper will increase in thickness on stretching, particularly in the final phase preceding the break, only to spring back to the original thickness after rupture (Fig. 8).[(17)] With creped papers, the stretching of the creping will cause an apparent decrease in thickness, followed by an increase just before break.

The causes of the thickness increase are debatable, but are likely to be related to a disintegration of the structure, which is also reflected in opacity changes and in load/elongation graphs. The thickness increase of a flat kraft paper at the point of rupture is about 15 μ; in the case of the compacted papers (Fig. 8), there is a similar thickness increase on stretching, the difference being that it occurs over a larger elongation interval. Some of the thickness increase tends to remain after rupture of the smooth extensible papers, but those with a more pronounced structure (see Fig. 6) were found to perform similarly to the wet-creped papers. No marked difference in the behaviour of blanket or double-roll compacted papers has been found.

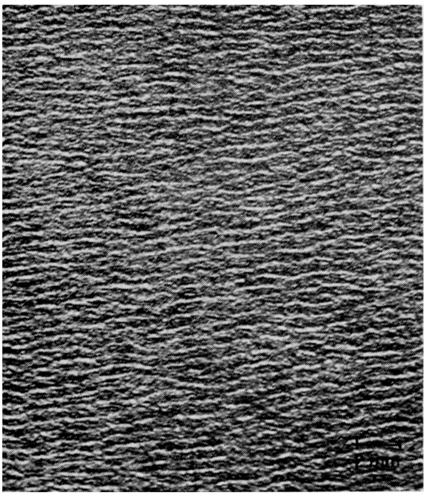
For denser papers than kraft such as sulphite greaseproof, compaction tends to give a more pronounced surface structure, which then disappears upon supercalendering to glassine (Fig. 9), but reappears as opaque lines when the paper is stretched. The corresponding thickness/stretch graph for a compacted greaseproof paper also tends to resemble that of a creped paper (Fig. 10).

These results indicate the following structural changes in the paper web upon the compacting of kraft paper. During the compacting process, the fibres are forced closer together. The forces working mainly in the machine-direction cause the fibres to become curved, but the nip pressure prevents the formation of a creped surface. During these changes in the network structure,

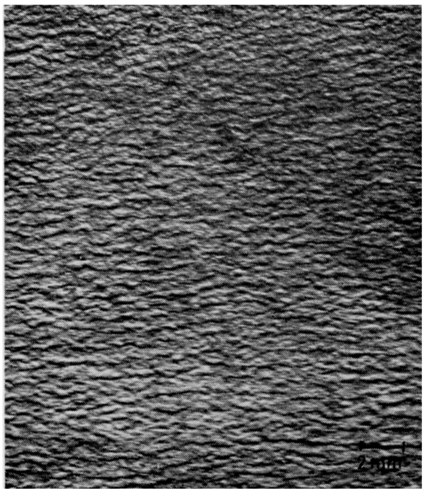


Ordinary flat kraft

German wet-creped kraft

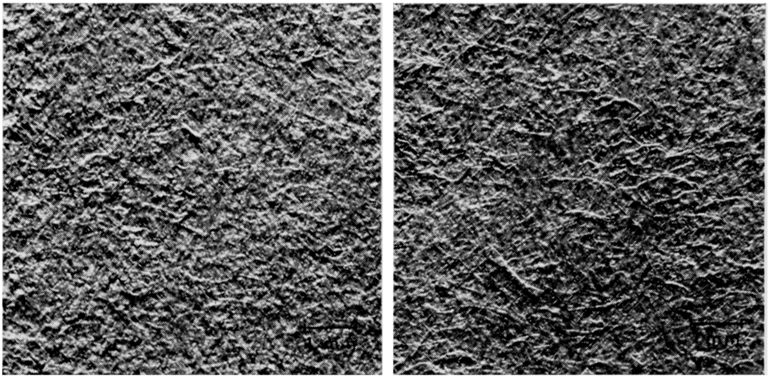


Double-roll compacted kraft

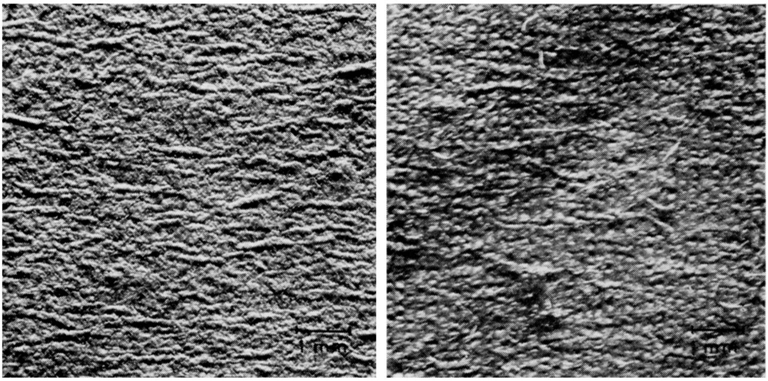


Blanket compacted kraft

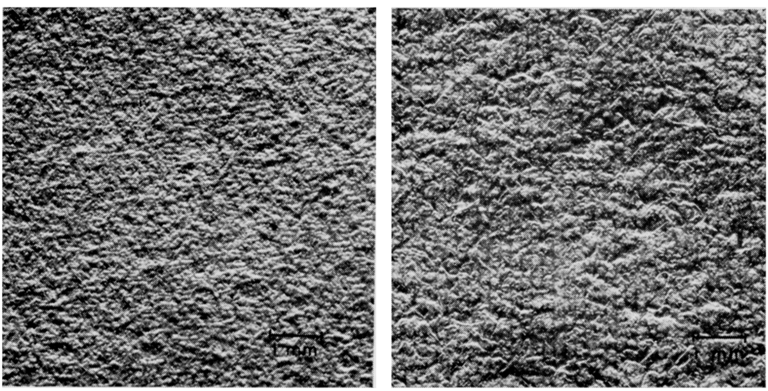
Fig. 5—Surface structures of some commercially available papers



Flat paper—top side *Flat paper—wire side*



Paper compacted at a moisture content of 30 per cent
Facing the rubber roll *Facing the steel roll*



Paper compacted at a moisture content of 40 per cent
Facing the rubber roll *Facing the steel roll*

Fig. 6—Surface structure of flat and compacted papers, the compacting being performed at different moisture contents to give 14 per cent MD stretch

