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BEATING AND HYGROSTABILITY OF PAPER

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Summary

The body material of paper is the vegetable fibre. Consisting mainly of cellulose, which because of its chemical character shows high hygroscopicity, the fibres enable the paper to take up water in its liquid phase, as well as in its vapour phase. The moisture content of the paper resulting from such absorption depends on the relative humidity and on the temperature of the surrounding air, on the composition (furnish) of the paper, on the manufacturing processes such as drying, also on the beating of the stock. These correlations are described.

Combined with changes in the moisture content are changes in the paper dimensions: their size is essentially given by the shrinkage of the paper during drying. As far as this shrinking is concerned, beating of the paper stock plays an important role. A special effect of dimensional instability is cockling.

The paper deals with the theories put forward by several authors who have investigated these correlations. It closes with some results obtained by using a new apparatus for measuring the hydrostability and the hygrostability of papers.

Introduction

It is known that the beating of fibrous material nearly always forms an indispensable step whenever paper of certain properties, particularly of greater strength, is to be produced. The beating affects the whole character and thereby also the hygrostability of the paper. Since hygrostability plays a fundamental part for most applications of paper in virtue of its important effects, a knowledge of the connection between beating and hygrostability is all the more valuable, as it clarifies a range of relationships of great technological significance.

Much research has, therefore, been carried out in this field. The difficulty in making a report is not so much following up the results of this research, but ordering the abundance of existing material and arriving at a concise presentation of the essentials.

It is difficult to shed one's background. As a technologist, I am inclined to view the facts from the aspect of their technical significance. As one can only do technical development work, if each step is clearly understood, well tried and built in a very simple way on the preceding one, I will try to make this report as simple as possible even at the risk of its appearing elementary.

The term *hygrostability* describes the behaviour of a paper subjected to changes in the humidity content of the surrounding air — that is, in the narrower sense, the resulting change in its own moisture content; in the wider sense, the effect on all its properties, particularly dimensions. This report deals firstly with hygrostability as such, then with its dependence on beating and, finally, with questions of dimensional stability and its connection with beating.

Moisture content of paper

Today, there exist clear ideas why a paper contains moisture under normal circumstances, in what form that moisture is held in the paper, on what its share of the total weight depends and how it changes when the condition of the surrounding air changes. The explanation of all these properties is found in the chemical and morphological nature of the cellulose fibre and in the way in which these fibres combine to build up the structure of the paper.

The chemical character is determined by the presence of the hydrophilic hydroxyl groups. The microfibrillar structure of the fibre facilitates the access of water to these groups and the porous structure of the paper offers capillary forces that attract and hold moisture.

This moisture is taken up by the fibre and the paper as a whole in three ways — firstly, as adsorbed water, secondly, as capillary water and, finally, as free water. For each of these three ways, the relative moisture content of the air surrounding the paper represents the determining factor.

Absorption isotherm

Fig. 1 shows an absorption isotherm. The water content of a certain pulp is plotted against the moisture content of the air. In the region of low moisture contents, the graph shows a rather steep gradient, which leads to about 4 per cent. moisture content, referred to the weight of dry fibre. Here, one is confronted solely with water held chemically or adsorptively, attached to the surface of the cellulose crystallites in a molecular layer without possessing the properties of free water. In the region of medium moisture contents, the curve shows a less steep, almost linear gradient. According to Stamm,[1,2] monomolecular sorption predominates up to 65 or 70 per cent. relative moisture content, but capillary condensation adds moisture filling the narrower cavities of the fibres. Barkas[3,4] has shown that, in the case of a moisture content below 60 per cent. R.H., no capillary condensation is possible. According to Brunauer, Emmett and Teller[5,6] the medium range of moisture contents is governed by multilayer, polymolecular adsorption. In consequence of increased capillary condensation, the graph rises more steeply up to the fibre saturation point, which is situated near 100 per cent. relative humidity of air and about 30 per cent. water content of the paper. Beyond this point, free water is taken up from the liquid phase only, filling the greater pores and cavities of the paper fibres, so that the moisture content of a paper can amount to as much as 300 per cent. of its dry weight.[7,8]

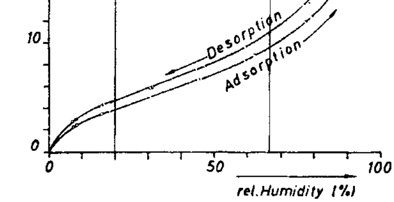

Fig. 1 — Sorption of water vapour by a sulphite pulp at 20°C

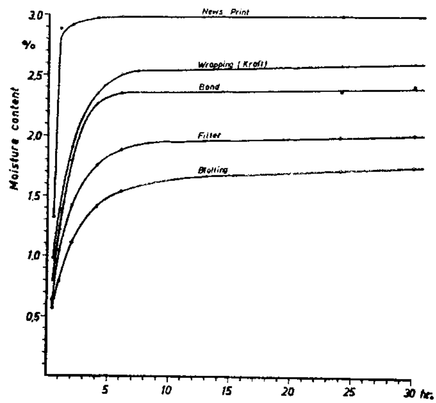

Fig. 4 — Rate of moisture adsorption from 35 per cent. to 65 per cent. R.H.
(Jarrell, T. D., *Paper Trade J.*, 1927, 85 (3), 47)

The shape of the curves depends on whether the saturation point is approached from the dry state through moistening the paper (proceeding from left to right) or whether, proceeding in the reverse direction, the dry state is approached from the saturation point through desorption. The two isotherms form a hysteresis loop. If the drying and the desorption that goes with it are followed by adsorption, then the paper exhibits less moisture content than before for equal relative humidity of air; the paper has suffered a loss of sorptive capacity for moisture.

