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Dimensional Stability of Paper: Papermaking Methods and Stabilization of Cell Walls

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Like other wood-based materials, paper also exhibits dimensional changes as a result of changes in moisture content that, at times, can seriously limit the performance and usefulness of paper. This dimensional instability of paper arises ultimately from the moisture sensitivity and swelling of the cell wall. In the dry state, the wood cell wall is almost poreless, yet it can take up moisture from the surrounding atmosphere while it seemingly remains dry. This adsoption of water on the vast internal surfaces within the cell wall results in a change in external dimensions. As the moisture of the surrounding environment increases, more water is accommodated within the cell wall until saturation is reached. In an ordinary wood fiber, the moisture content of the cell wall at the fiber saturation point is considered to be about 30 percent (30g of water/100g of dry fiber). But in a pulped fiber, the fiber saturation point may be several times larger. Pulp fibers can easily have fiber saturation points of 70 to 80 percent.(1) Never-dried pulp fibers have been reported to have fiber saturation points of 200 percent.(2) The large fiber saturation points of chemical pulp fibers are partially caused by removing the encrusting lignin and partially caused by the mechanical treatment of the fibers.

The anisotropic nature of cellulosic fibers is demonstrated in Table 1.(3) Not only is there a vast anisotropy in the dimensions of the fibers in length compared to width, but most properties measured along the fiber length are quite different from properties measured in the transverse direction. Whereas the longitudinal elastic modulus is much greater than across the fiber, both thermal expansion and moisture expansion across the fiber are greater than along the fiber. Moisture expansion across the fiber amounts to about 1 percent increase for each 1 percent increase in moisture content. Along the fiber, however, swelling is 10 to 20 times smaller.

TABLE I

SOME ANISOTROPIC PROPERTIES OF CELLULOSIC PULP FIBERS

Property	Longitudinal	Transverse
Dimension, mm	0.5 - 5	0.01 - 0.02
Moisture expansion, %/%H_2O	0.05 - 0.1	1.0
Thermal expansion, $^{\circ}C^{-1} \times 10^{6}$	0.1 - 1.4	12 - 14
Elastic modulus, GPa	5 - 20	0.5

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The swelling of a sheet of paper reflects the swelling anisotropy of the individual fibers. Paper is a structure of individual fibers that are layered one upon another. Therefore, swelling of a sheet of paper is largely in the thickness or z direction. Approximately 90 percent of the volume expansion of a sheet of paper occurs in its thickness,(4) but the absolute value of the dimensional change is small because of the small thickness of a sheet of paper. The troublesome dimensional changes, from a use standpoint, are in changes that occur in the plane of the sheet of paper. Therefore, the following discussion of dimensional instability will be restricted to changes within the plane of the sheet of paper (i.e., the x-y plane). Eliminated from this discussion are the out-of-plane phenomena arising from dimensional instability such as curl, twist, cockle, and baggy paper. These troublesome problems associated with paper are most often caused by nonuniformities of both moisture and stress gradients and are beyond the scope of this report.

As mentioned, the swelling of a sheet of paper reflects the swelling of the fiber cell walls. But the swelling of the cell walls must be transmitted through the complicated arrangement of fibers, voids, and interfiber bonds that make up the structure of paper. Because papermakers have some control over the structure of paper, they also have some measure of control over its dimensional stability. The papermaker, without greatly changing the nature of the affinity of the cell wall for moisture, can, to a degree, affect the dimensional stability of paper by having a choice of conventional papermaking options and practices available.

Papermaking Factors

Fiber Furnish

The first papermaking factor that influences the dimensional stability of paper is the choice of fiber furnish. Generally, there is an inverse correlation between interfiber bonding and dimensional stability.(5) Fibers that bond best and form well-bonded sheets also exhibit the greatest dimensional instabilities. Well-bonded sheets are denser and less bulky than poorly bonded sheets. When the cell walls swell, there is less available free volume within a dense sheet. Cell wall expansion in a bulky sheet, on the other hand, can be accommodated more readily into this available interior free volume and will not be transmitted to the external dimensions of the sheet. Table II presents dimensional swelling of handsheets ($60 g/m^2$) of several representative pulps.(6) The dimensional movement of the handsheets made from virgin fibers shows considerably more dimensional movement than the handsheets made from recycled fibers. Recycled fibers are fibers of choice when dimensional stability rather than sheet strength are desired. Small additions of glass or synthetic fibers that are moisture insensitive, when added to the fiber furnish, can also have marked effects in stabilizing paper, but unfortunately, they tend to lower strength.(7)

