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BEATING AND THE MECHANICAL PROPERTIES OF PAPER

A CRITICAL REVIEW

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Summary

A survey of existing standard and suggested methods of paper testing shows the need of increasing the battery of testing methods to enable a more thorough theoretical analysis of the influence of beating on mechanical properties of paper to be made. This statement is exemplified among others by a comparison of the vast quantity of scientific work on beating carried out using the Mullen tester and the small amount of new information reached over a period of years.

Only by using methods sufficiently well defined to allow physical interpretation either alone or in combination with other tests can a comprehensible theory of the influence of beating on paper properties be expected.

The problem of studying beating is complicated by the fact that there seems to be no method by which all fibres in a sample can be treated in the same way.

Fibre length determinations as a measure of beating have limitations. The important property of fibre flexibility ought to be made the *subject of closer study and a possible way of carrying out such studies is indicated.*

The need to study the stress distribution in paper under different conditions in order to understand its behaviour and the influence of its composition is stressed.

The problem is in all probability so complicated that any valuable theory must be supposed to include a number of independent factors.

THE two main methods used for judging the effect of pulp beating are to study the drainage resistance and the mechanical properties of handsheets made from the beaten pulp. The last method is of interest because the main purpose of most beating is to obtain a stock useful for producing papers with specified mechanical properties. The fact that beating also changes the sheet formation properties of the pulp, its optical properties, etc. need not concern us here.

It seems appropriate to start a survey of the influence of beating on the mechanical properties of paper by analysing what is implied in the phrase *mechanical properties of paper*.

Most people will associate the concept of mechanical properties of paper with properties like bursting or tensile strength, tear resistance or folding endurance.

The mechanical properties of paper is of course a much wider subject. We may first differentiate between wet strength properties and properties of paper in equilibrium with standardised humidity conditions. The first type will not be considered below.

Further, we may distinguish between two principal classes of mechanical properties, namely, prerupture properties and those of ultimate strength.

In the first class, properties like compressibility, modulus of elasticity, stress relaxation and creep properties, coefficient of friction, etc. are found. The basic concepts behind at least some of these properties are reasonably well defined. Others, although technically important, are still both poorly defined and measurable as, for instance, pliability and softness.

In the second class fall the ultimate strength properties as initially exemplified. As a matter of fact, these properties may in themselves be uninteresting. Paper under service conditions is hardly ever subjected to conditions identical with the highly specified conditions of the testing machines. Only to the extent that the strength data determined with these laboratory instruments correlate with the service strength performance are they of practical interest. However, even if there does not exist any sufficiently good correlation between service performance and the laboratory strength data, the latter may still be of interest, provided they lend themselves to relatively easy theoretical interpretations and thus enhance our knowledge of the mechanical properties of paper and give information about different factors such as the influence of beating. If, as is the case in many ultimate strength testing methods, the sample and not the operator determines the conditions of the test, there seems to be a waste of time in trying to arrive at basic relations.

Let us first deal briefly with the concepts of service strength performance and its relation to laboratory strength.

It is essential to bear in mind that requirements of ultimate strength conditions for paper products are essentially different from those in, for instance, civil engineering. A bridge is designed to allow any number of trains to pass without the bridge breaking. A paper bag containing cement is not supposed to stand indefinite handling. Studies at the Swedish Forest Products Research Laboratory indicate that there is a considerable fatigue effect in paper bags caused by repeated drops. To this problem of fatigue comes the natural variation of the paper properties from area to area. Variability has been mentioned as the only truly characteristic property of paper. What is of practical interest is the compound result determining the survival curve during repeated mechanical stresses caused by the hazards of service.

It follows that, in most practical cases, the average strength or average ultimate strength is not necessarily in itself an expression of the relevant strength. We do not know at the moment whether the survival curves in a fatigue process are symmetrical and/or can be fully represented by, say, the 50 per cent. survival figure.

Let me now return to the laboratory strength determination methods and try to evaluate to what extent these tests either correlate with service performance or whether they are reasonably interpretable from a physical point of view.

The Mullen test, especially favoured in the country of this conference, may be a useful production test for quick estimation of production conditions. To the writer's knowledge, there is not a single convincing report showing that this test is sufficiently closely correlated to any service performance strength for it to be of practical use. It is interesting to learn that the International Railway Union is seriously considering abolishing this test for paperboard packages.

