Dried-in shrinkage profiles of paper webs

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ABSTRACT: The wire mark technique of Wadhams et al. was used to measure CD (cross-machine direction) profiles of the lateral dried-in shrinkage in newsprints and kraft furnish printing papers. The edge-to-center shrinkage difference was about the same in both paper grades. However, in the newsprints the edge shrinkage was more acute, apparently because of wet straining. Comparison of the lateral shrinkage with CD paper properties shows that, in general, the latter cannot be used as an indirect measure of local shrinkage.

KEYWORDS: Cross direction, drying, free sheet, newsprint, paper properties, paper webs, profiles, shrinkage, strains.

Wet straining and drying cause the web to shrink laterally on the paper machine. The edges of the web are free and they shrink more than the central part. The dried-in shrinkage is adversely reflected in many paper properties. At the edges, the CD (cross-machine direction) tensile index and elastic modulus are lower and the CD breaking strain and hygroexpansivity higher than in the center. In contrast, the MD (machine direction) paper properties exhibit little variation across the web.

Nonuniform shrinkage deforms the basis weight profile leading to a proportionately higher basis weight at the edges that must be compensated by reducing the slice opening. This induces transverse suspension flows and fiber orientation misalignment *(1)* and can give rise to serious problems with, e.g., laser papers *(2)*. Runnability on the paper machine and in printing may also be endangered as nonuniform web tension appears to be related to shrinkage variations *(3)*.

The qualitative effects of drying shrinkage on paper properties have been demonstrated with laboratory experiments *(4, 5)*. However, such tests cannot reproduce real papermaking conditions where the rapid wet straining and drying have a significant impact on shrinkage. Also, the open draws on a paper machine are very short, the length-to-width ratio may be as low as 1/100. From finite element calculations on tensile testing *(6)* it can be inferred that the dimensions of open draws may have an effect on the shrinkage profile.

New equipment has been developed to reduce the lateral shrinkage on the paper machine. In a single-tier dryer section, the bottom rolls can be replaced with suction rolls. A 2 kPa suction pressure has been reported to lower shrinkage from 6.5% down to 1% *(7)*. In another device *(8, 9)*, the web edges are glued to belts that are kept in place by grooves in the dryer rolls. After the dryer section, the glued edges are cut off and removed from the belts.

Thus far, little has been known about the shape of the shrinkage profile and its dependence on the manufacturing process and web structure. One reason for this has probably been the lack of a good measurement technique. The overall reduction in web width from wire to reel gives no information on the local shrinkage. The only direct method has been to mark certain intervals on the wet web and then measure the same intervals in the dry paper. The CD breaking strain or elastic modulus might be used as indirect measures of shrinkage *(5)*, but even they would have to be calibrated.

Wadhams *et al. (10)* showed recently how wire mark can be used to measure the dried-in strains in paper. They found that lateral shrinkage and longitudinal stretch varied by 1–2%-units over a 50-cm wide paper web on a pilot paper machine. We applied the same principle to a few commercial papers in order to see what kind of profiles may occur. We also determined the effect of shrinkage on the mechanical properties of paper.

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Experimental

Measurement of dried-in strains

The measurement of dried-in strains *(10)* is based on the marking that the wires in the wet end and press section leave in the paper web. The subsequent MD strain and CD shrinkage alter the periodicity of this marking, increasing it in MD and decreasing it in CD. The dried-in strains can be determined from the two-dimensional basis weight spectrum ("formation spectrum") where the wire mark shows up as sharp peaks. The peak coordinates are inversely proportional to the longitudal and lateral wavelengths of the wire mark (or their harmonic manifolds).

