Preferred citation: M. Htun and A. de Ruvo. Relation between drying stresses and internal stresses and the mechanical properties of paper. In **Fibre-Water Interactions in Paper-Making**, *Trans. of the VIth Fund. Res. Symp. Oxford, 1977*, (Fundamental Research Committee, ed.), pp 477–487, FRC, Manchester, 2018. DOI: 10.15376/frc.1977.1.477.

RELATION BETWEEN DRYING STRESSES AND INTERNAL STRESSES AND THE MECHANICAL PROPERTIES OF PAPER

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Synopsis The purpose of this work is to study the relationship between the drying stresses and internal stresses and the mechanical properties of paper.

An apparatus was designed to measure the drying stresses, moisture content and surface temperature during the drying of paper.

The internal stresses in paper were measured using the technique described by Kubát *et al.*[1,2] The internal stress was found to be equal to the drying stress, independent of the structure of the sheet.

The results also show that the drying stress developed during restrained drying correlates strongly with the mechanical properties of the paper when different types of fibre are compared under the same drying conditions.

Introduction

THE drying stress that is built up during the drying of paper when shrinkage is prevented is a reflection of the state of swelling of the fibres in aqueous suspension. Considering the well-established correlation between swelling and mechanical properties of paper, an attempt was made to find out whether a similar correlation can be established between the drying stress as defined above and the mechanical properties of paper. Generally the relationship between swelling and mechanical properties is characteristic for each specific pulp. It would thus be advantageous to find a parameter that would correlate with the mechanical properties independent of pulp species.

Furthermore the relationship between the drying stress measured when shrinkage is prevented during drying and the internal stress evaluated by stress relaxation experiments was studied. Previous studies by Kubát *et al.*[2] demonstrated that internal stress as measured by the relaxation technique

Under the chairmanship of Dr J. D. Peel has a large influence upon the viscoelastic and expansional behaviour of paper. Consequently, an elucidation of the relationship between the drying stress and the internal stress must be of importance for an understanding of the influence of the drying conditions on the end-use properties of paper. Similar studies on synthetic polymers were made by Kubát and Rigdahl[3,4] who showed that for these materials the sign and intensity of the internal stress is a consequence of the processing conditions during injection moulding.

Background

IF a sheet of paper is allowed to dry under restraint, it will attain a higher elastic modulus and mechanical strength than a sheet which has been allowed to dry freely. This has been verified by Setterholm *et al.*[5] Schultz,[6] Gates and Kenworthy[7] and many others. A similar effect has also been observed in the case of single fibres.[8–10] This difference in paper properties resulting from different restraints during drying has generally been explained in the previous studies as being due to different drying stresses, to different stress concentration levels and to changes in crystallinity index and fibre orientation. The swelling stress in wood and fibrous material has been thoroughly discussed by Barkas[11] who postulated that the stresses exerted on the fibres during restrained swelling would be transmitted and locked into fibre elements during drying. Drying stresses were later measured and studied by Ivarsson,[12] Brecht *et al.*[13,14] and Byrd.[15] They found that the level of drying stress attained under restraint is dependent on the degree of beating and is related to the shrinkage of the sheet during unrestrained drying. Ivarsson also attempted to relate the swelling stresses and the drying stresses by using a simplified equation of Barkas. The internal stress built into the paper structure was first studied extensively by Kubát *et al.*[1,2]

Materials and experimental procedure

LABORATORY sheets were made from a newsprint furnish and from NSSC, 47 per cent yield unbleached kraft, 55 per cent yield unbleached kraft and bleached kraft commercial pulps.

Sheets were formed either by standard sheet forming (Scan) procedures (bleached kraft and newsprint pulps) or in a Formette Dynamique former. The latter technique leads to oriented sheets. The grammage of the sheets was 100 g/m^2. Relevant mechanical data are given in Tables 1 and 2.

The geometric mean values are used in the diagrams. The wet-pressed sheets were transferred to a drying chamber manufactured by Instron Inc. and tailored to fit the Instron tensile tester, and were dried under uniaxial restraint in a stream of hot air until no further change in moisture content was recorded (Fig. 1). The temperature of the drying chamber was controlled by means of a thermostat and the hot or cold air was circulated by a fan.

