Effect of papermaking variables on formation

John F. Waterhouse

ABSTRACT: The influence of papermaking variables on sheet formation was examined using a formation tester capable of measuring optical density and mass density. Formation was measured in terms of CV(W), the coefficient of variation for mass density. CV(W) was found to be inversely proportional to the square root of grammage, as predicted by theory. Flocculation adversely affected formation. Fiber orientation did not adversely affect formation for well-formed handsheets (i.e., those produced on a Formette Dynamique sheet former). Formation of these handsheets was improved through sheet densification achieved by refining and wet pressing.

KEYWORDS: Additives, basis weight, consistency, flocculation, formation, formation testers, handsheets, mass, density measurement, optical density, papermaking, variability.

Efforts to improve the quality of paper and board products are stimulating renewed interest in the topic of sheet formation. This report examines the impact of several papermaking variables on sheet formation. Results were obtained using a formation tester capable of measuring both optical density and mass density.

In many respects, sheet formation remains a confusing topic. This is due in part to the fact that there is no universally accepted definition of formation, although Dodson *(1)* has proposed the coefficient of variation of mass density, CV(*W*), as a universal measure of formation. Furthermore, sensor manufacturers have developed a variety of indexes to measure formation.

There are also problems in relating formation measurements directly to the converting and end-use performance of paper. The relationships in this new field of study can be quite complex, but it is imperative to recognize that variables other than formation may be involved. For example, we can show that sheet strength is dependent on formation, but there have been very few systematic studies *(2)* involving other variables controlling strength, such as fiber geometry, interfiber bonding, and grammage.

Life would be much simpler with one universally accepted measure of formation, particularly the CV(*W*) parameter suggested by Dodson *(1)*. The CV(*W*) parameter has merit and should be explored more thoroughly. However, as Cresson *(3)* and others have pointed out, papers with identical CV(*W*) can have very different texture or pattern features, such as floc size distributions. It might be useful to fingerprint a piece of paper with respect to its manufacturing process, i.e., twin wire, high-turbulence headbox, etc. Texture- or pattern-recognition techniques might be a realistic approach to this goal. Norman *(4)* has used the spectral density distribution toward satisfying this goal. Nevertheless, we still have to demonstrate how these additional measures of formation might be related to converting and end-use performance of paper, such as coating and printing.

The early work of Corte and Dodson *(5)* and Herdman *(6)*—and Dodson's more recent work *(1)*—has shown that the coefficient of variation of mass density, CV(*W*), of an ideal random network of fibers is related to a fiber-length parameter *k*, fiber coarseness *C*, and average sheet grammage *W* as follows:

$$CV(W) = \sigma(W)/W = (k \times C/W)^{1/2} \qquad (1)$$

where σ represents standard deviation.

It is perhaps surprising that Eq. 1 has not yet been completely verified. However, verification is not a trivial matter, since it is difficult to maintain

Waterhouse is a senior associate scientist at the Institute of Paper Science and Technology, 575 14th St. NW, P.O. Box 93366, Atlanta, GA 30318-3366.

constant forming conditions while changing the parameters contained in Eq. 1. Seth *(2)* has demonstrated that a formation index based on light transmission is proportional to the square root of fiber coarseness, i.e., the weight per unit length of fiber.

One useful feature of Eq. 1, which indicates that formation should improve with increasing grammage or basis weight, is that formation measurements made on sheets of different grammage can be compared. However, in practice, sheet basis weight is increased by increasing headbox consistency, and this usually has a negative impact on sheet formation.

Dodson and Fekih *(7)* modified Eq. 1 to account for fiber orientation. They predicted that formation, i.e., CV(W), would deteriorate with increasing fiber orientation. This result appears to be true for fourdrinier-made papers, as demonstrated by Svensson and Osterberg *(8)*. However, it seems counter-intuitive, since more uniform coverage might be expected with increased fiber orientation. More recently, Schaffnit *(9)* showed that formation is essentially independent of fiber orientation for an ideal nonrandom network of fibers.

