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FUNDAMENTAL PROPERTIES OF HIGH STRETCH PAPER

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Synopsis—The studies upon which this contribution is based were made to investigate the structure and properties of high stretch papers. Webs produced by compaction and by creping, the two main commercial processes, were examined by light microscopy and physical testing.

The microphotography shows a variety of web configurations found in crepe papers, including examples of wave formations, internal delamination and two-sidedness. The characteristic fibre orientation and densification are illustrated by photomicrographs of webs taken before and after the compacting process.

The mechanical behaviour of high stretch papers is illustrated by typical stress/strain curves and a discussion of their behaviour during the process of straining.

Preface

BY WAY of explanation, the word *fundamental* as used in the title has been thought of as meaning those constituents without which a product would not be what it is, as well as—in a broader sense—those particular combinations of structural and mechanical properties of high stretch papers that are not found in other grades of paper.

Secondly, I doubted whether a discussion of creped paper was outside the theme of this symposium, but compaction, however very much a consolidating process, is related to creping to the extent that these two processes are the only ones widely used for adding high extensibility to paper. Moreover, since there has been little published on the structure of either creped or compacted webs, I thought it logical to discuss both types of paper.

Introduction

PAPER webs are subjected in both wet and dry state to consolidating forces such as vacuum, pressing and calendering applied to remove water, reduce bulk or control surface finish. The main direction of these forces is normal to the plane of the web. Machine-direction forces are applied to paper webs as either tension or compression. Machine-direction tension is common to nearly all papermaking operations, but is limited in magnitude by the rupture strength of the web. High machine-direction compressive forces can be applied, however, resulting in the unusual changes in the structure and mechanical properties of paper that are identified with high stretch papers.

Perhaps the oldest method of applying machine-direction compressive forces is creping, a process of vague origin, but well known before the turn of this century. A more recent development is compaction, a process that applies simultaneously both high machine-direction and high normal forces to a moving web of paper.

One of the main results of both creping and compaction is increased stretch, a fundamental property of paper not controlled to any large extent by any other commercial papermaking process. Changes in the stretchability of paper, regardless of the means, affect many other sheet properties—flexibility, energy absorption capacity, hygroexpansivity, to name just a few.

An investigation was made of a number of the characteristics of high stretch papers, using light microscopy and conventional physical testing methods. The original study, a portion of which is presented here, was done in two parts—(*1*) an examination of papers produced on laboratory equipment by compaction and by creping and (*2*) examination of a number of commercial grades.

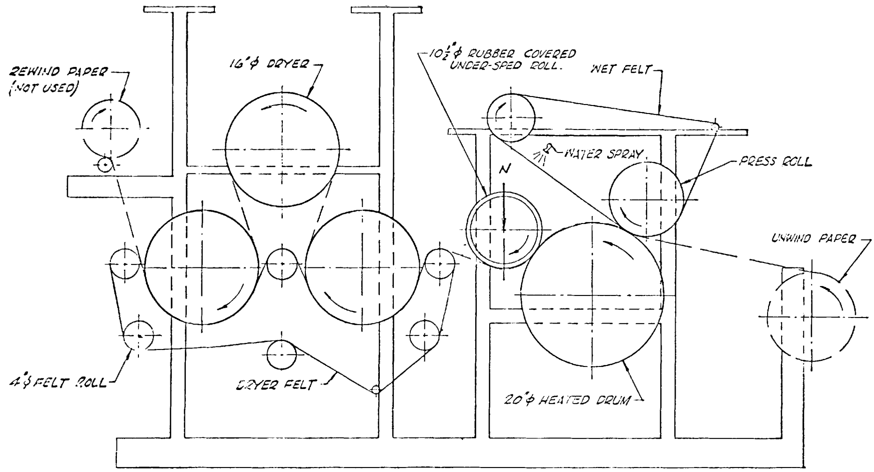
Process conditions

THE laboratory kraft paper webs were produced in a wet state by an experimental laboratory papermachine and subsequently converted to compacted or creped paper on the apparatus described below.

Fig. 1 is a schematic layout of the equipment used to produce the creped papers.[1, 2] The creping section consisted of a heated metal roll, a pressing roll with felt and a creping roll, the latter covered with 60 durometer rubber. Surface velocity of this roll was adjusted so that the heated roll oversped the creping roll by the ratio 2.5:1. These two rolls made line contact, thus nip pressure was nil. In practice, the high differential speed precludes using nip pressure because of high power requirements and roll damage.