TABLE II

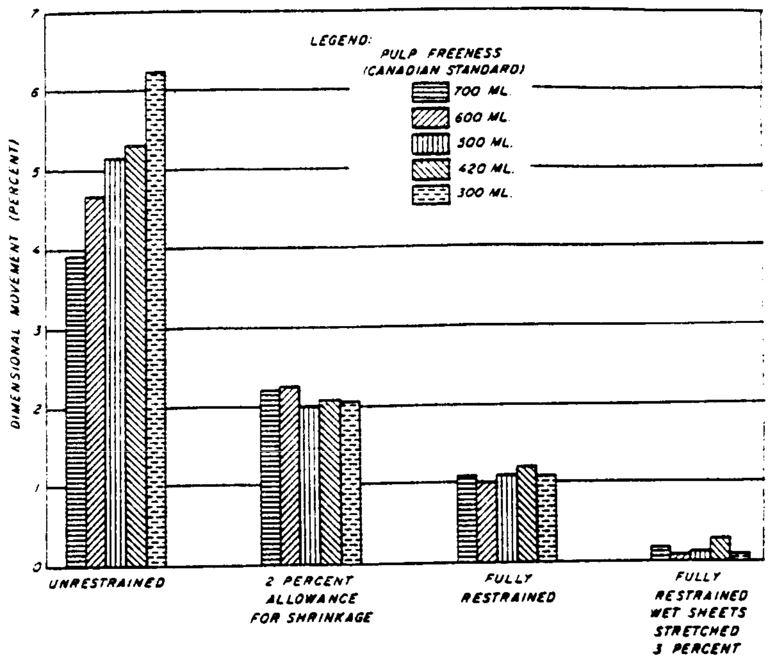
DIMENSIONAL INCREASE OF HANDSHEETS
(DRIED UNRESTRAINED)

Pulp	Dimensional increase (%)	
	30% to 90% RH	30% RH to water soak
Virgin fibers		
Southern pine	1.37	3.92
Douglas-fir	1.25	3.25
Spruce groundwood	1.37	2.44
Recycled fibers		
Tab cards	1.02	2.53
Milk cartons	0.85	2.53
Waste newsprint	0.86	1.54

Beating and Refining

Beating or refining pulp is the most effective means of improving interfiber bonding and thereby increasing both the density and strength of a sheet of paper. But by so doing, the dimensional stability of the sheet is reduced. Figure 1(handsheets dried without restraint) demonstrates the pronounced effect refining has on decreasing the dimensional stability of paper.(6) As the freeness of the pulp decreases because of beating, the dimensional movement (between 30% relative humidity [RH] and water soak) of the finished handsheet increases. This adds support to the general rule that those factors that improve the interfiber bonding in a sheet of paper also, unfortunately, decrease dimensional stability.

Figure 1: Effect of freeness of southern pine kraft pulp on the dimensional movement (30% RH to water soak) of handsheets dried with various degrees of restraint.



Fillers

Although there have been some reports to the contrary,(8) most researchers have found that fillers, if they are moisture insensitive, aid in increasing dimensional stability.(5) Again, it is thought that the effect sterns largely from the resultant decrease in the internal bonding in the sheet and from the reduced fractional content of the paper that is moisture sensitive.

Fiber Orientation

Fiber orientation and restraint during drying are related and probably have the largest effect on dimensional stability. On modern high-speed paper machines, the fibers are not isotropically oriented in the plane of the sheet. Instead, there is a definite preference for the fibers to lie with their long dimensions in the direction of manufacture (i.e., in the machine direction). Because fiber swelling in its longitudinal direction can be one-twentieth to one-tenth of the swelling in its transverse direction, dimensional movement of paper is less in the machine direction than in the cross-machine direction. Table III indicates typical values of machine and cross-machine swellings for machine-made papers. The general rule is that the cross-machine swelling is approximately three times greater than machine direction swelling. One often

TABLE III

EFFECT OF MOISTURE ON MACHINE DIRECTION (MD) AND CROSS -MACHINE DIRECTION (CD) EXPANSION OF PAPER (25% to 65% RH)

