Dimensional stability of mechanical pulps—drying shrinkage and hygroexpansivity

Y. Nanri and T. Uesaka

ABSTRACT: The dimensional stability of mechanical pulps was investigated in terms of drying shrinkage and hygroexpansivity. Results were evaluated against reference chemical pulps. While TMP and SGW pulps showed the lowest drying shrinkage, they did not show the lowest hygroexpansivity. The relationship between hygroexpansivity and drying shrinkage was investigated, with drying shrinkage expressed as a product of β_f (hygroexpansion coefficient for freely dried sheets) and Δm (moisture change from the onset of shrinkage to final dryness). Analysis revealed that low drying shrinkages for the TMP and SGW pulps were caused not by low β_f but rather by low Δm, which was found to be linearly related to water-retention value, a measure of pulp "swellability." A plot of $\Delta\beta$ (difference in hygroexpansion coefficient between freely dried sheets and restraint-dried sheets) vs. drying shrinkage yielded a strong linear relationship. This indicates that efforts to reduce hygroexpansivity by increasing drying restraint on the paper machine may be less effective on mechanical pulps because of their lower drying shrinkage.

KEYWORDS: Dimensional stability, drying, hygroexpansivity, measurement, mechanical pulps, shrinkage.

Dimensional stability is one of the most important properties controlling the end-use performance of paper *(1)*. Symptoms of dimensional instability include curl, wrinkle, cockle, grainy edge, moisture expansion, and shrinkage.

The evolution of high-speed, nonimpact printing technology has created new operational and quality problems related to dimensional instability, notably "fusing curl" for copy paper and "stack lean" for continuous-forms paper. Demands for much stricter control of dimensional stability have been increasing both in the marketplace and, therefore, in paper mills.

The demand for high dimensional stability is no longer limited to papers made from bleached kraft pulp, historically the major pulp source for fine paper grades. Recent improvements in the quality of mechanical pulps have led to their widespread use in higher-value-added grades and specialty paper grades. Dimensional stability of mechanical pulps, however, has not been well addressed in the literature.

This study was undertaken in an effort to characterize the dimensional stability of mechanical pulps in terms of drying shrinkage and hygroexpansivity. The analysis focuses on the relationship between hygroexpansion coefficient and drying shrinkage.

Experimental

Samples

The mechanical pulps employed in the experiments were selected from furnishes used to produce newsprint and groundwood specialty grades. They are identified as stone groundwood pulp (SGW), thermomechanical pulp (TMP), chemithermomechanical pulp (CTMP), and chemimechanical pulp (CMP). The SGW, TMP, and CMP were produced mainly from black spruce in eastern Canadian paper mills. The CTMP was produced in a western Canadian mill from a mixture of balsam and hemlock. Low-yield sulfite pulp (LYS) and bleached kraft pulp

Nanri is visiting scientist and Uesaka is director of Paper & Board Quality Division, Pulp and Paper Research Institute of Canada, 570 St. John's Blvd., PQ, Canada, H9R 3J9. Nanri is now with Nippon Paper Industry Co., Tokyo, Japan.

I. Fiber length and water-retention value

	Mechanical pulps				Chemical pulps		
	SGW	TMP	CTMP	CMP	LYS	LYS (beaten)	BKP (beaten)
Mean fiber length, mm*	0.72	1.62	1.54	1.33	2.31	2.10	2.29
Bauer–McNett fiber classification, %							
R-28	9.1	40.2	32.7	51.5	77.7	73.0	79.1
R-28/R-200	47.5	33.4	37.0	27.0	14.6	17.5	13.1
P-200	43.4	26.4	30.3	21.5	7.7	9.5	7.8
WRV, g/g	1.52	1.00	1.47	1.88	2.11	2.44	2.12

*Length weighted; measured by Kajaani FS 200

(BKP) were used as reference chemical pulps. These chemical pulps were also produced mainly from black spruce. All pulps were never-dried pulps, with the exception of BKP. Fiber length, fiber classifications, and water-retention value (WRV) for these pulps are shown in **Table I.** Typically, all mechanical pulps showed much lower WRV than the chemical pulps.