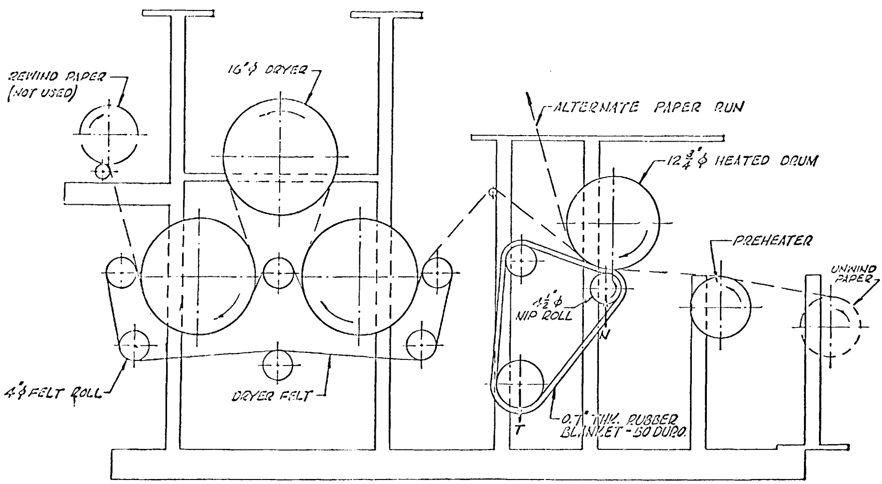
Fig. 2 is a layout of equipment used to produce compacted paper.[3, 4] A similar arrangement was used in which the rubber blanket was replaced with a low differential speed (1.2:1), rubber-covered roll. Because the products of the two systems were indistinguishable, results from both blanket and roll compacting equipment are included, but not separately identified.

The general scheme of operation is apparent from the sketches shown, but it might be well to mention one or two additional points. Although this creping system employed a doctor roll, successful operation depends (as does a doctor blade) on control of the adhesion of the web to a hard-surfaced roll.



"N" ARROW INDICATES DIRECTION OF LOADING FOR NIP.

Fig. 1



"T" ARROW INDICATES DIRECTION OF LOADING FOR BLANKET TENSION.
"N" ARROW INDICATES DIRECTION OF LOADING FOR NIP.

Fig. 2

Both roll and blade creping also depend on control of residual stretch, at least to some extent, by the draws following the point of creping. Examples of commercial creped papers presented are all of the doctor blade type.

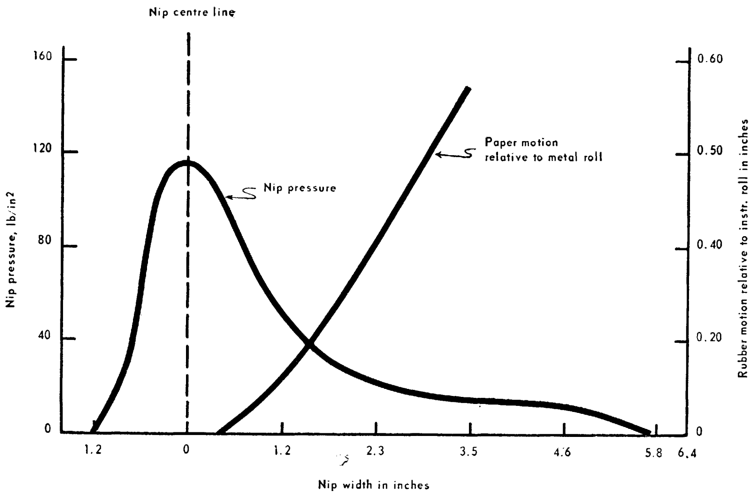


Fig. 3

Although detailed discussion of the mechanics of the compaction process is not a part of this presentation, general conditions of the pressure and velocity gradients in a compactor are shown in Fig. 3, data obtained from a special instrumented unit of about the size shown in Fig. 2.

Photographic studies

It is well known that creped papers of greatly different characteristics can be produced by changing the processing conditions. Most important among these are sheet plasticity, degree of adhesion of the web during creping, and extent of pull-out of crepe, either wet or dry. To study these characteristics, creped papers were produced in the laboratory by altering degree of adhesion of the web to the creping roll and the extent of wet pull-out of stretch after the point of creping, using as the base kraft web as shown in Fig. 4.

Fig. 5 is an example of the result obtained when creping at conditions of relatively low adhesion followed by pull-out of approximately 30 per cent of a total of 38 per cent crepe, leaving a residual of 8 per cent crepe. This web is an example of the familiar wave structure associated with creped paper. Waves of this sort, on both sides of the web and in-phase, are found also in various industrial papers such as the off-machine creped kraft bag grade

Fig. 4—Laboratory-made kraft, 45 lb/3 (

Fig. 5—Laboratory-creped kraft, 53 lb/3

Fig. 8—Laboratory-creped kraft, 53 lb

Fig. 9—Laboratory-creped kraft, 63 lb/3

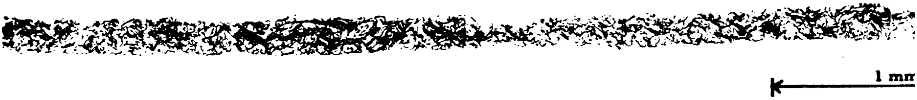
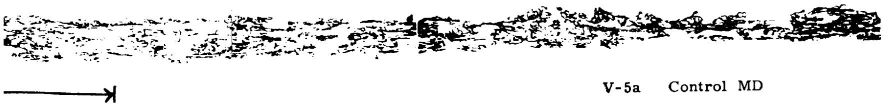
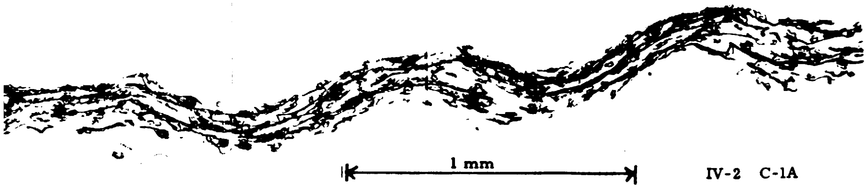


