DIMENSIONAL STABILITY NOTES

Charles Green, 23 Maryvale Drive, Webster NY 14580 (VER 2) techman@papercurl.com & http://www.PaperCurl.com

ABSTRACT. *This article attempts to discuss various aspects of dimensional stability that may be important to its understanding and application:*

1. *A basic measurement of dimensional stability is coefficient of moisture expansion or* ***CME****, in terms of % change in dimension/% change in moisture.*

2. *CME of paper correlates with a measurement called* ***wet expansion****, measured by wetting the sheet. Wet expansion is the same as (or very nearly so) its drying shrinkage in manufacture.*

3. *A more complete description of dimensional stability characteristics of a sheet can be obtained by wetting a manufactured paper, measuring its wet expansion, then free drying the paper, and measuring the* ***total shrinkage****. The difference between total shrinkage and wet expansion is* ***net shrinkage*** *(a "recovered shrinkage), also called* ***internal strain****.*

4. *Total shrinkage is a measure of how much the sheet could shrink, if it were free dried, and is the sum of wet expansion and internal strain. Each variable is important. A reduction in total shrinkage can also reduce wet expansion (therefore CME) and internal strain.*

5. ***Internal strain*** *is important because it manifests itself when paper is exposed to high RH and/or high temperature. It shows up as non-reversible shrinkage. It often occurs on one surface more than the other thereby causing curl in printing processes like offset and xerography.*

6. *Lowering drying shrinkage (and, therefore, lower wet expansion) increases tensile stiffness index and breaking length, while decreasing breaking strain and CME. For fine papers the relationships measured were as follows:*

   (specific elastic modulus, km) x CME = 33 (± 20%)
   (breaking length, km) x CME = 0.3 (± 20%)
   (% breaking strain) = 31 x CME (± 30%)

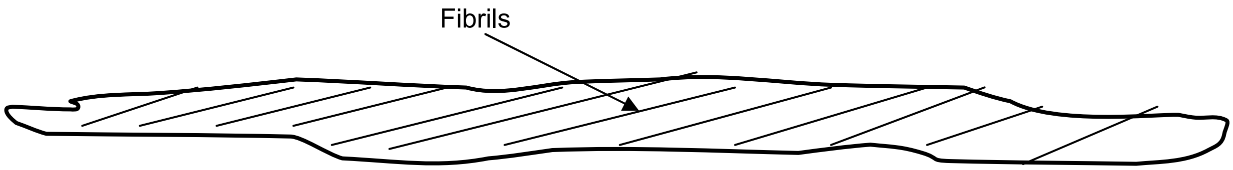
7. *CME improvements are possible by using pulps with lower free dried CME (or wet expansion). Maximizing drying restraint minimizes CME but maximizes the effects of internal strain. Therefore a balance has to be made between the two properties.*

TYPICAL VALUES (of dimensional changes)

	MD	CD
THERMAL %/1OO DEG. C.	0.04-0.07	O.O8-.16
MOISTURE %/% AS MADE	0.03-.06	0.07-. 17
FREE DRIED	0.05-.07	0.08-.19
WET EXPANSION, 50%RH TO WET, %	-0.1- 1.05	1.0-2.9
TOTAL CONTRACTION, WET - 5O% RH, %	0.6-1.05	2-3.7
NET SHRINKAGE, %	0.6-1.1	0.3-1.23

An important aspect of dimensional stability is effect of fiber properties and how they dry in paper. Fibers have drying contraction of 20 to 1 or more width to length (fig. 1). When fibers dry in a sheet, they bond at the crossings. The shrinkage in fiber width of one shortens the length of another by crimping or micro-compressing at the bond (fig 2). The amount of sheet shrinkage is directly related to this fiber shrinkage. Sheet shrinkage in manufacture is an important factor in sheet dimensional changes from changes in moisture.