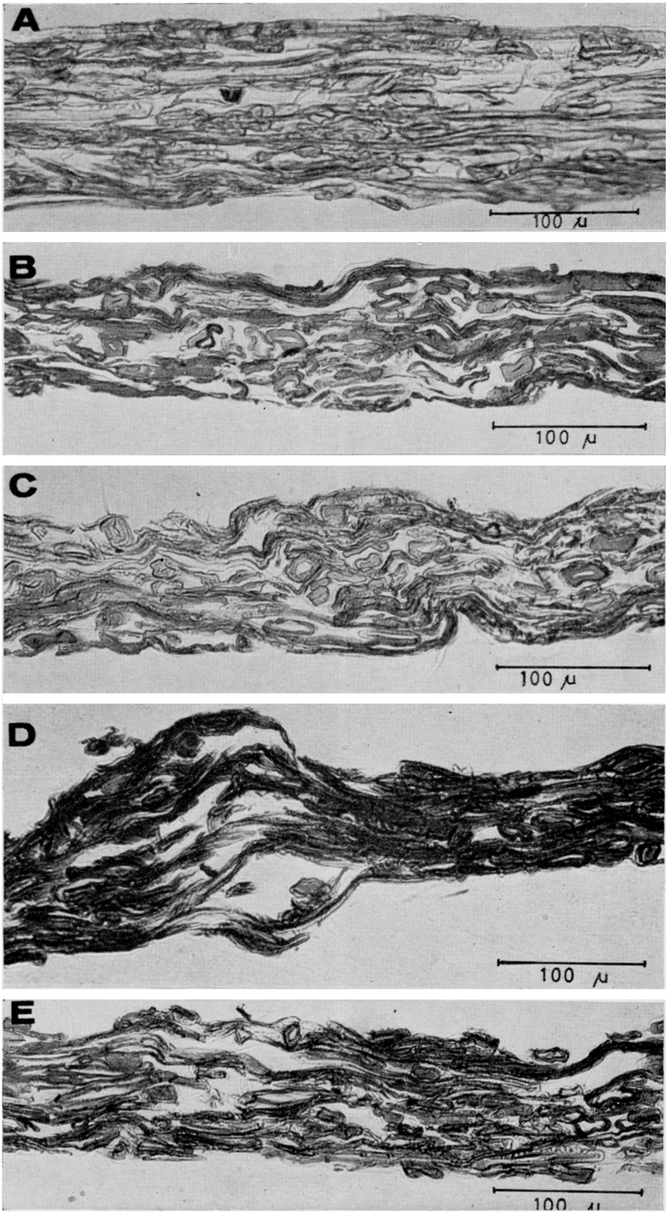


Fig. 7—Cross-sections of some commercially available papers—

A—Ordinary flat kraft
B—Double-roll compacted kraft
C—Double-roll compacted kraft, pronounced surface structure
D—German wet-creped kraft
E—Blanket compacted kraft

some bonds are inevitably broken; but, since the compaction process is carried out on a comparatively wet web, those bonds should mainly be of mechanical entanglement in nature. During drying, the new, compacted structure is fixed by the formation of hydrogen bonds and the resulting paper is somewhat denser and displays a radically different behaviour towards tensile stresses.

The evidence of the photomicrographs and the load/elongation graphs indicate that the interfibre bonding of the sheet compacted in the machine-direction involves the contact of curved fibres. These will eventually be broken when the papers are stretched, as photomicrographs (Fig. 11)

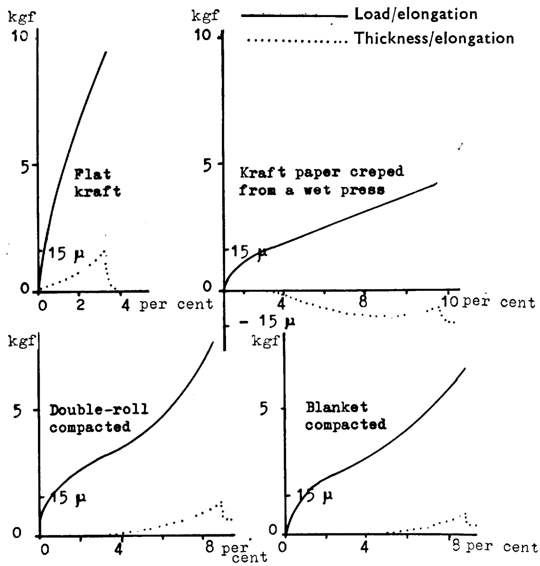
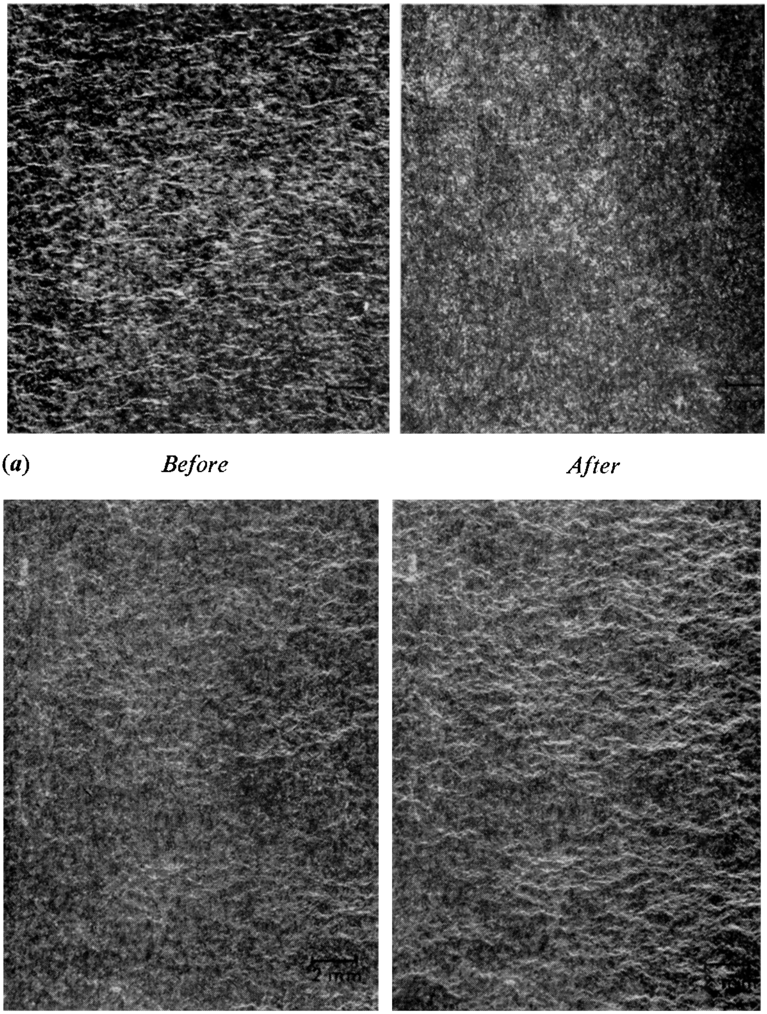


Fig. 8—Load and change in thickness with elongation for different kraft papers

indicate a straightening out of the fibres before rupture. Therefore, the bonding at ultimate stretch will not become as intense as with normal flat kraft paper, hence the breaking load will be lower. Because of the large number of bonds broken during the stretching of the paper, the total rupture energy of commercial papers is often about twice that of flat kraft.

