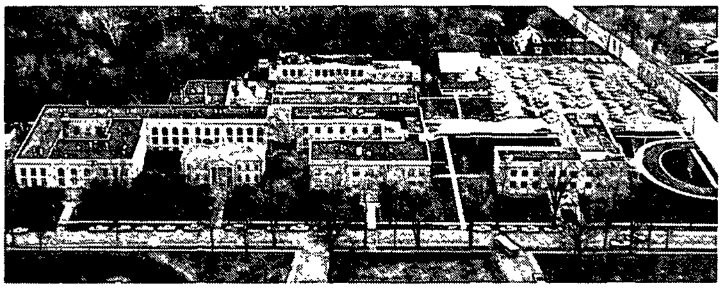
162



THE INSTITUTE OF PAPER CHEMISTRY, APPLETON, WISCONSIN

IPC TECHNICAL PAPER SERIES
NUMBER 162

PAPER PROPERTIES AND CONVERTING

JOHN F. WATERHOUSE

OCTOBER, 1985

PAPER PROPERTIES AND CONVERTING

John F. Waterhouse
The Institute of Paper Chemistry
Appleton, WI 54912

INTRODUCTION

Paper and board in recent years have gained recognition as challenging engineering materials whose full potential has yet to be realized. This recognition stems from a more fundamental but as yet incomplete appreciation of the structure and properties of paper and board and the great diversity of products derived from them.

Understandably, paper and board product growth has been greater than the acquisition of the fundamentals necessary to optimize their performance for converting and end-use applications. One consequence of this has been the development of numerous test methods purportedly related to converting and end-use requirements. Ideally, we would like to be able to completely characterize our papermaking raw materials with the minimum number of variables and then use this information together with our understanding of papermaking technology to design a product to meet certain converting and end-use requirements. This approach underlines another difficulty and a real need, irrespective of what our design strategy may be, and it is that of understanding and specifying the correct "environment" which our paper and board products may be subjected to during converting and end-use. The published papers devoted to understanding the "environment" to which paper and board are subjected to during converting and end-use are few in number. Nevertheless, in strength related requirements, for example, it is clear that paper and board are more likely to be subjected to complex combined stress situations than a simple tensile stress. A further complicating factor in dynamic situations is an appreciation of the viscoelastic nature of paper and board.

This report will therefore be concerned with some paper property related needs of converting.

Converting and Paper Properties

Converting processes are many and varied as are the paper and board property requirements associated with them. However, they do have more in common than is perhaps realized. Some of the main areas of converting (1,2), are given in the table below.

Table 1 Converting processes

1. Coating
2. Calendering and Supercalendering
3. Forming and Molding
4. Laminating
5. Impregnation
6. Modification of Deformation Behavior
7. Gluing, Bonding, Jointing
8. Printing
9. Size Reduction

In broad terms a base paper may be combined with other materials and subjected to one or more converting processes to produce a finished paper product. In general, converting processes are usually off the paper machine, i.e., "off-machine", but this is not always the case. For example, supercalendering is usually an off-machine process, but recently there has been renewed interest in on-machine supercalendering (3). Some of the more important paper property categories associated with the above converting processes are given in Table 2 below.

Table 2 Paper properties important to converting

- Deformation Behavior
- Dimensional Stability
- Wetting and Liquid Penetration
- Surface Characteristics

In what follows we will be mainly concerned with the deformation behavior and dimensional stability aspects of paper and the needs of converting.

Deformation Behavior

Paper is a network structure of fibers of finite length. This distinguishes paper from other foil-like materials. In some instances it is useful to treat paper as an anisotropic continuum, and to further simplify its description we can to a good approximation assume that paper can be represented as an orthotropic plate. A complete description of the elastic behavior of an orthotropic plate requires the measurement of nine elastic constants. These can be most conveniently measured using ultrasonic wave propagation techniques (4,5). In many instances an excellent correlation has been found between elastic properties measured nondestructively and failure properties (6). This is particularly valuable where one is contemplating the on-line measurement of a strength related property. When such on-line equipment becomes available commercially it may, in addition to the paper machine, find converting process applications.

Paper deformation behavior is in general controlled by network, fiber, interfiber bonds, and additive properties as shown in Fig. 1.

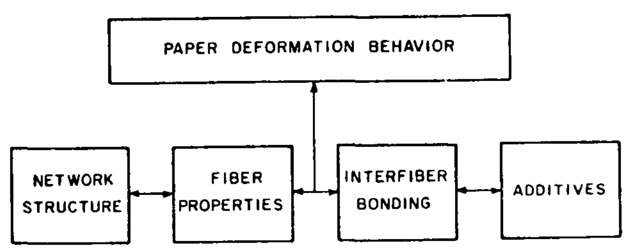


Fig. 1 Paper deformation behavior.