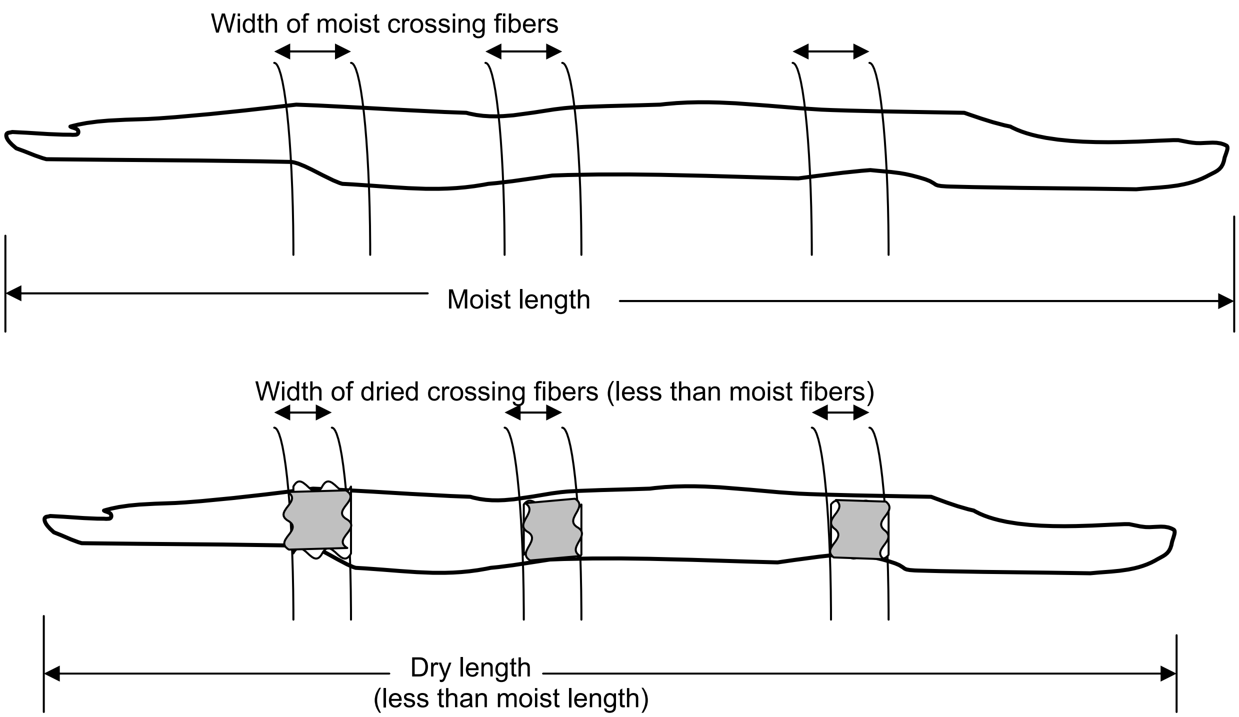
Figure 1. DIAGRAM OF FIBER



Fibrils are usually aligned 5-30 degrees to the fiber axis

Effects: higher longitudinal strength
higher radial moisture expansion

Figure 2. FIBER SHRINKAGE PRODUCED BY SHRINKAGE AT THE CROSSINGS



Gray areas represent shrinkage and crimping of the fiber(s), i.e. the formation of micro-compressions.

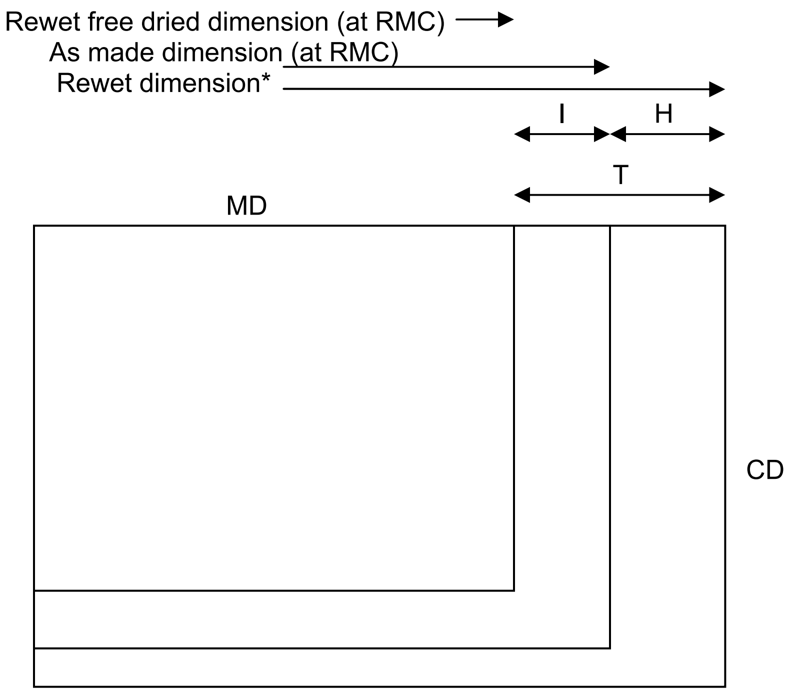
Changes in the cross direction are practically always higher than the machine direction. Typical coefficient of moisture expansions (**CME**) (% per % moisture change) are *0.03-0.06% (machine direction) and 0.07-0.17% (cross direction).* These numbers are normally valid in the 0-65% RH range, because the measurement is reversible here, i.e. your results are the same whether moisture is going up or down. CME (a reversible property) is used to define dimensional stability rather than relative humidity, because there is no hysteresis when moisture changes are used. We may note that in moisture changes in one direction, a 10% RH change approximates 1% change in moisture. Above 80% RH it is more difficult to measure CME as a reversible since we begin to see the effect of irreversible changes.

Reversible dimensional stability can also be measured as wet expansion from some standard **RMC** (reference moisture content) to completely wet. This measurement correlates with CME. Typical wet expansions are *-0.1-0.15% (machine direction) and 1.0-2.9% (cross direction) for machine made paper.* (note: RMC is chosen, but can conveniently be the moisture content at 50% RH, i.e. about 6%)

DRYING AND WETTING PAPER

When paper is dried without constraints, the result is called ***free dried shrinkage***. Typically paper made on a machine is dried with some restraint of shrinkage. The amount of shrinkage varies with how much restraint is applied, such as by drier felt tensions and draw tensions. Fig. 3a is a diagram (not to scale) of relationships between wetting expansion and drying shrinkage (note that drying shrinkage and dimensional change by wetting are approximately equal, depending on extent of shrinkage).

Figure 3a. Machine dried paper dimensional diagram



H = wet expansion (when rewet)
I = net shrinkage or **internal strain** (of rewet free dried sheet)
T = total free dried shrinkage (after being rewet)

Typically the following variations can be observed on machine made papers:

Table 1

	(H) Wet expansion	(T) Total Shrinkage	(I) Internal Strain
MD	-0.1 to 0.15%	0.6 to 1.05%	0.6 to 1.1%
CD	1.0 to 2.9%	2.0 to 3.7%	0.3% to 1.23%

The relationship between T, H and I (as defined in fig. 3a) can be written,

$$T = H + I \quad [1a]$$

First, we see that the T, the total free dried shrinkage after wetting remained the same, for the purposes of this model. Then, from [1a] we can see that when there is less shrinkage) i.e. "I" (internal strain) is increased, there is a reduction in how much H (wet expansion) is left.

Fig 3b depicts relationships when paper dimensions are obtainable by free drying paper that has not been originally dried with restraint of shrinkage. Part of the internal strain component is a plastic strain (P) and non-recoverable. For a sheet dried with restraint, then rewet and dried, total shrinkage is somewhat less (about 1.5%) than if free dried from original wet state:

$$T_o = H + I + P \qquad [1b]$$

Some typical data in which free drying without previous drying with restraint can be seen in table 2.

