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THE EFFECT OF MACHINE CONDITIONS AND FURNISH PROPERTIES ON PAPER CD SHRINKAGE PROFILE

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ABSTRACT

All conventional paper machines exhibit a profile of cross-machine direction (CD) shrinkage which is developed during the drying stage of production. This paper suggests a new approach to the understanding of these profiles by suggesting that CD shrinkage at a point in the paper depends on the distance of that point from both edges of the sheet and also on the length of the unsupported draws in the dryer section. The nature of the function is unimportant as long as it can be made to fit data for one combination of machine width and effective draw length; substituting other values will then change the shape appropriately. In this paper, a simple exponential decay of shrinkage with distance from the edge is used successfully.

This approach is initially demonstrated for laboratory results from the literature, where it successfully predicts changes produced by varying the length, width and by reversing the MD/CD orientation of samples. It is then shown to be consistent for changes of paper machine furnish, press section draw and sheet grammage produced in a series of trials on M-real, New Thames PM6. It is finally shown that theses ideas explain the effect on CD shrinkage results from the literature for splitting the sheet at the

press section of a newsprint machine and for reduction of dryer section restraint by deactivation of the blow-boxes.

INTRODUCTION AND BACKGROUND

Paper and board experience dimensional changes as they are transformed, on the paper machine, from a dilute suspension of fibres and minerals into the end product. Overall width is generally reduced during pressing and drying operations, with the edges experiencing more narrowing than the middle. Perhaps surprisingly, the most modern, highest speed paper machines tend to demonstrate the biggest middle-to-edge differences, although total CD (cross-machine direction) shrinkage is low. It is also well known that the strength properties of paper and board can vary by a significant percentage between middle and edge. It has been suggested that the extreme values of paper properties which can occur at the edges of the machine can lead to problems of dimensional stability and runnability on high-speed, high quality, multi-colour offset printing presses, but this is certainly not always the case. It is true, however, that maximising the reeled-up sheet width (even where gains are measured in millimetres) can lead to additional saleable paper being available and substantial economic benefits. It is clear that there is much to be gained from a better understanding of the details of CD shrinkage profiles for both of the above reasons.

Brecht and Wanka [1] obtained estimates of CD shrinkage profile in 1967 by measuring hydroexpansion at a range of positions across pilot machine paper made from mechanical and chemical pulps. This early work used the principle, discussed comprehensively by Gallay [2] that the degree of expansion when paper is exposed to water vapour or liquid is closely correlated with the amount it shrank during drying. Wadhams *et al.* [3] later made more direct estimates of CD shrinkage profile by measuring the dimensional change of forming fabric marks during drying and this was quickly improved by Viitaharju and Niskanen [4], who used the 2 dimensional FFT (fast Fourier transform) and made their measurements in the frequency domain. Praast [5] developed these ideas by using a method which corrected such measurements for the inevitable distortion of forming fabrics on the paper machine. This robust and accurate measurement method allowed Hoole *et al.* [6] to measure CD shrinkage profiles on a commercial newsprint machine for a series of experimental conditions, demonstrating that the profile was not caused in the press section and was already "set" at a dryness identified as being close to the fibre collapse point. They also showed that, when the fans in the dryer section blow-boxes were turned off, the CD shrinkage profile was significantly changed. Meanwhile Wahlström *et al.* [7] created a numerical model of dimensional change during drying, identifying and separating mechanical and hygroscopic driving forces. This model, for the first time, suggested the over-riding importance of shrinkage in the free draws between dryer section components and their ratio of width to length. In 2002 Phillips *et al.* [8] progressed the experimental technique by presenting a curve-fitting method for shrinkage profiles which allowed values of the key quantitative parameters to be robustly and repeatably estimated. This was done by dividing the profile into 2 halves and fitting to a function of the form:

$$y = \frac{ax + b}{x + c} \text{ where } a > 0, b > c. \tag{1}$$

Recently, Wahlström and Lif [9] made laboratory measurements of shrinkage along the centre line between two jaws holding paper samples during drying. Their results confirmed the importance of the shape of the free draw, demonstrating that values of W/L (whether obtained by varying W, L or both) controlled the resulting shrinkage profile.

On-machine, real-time measurement of CD shrinkage profile has been discussed by a number of authors. Guesalaga *et al.* [10] used a two-dimensional FFT method, making measurements on pilot and commercial paper machines. Kaestner and Nilsson [11] used a FFT method with a one-dimensional fluorescence sensor which detected the variations in lignin content in the forming fabric mark, although they do not appear to have taken account of forming fabric distortion in their calculations. Most recently, I'Anson and Sampson [12] presented a technique which used the displacements of the headbox slice lip (or dilution levels) at positions across the machine, along with grammage profile, to estimate real-time CD shrinkage after calibration with a laboratory measurement of the profile.

This paper presents a new model which predicts the change of shape of CD shrinkage profiles by considering draw shape, free shrinkage and paper machine running conditions. The model is applied to measured CD shrinkage profiles from two paper machines and laboratory data from the literature. The model is intended to predict the change of shape resulting from changes of raw materials, running conditions or machine design rather than attempting to provide a full explanation of what happens during shrinkage on a paper machine.

ASSUMPTIONS AND MODEL

In order to create the new model, it has been assumed that the cause of the CD shrinkage profile is hygroscopic shrinkage and that any direct influence of MD stresses and strains on sheet width is uniform from edge to edge. This is far from being intuitively obvious but we believe that this assumption provides a way of describing CD shrinkage profile with a clear separation of cause and effect. Mechanical engineering and finite element modelling of materials under stress suggest indeed that some profiling due to mechanical strains should be expected but our standpoint is that this effect will be small. It might also be argued that the variable restraint across the sheet is due to mechanical straining and that it is this which produces the variations in CD shrinkage and it is possible that this approach could be used to produce an alternative and equivalent model. We do not discount this approach, although we have not followed this path.

Following the work of Wahlström *et al.* [7] and [9], we assume that shrinkage occurs only in the free draws of the press and dryer sections of the paper machine and is fully restrained elsewhere. It may be that some shrinkage occurs on dryer cylinders and that some dryer fabrics may restrain this shrinkage better than others but we assume that this effect is small compared to the unrestrained draws.

By definition, when the paper is unrestrained, it will shrink by its free shrinkage, which will be different in the MD and CD because of fibre orientation. What stops it doing so in the free draws in the dryer section is the restraint supplied by the geometry of the draw. Along with the uniform narrowing caused by the MD strains, this is how we will model and discuss shrinkage.