Studies of the relation between Mullen data and tensile and stretch test data from handsheets indicate that no extra information is gained from the

Mullen test. Instead, a lot of information is lost. To this comes the doubtful calibration of the instrument.

It is difficult to conceive how any better understanding of the relation between beating and the mechanical properties of paper can be reached by using this test method. An indication of the probability of this statement can be reached by comparing the fantastic quantity of work being put into Mullen testing in connection with beating tests. Very little new knowledge has come from these tests over many years.

The tensile test also has considerable limitations. The result of the test is dependent on the dimensions of the sample. A theoretical basis can hardly be found for such methods as have been used[1] to obtain some physically significant figure by changing the length of the sample and extrapolating the values to zero length. Only one suggested method of paper testing is known to the writer, where the dimensions of the sample under test do not enter into the results, namely, the critical rate of elongation test method, discussed by Andersson and Steenberg.[2] Unfortunately, the instrument design problems make the method impractical.

In the current standard pendulum type of tensile tester, the rate of loading is determined by the paper sample and not by the operator. It is a surprising fact that no standard method of using this instrument includes a method for calibration of the stretch scale. A survey made by Bergström[3] shows that different apparatus, in all details conforming to standards like those of TAPPI, give appreciable differences in the stretch figures.

The increased use of more elaborate instruments for stress/strain studies —like the Instron tester and the STFI tester[4]—may enlarge the knowledge of the mechanical behaviour of paper. From studies with instruments of this type, a definite trend on the concept of strength of paper seems to spread through the paper world. The importance of the rupture energy determined from the area under the stress/strain curve, as pointed out especially in works from the Swedish Forest Products Research Laboratory,[5] has been relatively widely accepted, in some cases even overaccepted.

The tear tester of the Elmendorf type, measuring a physically interpretable concept, seems to be based on fairly sound principles. The theoretical discussions of the interpretation of tearing test data and their variability with beating in publications from the Institute of Paper Chemistry and the studies resulting in mechanical improvements by the Commonwealth Scientific and Industrial Research Organisation, Australia, are significant contributions to this aspect of mechanical strength properties of paper.

The folding test is one that is very sensitive to instrumental conditions. The character of this test as a fatigue test has been studied by Andersson[6] based on Weibull's[7] fatigue theory. A surprising agreement with the theory is found.[8] The change in folding strength with varying tensile stress in the testing can be treated mathematically. The empirical formula by van Nederveen and van Royen[9] published later can be shown to be an approximation of Andersson's formula, involving only the first term in a series development. Other suggested folding tests, characterised by a sequence of folding and tensile procedure,[10] for instance, do not seem to increase the arsenal of basic methods, but may be practical for routine testing.

The tearing test is a quasidynamic test. Most other tests are so slow that they definitely must be considered to give only a measure of the static mechanical properties. Several tensile testing instruments have been devised to carry out the tensile test rapidly.

This is an indication of the general feeling that dynamic or impact tests may be required to extend our knowledge regarding the properties that are of practical interest for judging the strength of papers. Still, most of the rapid testers mentioned are not of a true dynamic type: of course, there is no theoretical boundary between the static and the dynamic test. For a test to be truly dynamic, however, it is reasonable to require that the inertia of the sample must have an appreciable influence and thus shock waves must be responsible for its behaviour.[11] It is known that instruments, say, of the Bekk-van der Korput type correlate well with pendulum tensile testers and will consequently not significantly contribute to increased knowledge of the properties of the material.

The rate of elongation in all suggested instruments is below 1 or 1½ tenths of a metre per second. Experiments over a considerable number of years with several different instrumental set-ups in this laboratory has shown that, only if the rate of elongation on a strip of standard length is over 5 m./sec., will the dynamic properties enter the results considerably.[2] This is why the STFI impulse tester designed by Andersson[12] operates at a speed of 10 m./sec. Experimental designs have been run up to over 30 m./sec. The impulse test correlates neither with the tensile test nor with the work of breaking in a pendulum tester and consequently constitutes an unique strength property.

For non-destructive tests for mechanical properties, a number of stiffness testers exist. Due to the visco-elasticity of paper, it is deemed necessary to extend the basic knowledge of a number of phenomena in paper like compliance, relaxation time spectrum, creep functions, dynamic moduli, etc. A survey of how such properties are dependent on fibre properties, beating procedure, sheetmaking, etc. will be required to obtain a deeper insight into the subject.