With normal flat kraft paper, the shape of the load/elongation curves is rather similar for different papers which are therefore sufficiently characterised by the breaking load and stretch.[1-3] With extensible papers, it is



(a) *Before* *After*

(b) *0.5 per cent stretching* *5 per cent stretching*

Fig. 9—(*a*) Surface structure of compacted greaseproof paper before and after supercalendering
(*b*) Supercalendered paper stretched to 0.5 per cent and 5 per cent

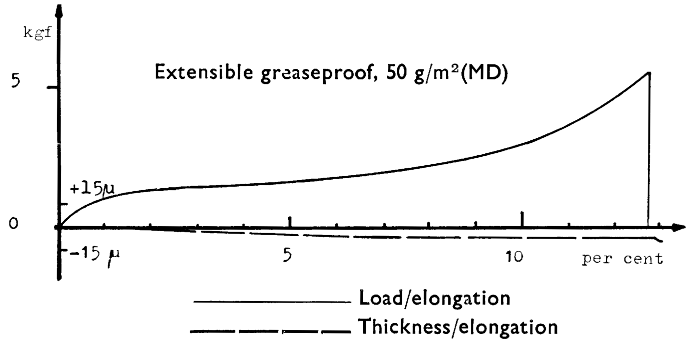


Fig. 10—Load and change in thickness with elongation for a compacted greaseproof paper

necessary to determine the rupture energy proper, because of the varying form factor of the load/elongation curve. The form factor, κ defined as—

$$\kappa = \frac{\text{rupture energy}}{\text{breaking load} \times \text{breaking elongation}}$$

has been found to vary considerably, as exemplified in Table 2 by some commercial papers. Their form factor varies from 0.48 to 0.56 (MD) and from 0.70 to 0.59 (CD), obviously in some manner related to the fibre orientation.

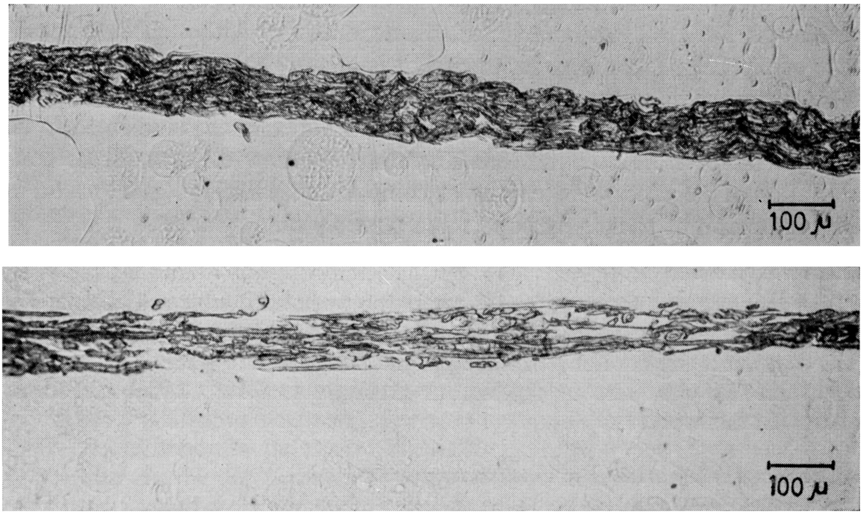


Fig. 11—Cross-sections of unstretched (*top*) and stretched (*bottom*) compacted papers

This was studied by changing the wire drag on a producing papermachine. A more oriented sheet gave a lower MD form factor, but a higher MD rupture energy, with no change in the CD rupture energy. Another factor affecting the shape of the load/elongation curve is the web draw during drying. A tighter draw will result in the loss of some stretch, but will increase the form factor.

TABLE 2—RESULTS FROM THE TESTING OF COMMERCIALLY AVAILABLE PAPERS

Property		*Specimens*			
		G	*D*	*E*	*M*
Substance, g/m^2		83.4	83.8	81.2	80.6
Air permeability sec/100 ml		20	37	16	29
Tensile strength, kgf	MD	7.0	7.0	6.2	5.7
	CD	3.9	5.1	6.2	6.7
Stretch, per cent	MD	8.7	8.8	9.3	7.8
	CD	7.0	7.3	5.5	6.8
Rupture energy	MD	2.9	3.4	3.1	2.5
	CD	1.9	2.5	2.1	2.7
Form factor, κ	MD	0.477	0.552	0.537	0.562
	CD	0.697	0.672	0.615	0.593
Tensile ratio, MD/CD		1.80	1.37	1.00	0.85
Work factor, kp cm	MD	3.5	4.0	3.8	3.1
	CD	2.3	3.0	2.6	3.3
Tear factor	MD	151	121	139	181
	CD	242	158	155	188

The behaviour of extensible kraft paper after conversion to sacks compared with flat kraft has been reported previously.[18] Although the importance of the CD properties was stressed, it is obvious that the improved MD rupture energy will improve the toughness of the sacks and a redistribution of stresses from CD to MD when using extensible paper was indicated to be a major factor in this connexion. Therefore, the new element in the consolidation of the paper web, lengthwise compacting, is likely to gain ground in the production of packaging papers and possibly other grades as well.

Acknowledgements

The reported results are part of the research work on double-roll compacting conducted jointly by Billerud AB, M. Peterson & Sön A/S and Uddeholm AB. The companies are cordially thanked for the permission to publish this part of the work. We want also to express our gratitude to Dr S. Rydholm for his interest in this work.