TABLE 1—THE DRYING STRESS AND MECHANICAL PROPERTIES OF PAPERS MADE FROM VARIOUS TYPES OF PULPS

		Newsprint (handsheet)	*NSSC*	*Unbleached kraft 47% yield*	*Unbleached kraft 55% yield*	*Bleached kraft (handsheet)*
Apparent density, kg/m^3		416	422	604	540	617
Drying stress, MN/m^2	MD	2·30	3·02	8·74	7·08	7·0
	CD	—	1·85	4·39	3·56	—
	$\sqrt{MD \times CD}$	—	2·36	6·19	5·02	
Tensile failure stress, MN/m^2	MD	9·32	27·14	86·07	65·34	47·6
	CD	—	9·41	20·31	17·76	—
	$\sqrt{MD \times CD}$	—	15·98	41·81	34·07	—
Compressive failure stress, MN/m^2	MD	—	8·22	16·77	17·60	15·17
	CD	—	3·57	5·12	3·78	—
	$\sqrt{MD \times CD}$	—	5·42	9·27	8·16	—
Elastic modulus, MN/m^2	MD	1 200	3 424	6 250	5 320	4 800
	CD	—	1 187	1 590	1 600	—
	$\sqrt{MD \times CD}$	—	2 016	3 152	2 918	—
Strain to failure, (%)	MD	1·6	1·51	3·85	3·13	2·91
	CD	—	1·60	4·29	2·92	—
	$\sqrt{MD \times CD}$	—	1·55	4·06	3·02	—
Symbols used in the figures		★	☆	△	▲	○

TABLE 2—THE DRYING AND INTERNAL STRESS AND THE MECHANICAL PROPERTIES OF HANDSHEETS OF A BLEACHED KRAFT PULP

	Unbeaten		*21° SR*		*43° SR*		*21° SR*	
	whole pulp	*without fines*	*whole pulp*	*without fines*	*whole pulp*	*without fines*	*whole pulp*	
Wet pressing, MPa	0·45	0·45	0·45	0·45	0·45	0·45	1·0 MPa	2·0 MPa
Apparent density, kg/m^3	453	397	617	558	703	607	663	700
Drying stress, MN/m^2	2·40	1·23	7·0	4·49	10·44	7·02	8·73	9·25
Internal stress, MN/m^2	2·40	—	6·8	—	9·20	6·6	7·6	8·6
Tensile failure stress, MN/m^2	8·24	3·17	47·6	25·0	65·7	39·2	51·5	58·2
Compressive failure stress, MN/m^2	2·6	1·25	15·17	9·36	19·34	12·89	16·86	17·16
Elastic modulus, MN/m^2	1 100	713	4 800	3 200	6 000	4 400	5 300	5 900
Strain to failure, %	2·62	0·92	2·91	1·93	3·01	2·52	2·70	2·66
Symbols in the figures	□	⊡	○	⊙	●	◉	○	○

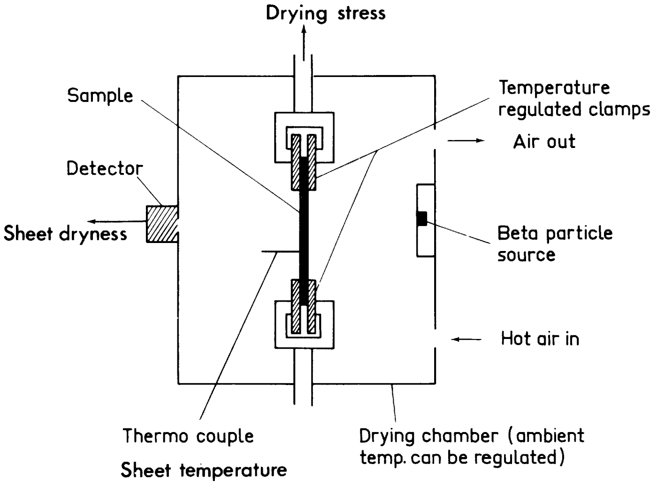

Fig. 1—A schematic drawing of the equipment used for measuring the drying stress

The clamps of the Instron were modified to suit the experiment. The width of the clamps was 100 mm and the edges of the clamps were made of sintered metal equipped with thermostated heating coils. Thus, during drying, the clamped area of the paper could be held at a slightly higher temperature than the ambient temperature which allowed the portion of the sample under the clamps to be slightly drier than the remaining portion of the sample.

The moisture content of the sample was measured continuously during drying with a β-ray gauge, calibrated for the basis weight range scanned during drying. The surface temperature of the sample was measured continuously during drying by means of a thermocouple.

With this arrangement, the uniaxial drying force developed in a paper web could be studied with reference to sheet dryness and temperature. In this paper, drying stress (drying force/cross sectional area, measured for the dried sheet) is given as the maximum stress developed in a sheet of paper under uniaxial drying when shrinkage is prevented.