Considerable effort has been devoted to understanding the deformation behavior of paper and board, but until recently has been concentrated on the uniaxial tensile deformation behavior. In reality paper and board are subjected to more complex stress situations. Work is ongoing at a number of laboratories in the U.S.A. and elsewhere to better understand deformation behavior when paper and board are subjected to combined stress situations including tension, compression, and shear (7,8). The familiar burst test is one example of a combined stress situation.

The above remarks have focused mainly on the in-plane deformation mode. However, the importance of the out-of-plane deformation mode is now beginning to be more fully appreciated. Out-of-plane deformation measurements are not readily made by mechanical means, although both the tensile (9,10) and shear modes (11-13) have been investigated using this approach. Again, as mentioned above, it is relatively easy to measure the out-of-plane elastic constants using ultrasonic wave propagation techniques. It is also interesting to note that some paper and board properties are directly dependent on both in-plane and out-of-plane properties, e.g., compressive strength. It may be anticipated that certain converting processes will not only depend upon, but may also modify the in-plane and out-of-plane properties of paper and board.

The viscoelastic nature of paper and board is another important factor which needs to be more fully appreciated in converting. Deformation behavior, for example, is dependent upon the time scale of loading. The time scale of laboratory testing is not always appropriate to many converting processes. Cellulose, at the molecular level, may be viewed as being comprised of ordered and less ordered regions. The less ordered or amorphous regions, which may be comprised of hemicelluloses, lignin, and cellulose, are mainly responsible for the viscoelastic nature of cellulose. An amorphous polymer is characterized by a well defined transition zone between its behavior as a glassy polymer and a rubbery polymer. For many polymers this well defined transition zone is usually denoted by a glass transition temperature. In the case of cellulose the transition zone is considerably broader, and the term softening temperature is preferred. Dry cellulose, hemicelluloses and lignin have softening temperatures of 230°C, 150-220°C, and 124-193°C, respectively (14) and in the absence of moisture, a very effective plasticizer, would exhibit glasslike behavior at room temperature. The deformation behavior of paper as a function of moisture content, will in part be determined by the amount of amorphous material present (when evaluated at constant temperature and humidity). However, if the moisture content is recalculated on the basis of the amount of amorphous material present, then the elastic properties as shown by Salmen (14), in Fig. 2 will essentially collapse onto a common curve. The amorphous content of a pulp may be changed by the type of species, pulping and bleaching process employed. Page (14a) has recently proposed that the difference in the behavior of sulfite and sulfate pulps may be attributable to differences in their viscoelastic nature.

So far we have reviewed the general nature of the deformation behavior of paper and board, and emphasized the importance of the out-of-plane mode. The deformation experienced by paper and board during converting operations, however, is not easily defined. It is apparent that failure, permanent set, and deformation modification mechanisms are involved, to some extent, in all of them and will be discussed in more detail below.

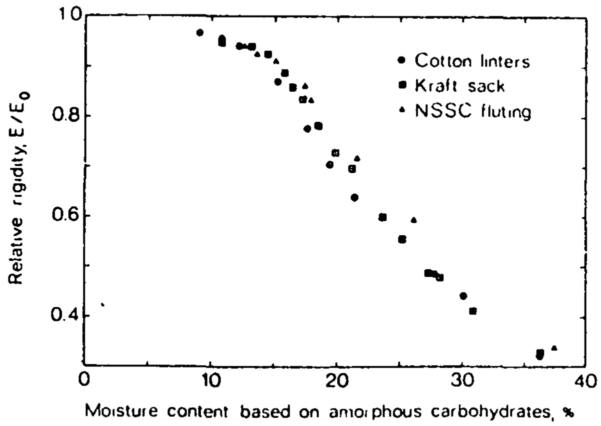


Fig. 2 Relative rigidity as a function of moisture content. Data of Salmen (14).

One important aspect of the runnability requirements of many converting processes is the ability of the web to withstand failure. In many instances the speed or productivity of the system may be limited by web breaks (e.g., newsprint) or by partial or total failure (e.g., flute fracture in corrugating). In web failure related runnability problems it is important to determine the nature of the loading.

Simplistically, in strength related runnability problems, failure will occur when the web loading exceeds the web's ability to carry a load. The applied loading is stochastic and it is usually not an easy matter to determine if the failure is a nonrandom event. This could be an important consideration, for example, when evaluating newsprint from different vendor sources.

The mode of failure is also not easy to define. In well run press rooms there is usually good documentation as to the category and causes of web breaks when some identifiable defect is present such as a shive or calender cut. The importance of shives has been investigated by Sears and coworkers (15), who found in laboratory runnability newsprint trials that shives were present in about 98.5% of the breaks. It is also interesting to note that the failures occurred at about only 20% of the web's tensile failure strain.