Table 2. Shrinkage data for trial runs

Machine Direction

	Wet expansion (%)		Shrinkage (%)				
Run no.	MFG (H)	Fdry (To)	MFG (T)	Fdry (To')	I (recov)	P (plastic)	P'
1	-0.35	2.42	0.73	2.72	1.08	1.69	1.99
2	-0.39	2.16	0.79	2.43	1.18	1.37	1.64
3	0.26	2.15	1.3	2.39	1.04	0.85	1.09
4	0.5	2.08	1.23	2.28	0.73	0.85	1.05
5	0.52	3.03	1.58	3.48	1.06	1.45	1.9
6	0.69	2.78	1.81	3.23	1.12	0.97	1.42
7	0.49	2.44	1.51	2.75	1.02	0.93	1.24
8	0.35	2.37	1.09	2.8	0.74	1.28	1.71

Cross Direction

	Wet expansion (%)		Shrinkage (%)				
Run no.	MFG (H)	Fdry (T_o)	MFG (T)	Fdry (T_o')	I (recov)	P (plastic)	P'
1	2.13	4.61	3.39	4.99	1.26	1.22	1.60
2	2.75	4.89	3.89	5.34	1.14	1.00	1.45
3	2.22	4.70	3.35	5.02	1.13	1.35	1.67
4	2.85	4.58	3.86	5.01	1.01	0.72	1.15
5	3.13	6.03	4.68	6.78	1.55	1.35	2.10
6	3.90	5.64	5.17	6.07	1.27	0.47	.90
7	3.12	5.64	4.62	6.44	1.50	1.02	1.82
8	3.13	5.55	4.42	6.20	1.29	1.13	1.78

MFG = paper made and dried on laboratory paper machine
Fdry = paper taken after wet presses and freely dried
T_o,T,H,I,P symbols in equations [1,2]
T_0', P' (see text for discussion)

Run 1-4: 500 Canadian Std. Freeness
Run 5-8: 325 Canadian Std. Freeness
Runs 2,3,6,7: filler content about 17%
Runs 2,4,7,8: have wet end addition of 2% cationic starch

Figure 3b Free dried paper dimensional diagram

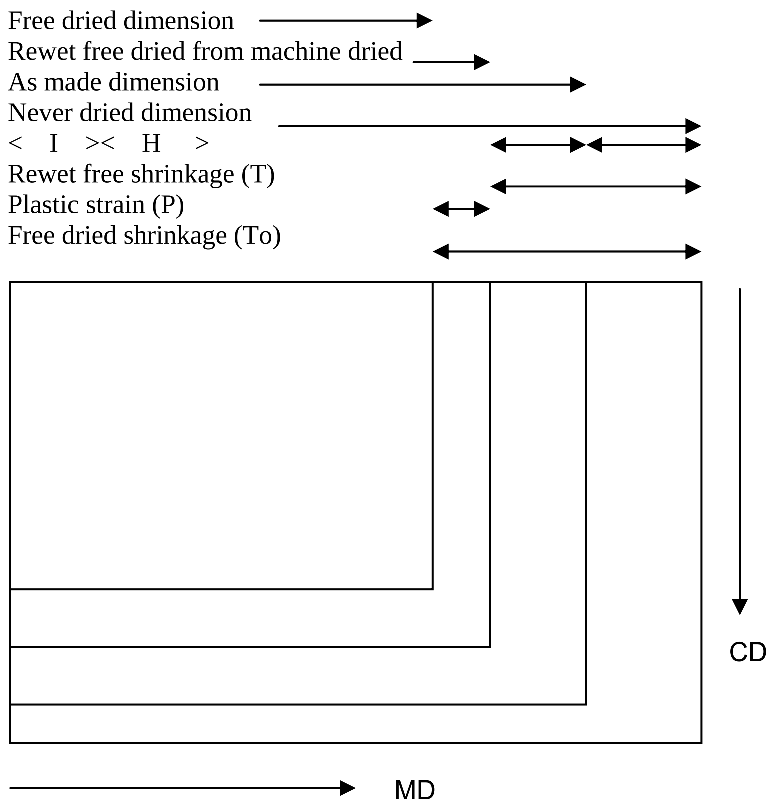
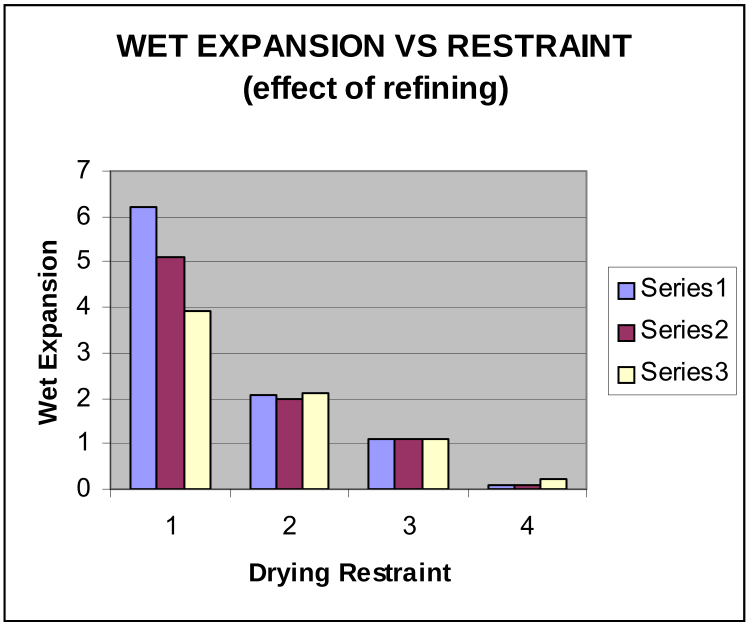


Fig. 4-5 (redrawn) are data from the literature (D. Fahey & W. A. Chilson, Tappi 46(7) 393-399 (1963)) which show the effect of refining, type of fiber and drying shrinkage on expansion on wetting. We can readily see that, except for unrestrained drying, rewet expansion is essentially controlled by the amount of drying shrinkage that is allowed.