The improvement of formation through network consolidation has also been considered by Dodson *(10)*. Using basically his approach, it can be shown that formation CV$(W)_{total}$, as a function of fiber network and network consolidation, is given by

$$CV(W)_{total} = [CV(W)]^2 + [lw/(l-\varepsilon)x^2] \quad (2)$$

where

l = fiber length

w = fiber width

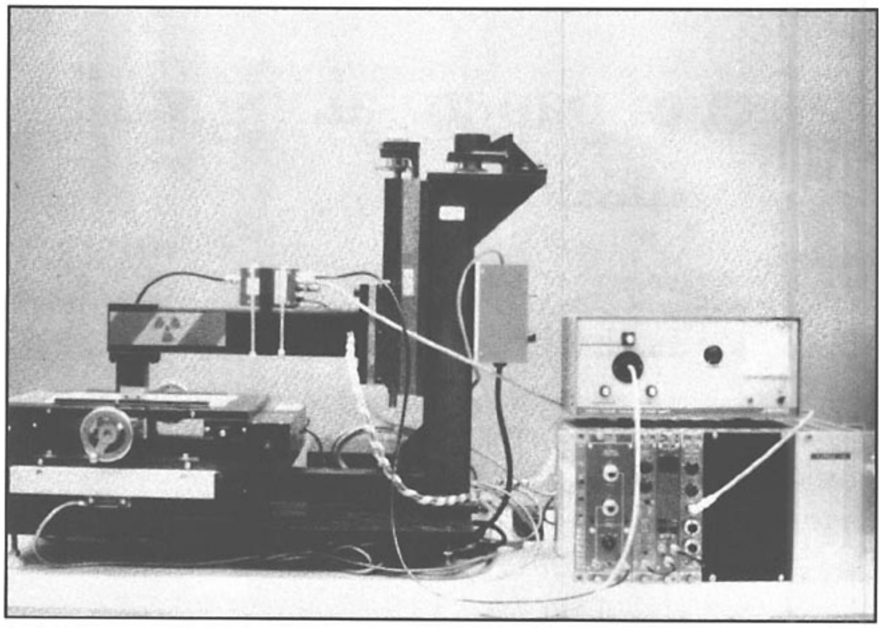
ε = sheet porosity

x^2 = aperture area.

The second term in Eq. 2 is the contribution from network consolidation.

In the results that follow, we will briefly examine the influence of refining, forming consistency, fiber orientation, and the combined effect of refining and wet pressing with regard to Eqs. 1 and 2.

1. IPST formation tester



Experimental

Handsheets were produced on three different formers—a Noble & Wood sheet former, a British handsheet mold, and a Formette Dynamique. All three formers are capable of producing a well-formed sheet of paper. The Formette Dynamique also can produce handsheets with a nonrandom fiber orientation.

Couched handsheets from either the Noble & Wood former or the Formette Dynamique were wet pressed and dried under full restraint using the IPST press and dryer combination. Handsheets from the British handsheet mold were produced using TAPPI recommended procedures.

Handsheet formation was measured using the IPST formation tester. The IPST formation tester in **Fig. 1** is capable of measuring (a) light transmission and reflectance in the wavelength range of 400 nm to 700 nm and (b) beta-particle absorption. An aperture of 1 mm x 1 mm is used for measurement of both light transmission and beta-particle absorption.