Using a fracture mechanics approach, Page and Seth (16) have established procedures for the measurement of fracture resistance of webs. Using this technique they have demonstrated, albeit with fifteen months of data collection, a correlation between runnability and fracture resistance. The process of fracture initiation in unflawed webs has received virtually no attention in the literature. This may be considered to be an extremely rare event but would certainly be part of the tally of breaks in a press room ascribed to unidentifiable sources. For example, it might be expected that sheet formation, i.e., small scale mass distribution variations, might play a vital role in runnability. This aspect has received limited

2

attention to date and includes paper machine wet-end runnability (17) and the effects of calendering on newsprint strength (17a). The work of Moffatt and co-workers (17a) shows that in uncalendered newsprint the failure path is connected through areas of low basis weight, whereas commercially calendered newsprint is through high basis weight zones. They also demonstrate the importance of long fiber content and fiber orientation in these areas. There is also a continuing controversy (18) regarding the appropriateness of certain tear measurements, i.e., Elmendorf vs. in-plane with respect to runnability.

Page and Seth (16) have also pointed out another important aspect of runnability, namely, seasonal variations, with peaks in break frequency occurring during the winter months. In press rooms which are not air-conditioned this behavior would be attributed to the viscoelastic nature of paper, i.e., it is expected that fracture resistance would decrease with decreasing moisture content. However, I am not aware of any results which have been published to substantiate this expectation.

Another example of a failure related runnability problem which has already been mentioned above is associated with the flute fracture of corrugating medium. The stresses to which the medium is subjected during the flute forming process are quite complex and include tensile, bending, shear, and compressive stresses. Other variables affecting the viscoelastic behavior which also have to be accounted for include moisture and temperature changes due to preconditioning. This author is not aware of any fundamental work which has been published in the area of failure under combined in-plane and out-of-plane dynamic loading, although there is clearly a need.

During a forming or molding operation the ability to retain shape is an important runnability consideration. Examples of converting operations where shape retention is important include corrugating, paper plate manufacture, pleating and embossing. Lack of desired shape retention can give rise to poor product performance such as in corrugating where "fluff out" contributes to highs and lows.

In order to retain shape, paper or board must undergo some degree of permanent set during forming or molding. Again the material will be subjected to a complex stress situation and loss of the formed shape will occur due to elastic recovery and relaxation effects, unless the material is perfectly plastic. As a simple illustration, consider the case of forming a segment of paper or board of thickness t to a radius R_i (where R_i is the radius at the neutral axis). It can easily be shown that the applied strain ε_i at $y = \alpha t$ (i.e., at the outermost fiber layer) is given by:

$$\varepsilon_i = \frac{\alpha t}{R_i} \qquad (1)$$

If the cross section of the paper segment is symmetrical both with respect to geometry and elastic properties, and there are no external forces applied to the segment, then the neutral axis will coincide with the geometric axis, e.g., for a rectangular cross section $\alpha = 1/2$. After release from the mold the final radius R_f will be given by an expression similar to Eq. (1), i.e.,

$$\varepsilon_f = \frac{\alpha_f \, t_f}{R_f} \qquad (2)$$

where ε_f now represents the amount of permanent set after initial elastic recovery and stress relaxation and α_f accounts for any change which might occur in the position of the neutral axis. We also note that the final caliper t_f may differ from the initial caliper, since in many forming processes the paper or board will also be subjected to compressive stresses and therefore undergo some permanent set in this deformation mode. If we define the amount of spring back S as

$$S = R_f/R_i - 1 \qquad (3)$$

then from the above equations we have;

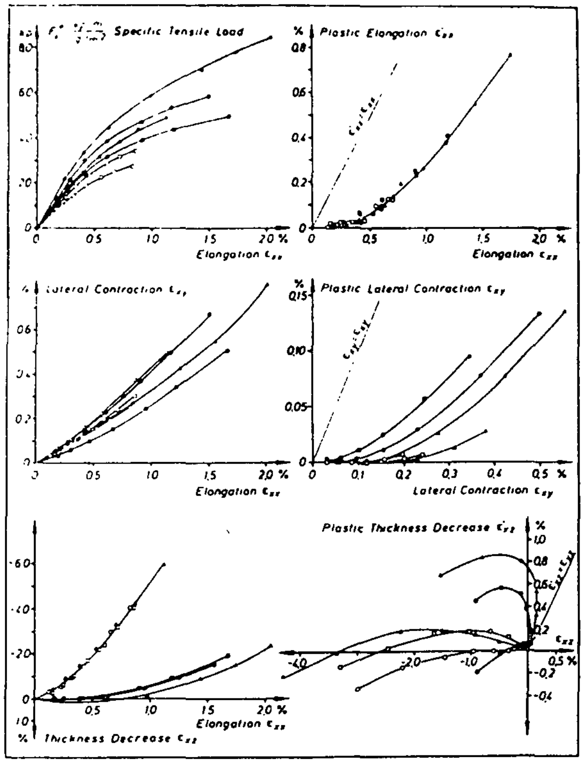
$$S = \frac{\alpha_f}{\alpha} \frac{\varepsilon_i}{\varepsilon f} \frac{t_f}{t} \qquad (4)$$

In order to estimate the spring back S we need to know the relationship between the amount of permanent set ε_f and initial elongation ε_i in the tensile deformation mode.