The considerable success studies of this type have had in elucidating and explaining properties of textiles[13] like handle drape, crease resistance, etc. indicates that similar studies of paper may be profitable to the understanding of the basic features of a number of technically important mechanical properties of paper.

It must be remembered that most of these properties are basically much easier to interpret theoretically than ultimate strength data, these being rupture processes due to randomly distributed discontinuities.[5]

Summing up, the following can be said. At the present advanced state of paper technology, current technological ultimate strength testing procedures no longer give information sufficiently detailed and highly correlated with paper properties as exhibited in actual use. Very few, if any, of these tests measure properties having sufficiently well defined physical interpretations to enhance theoretical analysis of the influence of beating on the mechanical properties of paper. This is much more the case with tests of the non-destructive type, determining properties like stiffness, modulus of elasticity, etc. This latter field, holding good promises for rapid theoretical and practical results, has not been studied to the extent its significance seems to justify.

Let us now consider the beating process. It is essential to remember that there is no beating in which all fibres are treated in the same way.[14] As a matter of fact, it does not seem possible to produce a beating process where all fibres are treated alike.

In all beating and refining machines, there is no positive barrier to prevent a fibre passing through the machine without having been in the beating zone. This is elementary to anyone who has worked with a Hollander, a conical refiner or a disc refiner. Let us now take a disc refiner, having completely smooth working surfaces, without any bars or pattern. If the clearance between the discs is sufficiently small, all fibres would have to pass an area where the beating action operates, provided a sufficiently high pressure difference exists to have the stock pass through the system. As a matter of fact, attempts to build such a machine in this laboratory have failed completely so far. Within a few seconds, the system is clogged if the slit is kept at the same order of magnitude as is the case in commercial beating machines and at normal beating consistencies.

The basic idea of the experiment is explained by reference to Fig. 1, which shows a laboratory disc refiner. The upper disc is rotated while the lower one is stationary and the clearance between the discs can be adjusted.

The stock enters upwards through a centre hole in the lower disc and is treated between the discs and leaves horizontally. The basic idea was to use flat discs and such a small clearance between them that you could assume that all fibres passing the clearance had been subjected to the same forces. This idea did not work. Even when the clearance was of the order of 0.1—0.2 mm., the system clogged very rapidly, more rapidly at higher pulp concentrations. Then we abandoned the idea of flat working surfaces and circular indentations were drilled at random over the working areas of both plates (exemplified by *A* and *B* in the figure). The system still did not work, though it did so when finally at least one indentation (say, *C*) was placed so that it broke the outer periphery of the working area of one of the discs and a beating effect was observed. The existence of the critical indentation implies that it is possible for fibres to pass through the working zone by passage from one indentation to another all the way when the two plates revolve relatively. There is nothing that forces the fibres to pass through only along a flat surface. Compare the importance of the so-called check ring of some commercial disc refiners.