Fig. 11—Laboratory-compacted kraft, 60 lb



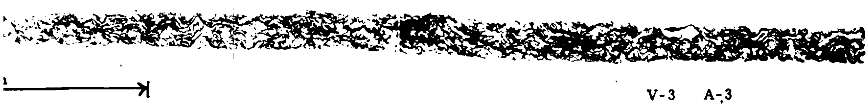
)00 ft^2, substance, 1.6 per cent stretch



000 ft^2 substance, 8.4 per cent stretch

ɔ/3 000 ft^2 substance, 10 per cent stretch

000 ft^2 substance, 10 per cent stretch



ı/3 000 ft^2 substance, 18 per cent stretch

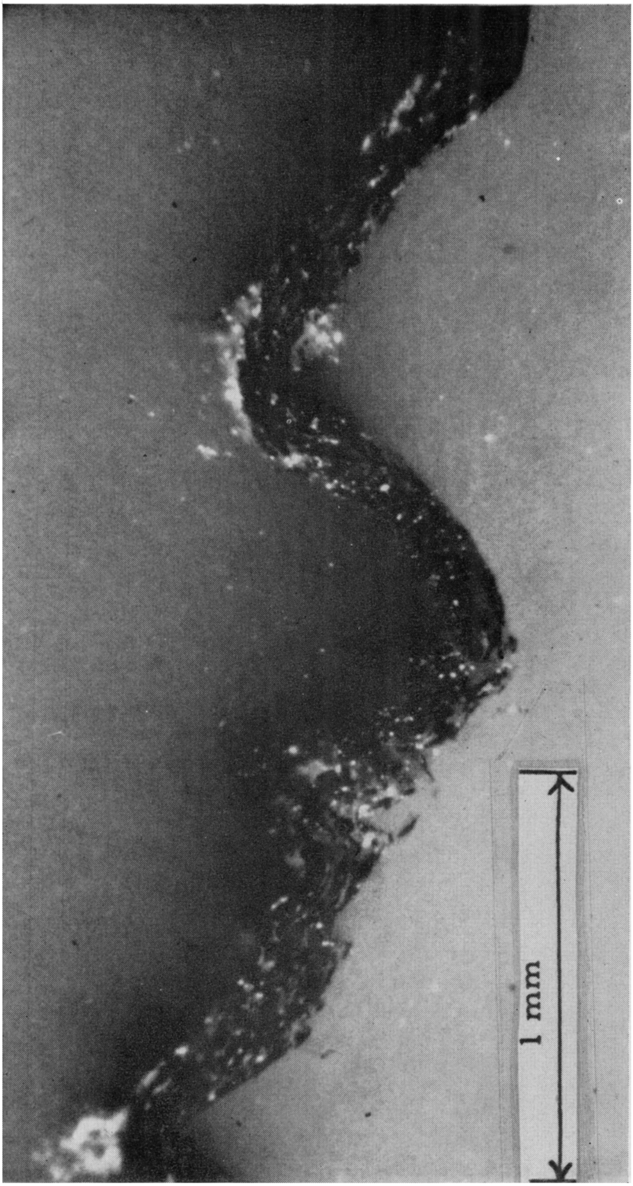


Fig. 6—Creped kraft with 38 per cent stretch, 75 lb/3 000 ft² substance

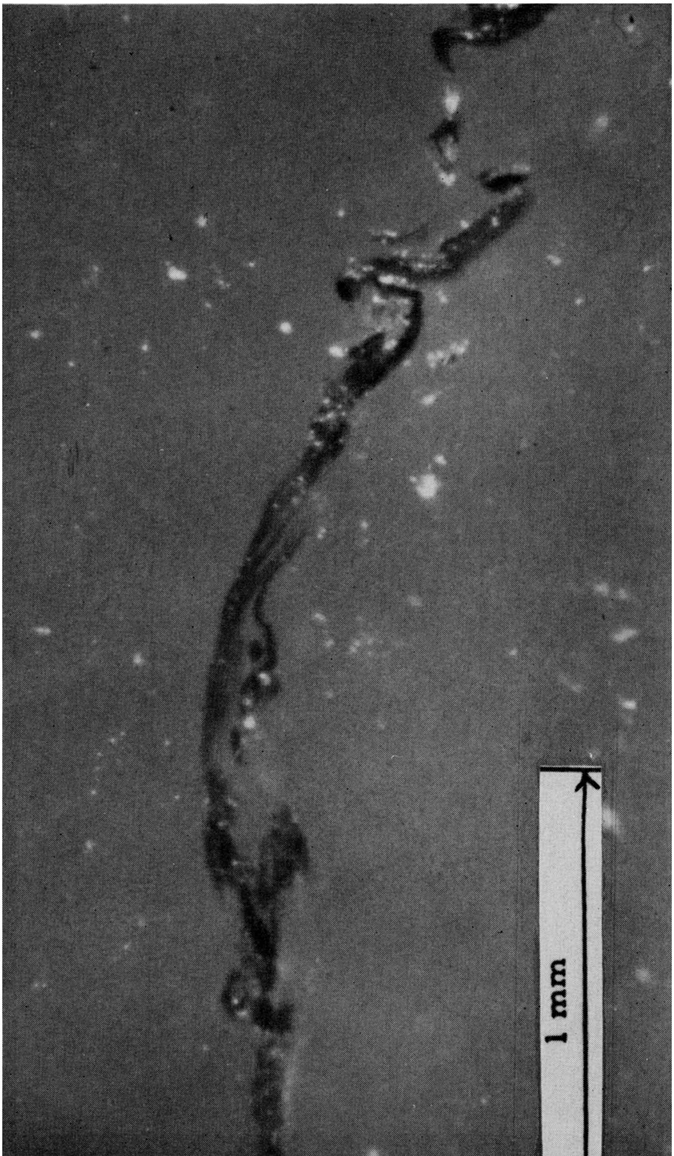


Fig. 7—Facial tissue, 10 per cent stretch

shown in Fig. 6. Waves of this type—that is, in phase—are simple body folds, however; they are often distorted and of erratic frequency such as the commercial tissues shown in Fig. 7.

If adhesion of the web is progressively increased, the web is forced to fail internally. Fig. 8, a creped web of the same base material as Fig. 5, is an example of non-uniform, internal delamination. Frequently, as is the case here, delamination is such that well-defined voids are present in the vicinity of the wave crests. Delamination, if more drastic, will destroy much of the original sheet formation. Fig. 9 illustrates the extent to which such destruction of sheet structure can be carried.

Creped papers that have internal delamination are characterised by two-sidedness, often very pronounced. In fact, Fig. 9 is an instance of the wave pattern not penetrating through the void zone. A still better example of this phenomenon is shown in Fig. 10, a commercial, heavyweight creped paper with 22 per cent stretch.

These few photographs also illustrate the wide range of fibre orientations and configurations that are produced by creping. Because of such diversity of structure, mechanical properties of creped paper in general vary perhaps more than those of any other general class of papers.

Compacted webs are produced under conditions designed to maintain the faces of the web substantially straight and parallel. As a result, structural changes are more easily described—in fact, the one web in Fig. 11 (an 18 per cent stretch compacted web produced from the base web of Fig. 4) shows the essential structure associated with any compacted web. As can be seen, the fibres comprising the web have been forced into the voids present in the base sheet, with the result that the individual fibres have assumed configurations characterised by high-frequency curl. At several locations in this photograph, fibres can be traced that remain within the depth of focus for some length and that contain this curl.

Stress/strain behaviour

GENERALLY speaking, high stretch papers, both creped and compacted, have lower initial slope (stress/strain ratio), lower tensile strength at yield, more rapid decay of stress after yield, lower ultimate tensile strength than their conventional counterparts and, frequently, pronounced post-yield inflection.

Stress/strain ratio

In creped papers, lowest stress/strain ratio was found in webs containing either large, well-defined body folds or very high stretchability. The curves in Fig. 12 are typical for such papers. At the other extreme, high ratios were