Test pieces were cut from these dried sheets for the measurement of the mechanical properties and, in the case of the bleached kraft pulp, for the measurement of the internal stresses. The internal stress was studied on sheets made from fibres at various beating levels and various wet pressing levels and from pulps fractionated to obtain different fibre length distributions and degrees of swelling.

Samples used for relaxation tests were cut from the middle of dried sheets and were kept at 65 per cent RH and 20° C. For the relaxation tests the samples were loaded to different initial stress levels with a strain rate of $1{\cdot}7 \times 10^{-3}$ per sec.

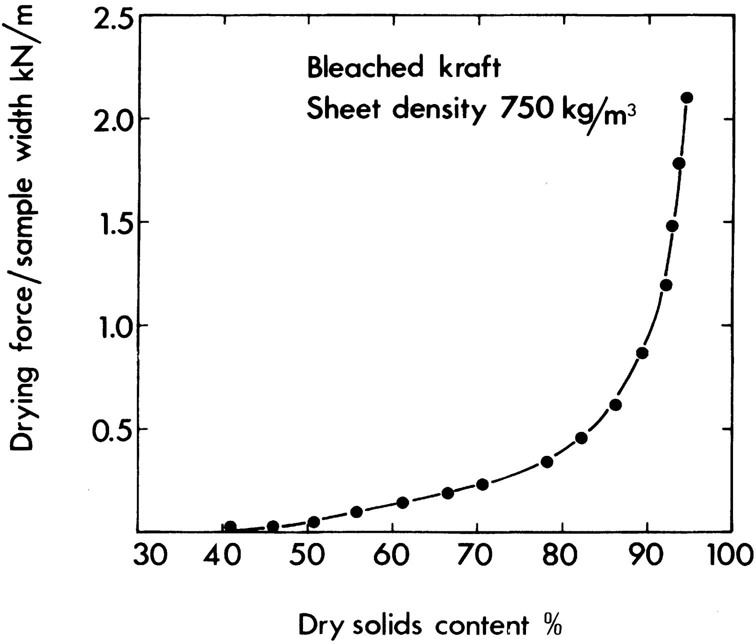

Fig. 2—The drying force per sample width in a sheet of paper is plotted against dry content

Drying stress

THE drying stress of the sheet increases slowly at first and then increases very rapidly after the sheet has reached 80 per cent dryness, as illustrated in Fig. 2 for a bleached kraft pulp. The type of pulp, the degree of beating and the level of wet-pressing usually determine the starting point for the drying stress of a sheet. An increased degree of beating favours an earlier starting point and *vice versa.*

For chemical pulps, the value of the drying stress remained constant at the maximum level, whereas a slight relaxation of the drying stress was observed for mechanical pulps. The drying was carried out at 100° C.

Internal stress

THE internal stresses of the paper were evaluated according to the method described by Kubát *et al.*[1, 2] According to this method the main inflexion $(-\mathrm{d}\sigma/\mathrm{d}\log t)$ of the relaxation $\sigma(\log t)$-curve is plotted against the initial stress i.e. stress at zero time, σ_0. Consequently, a number of relaxation curves with varying σ_0-values must be measured. The plots of $(-\mathrm{d}\sigma/\mathrm{d}\log t)_{\max}$

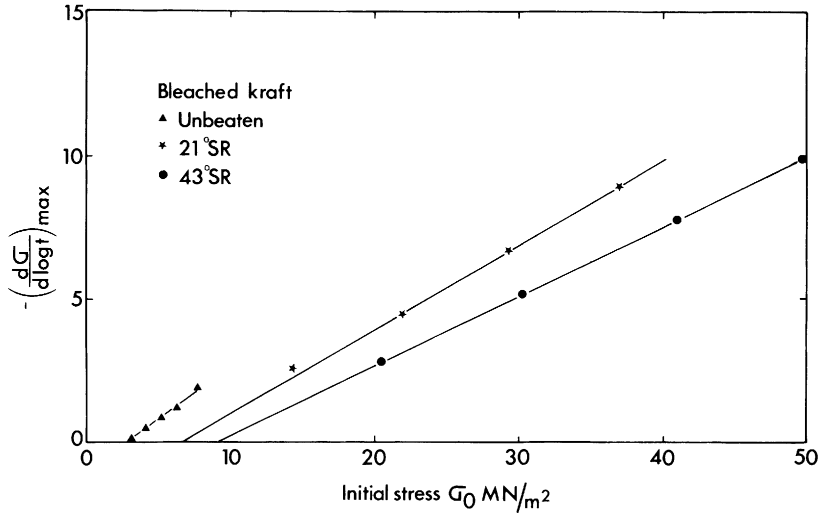

Fig. 3—A plot of $(-d\sigma/d \log t)_{max.}$ against the initial stress

against σ_0 are linear. The intercept on the σ_0 axis gives the value of the internal stress σ_i. A plot of $(-d\sigma/d \log t)_{max}$ against the initial stress is illustrated in Fig. 3.

