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THE BEATING OF CHEMICAL PULPS– THE ACTION AND THE EFFECTS

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ABSTRACT

The article reviews the state of knowledge of the action and effect of beating on chemical pulps. The view is put forward that the problem is so complex that researchers have been tempted to oversimplify it, but some of these simplifications now may represent a barrier to progress. New approaches incorporating newly developed research techniques are proposed for future research efforts.

INTRODUCTION

Another review on beating and refining? Is it really necessary? Over the years some excellent reviews have been written, notably those of Emerton (1), Higgins and de Yong (2), Fahey (3), Atack (4), Clark (5) and Ebeling (6).

The research effort on the subject has been both substantial and protracted, dating back to the early years of the century. By 1923, Sigurd Smith (7) was already writing "The existing state of knowledge of the principles which it (beating) involves is distinctly unsettled. This is pretty clearly evidenced by the numerous articles on beating appearing in the technical press, which gives the impression that the subject is practically inexhaustible".

Why are these words no less appropriate today? Why after all these years has the problem not been solved?

Researchers are unanimous on one point. The subject is very complex. Fahey (3) says, "The subject is very complex", Higgins and de Yong (2) say, "The complexity of the beating process has often been emphasized".

It seems however to this author that this statement has never been followed up by an adequate discussion of the complexity. Rather, it has led to attempts at oversimplification at too early a stage in the research process. The intent of this review is to explore the complexity, to spend time discussing what has not been done as well as what has, to pose questions for the future as well as to record the past and to speculate on fruitful new avenues for research rather than to retread old pathways.

For the purposes of this paper we need to make two definitions:

The Beating or Refining Effect

The changes that take place in the structure of pulp fibres, leading to changes in fibre properties and consequently pulp and sheet properties, as a result of subjecting the wet pulp fibres to a mechanical action.

The Beating or Refining Action

The history of strains and stresses that pulp fibres are subjected to, by devices that create a beating or refining effect.

A complete understanding of the beating process then requires attention to the following four questions:-

1. What is the molecular, supermolecular and morphological structure of a wood pulp fibre prior to the beating action? What is the distribution of structures within and among fibres?

2. What is the average stress and strain history of a fibre undergoing a specific beating action? What is the distribution of stress and strain histories within and among fibres? How do these strain and stress histories differ

from one beater to another and how do they depend on the conditions of operation of a particular beater?

3. In what way and by what mechanisms is fibre structure changed in response to the strain and stress history?

4. What are the consequences of this change in structure for the properties of pulps in suspension and sheets made from them?

We, of course, have no complete answer to any of these questions. The problem is that we do not even know enough answers to be able to design beaters and refiners, to predict the response of new or different pulps to specific beating actions, or to predict the sheet properties of beaten pulps.

In the author's view, while an interminable search for answers to the above questions may have purely philosophical value, considerable economic advantage can be derived from furthering our ability to respond more effectively than in the past.

Our lack of knowledge has encouraged certain patterns of thought within which we seem to have become imprisoned. For example the change of the internal structure of fibres upon beating was described long ago by the amount of water taken into the cell wall and this description is widely used today. Yet the uptake of water is not at all important. What is important is the change in structure of the wall leading to changes in its mechanical properties. The uptake of water is an indication of the loosening of the structure and may contribute to its loosening. The uptake of water may not however be the only or the best measure of the changes in properties of the cell wall.

Similarly the action of the beater has been described in terms of two parameters, one to indicate the number of impacts received by a fibre and the other to indicate their intensity. There is no question that this approach has engineering value, but as a research tool it has severe limitations. Caution must be exercised in assuming that a model based on the number and intensity of impacts has real physical significance; after all, it has yet to be demonstrated that any impacts actually take place. The model has served a useful purpose in the design of refiners, but meets with difficulties in describing the beating actions of a Lampen ball mill, a PFI mill or a Hobart mixer.

The purpose of this review then is to encourage an escape from earlier thought patterns, which may now be impeding our progress, and to provide a jumping-off ground for further work. Inevitably it must link firmly to existing knowledge and must be developed in these terms.

The starting point for the discussion will be the structure of fibres and its change by the beating action.

For the purposes of this paper the word beating will be used throughout to include both beating and refining.

The Structure of Wood Pulp Fibres

Although much is known of the structure of wood pulp fibres, too little of this knowledge has been applied in beating research, because there are no rapid generally available techniques for measuring the relevant parameters. The average fibre length and its distribution can be rapidly measured (8) as well as the average coarseness (8) but that is all. There is no technique available for the distribution of coarseness. Moreover coarseness is not itself an adequate descriptor of the transverse dimensions. Fibres of the same coarseness can have quite different wall thicknesses, and there is no rapid method for the determination of wall thickness. Such simple questions as, "Are the coarser fibres of a furnish more or less resistant to beating?" cannot readily be tackled, even though the answer may shed considerable light on the action of the beater.

Furthermore it is rare for researchers to characterize their pulps by providing values of fibre length, coarseness and wall thickness, and yet it is difficult for others to interpret their results unless this is done.

At the cell-wall structural level the layers P, S_1, S_2 and S_3 have been defined, of which certainly the S_1 and S_2 layers play separate roles in the beating effect (1, 9, 10, 11). Yet there is no rapid method for determining the thickness of the S_1 layer. It is known to differ greatly in thickness from spruces to pines (12) but there has been no systematic study of its variation either within or between species.

The fibril angle of the S_2 layer is an important fibre characteristic, yet it can be measured only by the tedious process of microscopical examination of each fibre in a pulp sample.

At the molecular level the problem is more a question of lack of knowledge than lack of readily applicable technique. The conventional model consists of microfibrils of cellulose embedded in a hemicellulose-lignin matrix (13), arranged in an interrupted lamellar structure (14). What is the structure of the matrix that links the fibrils? This is all important in beating research, since one of the main features of the beating effect is the breakdown of this matrix.

The fibrils may be linked together by cellulose molecules leaving the crystalline portion of one fibril and becoming part of the crystalline portion of another. (Fig. 1(a)) It is possible that adjacent fibrils co-crystallize forming an effective crosslink. (Fig. 1(b)) This could be considered to be a special case of the so-called fringed-fibrillar theory put forward by Hearle for regenerated cellulose (15).

The hemicellulose portion of the matrix is highly oriented as evidenced from both infrared data (16) and its contribution to birefringence (17). It is conceivable that the hemicelluloses are co-crystallized with the cellulose fibrils and provide a link between them. This can either be by direct linkage (Fig. 1(c)) or by covalent linkage with the lignin matrix (18, 19) (Fig. 1d).

Although there has been extensive work on the chemistry of the matrix, at the moment our quantitative knowledge of the physical parameters needed to describe the structure is limited to the DP of the hemicellulose, the acid group content and the water of swelling. There is no agreement on the number of covalent bonds between hemicellulose and lignin or the extent of crosslinking within the lignin.

The structure of the cellulosic fibrils is still a matter of debate although they appear to consist of single crystals of the order of 3.5 nm in diameter. An important unresolved question is their length. There are no published values at all. Yet the properties of any fibre-reinforced composite depend on the length of its fibres. Values for the DP of cellulose in wood or pulp lie in the range 3,000-10,000 (20) which would

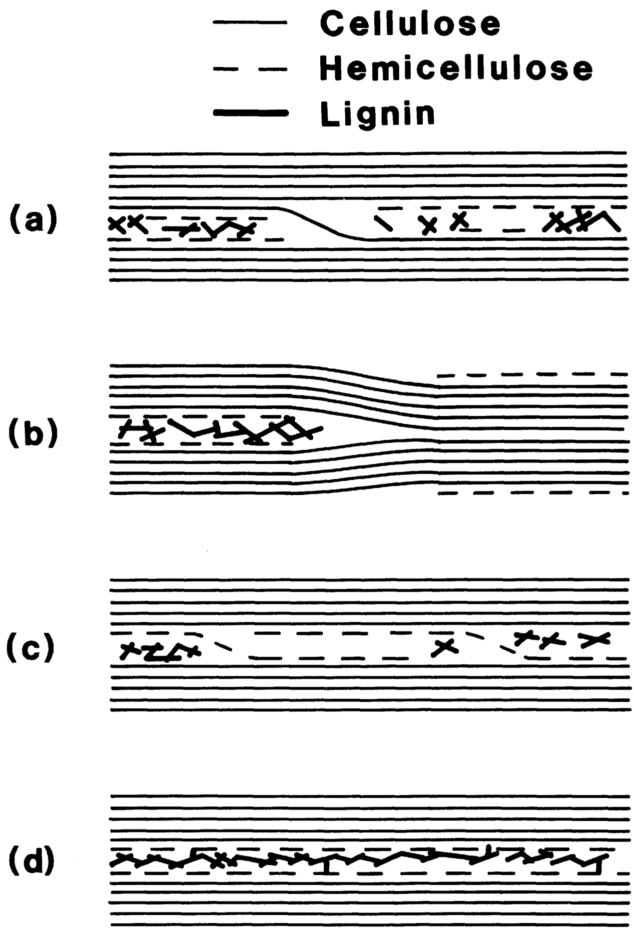


Fig 1 What holds the fibrils together in the cell wall?
Is it (a) bridging by cellulose molecules
(b) cellulose fibril cocrystallization
(c) bridging by cocrystallized hemicellulose molecules
(d) cocrystallized hemicellulose molecules cross-linked by lignin
(e) none of the above?

correspond to a fibril length of about 5 μm, giving a length/width ratio of about 1,500. This is not sufficiently high to consider the fibrils as of infinite length especially if the matrix is weak. Fibril length could well be an important unmeasured parameter.