Let us begin by considering how paper will shrink in a single free draw such as that used in the "Dryer Section Simulator" described by Wahlström and Lif [9], as illustrated schematically in Figure 1.

In their experiments, Wahlström and Lif performed a laboratory investigation of the shape of the profile of CD shrinkage at the midpoint of a paper sample held at constant MD length during drying for a range of original widths and lengths. These experiments were performed using a pair of jaws combined with an infrared heater, with the maximum width (W) being 600 *mm* and the maximum length (L) being 500 *mm*.

It is proposed that, for a sample of constant length, L, there will be a difference of restraint which will depend on the distance from each edge, implying that shrinkage along the centre line will be a function of x and $W - x$. It is also proposed that the degree of restraint at a position x will decrease as L, the sample length, increases and might be expected to depend in some

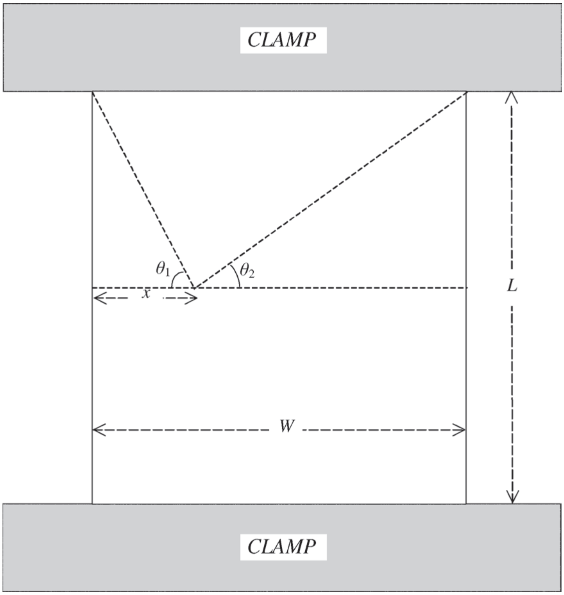


Figure 1 The geometry of a sample drying in a single draw, following Wahlström and Lif [9].

way on the angles of the line connecting the points with the edge of the restraining clamp. Taking both of these proposals into account, it is suggested that the hygroscopic shrinkage at a point x from one edge will be given by Equation (2):

$$S_h(x) = f\left(\frac{x}{L}, \frac{W-x}{L}\right) \tag{2}$$

We are concerned, for the present, with predicting the shape of the CD shrinkage profile rather than trying to relate the function f to the physical process of shrinkage and it was found that a simple exponential decay of restraint with distance from the edge could be used:

$$S_h(x) = S_{FCD}\left(e^{-\frac{K_1 x}{L}} + e^{-\frac{K_1 (W-x)}{L}}\right) \tag{3}$$

where K_1 is a constant and S_{FCD} is CD free shrinkage. In Wahlström and Lif's experiment [9], the applied MD strain was 0% but, as the sample dried a tension would have been created producing a narrowing effect, which we will assume was constant across the width of the sample. When the sample was dry the effect will have been the same as if the sample had been strained by an amount corresponding exactly to the MD free shrinkage (S_{FMD}) and the degree of narrowing will be given by this value multiplied by a factor K_2 which can be thought of as similar to Poisson's Ratio for the paper during drying. In order to determine the final width, and shrinkage, at each point x the two effects must be combined by multiplication:

$$S(x) = 1 - \left[1 - S_{FCD} \left(e^{-\frac{K_1 x}{L}} + e^{-\frac{K_1 (W-x)}{L}} \right) \right] (1 - K_2 S_{FMD}) \tag{4}$$

Figure 2 compares modeled results using Equation (4) with experimental results from Wahlström and Lif [9]. The parameters used are listed in Table 1.

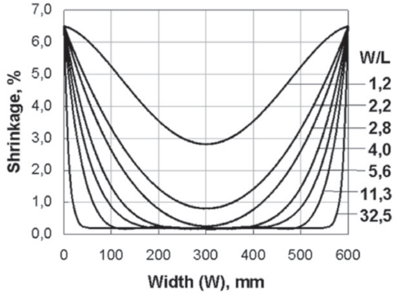
Clearly, for most of the range of values of W/L the shapes obtained using this very simple hypothesis are very similar to those obtained experimentally.

One of Wahlström and Lif's [9] experimental findings was that the shape of the shrinkage profile remained constant, when scaled to constant width, for a particular value of W/L and this is a feature of Equation (4), further strengthening the comparison.

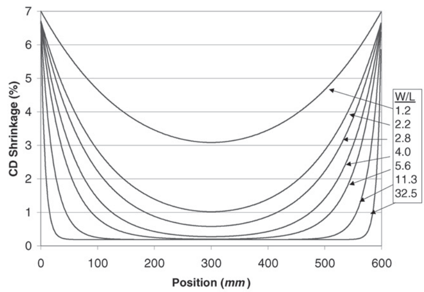
Wahlström and Lif considered the effect of sheet anisotropy by inserting a sample between the jaws with the CD vertical. Figure 3 shows their measured result and the curves obtained using Equation (4), with the MD and CD free shrinkages transposed for the second case. Figure 3 shows that the simple model accurately predicts this extreme change of anisotropy, without modification of parameters other than free shrinkage.

Table 1 Parameters used to create the modeled graphs shown in Figure 2 using Equation (4).

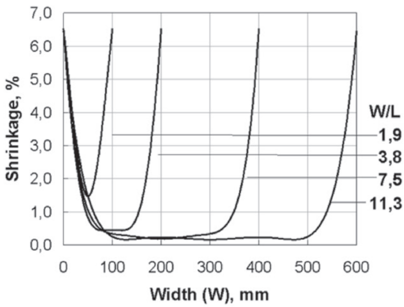
Parameter	Value
S_{FCD}	6.5%
S_{FMD}	2.1%
K_1	2.5
K_2	0.09



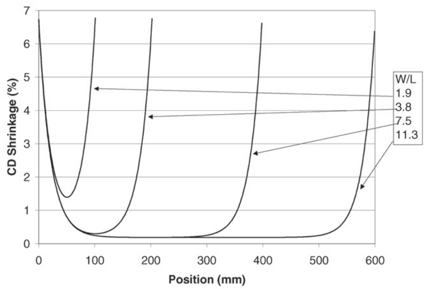
Wahlström and Lif's experimental results for constant *W* varying *L*. (9)



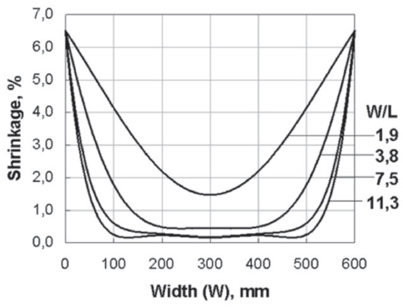
Modelled results using equation [4] for constant *W* (= 600 *mm*) and varying *L*. The parameters used are given in table 1.