Results

As can be seen in Fig. 4, the drying stress and internal stress are essentially equal. Apparently neither the degree of beating, the level of wet-pressing nor the utilisation of different fibre fractions in the sheet changes the correspondence between the two stresses in any significant manner. It thus seems that the basic mechanism responsible for the building up of the internal stresses is linked not to the structural characteristics of the sheet but rather to the deformation of structural elements in the fibres.

The drying stress measured under given conditions correlates well with the mechanical properties of the paper irrespective of the type of pulp, degree of beating, wet-pressing level or of different fibre fractions. As can be seen in Figs. 5–7, the strength properties in both tension and in compression as well as the modulus of elasticity show a linear relationship with the drying stress. Of course, the degree of fibre orientation or the level of stress distribution in the sheet may cause scatter but in general the drying stress, which develops in a sheet during restrained drying, clearly correlates strongly with the mechanical properties of the sheet independent of the pulp species.

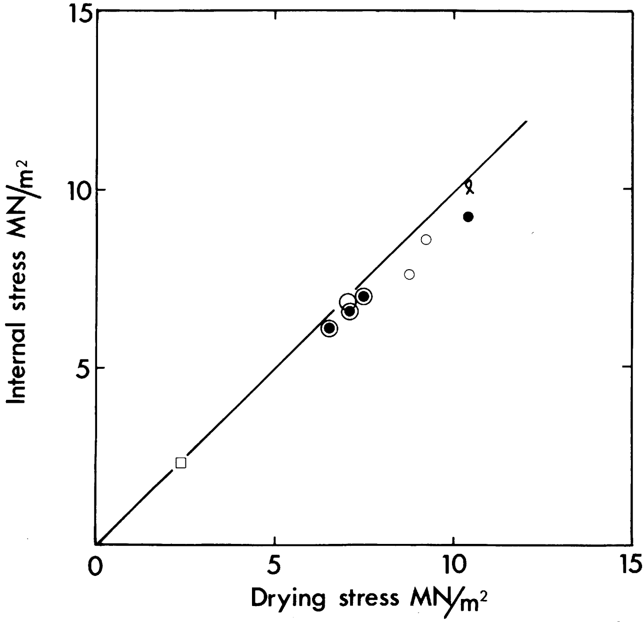

Fig. 4—Internal stress versus drying stress. (l = 50° SR beaten bleached kraft. The remaining symbols are given in Table 2.)

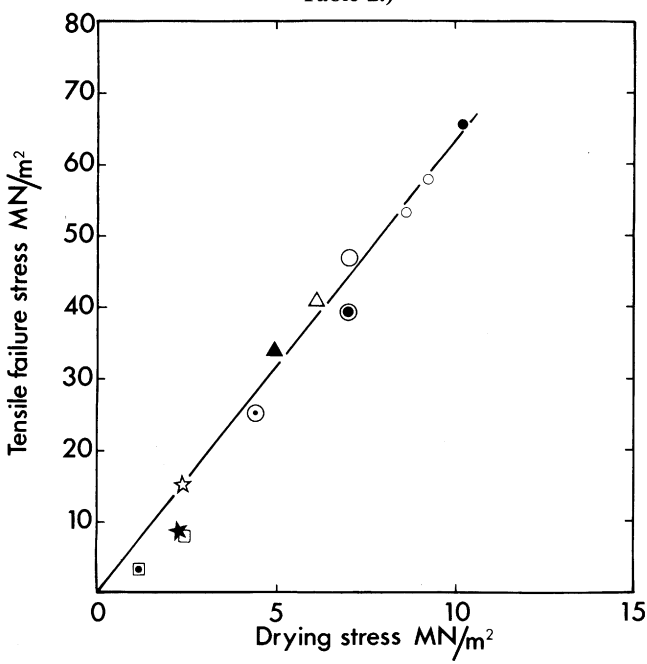

Fig. 5—A plot of tensile failure stress versus drying stress. (Symbols are given in Tables 1 and 2.)