It is with this inadequate background of knowledge of fibre structure, that we approach the change in structure produced by beating. If a single research topic were to be recommended by the author as an aid to understanding the beating effect, it would be a search for a more precise physical description of the structure of the cell wall matrix.

THE BEATING EFFECT

Early research on beating recognized that there were a number of effects. In his Chapters on Papermaking in 1908, Clayton Beadle (21) recognized that fibres are shortened or cut, that fibrils are teased away from the cell wall, and that fibres become swollen, leading to an increased flexibility and a denser sheet.

The late 20's and early 30's saw a retraction from this position. The scientists at the time, no doubt feeling that a complex subject such as beating ought to contain some underlying simplicity, argued interminably over what was the single most important beating effect. Strachan (22) believed it was the fibrillation he could see so readily in the light microscope. Cottrall (23) thought it was the flexibility of the fibres. The vehemence of the debates can be seen from a study of the Proceedings of the British Paper and Board Makers Association Technical Section, in the years 1930-33, where fortunately they have been preserved verbatim. These arguments influenced many researchers not only at the time but for many decades afterwards as they seemingly compelled scientists to adhere to one school or the other.

Today we recognize that there are numerous beating effects and all of them are at different times important.

A list of those appearing in the literature to date is as follows:

1. Cutting or shortening of the fibre

2. Fines production and the complete removal of parts of the fibre wall, creating debris in suspension

3. External fibrillation, the partial removal of the fibre wall, leaving it still attached to the fibre

4. Internal changes in the wall structure, variously described as delamination, internal fibrillation or swelling

5. Curling the fibre or straightening the fibre

6. Inducing nodes, kinks, slip planes, microcompressions in the cell wall; or removing nodes, kinks, slip planes, microcompressions from the cell wall

7. Dissolving or leaching out colloidal material into the external liquor

8. Redistribution of hemicelluloses from the interior of the fibre to the exterior

9. Abrasion of the surface at the molecular level to produce a more gelatinous surface

There is of course an endless list of effects ranging from the important to the trivial. Occasionally for example fibres are tied in overhand knots as shown in Fig. 2. This is so rare and so inconsequential that no purpose is served in listing it. But have we omitted any effects from the list that are consequential? Unfortunately we won't know until someone points it out or until we have proved that we require no other effect to explain the beating response.

The Tendency of Beaters, The Propensity of Fibres and The Sensitivity of Pulp and Sheet Properties

The level of independence of these beating effects is all important. If all beaters produced an identical combination of these effects on a given pulp a single number would describe the entire response, indicating simply the amount of beating that had taken place. However some beaters cut more than others, some produce fines more readily than others, some curl more readily than others and so on. Thus any beater operated in a particular way can be described by its tendency to cut, its tendency to produce fines, its tendency to curl and so on. Thus a beater can be characterized by n numbers, where n is the number of independent beating effects that can be created.

In a similar way pulps differ in their propensity to respond. Some cut readily, some produce fines readily, some curl readily and so on. Thus the beating propensity of a pulp may also be described by n variables.

Finally pulp and sheet properties are sensitive to the n variables, with some being more sensitive than others. Tear development would depend on the combined tendency of the beater and the propensity of the pulp to produce shortened fibres. Stretch development would depend on the tendencies of the beater and the propensity of the pulp to form microcompressions.

This discussion has been developed to emphasize the complexity of the beating process. If indeed there are 9 technologically important beating effects, and these can be manipulated independently then a beater requires 9 constants to define its actions, a pulp requires 9 constants to define its propensity to develop and each pulp or sheet property must be considered in terms of the effects of 9 variables. Since some of these will be highly correlated, it is likely that less than 9 constants will be required, but let us not oversimplify at too early a stage.

The problem of beating may thus be a problem in multivariate analysis, which can be usefully tackled through the tools of linear algebra. One particular tool is principal component analysis and this has been used (24) in a preliminary way to study the response of individual pulps in six different laboratory beaters. Already it has been shown that at least three variables are required to describe the response to a group of different laboratory beaters, emphasizing the inadequacy of any two-parameter description of a beater.

The Relation of Beating Effect to Beating Action

Most of our knowledge of the beating action comes from inference from the beating effect. In discussing the various beating effects, attention will be paid to this aspect, and the stress and strain histories that occur during beating will where possible be inferred.

Cutting or Shortening

Cutting was originally visualized as a direct scissor-like action involving metal-fibre-metal contact. The beater bars were even referred to as "knives" in the early writings, for example by Hofmann in 1873 (25). Sigurd Smith (7) pointed out that cutting might occur by the transfer of stress through many fibres, but nevertheless a pure cutting action was envisaged. A cutting action can however be readily discounted from the observation that different pulps, for example sulphite and kraft, vary greatly in their propensity to shorten (26, 27). If a sheet of paper is cut with a sharp pair of scissors the same number of fibres will be cut, regardless of the pulping process. Clearly shortening is not a pure cutting action.

Corte (28) in 1954 developed an approach to cutting that has not been fully utilized. He pointed out that in principle the fibre length distribution after beating may be predicted from the fibre length distribution before beating, provided that the probability of a fibre being cut is known as a function of fibre length, and that the probability of the position of cutting within each fibre is known. Alternatively, given the distribution of fibre length before and after beating, these probabilities may be deduced. The manual methods of fibre length determination at the time prohibited measurement of more than a few thousand fibres, and even the semiautomatic method of Nordman (27) permitted only 1,200 fibres per hour. While this number is perfectly adequate for precise determination of the mean fibre length it is quite inadequate for a description of the distribution. However recently automatic counting rates of 100,000 per hour have been demonstrated (8), so that with modern techniques, the probabilities defined by Corte could be calculated. A pure cutting action would give a probability of cutting proportional to fibre length with an equal probability of cutting occurring in any position down the length of the fibre. Different mechanical actions would lead to different probabilities so that an insight into the mechanism of the beating action could be derived. This approach merits re-examination using modern measurement techniques.

The concept of a scissor-like action in beating must surely have been founded in part on the appearance of sulphite pulps common in early research. As Forgacs (29) pointed out, sulphite fibres contain zones of weakness arising from acid hydrolysis at slip planes. Such a fibre failing in the tensile mode gives the impression of a sharp cut. Kraft fibres however show a more ductile break upon beating. In fact the broken ends of beaten sulphite and kraft fibres are very similar in appearance to the ends of single fibres broken wet in a tensile mode (30). This strongly suggests that fibres fail upon beating not by a cutting action but in tensile. This is supported by the work of Cowan (31) who has shown that pulps that shorten most readily are those with the lowest wet zero-span strength.

Little is known of the effect of fibre morphology and fibre structure on the shortening effect. Long-fibred pulps shorten more readily than short fibred pulps (27) but do the coarser fibres of a furnish resist shortening more than the finer fibres? They are known to be stronger. Are high fibril angle fibres shortened more readily than low fibril angle fibres? They are known to be weaker.

Cutting as a means of controlling stock properties has diminished over the years. It was especially important for rag stocks, somewhat less important for softwood furnishes, and even less important now as fibre length is often controlled by blending of softwood and hardwood furnishes. Nevertheless, the control of fibre length merits attention and its study may be particularly useful in shedding light on the action of the beater.

Fines in Suspension

A distinction is made (32) between on the one hand, the primary fines, present before beating, consisting of ray cells, bark residues, fibres cut during chipping and on the other the secondary fines that are created by beating. Only the secondary fines will be considered here.

Fines are generated apparently by the abrasion of fibres either with other fibres or with beater bars, and this implies a shearing action under a normal load. For chemical pulps, the fines consist almost entirely of fragments of the P_1 and S_1 layer of the cell wall, and only contain fragments of the S_2 layer after extensive beating. Quantification of the effect can be by fractionation, and by measure of specific surface or freeness.

Pulps differ greatly in their tendency to produce fines. The S_1 layer of unbleached kraft pulp remains intact after extensive beating whereas it is readily removed or dislodged from

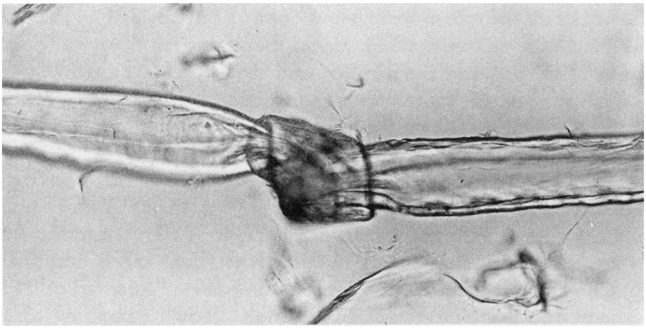


Fig 2 Some effects of beating are trivial, like the one illustrated here. But have we found all the important effects? (Note that the knot, created during beating, is pulled tight, showing that fibres undergo tensile strain during beating.)