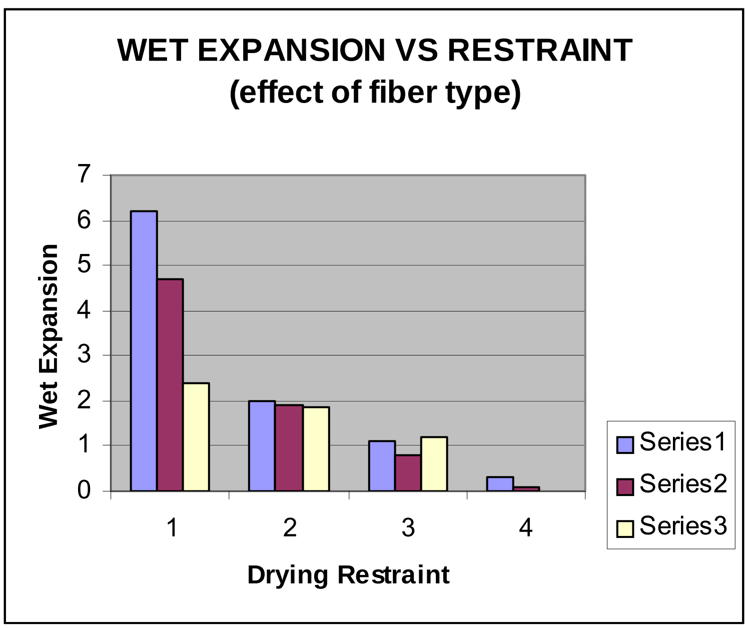
Figure 4. Wet Expansion vs. Restraint (effect of refining)



Series 1 - refined to 300 CSF Series 2 - refined to 500 CSF Series 3 - refined to 700 CSF

Drying restraint 1 - unrestrained
2 - 2% shrinkage allowed
3 - full restraint
4 - 3% stretched, full restraint

Figure 5. Wet Expansion vs. Restraint (effect of fiber type)



Series 1 - Southern Pine Kraft (300 CSF)   2 - Western Softwood Kraft (330 CSF)
3 - Spruce Groundwood (300 CSF)

Drying restraint 1 - 4 Same as figure 4

And as stated earlier, there is a correlation between CME and H, and it is such that

$$CME = H/(FSMC - RMC) \qquad [2]$$

We can also write [2] in terms of changes in CME and H

$$\Delta CME = \Delta H/(FSMC - RMC) \qquad [3]$$

Using this, we can estimate how much CME will increase by wetting and free drying. For 1% internal strain, and an FSMC of 30% and the RMC is 6% ,

$$\Delta CME = 1(30 - 6) = 1/24 = 0.04\% \qquad [3a]$$

Wetting and free drying paper increases the CME this order of magnitude. Actual increases will depend on the amount of internal strain that is recovered and FSMC and RMC.

SOME IMPORTANT RELATIONSHIPS

We can see from [1,2] that by controlling or adjusting the amount of shrinkage when paper is dried, wet expansion being (essentially) drying shrinkage, we also can change things like CME. How much paper shrinks also affects mechanical properties. ***Any decrease in drying shrinkage, and therefore an increase in dry dimensions, increases tensile stiffness index, breaking length, and decreases breaking strain and CME*** (and vice versa).

Also, it may important to know that a change in dry dimensions can occur after manufacture. When a tensile load is applied, and particularly when the paper's moisture and/or temperature is in transition, we can increase dry dimensions, and change properties as described above. Of course, the increase in dry dimensions decreases wet expansion and CME. Tensile loading pulls out the micro-compressed sections. For example, paper was loaded in tension in a "creep" experiment and results were obtained shown in fig. 6. The "creep" is the increase in dry dimensions of the paper. We see that CME decreases as dry dimensions are increased.

On the other hand, if we expose paper to high RH and/or temperature without any applied load, and the paper is returned to it RMC, we observe a net shrinkage. Some of the internal strain has been turned into drying shrinkage by the process. ***From this process we observe a lower tensile stiffness index, lower breaking length, higher breaking strain and CME.***

An example of how to each other are shown in fig. 7-9, which display the relationship between various paper properties of xerographic "bond" papers manufactured on 16 different machines in 10 mills. Fiber furnishes include northern and southern softwoods, sulfite and kraft pulps and a variation in hardwood and softwood percentages. Test results also include rewet samples.