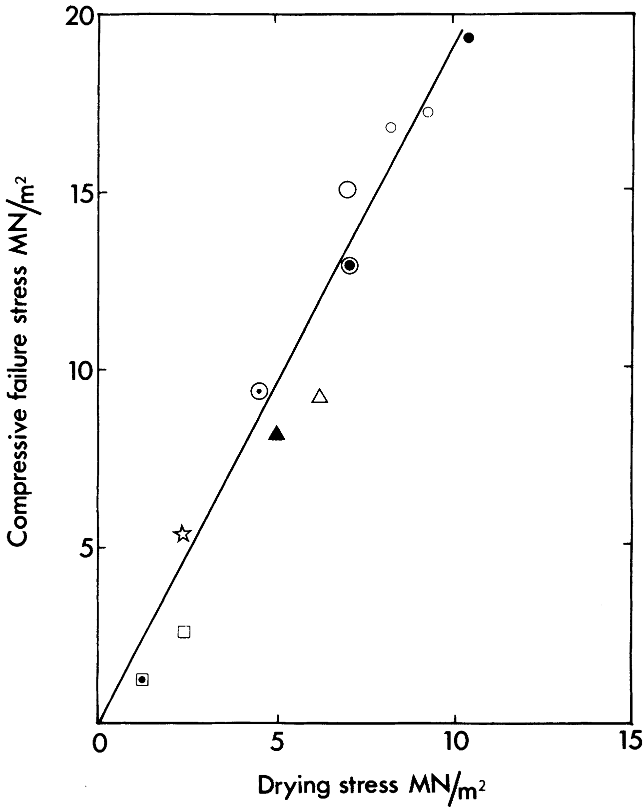

Fig. 6—The compressive failure stresses of different paper qualities plotted against drying stress. (The symbols are given in Tables 1 and 2.)

Final remark

THE close relationship between the drying stress, the internal stress and the mechanical properties is important technically. Firstly, it may allow prediction in the dryer section of the mechanical properties of the paper. alternatively, the measurement of internal stresses in dry paper could reveal the nature of the stress the paper has been subjected to during drying. However, it is essential to emphasise that the drying stress measured in this work refers to the situation when no shrinkage is allowed. Thus a general application should include measurement of the shrinkage during drying.

The identity between the internal stress as measured by the relaxation technique and drying stress indicates that these two parameters essentially

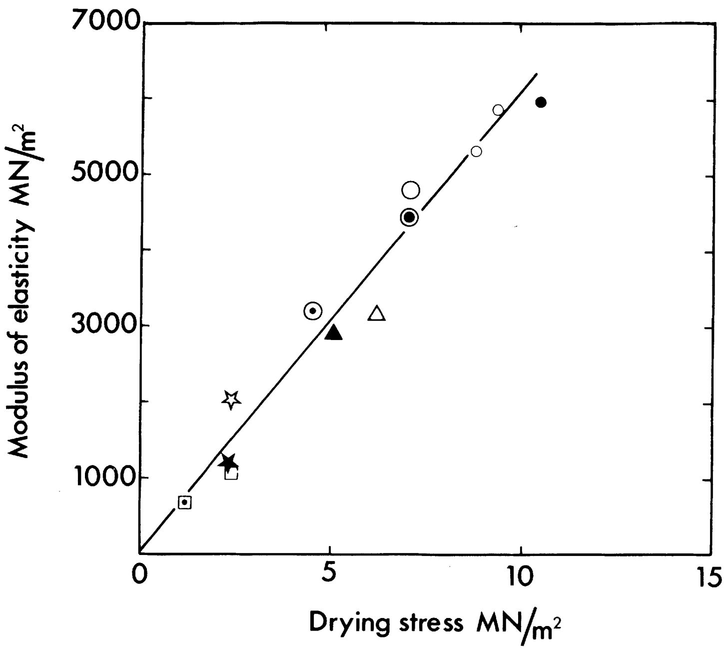

Fig. 7—Elastic modulus versus drying stress. (The symbols in the figure are given in Tables 1 and 2.)

give the same information about the mechanical character of the sheet. In fact it seems reasonable to assume that both methods give the stress level at which plastic flow is absent.

As pointed out earlier, drying stresses show no pronounced time dependence after drying has stopped. This indicates that the drying stress may only rise to or is limited to the level of, the onset of plastic flow. Furthermore, the relaxation method is based on a plastic flow mechanism. Thus the intercept obtained by extrapolation to zero relaxation rate should give the stress level for the onset of plastic flow.