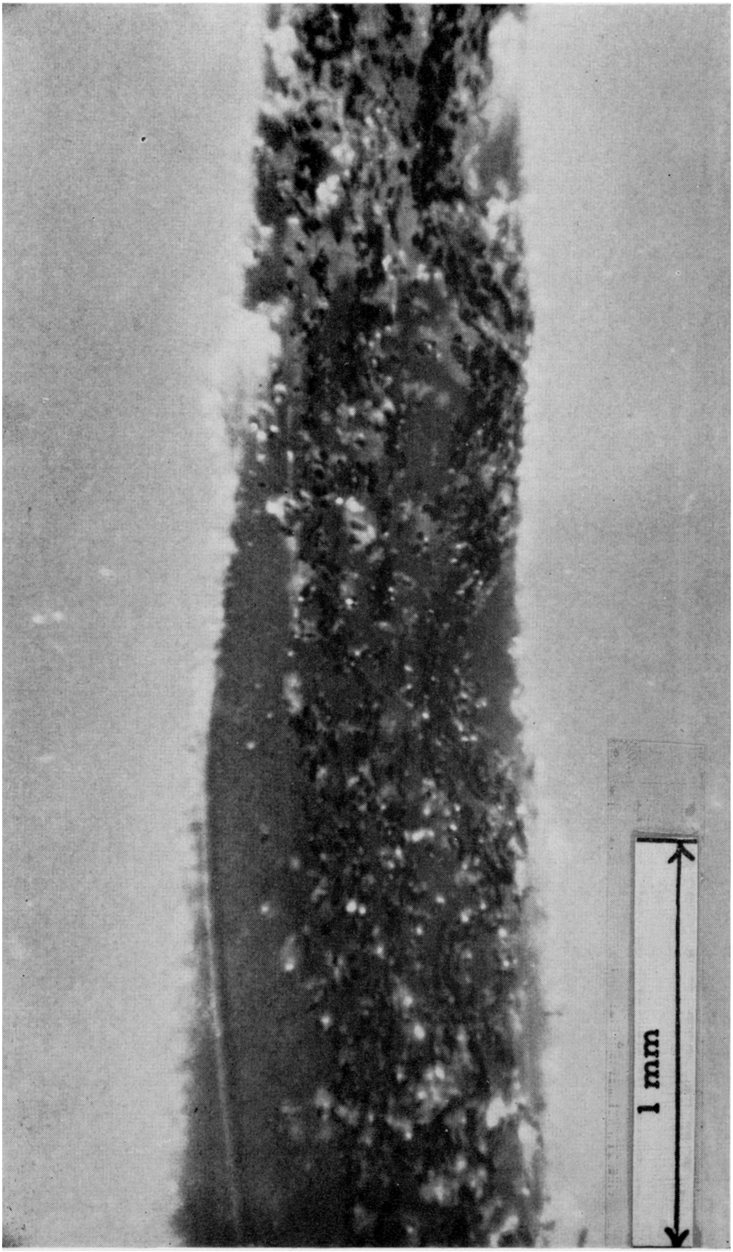
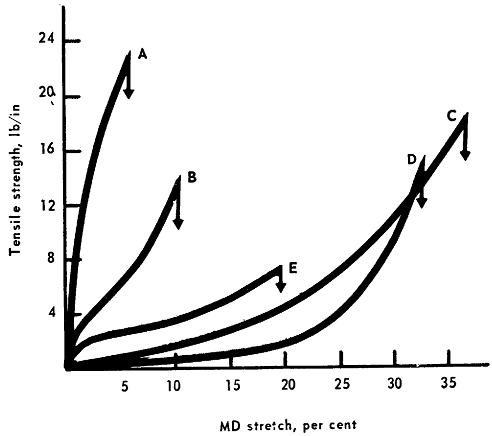


Fig. 10—Creped kraft with 22 per cent stretch, 150 lb/3 000 ft² substance

found in creped papers with lower stretch, particularly those produced by on-machine wet creping followed by multi-cylinder drying. In such cases, the stress/strain curves would be expected to show the influence of natural shrinkage.



A. Low-stretch machine crepe, 50 lb
B. Laboratory crepe, 50 lb
C. Off-machine crepe, 75 lb
D. Off-machine, crepe, 65 lb
E. Laboratory crepe, 60 lb

Fig. 12

Typical stress/strain curves for compacted paper are shown in Fig. 13. Within the process, the most important factor affecting the early part of the curve is amount of compaction. Additionally, if process conditions are not controlled properly—for example, poor condition of roll surface or poor moisture profile entering the compaction zone—surface imperfections occur that lower the stress/strain ratio. Once a web is compacted and dried, it is affected by moisture changes similar to conventional paper, but generally to a greater degree. A change in moisture from 4 per cent to 10 per cent, for example, will reduce the stress/strain ratio of commercial compacted sack paper by about one third.

At this point, note that good control of final moisture content in compacted webs is also important, because of its relationship to hygroexpansivity and permanent set. The amount of permanent stretch removal at low tension is a function of the stress/strain ratio and time-relaxation characteristics. Because of this, wide moisture differences in a roll can cause undesirable web length variations.

The amount of permanent stretch or set is additionally a function of the amount of strain in both creped and compacted papers, examples of which are presented in Fig. 14. It is interesting to note the reverse slope that develops in the stress/strain path during repeated loading of this creped paper.

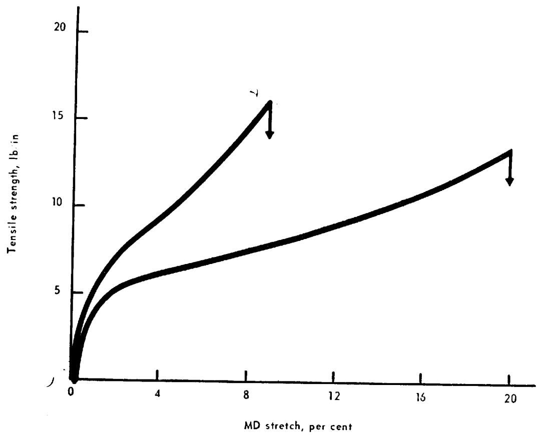


Fig. 13

Ultimate tensile loss

The amount of loss in the tensile strength of creped paper can be highly variable as is well demonstrated by Fig. 5, 8 and 9. These webs have ultimate tensile strengths, respectively, of 13, 8 and 3 lb/in. The first two have respective stretch values of 8 per cent and 20 per cent, so that tensile strength differences can be related to stretch and both webs have ultimate elongations