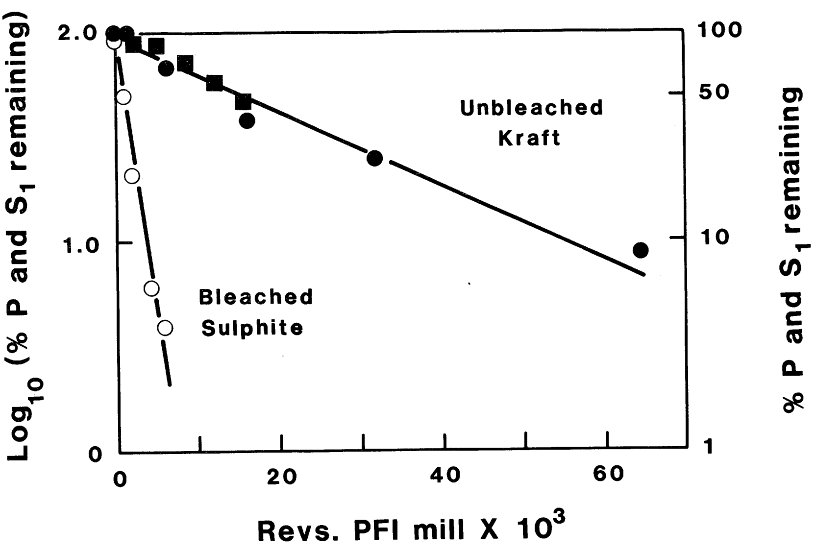


Fig 3 Removal of P and S_1 layers during beating, according to Giertz (circular symbols) and Kibblewhite (squares). There is no rapid method for determining the extent of removal

a bleached sulphite. This is clearly evidenced from the work of Giertz and Nisser (33) and Kibblewhite (34) as shown in Figure 3. The removal of the outer layers obeys the law of exponential decay implying that the rate of removal depends simply on the amount that still remains. The removal rate of the sulphite is fifteen times greater than that of the krafts and this enormous difference is presumably attributable to the degrading effects of sulphite pulping and bleaching on the strength of the S_1 layer.

Mancebo and Krkoska (32) showed however that the build-up of fines from pulp upon beating was not precisely one of a steady rise to a plateau according to an exponential law of removal. During the early stages of beating fines development was slow, indicating that initially the S_1 layer is not completely separated from the fibres, even though it may be dislodged and fibrillated sufficiently to reveal the S_2 layer.

Beaters differ in their tendency to remove the outer layers of fibres. Kibblewhite (35) found that the Lampen mill was ineffective in removing the S_1 layer of an unbleached kraft, in comparison with a Valley beater. The production of fines seems to depend on the shear rate in the beating gap. The shear rate in the Lampen mill is low since the action is one of a rolling metal ball, but high in the Valley beater. This concept is confirmed by Hamada and Matsumoto (36) who found that the S_1 layer was removed from a birch kraft pulp in a PFI mill at 5% consistency where the beating gap is low and the shear rate high, but not at 27% consistency, where the beating gap is much greater, and the shear rate consequently lower. Similarly Brown (37) found that an increase in consistency from 1.1% to 2.0% reduced the rate of fines formation.

No effort seems to have been made to relate the production of fines to the thicknesses of the P and S_1 layers. It might be expected that species with thicker layers would produce more fines, but this has not been shown. However it does seem to be found that the fines production plateaus out in the range of 5-15%. This may be an indication of the amount of material in the P and S_1 layers.

Fibrillation Attached to the Fibre

Micrographs of the long fraction of beaten fibres show material that has been loosened from the fibre but not completely removed. This external fibrillation can be measured, by determining the freeness or specific surface of the long fraction (38, 39, 40). This approach does not however seem to have been broadly used in systematic studies.

As mentioned in the earlier section, fibrillation attached to the fibre is produced by keeping the shear rate low. It is not known however whether any particular fibre morphology or pulp type tends to favour external fibrillation as opposed to fines production. Considerable economic advantage may accrue from an action that promotes external fibrillation rather than fines. The pulp would have high retention properties, good strength, and would make a sheet in which the distribution of the fine material throughout the sheet thickness was uniform.

Changes in the Internal Structure of the Cell Wall, Including Swelling, Internal Fibrillation and Delamination

This is the most extensively and systematically studied of all the beating effects, since it has been regarded by some as being the most important. Unfortunately it has been looked at almost entirely from a single viewpoint, the increase in the amount of water in the cell wall. This has been measured centrifugally (41), from hydrodynamic specific volume (42), and determined from the exclusion of molecules in solution (43). It has been inferred from a wide variety of properties, such as wet-web strength (44), conductivity (44), dye migration (44), and the rate of change of sheet modulus with moisture (45). The volume within the wall inaccessible to high polymers seems to have become the most precise and the most popular approach to measuring the water of swelling, although the centrifugal water retention value is certainly more rapid.

An important discrepancy, which seems to have been overlooked, exists between the results of the polymer exclusion method of measurement, and the observations from light and electron microscopy. The results from polymer exclusion show that as the size of the molecule increases, it is excluded from more pores until the water excluded reaches a plateau at a value of about 500 A° (Figure 4). This is taken to be the fibre saturation point. The pore size distribution may be derived as shown in the Figure. However light and electron microscopy tell a different story as first demonstrated simultaneously and independently by McIntosh (46) and Page and De Grâce (47). The electron microscope reveals cracks in the cell wall, present in

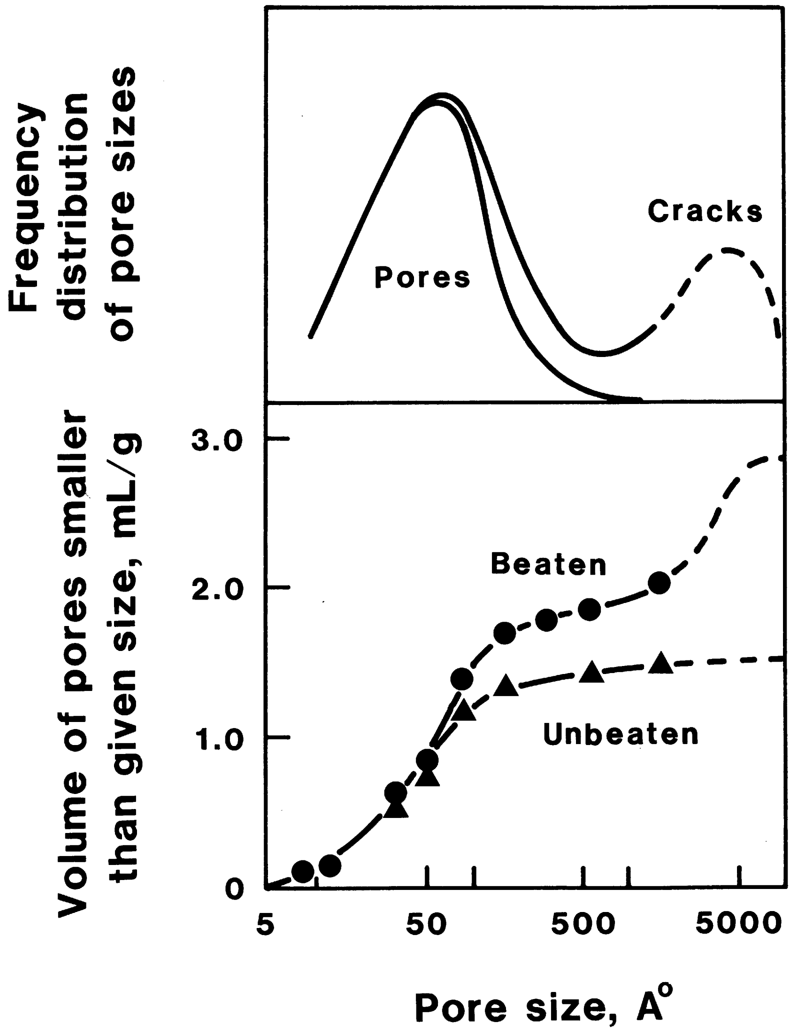


Fig 4 Solute exclusion data of Stone et al. Note that the data for the beaten pulp show the beginning of a second distribution, corresponding to the cracks seen by electron microscopy in Fig 5

beaten fibres but absent from unbeaten, that are enormous compared with the pores determined from polymer exclusion. They lie in the range 1,000 A°- 10,000 A°. These are not the artefacts of specimen preparation that were found in early work that used methacrylate embedding (48), for the use of epoxy resins has overcome this problem. In fact the cracks are sufficiently large, that they can be seen in wet-mounted beaten fibres using a good polarizing light microscope (47).