For a long time, the opinion was held that the loop mapped out by the first cycle would remain after repeated alternations of drying and moistening. Fig. 2, however, shows that this is not the case. Papers were exposed for three days at a time to air at the very high humidity of 97 per cent., followed by a humidity of 65 per cent. and then tested for their moisture content. After that, they were conditioned for three days in very dry air of only 3 per cent. humidity content, followed again by 65 per cent., after which their moisture content was again determined. Several repetitions of the process led to Fig. 2.

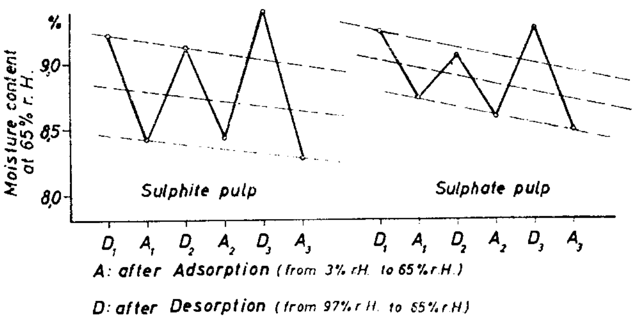

Fig. 2 — Hysteresis effect by humidity cycling
(Korn und Burgstaller, *Papierprüfung*, 1953)

The letter D always refers to moist conditioned and letter A to dry conditioned paper. The lefthand figure applies to paper of unbleached sulphite pulp, the righthand one to paper of bleached sulphite pulp. For both papers the moisture content decreased with the number of drying cycles.

Temperature

As regards the influence of temperature on the sorption of a paper, one should expect that sorption decreases with rising temperature, because sorption of water is an exothermal process. Investigations by Urquhart and Williams[10] and by Ulm[11] have confirmed this assumption for comparatively low and medium relative humidities of air. For high atmospheric humidity, however, it was found that sorption plotted against temperature shows a weak minimum at about 50°C.

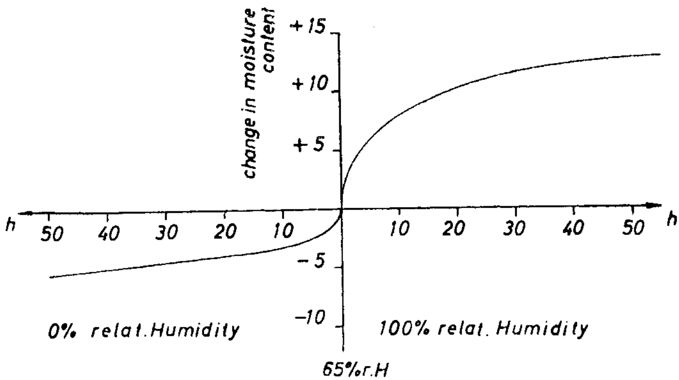

Fig. 3 — Rate of desorption and adsorption
(Walter, E., *Papierfabr.*, 1929, 370)

Rate of moisture exchange

The rate of change in the moisture content of paper has proved of great significance. In the interpretation suggested by Walter, [12] adsorption takes place much faster than desorption (Fig. 3), the exchange of moisture proceeding in both cases the slower, the nearer the moisture content of a paper approaches the equilibrium content, which depends on the prevailing humidity of air. This, however, is based on an old investigation of the year 1929. What speaks against the assumption is the fact that the moisture gradient of the paper was smaller during desorption than during adsorption. Actually, one should expect no difference in the rates of adsorption and desorption for equal gradients.

The determining factor for the rate of humidity exchange is, above all, the composition of the paper. Fig. 4 shows the increases in moisture content Jarrel[13] found when he tested various papers, previously conditioned at 35 per cent. atmospheric humidity, after treatment of varying duration with air at 65 per cent. R.H. The differences in behaviour among these papers were great. In all cases, the papers took up moisture rapidly at first, but the speed decreased as the moisture content approached the equilibrium content.

Papers of high equilibrium content showed a much greater initial rate than papers that adjust themselves to a lower equilibrium, the former reaching their equilibrium much sooner. It turns out that under the conditions described it took 1 – 8 hr. until equilibrium was reached.

Influence of paper composition

Fig. 5 brings some order into the variety that papers show in their reaction to moisture and expresses what numerous investigators have already found.[13-16] It is known that hemicelluloses are of higher hygroscopicity than pure cellulose. The nearer the purity of a fibre approaches that of cellulose, the smaller becomes the moisture content corresponding to a given atmospheric relative humidity. Therefore, it is paper made of rags or of purified and bleached chemical pulp that behaves in this sense like cellulose, whereas paper from unbleached and hard pulp or groundwood exhibits a

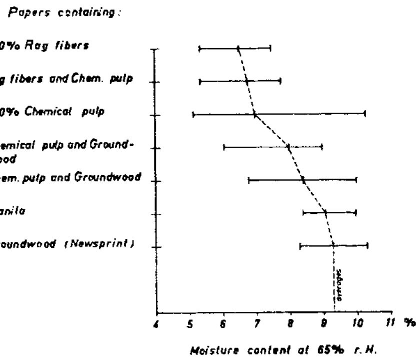

Fig. 5 — Moisture content of different papers (Korn and Burgstaller, *Papierprüfung* (1953), 121)

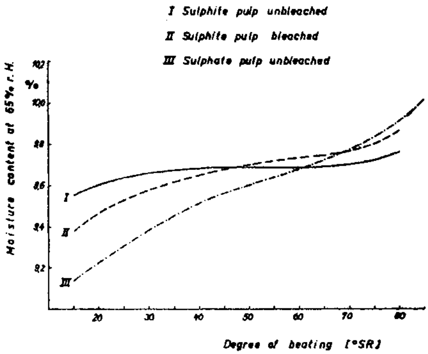

Fig. 6 — Beating and moisture adsorption (Korn and Burgstaller, *Papierprüfung* (1953), 121)

greater moisture content and a correspondingly livelier exchange of moisture.