Handsheets of basis weight 60 g/m^2 were made on a British handsheet machine. Densities were controlled by varying wet-pressing pressure from 27 kPa to 1.9 MPa. Handsheets were dried at 23°C and 50% RH either with a plate (restraint-dried handsheets) or without restraint on a Teflon mesh wire (freely dried handsheets).

Measurement of dimensional stability

Hygroexpansivity was measured using a hygroexpansi-meter constructed at Paprican *(2)*. Relative humidity was changed linearly from standard (50% RH) to low (30% RH) and then to high humidity (90% RH) for 4 h per cycle at 25°C. Moisture content in the paper was monitored simultaneously by weighing a reference sample with a microbalance.

Typical curves of hygroexpansion strain vs. sheet moisture content are shown in **Figs.** 1 and 2 for restraint-dried and freely dried SGW handsheets, respectively. For the restraint-dried handsheets (Fig. 1), the relationship between hygroexpansion strain and sheet moisture content was approximately linear and reversible in the low-moisture-content range, but in the higher-moisture range, the relationship was nonlinear and showed an irreversible shrinkage after the initial exposure at high humidity. Freely dried handsheets (Fig. 2), on the other hand, showed an almost linear and reversible response throughout the whole range of sheet moisture content.

From these curves, various effects of the moisture cycling can be determined, such as hygroexpansion coefficient, irreversible shrinkage, and the moisture dependence of hygroexpansivity *(2)*. This report considers only hygroexpansion coefficient, defined as a gradient of the linear part of the curves in the low-moisture range. The hygroexpansion coefficient (ß) was determined from the absorption stage of the first cycle and is expressed as hygroexpansional strain divided by moisture change.

$$\beta = \text{dimensional change(\%)} / \text{moisture-content change (\%)} \quad (1)$$

The coefficient of variation for the measurement of the hygroexpansion coefficient was 4%.

Drying shrinkage. Drying shrinkage was determined by making two marks 12 cm apart on a wet-pressed handsheet *(3)* and measuring their separation with a traveling microscope after drying on a Teflon™ wire. Drying shrinkage was measured only for freely dried handsheets.

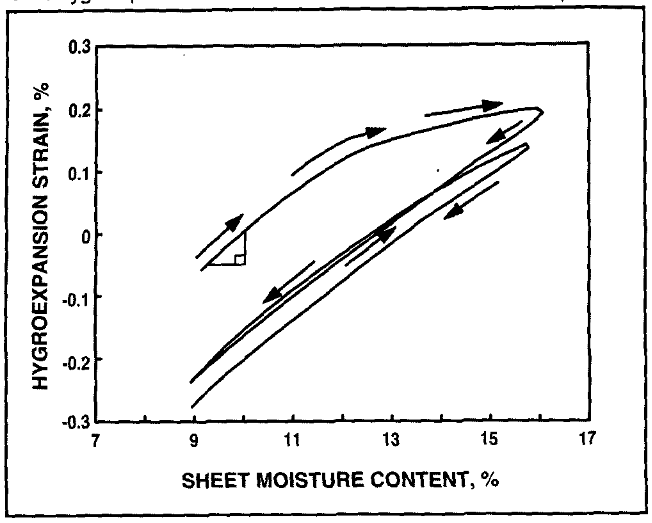
Results and discussion

Comparison of dimensional stability of mechanical pulps

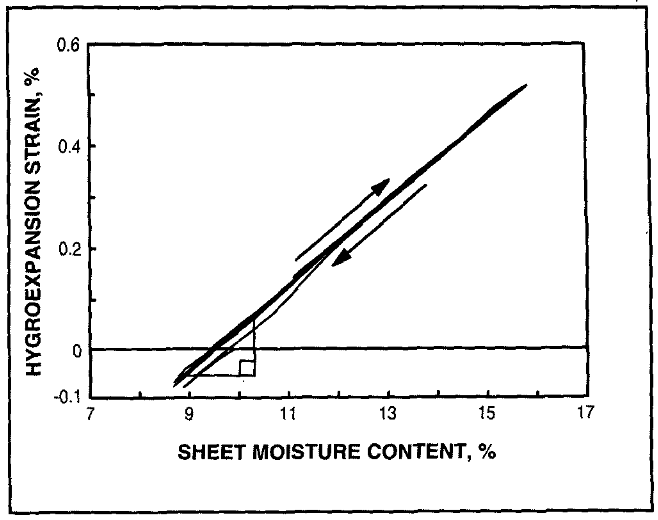
Table II shows hygroexpansivity and drying shrinkage for the pulps used in this study. For restraint-dried sheets, hygroexpansivity was similar for the mechanical and chemical pulps, with CMP showing the highest hygroexpansion coefficient among the pulps. For freely dried sheets, hygroexpansivity was greatest for CMP and beaten LYS, followed by beaten BKP. (The CMP tested had received a special treatment in the mill to enhance fiber curl and microcompressions.) Drying shrinkage for the mechanical pulps was significantly different from that of the chemical pulps. With the exception of CMP, drying shrinkage for the mechanical pulps was much lower than that observed for the chemical pulps. (The same trend was observed for other mechanical and chemical pulps that are not listed in Table II.) These results indicate that mechanical pulps generally have lower drying shrinkage than chemical pulps, although they do not necessarily have lower hygroexpansion coefficient.