It has been shown by a number of workers (19, 20) that the relationship between ε_f and ε_i is to a good approximation independent of species, pulping type and beating for wood fibers as shown in Fig. 3. However, if the fibers are highly curled and microcompressed, then this relationship may be altered (20). If synthetic fibers (20) are incorporated into the sheet or if the foil material is different, the relationship again will change as shown in Fig. 4. It is interesting to note in Fig. 4 that the aluminum foil behaves almost as a perfect plastic. Differences in permanent set behavior may be important when forming or molding laminates of different materials. This author is unaware of any published work which examines the influence of temperature, moisture and strain rate on the set characteristics of paper and board.

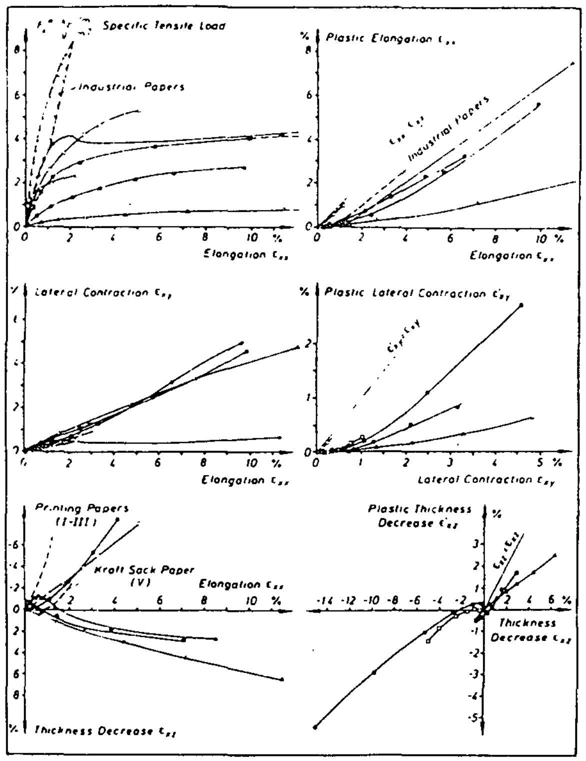
In converting there are some specific paper properties we deliberately try to improve (e.g., in supercalendering smoothness and gloss), however, they may be accompanied by losses in other properties. It is believed that with a better understanding of the process, these losses can not only be minimized, but these same properties enhanced. To illustrate this point strength changes as a function of calendering and supercalendering (21) are given in Table 3.

The data illustrate that properties may suffer a loss, remain unaltered, or be enhanced. The reasons for this range of behavior are not well understood. We know that in supercalendering the paper is subjected to a complex combined stress situation, including out-of-plane cyclic shear and compressive stresses, at elevated temperatures. The effect of these stresses on paper properties has yet to be determined. Crotogino (22) has sought to minimize the effects of calendering on paper property degradation. He has limited the calendering effect to the surface of the sheet in a process called "temperature gradient" calendering.



—Deformations in tensile tests with straining cycles
Industrial papers (machine-direction)
○ Uncoated illustration printing paper (I)
△ Coated illustration printing paper (II)
□ Newsprint paper (III)
● Offset printing paper (IV)
▲ Kraft sack paper (V)
■ Folding boxboard (VI)

Fig. 3 Data of Gottsching and Baumgarten (19).



Deformations in tensile tests with straining cycles packaging foils and printing substrates (machine-direction)
○ Aluminium packaging foil (XI)
△ Polythene packaging foil (XII)
□ Printing paper from synthetic fibres (XIII)
● Printing paper from synthetic fibres (XIV)
▲ Polystyrene printing foil (XV)
■ Polythene printing foil (XVI)

Fig. 4 Data of Gottsching and Baumgarten (19).

Table 3 Effects of calendering and supercalendering on the strength properties of some grades of paper. Data of Rance (21).

