Preferred citation: M. Htun and A. de Ruvo. The influence of drying strategies on the relationship between drying shrinkage and strain to failure of paper. In **The role of fundamental research in paper-making**, *Trans. of the VIIth Fund. Res. Symp. Cambridge, 1981*, (Fundamental Research Committee, ed.), pp 385–398, FRC, Manchester, 2018. DOI: 10.15376/frc.1981.1.385.

THE INFLUENCE OF DRYING STRATEGIES ON THE RELATIONSHIP BETWEEN DRYING SHRINKAGE AND STRAIN TO FAILURE OF PAPER

Myat Htun and Alf de Ruvo
Swedish Forest Products Research Laboratory
Box 5604
S-114 86 Stockholm
Sweden

Abstract

The effects of different drying strategies on the development of the strain to failure of paper and its relationship with drying shrinkage is studied. It is postulated that the linear superposition principle can be applied to drying strategies. The general mathematical expressions to describe the strain to failure due to drying strategies are given.

The linear relationship between the strain to failure and sheet shrinkage is not found. The relationship is entirely dependent upon the drying strategies.

Using the linear superposition principle, a graph which can predict the strain to failure by different drying strategies is constructed.

Introduction

It is well known that the degree of drawing has a strong effect on the mechanical properties of polymeric materials. Paper displays a similar behaviour. It has been observed by earlier workers[1-4] that the strain to failure of paper is linearly related to the sheet shrinkage due to drying. This observation has led to the application of tensionless drying in the manufacture of sack paper in order to obtain a sheet with a high strain to failure. In practice, however, the configuration of the press section and of the early stage of the dryer section often limits the extent to which the wet web can be transported without tension. A considerable amount of tension is often applied to secure the transport of the web between the press and the dryer section. The tension applied to the web in the early stage of drying has been found to have a detrimental effect on the extensibility of paper[5]. Even if paper has been dried without tension in the remaining stages of the dryer section, it has often been noticed that the strain to failure in the machine direction (MD), i.e., in the direction which has been under tension, of e.g. sack paper is much lower than expected. A light creping of the wet web is therefore sometimes introduced to attain a higher strain to failure. Unfortunately, creping often reduces the strength and stiffness of the paper.

Brecht and Pothmann[1] have in fact observed that drying shrinkage takes place mainly in the dry solids content range of 60-85 per cent and that only minor shrinkage occurs at the beginning and at the end of drying. This suggests that, if the strain to failure is determined entirely by the drying shrinkage, the tension applied at the beginning of drying (35-60% dryness) should have no marked effect on the strain to failure.

However, practical experience in paper mills reveals that restraining the skrinkage at the lower solids content region has a considerable effect on the extensibility of paper. It seems that strain to failure cannot be related simply to the sheet shrinkage but that the influence of different drying strategies in different dryness regions must also be taken into consideration. The term drying strategy here refers to the pattern of restrained and tension-free drying adopted at different dry solids contents.

The purpose of this work therefore has been to determine the influence of different drying strategies on the development of the strain to failure of paper and the relationship between the strain to failure and the drying shrinkage.

To study these questions, a series of laboratory sheets was dried in a special chamber where the tension could be varied and the solids content and shrinkage continually monitored.

Experimental Considerations

Drying strategies and linear superposition

There are basically two alternative drying strategies which may be adopted. One is to allow the sheet first to shrink freely during drying until a specific dry solids content is reached and then to restrain it from shrinkage during the subsequent drying: that is here referred to as the FR strategy. The opposite strategy, referred to as the RF strategy, is to restrain the sheet initially until a specific dry solids content is reached and then to allow it shrink freely during the subsequent drying.

The strain to failure of a sheet subjected to a simple FR or RF strategy, e^{FR} or e^{RF} respectively, can then be expressed as a general function of the dry solids content at which the change in drying tension occurs as follows:

$$e^{FR} = e^{R} + e^{FR}(w) \tag{1}$$

$$e^{RF} = e^{F} - e^{RF}(w) \tag{2}$$

where e^{F} is the strain to failure of a sheet which has been allowed to shrink freely throughout drying and e^{R} is the strain to failure of a sheet which has been restrained throughout drying.