Nordman *(4)*, who compared dimensional stability of various pulps dried *under different restraint conditions*, found that moisture expansivity (hygroexpansivity) was linearly related to drying shrinkage. **Figure** 3 is a plot of hygroexpansion coefficient against drying shrinkage for the freely dried sheets of the pulps listed in Table II. It is apparent that the hygroexpansion coefficient did not show a particularly high correlation with the drying shrinkage (r^2 = 0.618). Salmén *et al. (5)* also found no evidence of the relationship observed by Nordman *(4)* between drying shrink-

1. Hygroexpansion behavior of a restraint-dried sheet made from SGW pulp. The gradient of the linear portion of the curve at low moisture content is the hygroexpansion coefficient for the restraint-dried sheet ($ß_r$)



2. Hygroexpansion behavior of a freely dried sheet made from SGW pulp. The gradient of the linear portion of the curve at low moisture content is the hygroexpansion coefficient for the freely dried sheet ($ß_f$)



age and hygroexpansion coefficient when these properties were varied by changing the degree of wet-pressing. Since drying shrinkage is often used in mills as a predictor of dimensional stability for "dry" sheets (hygroexpansivity), it is important to clarify the relationship between hygroexpansivity and drying shrinkage.

Relationship between hygroexpansivity and drying shrinkage

Drying shrinkage is affected not only by pulp properties but also by papermaking variables, such as wet-pressing pressures. **Figure 4** shows a relationship between drying shrinkage and sheet density for four different pulps. (Density was varied by changing wet-pressing pressures.) In this figure, drying shrinkage appears to be almost constant with increasing density for all four pulps until the density reaches a certain threshold, beyond which drying shrinkage decreased.

Salmén *et al.* *(5)* observed that wet-pressing affects sheet density as well as solids content after wet-pressing, with solids content after wet-pressing increasing with increasing wet-pressing pressure. In **Fig. 5**, drying shrinkage was replotted against solids content after wet-pressing. There appear to be threshold solids contents beyond which shrinkage starts falling, and these solids contents seem to be related to the WRV of the pulps.

Wet-pressing has at least two effects on shrinkage. The first involves compaction of the sheet and an associated increase in fiber–fiber bonding. The second is restraint of drying shrinkage when the web is wet-pressed to a solids content beyond the point where shrinkage starts. This restraining effect of wet-pressing retards the initiation of shrinkage and thus reduces shrinkage, even if sheets are freely dried. Therefore, it can be speculated that the critical solids contents, as seen in Fig. 5, are related to the solids contents at which shrinkage starts.

To confirm this hypothesis, we consider first a typical shrinkage curve during the drying process, as illustrated in **Fig. 6**. During drying, the wet web starts shrinking when the moisture content (or solids content) passes beyond a certain threshold. The entire curve of shrinkage vs. moisture content is generally nonlinear, as was shown in the literature *(6, 7)*. However, since the gradient of the strain-vs.-moisture-content curve for freely dried sheets was approximately constant in the low-moisture range (Fig. 2), drying shrinkage is expected to be linear against moisture content in the low-moisture range (or in the high-solids-content range). Such shrinkage behavior can be characterized by expressing shrinkage as a product of the gradient of the linear portion of the curve and the corresponding change in moisture content, as seen in Eq. 2