The effect of additives on the humidity behaviour of paper is not significant[17] in the case of normal rosin sizing, whereas fillers reduce the water content of paper owing to their small hygroscopicity.[18, 19]

Thickness and density of paper

The external appearance of a sheet of paper, too, permits one to draw certain conclusions. With increasing thickness, adjustment to the humidity of the surrounding air is retarded. The same applies to papers of less bulk, for which reason thick, dense papers need longer conditioning than those worked thin and porous.[14]

Drying and hornification

The method of drying pulp and paper is also of importance. Whenever hornification has taken place during drying, be it through excessive temperature or excessive contact with the heating surface, the paper suffers an irreversible loss of sorptive capacity.[20]

Beating and humidity content of paper

This cursory survey of the humidity characteristics of paper is now to be supplemented by the opinions that have been put forward on the effect of beating.

Strachan,[21] also Seborg, Simmonds and Baird[22] and Weidner,[23] as well as others,[24, 25] found that the equilibrium moisture content rises with beating. This is also indicated by Fig. 6, taken from the book by Korn and Burgstaller.[14] It has been established, however, that the increase in moisture content is but small and amounts from 0.3 per cent. to 1 per cent. at most, even for highly beaten pulp, compared with unbeaten pulp at 65 per cent. atmospheric relative humidity. When Bell[26] and Jahn[27, 28] beat pulp for various times and applied water under pressure for an appreciable length of time, they found no differences whatever in sorption.

It is mainly the work of Campbell[24] and Stamm[1] that has contributed to an explanation of these observations. According to them, beating does not cause hydration in the chemical sense, that is, no water penetrates into the crystalline regions, otherwise the adsorption isotherm would show breaks. Regarding the nature of adsorption, it is known today that water can hardly enter the crystalline region, but distributes itself over the surfaces of the cellulose molecules in the amorphous regions most rich in hemicellulose. The water accessibility is thus the greater, the smaller the degree of crystallisation. A change in the degree of crystallisation in the form of a crushing of the crystals, effected by beating, takes place to only an extremely small extent. In consequence, the pulp is completely ready for the sorption of water even before beating. The pulp is prepared for beating through a process of soaking. The longer the soaking lasts, the more the bonds between the cellulose fibrils weaken through the intrusion of water, so that the fibres offer themselves soft and supple to the subsequent beating. The beating itself produces internal and external fibrillation. The former means a loosening of fibrils inside the fibre. The latter means a loosening of fibrils on the surface of the fibre. On the surface of the fibrils, in turn, finest crystallites start projecting in the shape of very thin hairs. The loosening of the fibrils enhances the suppleness of the fibres, whilst the tiny hairs increase the outer surface of the fibres and, consequently, the number of points of contact. It depends on the interplay of the two effects whether the total surface area increases and more water is thereby retained in the fibre network or whether the inner fibre surface is converted into the outer, so that the total surface area — and, consequently, the extent of water sorption — remains unchanged.[28]

These relations throw a light on the significance of a number, recommended by Jayme[29] to indicate the physical reaction of pulp or paper to water, called *water retention value* (WRV) and determined by spinning a suspension in a centrifuge. As the WRV is connected with the outer fibre surface, it rises strongly with beating.

Beating and dimensional stability

Publications in English do not use the term hygrostability in the sense of general constancy of a paper exposed to changes in atmospheric humidity, that is, to what degree its own moisture content remains unaffected by variations in the humidity of the air; in fact, the term denotes a very specific property, namely, the dimensional stability. This signifies the extent to which a paper retains its dimensions when water in its vapour or in its liquid phase acts on the paper. The former case is referred to as hygrostability, the latter as hydrostability.

The influence of beating on the dimensional stability of paper by far exceeds the effect that ought to be expected considering the small increase in humidity content of paper produced by beating.

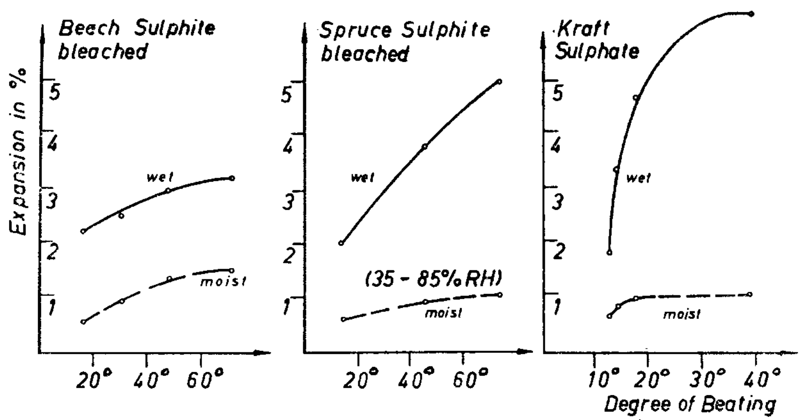

Fig. 7 — Hygro- and hydro-expansivity on beating
(Brecht, W., Gerspach, A. and Hildenbrand, W., *Das Papier*, 1956, **10** (19/20), 454)

Fig. 7[30] shows the expansion of a strip of paper as a function of the degree of beating (°S.R.) produced through beating in the Jokro mill. The upper curve refers to the hydroexpansivity, the lower to the hygroexpansivity. It becomes apparent that the influence of beating depends on the nature of the pulp, further that this influence may differ for hydroexpansivity and hygroexpansivity. At any rate, there is always an effect of considerable magnitude. It has to be added, however, that, for reasons yet to be discussed, the expansivity values can only be sensibly compared either if the papers investigated have been dried in such a way that throughout the drying process no tensions have arisen, so that shrinking has had a chance of developing fully or if the tensions arising have remained equal.