Wadhams *et al.* *(10)* determined the wire mark from optical transmittance (50 mm by 50 mm sampling area) and converted the wavelengths to strains by using the known wire periodicity as the zero strain reference. Our sampling area was 60 mm by 60 mm. We used an image analyzer *(11)* to record and digitized the transmittance image into 512 by 512 pixels each having 256 gray levels. Two peaks of the two-dimensional Fourier spectrum were chosen such that they were close to the lateral and longitudinal axes of the phase space and had a small wavenumber *s*. The corresponding wavelengths were calculated from Eq. 1:

$$\lambda = d/s \qquad (1)$$

where d = 60 mm is the size of the image, and s the longitudinal or lateral wavenumber in pixels. The largest possible wavelength is $\lambda = d$ (one wavelength per image) and the smallest $\lambda = d/256$ (two pixels per period).

The resolution $\Delta\lambda/\lambda$, is limited by the discrete values of the wavenumber s. It follows from Eq. 1 that

$$\Delta\lambda/\lambda = \lambda/d = 0.7 - 1.7\% \qquad (2)$$

when λ = 0.4 – 1 mm and d = 60 mm. This is the absolute accuracy of the strain measurement. The lateral shrinkage varied usually by several %-units across the web, and could thus be detected. However, the longitudinal strain had a much more uniform profile and the accuracy was insufficient to resolve the details of its profile. A smaller image (smaller d) would give better resolution (sharper Fourier peaks) but a lower signal-to-noise ratio. In other words, the wire mark cannot be separated from random noise if the image is too small. For better resolution, one needs more pixels per image. Also, the number of gray levels should be high especially at high basis weights where the wire mark is weak. With the image analyzer at our disposal *(11)*, the wire mark could be detected up to basis weights of about 80 g/m². Supercalendered papers yielded no results.

A strain reference is needed for the absolute values of the dried-in strains. Wire dimensions cannot be used because not all the threads mark paper, the wire periodicity may change when the wire is mounted, and there may be several wires on the machine. The periodicity may even vary across the wire, though this should not happen if the wire has a rectangular texture aligned in MD. The wire-to-reel reduction ε_w in the web width can be used as the strain reference. Then the shrinkage profile $\varepsilon(y)$ is given by Eq. 3:

$$\varepsilon(y) = 1 - (1 - \varepsilon_w)\lambda(y)/\lambda_{AVG} \qquad (3)$$

where λ_{AVG} is the mean of the wavelength profile $\lambda(y)$. Even if no strain reference is available, the shrinkage variation can still be calculated from Eq. 3 by setting ε_w = 0. The profile moves up and down with ε_w but its amplitude does not really change as $1 - \varepsilon_w \approx 1$ always.

I: Characteristics of the paper machines and samples. Edge width was calculated as the distance from edge to the point where shrinkage first becomes smaller than the average (i.e., $\varepsilon(y)$ becomes negative). The edge-to-center shrinkage difference and the edge width are mean values of the two edges. The ratio E_{MD}/E_{CD} of the elastic moduli characterizes the degree of fiber orientation.

	Paper grade	Furnish	Basis weight, g/m²	Web width, m	Edge-cntr shrinkage diff., %	Edge width, m	E_{MD}/E_{CD} (at web center)
A	Newsprint	TMP	36	6.8	3.0	0.8	4.9
B	Newsprint	TMP	45.5	6.8	3.2	1.1	3.6
C	Newsprint	TMP+ deinked	45	8.5	4.3	1.1	5.2
D	Newsprint	TMP+ bl. kraft	48.8	8.6	2.2	1.1	5.3
E	Newsprint	TMP+ deinked	45	8.8	3.5	1.1	5.6
G	Printing	bl. kraft (HW+SW)[a]	75	6.6	5.3	1.3	2.5
H	Printing	bl. kraft (HW+SW)	65	8.5	2.5	1.4	2.5
I	Printing	bl. kraft (HW+SW)	50	4.5	3.0 4.0	0.7 0.6	1.7 2.5
J	MG-envelope	unbl. kraft SW	60	4.9	0.2	---	3.0