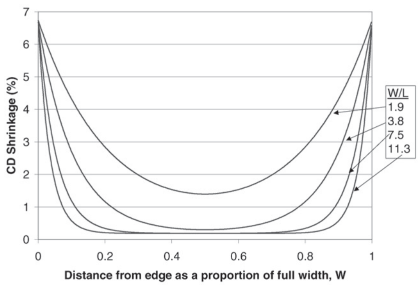
Wahlström and Lif's experimental results for constant *W* varying *L*. (9)



Modelled results using equation [4] for constant *L* (= 18.5 *mm*) and varying *W*. The parameters used are given in table 1.

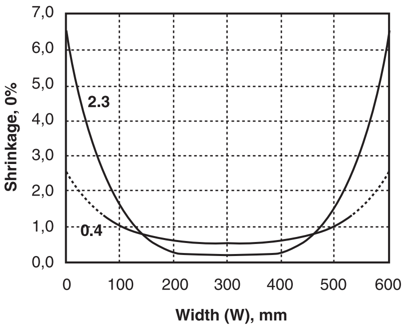


Wahlström and Lif's experimental results for constant *W* varying *L*, scaled to full width (9)

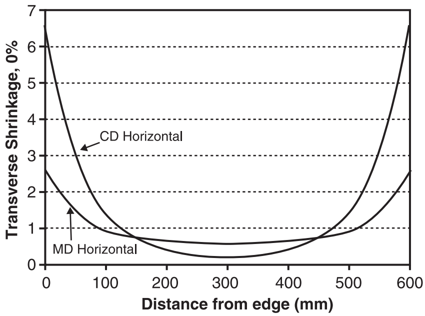


Modelled results using equation [4] for constant *L* (= 18.5 *mm*) and varying *W*, scaled to full width.

Figure 2 Comparison of modelled results with those obtained experimentally by Wahlström and Lif [9].



Wahlström and Lif's experimental results for constant $W/L = 4$, scaled to full width. The labels on the figure are degree of anisotropy measured as the ratio of vertical to horizontal tensile stiffness [9].



Modelled results using Equation (4) for constant $W/L = 4$ for the conditions in Table 1 and with the MD and CD free shrinkages transposed.

Figure 3 Comparison of modelled results with those obtained experimentally by Wahlström and Lif [9] when the MD and CD of the paper sample is transposed. The parameters used are those given in Table 1.

PAPER MACHINE MODEL OF CD SHRINKAGE

The success of the very simple model given by Equation (4) in predicting the CD shrinkage profile obtained in a laboratory experiment suggests that it may be possible to use a similar approach to predict the effect of stock, machine and running parameters on the paper machine. As has already been mentioned above, the approach used here has been to assume that the shape of the profile comes entirely from the variably restrained hygroscopic shrinkage occurring in the free draws of the dryer section. There is some evidence that neither press section nor dryer section strains in themselves produce a profile. Hoole *et al.* [6] showed that, for a newsprint machine, press section draw produced little if any profile of CD narrowing. Mäkelä [13] has studied the effect on profiles of MD and CD tensile stiffness index (TSI) of different applied strains during drying and of different combinations of draw length and width. His results show that CD TSI varies significantly with the length to width ratio of the draw but is not greatly affected by increasing MD strain. This implies that any effect of increasing dryer section draw on CD shrinkage profile (and by inference dryer section tension) will be minor compared to the effect of variable hygroscopic shrinkage, meaning that we do not have to consider it in this context.

Let us now consider the influence of three shrinkage effects (press section mechanical narrowing, dryer section mechanical narrowing and hygroscopic shrinkage) and how they could combine together and determine whether the net effect is consistent with experimental results. The primary aim in doing this is to gauge the importance of the contributing factors and how we might expect a change of furnish, machine design or operating conditions to affect CD shrinkage.

Press section

There are several draws to be included in this section from the couch to the entry to the first dryer. There is also the possibility of sheet widening due to the pressing process. We will assume that this can be approximated by one draw, D_p, which has the effect of narrowing the sheet by a factor $S_p = K_p\ D_p$ where K_p is the coefficient of press narrowing. This narrowing is assumed to be constant across the width of the sheet, in line with the discussion above. D_p will vary during running of the machine, especially at grade changes, due to its controlling effect on tension in the dryer section but it also depends on the degree of adhesion to press rolls amongst a variety of factors. Measurements on Mreal New Thames PM6 suggest that narrowing of the sheet between the forming section trim jets and the start of the dryer section can be very small (< 0.6%) despite total draws over this section of more than 6%. Hoole *et al.* [6] reported similar figures for the UPM Shotton PM2 newsprint machine of typically 0.4% between press pick-up and 1st Dryer cylinder out of a total of 3.4% shrinkage.

Hygroscopic shrinkage

The hygroscopic CD shrinkage, S_h, is assumed to depend on distance from both edges:

$$S_h(x) = S_{FCD}\left(e^{-\frac{K_h x}{L}} + e^{-\frac{K_h (W-x)}{L}}\right) \tag{5}$$

where S_{FCD} is the CD free shrinkage,
K_h is a constant for a particular machine (and possibly for all machines),
L is a measure which takes account of the length of the draws in the dryer section,
W is the couch width of the paper
and x is the distance from one edge.

This is similar to Equation (3) but the symbol K_h is used rather than K_1 because we expect a different value of CD shrinkage to that determined in the laboratory. This is because, in this case, restraint is continually being released and reapplied, meaning that the constant has a somewhat different role.

Equation (5) determines the shape of the modelled profile of CD shrinkage. The value of K_h is easily determined since, using this model, it is entirely responsible for the shape of the CD shrinkage profile and only one value will yield a curve which resembles an experimental result. The parameter L used in Equation (5) represents draw length but whether this number is more closely related to the longest draw, average draw length or total draw length is in doubt at this stage.