It must be concluded that there is a bimodal distribution of pores within the cell wall, one with a peak at about 50 A ranging from about 10 A° to 500 A° the other with a peak about 3,000 A° ranging from 1,000 A° to 10,000 A°.

An indication of the beginning of a second distribution is actually shown by a single point in the work of Stone et al. (49) reproduced in Figure 4. The suggestion of a second distribution after beating is also contained in the solute exclusion curves of other authors (50). The remainder of the distribution in the Figure has been roughly estimated from the micrographs of references (46) and (47).

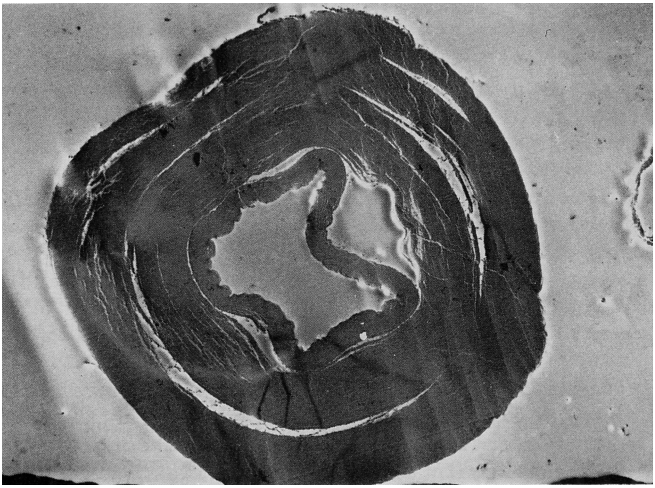
The two distributions are really two effects. The increase in the fibre saturation point is caused by a random breakage of the crosslinks in the interfibrillar matrix during beating, causing a loosening of the structure and a swelling of the fibre. The large cracks are caused by a coherent breakage of the interfibrillar matrix in planes, allowing complete separation of whole chunks of the cell wall. There is at present no technique that measures the cracks. The polymer exclusion technique cannot be easily extended to measure it, since molecules or particles in the size range 1,000 - 10,000 A° are not easily handled. In any case the volume of water may be unimportant. The surface area of the cracks, which would give a numerical indication of the number of cracks, would be more relevant.

Which is the most important, the development of pores (10 - 500 A°) or the development of cracks (1,000 - 10,000 A°)? In terms of changes in volume, the cracks exceed the pores. The transverse elastic modulus of the wet cell wall material (ignoring the effects of cracks) may change because of swelling, and this may change the fibre flexibility. However an enormous reduction in fibre rigidity can be obtained simply by creating a few cracks. On the other hand, cracks may have little effect on the local plasticity of the cell wall, which may be important in fibre - fibre bonding. Clearly pores and cracks do not have the same effects.

Pulps differ in their propensity for swelling upon beating. Sulphite pulps swell more rapidly than kraft. Cracks in the cell wall develop faster for sulphite than for kraft as shown in Figure 5 (47). The reason is almost certainly related to the difference in structure of the matrix, and this is not adequately revealed from conventional analyses, such as the lignin and hemicellulose content. In the author's opinion, the most probable explanation is the one given by Rydholm (51). He and his coworkers (52) found that the DP of the hemicellulose of sulphite fibres is about half that of kraft, 70 compared with 140. This has been independently confirmed by Sears et al. (53) and Kettunen et al. (54). The strength of the water-swollen sulphite matrix may thus be expected to be less than half that of kraft, allowing a much faster rate of cell wall breakdown under mechanical action. Since lignin acts as a crosslink in the matrix its removal may also be expected to reduce the cell wall strength, explaining the effect of bleaching on beating rate.

Beating rate depends on the presence of ions in solution. For example, in 1908 Clayton Beadle reported that pulps beat faster in the presence of caustic soda and sodium carbonate but slower in the presence of alum. For many years this phenomenon remained a mystery but largely as a result of the work of Scallan (55) and others (56) it is now understood both qualitatively and quantitatively.

Generally in chemical pulps the hemicelluloses and lignin contain acid groups that are dissociated at conventional pH values. The counterion may be monovalent such as sodium, bivalent such as calcium or magnesium or trivalent such as aluminum or iron. The concentration of ions in the wall can be high enough to provide an appreciable osmotic pressure tending to swell the wall. The pressure depends on the number of ions present, and is therefore highest for monovalent ions. The osmotic pressure turns out to be an appreciable part of the transverse strength of the matrix, so that upon beating the fibre swells more rapidly as crosslinks break under the combination of the beating stress and the osmotic stress. The acid group content of the matrix, the nature of the counterion and the pH and ion content of the solution thus become important in any consideration of the beating effect.



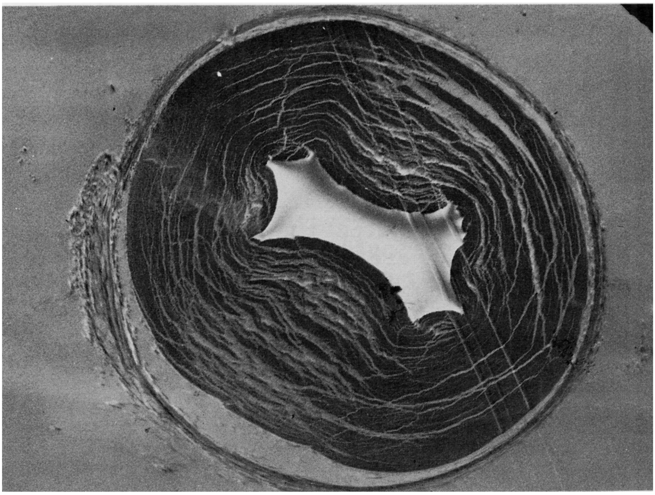


Fig 5 Above, kraft, below sulphite, beaten 5,000 revs in a PFI mill. The cell wall of sulphite breaks up more readily. There is at present no technique that measures the number or volume of the cracks

Centola and Borruso (57) first observed that the beating rate for pulp could be enhanced by the addition of certain dyes, notably Congo Red. Such dyes sorb onto the cell wall, and contain sulphonic acid groups, whose counterion provides an osmotic pressure. This work has spawned an interest in the prospect of additives that produce a similar effect. In fact, many have been found, for example:

Sodium carboxy-methyl cellulose (58,59,63)
Oxidised starch (58,63)
Lignosulphonates and modified lignins (60,61,63,64)
Naphthalene, benzene and stilbene based dyes (62)
Hydrolysed polyacrylonitrile (63)

These compounds all have in common the presence of acid groups, and a molecular weight low enough to penetrate the cell wall yet high enough for the molecule to be absorbed within it. As delivered or prepared, they also usually carry the sodium counterion. None of these has proved to be commercially useful, but the specifications for such a compound, together with the maximum allowable cost that would compensate for beating energy seem to be estimable.

Although the explanation given here of the effect of ions and other additives on beating has received wide recognition, it should be cautioned that other effects of additives are possible and should not be dismissed. It is conceivable for example that they may affect fibre - fibre friction and fibre-metal friction by changing the hydration of the fibre surface and thus changing the nature of the stresses that the fibres experience.

Curling or Straightening the Fibre

A recent review by Page et al (65) has already considered this subject and the findings in this and the next section will only be briefly summarised.

Fibres are curled whenever they are subjected to shear at a high enough consistency and at a suitable shear rate. The mechanism appears to be the repeated flexing and bending of fibres beyond their yield point. Curling may be carried out deliberately during stock preparation of certain products but the early "Curlator" has now given way to other devices notably the "Frotapulper". Curling is also carried out unintentionally, for example in any medium-high consistency shearing treatment that a pulp may receive in a mill. For example, it can occur in a bleach plant during pumping, transport, or mixing (66).

Fibres differ in their susceptibility to curl. Low yield chemical pulps curl easily, higher yield less so. Low yield pulps stay curly, high yield pulps tend to straighten spontaneously under very mild conditions of agitation.

Low yield chemical pulps are often dried prior to shipment, and if at the time of drying they are curled, this curl is not readily removed upon reslushing. (Fig. 6) In this case beating and refining at low consistency carries out the useful function of straightening the fibre.

When curl is introduced into a pulp it has the effect of raising freeness, bulk and tear and reducing tensile strength. Thus curling is in some ways a negative effect of beating. When curl is removed freeness, bulk and tear are lowered and tensile increased. This had led Page (67) to suggest that a substantial part of the development of properties of dried chemical pulps upon beating, comes from the straightening of the fibres.

Curl, its introduction or its removal during mechanical action, is without doubt an important beating effect. It is unfortunate that no method exists for its measurement other than by microscopical observation. Modern techniques of image analysis have been used but even then the measurement of curl is beyond the present capability of most research laboratories. Furthermore, no single simple test has been developed that correlates with curl. Development of such a test would go a long way to aiding in the appreciation of this important beating effect.