Figure 6. CME versus creep

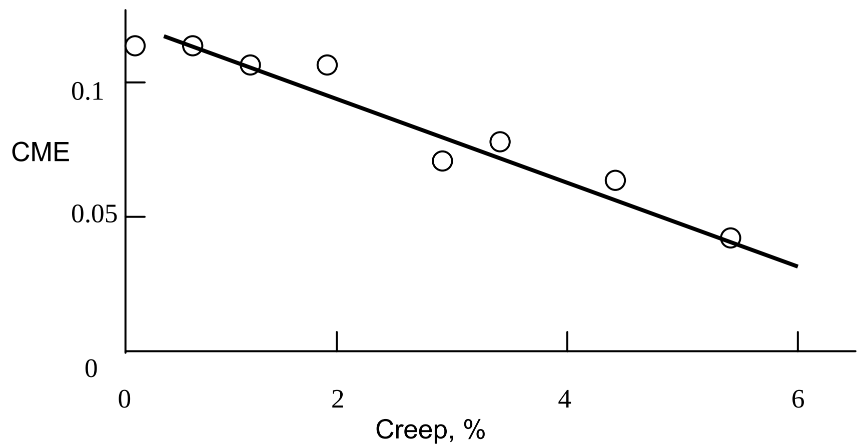
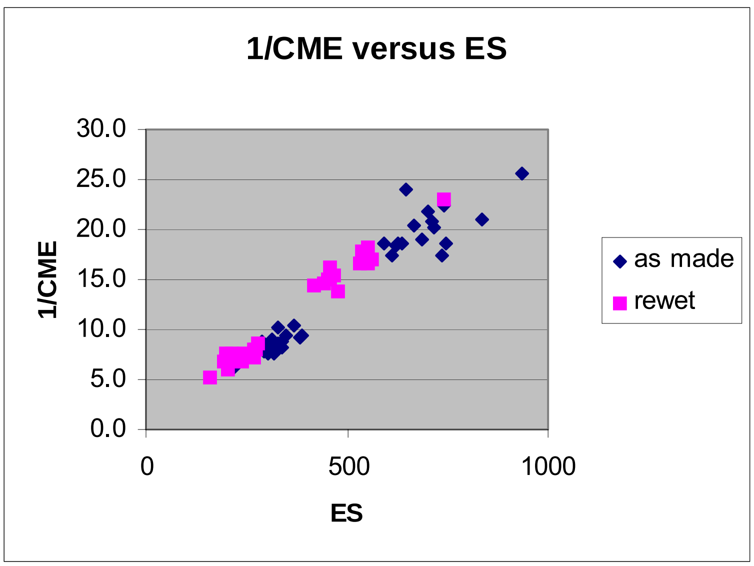
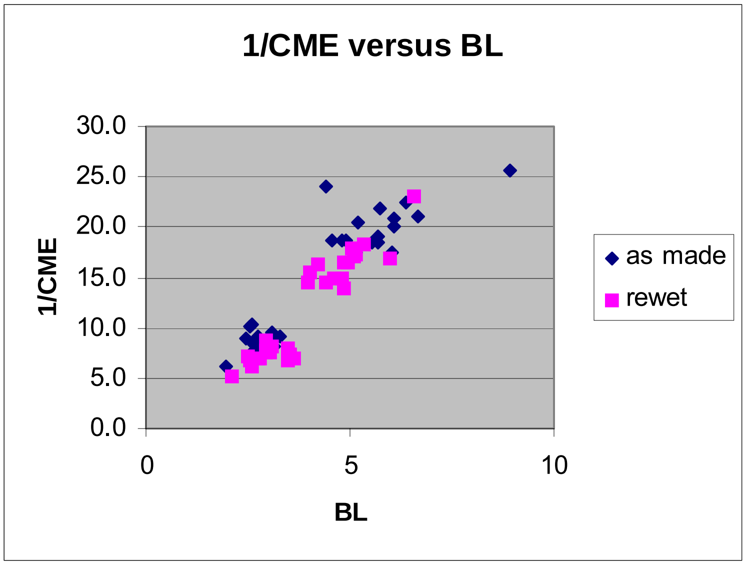


Figure 7. CME versus ES



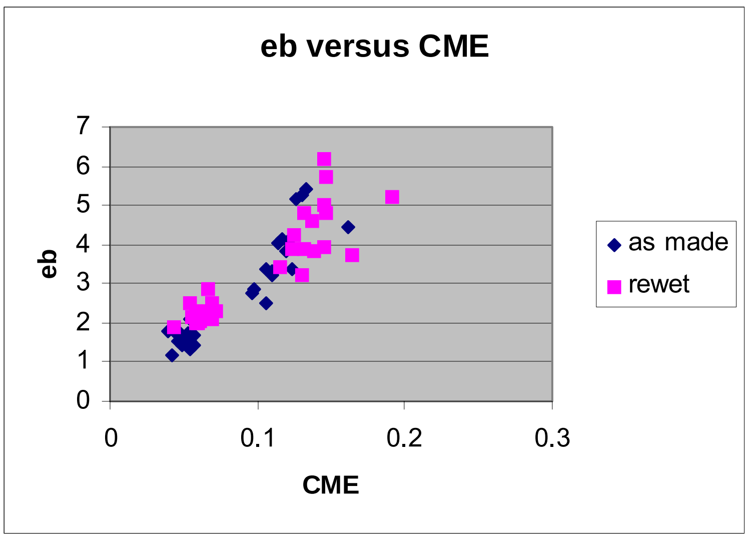
ES is specific elastic modulus in km.

Figure 8. CME versus BL



BL is breaking length in km.

Figure 9. eb versus CME



eb is % breaking strain

IMPROVING DIMENSIONAL STABILITY

Some actions we can take include choosing pulps with lower inherent CME (or wet expansion) and reducing refining. The objective is to reduce the inherent moisture expansion as much as possible. ***To measure the effect of pulp and furnish on CME with any reasonable degree of precision with handsheets, it is necessary to dry them without restraining shrinkage*.** After handsheets are removed from the mould using blotters. Then the sheets are separated from the blotters and dried without constraining shrinkage. After drying, strips cut from the handsheets are used to measure CME or wet expansion characteristics.

Wet expansion of pulp handsheets, such as those listed below, is an indication of the variation in wet shrinkage adjustment that could be made by choice of pulp (table 3).

Table 3 Wet expansion of free dried handsheets of pulps

PULP	WET EXPANSION,%
Douglas-fir kraft	4.1
Southern pine kraft	5.2, 4.8
Sweetgum kraft	4.3
Western hemlock sulfite	4.1, 3.7
Eastern softwood sulfite	2.7
Mixed hardwood NSSC	2.1 (450 csf)
Aspen cold soda	4.7 (320 csf)
Spruce groundwood	2.4 (100 csf)
Manila tab cards	2.5 (560 csf)

notes: second value is unbleached pulp; all values at or near 500 csf except where noted.

Refining increases wet expansion of free dried handsheets (example, table 4)(southern pine kraft)

Table 4 Effect of refining on wet expansion of free dried handsheets

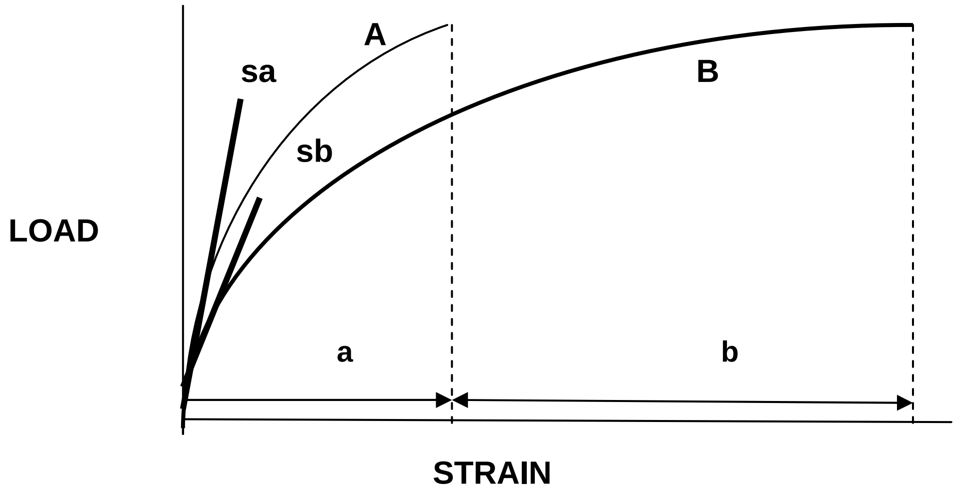
FREENESS	WET EXPANSION, %
700	3.9
600	4.7
500	5.2
420	5.3
300	6.3

.