In a system where there is zero MD stress, the shrinkage at the edge will be a good estimate of S_{FCD}. For real situations where there are positive draws and non-zero MD free shrinkage, the difference between middle and edge shrinkage is an appropriate approximation, since the effects of these draws will be to raise the shrinkage at all points by a similar amount. This way of estimating S_{FCD} will only work for shrinkage profiles with a flat middle section because otherwise the combined effect of the two edges will have increased the centre value of shrinkage.

Dryer section mechanical shrinkage

There are also two components to the mechanical narrowing in the dryer section, both of which are assumed to produce even narrowing across the width of the machine. The first, S_{d1}, is the mechanical narrowing which occurs in response to the draws between components of the dryer section. The second, S_{d2}, is produced in response to the tension caused by the attempt of the sheet to shrink in the MD, which is of course a similar effect to straining the sheet by the amount it would have freely shrunk. This second type of mechanical shrinkage will include any component of hygroscopic shrinkage from late in the drying process which has an even effect across the width.

$$S_{d1} = K_d D_d \tag{6}$$

$$\text{and} \quad S_{d2} = K_d S_{FMD} \tag{7}$$

where K_d is the coefficient of dryer narrowing,
D_d is a single strain accommodating the effect of the dryer section draw
and S_{FMD} is the MD free shrinkage.

In order to explain the laboratory results discussed above, it has been necessary to use a value of 0.09 for K_d. This value is unlikely to be appropriate for a paper machine, since, rather than a single free draw, the paper is continually being constrained and released. A rather higher figure would therefore be expected for a paper machine.

Overall effect

The overall effect is obtained by combining the above processes (Equations (5) to (7)) by multiplication of the fractional changes in width.

The shrinkage of an increment at a distance x from one edge is:

$$S(x) = 1 - (1 - S_p)\,(1 - S_h(x))\,(1 - S_{d1})\,(1 - S_{d2}). \qquad (8)$$

APPLICATION OF THE PAPER MACHINE MODEL OF CD SHRINKAGE

Difference of fibre furnish

M-real New Thames PM6 is a paper machine which manufactures a range of copier and similar grades using a range of RCF (recycled fibre) contents up to 100%. The machine has a Fourdrinier forming section with a separate top wire former, three conventional roll presses and a dryer section consisting of single and double tier sections with a film coater used to apply surface size part way through. Speeds can reach 1000 *metres per minute* for lighter grades. This machine was of particular interest for this study because the CD shrinkage profile varies greatly between grades. Figure 4 shows CD shrinkage profiles for 2 grades of copier paper – 100% and 15% RCF – made on M-real New Thames PM6, along with curves obtained using the model for a set of reasonable values given in Table 2.

It is clear from Table 2 and Figure 4 that this simple model only requires MD and CD free-shrinkage and press-section draw to be different to make quite a reasonable estimate of the differences between the two shrinkage profiles. The values of all the parameters are estimations based on paper mill experience and experimental work but are quite reasonable figures. The CD free shrinkages have been taken from the experimental curves, but the MD values are estimated. Wahlström [14] has shown that free shrinkage of laboratory handsheets S_{Fiso} is related to MD and CD free shrinkage of paper made on a machine with the same stock by:

$$S_{Fiso} = \sqrt{S_{FMD} \cdot S_{FCD}} \qquad (9)$$

Table 2 Values of parameters used in producing the simulation curves shown in Figure 4. Note that only the shaded parameters have changed.

	100% RCF	15% RCF
K_p	0.1	0.1
K_h	0.75	0.75
K_d	0.45	0.45
$L(m)$	0.5	0.5
$W(m)$	7.02	7.02
S_{FCD}	0.0641	0.0389
S_{FMD}	0.03	0.02
D_d	0.016	0.016
D_p	0.04	0.025

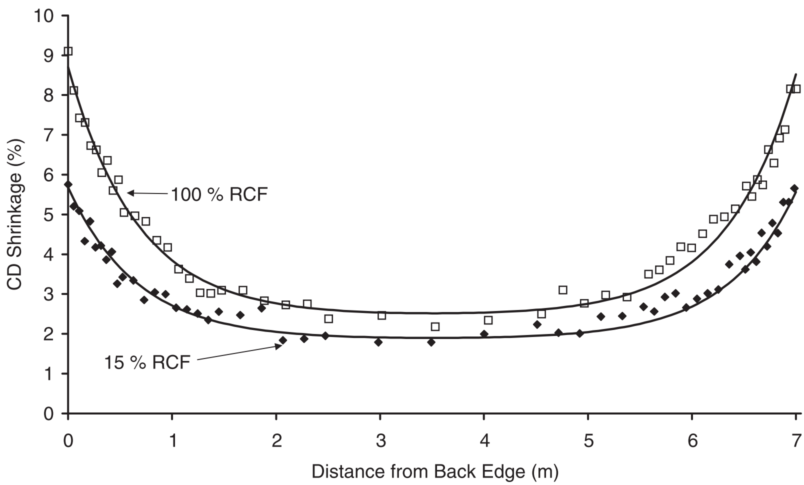


Figure 4 Graphs of CD shrinkage profile for paper made on M-real New Thames PM6. Note that the curves are not fitted but are simulations using reasonable numbers and our simple model.

If headbox stock had been available for this sample (for a measurement of isotropic free shrinkage) a more accurate estimate of S_{FMD} would therefore have been possible. K_p has been set to give the approximate level of narrowing before the dryer section for this machine of around 0.5%. The figure for press section draw is an approximation of the control room figure for the second to third press draw and it is assumed that the overall figure will vary in proportion to this. It was necessary to set K_d at the value of 0.45 to account for the non-profiled narrowing which happens in the dryer section, this has been accompanied by a small positive draw through the dryer section, which is typical of measured values (by Voith Fabrics Blackburn Ltd) for this paper machine. The length of the dryer-section draw (L) has been somewhat arbitrarily set to 0.5 and the value of K_h has been adjusted so that the two curves had the correct shapes. Since both curves are reasonable fits, it appears that the combination of K_h/L is about right for this machine. For wider application of Equation (8), K_h and L would have to be separated by considering them simultaneously with several other machines.