$$\text{drying shrinkage} = ß_f \Delta m \qquad (2)$$

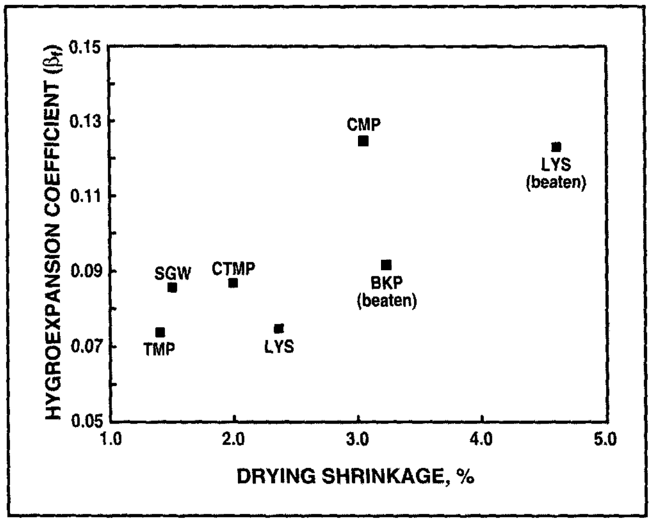
where

$ß_f$ = the hygroexpansion coefficient of freely dried handsheets, i.e., the gradient of the linear portion of the curve

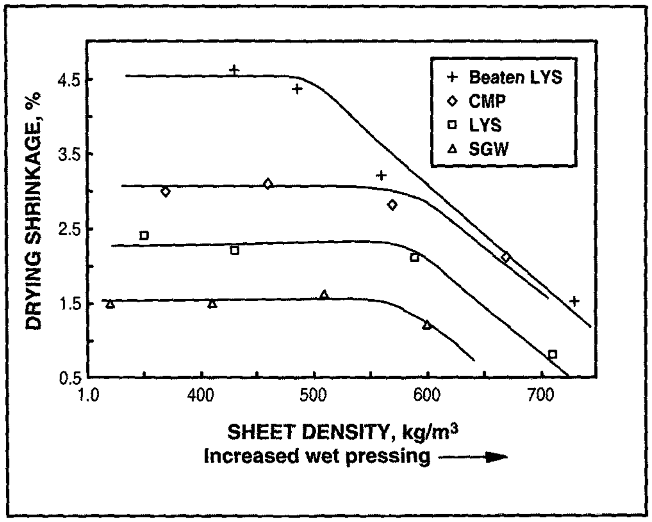
Δm = moisture change from onset of shrinkage to final dryness.

The onset of shrinkage in this case was defined as the intercept point, which is obtained by extrapolating the linear portion of the curve to the moisture axis in Fig. 6. (The gradual increase in shrinkage, usually observed in the shrinkage-vs.-moisture-content curve, may be controlled by a different mechanism from the "hygroshrinkage" assumed in this study.)

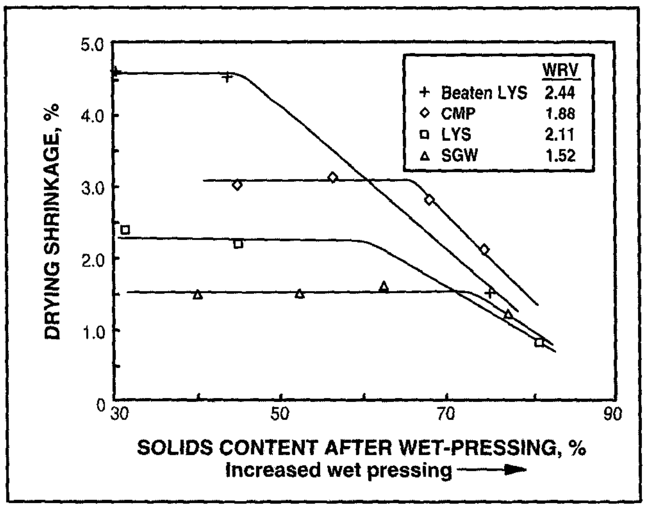
Using the data on the shrinkage and hygroexpansion coefficient of freely dried sheets (Table II), we can calculate Δm and thus the intercept point by using Eq. 2. Since $ß_f$ varied very little with wet-pressing for the pulps tested—in contrast to the results for bleached kraft pulps in the literature *(5)*—values of $ß_f$ at the standard wet-pressing pressure (60 psi, 0.41 MPa) were used for the calculation.