By maximizing drying restraint we can minimize CME. However, now internal strain (I), is at a maximum. On the other hand, minimizing drying restraint reduces internal strain but increases CME. Also, by allowing too much shrinkage, cockles can form. An optimum balance between internal strain and CME is desirable. Internal strain becomes an undesirable property when paper is subjected to high RH, wetting, and/or heating. These conditions help release internal strain. For example, wetting one surface of a sheet, such as in offset printing, will cause that surface to shrink irreversibly on drying, causing curl toward that surface. Curl in copy machines may also be a result of internal strain release under some conditions.

APPENDIX A: Some additional topics

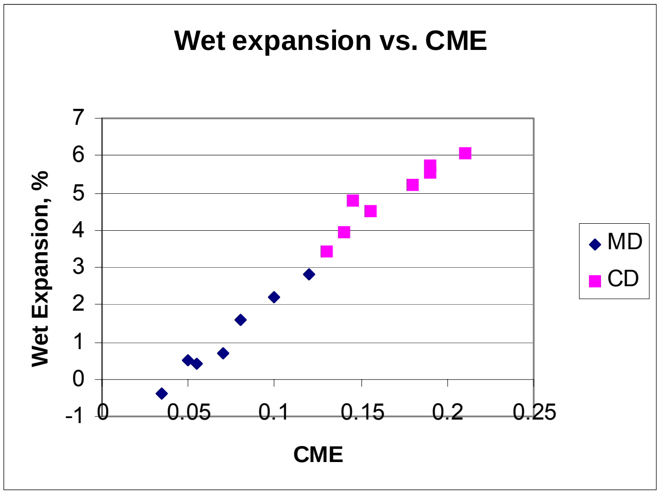
Figure 10. Load-Elongation Vs. Drying Shrinkage



CURVE A - low drying shrinkage
CURVE B - high drying shrinkage

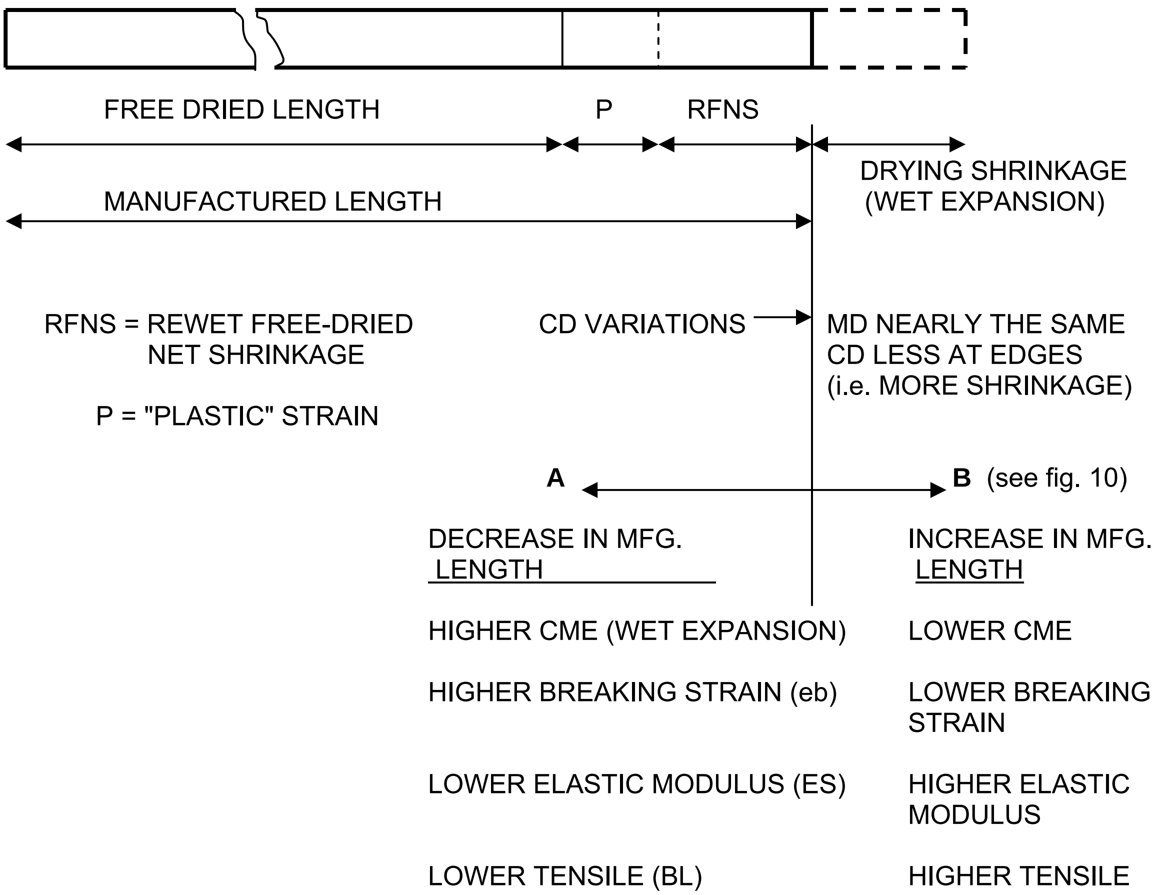
"**a**" = strain to break of "low shrinkage" paper
"**b**" = additional strain to break, "equal" to additional drying shrinkage
"**sa**" = higher slope, modulus of elasticity
"**sb**" = lower slope, modulus of elasticity