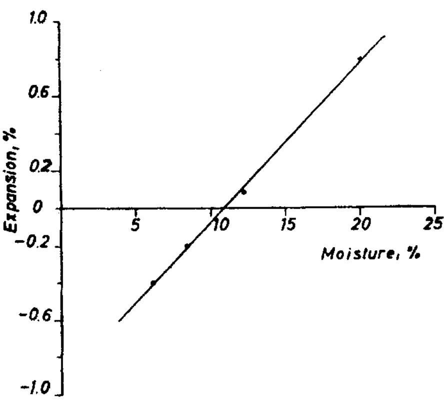

Fig. 8 — Relation between sorbed water content and expansion of paper
(Rance, H. F., *Tappi*, 1954, 37 (12), 640)

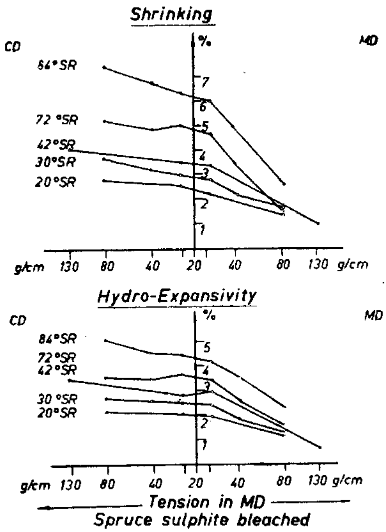

Fig. 14 — Shrinking and hydro-expansivity at varying tensions during drying for different degrees of beating
(Brecht, W., Hildenbrand, W., and Gerspach, A., *Das Papier*, 1956, 10 (19/20), 454)

It follows from the work of Reed[31] and Fig. 8 and 9, both supplied by Rance,[32] that papers generally react to changes in their moisture content with approximately proportional changes in length of equal sense. Comparison of Fig. 9 with Fig. 2 shows how, during the alternation of moistening and drying cycles, the paper becomes drier and accordingly shrinks until constancy is reached after about 7 cycles.

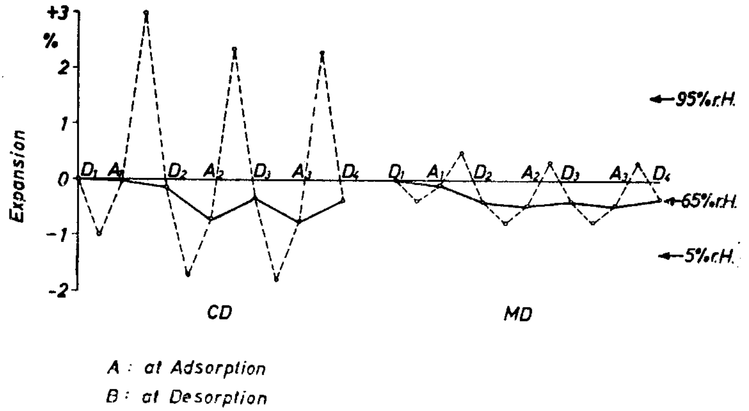

Fig. 9 — Hysteresis effect by humidity cycling
(Rance, H. F., *Tappi*, 1954, 37 (12), 640)

Nevertheless, beating leads to greater hygro- and hydro-expansivities than ought to be the case in agreement with the moisture content of the paper enhanced by beating; besides, the connection between the moisture content of paper and its dimensions turns out to be rather involved. In Fig. 10, three examples are picked out from among the 23 investigated by Laroque.(33) For all three papers, the sorption isotherms show the well-known S-shaped hysteresis. The curves for the dimensional changes, however, give a different picture. The offset paper (*left*) shows a course similar to that of the sorption in the cross-direction, that is, expansion and shrinkage of the paper follow its humidity content, so that a hysteresis loop of the same kind results. In the machine-direction, however, the contraction linked with

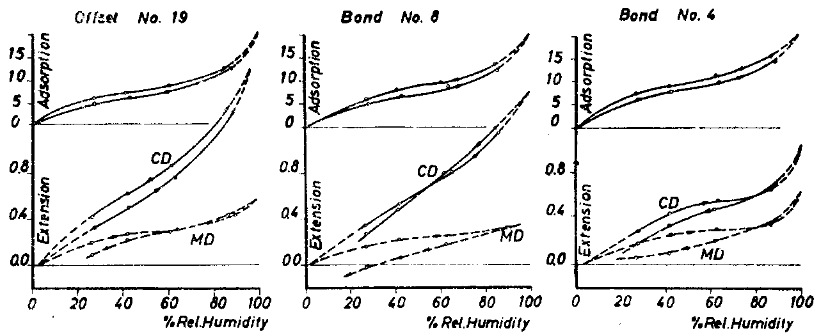

Fig. 10 — Moisture content and dimensions at desorption and adsorption for different papers (negative hysteresis)
(Laroque, G., *Pulp and Paper Mag. Can.*, 1936, 37 (4), 199)

desorption is stronger than the preceding moist expansion. Bond No. 8 (*middle*) shows this in the machine-direction more markedly; in the cross-direction, the curves for expansion and contraction match. Bond No. 4 exhibits a negative hysteresis in both directions. The connection between humidity variation and dimensional variation thus proves to be disturbed. In successive cycles, the dimensional curves of that paper for the cross-direction roughly coincide as shown in Fig. 11, whilst, in the machine-direction, the paper keeps shrinking in the sequence of cycles. This contraction dies away after about 7 cycles, which was also observed by Smith.(34)

The cause of these phenomena is to be found in the greater or lesser inhibition of shrinkage that takes place during drying.