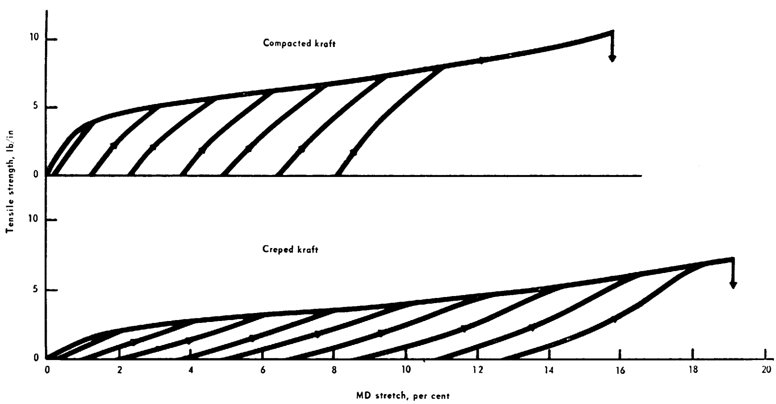


Fig. 14

approximating that indicated by actual shrinkage. The web with only 3 lb/in tensile strength has less than half the predicted amount of elongation, indicating that the web structure has been severely damaged.

Loss of ultimate tensile strength by compacted papers usually follows a pattern such as shown in Fig. 15. We have found no mechanical treatment that materially changes the extent of loss in tensile strength, although we have compacted several commercial grades of electrical papers that showed little change of either initial stress/strain ratio or ultimate tensile strength.

One surprising fact about tensile strength loss in compacted papers (and to

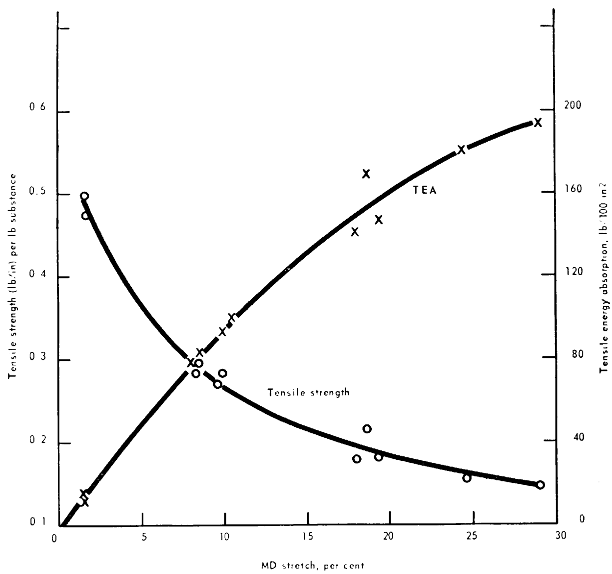


Fig. 15

some extent in creped papers as well) is shown in Fig. 13 and 16. Strain, short of rupture, has little effect on the ultimate tensile strength of dry compacted papers at normal testing speeds; if a wet compacted web is stretched after compaction, but before drying, a 'tensile strength loss recovery' follows. Fig. 16 illustrates this effect. The paper with 18 per cent stretch did not have any stretch removed while in the wet state. The two samples showing 4 per cent and 9 per cent elongation were first compacted to 18 per cent, then stretched immediately afterwards before drying. The control was dried, only without any compaction or stretching.

Visual changes during straining

A number of surface, cross-sectional and edge photographs were made of high stretch papers during the straining process. Creped papers show a reduction in surface roughness, although none approached the surface quality of the base paper webs. Compacted papers after straining have a more open surface structure, readily observed at low magnification.

Perhaps the most interesting photographs of this group are those shown in Fig. 17. These are edge pictures of a compacted web after removal of three quarters of a total of 19 per cent stretch. Although caliper measurement by

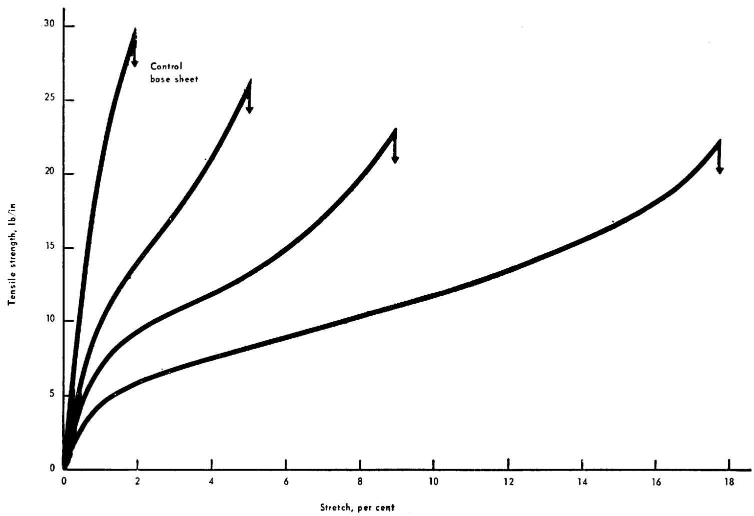
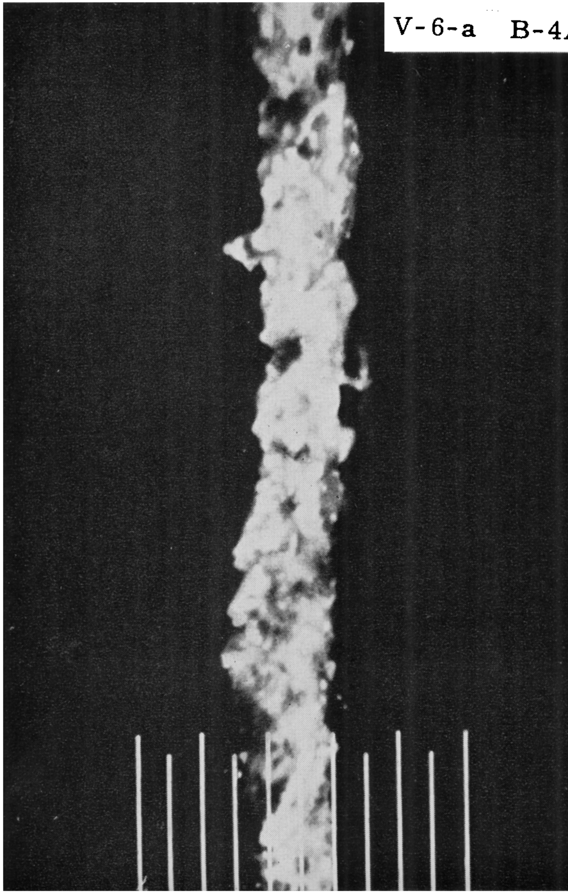