Figure 11



Appendix B. PROPERTY RELATIONSHIPS DIAGRAM

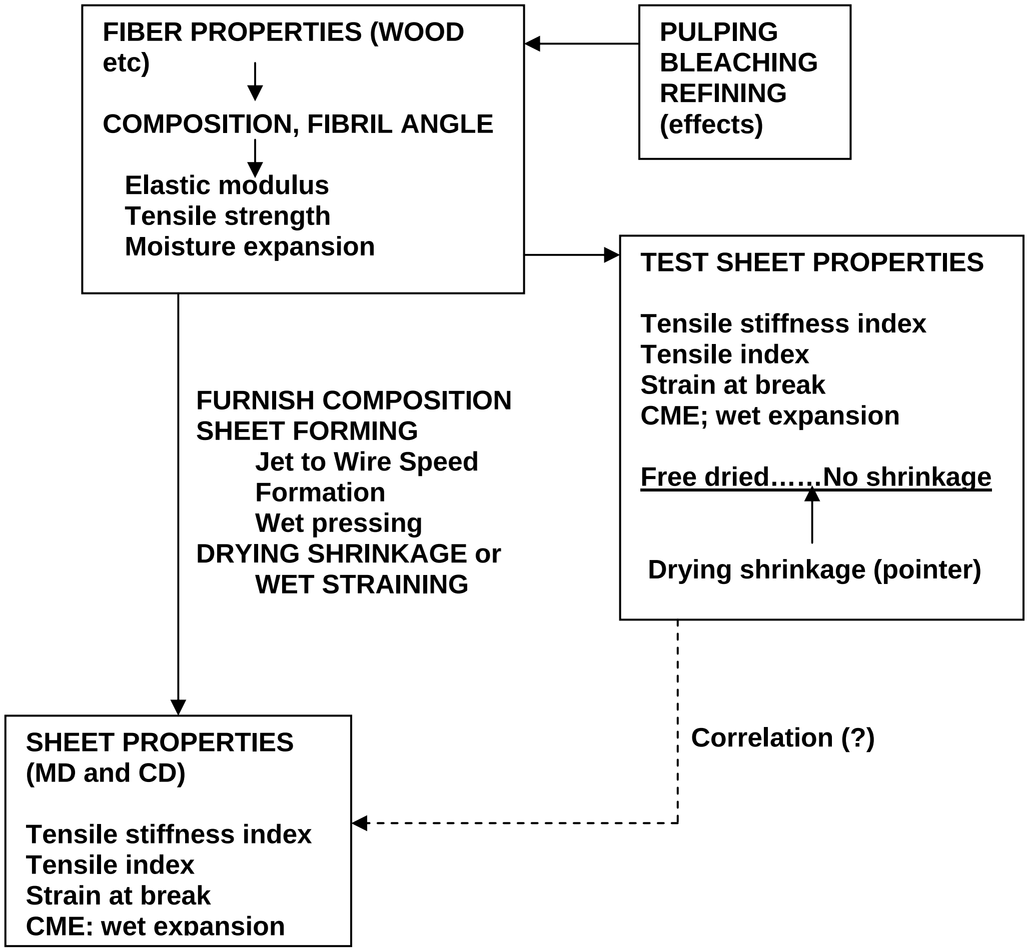
Charles Green, 23 Maryvale Drive, Webster, NY 14580



eb APPROXIMATELY = WET EXPANSION + 1.5

Appendix C. BASIC OUTLINE OF PAPERMAKING PROCESS

Charles Green, 23 Maryvale Drive, Webster NY 14580



Appendix D SHEET DIMENSIONING DEVICE AND METHOD (v3)

INTRODUCTION – the device described here can be used in place of a Quick Scan, if one is not available. It is not as versatile but it can be used to measure changes in sheet dimensions with reasonable accuracy and proficiency. These instructions are for 8.5 x 11 inch paper, but can be modified to accommodate A4 and other sizes.

THE EQUIPMENT – (1) Place a sheet of 11 x 17 inch graph paper (with grids of 0.25 inch or less) on a flat surface, with the 17 inch dimension horizontal. Taping it in place may be desirable. If the graph paper is placed on a board or rigid plastic, it can be moved between various locations. This would be desirable, so that measurements can be made in places with different humidity conditions (2) Draw a reference line 1-2 inches from the bottom edge. (3) In the middle of the paper draw a "normal" line perpendicular to the two lines and draw a tick mark 11 inches from the bottom line, also place a tick mark at 8.5 inches. (4) Through each of these points on the vertical line where the tick mark crosses it draw a line with a pitch of 0.5 inches per 20 inches, 10 inches to the right and left of the tick mark. (5) Mark off 0.5 inch increments on the line (using the graph paper increments). (6) Tape a clear plastic ruler (approximately 12 inches long) on the reference line. See figure 1.

THE PROCEDURE – (1) Place a tick mark in the middle of the top edge of the sheet to be measured. (2) Place the sheet on the board and move it left or right until the sheet crosses the pitched line near the tick mark. (3) Determine the paper dimension as follows: Read the number of inches from the vertical reference at least to the nearest 0.25 inches where the paper crosses the pitched line. Multiply this by 0.025 and add or subtract this from the "nominal" length (8.5 or 11 inches) to obtain sheet dimension. See figure 2.

EXAMPLE – A sheet crosses the pitched line at 0.75 inches to the right of the vertical reference on a 11 inch sheet. The sheet dimension is 11 + (0.75)(0.025) or 11.019 inches.