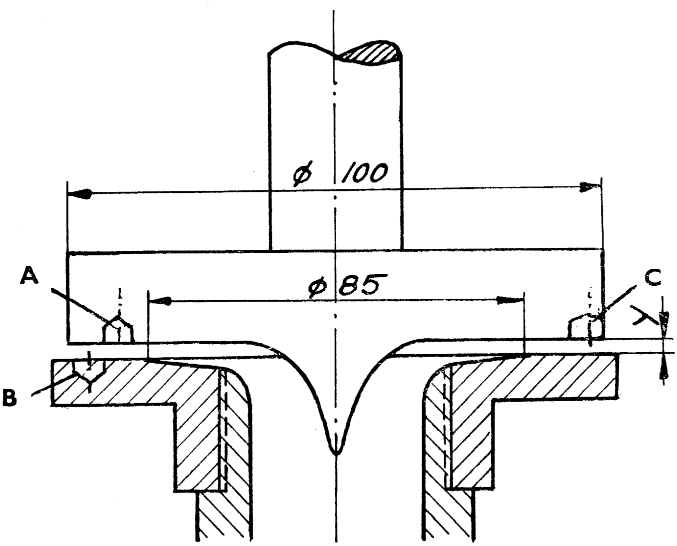

Fig. 1

It took us a long time to realise the reason for this. The statistical theory of screening explains the effect.[15,16] The slit acts as a screen slit and the probability of passage of water molecules through this slit is much higher than the probability for a fibre to pass through it. Consequently, the consistency of fibres at the entrance will increase and the system will clog like a pulp screen without pulsations. It is necessary to introduce a flushing device. This flushing device is the separation between the bars. In order to demonstrate this, the following experiment has been carried out. In one of the flat surfaces of the disc refiner, circular indentations were drilled at random over the surface, each 5 mm. deep. The system still clogged. Then, similar irregularly spaced indentations were drilled in the other plate, with the same result. Finally further indentations, two in number, were made with their centres outside the edge of one plate. Immediately, the system started to work, having a strong beating action. It was easy to find out that, with these last extra holes, there existed the possibility of an open channel across the surface at least at some relative positions of the two plates. All sorts of indentations of the working surface producing a channel from the centre inlet to the outer periphery of the system allowed beating to be carried out.

These observations alone are sufficient to understand that the fibres are treated differently.

Consequently, when strength data are measured on sheets from beaten pulp, we obtain a result from a very composite mixture of differently treated fibres.

Of the many experiments on beating and paper properties, two different types of studies seem worth consideration here. The first are fractionation experiments with beaten pulps. Many such experiments have been carried out. Some of the most comprehensive recent experiments have been carried out by Stephansen,[17] who, beating in a PFI laboratory beater, first confirmed Strachan's view that the fines contribute little towards the ultimate strength of the pulp. The tensile strength of a handsheet made from the fibres left on mesh 20 was higher than that of the composite stock within the range of beating of technical interest. Sheets from fractions on meshes 20 and 35, drawn from pulp samples after different beating times, all showed a very small slowness range measured as °S.R. Within the range observed (13°—18°S.R.), however, the breaking length of the handsheets increased from about 2 500 m. to about 10 500 m. The original pulp had a freeness of 78°S.R. when beaten to the higher strength figure. Stephansen notes that the trends obtained in tensile testing agreed with those found for other ultimate strength properties.

The other experimental observation that is thought pertinent in this connection emanates from experiments by Doughty[18] on the influence of wet pressing on the mechanical properties of a sheet. Doughty found that, by increasing wet pressing in a flat press to high figures, it was possible to obtain from one pulp sample results that, when plotted against applied pressure, showed all the well-known details of the so-called beating curve, showing the variation in ultimate strength properties with beating time. Of special interest is Doughty's observation that this was impossible if the pulp was unbeaten. If the pulp was beaten very mildly, however, further beating did not change the picture. Later, Nordman and Gustafsson[19] confirmed these results and extended the study by opacity measurements. It was found that any tensile strength could be obtained through a suitable combination of beating and wet pressing.

From optical studies, they concluded that the whole bonded area of the paper, as inferred from opacity measurements, does not contribute to the ultimate strength of the paper.[20] In this connection, it is worth remembering that the apparent specific volume of paper has been shown many times to be closely related to its strength.[21,22]

Experiments by the present writer have shown that, if a beaten pulp is classified, not primarily according to fibre length, but according to the ability of the fibres to build up drainage resistance, these fractions, converted into handsheets, have small ultimate strength variations, but considerable variations in opacity and porosity.

The experimental method used is essentially described by Steenberg and co-workers.[23] From a flowing pulp suspension, a sheet is made on a wire at rightangles to the direction of flow under known dynamic pressure drop through the wire. The type of fibres to accumulate on the wire will be determined by the relation between the pressure forcing them on to the fibre layer caused by the pressure drop and their hydraulic resistance properties, which tend to wash them off the wire. The method consequently separates the fibres partially by their size, but also according to their hydraulic resistance in the flow, being smaller for a flexible particle than for a stiffer one. By varying the rate of flow, it was possible to obtain fractions giving handsheets with air resistance ranging 75—1 000 sec. (Gurley) from one beaten strong sulphite pulp. In this range, there was a variation of less than 15 per cent. in tensile strength, the sheets with the higher air resistance figure being weakest.

All these observations seem to indicate that the ultimate strength properties are essentially determined by the less damaged fibre material and the contact these fibres make.

Generally, beating is thought of as a process of shortening fibres and of increasing their surface by bruising, splitting, fibrillation, etc. One very important property in this connection is obviously the flexibility of the fibres. Much seems to be in favour of the opinion of Clark[24] that fibre flexibility, both dry and wet, is the second most important item in this connection, its importance only overshadowed by fibre length according to this writer.