The function $e^{FR}(w)$ thus indicates the increase in strain to failure achieved by free drying up to the dry solids content w, and the function $e^{RF}(w)$ represents the loss in strain to failure resulting from the application of restraint until the dry solids content w is reached.

It is here postulated that if a multiple FRFR ... or RFRF ... strategy is adopted, the strain to failure of the dried sheet is dependent not on the shrinkage occurring during drying as previously suggested[1-4] but on the choice of dry solids content levels at which the changes from free to restrained drying or vice-versa are introduced. It is further postulated that the strain to failure is affected solely by the free-drying periods and that the contribution to the strain to failure of a period of restrained drying is zero, see figure 1.

This leads to the supposition that the strain functions $e^{FR}(w)$ and $e^{RF}(w)$ should be identical and that equations (1) and (2) should describe curves which are symmetrical about the mean value of the strains to failure of the restrained and freely dried sheets.

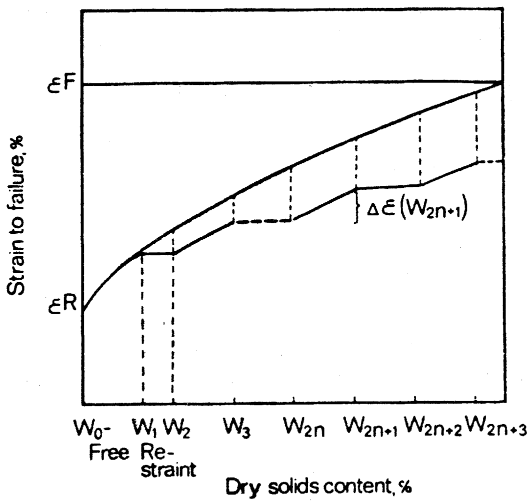

Fig 1—A schematic presentation of the FRFR . . . strategy.

It also implies that it is possible to use the curves of equations (1) and (2) as master curves and that it is possible to predict the strain level for any general multiple strategy by adopting the principle of superposition for those sections of the drying process in which free drying is permitted.

The general expression for a multiple FRFR..strategy is then:

$$e^{FRFR\cdots} = e^{R} + e(w_1) + \ldots \left[e(w_{2n+1}) - e(w_{2n})\right] + \ldots \qquad (3)$$

This equation can be simplified to

$$e^{FRFR\cdots} = e^{R} + e(w_1) + \ldots \Delta e_{2n+1} + \ldots \qquad (4)$$

where $\Delta e_{2n+1} = e(w_{2n+1}) - e(w_{2n})$ and represents the contribution to the strain to failure resulting from the fact that the sheet is allowed to dry freely in the solids content interval

$$w_{2n} - w_{2n+1}.$$

Similarly for a multiple RFRF.... strategy

$$e^{RFRF\ldots} = e^{F} - e(w_1) - \ldots \Delta e_{2n+1} - \ldots \qquad (5)$$

In this case Δe_{2n+1} represents the contribution to the strain to failure which would have been obtained if the sheet had been allowed to dry freely instead of being restrained in the dry solids content interval $w_{2n} - w_{2n+1}$

The concept of linear superposition of strain curves may also be applied to the relation between strain to failure and shrinkage.

Results and Discussion

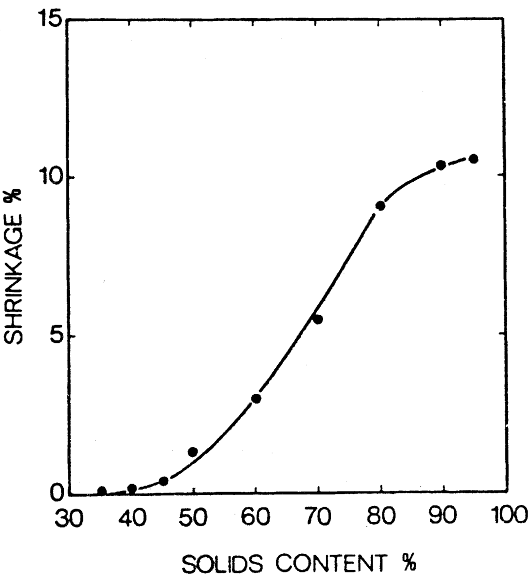

Fig 2—The curve showing the drying shrinkage at various dry solids content.