DIMENSIONAL CHANGES – The procedure is best used for measuring changes in dimensions to measure dimensional stability. To avoid errors, it would be best to record only the point at which the sheet crosses the line at each (humidity) condition and find the difference between the two. Example – at condition one, the sheet crosses the line at 0.75 inches to the right of the vertical reference. At condition two, the sheet crosses at 0.5 inches to the left. To calculate the difference, we have (0.75) – (-05) = 1.25. The change in sheet dimension is 1.25 x 0.025 or 0.031 inches. To calculate percent change, divide by sheet dimension and multiply by 100 (or multiply by 11.8 for an 8.5 inch dimension or 9.1 for an 11 inch dimension)

INTERNAL STRAIN MEASUREMENT - To measure internal strain, a sheet is first divided in half. The center of each sheet is marked. Measurement of both of the sheet's relative length compared to the standard length is recorded. One sheet is wet with water (a solution of 5% isopropyl alcohol in water can be used to speed up the wetting). The sheet is dried flat without constraining shrinkage. After drying, both sheets are placed in an oven at 90 degrees C. for 5 minutes. The sheets are then conditioned at ambient for 15 minutes. The relative length of each sheet is measured. The percent sheet shrinkage is calculated. If the sheet that has not been wet (control) did not change dimensions, then the shrinkage is calculated from the difference in length between the dry dimensions before and after wetting of the sheet that has been wet. Adjustment in this difference is made using the change in dimensions of the control sheet. If it shrinks between original and final measurement, the difference is added. If the dimensions increase, it is subtracted. The oven drying is to remove the effect of hysteresis caused by wetting. The adjustment of shrinkage using the control sheet allows for changes in relative humidity between initial and final measurements and possible hysteresis. If measurements are done in a controlled humidity, corrections may not be necessary, if there is no hysteresis in the original sheet. The splitting of a sheet in half is to make measurements on the same sheet and thereby eliminate errors introduced by using more than one sheet. Internal strain should be measured on several successive sheets from a ream to obtain an average result.

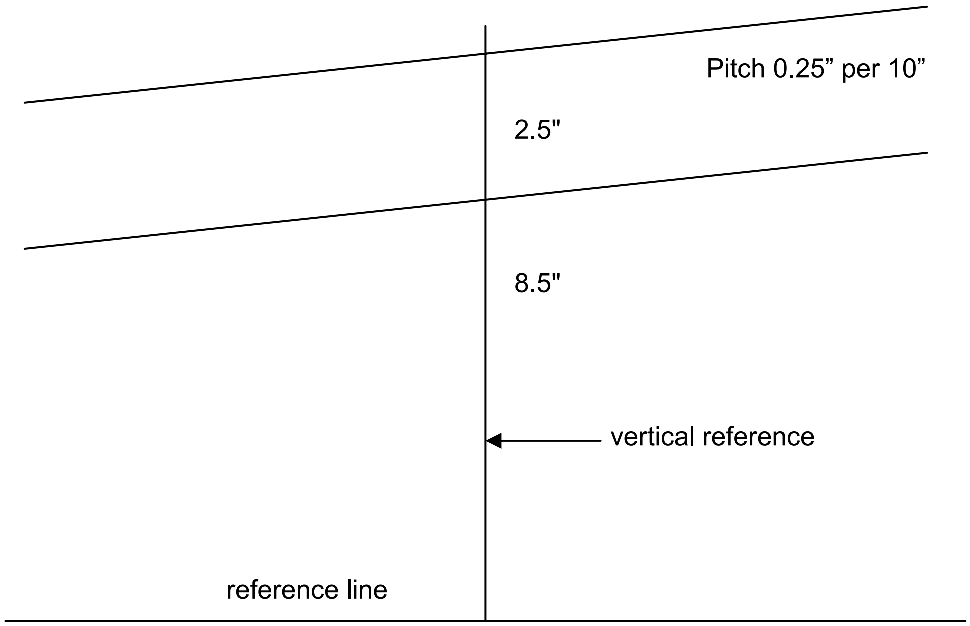


Figure 1. schematic layout

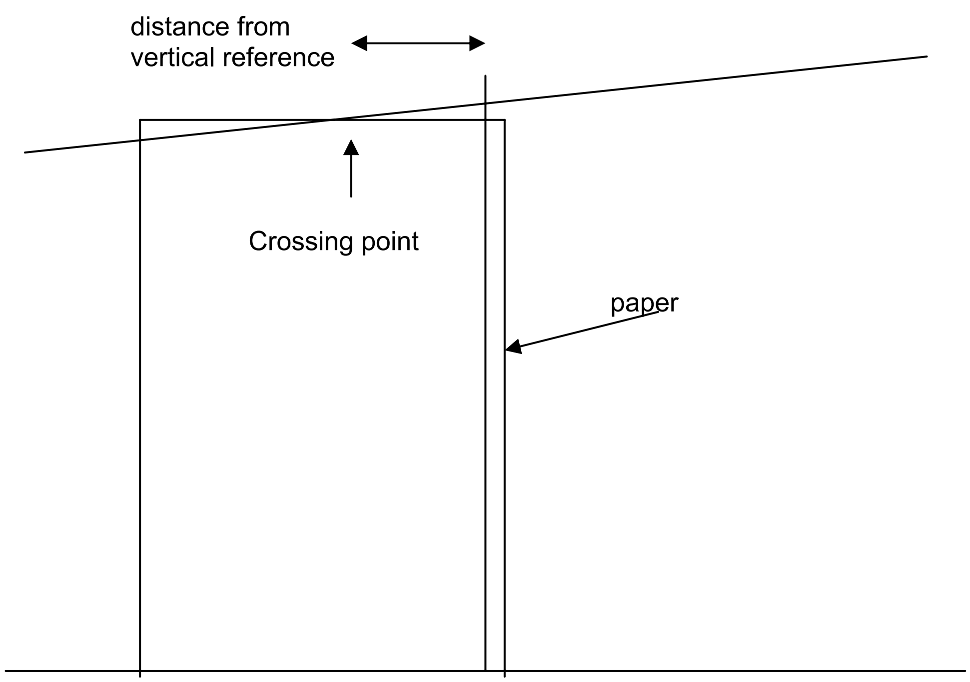


Figure 2. measuring the paper

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