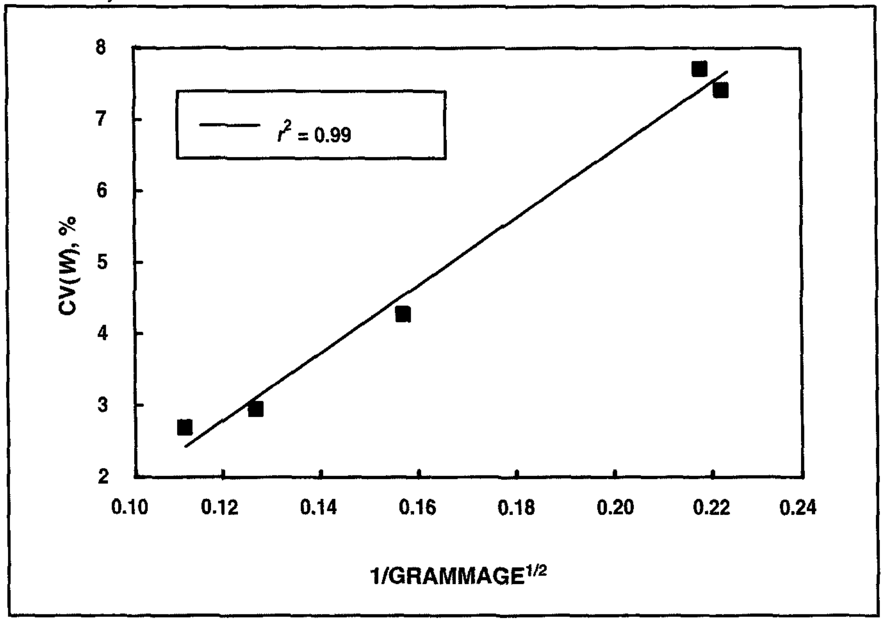
The formation tester can accommodate a variety of sample sizes. Samples are held in place on the x–y table by magnetic clamps. Software developed for the x–y table makes it easy to transport the sample so that formation can be measured over the selected area.

The incident illumination is through a fiber-optic cable. The light source is a 100-W quartz halogen lamp. A bifurcated cable is used when reflectance is measured. The beta emitter is a 50 mCi promethium source mounted on a 5-mm-diam. aluminum disc with a 2-μm silver window (Amersham International).

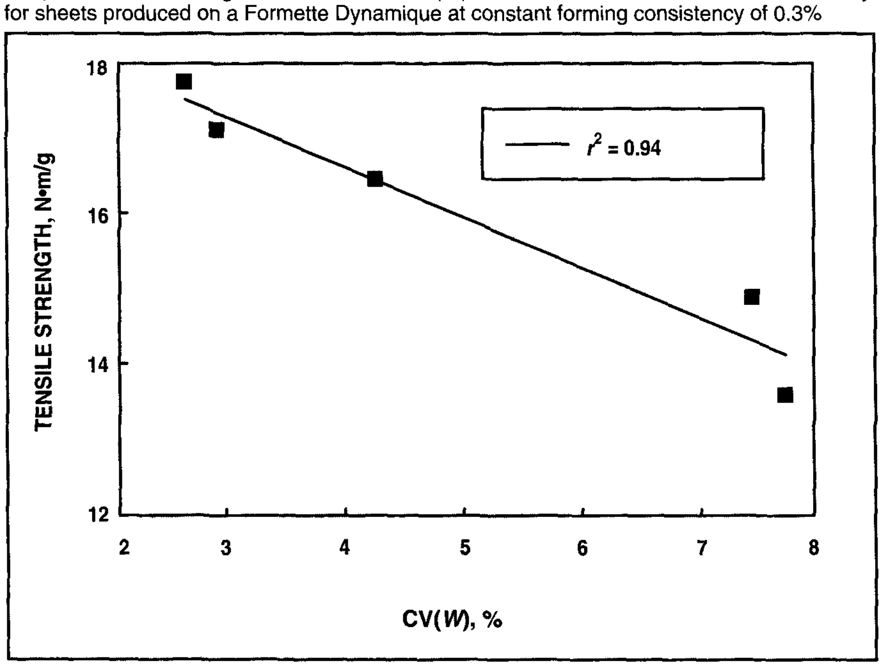
Optical measurements can be made continuously. Mass density is measured using a discontinuous mode, with delay times varying from 1 s to 30 s, depending on the average grammage of the sample.

Software for the IPST formation tester is user friendly, with options for formation measurement and presentation, including the coefficient of variation of mass density CV(W), the coefficient of variation of light transmission CV(T), fast Fourier transforms (FFT), and the spatial gray-level dependence (SGLD) method. The repeatability of mass and optical formation measurements CV(W) and CV(T) for 6400 data points, i.e., over an area of 80 mm x 80 mm, is 2% or better.