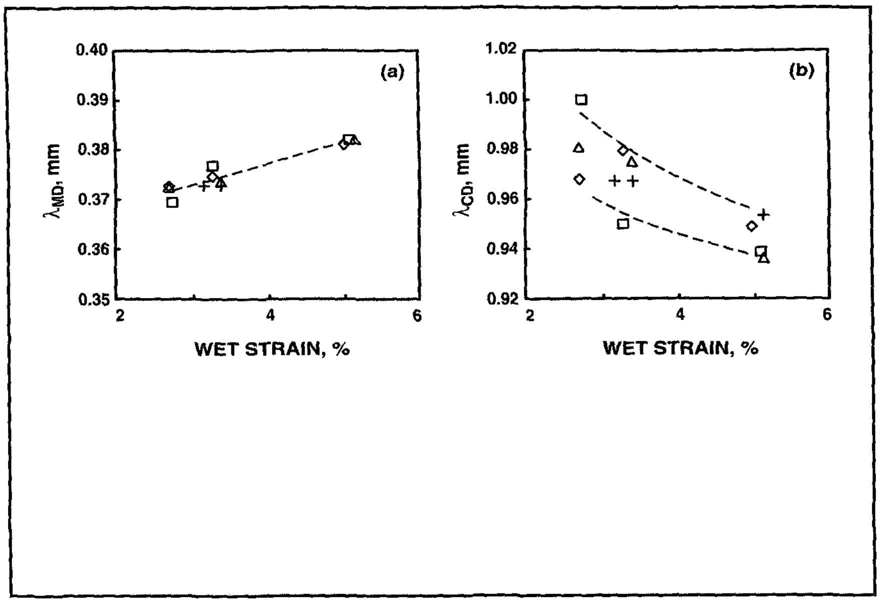
[a] Hardwood + softwood

Materials and measurements

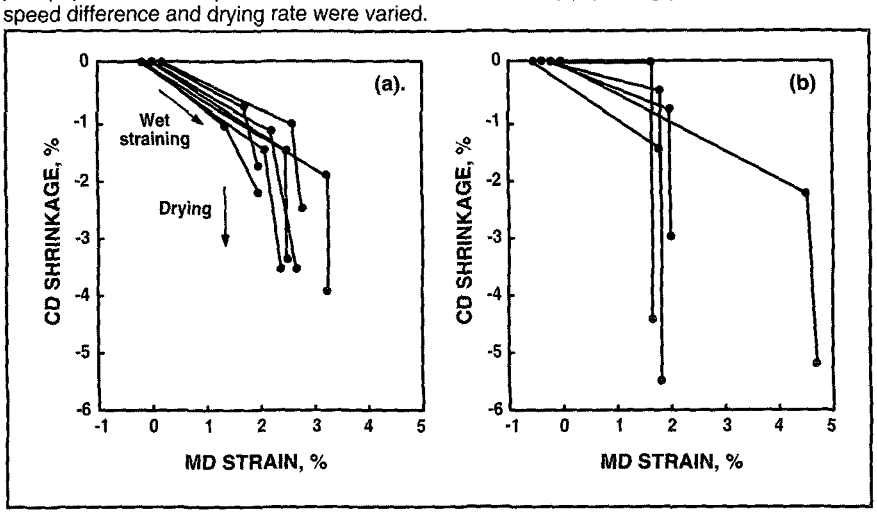
Tests were run on the KCL pilot paper machine which is a slow fourdrinier (1–2 m/s) complete with a dryer section, and on a fast (20 m/s) gap (roll and blade) former. In the latter case, paper was dried on a separate laboratory dryer with special care taken to ensure that all the samples were dried in the same way. Commercial newsprint and printing paper kraft furnishes were used on the fourdrinier and a supercalender furnish on the gap former.