Effect of press section draw

It is now possible to consider the effect of paper machine changes on shrinkage profile. In particular, we might want to know how to change the process so that the shrinkage profile of the 100% RCF grade becomes more like the 15% RCF grade in Figure 4. Let us consider the parameters in Table 2 which are different for the two paper grades: MD and CD free-shrinkage and press-section draw. With this model, these are the only opportunities for changing the shrinkage profile, but they are certainly not independent. For example, if it is decided to reduce the press section draw on the paper machine, it will also be necessary to increase the tensile stiffness of the paper in order to maintain adequate tension and runnability in the dryer section. If this increase in tensile stiffness has been obtained by, for example, refining or by reducing filler content, the free-shrinkage in both the MD and CD is likely to go up, which will increase shrinkage across the full width of the machine, in opposition to any benefits. The increase in MD free shrinkage will also, independently of the increase in tensile stiffness, tend to cause an increase in dryer section tension since the “virtual strains” caused by the restraint in the MD will also be higher. In fact, far from being a variable which can be independently changed, press draw can only be changed as an effect of changing other properties.

A trial run on M-real, New Thames PM6 attempted to explore these relationships by making paper at a number of filler levels but without changing any other machine parameters, including press draw. The grade used includes

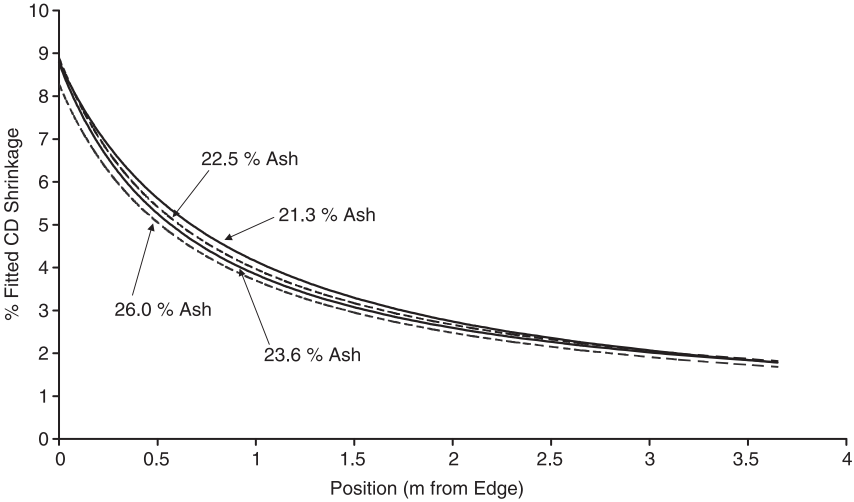


Figure 5 Measured shrinkage profiles obtained from M-real, New Thames PM6 for a range of filler addition levels to 68 % RCF, 80 gm^{-2} copier paper but otherwise constant conditions (as far as possible). The curves have been fitted to the profiles using the method described in reference [8] assuming central symmetry.

68% recycled fibre along with softwood chemical pulp and some broke and contains approximately 26% ash (added filler + the ash content of the recycled fibre) in normal running conditions. The trial consisted of making paper with ash levels down to 21%, at which level all product specifications, including optical properties, could still be met. Figure 5 shows the fitted curves obtained, using the method described by Phillips *et al.* [8]. It was found that, for this machine, the CD shrinkage profile for the machine could be treated as symmetrical and the data for the front and back sides pooled, giving an increase in accuracy. This extension to the published method has been used here. These results show the highest ash content as having a lower CD shrinkage at all points than the other three ash levels. The three lower filler level curves have common start and end points but are differently shaped in between these extremes. Figure 6 shows modelled curves created using the conditions listed in Table 3.

The modelled curves in Figure 6 show a difference in edge shrinkage between the highest filler level and the other three, but a very similar centre value. The three lower filler levels are more or less coincident for the whole width. This comes about because the estimated levels of free shrinkage in both the MD and CD are very similar for all but the highest filler level. There

Table 3 The parameters used to calculate the CD shrinkage profiles shown in Figure 6. D_p is the control room measurement of press draw. S_{FCD} is calculated as the difference between the edge and centre shrinkage taken from the fitted curves shown in Figure 5. The S_{FMD} for the 26.0% ash sample is an estimated value and the others have been changed in proportion to the values of S_{FCD}. Note that only the shaded parameters have changed.

Ash Content	26.0	23.6	22.5	21.3
K_p	0.1	0.1	0.1	0.1
K_h	0.75	0.75	0.75	0.75
K_d	0.375	0.375	0.375	0.375
$L(m)$	0.5	0.5	0.5	0.5
$W(m)$	7.08	7.08	7.08	7.08
S_{FCD}	0.066	0.070	0.071	0.070
S_{FMD}	0.030	0.032	0.032	0.032
D_d	0.016	0.016	0.016	0.016
D_p	0.037	0.037	0.036	0.036

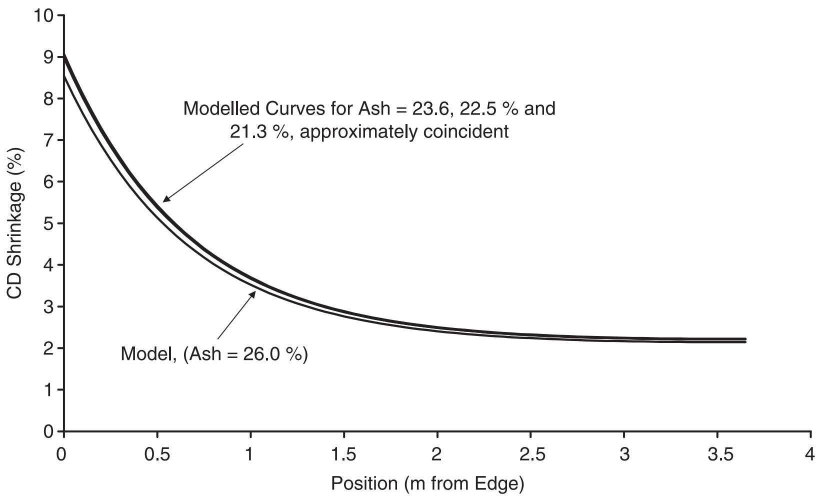


Figure 6 Values of shrinkage calculated using the model given in Equation (8), using the values in Table 3.