Appendix 1—Experimental compacting press

ON double-roll compacting (Fig. 12), the press had a closed power loop from the soft roll to the hard roll by means of chains. The same kind of differential pulleys mounted on the shafts were used in the loop for the measuring of the pulling force in the chains. The power was measured and indicated as a moment, for convenience referred to the driving shaft of the hard roll. Thus, the feedback power from the soft roll as well as the input power to the press could be calculated when the speed was known. Through shifting of the chain wheels on either roll, the set speed difference could be changed.

On blanket compacting, the loop was not needed, but the same pneumatic means for the pressure was used.

A pressure force of up to 30 kgf/cm could be applied. Normally, the soft roll or the blanket had a hardness of 50° Shore or about 100 P&J with the $\frac{1}{4}$ in ball, but other rubbers were also tried.

For the driving of the machine a dc motor was used. Speed reductions were realised with belt drives in the high speed and chain drives in the low speed region. When slip would be inconvenient, chains were always used.

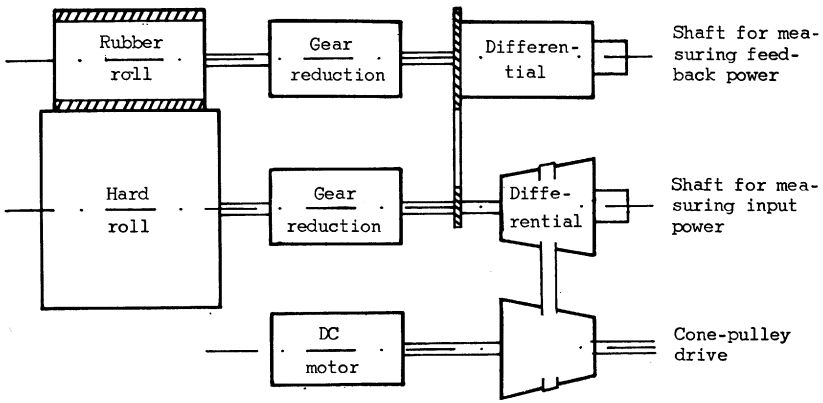


Fig. 12—Experimental compacting press represented schematically

The speed could continuously be regulated 0–110 m/min. The speed difference between the dryers and the compacting press could be varied continuously up to 12 per cent. A mechanical differential reduction pulley was used for this and power was fed to this pulley over a cone-pulley drive for the regulation and over chains for the main setting.

A drying section consisting of eight steam-heated cylinders all driven at the same speed was used. Preceding the compacting press was a size press. The paper was reeled on a friction driven reeler after the dryers or a reeler after the compacting press. The latter could also be used as bottom roll in a breaker press. This reeler was used for reeling paper that was rewetted in the size press. The size press could be used either as a wringer after a saturating bath or as an ordinary size press. It was driven by the paper.

The stress in the web between the compacting press and the first dryer could be measured with strain gauge devices sensing the bending of two beams holding a small roll over which the web was led. The moisture content of the web could be measured before the compacting press and after the dryers.

Appendix 2—The press function

The nip—Double-roll compacting in the *z*-direction has not been treated mathematically in much detail, in spite of being a very common process. In wet pressing, the interest has been centred around the flow of water; in calendering, around the crown and barring problems. A method for measuring the nip pressure between two rolls has been described,[19] as well as measurements on the pressure distribution in the nip.[20] It was shown that the highest pressure occurred *before* the centreline between the two rolls, one of which driven by the other, as seen in the running direction. The pressure distribution curve was expressed mathematically in an analysis of the slip phenomena in rolling.[21] Recently, the slip between paper and steel rolls in a supercalender was stated to equal the tangential elongation of the circumference of the paper roll in the nip.[22] The slip was at maximum at rather low pressures. In an investigation on power consumption, it was found,[23] that, because of hysteresis, the power required per nip is proportional to the speed and to the 'linear pressure' to the power of 1.5, roll diameters and materials being kept constant.

If in a press, the shortest roll has the length L and a force $P \cdot L/2$ is applied to each of the bearings of the rolls, the pressure distribution, $p(x)$, over the nip according to the Hertz theory will follow—

$$p(x) = \frac{2P}{\pi b^2} \sqrt{(b^2 - x^2)}; \qquad |x| < b$$

where $2b$ is the width of the nip and x the projected distance in the running direction of the nip, counted from the centreline (see Fig. 13). The nip width can be calculated from—

$$b^2 = \frac{8P}{\pi}\left(\frac{1-v_1{}^2}{E_1} + \frac{1-v_2{}^2}{E_2}\right) \Big/ \left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

In this formula, E_i is the Young's modulus, v_i the Poisson ratio and R_i the radius of the respective rolls, with 1 indicating the driving, hard roll and 2 the driven soft roll.

The formula can be used in the static case or if there is no friction between rolls. Those conditions are seldom fulfilled in practice, since roll friction, friction in bearings or machinery connected to the driven roll will add tangential forces on the rolls in the nip. This will lead to asymmetrical distribution of the pressure in the nip, as previously indicated.

On studying locomotive wheels in contact with the tracks, it was shown[24] that, when the coefficient of friction is constant, the nip width (b) will remain proportional to the square root of the 'linear pressure' (P), that is—

$$b = \text{const.}\ P^{0\cdot 5}$$

In order to study the nip width of the pilot press, a heat-sensitive paper was used, the steel roll being heated. The nip width should be zero with the rolls just touching each other, though disturbance through heat radiation and conduction caused some width to be imprinted. Since the nip width was found to vary lineally with the square root of the pressure applied, correction for those disturbances could be made. Fig. 14 thus shows the corrected nip width, expressed as a percentage of the undeformed roll diameter.

Since the nip width was found to vary lineally with the square root of the applied pressure, the bracket of the previous formula containing the Young's moduli remained essentially constant up to the maximum deformation reached within the pressure range used, which was the same as in the compaction trials. In Fig. 15, the radial movement y of the soft roll is plotted against the 'linear pressure'. According to previous investigations[22] and neglecting the elasticity of the hard roll, the following relationship holds—

$$y = \frac{4P}{\pi} \cdot \frac{1 - v_2^2}{E_2}$$

The fitted lines are in accordance with theory in the range of interest, 7–20 kgf/cm, which is still a narrow one.