The MD and CD wavelengths of the wire mark were measured on the gap former. Both exhibited little variation across the narrow (60 cm) web. On both machines, web width was measured at the pickup and after drying. The difference between the two gives the total shrinkage ε_w. On the KCL pilot machine, the web width was also measured before the dryers, which al-

1. Lateral and longitudinal wavelength, λ_{CD} and λ_{MD}, against wet strain on a pilot gap former; speed 20 m/s supercalender furnish. Squares, crosses, diamonds and triangles correspond to the jet-to-wire speed ratios 1.04, 1.06, 1.08 and 1.10.



2. Reduction in web width against MD straining before drying and during drying on the KCL pilot paper machine; speed 1 m/s, kraft furnish newsprint (a), printing paper (b). Jet-to-wire speed difference and drying rate were varied.



lowed us to separate the shrinkage induced by wet straining and by drying.

The main body of experimental material consisted of CD paper webs taken from the standard production of a few commercial paper machines (cf. **Table I**). Therefore controlled information on the machine operation could not be obtained. Rather than trying to explore the effects of machine conditions, we wanted to see what a "typical" shrinkage profile would look like. Newsprints and kraft furnish printing papers were studied. A machine glazed (MG) envelope paper (sample *J*) was also included as the Yankee dryer was expected to reduce lateral shrinkage significantly. This was also the case. In one case, the jet-to-wire speed difference was varied with corresponding changes in web properties (sample *I*).

On the full size webs, we measured the lateral dried-in shrinkage from the wiremark at 6-cm intervals at the edges and 10 cm in the center of the web. A floating mean over 2–5 adjacent points (12–50 cm in range) was used in the analyses. The value of total contraction, ε_w, was unavailable in some cases and uncertain in others. We therefore set $\varepsilon_w = 0$ in Eq. 3 for all the samples and determined only the variation of the lateral shrinkage around its mean value.

We also measured the CD elastic modulus, tensile index, and breaking strain at 20-cm intervals. The elastic modulus was obtained with an ultrasonic device *(12)* as sound velocity squared, the other properties were measured according to the standard SCAN P38:80. The MD paper properties were not analyzed as they exhibited only little irregular variation (5–10%) across the web.