Two fibres, originally identical, may become differently treated during beating so that they still have the same length, though one of the fibres is more flexible than the other, because of the mechanical action of the beating engine. These two fibres contribute differently to hydrodynamic resistance. The hydraulic properties of the fibres will have an effect on sheet formation. Furthermore, the lower springback of the flexible fibre will increase the possibilities of surface tension forces during drying keeping the fibres in such intimate contact that an increased area of bonding is produced. The results of Doughty's experiments are then explained on the basis of the plastic deformation of the fibres caused by the high pressure.

From the above, it is obvious that fibre length determinations as a measure of beating action have many limitations. If the fibre length distribution curve is determined by microscopical measurements, the influence of flexibility is overlooked. Furthermore, spring and summer fibres of the same length must be supposed to be different in this respect and to respond differently to beating. If the fibre length determination is made by some kind of fractionating experiment, the probability of passage through the different screens is determined not only by the fibre dimensions, but also by their stiffness. It is obvious that a highly flexible fibre will have greater possibilities of passing through a hole than a stiff one, especially if the flow conditions are laminar.

A higher degree of swelling increases the flexibility. Removal of the outer parts of the cell wall, acting as a swelling restraint, must also be supposed to increase flexibility. The brittle character of this part of the fibre and the fact that it is damaged or even removed in the early stages of beating is apparent from many observations.(25,26). This may explain why Doughty had to use some beating before he could observe by wet pressing any considerable strength effect of the applied pressure.

The different response to beating by virgin, unprocessed cotton fibres and fabrics or textile yarns may be due to the flexing of the cotton fibre in the textile machinery, etc. As a matter of fact, the energy used in a cotton mill to produce yarn is considerably higher than the energy required to convert round logs to newsprint, amounting to some 2 500 kWh. per ton of cotton yarn. It is also known that linters have to be treated by a preliminary bruising action in the beater before any normal beating results can be obtained. Only then will linters give paper properties characteristic of cotton rags.

A strong pulp compared with a soft one must be assumed to differ in fibre flexibility. The strong pulp, containing more material capable of swelling, will in the swollen state, with the outer restraining layer removed, constitute a more flexible material than the soft pulp made from the same raw material, but which is only the skeleton of the more highly organised material of the original fibre. The flexible material will increase its flexibility further by mechanical action and be less liable to brittle breaking or shear action than will the soft pulp fibres. Beating will produce more debris to obstruct drainage from a flexible material than will a stiff one. These fines do not materially influence the ultimate strength properties of the sheet, but may be essential to other mechanical properties, like stiffness, irreversible work of straining, etc.[(20)] and will also be of great importance for properties like porosity and opacity.

The larger the contact area between elements capable of supporting stress, the higher will be the ultimate tensile strength. Such an effective bonding area can be reached by increasing the flexibility of the fibre by beating or by wet pressing, provided the surfaces of the fibres are capable of bonding. A method to determine the spectrum of flexibilities of fibres in the course of the beating and to compare different pulps in this respect may be of the greatest interest. A solution to this intricate problem may have to come over a working hypothesis based on preliminary experiments with model fibre systems.

Summing up, it is necessary to bear in mind that even for relatively homogeneous systems like foils or plastics, knowledge of the relationship between the chemical composition, molecular weight distribution, plasticisers, etc. and mechanical properties is limited and essentially empirical. A prerequisite seems to be an analysis of stress distribution in the system.

We know very little about the stress distribution of paper under stress and strain, even under the simplified conditions of the laboratory tests. The microstress distribution, as determined by the testing system, may be found from relatively simple studies. The microsystem of stress distribution is much more intricate.

It is known, for instance, that permanent deformations of the fibres themselves caused by beating, curlation, etc. is of importance. Deformations of the wet and dry sheet or stresses set up in it during drying have considerable influence on its behaviour. Fibres of different types like long and short, fibrillated or non-fibrillated, those having higher or lower pentosan contents, etc. can not in all probability be considered separately. The interaction between all present classes of fibres and fibre fragments in the sheet must be so strong that it may be futile to work on the hypothesis that one single factor is the main cause. No such type of fibre particles can be considered as constituting one independent part of the sheet. In all probability, only a theory based on the assumption that a number of factors mingle can be supposed to have any possibility of success.