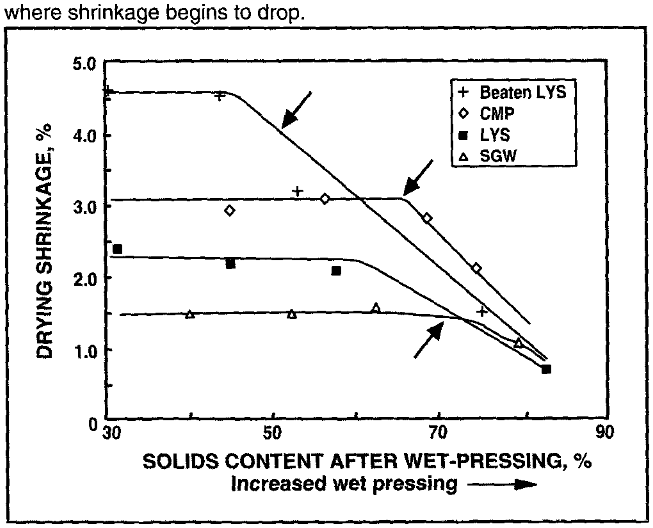
3. Relationship between hygroexpansion coefficient for freely dried sheets (β_f) and drying shrinkage



4. Drying as a function of density. Density was varied by wet-pressing.



5. Drying shrinkage as a function of solids content after wet-pressing for four pulps

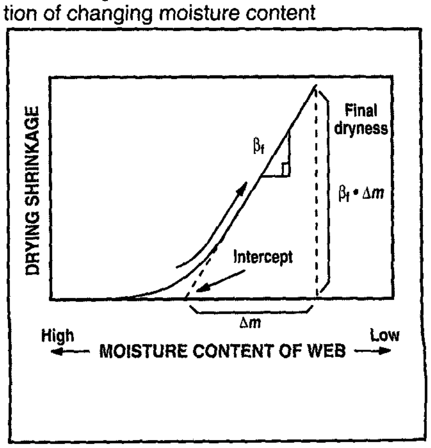


7. Relationship between calculated critical solids content (Eq. 2) and solids contents observed at transition point (Fig. 5) for four pulps. The calculated values are close to the observed critical solids contents, where shrinkage begins to drop.

II. Hygroexpansion coefficient and drying shrinkage

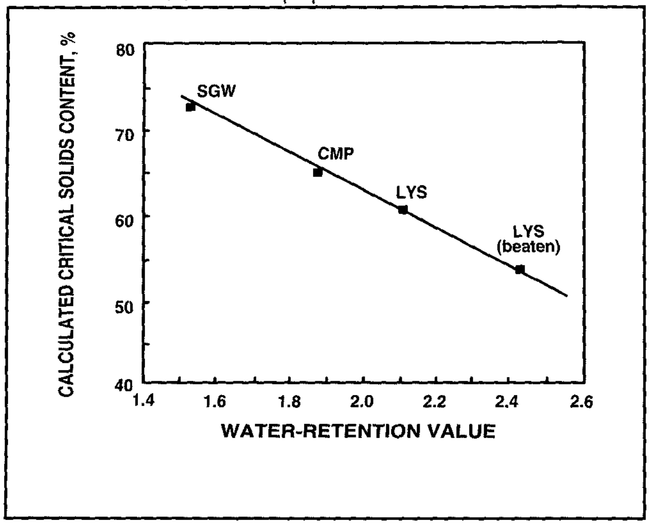
	Mechanical pulps				*Chemical pulps*		
						LYS	*BKP*
	SGW	*TMP*	*CTMP*	*CMP*	*LYS*	*(beaten)*	*(beaten)*
Hygroexpansion coefficient [a]							
Restraint-dried sheet (β_r)	0.068	0.057	0.063	0.081	0.048	0.063	0.053
Freely dried sheet (β_f)	0.086	0.074	0.087	0.125	0.075	0.123	0.092
Drying shrinkage[b], %	1.50	1.40	1.99	3.06	2.35	4.60	3.23