2. CV(W), the coefficient of variation for mass density, as a function of the inverse of the square root of grammage for sheets produced on a Formette Dynamique at constant forming consistency of 0.3%



3. Specific tensile strength as a function of CV(W), the coefficient of variation of mass density for sheets produced on a Formette Dynamique at constant forming consistency of 0.3%



Impact of papermaking variables

Grammage

The variation of CV(W) with the inverse of the square root of mean grammage, $1/W^{1/2}$, is shown in **Fig. 2** for sheets made on the Formette Dynamique at a constant forming consistency of 0.3%. We see that there is good agreement with the prediction of Eq. 1.

As formation deteriorates, i.e., as CV(W) increases, tensile strength is expected to drop. As shown in Fig. 2, a reduction in grammage results in a deterioration in formation. Using these data, **Fig. 3** shows that as formation deteriorates in response to grammage reduction, tensile strength decreases.

Consistency

An increase in headbox consistency usually produces a sheet with poorer formation and, consequently, a weaker sheet. This is illustrated in **Fig. 4** for handsheets produced on a Noble & Wood former at a constant grammage of 60 g/m^2. By contrast, Fig. 4 also shows that for handsheets formed at constant grammage on the Formette Dynamique, tensile strength is invariant with forming consistency over the range of 0.2% to 2.0%. It is interesting to speculate on whether a universal relationship between tensile strength and CV(W) might exist for a given furnish at constant refining, wet pressing, and drying-restraint conditions.

Furnish and refining

The effects of furnish and refining on formation for a bleached eucalypt kraft and bleached northern softwood pulp are summarized in **Table I.** The predicted values of formation index CV$(W)_{pred}$ in Table I were calculated from Eq. 1 using measured values of coarseness and fiber length. Fiber length was used to estimate the value of k, whose variation with fiber length is shown graphically by Herdman *(6)*. In these experiments, conducted as part of a project for a Fibrous Structures class at IPST, very little change in mean fiber coarseness and length (measured with a Kajaani FS100) was found with PFI refining.

The hardwood handsheets show better formation than the softwood sheets, a predictable result for the shorter and less coarse hardwood fibers. Both sets of handsheets were formed using a British handsheet mold. It is interesting to note that at the highest level of refining, formation as measured by CV(W) shows significant deterioration, particularly for the softwood handsheets. This is attributed to the longer drainage time that occurs at low freeness levels, thus allowing more time for flocculation to occur. Data in the literature commonly shows tensile strength falling off at high levels of refining, and deterioration in formation could be partly responsible for this phenomenon.

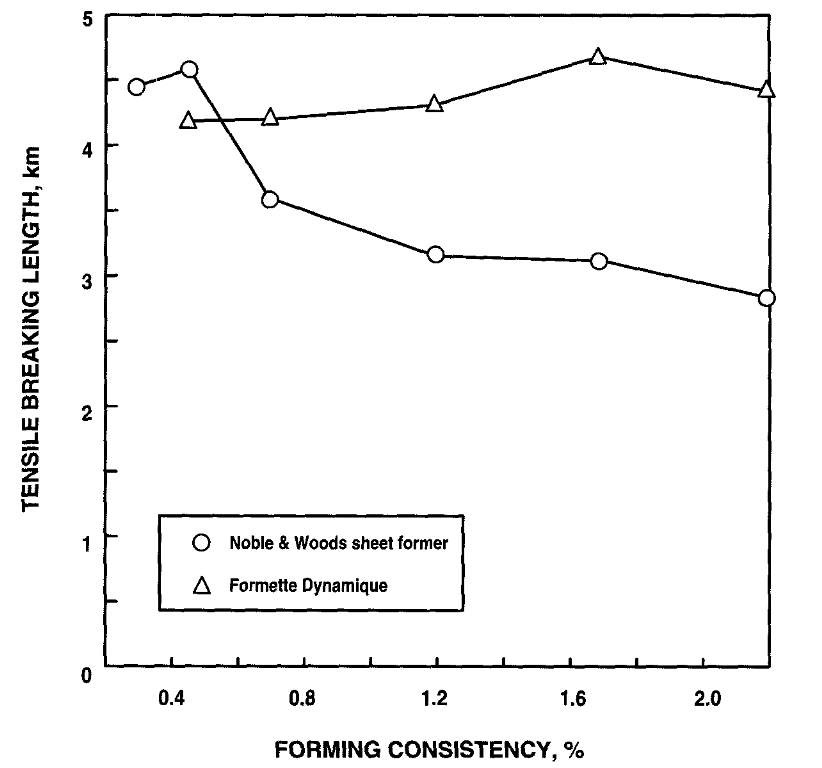
Even at high freeness levels, measured values of formation are higher than the predicted values. This difference presumably reflects a deviation from an ideal random network of fibers. Agreement between theory and experiment might be improved if fiber length or coarseness distribution are included. The influence of fiber length distribution has recently been discussed by Dodson *(11)*. We also see that as formation deteriorates (i.e., as CV increases), the difference between light transmission CV(T) and mass density CV(W) increases.