Figure 2 illustrates the drying shrinkage over the whole range of dry solids content for a single sample maintained in a tension free state throughout the drying process. In agreement with the results by Brecht and Pothmann[1], the rate of shrinkage (Δshrinkage/Δsolids content) is lower in the beginning and at the end of drying than it is in the 55-80 per cent dry solids content region.

If the strain to failure is directly related to the drying shrinkage, the greater part of the strain to failure of the dry sheet should be attributed to the shrinkage which takes place in the 55-80 per cent dryness region(1). This is, however, not the case according to the results presented in figure 3, where the strain to failure values of a series of sheets subjected to single FR (open symbols) and RF (filled symbols) strategies are plotted against the dry solids content at which the change in drying strategy occurred. The plotted values at 35 per cent dry solids content indicate the reference values for restrained and tension-free dried handsheets and these values therefore represent e^R and e^F respectively as defined in the previous section.

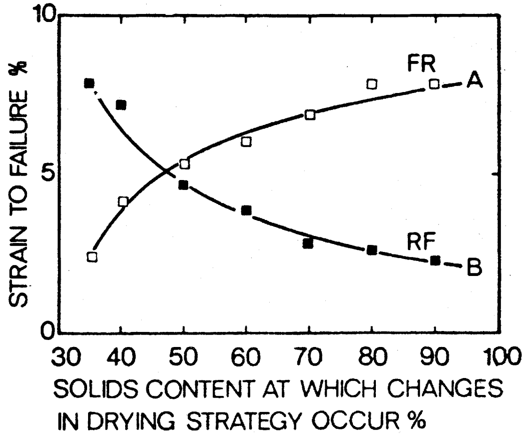

Fig 3—Strain to failure *vs.* dry solids content at which changes in the drying strategy occur. (□ solids content at which restrained drying starts, ■ solids content at which tensionless drying starts.)

It is rewarding that these strain to failure versus dry solids content relationships display the symmetry around the mean strain to failure level prescribed by equations (1) and (2). It may therefore be concluded that the RF and FR strategies may be treated by means of linear superposition in the form suggested by equations (1) and (2), although further tests must be made with multiple strategies before the general validity of the postulated expressions can be established.

The results shown in figure 3 clearly indicate that the strategies which involve a change in the lower dryness region have the most significant impact on the strain to failure of the sheets. Tension-free drying to 60 per cent solids content gives the largest increase in strain to failure. This is due to the large amount of water which evaporates from the web during drying from 35 to 60 per cent solids. Further tension-free drying beyond that dryness level hardly affects the strain to failure. Restrained drying to 60 per cent dryness also drastically reduces the strain to failure even though the subsequent drying is carried out under tension-free conditions. Further extension of restrained drying does not significantly affect the strain to failure. It is evident that there is no constant relation between the strain to failure and the development of shrinkage. It seems that the amount of water which has been allowed to evaporate under specified restraint condition relates better to the development of strain to failure than the sheet shrinkage does (figure 4).

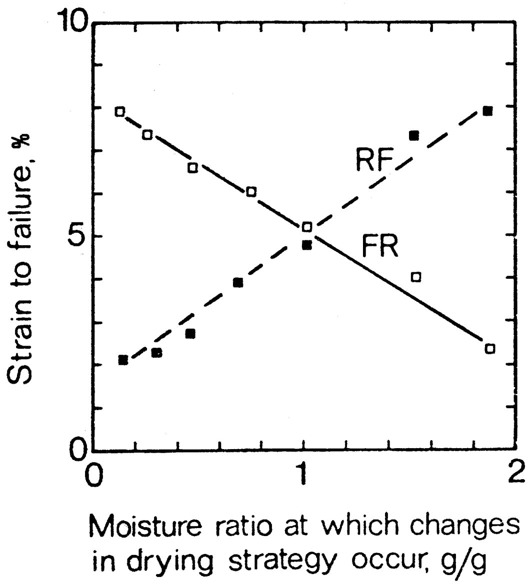

Fig 4—Strain to failure *vs.* moisture ratio at which changes in drying strategy occur. Symbol key: see Fig 3.