[a]Hygroexpansion coefficient = dimensional change (%)/moisture-content change (%)
[b]Freely dried handsheets

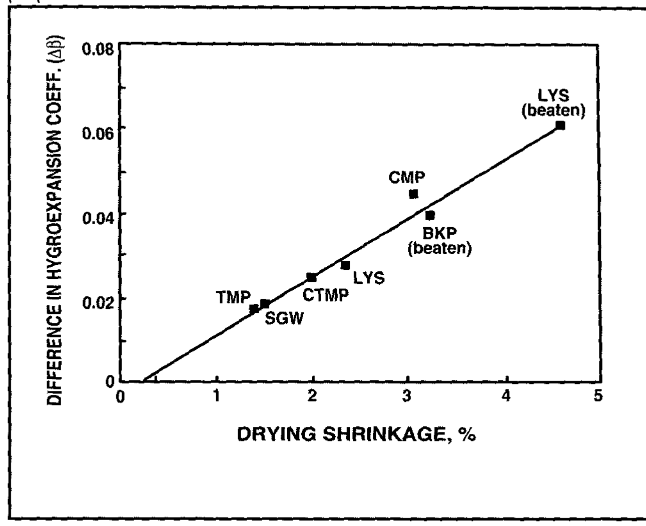


6. Shrinkage behavior of wet web as a function of changing moisture content

8. Relationship between calculated critical solids content (Eq. 2) and water-retention value for four pulps



9. Relationship between $\Delta\beta$ (i.e., $\beta_f - \beta_r$) and drying shrinkage for all pulps



According to the preceding hypothesis, this intercept point is related to the critical solids content at which shrinkage starts falling (Fig. 5). In **Figure** 7, the solids contents calculated by Eq. 2 are indicated by arrows. The calculated values are closely located in the critical range of the solids content.

Figure 8 is a plot of calculated critical solids content against WRV for the four pulps. The calculated solids content at the intercept point—the transitional solids content—showed a linear relationship with WRV. Since the onset of shrinkage is generally related to the fiber saturation point *(6, 8)*, and since the fiber saturation point was found to have a strong correlation to WRV *(9)*, the results in Fig. 8 suggest the validity of the interpretation of the intercept based on the hypothesis.

The preceding analysis indicates that drying shrinkage is determined by two factors, the hygroexpansion coefficient (β_r) and the moisture change during shrinkage (Δm). The latter factor is associated with a pulp's so-called "swelling ability." Mechanical pulps in general have lower swelling ability (i.e., lower Δm) and thus lower drying shrinkage than chemical pulps. This does not necessarily imply a lower hygroexpansivity for mechanical pulps. The hygroexpansion coefficient is, on the other hand, determined by structural and mechanical properties of fibers and the fiber network *(10)*. Therefore, it is natural to expect that drying shrinkage itself, which changes the *z*-directional structure of paper and single-fiber properties, affects the hygroexpansivity.

In **Fig.** 9, $\Delta\beta$ (the difference in hygroexpansion coefficient between freely dried and restraint-dried sheets) is plotted against drying shrinkage. It is interesting to note that this plot gives a better correlation ($r^2 = 0.976$) than Nordman's plot. The results in Fig. 9 imply that the effect of drying restraint on hygroexpansion coefficient for mechanical pulps is not as large as that for chemical pulps because of the lower drying shrinkage of mechanical pulps.

Conclusion

The dimensional stability of various mechanical pulps was investigated in terms of drying shrinkage and hygroexpansivity. The following conclusions were drawn.

- The mechanical pulps (SGW, TMP, CTMP) had lower drying shrinkage than the chemical pulps (LYS, BKP). The lower shrinkage is due mainly to the lower WRV (lower swelling ability) of the mechanical pulps. Low drying shrinkage does not necessarily imply low hygroexpansivity.
- The effect of drying restraint on hygroexpansivity is lower for the mechanical pulps because of their lower drying shrinkage. ◼

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The authors thank C. Moss for help in operating the hygroexpansimeter, A. Kingsland and R. Howard for helpful advice concerning drying shrinkage measurements, and J. Wood for valuable discussions.

Received for review Aug. 25, 1992.

Accepted Nov. 10, 1992.

Presented at the TAPPI 1992 International Paper Physics Conference.