Calender Grade	Newsprint Before	Newsprint After	Rotary Print Before	Rotary Print After	6-ply Board Before	6-ply Board After
Grammage, g/m^2	54		52			
Density, g/cm^3	0.376	0.549	0.535	0.709	0.556	0.680
Breaking Length (km)	4.8	5.0	3.8	3.3	5.6	6.0
Tear MD (mN)	23	19.5	48	39		

Supercalender Grade	Newsprint Before	Newsprint After	Machine Coated Before	Machine Coated After	Glassine Before	Glassine After
Grammage, g/m^2	54		105		32	
Density, g/cm^3	0.408	0.633	0.909	1.163	0.8	1.316
Breaking Length (km)	2.2	2.2	4.6	1.1	1.1	1.3
Tear MD (mN)	19	16	55	47	17	15

The fluting of medium is an example where significant compressive strength losses are incurred during forming. The complex stresses involved have already been referred to above. Whitsitt (23) has demonstrated that bending stresses are mainly responsible for these losses. This author (13) has investigated the role of shear deformation, another important forming stress, on compressive strength and found no significant changes.

Dimensional Stability

Dimensional stability is an important problem often encountered in the converting and end-use properties of paper and board. The papermaker strives hard to minimize subsequent dimensional stability problems, but in spite of his best efforts they still arise. The converters approach to dimensional stability problems will of necessity be different from the papermakers.

Dimensional stability is concerned with changes in the dimensions of paper and board when subjected to a change in their environment, for example, moisture, temperature, stress or some combination thereof. Moisture or moisture related dimensional changes are usually the most important. Planar dimensional stability is very critical in most printing processes, particularly multicolor processes where register is of paramount importance. In machine-made papers the thickness direction is the least stable, usually followed by the cross machine and machine directions, respectively.

In this brief review, our main concern will be with a particular dimensional stability problem called curl, or in the case of combined board, warp. Curl or warp, in addition to being unacceptable from an aesthetics point of view, are the prime causes of many runnability problems. They also affect end-use performance. The base stock may be essentially curl free, but unacceptable curl characteristics may develop in subsequent converting operations. An added complication is that the curl may be time dependent. Curl is basically associated with property nonuniformities from plane to plane in the thickness direction of paper or board (more generally known as two sidedness). These potential nonuniformities can arise from many different sources in the papermaking process. Although they can be controlled, it is unlikely they can be completely eliminated. Even with materials which are dimensionally stable with respect to moisture changes (low hygroexpansivity), curl can be induced during converting operations, such as coating and laminating, due to differential thermal shrinkage of the components. Much has been written on the subject of dimensional stability and curl, and the interested reader is referred to the surveys by Gallay (24,25), Green (26), and Rutland (27).

There are two basic types of curl: reversible curl and irreversible curl. Ideally, one would like to be able to monitor the curl potential of a substrate so that during converting, strategies can be adopted in order to correct for the likelihood of induced curl in such a way as to minimize any adverse effects on paper properties.

In what are now regarded as classical experiments, Page and Tydeman (28) deduced that the amount of shrinkage which occurs during the unrestrained drying of paper must be attributed to lateral shrinkage of the fiber. From geometrical arguments the fibers in the dried sheet had to be shorter than those in the wet sheet. They established that the lateral shrinkage of an isolated fiber is considerably greater than the shrinkage along its axis. The axial shrinkage is negligible compared to that which must be experienced by the fibers in a freely dried sheet. Therefore, the shortening of the fibers in the sheet must be the result of interfiber bonds. The lateral shrinkage of one fiber induces longitudinal shrinkage in the fiber to which it is bonded.

Surprisingly little data have been published on the lateral shrinkage or expansivity behavior of papermaking fibers. Page and Tydeman (29) used direct measurements to show that the lateral shrinkage of fibers could vary widely, but was moderately increased by refining. The differences between bleached spruce sulfite and unbleached pine sulfate cooks were small. It was also found that lateral shrinkage was not completely reversible upon rewetting the fiber.

Another novel technique for measuring the lateral hygroexpansivity of single fibers was developed by Mark (30). It basically consists of measuring the angular torsional displacement of a fiber when its moisture content is changed. This displacement will also be a function of fibril angle. deRuvo and co-workers (31) used this technique and found that the twist angle was a linear function of moisture regain, up to relative humidities in excess of 80%.

The amount of shrinkage which a freely dried paper undergoes will depend on the extent to which the lateral shrinkage potential of the fibers is realized through interfiber bonding. Therefore, both refining and wet pressing will be effective in this respect.

The dimensional changes which occur when paper is subjected to humidity changes will also depend on the level of restraint or the amount of shrinkage which has taken place during drying. The greater the shrinkage, the greater the subsequent dimensional change of the sheet. It is proposed [following a similar argument by Corte (32)] that humidity changes will mainly produce a lateral expansion in the fiber cross section, and the resistance to this expansion will in part be controlled by the effective fiber modulus at the interfiber bond. The lower the effective restraint during drying, the greater the induced "shrinkage" and the lower the effective fiber modulus at the interfiber bond. Thus, a freely dried sheet will be less dimensionally stable than one dried under restraint or wet strained. As an aside, it should also be realized that the extent of interfiber bonding for a given level of wet pressing will also increase with increasing sheet shrinkage during drying. This is illustrated in Fig. 5 where a typical variation of apparent density* (which is used as a measure of bonding) with drying restraint is shown.