Creation and Removal of Slip Planes, Dislocations, Nodes and Microcompressions

Fibres undergo a particular structural change when subjected to stresses of axial compression. Robinson (68) in 1920 observed that the fibres in compressed wood appeared to have a structure similar to the slip planes observed in strained metals and in geological faults. The same structure is found to be present in wood pulp fibres, since the stresses in a sheared pulp suspension inevitably provide fibres with a component of axial compression.

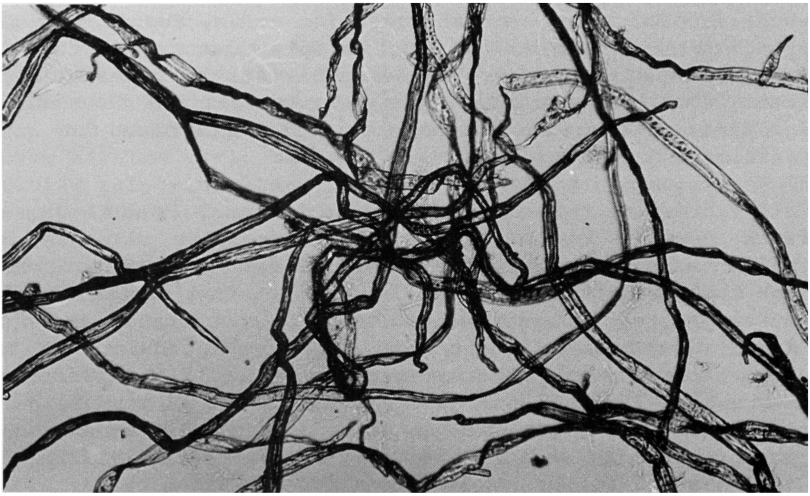


Fig 6 There is no rapid method for determining fibre curl

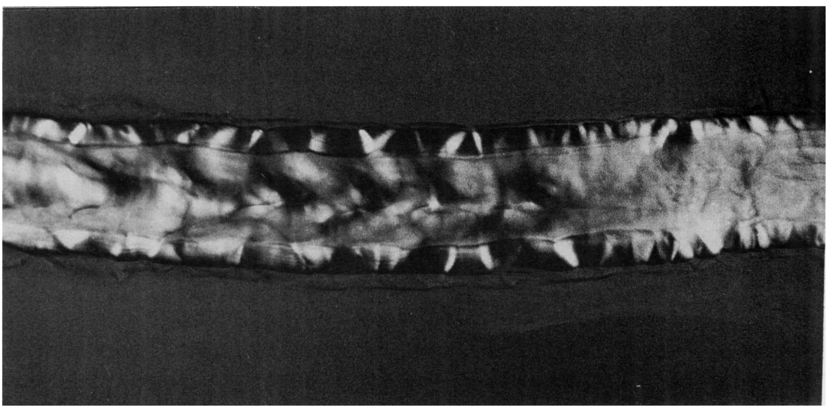


Fig 7 There is no method at all for quantifying the degree of microcompression

In the early stages of disintegration of a wood chip, the slip planes tend to concentrate at a few nodes, and further mild shearing of low consistency stock simply accentuates the slip planes at these nodes. It is clear that at the nodes, the deformation consists of crack propagation between the fibrils, allowing shear deformation in the matrix to accommodate the axial compression and bending.

If fibres are refined at a high consistency ($\sim$20%) they experience repeated bending and axial compressive stresses down their length, since at this consistency stresses are transmitted through the direct fibre - fibre interaction that occurs in a coherent structure. Fibres refined at high consistency are noted for their closepacked structure of slip-planes and in this form they came to be termed microcompressions (Fig. 7). A fibre can be reduced in length by as much as 5% by the introduction of microcompressions. At lower consistencies the introduction of microcompression is reduced, though they are still a factor in PFI mill beating at 10% consistency (69).

Low consistency beating has the reverse effect. If fibres already contain nodes, slip planes and microcompressions they may be released by low consistency refining (67). This is a particularly important phenomenon for dried pulps or recycled fibres. The intra-fibre bonds that form during drying hold in place any nodes and microcompressions that are present and the bonds must be broken if they are to be released. Low consistency beating can however achieve this. The dried or beaten fibre contains nodes, but these are relaxed in the beaten state and the fibre is actually extended by several percent. The mechanism of relaxation of the nodes and extension of the fibre is not completely understood, but it is presumably a combination of breakage of the bonds allowing the nodes to be removed, transverse swelling of the cell wall forcing the fibre to straighten, and extension of the fibre by the tensile forces it experiences in low consistency refining.

The presence of microcompressions, nodes and slip planes is important for many properties of paper and board products notably extensibility and dimensional stability. Yet there is no method at all, not even in the research laboratory for measuring the amount of microcompression present in a sample of pulp. At present, it can only be estimated by the ranking of micrographs (66). As a result almost nothing is known of the susceptibility of different pulps and fibre types to form microcompressions. There is a sense however that fibres that are more swollen resist microcompression; for example holocellulose resists being microcompressed. The use of high consistency treatment followed by a low consistency beating (70) has interesting features. The high consistency refining stage introduces both curl and microcompression, while the low consistency stage removes all the curl, but not all the microcompression. The resulting pulp with its straight partially microcompressed fibres has good strength and stretch properties.

Leaching Out or Dissolution of Material into the Surrounding Liquor

In recent years the liberation of carbohydrate and lignocelluloses during beating has been recognised as an important part of beating. The consequences are mostly negative, in part because of interference with paper machine operation and with the effective use of additives, and in part because of their possible environmental impact.

The literature on the subject, though small, is reasonably consistent. Pulps lose carbohydrates if bleached and also ligno celluloses, if unbleached, depending on pulp yield, pulp type, material source, ionic content of the water, beating degree and type of beating (71 - 75).

The loss of material first increases with beating and then plateaus out at high beating degrees. This plateau is characteristic of the raw material, pulp yield and pulping process. For any given pulping process the height of the plateau depends on the yield being at a maximum at intermediate yield. It seems that at low yield there is very little material to be lost, at high yield the material is highly crosslinked and unavailable; at intermediate yields chemical attack has been sufficient to allow mechanical action to cause further release.

The amount of material released can be significant, varying from a fraction of a percent for bleached kraft pulps, to several percent for unbleached high yield sulphites.

The rate of loss depends on the type of beating, the more severe the action the faster the loss. According to Levlin (71) the total amount lost is independent of beating severity, but this is not in accord with the work of Sjostrom et al (73) who found that the total amount of dissolved carbohydrate plateaus out upon Valley beating at twice the amount obtained with PFI mill beating. Furthermore, El-Karim found that the material lost from a bleached pine kraft pulp was largely xylan, when Valley beaten, but was both xylan and glucomannan, when beaten in a Medway beater (75).

Lindstrom et al (74) proposed that the mechanism of loss upon beating was the opening of pores in the cell wall to release already degraded and isolated parts of the hemicellulose-lignin matrix that are trapped. While this explanation fits many of the facts, the observations listed in the last paragraph are not so easy to explain. It is not at all inconceivable that covalent bonds are broken during mechanical action, and that this mechanism contributes to material release.

Change in the Molecular Nature of the Fibre Surface

The concept that the molecular nature of the fibre surface is changed by beating has a lengthy history (76). Two mechanisms are usually proposed. One is the dissolution of hemicelluloses from the body of the fibre followed by absorption onto the exterior surface (77). The other is the mechanical abrasion of the exterior surface. Whatever the mechanism may be, the consequences are seen as a gelatinous layer of "molecular fuzz" (5) on the outer surface that is capable of providing improved fibre-to-fibre bonding upon drying, perhaps by interdiffusion of molecules from adjacent fibres (78). Unfortunately, while the concept is attractive from the principles of polymer physics, there are no experiments that unequivocally demonstrate it to be correct. The fact is that techniques are not available for examining and characterizing the molecular state of the exterior surface of water-swollen solid polymers. In the absence of such a technique, the hypothesis cannot be pursued.

THE BEATING ACTION

Smith (7) began the work on our understanding of the action of Hollander beaters. He considered many aspects of the flow of stock in the beater, as well as the mechanism by which fibres enter the beating zone. He postulated that the fly-bar, in passing through the stock picked up fibres on its edge and these were then treated by being abraded against the stationary bar. In translation from the original German, the word "fibrage" was coined to describe the fibres lying over the bar edge and this usage has remained.

It was known even to Hofmann (25) in 1873 that with the same total energy input, different stock properties could be obtained depending on the severity of the action. Thus beating must be described not by one parameter, the specific energy input, but also by a second. The "fibrage" theory proved to be the forerunner of the development of a second parameter, the specific edge load, that is, the amount of power input per unit length of bar edge per second. After the work of Brecht and Siewert (79) the specific edge load concept was extensively adopted. Danforth (80) and Leider and Nissan (81) have developed theories that speak of the number of impacts and severity of impacts, but their equations are essentially similar to the specific energy and specific edge load equations. Successful as the model has been, it is not able to explain all the differences between beating results. Changes in consistency, bar angle, speed, material of bar, sharpness of bar edge, (6) can produce different results at the same energy input and specific edge load.