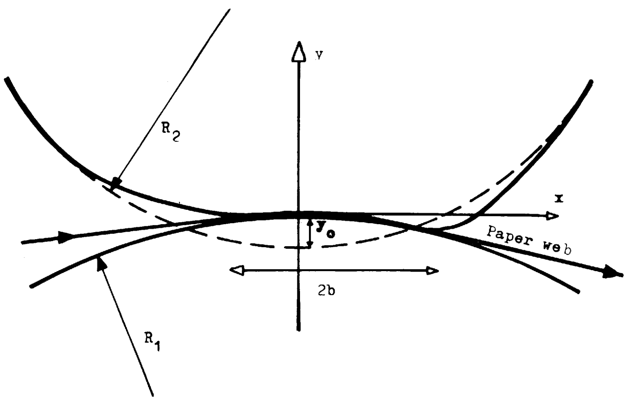


Fig. 13—The pressure nip

The approximate character of the relationship is also accentuated by the fact that y is found to decrease at increasing speed. This is explained by rubber not obeying Hooke's law. The experimental evidence indicates, however, that, in the stress range applied in double-roll compacting for extensible paper, Hooke's law may be used as an approximate description of the elastic interactions in the nip region.

The slip—In the literature on calenders and presses, the occurrence of slip is often debated. Mathematical treatments[21, 22, 24] have demonstrated that two cylindrical press rolls forming a rectangular nip require a slip in the contact zone when one of the rolls is driving the other. For the continual compacting of paper in the machine-direction, the driving roll is forced to slip against the other or

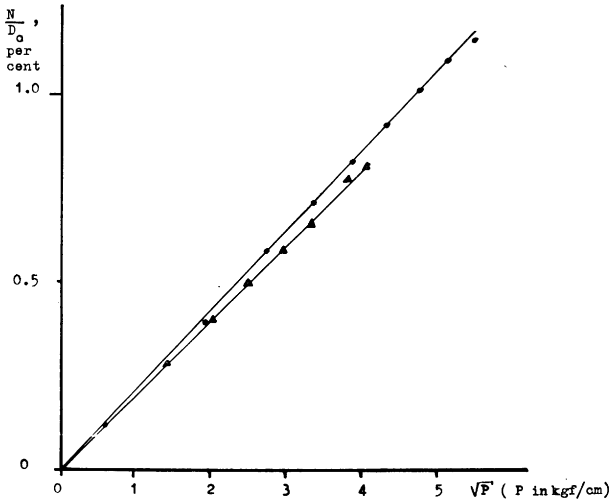
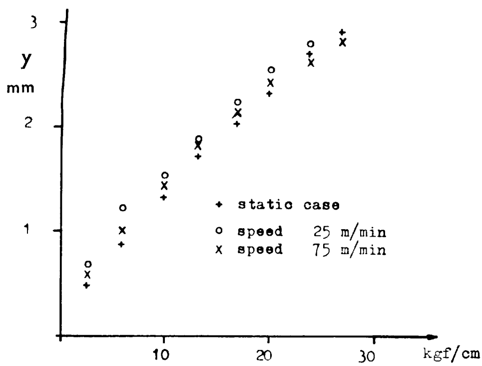


Fig. 14—Changes in the nip width N with the following rubber roll characteristics—

● D_0=415 mm, length 500 mm, 50° Shore
▲ D_0=379 mm, length 530 mm, 46° Shore

rather against the paper web. From the shaft of the driven roll, power is fed back to the driving roll and power circulation will take place. Obviously, some external power has to be added to the system to keep up the circulation and the process.



Rubber roll diameter 379 mm, 46° shore
Steel roll diameter 597 mm

Fig. 15—Radial movement plotted against line pressure

In the slip studies, the slip was observed as a change in shaft speed. In the compacting process, the shaft speeds are regulated to fixed values, but this does not define the slip. Instead of relating the slip to the number of revolutions of two shafts, the slip will be described as an apparent change in diameter of the soft, deformable roll.

The forced speed difference d between the rolls is defined by—

$$d = (w_1 - w_2)/w_1$$

where the mean surface speeds of the rolls are represented by w_1 and w_2. Relating the speeds to the diameters will give—

$$d = 1-(n_2 D_2)/n_1 D_1$$

Here, the diameter of the soft roll D_2 is assumed to be a function of the nip pressure P. Consequently, the speed difference d should vary with P, according to—

$$d(P) = d_0 - \frac{n_2 D_2(0)}{n_1 D_1} \cdot \frac{D_2(P) - D_2(0)}{D_2(0)}$$

where d_0 is the set speed difference at zero pressure. This expression is used to define the mean speed difference in the nip d. It can be transformed to—

$$d(P) = d_0 - (1-d_0)\left[\frac{D_2(P) - D_2(0)}{D_2(0)}\right] \approx d_0 - \frac{D_2(P) - D_2(0)}{D_2(0)}$$

Small forced speed differences should thus be reduced with the apparent increase in diameter of the soft roll to derive the mean speed difference in the nip. This can therefore explain why the MD stretch at the lowest speed difference showed a maximum in Fig. 2 on increasing the pressure.

Any slip involves friction work. On the other hand, should the shaft speed difference and pressures be so chosen that the resulting slip would be zero, no power would be transmitted to the driven shaft (neglecting bearing friction). Acting on this hypothesis, a rewetted kraft paper was run at different pressures with a set speed difference of 3 per cent. The input power, as well as the feedback power were measured and related as moments to the shaft of the steel roll. The apparent increase in diameter of the rubber roll was separately measured through the counting of teeth of chain wheels on the rolls when the rubber roll was freely driven by the steel roll.

The results are shown in Fig. 16 as functions of P. One can read from the graph that, at about 16 kgf/cm, the mean speed difference became zero, since no power was transmitted through the press nip. Above this pressure, the rubber roll took over the driving of the press as indicated by the negative sign of the moment. The increase in rubber roll diameter also reached the magnitude of the set speed difference at about the same pressure.

The paper compacted at 7.4 and 22.2 kgf/cm was found to have an MD stretch of 2.6 and 2.4 per cent, respectively, the latter value being significantly different statistically from the former at the 0.1 per cent level. Apparently, the rubber roll stressed the paper instead of compacting it at the higher pressure level and this might well be so in all normal pressing of paper between a hard and a soft roll.

These results are in agreement with earlier observations[26] on small press rolls, one being made of rubber. From the studies on locomotive wheels,[24, 25] it can be derived that the apparent change in diameter should be proportional to the square root of the pressure. The experimental results of this study as shown in Fig. 17 indicate that this is the case, disregarding the lowest pressure range.