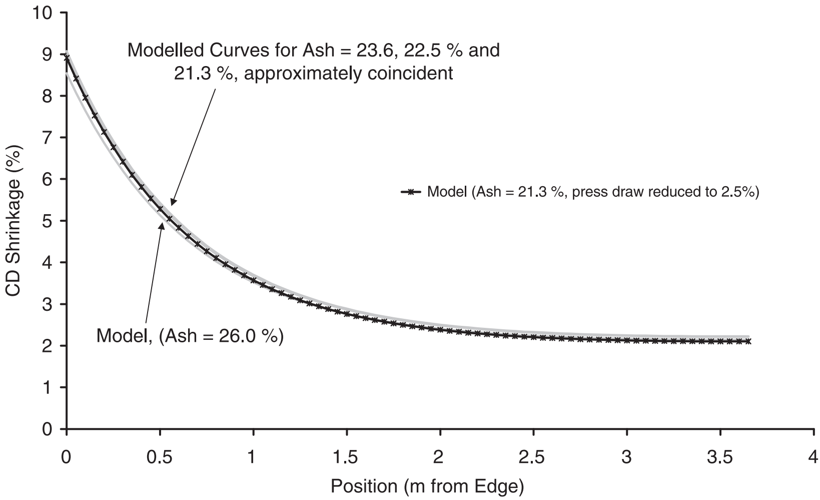


Figure 7 As Figure 6 but with the press draw reduced to 2.5 % from 3.6 % to simulate the effect of resetting the press draw to account for the increase in tensile stiffness due to the reduced filler level.

is reasonable correspondence between the curves shown in Figures 5 and 6 bearing in mind that so few of the parameters used have been measured. As a summary, edge CD shrinkage has increased significantly due to the decrease in filler content, whereas centre shrinkage has increased by a smaller amount.

It is now possible to take one of these curves and estimate what might be expected to happen if press draw was reduced to accommodate the increased tensile stiffness.

Figure 7 demonstrates the effect of reducing press section draw, showing that the edge shrinkage is more or less unaffected but the centre shrinkage has been reduced to a similar level to the highest ash content level. Clearly this is not a big effect and would have changed the average shrinkage from 3.5% to 3.4%.

Effect of sheet grammage

Equation (8) suggests that there will be no effect on CD shrinkage profile of higher sheet grammage other than, for example, the effect due to lower production speed requiring lower draws. Higher grammage will also result in higher dryer section tensions and this can allow lower press section draws to be used. There are also possible effects on the difference between MD and

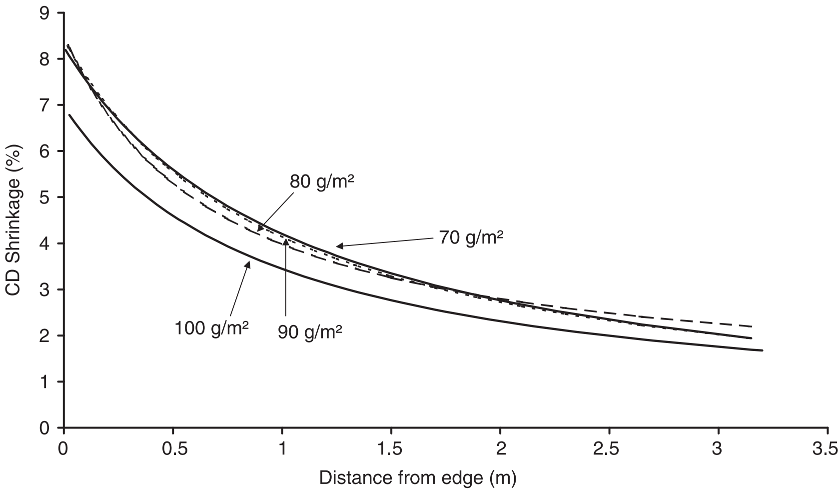


Figure 8 CD shrinkage profiles of 4 samples of the same grade type but different grammage. Details of fibre furnish are shown in Table 4. The curves have been fitted to the profiles using the method described in reference [8] assuming central symmetry.

CD shrinkage due to differences in fibre orientation at lower speeds. Figure 8 shows CD shrinkage profiles for 4 different grammages of the same grade made on M-real New Thames PM6 over a short time period. Fibre furnish is not identical for these samples but is similar, with the details shown in Table 4.

The effect of grammage on shrinkage profile for the 4 samples has been modelled in Figure 9 using the parameters in Table 5. The differences in the

Table 4 Fibre furnish details for the paper samples whose CD shrinkage profiles are illustrated in Figure 8.

Grammage / $g.m^{-2}$	Bleached Softwood / % by weight	Bleached Hardwood / % by weight	RCF / %	Broke / %
70	26.3	11.3	37.5	25
80	30	0	45	25
90	21	7	42	30
100	24.5	0	45.5	30

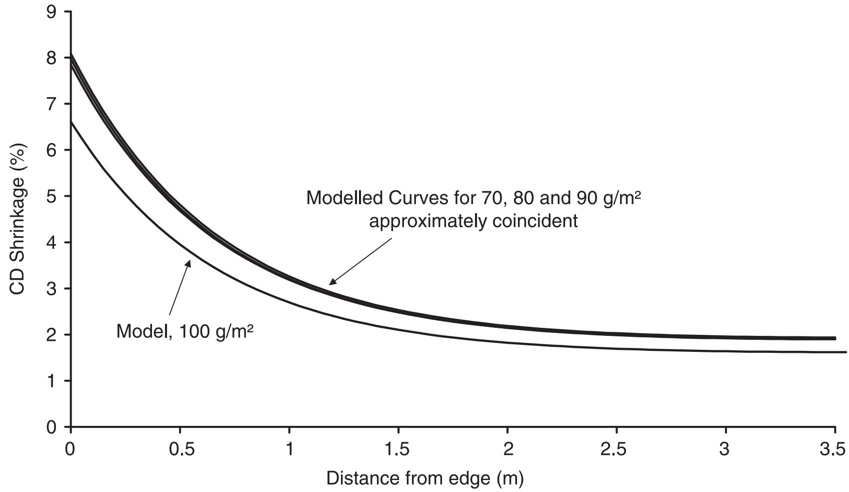


Figure 9 Modelled CD shrinkage profiles for the 4 samples analysed experimentally in Figure 8. The values for the various parameters in the model are given in Table 5.

Table 5 The parameters used to calculate the CD shrinkage profiles shown in Figure 9. D_p is the control room measurement of press draw. S_{FCD} is calculated as the difference between the edge and centre shrinkage taken from the fitted curves shown in Figure 8. The S_{FMD} for the 70 $g\ m^{-2}$ sample is an estimated value and the others have been changed in proportion to the values of S_{FCD}. Note that only the shaded parameters have changed.