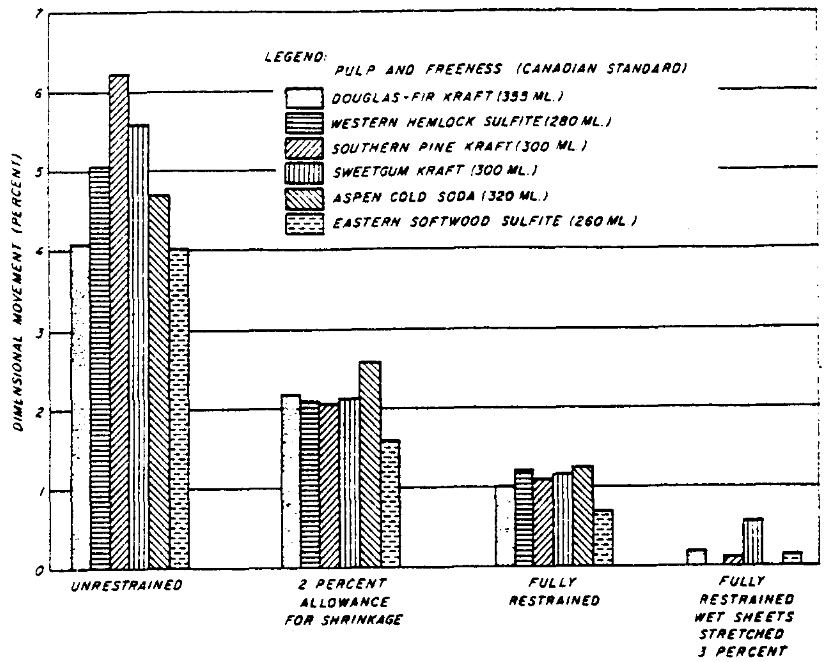
Paper	Machine direction increase (%)	Cross-machine direction increase (%)	Ratio CO/MD
Bond	0.11	0.48	4.4
Tablet	0.12	0.38	3.2
Newsprint	0.13	0.35	2.7

thinks of paper as being more isotropic than wood, but we see from the anisotropy of paper swelling in three directions that paper, too, is an orthotropic solid with different properties in its three directions. The relative swelling in machine direction to cross-machine direction to thickness direction (x:y:z) is in the approximate ratio of 1:3:30.

Restraint During Drying

Fiber orientation accounts for only part of the difference between machine and cross-machine dimensional movement. A large part of this dissymmetry can also be ascribed to drying restraints that occur during manufacture. During paper manufacture, as the web dries, paper shrinks. It is the reversal of this process, as paper becomes wet, that is responsible for the dimensional instability of paper. If paper is restrained from shrinking during manufacture, its dimensional stability is improved. The effects of restraint during drying can easily overcome the effects of fiber furnish, beating, and fiber orientation. Figure 1 shows how restraint during drying can outweigh the effect of beating.(6) For the unrestrained handsheets, as freeness decreases, dimensional movement increases. However, if the sheets are dried with increasing levels of restraint to prevent some of the initial shrinkage, the dimensional swelling on subsequent exposure to moisture is markedly reduced and the effect of freeness disappears. Figure 2 shows similar results of what effect restrained drying has on masking the effect that species has on the dimensional stability when dried without restraints.(6)

Figure 2: Effect of type of bleached pulp on the dimensional movement (30% to water soak) of handsheets dried with various degrees of restraint.



On a modern paper machine, the paper web travels faster at the dry end than at the wet end. This difference in velocity is called machine draw and is evidence that the web is dried under tension. This machine draw or drying restraint improves the machine direction dimensional stability of the paper. However, it is very difficult to apply tension to a moving web in the cross-machine direction. Fahey and Chilson,(6) in their research on restrained drying, showed that using expander rolls in the wet-press section and in the dryer section of the paper machine can reduce shrinkage in the cross-machine direction. Other methods of restraining cross-machine shrinkage during manufacture can be effective. In a Yankee dryer, shrinkage is avoided by drying the sheet in contact with a steel cylinder which reduces cross-machine dimensional instability.(5) Tight felts in the dryer section and drying between screens or fabrics, such as in press-drying, are also effective in reducing cross-machine shrinkage during manufacture.

Horn's recent research(9) shows that press-drying may have a significant effect on improving the dimensional stability of printing grade papers.

Surface Sizes, Coatings, and Wet-Strength Agents

Surface sizes are very effective in hindering wetting of a sheet by liquid water. Therefore, they are of great value in ensuring the dimensional stability of paper which is only transiently exposed to liquid water, as in certain printing. However, surface sizes have little ultimate effect upon prolonged exposure to water and especially to water vapor. Similarly, coatings can be effective in controlling the dimensional stability of paper only if they can prevent moisture from entering or leaving the sheet. Typical wet-strength resins, unless present in large quantities, do not significantly affect the dimensional changes caused by wetting or humidity change.