This suggests that both drying stress and internal stress are closely related to or identical with the yield stress of the material.

Furthermore, the elastic properties and strength properties should correlate well with the yield stress and thus also with the drying stress and the internal stress measured by the relaxation method.

Further experimental work to verify the suggested identity between yield stress, drying stress and internal stress is in progress.

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Transcription of Discussion

Discussion

Mr J. F. Waterhouse Creep occurs in paper at very low stress levels. Therefore, do you think that there is some time-scale effect in determining these yield stresses? If so, how would you account for the effect?

Htun Internal stress can be increased by cyclic strain hardening. The internal stress introduced during manufacture is irreversible, and depends on the manufacturing parameters.

Waterhouse In the data that I used to illustrate the tensile strength/density relationship with beating, I also divided the stress levels by the modulus and the data almost collapsed on to one line. This is a further confirmation of your results.

Dr T. Helle Your Table 2 gives some clarification to earlier questions on the importance of fines in chemical pulps.

Htun If you refer to Fig. 7 of my paper where I plotted the modulus of elasticity against drying stress, the highest point corresponds to bleached sulphate at 43° SR, but when the fines were removed it jumped down to the circled large dot. The same is also true to the lightly beaten pulp. This point for 20° SR pulp removal of the fines caused a jump from 4 800 to 3 200. In slide 7 you can see the same thing. Whenever the fines are removed the point jumps down the line. I hope that this clarifies the effect of fines on the properties of paper.

Dr J. D. Peel The internal stress has been obtained as a quantity, largely from mathematical considerations and yet it obviously has a physical significance. What is the physical meaning of the internal stress?

de Ruvo The internal stress is not a net stress because the internal structure does not move and it would have to do so if it were present, except in transient

Under the chairmanship of Dr J. D. Peel situations. What we have shown in this specific case is that the concept of internal stress is nearly identical to the yield stress of the material. That is the amount of stress that you have to put in in order to get an appreciable amount of plastic flow. We have basically shown that the dryer section can be seen as an Instron tester for paper and these results can be used for on line testing of mechanical properties of paper.

Dr D. H. Page Can I refer to my standard drawing which refers to the origin of the drying stress? We are holding the paper at constant length and so fibre A has a constant length. With the shrinkage of fibre B forces develop in the directions shown (Fig. 1). This then is the situation that is present during drying, with compression in the central (bonded) region of A and

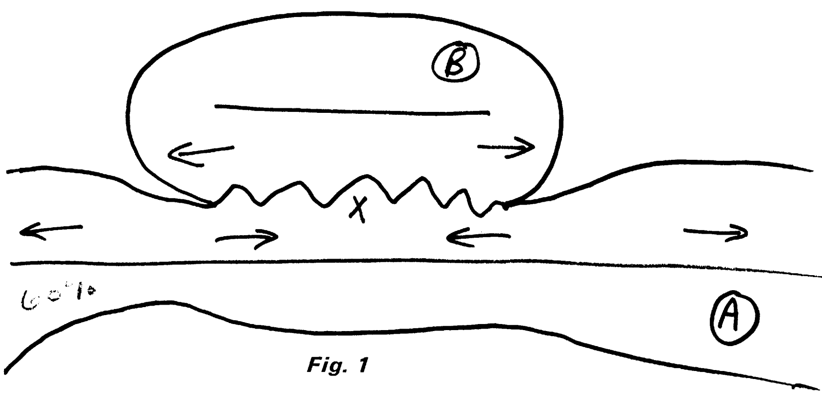

Fig. 1

tension in the unbonded region. We should really consider what is happening in both regions, but it is simpler only to consider the unbonded region. Here, while the matrix material is swollen and therefore stress-free, the fibrils bear the load. This condition remains upon drying, and the entire sheet is under tension. We then release the external tension. The stress in the fibrils then is shared with the matrix, so that the matrix goes into compression while the fibrils are still under tension. These stresses may relax somewhat but essentially they remain and constitute the internal stress. When we now again stress the paper in the stress–strain apparatus, the matrix is initially under compression, and it is not until the stress reaches a quite high value that this stress is reversed and yield on the matrix occurs. Thus the drying stress is highly correlated with no internal stress or yield stress. To sum up, the internal stresses are real. Tensile stress in the crystalline fibrils are opposed by compressive stresses in the amorphous matrix within each fibre.

de Ruvo I basically agree with Dr Page but we are only interested in the large scale phenomena.