Thus it cannot be expected that there is either a unique or a linear strain to failure-shrinkage relation independent of drying strategy.

The relationship between the strain to failure and the shrinkage for these samples subjected to different drying strategies is shown in figure 5. These results are in agreement with the present prediction but do not substantiate previous reports of a linear relationship(2-4).

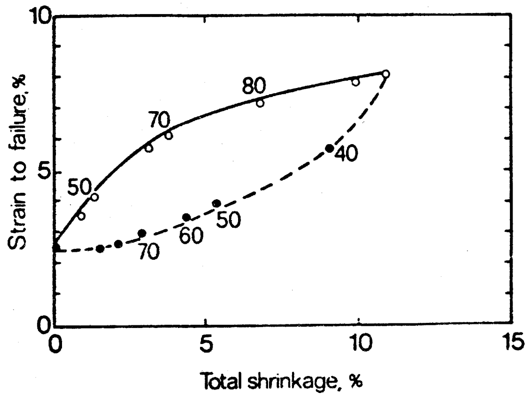

Fig 5—The relationship between the strain to failure and the sheet shrinkage for sheets dried under different strategies (○ drying initiated by tension free, ● drying initiated by restraining).

The strain to failure is evidently dependent on the choice of drying strategy rather than on the overall shrinkage of the sheet. The introduction of tension-free drying in the wetter stages of the drying process gives a sheet with a higher strain to failure at a given shrinkage level than that of a sheet which has been restrained from shrinking in the wetter region of the process.

The linear relationship which earlier workers have observed is perhaps a rationalisation of data obtained from a single drying strategy. The present results (figure 5) indicate that the strain to failure is not a linear function of the shrinkage but is dependent on the choice of drying and on the dryness level at which the change in drying tension takes place. Although the shrinkage is relatively low in the initial phase of drying, its influence on the strain to failure of the dry sheet is large. In the final phase of drying, the effect of shrinkage on the strain to failure is insignificant.

The general equations (4) and (5) are based on the assumption of linear superposition of the strain function, ie the assumption that the strain function is not influenced by the previous drying strategy and that the strain to failure for any drying strategy may be calculated from the general master curves by linear superposition.

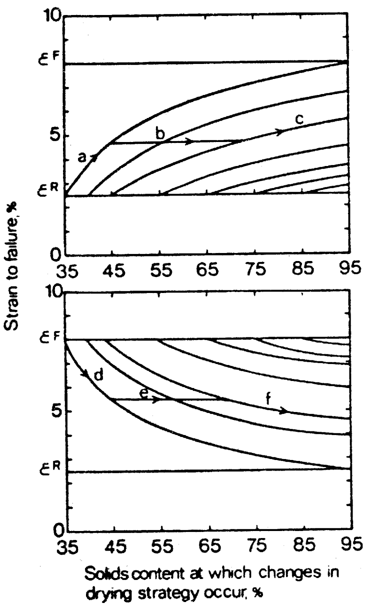

Fig 6—A graph which can be used to predict the strain to failure and loss in potential strain to failure of paper subjected to various drying strategies.

The agreement between experiment and the prediction of symmetry for the simple FR and RF strategies suggests that the superposition of the strain function is a valid tool to deal with the influence of complex drying strategies on the strain to failure in paper. It is possible to construct a graph based on the general relationships between strain to failure and the solids content at which the drying strategy is changed which may be useful to predict the total strain to failure. The graph is shown in figure 6.

In each part of the figure, the two horizontal upper and lower boundaries represent respectively the strain to failure of sheets dried under fully tension-free and fully restrained conditions. The curved lines represent the master curves of equations (1) and (2) and an arbitrary series of vertical transpositions of these curves.