Grammage ($g\ m^{-2}$)	70	80	90	100
K_p	0.1	0.1	0.1	0.1
K_h	0.75	0.75	0.75	0.75
K_d	0.375	0.375	0.375	0.375
$L(m)$	0.5	0.5	0.5	0.5
$W(m)$	7.03	7.03	7.03	7.03
S_{FCD}	0.063	0.061	0.063	0.051
S_{FMD}	0.025	0.024	0.025	0.020
D_d	0.016	0.016	0.016	0.016
D_p	0.031	0.034	0.034	0.021

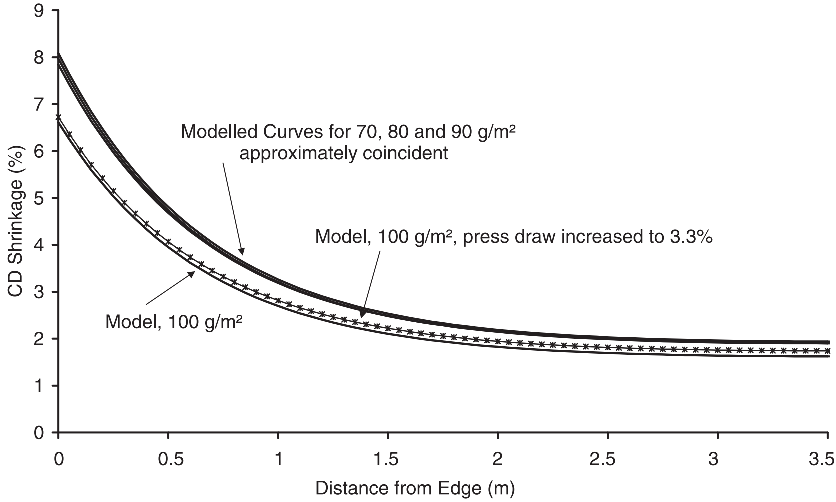


Figure 10 Modelled CD shrinkage profiles for the 4 samples analysed experimentally in Figure 8. The values for the various parameters in the model are given in Table 5, except that the press draw has also been changed to 0.033 to determine the effect of this change.

modelled values for the 4 samples are the CD free shrinkage, which is taken as the difference between middle and edge in the modelled profile, and the press draw, which is a measured value taken from the machine control system. The MD free shrinkage is also different but this is assumed to be proportional to CD free shrinkage. The relative importance of the 2 differences can be assessed by changing the press draw in the model for the 100 $g\ m^{-2}$ to a more similar value to the other 3 grammages: 0.033. The result of doing this is shown in Figure 10.

The result illustrated in Figure 10 suggests that the difference in CD shrinkage profile is partially due to a change of press draw made possible by the increased grammage but also to a reduction of free shrinkage likely to have been caused by furnish variations.

Effect of reduction of dryer section restraint

Hoole *et al.* [6] showed that, when the blow-boxes in the dryer section of a high-speed newsprint machine (UPM Shotton PM2) were turned off, there was a significant change of shrinkage profile. This was interpreted as being due to the resultant reduction in restraint. Their graphs of relative shrinkage

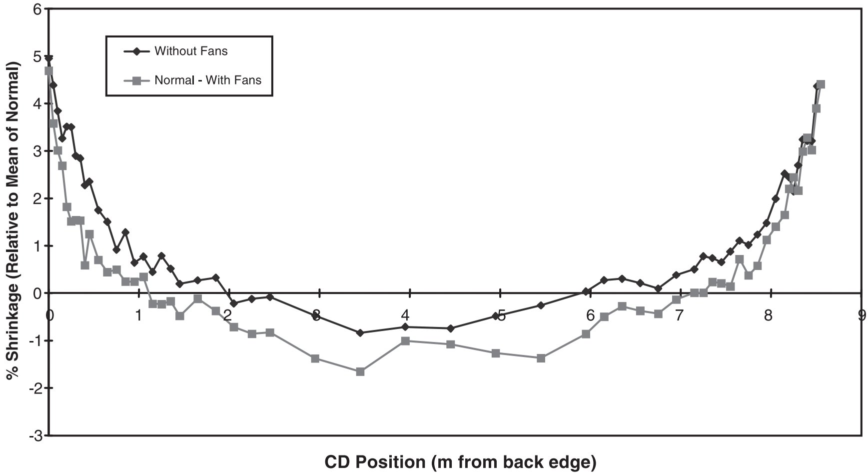


Figure 11 Graphs from Hoole *et al.* [6] showing how the shrinkage profile of paper made on a high speed newsprint machine changes when dryer section blow-box fans are turned off.

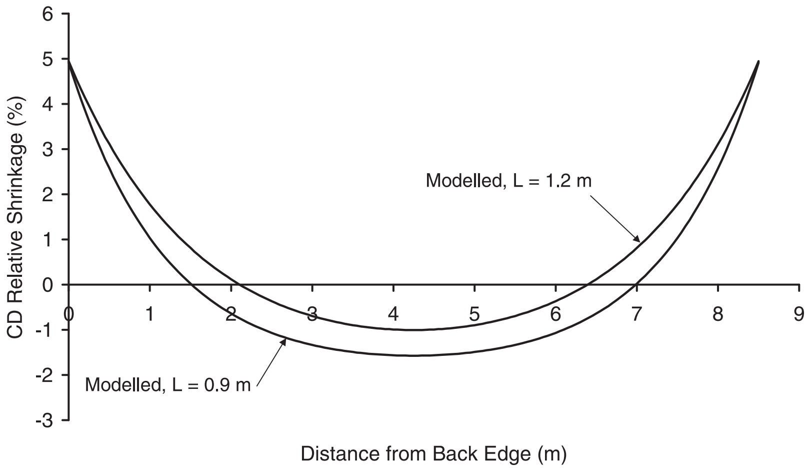


Figure 12 Modelled relative shrinkage profiles using Equation (8) showing the difference caused by a change in dryer section draw length from 0.9 *m* to 1.2 *m*. The parameters used are given in Table 6.

Table 6 Parameters used in Figure 12. All parameters have been estimated. Note that the CD free shrinkage cannot be directly estimated from the measured shrinkage profile because each edges is clearly still lessening restraint past the middle of the sheet, reducing the central value above its minimum. Note that only the shaded parameters have changed.

	Normal Running Conditions	Blow-Boxes Off
K_p	0.1	0.1
K_h	0.75	0.75
K_d	0.18	0.18
$L(m)$	0.9	1.2
$W(m)$	8.5	8.5
S_{FCD}	0.0675	0.0675
S_{FMD}	0.03	0.03
D_d	0.02	0.02
D_p	0.04	0.04

profile (*i.e.* shrinkage compared to mean shrinkage of the sample made in normal conditions) are reproduced in Figure 11. Figure 12 shows that, for reasonable values of the model parameters (Table 6), this difference of shrinkage profile can be quantitatively interpreted as being due to an effective increase in dryer section draw length.