Forming conditions

The effects of different forming conditions are illustrated in **Table II**. The top portion of Table II (Noble & Wood handsheets) shows the effects of forming consistency, delay time before sheet formation, and addition of a cationic wet-strength agent on sheet elastic properties. As expected, increases in these variables lead to a deterioration in formation. Interestingly, the average values of in-plane elastic properties (V^2) are maintained, while there is an improvement in the average out-of-plane elastic constant (V_z^2). However, there is a significant increase in the variability of those measurements, particularly for the out-of-plane elastic constant.

Table II also shows results for Formette handsheets made using the same furnish at two levels of fiber orientation R ($R = E_{MD}/E_{CD}$). Fiber orientation was controlled at constant grammage by changing the difference between nozzle jet velocity and wire speed velocity. The Formette handsheets have a slightly better formation than the best-formed Noble & Wood handsheets, and we note a small improvement in formation with increased delay time for the Formette handsheets. In the case of the Formette, the delay time is the time between network formation on the

4. Tensile strength as a function of forming consistency for 60-g/m² sheets produced on a Noble & Wood former and on a Formette Dynamique



I. Effects of furnish and refining on formation of handsheets [a]

PFI refining, revs	Pulp freeness, mL CSF	Formation index, % Measured: Light transmission CV(T)	Measured: Mass density CV(W)	Predicted $CV(W)_{pred}$[b]
		Bleached hardwood kraft[c]		
0	580	2.79	2.58	2.05
500	476	2.87	2.60	1.98
1,500	341	3.38	3.15	2.23
3,000	134	3.24	2.66	2.15
5,000	79	4.48	3.23	2.27
		Bleached softwood kraft[d]		
0	623	5.38	5.43	3.85
2,500	406	5.49	...	3.70
5,000	224	7.78	5.14	3.64
7,500	84	10.21	4.95	3.70
10,000	41	25.27	15.63	3.61

[a]Formed on British handsheet mold
[b]Calculated from Eq. 1 using measured values of fiber coarseness and length
[c]Eucalypt
[d]Northern softwood

II. Characterization of handsheets at various levels of formation

Consistency, %	*Delay time,[a] s*	*Wet-strength agent,[b] %*	R [c]	*Grammage, g/m²*	*Sheet density, g/cm³*	*Formation index, %* Light transmission CV(T)	*Formation index, %* Mass density CV(W)	*Elastic constants, In plane* V^2,[d] $(k/s)^2$	*Elastic constants, In plane* $CV(V^2)$, %	*Elastic constants, Out of plane* V_z^2,[e] $(k/s)^2$	*Elastic constants, Out of plane* $CV(V_z^2)$, %
					Noble & Wood handsheets						
0.025	0	0	...	59.2	0.738	8.88	6.94	8.36	5.1	0.145	8.9
0.025	0	0.6	...	58.3	0.765	16.93	11.14	8.64	5.2	0.141	9.9
0.025	5	0	...	61.1	0.795	17.82	12.51	8.28	4.4	0.159	15.0
0.025	5	0.6	...	67.9	0.800	22.00	15.61	8.74	4.9	0.161	20.6
0.250	0	0	...	61.3	0.741	29.14	18.09	8.05	9.6	0.167	22.6
0.500	0	0	...	65.0	0.799	70.40	30.78	7.74	12.4	0.167	31.5
					Formette handsheets						
0.4	0	...	1.12	67.4	0.773	5.61	6.78	8.79	1.8	0.188	4.4
0.4	5	...	1.15	70.2	0.769	5.53	6.54	9.05	2.0	0.184	2.1
0.4	0	...	3.46	68.1	0.830	5.34	6.70	8.13	2.9	0.195	5.3
0.4	5	...	3.22	72.0	0.808	5.34	6.25	8.13	2.5	0.185	3.4