Heterogeneity of Treatment

Not all fibres are treated equally. Some fibres in a furnish may be heavily treated, and some not at all, depending on the design of the beater. For example the chances of a fibre escaping treatment in a single pass through a pump-through refiner are appreciable. On the other hand a fibre in a Valley beater passes through the roll as many as a hundred times during a typical beater run and can hardly escape treatment. Differences in homogeneity between fibres beaten in a Valley beater and in an Aylesford beater have actually been observed microscopically by the author. As Danforth points out (82) this effect can be appreciable and must be taken into account in any beating theory.

Direct Observation of the Beating Action

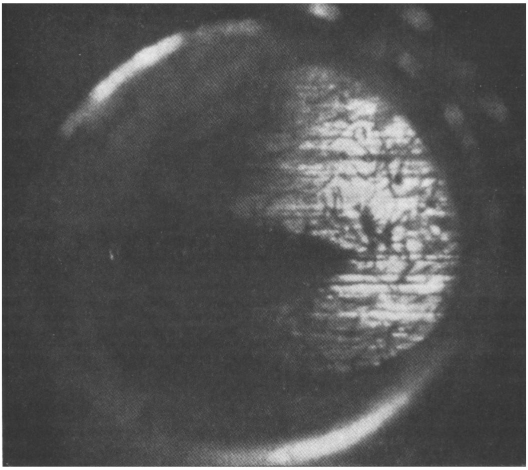
Sigurd Smith said of the beating action "It is impossible to observe by eye what goes on for the action takes place at high speed and in an inaccessible spot". This statement held true until 1962 when the first attempt to image fibres in the beating zone was made by Page et al. (83) They drilled a hole through one of the stator bars of an Aylesford beater and replaced the material with clear plastic. A 1μs flash was used to provide the still images shown in Figure 8.

The micrographs show very clearly single fibres in the beating zone. In fact they still represent the highest resolution images of the beating zone that have been obtained to date. Subsequent efforts (84,85) to photograph the beating zone have used high-speed cinefilm and while these have given good general impressions of pulp flow they have shed little light on the movement of individual fibres.

The results of the work of Page et al (83) were startling. No fibrage was observed. Many fields of view showed no fibres at all while others contained appreciable numbers of fibres distributed throughout the beating zone. This led the authors to suggest that "the whole action of the beater may be the breaking down of flocs of fibres trapped when the two bars approach one another".

Work by others has been interpreted as supporting the fibrage concept. The sketches of Banks (84) taken from his cinefilms show fibres concentrated at the bar edge and lying perpendicular to it. Similarly Fox (85) showed cinefilms that were interpreted as revealing fibrage. Goncharov (86) has shown that the pressure on the bar face is highest at the leading edge and falls off towards the trailing edge, and this is also consistent with fibrage.

The discrepency between the "floc" thoery of beating and the "fibrage" theory has been discussed by both Ebeling (6) who tends to support the "floc" theory and Atack (4) who tends to support the "fibrage" theory. It does not seem to have been realised however that the two theories are really very similar and can indeed merge. The floc theory suggests that a floc is trapped by passage of a rotor bar over a stator bar. If the floc is completely broken down at this time and fibres dispersed, then the next passage of a rotor bar over another stator bar must trap a fresh group of fibres. If however there is a residue of the first floc on the rotor bar it will be treated by the next stator bar and we have the fibrage theory. The floc theory is simply the fibrage theory in which fibres are picked up collectively rather than individually and the mass is dispersed over a single bar passage rather than over many bar passages. Whether or not the residue of a floc might survive on a bar would be expected to depend very much on the conditions of



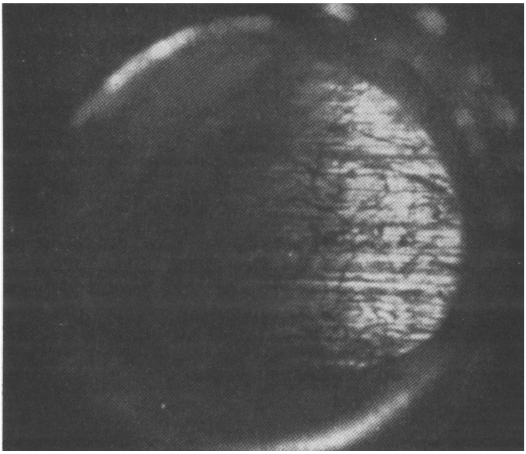


Fig 8 Micrographs (X6) of fibres in the beating zone of an Aylesford beater, taken in 1962 with a $1\mu s$ flash. The rough leading edge, above, shows no indication of fibrage. Images sometimes showed many fibres as here and in the micrograph of the centre bar face, below. However, most micrographs showed no fibres at all. The resolution achieved here has not to this date been surpassed

refining. If the fibres are weak, the gap small and the conditions harsh, a single pass over a bar edge may be sufficient to destroy the floc and therefore the fibrage. If on the other hand the pulp is strong and the gap large, fibres remaining from the break-up of one floc may hang over the bar edge.

The evidence seems to support this conclusion. The work of Page et al was carried out with a weak bleached sulphite pulp in an Aylesford beater that is noted for its harshness. On the other hand, the work of Fox, in which fibrage was observed was, according to Ebeling, carried out with a large gap so that the conditions were mild.

Many of these comments are speculative. Our understanding of the beating action is being held back because high resolution images of the beating zone are not available. Surely modern video techniques can solve this problem?

TOWARDS A NEW THEORY OF THE BEATING ACTION

The time seems ripe for the development of a new theory of beating based on the history of stresses and strains that fibres experience during floc breakdown.

First it seems important to recognise that it is the solid fibre phase that transmits the forces across the beating gap; forces in the liquid phase are negligible. The hydrodynamic forces control the presentation and arrangement of the fibres in the beating zone, but once present, they are acted on by mechanical forces in exactly the same way that on a paper machine, formation of a thin sheet is controlled by hydrodynamic forces, but in the press-nip, it is the fibres that bear the load. This proposal is supported by the observation that the work of beating is far greater than the work of circulating the beater roll without stock at the same gap. In addition, factors that affect the mechanical rather than the hydrodynamical forces such as the friction of the bar or the shape of the bar edge are known to have a substantial effect on the beating action. The sketch of Figure 9 is intended to portray a typical arrangement of fibres between the beater bars. Fibres are acted upon by the normal force of the bar as well as the frictional shearing force. This shearing force has two components, one the frictional force along the width of the bar face, the other the force associated with the bar edge. This latter force is generally called the

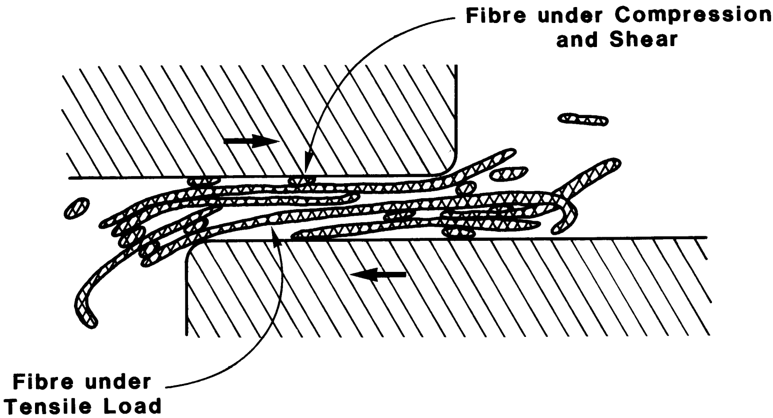


Fig 9 Impression of fibres trapped between the passing stator and rotor bars. The stresses that fibres experience under these conditions are responsible for the beating effects

"ploughing" term of friction (87) and arises because the front edge meets material that has not been compacted by the bar pressure and it must plough through it. Fibres close to the bar edge, therefore tend to move with it. Thus fibres at the centre of the sheared floc are subjected to tension which depends to a large extent on the size of the "ploughing" term. All fibres in the floc are subjected to shear depending on the coefficient of friction between fibre and metal and fibre and fibre.

This simple model of floc breakdown already explains a number of well-known phenomena. For example, materials that have a high coefficient of friction such as basalt lava (88) or sintered bronze (89) would have a high shearing term and therefore favor the production of fines whereas bars with sharp edges would produce a high "ploughing" term tending to break fibres under tensile load. The higher the cutting angle of the bars, the less the tendency to cut (90) as the ploughing forces move across the floc on the bar, rather than being exerted simultaneously on the entire floc.

It seems to the author that further development of such a theory might well explain many of the hitherto unexplained phenomena of beating.