Calendering

Calendering, a process where the paper is pressed between hardened steel rolls, is one way to increase the density of a sheet without necessarily increasing the degree of interfiber bonding. If the papermaker needs to produce a sheet with a higher density, it maybe obtained by increased beating of the pulp prior to sheet forming or by calendering the paper. By choosing calendering rather than beating, density can be increased without sacrificing as large a loss in dimensional stability.(5)

These conventional process and furnish options that the papermaker uses to influence or control dimensional stability are rather limited in their effectiveness because, in general, they do not deal with the cellulosic fiber's inherent affinity for moisture and its swellable nature. Rather than affecting the swelling of the cell wall, these methods rely on affecting either the way water gets to the cell wall or how the instability of the cell wall is transmitted through the structure of fibers, voids, and interfiber bonds to the external dimensions of the sheet.

Cell Wall Modifications

Methods for cell wall modification to improve dimensional stability involve chemical modification through derivatizing, bulking, and cross-linking. When the derivative or chemical modification improves dimensional stability, it usually involves replacing some of the hydroxyl groups in the cell wall polymers with other chemical moieties that are less hydrophilic. Bulking involves filling cell wall volume with extraneous material that occupies sites that could otherwise be occupied by water. Cross-linking involves the introduction of new chemical covalent bonds within the cell wall polymers that act as swelling restraints and effectively limit the access of water into the cell wall. Some cell wall modification, such as grafting, can affect dimensional stabilization by a combination of these mechanisms.

Esterification and Etherification

Acetylation and cyanoethylation are examples of esterification and etherification, respectively, and are chemical modifications that have been employed to improve the dimensional stability of paper.(l0)

Improvement in dimensional stability by acetylation stems from the reduced affinity for water by acetyl groups compared with hydroxyl groups. Acetyl groups may be introduced to either pulps or papers, but Nissan and Higgins showed that when about 24 percent of the hydroxyl groups are substituted, the resulting sheet loses all coherence(11). This is because the same hydroxyl groups responsible for dimensional instability are essential for good hydration and subsequent hydrogen bond formation during sheet consolidation. Nevertheless, Stamm and Beasley(12) showed that swelling in water of a heavily acetylated sheet could be reduced to one-tenth of the swelling of an unacetylated sheet. Recently, Rowell(13) reported similar reductions in swelling of pine wood cell walls at acetyl contents of 15 to 20 percent. Rowell attributes this cell wall stabilization largely to the bulking effect of the acetyl groups. Esterification has been proposed as the mechanism by which alkyl ketene dimers impart moisture resistance to papers, and their use as commercial paper sizes has grown(14). However, the number of ester bonds necessary for good sizing is small, and little effect on long-term dimensional stability has been claimed at these low levels.

A number of reports and patents have established the use of cyanoethylated paper for improved dimensional stability.(10) Fifty percent reductions in the dimensional expansion of papers can be obtained; however, serious losses in sheet strength accompany the treatment.(15)

Grafting and Polymer Impregnations

Moisture regain is sharply reduced with hydrophobic fibers, and paper grafted with ethyl acrylate, acrylonitrile, or any relatively hydrophobic polymer has a considerably lower moisture regain than an untreated sheet. Dimensional stability is closely related to this reduction in moisture regain. In a highly grafted fiber there is less cellulose by weight, and hence less material to swell. Moreover, the polymer can prevent normal fiber collapse during sheet drying, resulting in less expansion on dehumidification. Stamm and Cohen(16) showed that this bulking effect of grafted polymers was similar to the effect of simple inclusion of preformed polymers, the number or existence of actual grafted bonds being relatively unimportant.

Phenolic resin impregnated paper exhibits marked improvements in dimensional stability when the molecular size of the resin is small enough to penetrate the fiber cell wall. Highly stabilized resin-treated paper exhibits improved wet-stiffness. The connection between dimensional stability and wet-stiffness of phenolic resin-treated paper maybe illustrated by a discussion of some previously unpublished results. Linerboard (185 g/m^2) was impregnated with a fiber-penetrating phenolic resin and, after curing, subsequently swollen in sodium hydroxide solutions, thoroughly rinsed, and dried. Using five levels of resin loading (including 0), and five concentrations of sodium hydroxide (including 0), 25 papers exhibiting a wide range of swelling in water were prepared. The fiber saturation points of these papers and the moisture regains as a funtion of relative humidity are presented in Table IV. The swelling of strips of these papers was measured in the cross-machine direction, and the linear dimensional stability (D_ℓ) was compared to the volumetric stability of the cell wall ($D_{F.S.P.}$), as measured by changes in fiber saturation points (F.S.P.)(Table V). Figure 3 is a plot of linear dimensional stability compared to volumetric or cell wall stabilization. Note that for those papers showing improved stability, the linear dimensional stability is directly correlated with cell wall stability; linear dimensional stability improves as ceil wall swelling decreases.