Beating and the mechanical properties of paper is a challenge to the increasing number of physicists working in the field of pulp and paper and one to be approached humbly.

REFERENCES

1. Corte, H. and Schaschek, H., *Das Papier*, 1955, **9** (21/22), 519
2. Andersson, O. and Steenberg, B., *Svensk Papperstidn.*, 1950, **53** (1), 1
3. Bergström, J., *Svensk Papperstidn.*, 1956, **59** (8), 305
4. Ivarsson, B. and Steenberg, B., *Svensk Papperstidn.*, 1948, **51** (2), 23
5. Steenberg, B., *Svensk Papperstidn.*, 1947, **50** (6), 127
6. Andersson, O., *Svensk Papperstidn.*, 1951, **54** (17), 591
7. Weibull, W., *Trans. Roy. Inst. Techn. Stockholm*, 1949, No. 27
8. Wahlberg, T., *Svensk Papperstidn.*, 1951, **54** (20), 710
9. Nederveen, G. van and Royen, A. H. H. van, *Paper-Maker*, 1952, **124** (4), 316
10. Brecht, W., *Das Papier*, 1952, **6** (21/22), 443
11. Steenberg, B., *Pulp and Paper Mag. Can.*, 1949, **50** (3), 207
12. Andersson, O., *Svensk Papperstidn.*, 1953, **56** (11), 403
13. Hamburger, W., *Edgar Marburg Lecture, A.S.T.M.*, 1955
14. Bozza, G. and Ghisoni, P., *Nuovo cimento* (Suppl. Series 11), 1954, **9**, 1
15. Steenberg, B., *Svensk Papperstidn.*, 1953, **56** (20), 771
16. Steenberg, B. and Kubát, J., *Das Papier*, 1956, **10** (5/6), 83
17. Stephansen, E., *Norsk Skogind.*, 1948, **2** (8), 207
18. Doughty, K. H., *Paper Trade J.*, 1931, **93** (15), TS 162
19. Nordman, L. and Gustafsson, C., *Paper and Timber* (*Finland*), 1951, **33** (2), 36
20. Nordman, L., Gustafsson, C. and Olofsson, G., *Paper and Timber* (*Finland*), 1954, **36** (8), 315
21. Gustafsson, C. and Nordman, L., *Pappers-och Trävarutidskr.* (*Finland*), 1949, **31** (19), 353
22. Giertz., H. W., *Proc. Tech. Sect. B.P. & B.M.A.*, 1952, **33** (3), 487
23. Steenberg, B., Bergström, J., and Kjensjord, R. I., *Tappi*, 1954, **37** (11), 512
24. Clark, J. d'A., *Cellulose and Cellulose Derivatives II* (Interscience, New York, 1954, 627
25. Steenberg, B., *Svensk Papperstidn.*, 1947, **50** (11 B, Jubilee Vol. E. Hägglund)
26. Algar, W. H. and Giertz, H. W., *Svensk Papperstidn.*, 1951, **54** (20), 693

Transcription of Discussion

DISCUSSION

CHAIRMAN: I would like to give an opportunity now for the discussion of any details of Mr. Hunger's paper, in advance of Session 3.

MR. P. E. WRIST: In the light of your subsequent argument about the difference of drying down the parallel fibrils and the reticular fibrils, Mr. Hunger, to what factors do you attribute the difference between the sulphite and sulphate pulp micrographs that you showed very early on in your contribution?

MR. HUNGER: We found that the sulphite process only proceeds topochemically, thus leaving the deeper walls untouched in their later state, so that the microfibrils are more or less still surrounded with their protective substances such as hemicellulose and lignin. In the sulphate fibre, however, after the cellulose is destroyed, the lignin is found as an amorphous mass, contrary to the sulphite fibre, when it still remains in the form of the fibre. This sulphate fibre is swollen to such an extent that all its amorphous layers have been destroyed. Though still there, they are more or less statistically distributed over the fibre and, to a certain extent, no longer in their native places; these fibres are thus usually able to dry together in high hornification.

MR. A. P. TAYLOR: Might we have an idea of the approximate range of magnification in the slides we have just seen?

MR. HUNGER: The dot shown is one micron. The magnification you saw, with the enlargement of the projector, would have been 100 000 — 300 000.