RECOMMENDATIONS

In spite of the considerable research effort on beating in the last fifty years, success has been limited. The following goals are recommended by the author for future beating research:

1. Development of a more precise physicochemical description of the structure of the pulp cell wall matrix.

2. Development of rapid methods of measuring fibre properties such as length, coarseness, wall thickness and fibril angle.

3. Better characterisation of raw material and pulps, so that researchers in different groups can interpret better the work of others.

4. Development of rapid methods of measuring beating effects such as fibrillation, cell wall cracks, microcompressions, kinks and curl.

5. Recognition of the multi-dimensional character of the beating effect and the application of multivariate analysis.

6. Improvement of the quality of micrographs of the beating zone, so as to image the movement of single fibres and so provide the data on which to base a mechanistic theory of beating.

7. Development of a mechanistic theory of the beating action in terms of the stresses that fibres experience in the beating zone, and their response to those stresses.

Acknowledgement

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REFERENCES

1. Emerton, H.W. "Fundamentals of the Beating Process", British Paper and Board Industry Research Association, 1957.

2. Higgins, H.G. and de Yong, J. "The beating process - primary effects and their influence on paper properties", Transactions of the Oxford Symposium, Tech Sect B.P. and B.M.A., p.651, 1961.

3. Fahey, M.D. "Mechanical treatment of chemical pulps", Tappi 53 (11), 2050 (1970).

4. Atack, D. "Advances in beating and refining" Transactions of the Oxford Symposium, British Paper and Board Industry Federation p261, 1978.

5. Clark, J.d'A. "Pulp Technology and Treatment of Paper" Miller Freemans Publications Inc., San Francisco, 1978.

6. Ebeling, K. "A critical review of current theories for the refining of chemical pulps" Proceedings of the Symposium on Fundamental Concepts of Refining, Appleton, 1980.

7. Smith, S. "The Action of the Beater" Tech Sect., Paper-makers Association of Great Britain & Ireland, London, 1923.

8. Kajaani FS-200 Fibre Analyser, Kajaani Electronics Ltd., Kajaani, Finland.

9. James, C.F. and Wardrop, A.B. "A microscopic study of structural changes during the beating of wood fibres" Appita 9, 107 (1955).

10. Giertz, H.W. "The effect of beating on individual fibres" Transactions of Cambridge Symposium, British Paper and Board Makers Association, p.389 (1958).

11. Kibblewhite, R.P. "Effect of beating on fibre morphology and fibre surface structure", Appita 26 (3), 196 (1972).

12. Page, D.H. "The birefingence of wood pulp fibres and the thickness of the S_1 and S_3 layers" Wood and Fibre 6 (3), 186 (1974).

13. Mark, R.E. "Cell wall mechanics of tracheids", Yale University Press, 1967.

14. Kerr, A.J. and Goring, D.A.I. "The ultrastructural arrangement of the wood cell wall" Cellulose Chemistry and Technology 9, 563 (1975).

15. Hearle, J.W.S. "The fine structure of fibres and crystalline polymers, J. Appl. Polymer Sci. 7(4), 1175 (1963).

16. Liang, C.Y., Bassett, K.H., Mcginnes, E.A. and Marchessault, R.H. "The infrared spectra of crystalline polysaccharides - thin wood sections" Tappi, 43(12), 1017 (1960).

17. Page, D.H., El-Hosseiny, F., Bidmade, M.L. and Binet, R. "Birefringence and the chemical composition of wood fibres" Appl. Polym. Symp. 28, 923 (1976).

18. Ericksson, O., Goring, D.A.I. and Lindgren, B.O. "Structural studies on chemical bonds between lignins and carbohydrates in spruce wood" Wood Sci. Technol. 14(4), 267 (1980).

19. Page, D.H. "A note on the cell-wall structure of softwood tracheids" Wood and Fibre 7(4), 246 (1976).

20. Goring, D.A.I. and Timell, T.E., "The molecular weight of native celluloses" Tappi, 45(6), 454 (1962).

21. Beadle, C., Chapters on Papermaking, Vol. 1, Crosby Lockwood and Son, London, 1908.

22. Strachan, J., "Further notes on the hydration of cellulose in papermaking" Proc. Tech. Sect. P.M.A. Gt. Brit. and Ireland, 13(1), 61 (1932).

23. Cottrall, L.G., "Recent advances in the knowledge of cellulose and fibre structure and their relation to the beating process" Proc. Tech. Sect. P.M.A. Gt. Brit. and Ireland 14(2), 241 (1934).

24. Page, D.H. and Howard, R.C., (unpublished work)

25. Hofmann, C. "A practical treatise on the manufacture of paper" H.C. Baird, Philadelphia (1873).

26. Kilpper, W. "Changes in fibre length distribution during beating" Papier, 3(17/18) 342; 3(19/20) 386 (1949).

27. Nordman, L.S. and Niemi, J.A. "The determination of fibre length distribution in connection with beating research", Tappi 43(3), 260 (1960).

28. Corte, H., "The shortening of cellulosic fibres during beating", Papier, 8 (9/10), 163 (1954).

29. Forgacs, O.L., "Structural weaknesses in softwood pulp tracheids", Tappi 44 (2), 112 (1961).

30. Vondrakova, M. and Page, D.H. (unpublished work)

31. Cowan, W., "Fibre strength in the production of pulp and paper", Proceedings of Tappi Seminar on Managing Quality Techniques for Measuring, Controlling and Monitoring Paper Quality, p45 (1987).

32. Mancebo, M. and Krkoska, A.B., "The concept, properties and papermaking role of fines", Papier a Celuloza, 36 (11), V75 (1981).

33. Giertz, H.W., and Nisser, W., cited in Giertz, H.W.. (reference 10).

34. Kibblewhite, R.P. "Interrelations between pulp refining treatments, fibre and fines quality, and pulp freeness" Paperi ja Puu, 57(8), 519 (1975).

35. Kibblewhite, R.P., "Effect of beating on fibre morphology and fibre surface structure", Appita 26 (3), 196 (1972).

36. Hamada, T. and Matsumoto, H., "Morphological and surface structural changes of hardwood components through beating of pulp", Mokuzai Gakkaishi 23 (7), 327 (1977).

37. Brown, K.J., "Influence of consistency in a laboratory beater on beating rates and pulp properties", Tappi, 51(12), 67A (1968).

38. Ingmanson, W.L., and Andrews, B.D., "The effect of beating on filtration resistance and its components of specific surface and specific volume", Tappi 42 (1), 29 (1959).

39. Malmgrem, M., "The next step in pulp quality measurement and refiner control", Proc. Tappi Pulping Conference 2, 377 (1985).

40. Szwarcztajn, L. and Przybysz, K. "External fibrillation of beaten cellulose fibres" Cellulose Chem. Technol. 6(2), 223 (1972).

41. Jayme, G. and Rothamel, L. "Experiments for developing a standard centrifugal method for determining the swelling value of pulps" Papier 2(1/2), 7 (1948).

42. Robertson, A.A. and Mason, S.G. "Specific surface of cellulose fibres by the liquid permeability method" Pulp and Paper Mag. Can. 50(13), 103 (1949).

43. Stone, J.E. and Scallan, A.M. "The effect of component removal upon the porous structure of the cell wall of wood" Pulp and Paper Mag. Can. 69(6), 288 (1968).

44. Robertson, A.A. "The physical properties of wet webs" Svensk Papperstidn. 66(12), 477 (1963).

45. Caulfield, D.F. and Weatherwax, R.C. "Tensile modulus of paper wet stiffened by crosslinking" Fibre-water Interactions in Papermaking, Tech. Div. B.P. & B.I.F., p741 (1970).

46. McIntosh, D.C. "The effect of refining on the structure of the cell wall" Tappi, 50(10), 482 (1967).

47. Page, D.H. and De Grace, J.H. "Delamination of fibre walls by beating and refining" Tappi, 50(10), 489 (1967).

48. Dlugosz, J. "Fibre structure of cotton as revealed by swelling during methacrylate embedding." Polymer, 6(8), 427 (1965).

49. Stone, J.E., Scallan, A.M. and Abrahamson, B. "Influence of beating on cell wall swelling and internal fibrillation" Svensk Papperstidn. 71(19), 687 (1968).

50. Kitayama, T., Okayama, T. and Oye, R. "Changes in pore volume of pulp fibres by recycling" J. Japan Tappi 35(12), 1057 (1981).

51. Rydholm, S.A. "Pulping Processes", Interscience Publishers, New York, N.Y. 1965.

52. Annergren, G., Rydholm, S.A. and Vardheim, S. "Influence of raw material and pulping process on the chemical composition and physical properties of paper pulps" Svensk Papperstidn. 66(6), 196 (1963).

53. Sears, K.D., Alexander, W.B., Goldschmid, O., and Hamilton, J.K. "Characterization of hemicelluloses" Tappi, 61(9), 105 (1978).

54. Kettunen, J., Laine, J.E., Yrjala, I., and Virkola, N-E. "Aspects of strength development in fibres produced by different pulping methods" Paperi ja Puu, 4, 205 (1982).