When the wet and dry tensile moduli of the same resin impregnated and alkali swollen papers were measured, an important relationship between cell wall swelling and set-stiffness became apparent. For each of the same 25 papers, Young’s modulus was measured at 50 percent RH(E_{50}) and after water soaking (Ew). With any fixed alkali post-treatment, as the resin content increases, both wet and dry tensile modulus increase. However, the improve-

TABLE IV

MOISTURE SORPTION OF RESIN IMPREGNATED AND ALKALI WASHED LINERBOARD

Paper identification code	Phenolic resin content (%)	Concentration of NaOH wash solution (%)	Moisture content (%)					
			30% RH	50% RH	65% RH	80% RH	90% RH	Fiber saturation point
H 0[a]	0	0	4.50	9.02	10.22	14.74	22.25	57.2
H 4	0	4	4.82	9.45	10.73	15.44	23.15	79.3
H 10	0	10	4.92	9.51	11.04	15.72	23.27	100.4
H 18	0	18	6.46	11.53	13.15	17.94	25.82	111.0
H 25	0	25	6.05	11.24	12.85	17.60	25.78	95.2
A 0	5.3	0	4.27	7.90	9.02	11.71	16.00	28.6
A 4	5.3	4	4.50	8.39	9.69	13.10	--	31.8
A 10	5.3	10	4.96	9.18	10.51	14.22	19.56	56.0
A 18	5.3	18	6.24	11.96	13.57	18.27	25.53	73.2
A 25	5.3	25	6.60	12.27	13.98	18.93	26.27	84.1
C 0	7.8	0	3.96	7.49	8.42	11.32	--	27.6
C 4	7.8	4	4.58	8.37	9.51	--	17.00	28.8
C 10	7.8	10	4.86	9.11	10.32	13.96	18.95	46.0
C 18	7.8	18	6.37	11.85	13.30	18.08	24.87	64.0
C 25	7.8	25	6.53	12.19	13.66	18.35	25.46	76.2
B 0	11.5	0	3.91	7.04	7.94	10.53	13.43	21.8
B 4	11.5	4	4.50	8.16	9.27	12.30	16.00	24.1
B 10	11.5	10	4.66	8.82	9.85	13.45	18.05	36.2
B 18	11.5	18	6.20	11.51	13.00	17.50	23.97	53.0
B 25	11.5	25	6.21	11.82	13.31	17.83	24.65	63.1
D 0	15.6	0	3.63	6.54	7.22	9.55	11.72	19.2
D 4	15.6	4	4.04	7.67	8.57	11.52	14.84	19.3
D 10	15.6	10	5.57	9.51	10.59	13.75	17.24	30.0
D 18	15.6	18	5.82	11.06	12.48	16.87	22.91	44.3
D 25	15.6	25	5.82	11.27	12.65	17.18	23.32	51.5

(a) H 0 was used as the control.

TABLE V

LINEAR AND VOLUMETRIC DIMENSIONAL STABILIZATION

Paper identification code	L (%)	D_{ℓ}[a] (%)	Ranking	Fiber saturation point	$D_{F.S.P.}$[b] (%)	Ranking
H 0[b]	3.73	0	21	57.2	0	16
H 4	4.72	-26.5	22	79.3	-38.6	21
H 10	6.88	-84.5	23	101.4	-77.3	24
H 18	7.53	-101.9	25	111.0	-94.0	25
H 25	7.13	-91.1	24	95.2	-66.4	23
A 0	1.19	68.1	7	28.6	50.0	6
A 4	1.63	56.3	10	31.8	44.4	9
A 10	1.84	50.7	12	56.0	2.1	15
A 18	3.60	3.5	19	73.2	-28.0	19
A 25	3.63	2.7	20	84.1	-47.0	22
C 0	0.94	74.8	3	27.6	51.7	5
C 4	1.44	61.4	8	28.8	49.7	7
C 10	1.77	52.5	11	46.0	19.6	12
C 18	2.95	20.9	17	64.0	-11.9	18
C 25	3.24	13.1	18	76.2	-33.2	20
B 0	0.63	83.1	2	21.8	61.9	3
B 4	1.13	69.7	6	24.1	57.9	4
B 10	1.58	57.6	9	36.2	36.7	10
B 18	2.45	34.3	15	53.0	7.3	14
B 25	2.55	31.6	16	63.1	-10.3	17
D 0	0.50	86.6	1	19.2	66.4	1
D 4	1.13	69.7	4	19.3	66.3	2
D 10	1.13	69.7	5	30.0	47.6	8
D 18	2.10	43.7	13	44.3	22.6	11
D 25	2.25	41.0	14	51.5	10.0	13