Comparison of Figures 11 and 12 shows that the modelled increase of dryer section draw length explains the observed differences very effectively. When the blow-boxes of a single tier dryer section are inoperative the sheet will be in less good contact with the dryer fabric on the outside part of the run and may be completely separated from it allowing free drying as well as runnability problems, producing a longer effective dryer section draw.

Modelling a split newsprint sheet

Hoole *et al.* [6] demonstrated that, if the sheet is split into two between the press and dryer sections which are subsequently dried and reeled up separately, it will shrink as if the two sections had been made separately, *i.e.* with 4 similar edges. Figure 13 illustrates the result of such an experiment for UPM Shotton PM2, a high-speed newsprint machine. Since this operation will cause a decrease in draw shape, we might expect Equation (8) to

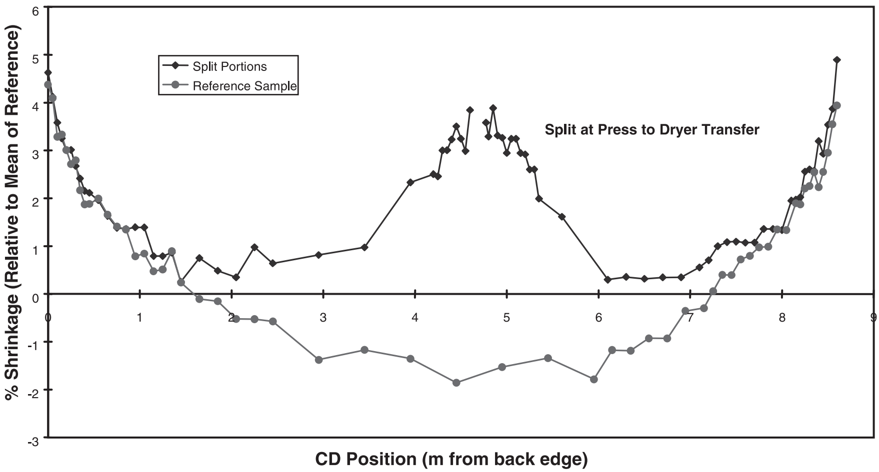


Figure 13 Graphs from Hoole *et al.* [6] showing how the shrinkage profile of paper made on a high speed newsprint machine changes when the sheet is split between the press and dryer sections.

predict the shape produced by changing the value of W. This has been done in Figure 14 where the "unsplit" comparison has been produced using the parameters listed for the normal condition in Table 6 and the "split" result uses $W = 4.25\ m$.

Comparison of Figures 13 and 14 suggests that the model has been successful in predicting the effect of splitting the sheet just before the dryer section of the paper machine.

CONCLUSIONS

A relatively simple model of CD shrinkage profile has succeeded in quantitatively explaining shrinkage profiles obtained during experiments on two paper machines and results of laboratory drying experiments.

There has been no attempt to produce exact fits to experimental data but rather to explain differences in shape caused by differences of furnish, machine design and operating conditions. Where parameters were unknown, reasonable estimates have been used allowing the effects of changes to be estimated. In no case does the model require unrealistic values which are distanced from what is known to exist to be used.

The model is not fully understood and, indeed, this would not be possible

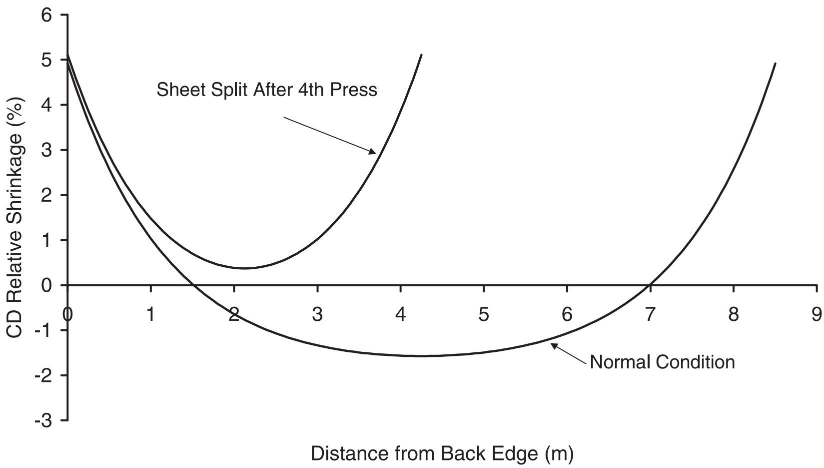


Figure 14 Modelled relative shrinkage profiles using Equation (8) showing the expected effect of a change of width from 8.5 *m* to 4.25 *m*. The other parameters used are given in Table 6.

without applying it to a wider variety of paper machines. This has not prevented a useful analysis of all the available data but there are some questions which remain to be answered and will be investigated in the future. For example, what is the real significance of the effective draw length L – is it closely related to the total length, an average length, a longest length or an effective length? How does K_h, the parameter controlling the degree of hygroscopic shrinkage which appears to be constant for a range of copier grades and newsprint, vary with other grades?

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Transcription of Discussion

THE EFFECT OF MACHINE CONDITIONS AND FURNISH PROPERTIES ON PAPER CD SHRINKAGE PROFILE

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Joel Panek Iggesund Paperboard

You claim it is a predictive model, but to me it seems as if it was just fitting data. There were incidences where it did predict the change in shrinkage with the width, but your last example with effect of the ash, arguably you could say, there is a linear change in shrinkage with the amount of ash. Yet in your model, three of the levels of ash, all compiled into one curve and only one was different. Basically you said the free shrinkage of those were the same, for three levels of ash. Did you independently measure the free shrinkage of these furnishes, and the effect of ash on that?

Raimundo Constantino

Well, the free shrinkage in that particular comparison was measured by the difference between the edge and the centre shrinkages of those measured profiles and as it happens when I measured those, they are very similar. That is why they all sit on top of each other.

Joel Panek

The question is the effect of the furnish. The ash on the furnish could be causing an effect of the drying rate that could affect the total amount of shrinkage, for example.

Discussion

Raimundo Constantino

I think in our model, the effect of ash is accommodated in the procedure and the shrinkage and I would say it is because of that, that the profiles would be different.