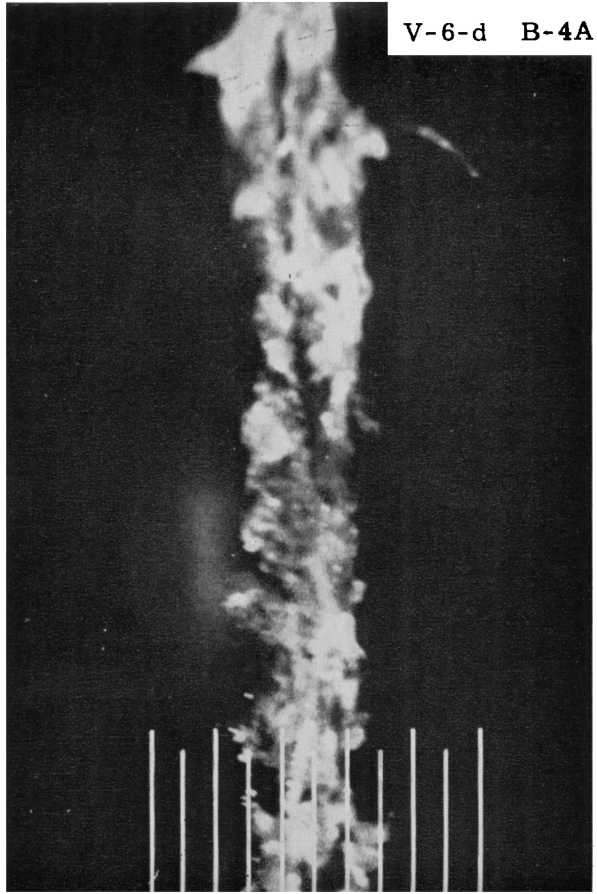
Fig. 16

several mechanical means also showed increased thickness during stretching, the amount was usually below 10 per cent, much less than shown by photographs. It is likely that fibres that spring up on the surface during straining are easily laid down by external pressure of calipering instruments, accounting in part for the difference. The fibres photographed are also on the extreme edge and may not be entirely representative of the rest of the web.

Other properties

Test values related to energy absorption capacity such as stress/strain work area and impact fatigue are increased with stretchability, unless the ultimate tensile strength loss is extreme. Typical gains of energy absorption capacity in compacted paper are shown in Fig. 15.