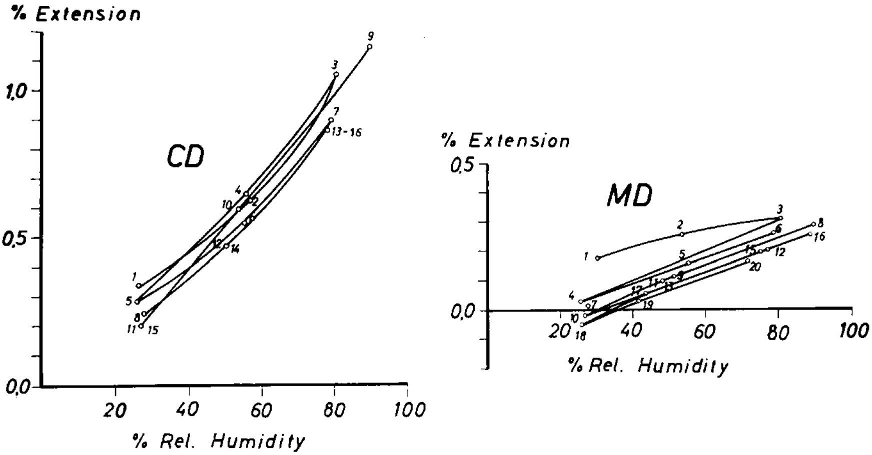

Fig. 11 — Dimensions on continued humidity cycling
(Laroque, G., *Pulp and Paper Mag. Can.*, 1936, 37 (4), 199)

Shrinkage of paper during drying

The part that the beating of pulp plays in the dimensional stability of paper thus does not take effect until the paper is being dried and attention is specially focused on the shrinkage that the paper undergoes in the drying section of the machine.

In a brilliant paper, Smith(35) developed ideas that have rendered excellent service. A paper suffering no tension during drying and thereby able to shrink unhindered shows its maximum shrinkage. Smith called it potential shrinking. Tensions that are effective during drying permit only a certain amount of shrinkage. It is the difference between potential and

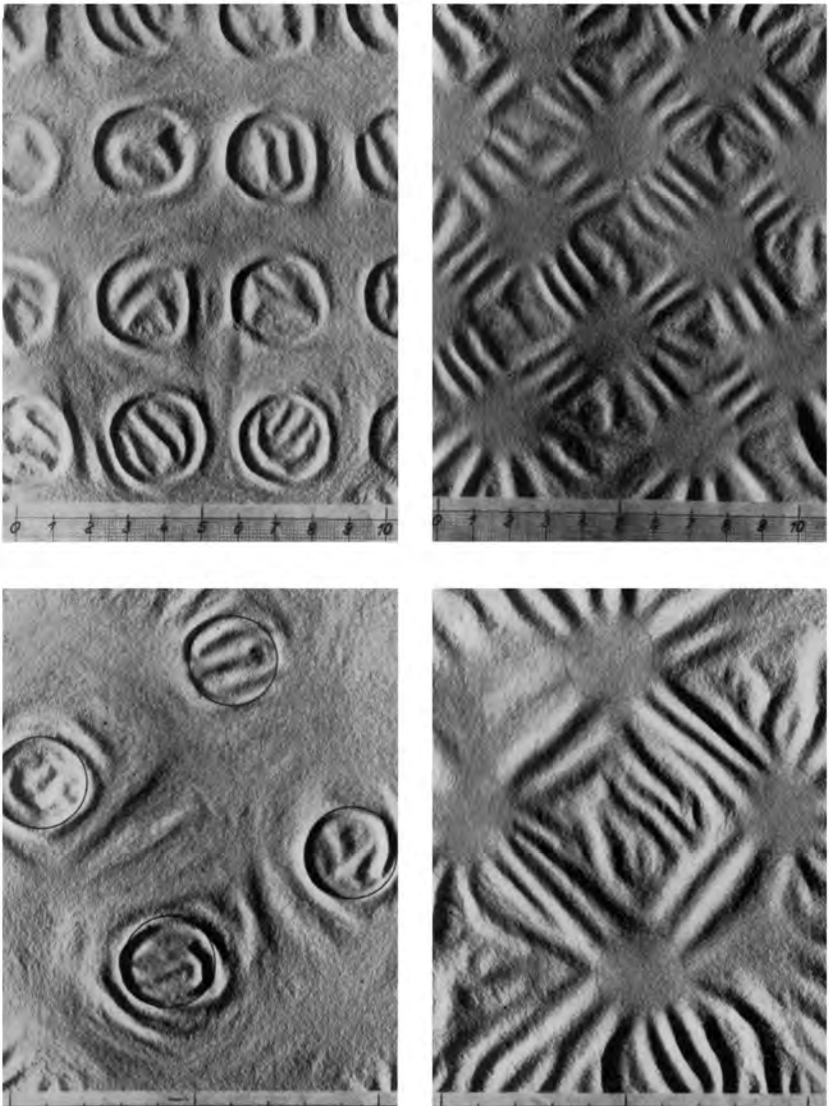

Fig. 12 — Cockling caused by non-uniform moisture content before drying

Left—Cockled areas = Dryer areas before drying

Right—Flat areas = Wetter areas before drying

Unbleached spruce sulphite, 69° S.R.; Basis weight of sheets 75 g/m.^{2}; drying temperature 80°C

(Brecht, W., Muller, F. and Weiss, H., *Das Papier*, 1955, 9 (7/8), 133) actual shrinkage, the *dried-in strains*, that becomes apparent later in the form of shrinkage, when the paper is dried tension-free after moistening. Ivarsson and Steenberg [35-37] meant the same when they spoke, even earlier, of frozen-in stresses.

Experimental test of Smith's theory

Smith's theory in an instructive way points also to that special manifestation of hygrostability that stems from its irregular distribution over a paper surface and leads to cockling. According to that theory, cockling takes place if paper inhibited in its shrinking and consequently affected with dried-in strains is dried with the dried-in strains differing from point to point.

Brecht, Müller and Weiss[38] have tried to establish the correctness of this theory. Moist sheets of paper were prepared, which had an uneven distribution of moisture over its surface corresponding to a certain pattern. When the sheets were subjected to contact drying, there resulted the artificially produced cockling shown in Fig. 12, which exactly reproduced the pattern of moisture distribution just mentioned. There were circular patches on the sheets, which before were less moist than the remaining regions in the two lefthand pictures and more moist in the two righthand pictures. The cockles always coincided with the initially less moist spots, whereas the initially moister patches remained flat. The explanation is that the initially drier patches enter that stage sooner during the drying in which fairly large shrinkage is connected with relatively small evaporation. These spots thus tend to shrink more than the others. Consequently, there arise tensions on their margins that hamper shrinking. If the sheet was flat until then, the other parts of the sheet shrink as a whole towards the sheet centre in the further course of drying. The patches already dried cannot shrink any more; they are warped out of the plane and form cockles.