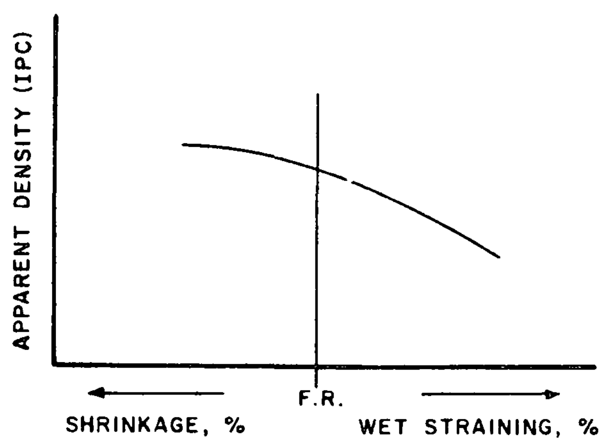


Fig. 5 Variation of apparent density with drying restraint.

Machine made papers are invariably less dimensionally stable in the cross machine direction and this is further exacerbated by increasing MD fiber orientation. It should be emphasized, however, following Wink (33), Back (34) and others, that dimensional changes depend on the range, particularly the upper limit, of humidity used. It is possible with high levels of wet straining, that MD changes will be greater than CD changes if the humidity change is not too great (34). Again we should remind ourselves that curl may be partly reversible and partly irreversible.

*The apparent density is calculated using soft platen caliper measurements (35).

5

Carlsson (36) and co-workers have analyzed the reversible curl problem using elastic lamination theory and a linear relationship between the coefficient of hygroexpansion and moisture content H. Their result for the curvature K of a two layer laminate, when exposed to a uniform change in moisture content, where 1 and 2 might represent the wire and felt sides, is given as follows:

$$K = \frac{1}{R} = \frac{24\ (\beta_2 H_2 - \beta_1 H_1)}{t(E_1/E_2 + E_2/E_1 + 14)}$$

E_1, E_2 and t are the respective moduli and sheet thickness. The coefficients of hygroexpansion, β_1 and β_2, will depend on the type of pulp, level of refining, wet pressing and fiber orientation pertaining to that layer. The prediction appears to work quite well for the humidity range where reversible curl is expected, i.e., less than about 65% RH. Above this RH (or critical moisture content) relaxation effects and irreversible curl have to be accounted for.

Internal or residual stresses are established in paper and board during the drying process. The modification of these by externally applied stresses, or the relaxation of them by moisture, temperature or some combination of the above, will produce a permanent or irreversible dimensional change. Johanson and co-workers (37) demonstrated the relationship between internal stress and dimensional stability. Internal stress was determined using stress relaxation measurements, and it was shown that moisture treatment of the samples reduced the level of internal stress and dimensional stability, while the application of an external cyclic stress increased the level of internal stress and dimensional stability. A further interesting finding was that a combination of external stress and moisture treatment resulted in a greater relaxation of internal stress and reduction in dimensional stability than a moisture treatment alone! It has also been shown by Htun (38), employing a relaxation technique developed by Johanson and co-workers (37), that the level of internal stress is equal in magnitude to the drying stress. Relevant to the problem of curl and other paper properties is the distribution of this internal stress in the thickness direction. Under equilibrium conditions there is no resultant stress acting on the paper. This implies that the internal stress is a balance between compressive and tensile stresses as shown in Fig. 6.

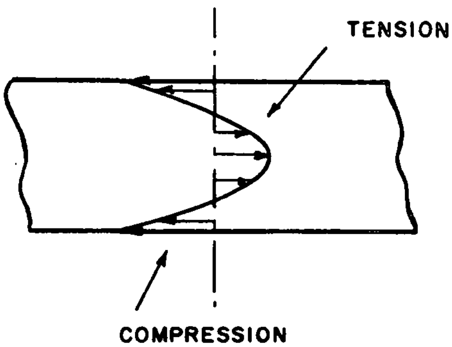


Fig. 6 Internal stress distribution of paper.

Direct evidence for the existence of internal stresses and alternative methods of measurement has been sought by this author. Using a surface grinding technique, developed by Wink (39) and Beckman (40), a 42-lb linerboard sample was surface ground to produce felt, middle and wire side sections. The properties of these are given in Table 4. The significant changes in curvature of these sections, particularly the felt and wire sections, are shown in Fig. 7. These are attributed to the release of internal stress. Indeed it can be shown that curvature measurements on these sections, together with measured elastic properties, can be used to estimate the internal stress distribution.