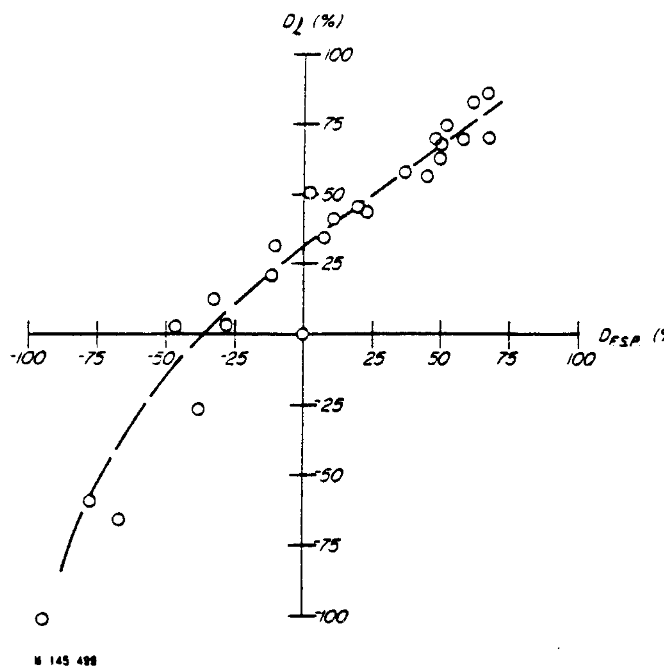
(a)
$$D_{\ell} = \frac{\Delta L_{HO} - \Delta L}{\Delta L_{HO}} \times 100$$

where L_{HO} refers to the linear dimensional change of paper coded H 0, the control.

(b)
$$D_{F.S.P.} = \frac{F.S.P._{HO} - F.S.P.}{F.S.P._{HO}} \times 100;$$

where $F.S.P._{HO}$ is the fiber saturation point of control H 0.

Figure 3: Correlation between linear dimensional stabilization (D_ℓ) and volumetric stabilization ($D_{F.S.P.}$) as measured by fiber saturation points.

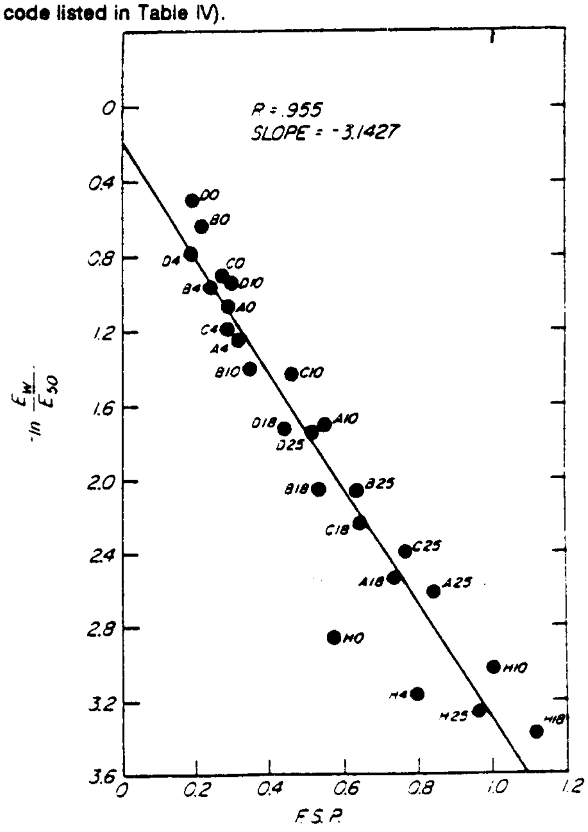


ment in wet modulus is greater than the improvement in dry modulus, and the ratio E_w/E_{50} increases with resin content. At any fixed resin content, the effect of increasing the concentration of alkali wash solution is both to increase the swelling and to decrease the tensile modulus of the paper. The swelling effect of sodium hydroxide is substantial in reducing the wet-stiffening effect of the phenolic resin. Figure 4 shows the tensile modulus ratio for all of the papers compared to their respective fiber saturation points. The correlation between wet-stiffness expressed as the ratio, E_w/E_{50}, and fiber saturation point is remarkable because all the different resin contents are included in the same plot. It appears that wet-stiffness depends upon resin content only in so far as the resin content is effective in reducing the cell wall swelling as measured by the fiber saturation point of the paper.