Since cockling comes from uneven shrinkage conditions, one may expect that it will manifest itself more markedly, on the whole, where greater shrinking is to be anticipated than in the case of lesser tendency to shrink. Beating enhances the shrinking tendency. The lefthand picture of Fig. 13 shows a sheet of medium degree of beating, the righthand picture a sheet of the same pulp more highly beaten, but otherwise produced and dried under exactly the same conditions. This confirms the fact known in practice that beating increases the tendency towards cockling.

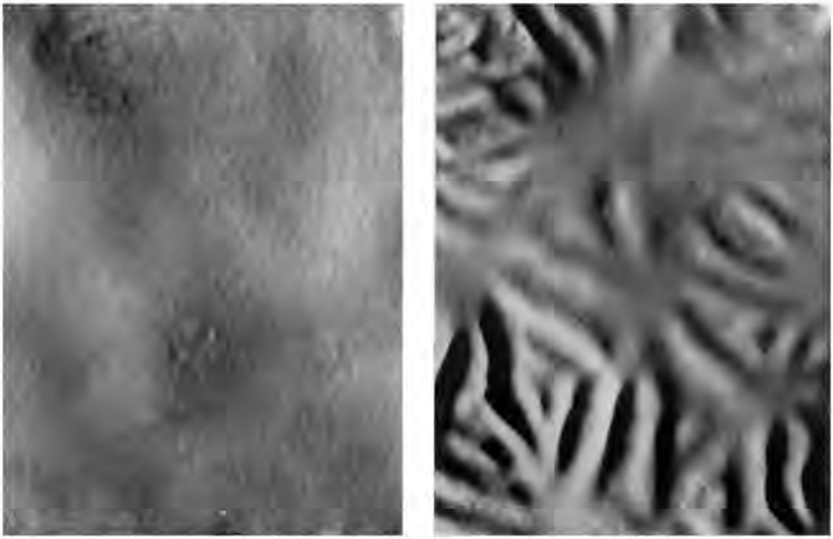

Fig. 13 — Influence of beating on cockling
Bleached beech sulphite, basis weight of sheets 75 g/m²; drying temperature 120°c
(Brecht, W., Muller, F. and Weiss, H., *Das Papier*, 1955, 9 (7/8), 133)

Further investigations

From the area distribution of hygrostability, let us return to the *general* dimensional stability and the shrinkage connected with drying, which so to speak forms the operative link between beating and wet expansion.

In Fig. 14, which is taken from a paper by Brecht, Gerspach and Hildenbrand,[30] the results are shown for sheets of a sulphite pulp, which during drying were exposed to varying tensions in a direction that shall be called the machine-direction. The shrinkage is shown above and the wet expansion below, with each curve belonging to a different beating condition of the pulp. The curves to the right of the vertical refer to the machine-direction, in which the drying tension was acting, those to the left refer to the cross-direction. One immediately recognises the fact, already noted by various authors, that wet expansion and its change always correspond to shrinkage and its change. High degrees of beating cause far greater shrinking, consequently, much greater wet expansion than do lesser degrees of beating. Since shrinkage and wet expansion only develop completely when shrinking is not hindered by tensions during drying, shrinkage and wet expansion decrease to the extent in which rising drying tensions 'dry in'. The same drying tensions lead to a greater fall in shrinkage and wet expansion for high degrees of beating than for free beaten pulps.

The tensions applied during drying thus provide a tool for influencing wet expansion. Maynard and Newman[39, 40] by their beautiful investigations, in which they varied within wide limits the shrinking of the paper during drying could in fact prove that it is possible to compensate the influence of beating on wet expansion by the tensions applied, which control the shrinkage permitted.

In 1951, Glover, Pritchard, and Ray[41] and later again Pritchard[42] worked on the connection between beating, drying tension and wet expansion. Just as the density of sheets of paper grows with beating, beating and wet expansion also increase, but it is only the total amount of beating that matters and not whether low beating pressure was exerted for a long period or high beating pressure for a short period.

Fig. 7 has already made it clear that the effect of beating upon dimensional stability varies with the nature of the pulps. Fig. 15 presents results of experiments carried out by Brecht, Gerspach and Hildenbrand[30] in a more cursory fashion. They roughly agree with observations made by Arnamo[43] in 1954, but bring into relief the strikingly favourable behaviour of groundwood.

When Lory and Libby[44] were working in 1954 on the hygrostability of paper as a function of a number of technological data, they unfortunately used a method of drying that completely inhibited shrinking. They were, therefore, unable to establish definite relationships. Nevertheless, their results formed a useful contribution, as they proved that the influence of the degree of beating on wet expansion can be suppressed by inhibition of shrinking. Even in 1932, McKee and Shotwell[45] gave some information on the rate at which moist expansion takes place. They found that both equalisation of moisture content and changes in dimension proceed the faster, the greater the difference between the prevailing air humidity and the equilibrium humidity content of the paper.

It is perhaps surprising that wet expansion was mentioned on one occasion and moist expansion on another. Investigating paper some time ago, Laroque[33] found rather divergent results for wet expansion and moist expansion. Fig. 7 taken from the paper of Brecht, Gerspach and Hildenbrand[30] also points to the fact that there exists no simple and obvious connection between the two properties.

Theoretical considerations

If one inquires into the reasons for the effects of the beating of fibres on the dimensional stability of paper, two things have to be taken into consideration — the individual fibre and the arrangement of the fibres in the network of the paper. The question has to be examined whether the change in paper area is perhaps due to a combined effect of these two structure characteristics, when they are both subjected to beating.