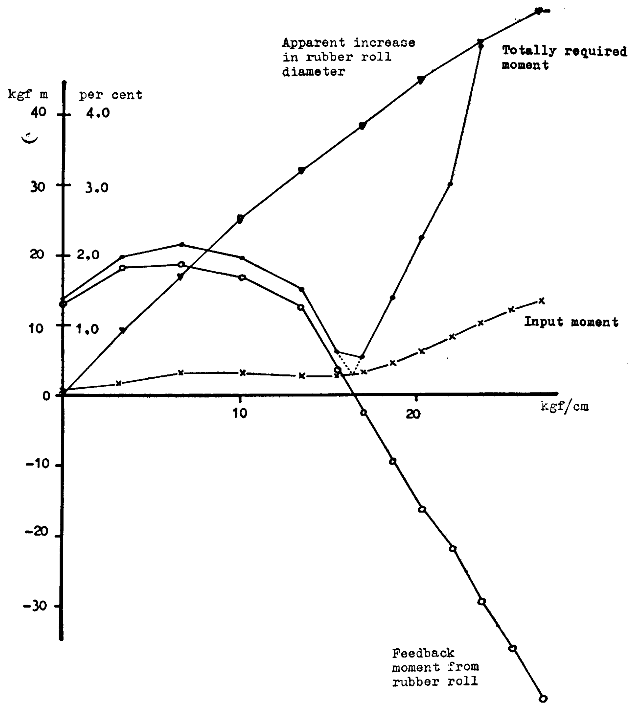


Fig. 16—Moments needed for the driving and apparent increase in diameter of a double-roll compacting press—on compacting a rewetted kraft paper, the speed difference was set at 3 per cent

Using the feedback power to indicate zero slip, the deformation was studied on a full-scale papermachine run at a speed of 320 m/min. The results given in Table 3 in general confirm the observations from the pilot plant press. The less-pronounced increase is explained by the fact that a fully developed deformation does not take place at higher speeds, since a change in the Young's modulus with the rate of deformation must be expected.

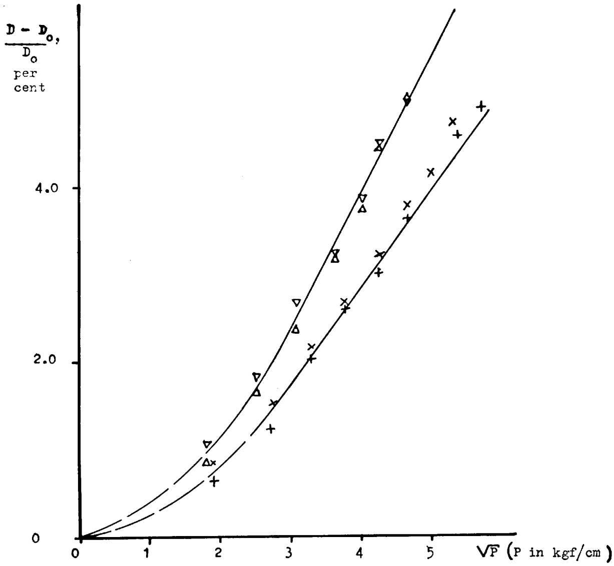


Fig. 17—Percentage change in rubber roll diameter plotted against the square root of the linear pressure for rolls of the following characteristics—

(*a*) Diameter 415 mm, length 500 mm, 50° Shore
+ Driven × Driving

(*b*) Diameter 379 mm, length 530 mm, 46° Shore
△ Driven ▽ Driving

TABLE 3—TEST ON SLIP IN A FULL-SCALE DOUBLE-ROLL COMPACTING PRESS WITH THE SPEED DIFFERENCE SO CHOSEN THAT NO POWER WAS FED BACK

Speed of steel roll = 320 m/min

Linear pressure, kgf/cm	*Speed difference, per cent*
15	0.63
18	1.25
20	1.56

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Discussion

Dr H. F. Rance—Each of the two papers on compaction has dealt with two distinct subjects, one being mechanical operation of compaction and the other being the properties of the compacted sheet. For the purpose of opening this discussion, I will concentrate upon the properties and characteristics of the compacted sheet; no doubt somebody later on will want to comment upon the mechanical operation as such.

For more than 100 years, we have had to accept a significant planar anisotropy in most machine-made paper. Admittedly, MG paper is not anisotropic, but it has low extensibility in both directions and, apart from the relatively crude operation of creping, we have been unable to obtain an isotropic extensible paper. Now, this anisotropy has been due to what I call accidental features of design in the machine (using the word accidental in its proper sense, not its popular sense). Despite this anisotropy being dependent upon accidental design, much of the fundamental research work question reported at this symposium and at the last one has been concerned with structure and properties arising from this anisotropy. In the earlier papers this afternoon, much interest was focused upon the comparison between stretched paper and paper dried free to shrink. This is right, because this anisotropy is of great importance to us in the manufacture and use of paper. It is equally right, I suggest, that we should concentrate a little upon the structural effects derived from deliberate compaction. I would also like to draw attention to the fact that compaction is a very real case of consolidation. So far in this conference, consolidation has not become a real focus of attention. Compaction is deliberate specific consolidation and it introduces consolidation into a new dimension, one that hitherto we have been unable to influence.

These two papers constitute the first real probing in the fundamental sense that we have seen on this subject and I hope the authors will not be depressed by my saying that there is a long way yet to go before we understand the fundamentals of this subject: before we understand what happens when a sheet is compacted. The authors have, of course, rightly included creping in their comparative work, because there are two practical bases of reference in this subject, one being creped papers, the other being cross-direction paper that has dried free to shrink. There is much yet to learn, because, if you look through these two papers and at the detail—not only the detail mentioned in the expositions, but that printed in the papers—you will find at least three distinct types of distortion that appear to be involved in this compaction. Firstly, there seems to be something in the nature of a microcompression of fibres. If you examine one of the micrographs more carefully later on (not printed in the paper, but one of the three shown during its presentation today), you will find evidence of microcompression of fibres of the type already referred to in other contexts. Then there is another type of distortion in the curved or curled fibres (which Welsh especially emphasised); thirdly, we have body wave distortion, mentioned specifically by the author in connection with creped paper. If you look carefully into Ihrman & Öhrn's work on greaseproof, however, you get the impression that body waves are involved in the compaction of the greaseproof type of paper, because in two respects this compacted greaseproof paper appears to be similar to creped paper. It shows strain lines reminiscent of creped paper and it shows a *decrease* in thickness under tensile straining towards rupture compared with the thickness *increase* obtained with normally compacted paper. The question arises—do we have two quite different mechanisms for compaction, one for bulky, free-beaten papers and the other for wet-beaten papers like greaseproof and tracing paper? I am somewhat reluctant to accept a clear distinction between these two types of paper and it may be that the strain lines in compacted greaseproof paper that Ihrman has referred to are not necessarily indicative of creped structure: they could be strain lines akin to those produced when ordinary greaseproof paper is stretched in the cross-direction. That is a matter for discussion. The distinction between wet-beaten papers (solid papers as I would call them, in which there are virtually no voids) and papers in which there are voids is a very important one that I think we should try to clarify.