Cross-linking

Unlike the bulking type-agents, which afford dimensional stabilization by occupying space within the cell wall that water would occupy, cross-linking involves adding chemical covalent bonds within the cell wall polymers to provide swelling restraints that prevent access of water. Cross-linking, when applied to dimensional stabilization of paper, has a long history. The pioneering work using formaldehyde as the cross-linking agent was done by Stamm and coworkers at the Forest Products Laboratory in the late 1950's.(17) They showed that considerable improvements in both dimensional stabilization and wet-stiffness properties could be achieved by considerably less chemical add-on than is necessary with bulking types of treatments. Stamm(18) investigated the auto cross-linking that occurs on heat treatment of paper and he experimented with other aldehyde-type reactants as cross-

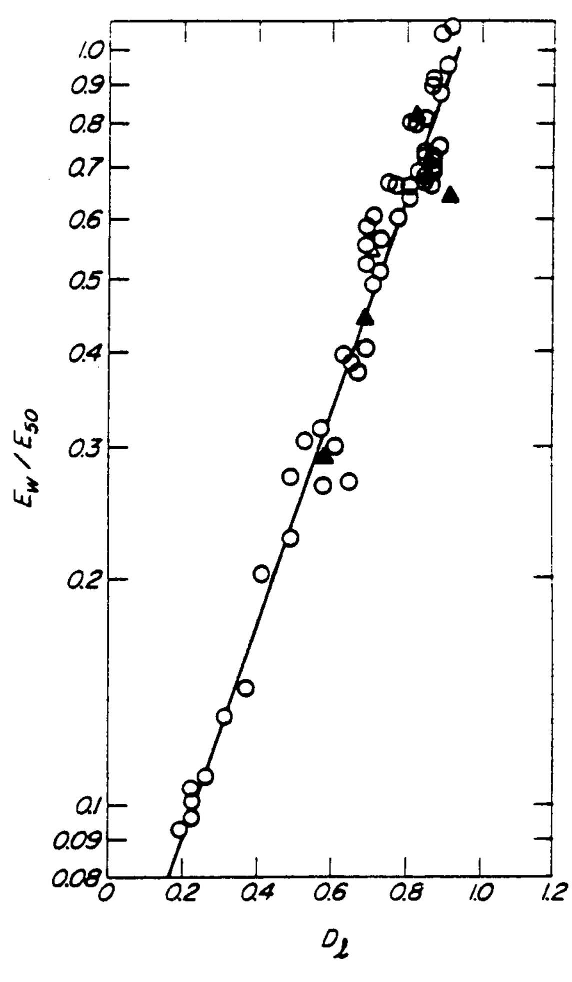
Figure 4: Natural logarithm of ratio (S_w/E_{50}) wet-to-dry tensile modulus as a function of fiber saturation point (F.S.P.). (Paper code listed in Table IV).



linking agents, but concluded that formaldehyde appeared to be the most effective.

Current research shows that formaldehyde cross-linking with sulfur dioxide as catalyst (SOFORM cross-linking) is an effective method to obtain both dimensional stability and good wet-stiffness.(19) The mechanism to achieve these improvements is well understood. The SOFORM cross-linking reaction is accomplished in a heated dehydrating environment following exposure of moist paper to formaldehyde and sulfur dioxide vapor. Moisture is necessary initially because it opens the vast internal structure of the cell wall and makes it accessible to the reactants. Dehydration is essential because only in the collapsed state are the internal cellulosic surfaces in close enough proximity so that effective cross-links are formed, and the state of swelling at the time of cross-linking determines the effectiveness of cross-linking. A wide range of cross-linking levels are possible by varying the concentration of the reactants, time, and temperature.