Results and discussion

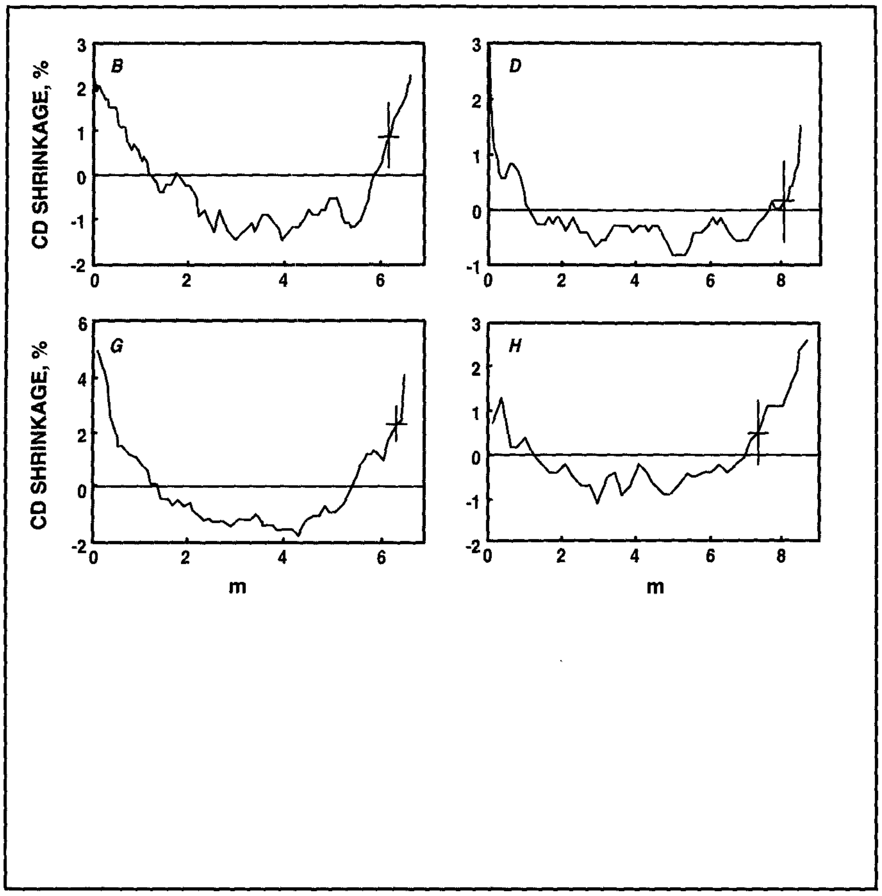
Pilot machine trials

The measurement technique was tested with the pilot gap former. An increase of 2% (from 3% to 5%) in the wet strain caused a roughly equal increase in the MD wavelength of the wire mark (**Fig. 1**). The CD wavelength decreased by about 3%, as did also the web width (not shown in **Fig. 2**). We conclude that the measurement technique yields correct values with the expected accuracy of about ± 1% (cf. Eq. 2).

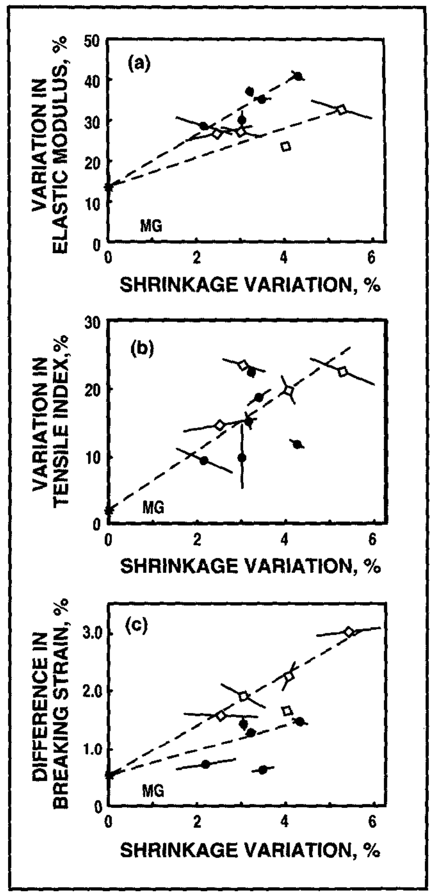
On the KCL fourdrinier machine, the newsprint furnish gave rise to roughly equal shrinkage in wet straining and in drying, but the bleached kraft shrunk mostly during drying (Fig. 2). Apparently mechanical pulps are more sensitive to wet straining than kraft furnishes that shrink mostly during drying. The Poisson ratio in wet straining is 1–1.5 and 0–0.5 for the two furnishes (cf. Figs. 1 and 2). The jet-to-wire speed difference was varied on both machines, but it had no systematic effect on the shrinkage.

CD profiles of dried-in shrinkage

Four examples of the CD profile of lateral shrinkage are displayed in **Fig.**



3. Dried-in shrinkage profile on machines *B, D, G, H*. The abscissa gives distance from the front side. The mean shrinkage has been set to $\varepsilon_w = 0$. Crosses indicate experimental uncertainty (Eq. 2).