Finally, I would like to ask one question. Has either of the authors any information on the correlation between mechanical extensibility of compacted papers and moisture expansion? I think this again is quite important, because we know that in ordinary paper there is a correlation between extensibility and moisture expansion when we compare the cross-direction with the machine-direction. Do you get the same effect with compacted paper? If neither of the authors has any information on this, Newman may be able to tell us something about it.

Mr H. S. Welsh—Referring to the second point first, we have data on moisture activity and its relation to stretch (though not with me): without exception, the more stretchability in the paper, the higher the hygroexpansivity.

Reverting to your first point, we consider the moisture content compaction of so-called solid papers can be carried out at quite high moistures. When producing glassine, for example, as a final product, it is being compacted in the form of a wet greaseproof web, which has a substantial amount of void space in it. We have found, too, that plasticising agents such as glycerine act in these cases just like water. If we replace water by glycerine, the moisture content needed at compaction is less.

Dr Rance—Taking up the point about solid papers, you can of course compact high density papers containing as little as 25 per cent moisture and most of it must be within the fibres. Tracing paper has virtually no air space and can be compacted at 25 per cent moisture content. I think there is a problem to be resolved here.

Mr J. A. S. Newman—I regret I can recall only two figures. Before compaction, a certain sheet had a machine-direction water expansion of 1.1 per cent. After compaction, to give a machine-direction tensile stretch of 11 per cent, the water expansion was 4.6 per cent.

Dr H. K. Corte—I would like to ask two questions. One of the graphs showed that the tensile strength decreases when the breaking elongation increases. You mentioned that, with one exception, this is generally found. Is the product of the two constant and, if so, is the area under the curve constant and is it roughly two thirds of the product of the two? The second question refers to the photograph showing the increase in thickness when the paper has been stretched. Is this increase in thickness reversible when the paper is not stretched?

Mr Welsh—No, the product of tensile strength and stretch is not constant. I have never worked out what the ratio is that you have referred to, but it will tend to a larger increase in tensile energy adsorption during the earlier part, then taper off at higher stretches.

On the second question of irreversibility, I do not know whether it is reversible or not. I think it might be partially reversible. With changes as much as shown, it can be measured with even an ordinary hand caliper. We have measured the strained papers after removal of the strain by direct calipering, with results less than shown in these photographs. I question results by a caliper-measuring device because of the effect of the pressure of the anvils, so I do not know if the differences observed were due to reversible effects.

Mr C. B. Ihrman—I would like to mention that in our paper Table 2 contains data on the area under the stress/strain curve: we called it *form factor*. As there are commercially available papers with the same tensile strengths and stretch properties, but different rupture energies, this form factor is important. We have found that it is closely connected with the fibre orientation in an extensible sheet. It tells something also about the softness of the sheet.

Mr O. E. Rodgers—Because of Rance's expressed desire for more information on experimental techniques, I would like to draw attention to a paper by A. C. Spengos to be presented at the Annual Meeting of the American Society of Mechanical Engineers in November, describing an instrumented apparatus capable of measuring normal pressure tangential unit force and tangential motion in a two-roll nip. Experimental results are given for the condition of no paper in the nip. The basic features are as described by Ihrman and additional work indicates that these features are unchanged whether or not paper is present in the nip.

In our experience, the locked region always begins at the nip entrance. The fraction of the nip in the locked region decreases as the torque transmitted through the nip increases and it becomes zero when there is complete skidding. The same feature can be found also in other cases of rubber contact with a rigid surface in which tangential force is transmitted—such as rubber tyres on a road surface. The stress/strain curves in Welsh's paper for laboratory-made creped and compacted papers can be used to illustrate the previous discussion on T.E.A. of creped paper and compacted paper. When these curves are normalised by plotting percentages of breaking lead and breaking elongation, the forms of the curves are seen to be identical. This suggests that no basic difference exists between the shortening processes with respect to T.E.A. development, since the same furnish was used for all specimens.

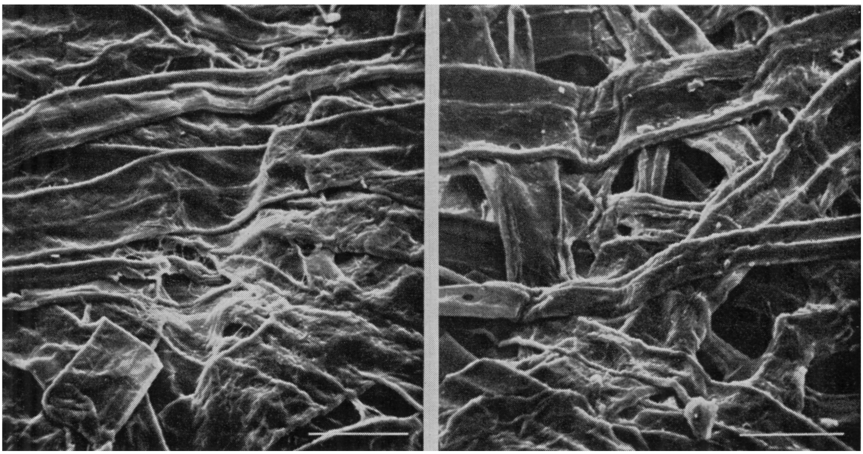
Mr Ihrman—No, I rely on the behaviour of the locomotive wheel, but I will make a comment later to Peel's contribution.

Dr O. E. Öhrn—The thickness curves in our paper are, so to say, direct copies of the original recordings. After the breaking points, of course, they give only the relaxation of thickness after break, when the load disappears. In most cases, the thickness will then really decrease.

Mr I. T. Pye—The scanning electron micrograph of Fig. E shows the surface wrinkles of a commercial compacted kraft paper: they do not appear in the same position on both sides of the sheet.

Mr J. Mardon—Many of the points that have just been discussed are dealt with in detail in Hill's *Mathematical Theory of Plasticity* (Oxford University Press).