About the behaviour of the individual fibre, it is known mainly through the work of Collins[46] that the sorption isotherms form the same hysteresis loop as for the paper, the alteration in the fibre diameter being about 20 times as great as that in the fibre length. At saturation point, the diameter is 15 — 20 per cent. greater than that of the dry fibre. But the swelling remains proportional to the water uptake only for slight water adsorption; for higher humidities, it lags behind. Initially, beating leads to a rise in the moist expansion of single fibres, because of the destruction of the primary wall, which envelops the interior of the fibre in a spiral-like, fibril structure similar to a rigid skin. Beating as a whole even seems to diminish the moist expansion of the individual fibre, however, as the fibrous structure is loosened, so as to admit more water without any change in the fibre's external dimensions, though the relatively slight effects observed on the individual fibre can in no way explain the great increase that the wet expansion of paper exhibits with rising degree of beating.

Attention, therefore, has to be shifted to the fibre network. If all fibres were parallel, says Rance,[32] the shrinkage and wet expansion of the web should have the same anisotropy as a single fibre, which is about 1:20. Wet expansion makes indeed a substantially greater contribution normal to the fibre direction than parallel to it. Since beating shortens the fibres and thereby increases the randomness of fibre orientation under otherwise the same conditions, we have in fact found that pulp of a higher degree of beating shows better balance of wet expansion between machine- and cross-directions.

One only penetrates to the core of the problem, however, if one scrutinises the shrinkage of paper on drying, on the one hand as a consequence of the beating and, on the other, as cause of the wet expansion, at the same time paying sufficient attention to the behaviour of the individual fibre and the fibre network. Ivarsson,[36] using a thermodynamic theory of Barkas[47] and treating paper as a gel, has calculated the shrinking tensions arising during drying. As a parameter and also as a direct measure for the degree of beating, he used free shrinkage.

It is a great achievement of Rance[32, 47-51] to have developed a comprehensive picture that makes the effect of all operative factors clearly understandable. Despite the risk of serious omissions, only the most important features of his theory can be presented here.

Rance subdivides shrinking into interfibre shrinking and intrafibre shrinking.

Interfibre shrinking shows itself as a consequence of the surface tension of the water between the individual structure elements, such that the combined effect of these forces rises as drying progresses. When the structural elements are soft and supple, sliding over one another easily, surface tension leads to a noticeable densification of the sheet. In this condition, the fibres are held together by the interfibre bonds arising.

Beating promotes these conditions, because the fibres still gain in suppleness, they fibrillate and thus move still more closely together, thereby producing more interfibre bonds — in short, the densification forces increase with the growth of the external fibre surface.

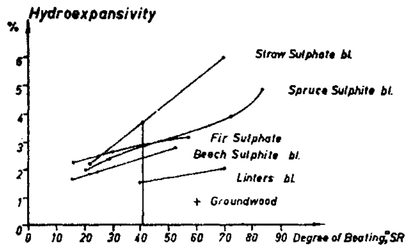

Fig. 15 — Hydro-expansivity and beating
(Brecht, W., Gerspach A. and Hildenbrand, W., *Das Papier*, 1956, 10 (19/20), 454)

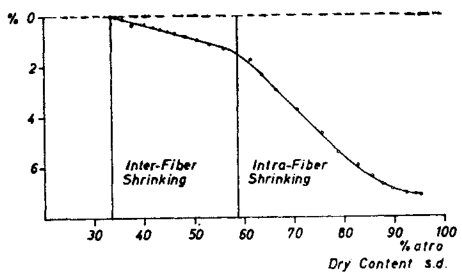

Fig. 16 — Shrinking during drying
(Brecht, W. and Pothmann, D., *Das Papier*, 1955, 9 (13/14), 304)

Single fibre shrinking, on the other hand, is practically independent of beating, but is transferred to the whole sheet to the extent in which the fibres are in contact. Its effect on the web, the *intrafibre shrinking*, therefore is also enhanced by beating. (It is intrafibre shrinking that causes micro-cockling in the sheet structure, since the fibre diameter shrinks much more strongly during drying than does the fibre length.)

Although both kinds of shrinking are furthered by beating in their effect upon the dimensional variation of the paper, nevertheless, they are distinctly different from each other. Interfibre shrinking sets in long before intrafibre shrinking during drying, — the sooner, the greater the degree of beating. It shapes the beginning of the shrinkage curve, which is shallow, because only capillary water evaporates; the shrinking follows this evaporation linearly. Intrafibre shrinking, on the other hand, determines the steeply rising part at the end of the curve (Fig. 16).[52] So much about the work of Rance in this connection.

We see that, depending on the beating, there results a certain (potential) shrinking of the sheet, which in turn fixes the corresponding (potential) wet expansion. Drying tensions diminish the effective shrinkage and thereby the wet expansion. The higher the degree of beating, the higher consequently the drying tension has to be, in order that sufficiently small shrinkage and wet expansion are secured. The cross-direction drying tension that can be applied in a papermachine is limited, however, for which reason a more highly beaten pulp leads to a greater wet expansion of the paper. It may happen quite readily that the more highly beaten paper has the smaller wet expansion, as it has been produced on a broader papermachine. The greater the paper width, the smaller is the effect of the edges upon the average shrinkage. A broader paper thus has to stand greater cross-tensions; consequently, it suffers greater shrinking inhibition, which in turn produces smaller wet expansion.

I now continue to quote Rance. The moist expansion takes place when the paper absorbs moisture and the shrinkage that occurred during drying recedes.

The degree of shrinking reversibility can be derived from the ratio of intrafibre shrinking to interfibre shrinking; for intrafibre shrinking proves reversible in its whole effect, whereas interfibre shrinking, according to Pritchard,[42] is completely irreversible.

Given two pulps of equal magnitude of shrinkage, the one characterised by a greater ratio of interfibre shrinking to intrafibre shrinking may thus produce a greater wet expansion of the paper.