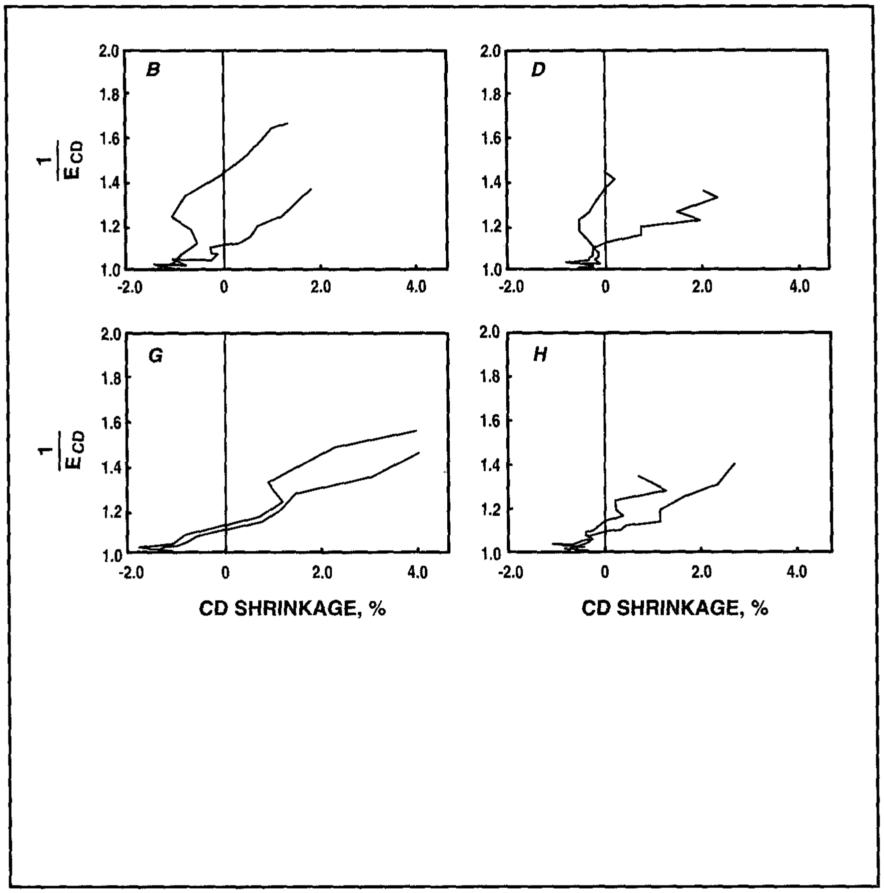
4. Edge-to-center difference (relative) in the CD elastic modulus (a), tensile index (b), and breaking strain (absolute diff.) (c), against the shrinkage difference in the newsprint and printing papers, bullets and diamonds, respectively. Sample *J* (MG paper) is shown separately. The two edges of each web are connected with a solid line while the dashed lines are drawn by hand to follow the data.

3. Samples *B* and *D* are newsprints and samples *G* and *H* kraft furnish printing papers. On the wide machines *(D* and *H)*, the shrinkage varied less than on the narrow machines *(B* and *G)*. Largest edge-to-center shrinkage difference was the printing paper *G*, but as a whole the printing papers had no larger shrinkage difference than the newprints (cf. Table I). In the MG paper *(J)*, no shrinkage variation was observed, presumably because of the Yankee dryer on that machine.

Fiber orientation anisotropy, controlled with the jet-to-wire speed difference, had an amplifying effect on the edge-to-center shrinkage difference on machine *I*. An increase of the modulus ratio MD/CD from 1.7 to 2.5 (at the web center) led to a 1% increase in the shrinkage difference (Table I). On the other hand, fiber orientation had no systematic effect on shrinkage on the pilot machines.

In the sample *D*, shrinkage increased abruptly at both edges (Fig. 3). The same character was also observed in the newsprint samples *A, C,* and *E*, and even in sample *B* on the back side; whereas, on the printing papers, the shrinkage profile was rather smooth. If edge is defined as the region where the dried-in shrinkage $\varepsilon(y)$ exceeds the mean value ε_w, then the edge was wider in the printing papers than in the newsprints (cf. Table I), except in the narrow machine *I* that had, however, an almost parabolic profile. Thus it seems that, in newsprints, the dried-in shrinkage increases abruptly in a narrow edge region; while, in kraft furnish printing papers, the shrinkage profile is smooth and no clear-cut edge region can be distinguished. We have made the same observation in other instances, too. The acute shrinkage in newsprints is apparently caused by wet straining (nb. the large Poisson ratio). In contrast, a kraft furnish paper should shrink mainly during drying (Fig. 2) where the gradual shrinkage accumulation may lead to a smoother profile. The fast drying rate of a newsprint may also play a role in amplifying the edge shrinkage.