[a]Delay time in headbox for N&W handsheets; delay time before drainage for Formette handsheets
[b]Polyaminoamide–epichlorohydrin (PAE) Kymene 557H
[c]$R = (V_x^2/V_y^2)$ ratio of in-plane elastic constants
[d]V^2 =geometric mean of in-plane elastic constants
[e]V_z^2 =out-of-plane elastic constant or modulus

forming fabric and the initiation of drainage from the network. The improvement in formation may be due to increased fines retention, since there is a slight increase in grammage with the increase in delay time.

We note that there is no adverse effect of fiber orientation on sheet formation. In fact, it appears that formation is improved slightly with increasing fiber orientation. There is also a lower variability in both in-plane and out-of-plane elastic properties when the Formette handsheets are compared with the Noble & Wood handsheets. Based on these results, it appears that fiber orientation *per se* does not adversely affect formation. These findings, albeit with limited data, are in agreement with the theoretical predictions of Schaffnit *(9)*.

In practice, creating a nonrandom fiber orientation on a paper machine—by adjusting the jet speed, just downstream of the slice, to that of the wire—usually has an adverse effect on formation, as seen in the work of Svensson and Osterberg *(8)*. Obviously, the papermaker would like to change fiber orientation without adversely affecting formation.

Refining and wet pressing

Bither and Waterhouse *(12)* examined the effects of refining and wet pressing on network consolidation and formation, and the results are summarized in **Table III.** We see that refining and wet pressing improve the formation CV(*W*) of the handsheets, which were made on the Formette Dynamique. At a constant refining level, sheet densification by wet pressing implies a reduction in void volume, and therefore an improvement in formation might be expected. This result is also in agreement with the trend predicted by Eq. 2. The limit, of course, would be the densification of the sheet to a non-voidal continuum with a formation index close to CV(*W*) =0.

The relationship between mass density and optical density is affected by changes in light scattering and absorption coefficients, as predicted by Norman and Wahren *(13)*. In this case, the changes were brought about by refining and wet pressing. Therefore, the lack of agreement between CV(*T*) and CV(*W*) shown in Table III is not unexpected.

At constant density or void volume, it is estimated that formation improves as the level of refining increases. This implies that the average pore size and its distribution at the two levels of refining must be different, and this has been found to be the case *(12)*.

The reader might expect a similar trend to have appeared in the results shown in Table I, i.e, formation should have improved with an increase in refining. In discussing Table I, we have already noted that no significant change in average fiber length or coarseness was observed. However, it is possible that the increased drainage time may have negated the effect of increased refining.

Conclusions

The influence of several papermaking variables on sheet formation was examined using CV(W), the coefficient of variation for mass density, as an index for formation. The results showed that

- CV(W) is inversely proportional to the square root of grammage, as predicted by theory.
- Flocculation adversely affects formation, which may be a factor in the drop in tensile strength sometimes observed at high levels of refining. (Flocculation was induced by delaying drainage, by adding a wet-strength resin, and by increasing forming consistency.) The mean values of in-plane and out-of-plane elastic constants were not changed by flocculation, but their variability increased significantly.
- Fiber orientation did not adversely affect formation of handsheets produced on a Formette Dynamique, a sheet former known for its ability to produce a very uniform formation. Formation of handsheets produced on the Formette Dynamique was improved through sheet densification achieved by refining and wet pressing. TJ

III. Effects of refining and wet pressing on formation of handsheets*

Pulp freeness, mL CSF	Wet pressing, psig	Sheet density, g/m³	Formation index, % Light transmission CV(T)	Formation index, % Mass density CV(W)
741	0	0.300	6.86	5.21
741	40	0.810	5.72	4.72
156	0	0.791	4.49	4.00
156	40	0.880	5.38	3.70

*Formed on Formette Dynamique

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