There are anomalies, however — for example, the slight shrinkage of very free beaten pulps is fully reversible; full reversibility is also observed for all pulps at the beginning of beating, which extends to 2 per cent. shrinkage and wet expansion.

There remains the question how to explain the inhibiting influence of the drying tensions on shrinking. The wet paper has indeed a (potential) shrinking capacity whose magnitude is derived from the influence of beating on intrafibre and interfibre shrinking: but, if there are tensions during drying, the fibres cannot close up and join each other unhindered in the direction of tension. Also slighter in the direction of the tension are compression and cockling, owing to the greater shrinkage of fibre thickness compared with fibre length. Particularly the work of Corte, Schaschek and Broens[53-56] has confirmed that fewer interfibre bonds originate from drying tensions. Highly beaten pulps dried under tension yielded papers of lesser density than those dried tension-free. Papers dried in this way offer less possibility of wet expansion, as, from the lack of bonds, the strong, single fibre cross-expansion is transferred to the sheet only to a small degree.

One may also look at things this way — the tension during drying blocks shrinking, thus causing elastic deformations, which are retained in the finished paper by considerable forces. If the paper takes up moisture, it expands to an extent that corresponds to free (unblocked) shrinking. If moistening and drying are repeated, the latter without tension, the elastic deformations diminish in the sequence of cycles, free shrinking increases, so that the sheet shortens in the manner found by Laroque and Smith, until stagnation sets in after perhaps 7 cycles. Wet expansion then exactly equals shrinkage.

Fig. 17 — Apparatus for the study of hygro- and hydrostability

Fig. 17 shows the device used, with which 12 specimens can be tested on wet expansion, as well as on moist expansion. It is essential that each specimen can be treated separately. The small size of the chambers permits a change of the climate within the short time of a few seconds. Not only are the changes in dimensions measured, but also those in the weight of the specimen.

Just by way of demonstration, a sulphite pulp and a kraft pulp were beaten to three different wetnesses (°S.R.). Handsheets were made and dried in such a way that during drying high tension existed in one direction — let us call it the 'machine-direction' — and a very small one across the sheet.

Fig. 18 shows the development of wet expansion with time. The strongest influence was exerted by beating. The greater wet expansion was always connected with the higher degree of beating. In the difference between the upper and the lower picture, one sees clearly that the high drying tension diminished the wet expansion in a very pronounced manner. Of the two pulps, it was always the sulphite pulp that had the greater wet expansion. The rate the wet expansion developed was greater in the case of the freer beaten specimen than in those of the slower ones, doubtless because the freer beaten pulp had the greater porosity. Presumably, also on account of the higher porosity of the sheets, the strips made from the kraft pulp expanded faster than those made from the sulphite pulp. As in the case of beating, the pulp with the higher wet expansion gave a lower rate than the pulp with the lower wet expansion.

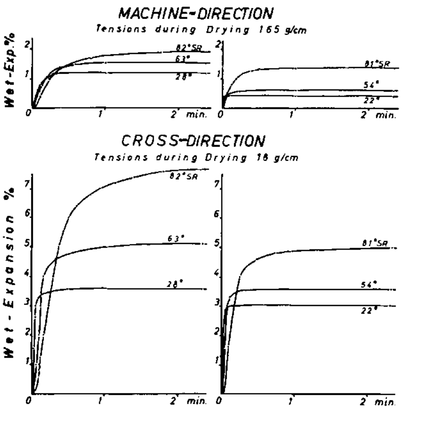

Fig. 18

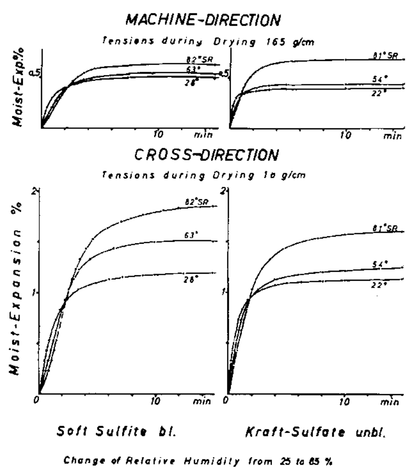

Fig. 19

Fig. 19 demonstrates in the same way the moist expansion, which, of course, takes more time than the wet expansion. The diagram corresponds to the preceding one with the exception that here differences between the two pulps were not as distinct.

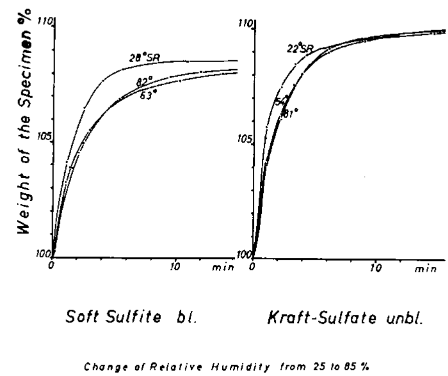

Fig. 20

In Fig. 20, the corresponding amount of water absorption has been drawn.

In accordance with theory, it would appear that all degrees of beating for the same pulp lead to the same moisture content of the specimen.

As far as the rate is concerned, the moisture absorption as well as the expansion are larger for the free-beaten pulp than for the more highly beaten one.

Summarising, one would say that the speed with which the moisture content and the dimensions change depends on the porosity. The more porous the paper, the faster the changes develop. The extent of the moist expansion is determined by the behaviour in shrinkage during drying under the same conditions. The more highly beaten pulp causes the greater shrinkage and therefore the greater moist expansion; but, since the paper is denser, the expansion takes more time.

Much of the work done by investigators has had to be neglected in this paper, though there remains the hope that the discussion, enlivened and fostered by the presence of famous authors, will close the gaps and impart well-founded knowledge on this important subject.

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Transcription of Discussion

DISCUSSION

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

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

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

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

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