Table 4 Properties of surface ground sections.

Sample	BW, g/m^2	IPC Cal., mm	Density, g/cm^3	E/ρ MD $(km/sec)^2$	E/ρ CD $(km/sec)^2$	R	E_z/ρ $(km/sec)^2$
Felt	94.1	0.1219	0.772	12.43	5.19	2.39	0.0692
SD				0.426	0.263		
Middle	98.7	0.1358	0.727	11.43	5.04	2.27	0.0428
SD				0.765	0.263		
Wire	86.9	0.1191	0.729	12.09	3.81	3.17	0.0595
SD				0.608	0.281		
Whole sheet	207.5	0.287	0.723	13.1	6.23	2.10	0.0639

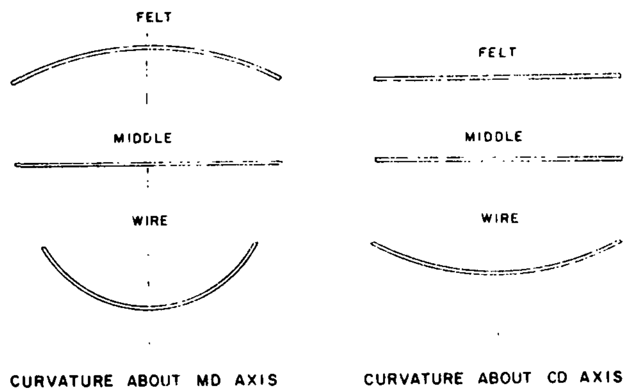


Fig. 7 Curvature measurement on the felt, middle and wire sections of 42-lb linerboard.

An ideal paper, i.e., one which has uniform composition, fiber orientation and bonding at any plane in the thickness direction, will also have an internal stress distribution similar to that shown in Fig. 6. The magnitude of the stresses will be dependent on the drying rate, since paper is a viscoelastic material. The effect of drying rate on the level of internal stress has also been studied by Htun (41). It is interesting to note that internal stress development in other viscoelastic materials, is vital to their properties. Examples include the thermal toughening of glass, the kiln drying of wood, and the processing of plastics.

Therefore, if the internal stress distribution of paper or board is altered by some means, e.g., moisture, temperature, or externally applied stresses, their curvature must also change. We can therefore refer to curl as a manifestation of internal stress changes. Again it should be noted that this type of curl is permanent.

SUMMARY

Certain paper property needs of converting, namely, deformation behavior and dimensional stability have been the subject of this review. The anisotropic and viscoelastic nature of paper, and the growing importance of out-of-plane properties is emphasized. The possibility of measuring both in-plane and out-of-plane elastic properties using ultrasonic wave propagation techniques is considered as a possible future application for converting. Other aspects of deformation behavior examined include strength related runnability problems, permanent set and the modification of paper properties.

The basic mechanisms controlling dimensional stability and curl are reviewed from the converter's point of view. Both reversible and irreversible curl are discussed, in particular, the relationship between the internal stress distribution in paper and irreversible curl. An appreciation of the mechanisms and types of curl should aid in the development of effective strategies for dealing with it in such a way as to minimize any adverse effects on other paper properties.

REFERENCES

1. Casey, J. P., Pulp and Paper, Chemistry and Technology, 3rd edn., Vol. 4, John Wiley and Sons, Inc., 1983.

2. Satas, D. Web processing and converting technology and equipment. Van Nostrand Reinhold Company Inc., 1984.

3. Ichinose, L. Y., PIMA, Dec., 1984, p. 34.

4. Mann, R. W., Baum, G. A., and Habeger, C. C. Tappi **62**(8): 115(1979).

5. Baum, G. A. The elastic properties of paper. Progress in paper physics seminar. Stockholm, June, 1984, To be published.

6. Baum, G. A. Paper **19**: 65, 67(March, 1984).

7. de Ruvo, A., Carlsson, L., and Fellers, C. Tappi **63**(5): 133(1980).

8. Gundersson, D. E., and Rowlands, R. E. Determining paperboard strength - Biaxial tension, compression and shear. Proceedings of the International Paper Physics Conference. TAPPI Press, 1983, p. 253.

9. Wink, W. A., and Van Eperen R. H., Tappi, **50**(8): 393(Aug., 1967).

10. Van Liew, G. P., Tappi, **57**(11): 121(Nov., 1974).

11. Byrd, V. L., Setterholm, V. C., and Wichmann, J. F., Tappi, **58**(10): 132(Oct., 1975).

12. Fellers, C., Svensk Papperstid., **3**(80): 89(1977).

13. Waterhouse, J. F., Tappi J., **67**: 6(1984).

14. Salmen, L. Temperature and water induced softening behavior of wood fiber based materials. Doctoral Thesis. Stockholm, Sweden. The Royal Institute of Technology. Dept. of Paper Technology, 1982.