The upper part of the figure may be used to predict the strain to failure resulting from an FRF strategy by drawing, for example, the line a-b-c in the figure. The first region of the curve, (a), shows the strain to failure developed during the initial period of tension-free drying. During the period of restrained drying there is no contribution to the strain to failure and the process follows the horizontal region, (b). The final period of tension-free drying provides a further contribution to the strain to failure as indicated by the curve, (c), which is a linear transposition of the upper region of the master curve.

Since the results in figure 3 demonstrate the equality of the two strain functions, the upper part of figure 6 can also be used to predict the strain to failure of an RFR strategy. In this case the first period of restrained drying is represented by a horizontal line along the lower boundary of the figure and the subsequent FR strategy follows the curves in the same manner as indicated above.

The lower part of the figure is an advantage in cases where it is desired to predict the loss in strain to failure to a given drying strategy. The region d-e-f in this figure shows the effect of an RFR strategy. The first region, (d), here indicates the loss in potential strain to failure which is incurred as the result of the initial period of restrained drying. The horizontal section, (e), here indicates that during the period of tension-free drying there is no further loss in strain to failure. The curve (f), represents the final period of restrained drying and shows that there is a further loss of potential strain to failure as a result of this treatment. The curve in this region is a linear transposition of the lower part of the master curve. The intersection of the curve d-e-f with the right-hand ordinate indicates either the loss in strain to failure or the predicted level of strain to failure attained as a result of this strategy. In the figure it is assumed that the final dry sheet may be represented by a dry solids content of 95 per cent, as was the case in the study shown in figure 3.

The gain in strain to failure incurred as the result of an FRF strategy can also be predicted from this figure. The curve for such a strategy begins with a horizontal portion, since there is no loss in strain to failure as the result of an initial period of tension-free drying.

It is to be noted that the upper and lower boundaries given in the graph are valid only for the pulp furnish used in this study. Similar graphs can of course be constructed with different pulp furnishes by following the same procedure.

The experimentally determined strain to failure values obtained for sheets which have undergone different drying strategies are found to be in excellent agreement with values evaluated from the graph. This is shown in table 1.

Drying strategy	Strain to failure %	
	Graphical	Experimental
Restrained to 40 %, tension-free to 60%, restrained final	5.0	4.9
Restrained to 60 %, tension-free to 80 %, restrained final	3.1	3.2
Tension-free to 50 %, restrained to 80 %, tension-free final	6.0	5.8

Table 1
The strain to failure values evaluated experimentally and by prediction from the graph.

Conclusions

It has been demonstrated in this investigation that the strain to failure derivative with respect to shrinkage is highest at the beginning of the drying process. This means that the loss in strain becomes more pronounced if drying starts with tight draws or that the gain in strain is greater when tension-free drying is applied in the beginning of the drying process. A model which can adequately explain such a behaviour must be based on the shrinkage phenomena taking place at an ultrastructural level in the cell wall. Simple arguments based on micro-creping due to transverse shrinkage in fibre crossings would suggest that the strain to failure would be enhanced by greater shrinkage. This is exactly contrary to what has been found in this study where tension-free drying at low dry solids contents (where very little macroscopic shrinkage takes place) leads to the largest increase in the strain to failure of the dry paper. This by definition leads to a pronounced dependence of the strain to failure on the choice of drying strategy, a behaviour which a model based on microscopic creping due to shrinkage differences can hardly deal with.

The strain to failure in paper should therefore be ascribed to the distortion of irregular zones in the load-bearing elements which are aggregates of crystalline cellulose in the fibrillar form. Such distortions will occur as long as the surrounding matrix is thoroughly plasticised.

Experimental

Materials

Unbleached industrially prepared pine kraft pulp (Kappa number 45) was used. The pulp was beaten to ca 22°SR in a Valley beater following the Scan procedure.

Isotropic laboratory sheets of ca $90 g/m^2$ grammage were formed on a Formette Dynamique former[6].