5. Inverse of the CD elastic modulus against the dried-in shrinkage across the same webs as in Fig. 3. The modulus values are multiplied by a constant such that $1/E_{CD} = 1$ at web center, and $\varepsilon_w = 0$.



II: Characteristic edge-to-center difference (relative) in the CD elastic modulus, tensile index and breaking strain (absolute diff.) when the shrinkage difference is 3%. Values are obtained from the dashed lines in Fig. 4.

	Printing paper	*News-print*
CD Elastic modulus	25%	35%
CD Tensile index	15%	15%
CD Breaking strain	2%	1%

CD profiles of paper properties

We also explored the relationship between the shrinkage profile and the CD elastic modulus, tensile index, and breaking strain. **Figure** 4 shows the edge-to-center difference against the shrinkage difference. The data are somewhat unreliable because of the rapid variation at the web edge. The qualitative results, indicated by the dashed lines, are summarized in **Table II**. The dashed lines are drawn by hand through the data (separately for the two paper grades) including the MG paper that is a realization of a shrinkage difference zero.

The results are consistent with the reported laboratory experiments *(4, 5)* in that the elastic modulus was more sensitive to shrinkage than was the tensile index. The shrinkage difference explains best the variation of the elastic modulus in the newsprints and the breaking strain in the printing papers. If the lateral shrinkage were the only source of CD variation in the paper properties, then the data in Fig. 4 should go through the origin. This holds in essence for the tensile index and breaking strain but not for the elastic modulus. Even in the MG paper *J* the CD modulus is 12% lower at the edge than in the center. It appears that there must be another systematic cause for the variation in the elastic modulus. One candidate is the generally faster drying of the edges. High temperatures together with flutter may induce stress relaxation at the edges. Relaxation could be related to the low edge tensions reported by Linna *et al. (3)*.

Finally, we show in **Fig. 5** how the inverse CD elastic modulus varied across the web when plotted against the lateral shrinkage. The inverse modulus is expected to be linearly proportional to the drying shrinkage and could thus serve as an indirect shrinkage measure *(13)*. Indeed, the curves for samples *B* and *G* contain linear segments at the web edges, and the slopes agree roughly with the results in Table II.

However, no unique relationship exists between the elastic modulus and shrinkage as the two branches of the curves are displaced from one another. In samples *D* and *H*, changes in the elastic modulus do not at all reflect changes in the shrinkage. This shows that it is in general impossible to use the CD elastic modulus (or the CD breaking strain for that matter) as an indirect measure of the dried-in shrinkage. Local disturbances, e.g., wet streaks, break the required connection. It will be interesting to see if such defects can be resolved by analyzing the CD profiles of paper properties together with the dried-in shrinkage profiles

Summary

We employed the wire mark technique of Wadhams *et al. (10)* to measure the CD profiles of dried-in lateral shrinkage of full size paper webs. With a standard image analyzer, the absolute resolution was about ± 1% as long as the basis weight was below 80 g/m^2. Bleached kraft furnishes induced no more edge-to-center shrinkage variation than did newsprint furnishes. Instead, the edge shrinkage was acute in the newsprints but smooth in the printing papers. Apparently, wet straining affects the shrinkage profile in mechanical papers, but in kraft furnish papers the profile is governed almost solely by drying. We also showed qualitatively how shrinkage affects CD paper properties. The latter cannot be used as indirect measures of the shrinkage because local disturbances in drying break the connection.

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