55. Scallan, A.M. and Grignon, J. "Effect of cations on pulp and paper properties" Svensk Papperstidn. 82(2), 40 (1979).

56. Lindstrom, T. and Kolman, M. "Effect of pH and electrolyte concentration during beating and sheet forming on paper strength" Svensk Papperstidn. 85(15), R140 (1982).

57. Centola, A. and Burroso, D. in Fundamentals of Paper-making Fibres, Tech. Sect. B.P. & B.M.A., England (1948).

58. Endelvi, J. and Kutasi, T. "The effect of additives on beating" Zellstoff und Papier, 3, 129 (1981).

59. Afonchiv, N.A. and Terentev, F.A. "Effect of sodium-CMC on pulp beating and the properties of paper" Bumazh Prom. 11,8 (1963).

60. Nedelcheva, M., Dragonova, R. and Tzolova, E. "Influence of modified lignin on beating" Cellulose Chem. Technol. 15, 349 (1981).

61. Levon, K., Meshitsuka, G., and Nakano, J. "Acceleration of the beating of pulp by the use of modified lignosulphonate" Mokuzai Gakhaishi 32(12), 1011 (1986).

62. Levon, K., Meshitsuka, G., and Nakano, J. "Effect of organic materials on the beating rate" Mokuzai Gakhaishi 32(9), 691 (1988).

63. Valtshav, V. and Ivanova, N. "Chemical auxiliaries for fibre beating" Zellstoff Papier 36(6), 212 (1987).

64. Nedelcheva, M., Tsolova, E., Petkova, V. and Litoniski, I. "Behavior of pulp in solutions of lignin preparations" Novosti Tselvi:Khart Prom. 16(1), 7 (1986).

65. Page, D.H., Seth, R.S., Jordan, B.D. and Barbe, M. "Curl, crimps, kinks and microcompressions" Transactions of Eighth Fundamental Research Symposium, Mechanical Engineering Publications Ltd., London (1985).

66. De Grace, J.H. and Page, D.H. "The extensional behaviour of commercial softwood bleached kraft pulps" Tappi 59(7), 98 (1976).

67. Page, D.H. "Mechanism of strength development of dried pulps by beating" Svensk Papperstidn. 88(3), R30 (1985).

68. Robinson, W. "The microscopical features of mechanical strains in timber and the meaning of these on the structure of the cell wall of plants" Trans. Roy Soc. B. 210, 49 (1920).

69 Page. D.H. "The axial compression of fibres, a newly discovered beating action" Pulp and Paper Mag. Can. 67(1), T2 (1966).

70. Peakes, D.E. "Combined high and low consistency refining of bleached kraft pulps" Tappi 50(9), 38A (1967).

71. Levlin, J.E. and Nordman, L. "Material losses during defibration and beating of high-yield pulps" Transactions of Oxford Symposium, Tech. Div. B.P. & B.I.F. p289, 1977.

72. Berg, L. and Norrstrom, H. "Removal of organic substance during defibration and refining of semichemical pulps" Svensk Papperstidn. 81(11), 375 (1978).

73. Sjostrom, E. and Haglund, P. "Dissolution of carbohydrates during beating of chemical pulps" Svensk Papperstidn.

66(18), 718 (1963).

74. Lindstrom, T., Ljungren, S., de Ruvo, A. and Soremark, C. "Dissolution of carbohydrates and lignin during beating of kraft pulps" Svensk Papperstidn. 81(12), 397 (1978).

75. El-Karim, S.A. "Water soluble polysaccharides in bleached pine kraft pulp" Drvna Ind. 38(5/6), 99 (1987).

76. Campbell, W.B. "A physical theory of the beating process", Paper Trade J. 95(8), 81 (1932).

77. Gallay, W. "Some aspects of the theory of the beating process", Fundamentals of Papermaking Fibres, Tech. Sect. B.P. and B.M.A., 1958.

78. McKenzie, A.W. "The diffusion theory of adhesion applied to inter-fibre bonding", Appita, 37(7), 580 (1984).

79. Brecht, W. and Siewert, W. "On the theoretical classification of the beating process in modern refiners" Papier 20(1), 4 (1966).

80. Lewis, J. and Danforth, D.W. "Stock preparation analysis", Tappi 45(3), 185 (1962).

81. Leider, P.J. and Nissan, A.H. "Understanding the disk refiner", Tappi 60(10), 85 (1977).

82. Danforth, D.W. "The effect of refining parameters on paper properties", Advances in Refining Technologies, PIRA, England, 1986.

83. Page, D.H., Kosky, J. and Booth, D., B.P. and B.I.R.A. Bulletin 28, 15 (1962).

84. Banks, W.A., "Design considerations and engineering characteristics of disk refiners", Paper Technol. 8(4), 363 (1967).

85. Fox, T.S., Brodkey, R.S. and Nissan, A.H., "High-speed photography of stock transport in a disk refiner", Tappi 62(3), 55 (1979).

86. Goncharov, V.N., "Force factors in a disk refiner and their effect on the beating process", Bumazh. Prom. 5,12 (1971).

87. Bowden, F.P. and Tabor, D. "The Friction and Lubrication of Solids" Clarendon Press, Oxford, 1950.

88. Bachmann, H. "Laboratory comparison of primary and secondary beating with basalt bars and knife tackle" Wochbl. Papierfabrik 98(6), 237 (1970).

89. Chiaverina, J. "Production increase by use of sintered metal beater tackle" Allg. Papier Rundschau 14, 516 (1972).

90. Brecht, W., Athanassoulas, M. and Siewert, W. "The influence of the angle between the tackle bars on the performance of beaters and refiners" Papier, 19(3), 93 and 19(4), 145 (1965).

Transcription of Discussion

THE BEATING OF CHEMICAL PULPS— THE ACTION AND THE EFFECT

D. H. Page (Review Paper)

J. Grant, Hehner & Cox Ltd.

Four years ago, I suggested that if you used rag pulps instead of solely wood pulps, you would obtain very valuable information as to the nature and extent of fibrillation because they fibrillate much more readily. You said that you thought my suggestion was sensible and that you would try it. I was hoping to hear the result.

D.H. Page

I am afraid that I forgot, was it noted in the Proceedings of the Discussions? If not, well it is now and that will remind me. So maybe next time, I will indeed have an answer.

J. Grant

I will endeavour to be here in four years time!

C. Dunning, James River Corporation

Your last point raises the question. If we are to use standard fibres, what would be your choices?

D.H. Page

I don't think it matters. What should really happen is that everyone should work on their own pulp, but in addition, once they have decided what to do they should pick a standard pulp where they know, for example, Scallan's values for fibre saturation point and accept other people's values for fibre strength, etc. That is my current thinking. In this way, we can enrich the body of knowledge.

Dr. P. Noe, CTP

You have not been talking about energy consumption in refining. People say it is very high, but Europe is very low. What are your comments about that?

D.H. Page

My opinion is very simple. I took off several weeks ago from Canada to England, and will return next week at a considerable cost of energy. My change in potential energy will be zero by the time I have finished, so the efficiency of the whole process is zero. We are familiar with such low efficiencies, and tend not to worry about it. I am not saying that there may not be methods of improving efficiency of refining by a factor of, say, two. After all, most of the energy goes into heat, but then the energy of me coming over here to England and then returning to Montreal also goes into heat. I am not sure that I agree with using classical concepts of efficiency here. It is more important in many contexts to do what we want to the fibres, rather than conserve energy.

Prof. H. Kropholler, UMIST

A splendid paper as usual Derek. Just to comment on cracks in the fibre, I think that the technique we have been publishing on low temperature SEM at least gives us a chance to see the cracks in fibres fairly quickly.(Mors P.A. et. al. "LTSEM - Potential for Pulp Evaluation" Paper Technology 30 No. 9 12-14, 1989). Looking at 1 mm square of copier paper it will contain about 50 fibres so do you think that one may simplify the size of the multi-variate problem we have to look at? In other words, not what happens to a single fibre, whether it is tied in knots, etc., but looking at an average group property of a lot of things that have happened. That may make the multi-variate problem more tractable.

D.H. Page

The only way of reducing the number of variables is that if some of these effects are so highly correlated that they can be merged as if they were one effect. For instance, if internal fibrillation is highly correlated with the material being leached out of the cell wall, which is a reasonable assumption, then you have one effect instead of two. However, a single piece of research with one pulp at a time produced three effects using five reasonably similar beaters. So I do feel that we will need in the region of five variables to describe a beater's action, but probably not nine.

D.G.N. Stirling, Wiggins Teape

In your description of the various variables you have kept fairly closely to physical ones. Do you think there is an historical blindness here and that we should be paying more attention to the chemical variables? I believe that you were starting to unravel the situation when you asked about the possible links between hemicelluloses, also the leaching of chemicals from the cell wall and re-distribution of chemicals within the structure.

D.H. Page

The chemistry does not change very much when you carry out a mechanical action such as beating and refining. Some things change, such as the degree of polymerisation of the cellulose which goes down. However, I have not considered that but maybe we should.