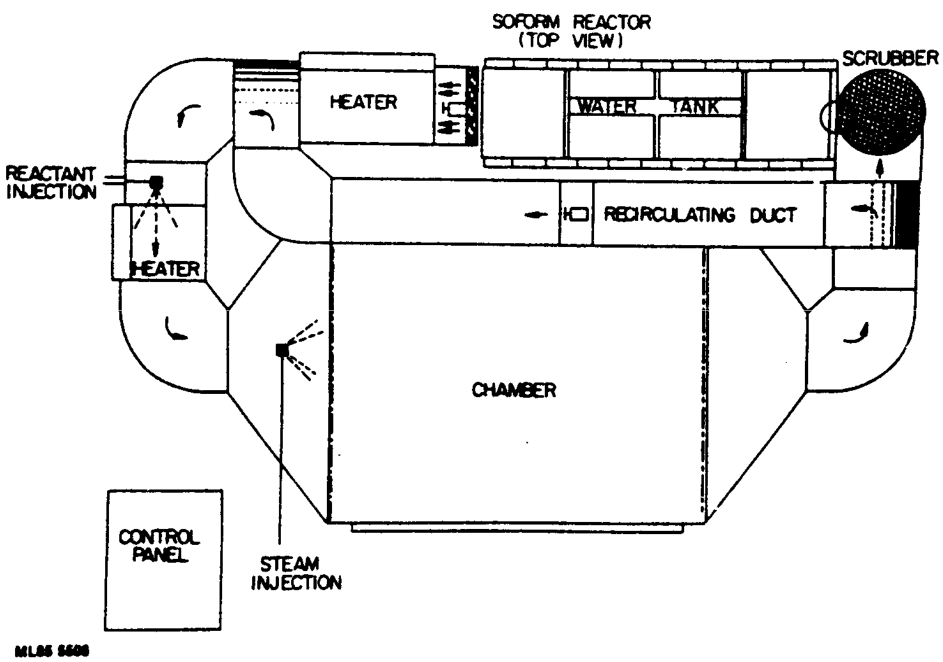
Figure 5: Relationship between tensile modulus ratio (E_w/E_{50}) and linear dimensional stability (D_ℓ) of cross-linked papers.



In Figure 5, the wet-to-dry tensile modulus ratio for several cross-linked papers is plotted as a funtion of dimensional stability. In this plot, a value of unity for both coordinates corresponds to a paper that does not swell upon wetting, and one whose wet tensile modulus equals its dry tensile modulus. Thus, exceptionally high levels of both dimensional stabilty and wet-stiffness are possible through cross-linking. These results also indicate that the same cross-links that are effective in providing dimensional stability are those that contribute to the wet-stiffening of paper. Effective cross-links are those between cellulose surfaces, surfaces that would ordinarily separate on wetting, if it were not for the swelling restraint that the cross-links afford. Unlike the mechanism of stiffening in cross-linked rubbers, the additional load-bearing capacity provided by the additional covalent bond is not responsible for the high wet-stiffness of cross-linked paper. Rather, cross-links function as swelling restraints to the cell wall polymer network so that a larger fraction of the preexisting hydrogen bonds can still function to retain a larger fraction of the dry tensile modulus of the paper.

Based on an understanding of the mechanism by which vapor phase cross-linking imparts dimensional stability and wet-stiffness to paper, we have constructed a large-scale SOFORM reactor (Figure 6) that we have been using to learn something about the difficulties and potentialities of cross-linking large 4 ft by 8 ft(l.2 m by 2.4 m) panels of heavy-weight double-

Figure 6: Schematic of SOFORM reactor.



wall corrugated board.(21) With this reactor, it is possible to prepare boards with promising dimensional stabilities and wet-stiffnesses. At a bound formaldehyde content of about 1.5 percent by weight, cross-linked boards show a reduction in swelling of about 70 percent, and exhibit wet-compressive strengths and wet-bending stiffnesses that are 50 percent of the dry values.

Conclusion

In discussing the dimensional stability of paper, I have attempted to show that a certain measure of control of dimensional stability can be achieved using conventional papermaking practices. However, these conventional methods rely largely on affecting how the swelling of the cell wall is transmitted through the paper's structure of fibers, voids, and interfiber bonds. These conventional methods are rather limited in their effectiveness, because they do not tackle the root cause of paper's inherent dimensional instability, the swelling and instability of the fiber cell wall. If, on the other hand, dimensional stability of paper is modified by changing the swelling of the cell wall, greater levels of control can be achieved. An additional benefit may also result in terms of increased wet-stiffness. Additional research is needed in this area, because dimensional instability not only reduces paper and paperboard performance in printing and packaging applications, but the dual problems of dimensional instability and poor wet-stiffness of paper and paperboard limits their acceptance as engineered materials of construction.

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Q: I was wondering about the fiber saturation points. They seemed extremely high for the papers. Is that because of lack of restraint? They are much higher than for wood.

A: It doesn't seem to be unusual for papers to have considerably higher fiber saturation points, especially when you consider that a non-dried pulp fiber can have a fiber saturation point of 300 percent.

Q: How long does the Soform process take to complete a reaction?

A: It depends. If you start with a moist sheet of paper, a single sheet of paper, then you can do that in 20 seconds. Just expose it to formaldehyde vapors and $(S0)_2$. But in our chamber we have to humidify the paper to 92 percent relative humidity. That takes a long time.