Chairman—I am glad about that comment, because one of the tendencies that I have been observing with tremendous delight and pleasure in these symposia is that we are making much less of an island in paper research than we need to do. We are trying to relate our work to the general field of science. In all the papers over the years, there are increasing attempts to relate findings, theories and observations not to paper as a unique God-given system that is separated from all others, but as part of materials, as part of fluid mechanics, as part of heat transfer, as part of the theory of elasticity. Let us welcome these developments.



(a) Top (blanket) side **(b)** Wire (roll) side

Fig. E—Surface grooves in a commercial compacted paper (a) fibres are bent into the grooves and (b) individual fibres are compressed and buckled

Dr M. Rothman—I have always felt that, speaking generally, if you compact a paper in the machine-direction, by virtue of the Poisson's ratio effect, it will expand in the cross-direction. As it is not free to do so, however, it becomes compacted in the cross-direction (CD) as well, hence the increase in CD stretch. If this interpretation is correct, the increase in CD stretch should be about one third of that in the machine-direction (MD)—that is, assuming a Poisson's ratio of one third, which is a figure commonly quoted. I have seen some results of uncompacted and compacted paper from the same initial roll and they did agree with this fact. In the conclusion to his paper, however, Welsh suggests in his summary statement figures of about half this amount

(10–15 per cent). Does this mean that the figures I have seen are a happy coincidence or that the amount of compaction in the cross-direction can be controlled; if the latter is true, between what limits can one control it?

Mr Welsh—CD stretch does increase and will continue to do so as the MD stretch is increased. We have studied this phenomenon recently, but are not sure what the mechanism is. We do know, for example, that you can compact a sheet, say, to 20 per cent, remove 10 per cent of the stretch, bringing it back to a net 10 per cent: the sheet will, when dry, have a CD stretch equivalent to a sheet compacted to 20 per cent. So you remove the MD stretch, but it will hold the increased CD stretch.

Mr Ihrman—It is very difficult to generalise on the increase in CD stretch after compaction. We have to take into account the well-known parabolic function of CD stretch and position measured across the web of a commercial machine. In the middle of the web, about 1 per cent increase in stretch is found and at the edges about 2 per cent might be found, though it is very easy to change these figures. In my opinion, a converter wants a kraft paper as uniform as possible and therefore one might try to destroy some of the CD stretch at the edges. The mean over the web will thus be lower than it would be if one tried to increase the CD stretch at the edges.

I believe that the soft pliable web that is found after the compactor will more easily shrink in the cross-direction than will a flat paper. Indeed, a splitting of the web to just after the compacting press will cause an increase of more than 2 per cent in stretch taken as a mean over the width. Other means of controlling the stretch have been studied, but the results have not yet been published.

Dr Rance—I would like to say something about these visible grooves on compacted paper. We have been shown a very nice micrograph of one of these grooves, but I think that we have to be very careful not to assume that the main part of compaction is necessarily attributable to such grooves. Almost all compacted sheets of paper show some grooves, especially if the compaction has been done at a relatively low moisture content. You can see this with the naked eye, but I think there is no evidence that these grooves constitute the major part of the compaction. They may be only incidental to compaction. We should keep an open mind on this, pending the emergence of quantitative evidence.

Dr R. J. Norman—I would like to mention a few experimental results that refer to the applicability of T.E.A. as an indicator of butt drop performance of sack kraft paper. In the first, we wrapped the paper with the machine-direction around the sack instead of along it: for this, the butt drop number was four times greater than expected from the machine-direction T.E.A. of the paper. Next, using glassine in making up the sack produced sacks with very high butt drop numbers. Both experiments suggest that T.E.A. gives insufficient emphasis to tensile strength.

Dr Corte—Can compaction be carried out and completed at such a moisture content that the paper can subsequently be machine-glazed?

Mr Ihrman—We have argued that point with our patent authorities.

Mr D. H. Page—I would like to agree with what Rance said. Emerton and I saw microcompressions on Clupak paper nearly ten years ago. We did not call them microcompressions then, but we considered at the time, I remember, that these compressional distortions of the fibres were probably the major source of the stretch produced. I think the origin of the stretch is not fully understood and it may vary from paper to paper, according to the method of compaction used.

Mr Newman—You mention that compaction also increases CD tensile stretch. How do you explain this? Supercalendering is known to extend a sheet in the cross-direction: I would have expected compaction to do the same. Moreover, a CD extension should lead to a decrease in the CD tensile stretch.

Chairman—May I suggest that this effect is obtained when the fibre is compacted in the machine-direction: it undulates in both the cross-direction and the thickness of the sheet. When we think of paper, we always regard it as flat; actually, there is this forgotten dimension of depth. Similarly, when we view a sheet section in the z-direction, we are apt to forget the others. The undulation, in other words, will have components in both z-direction and cross-direction.

Dr D. L. Taylor—Following yesterday's discussion, I would like to read a paragraph from a recently published book* that is pertinent to this matter—

'. . . the interfaces of biological membranes (and colloids in general) with aqueous phases are encased in a thin crust of bound water molecules at least one molecule thick. The weight of the more conclusive evidence argues against

* Kavanau, J. Lee, *Water and Solute-Water Interactions* (Library of Congress, Washington, 1964, No. 67–21713), 47

gross (that is, long-range) *immobilisation* of water into thick *ice-like* hydration crusts about macromolecules. But NMR and other studies make it clear that *ordering* and *immobilisation* do not go hand in hand. Thus, the *net* time which solvent water molecules spend in a given orientation doubtless is lengthened to varying degrees in solutions of macromolecules. However, the lengthening is only from about 10^{-11} sec to . . . , at most, 10^{-8} sec, which falls far short of the time of 10^{-5} sec or longer for the water molecules in ice. . . . The degree of polarisation and compression or expansion of the water lattice in the hydration crust depends upon the specific binding interactions. Precise determination of the extent of long-range ordering of water near micellar interfaces and near other interfaces having quasi-crystalline structures that are of biological significance remain important problems for future studies.'

Chairman—While on this subject, may I mention that Prof. Preston of Leeds University published a letter about eight years ago in *Nature* in which he dealt with the subject of wood treatment with preservatives containing copper salts: he found that there is adsorption of copper salts on cellulose. He did it later with pure cellulose: the salts were adsorbed in a highly ordered state and the order gave clear X-ray diffraction pictures, but the pattern so found was not that in any crystalline structure of the salt in bulk that he was using. So that when cellulose attracts molecules to it and they are adsorbed in an ordered manner, it does not necessarily order it in a pattern found in bulk such as free bulk ice or copper sulphate crystals, etc.