14a. Page, D. H., J. Pulp Paper Sci., March, 1983, p. TR15.

15. Sears, G. R., Tyler, R. F., and Denzer, C. W., Pulp Paper Mag. Can., **66**(7): T351(July, 1965).

16. Page, D. H., and Seth, R. S., Tappi, **65**(8): 92(Aug., 1982).

17. Yang, C. F., and Thorpe, J., Tappi, **60**(12): 141(Dec., 1977).

17a. Moffatt, J. M., Beath, L. R., and Mihelich, W. G. Major factors governing newsprint strength. The fundamental properties of paper related to its end uses. Trans. of Symposium held at Cambridge, 1973.

18. Van den Akker, J. A., Wink, W. A., and Van Eperen, R. H., Notes to the editor. Tappi, **59**(11): 130(Nov. 1976).

19. Gottsching, L., Baumgarten, H. L. Triaxial deformation of paper under tensile load. The fundamental properties of paper related to its uses. Trans. of Symposium held at Cambridge, 1973.

20. Waterhouse, J. F., Tappi, **59**(7): 105(July, 1976).

21. Rance, H. F. Consolidation of the paper web, Chapter 5 Handbook of Paper Science Vol. 1 Edited by Rance, H. F. 1982 Elsevier, Publ.

22. Crotogino, R. H., Tappi J., 65(10): 97(Oct, 1982).

23. Whitsitt, W. J., and Sprague, C. Mechanics of fluting. Report One, Project 3396. The Institute of Paper Chemistry, Internal Report. (June 15, 1981).

24. Gallay, W., Tappi, **56**(11): 54(Nov., 1973).

25. Gallay, W., Tappi, **56**(12): 90(Dec., 1973).

26. Green J. G. Jr. Curl, expansivity, and dimensional stability. Chapter 27, Vol. 2 Handbook of physical and mechanical testing of paper and paperboard. Ed R. Mark. Marcel Dekker Inc., 1983.

27. Rutland, D. F. Dimensional stability and curl of papers. Proceedings of the C.P.P.A. 71st Annual Meeting, 1985.

28. Page, D. H., and Tydeman, P. A. Formation and structure of paper. Symposium F. Bolam Ed Tech. Section B.P.B.M.A. London, 1962.

29. Page, D. H., and Tydeman, P. A., Nature, 199: 471(Aug. 3, 1963).

30. Mark, R. E., Thorpe, J. L., Angello, A. J., Perkins, R. W., and Gillis, P. P., J. Polymer Sci., (C Polymer Symposium) **36**: 177(1971).

31. de Ruvo, A., Lundberg, R., Martin-lof, S., and Soremark, C. The influence of temperature and humidity on the elastic and expansional properties of paper and the constitutient fiber. The fundamental properties of paper related to its uses. Trans. of Symposium held at Cambridge, 1973.

32. Corte, H. Cellulose - Water Interactions. Chapter 1, Pg. 50, and 71. Handbook of Paper Science Vol. 1 Edited by Rance, H. F. 1982. Elsevier, Publ.

33. Wink, W. A., Tappi, **41**(6): 171A(June, 1961).

34. Back, E. L., and Klinga, L. O., Tappi, **46**(5): 284(May, 1963).

35. Wink, W. A., and Baum, G. A., Tappi J. **66**(9): 131(Sept., 1983).

36. Carlsson, L. A study of the bending properties of paper and their relation to the layered structure. Doctoral Dissertation, Chalmers University of Technology, Gothenberg, Sweden, 1980.

37. Johanson, F., Kubat, J., and Pattyranie, C., Svensk Papperstid. (10):333(May 31, 1967).

38. Htun, M., and de Ruvo, A. Relation between drying stresses and internal stresses and the mechanical properties of paper. Fiber - Water Interactions in Paper-Making. Trans. of the Symposium held at Oxford, Sept., 1977.

39. Wink, W. A., Private Communication.

40. Beckman, N. J., and Plucker, E. I. Z direction analyses of coated papers using large area sectioning techniques. TAPPI Coating Conference Preprint April 30-May 2, 1973.

41. Htun, M. The influence of drying time and temperature on drying stress and related mechanical properties of paper. Doctoral Dissertation. The Royal Institute of Technology, Stockholm, Sweden 1981.

8

IPC TECH. Paper Series #162

Paper Properties and Converting

IPC TECH. Paper Series #162

Paper Properties and Converting

GEORGIA-PACIFIC CORPORATION
ATLANTA, GEORGIA