The sheets were then pressed in a dynamic laboratory roller press, the load being chosen to give an initial dry solids content of about 35 per cent and an apparent sheet density of about $500\ kg/m^3$.

Drying

The Formette Dynamique formed sheets were cut into 100 mm wide and 200 mm long samples. The drying experiments were performed in a drying chamber which enclosed the clamps of an Instron tensile tester. This arrangement made it possible to perform tensionless drying over the desired sheet dryness range. The clamps were specially designed with a heating system to avoid clamping problems. A detailed description of the apparatus is given in reference(7). The drying temperature was 100°C.

During the tensionless drying the lower clamps were allowed to move upwards so that the stress (due to the sheet shrinkage) was kept at zero. The distance moved by the clamps at zero stress was taken as the sheet shrinkage.

Different drying strategies were studied in a random order.

Evaluation of the dry solids content

The dry solids content of the sheet was monitored continuously with the help of a beta-gauge meter calibrated for the grammage range concerned. The radioactive source used was Tl^{204} with a maximum energy (E_{max}) value of 0.77 MeV, a half-life of 3.76 years and an activity of approximately 6 m Ci (manufactured by Amersham Radiochemical Centre, Amersham, England).

The detector used was a Geiger-Mueller tube with a window thickness of 1.5 to 2 mg/cm^2 and effective diameter 19.8 mm, and an operating voltage of 500 to 700 V. The detector was cooled by an air stream.

The measurements on the reference sample (bone dry sample) were corrected for the sheet shrinkage or the wet draw since the final mass per unit area is dependent on the drying conditions.

The gravimetrically evaluated and the beta-gauge measured solids contents were found to agree to within ±1% solids content.

Evaluation of mechanical properties

The dried samples were conditioned at 23^{o}C, 50 % RH and the sheet properties were evaluated in this climate according to Scan standard methods. The caliper of the sheets was measured as described by Fellers(8) where the integrated mean value of the thickness was obtained by scanning the thickness between two spherical anvils. The strain to failure was evaluated with an extensometer.

REFERENCES

1. Brecht, W. and Pothmann, D., Das Papier, 1955, 9(17/18): 429.
2. Gates, E. and Kenworthy, I., Paper Technol., 1963, 4(5):485.
3. Setterholm, V. and Kuenzi, E., Tappi, 1970, 53(10): 1915.
4. Lobben, T., Thesis, Norwegian University of Technology 1971.
5. Kenworthy, I.C., Paper Tech., 1964, 5(4):359-365.
6. Sauret, G., Trinh, H. and Letebvre, G., Das Papier, 1969, 23(1):8.
7. Htun M. and de Ruvo A., Trans. Symp. Oxford Tech.Div. B.P.B.I.F. London 1978.
8. Fellers, G., SCAN-Forsk. report no 206 1977 (Swedish).

Transcription of Discussion

Discussion following prepared contribution from Dr. M.T. Htun

Dr. S.D. Alexander, Scott Paper Co., USA.

Some work we did in this area some years ago produced results totally in agreement with yours, in that both stress as well as strain showed superposition. Even if we interrupted the drying process, we found we could pick up the curves again, just as you could.

Prof. K.I.Ebeling, Helsinki University of Technology, Finland.

Without air-flotation driers, this advocated total split between entirely unrestrained and restrained drying, is very difficult to achieve on an ordinary paper machine. Our research shows that, on a conventional machine, shrinkage determines the strain to failure in both the machine and cross directions. It is only in those rare situations that an air-flotation drier is available that drying strategy becomes important.

Dr. M.T. Htun

From the results I have shown here I conclude that a paper machine needs a different sort of drier according to what sort of product it is going to make. We should modify pick-up sections too for sack-paper and box-board machines, because we simply cannot obtain the properties we need with conventional drying systems.

Prof. K.I. Ebeling

It seems to me that fibre orientation must play a part in the influence of drying strategy on the strength properties of the paper. At the edges of the sheet, where the cross direction shrinkage is greatest, the strain to failure is also greatest. This suggests some relationship between the cross direction shrinkage and the strain to failure across the width of the sheet.