V-6-a B-4A


V-6-d B-4A

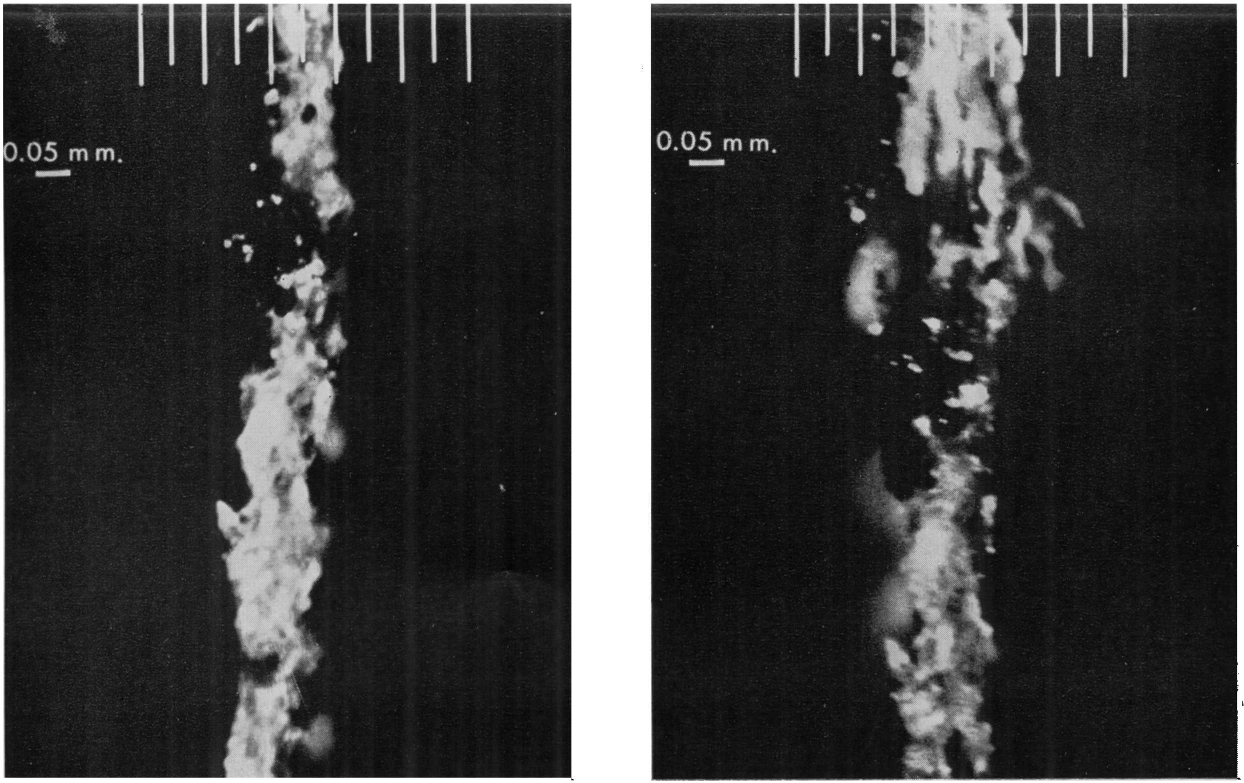


Fig. 17—Edge photographs of compacted paper (*left*) before stretching and (*right*) after removal of three quarters of a total of 19 per cent stretch

Higher density is usually associated with increases in tensile strength when brought about by beating or wet pressing. Density of compacted webs is additionally controlled by the amount of compaction and the normal pressures applied in the compaction zone. Density increase of 1 per cent for each 1 per cent compaction is common commercially and much more than this is not difficult to obtain.

Creping lowers density, although precise measurement is very difficult. Table 1 gives the density of those laboratory webs previously shown as determined by caliper and substance measurement. Air resistance changes are also included.

TABLE 1

Sample	*Substance, lb/8 000 ft²*	*Stretch, per cent*	*Bulk density, lb/in*	*Air resistance, sec/100 cm³*
C-1A (Fig. 5)	53	8.4	0.0113	0.4
C-1 (Fig. 8)	54	9.9	0.0114	0.4
C-3 (Fig. 9)	63	10.4	0.0107	0.2
A-1	50	8.6	0.0215	3.5
A-3 (Fig. 11)	62	19.2	0.0264	9.3
Control (Fig. 4)	44	1.6	0.0179	2.5

Conclusions

THE TWO types of high stretch paper discussed are illustrative of the major mechanical methods of obtaining high stretch in paper. Creping imparts either body folds or a combination of body folds coupled with fibre rearrangement and sheet bulking.

Compaction depends on fibre bending and buckling. The effect of compaction is predominantly in the direction of recoil of the elastomeric surface, but some increase in stretch occurs in all directions. In a web compacted 10 per cent in the machine-direction, the cross-direction stretch generally will increase 1–1.5 per cent. Although smaller, this is a significant change, because of the importance of cross-direction strength in many packaging applications.

There is no doubt that high stretch papers introduce drastic changes in the configuration of an already complex fibrous network; on the other hand, a better understanding of their particular mechanical behaviour should lead to a more complete understanding of the fundamental properties of paper.

References

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Transcription of Discussion

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.

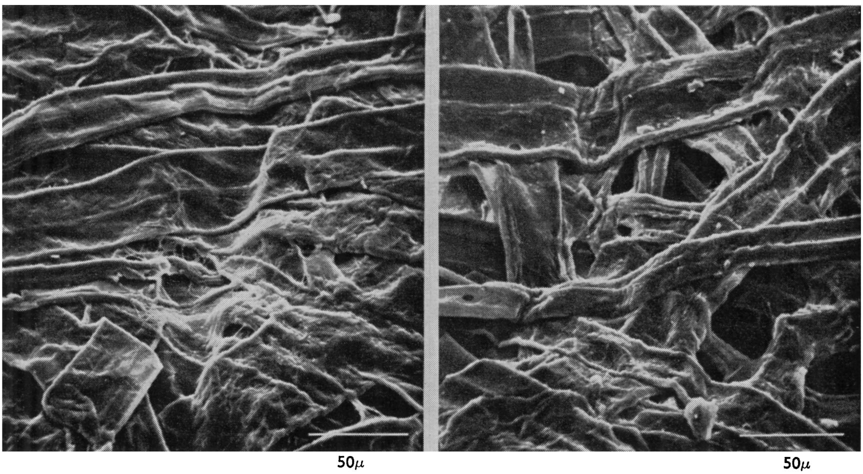
Mr Ihrman—No, I rely on the behaviour of the locomotive wheel, but I will make a comment later to Peel's contribution.

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.