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ABSTRACT

The influence of a number of papermaking variables on sheet formation has been examined using the IPST Formation Tester, which has the capability of making optical and mass density measurements. It has been shown that the coefficient of variation of mass density CV(W) is inversely proportional to the inverse square root of grammage as predicted by theory for an ideal two dimensional random network of fibers.

The formation of TAPPI handsheets can deteriorate at low freeness levels, due to an increase in drainage time, and could be responsible for the drop off in tensile strength, sometimes found in pulp beating evaluations.

Flocculation effects produced by a delay in drainage, cationic strength additives, and increased forming consistency, were found to have an adverse affect on formation, and although the mean values of in-plane and out-of-plane elastic constants were not changed, their variability increased significantly.

It was found with handsheets formed on the Formette Dynamique (close to ideal forming conditions) that an increase in fiber orientation did not have an adverse affect on formation. Using the same forming method, it was also found that formation improved through densification by refining and wet pressing.

KEYWORDS

Formation, Optical Density, Mass Density, Grammage, Fiber Orientation, Elastic Properties, Beating, Strength Additives

INTRODUCTION

The purpose of this contribution is to report on the impact on formation of some papermaking variables we have recently examined using a formation tester which has the capability of making both optical and mass density measurements.

With the recent emphasis on improving the quality of paper and board products there has been a resurgence of interest in formation. To many, formation still remains a confused area. This is in part due to the fact that there is no universally agreed upon definition of formation, although the coefficient of variation of mass density, i.e., CV(W), has recently been proposed by Dodson (1) as a universal measure of formation. Furthermore, makers of either off-line or on-line formation sensors have their own index or measure of formation.

Problems also arise when we try to directly relate formation measurements to the converting and end-use performance of paper, an area which is still in its infancy. These relationships can be quite complex, but it has to be realized that in addition to formation other variables may be involved. For example, we can show that sheet strength is very much dependent on formation, but there have been very few systematic studies (Seth [2]) involving other variables controlling strength, e.g., fiber geometry and strength, interfiber bonding, and grammage.

We have already mentioned measures or indexes of formation, and of course, it would be nice to keep life simple with one universally agreed upon measure of formation, i.e., CV(W), as suggested by Dodson (1). This author believes that we can go a long way with this definition, and need to more thoroughly explore its possibilities. However, as Cresson (3) and others have pointed out, papers having identical CV(W)'s can have very different texture or pattern features, e.g., floc size distributions, to use the jargon of image analysis. Clearly, it would be nice to fingerprint a piece of paper with respect to its manufacturing process, i.e., twin wire, high turbulence headbox, etc., and texture or pattern recognition techniques might be a realistic approach to 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, e.g., coating and printing.

The early work of Corte and Dodson, and Herdman (4,5), and more recently Dodson (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:

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

It is perhaps surprising that equation (1) has not yet been completely verified. However, this is not a trivial matter since it is difficult to maintain constant forming conditions while changing the parameters contained in equation (1). In recent work Seth (2) has demonstrated that CV(W) is proportional to the square root of fiber coarseness, i.e., the weight/unit length of fiber. However, this result was based on light transmission measurements.

One useful feature of equation (1) is that it can be used to compare formation measurements made on sheets of different grammage or basis weight. In practice, sheet basis weight is increased by increasing headbox consistency, but this usually has a negative impact on sheet formation. However, equation (1) indicates that formation should improve with increasing basis weight.

In a further paper, Dodson and Fekih (6) have modified equation (1) to account for fiber orientation. They have predicted that formation will deteriorate, i.e., CV(W) will increase with increasing fiber orientation. This result appears to be true for Fourdrinier-made papers as demonstrated by the work of and Svensson and Osterberg (7). This result seems counter-intuitive, since one might expect to get more uniform coverage with increased fiber orientation.

Dodson (8) has also shown that network consolidation during forming and should lead to improved formation. Using his approach it can be shown that $CV(W)_T$ as a function of consolidation is given by

$$CV(W)_T = [(CV(W))^2 + (1/1\text{-}\epsilon)(lxw/x^2)]^{1/2} \qquad (2)$$

where ϵ is the porosity, l, and w are fiber length and width, and x^2 is the aperture area. In the results which follow we will briefly examine the effects of refining, forming consistency, fiber orientation and wet pressing with reference to equation (1).

EXPERIMENTAL

Formation measurements have been made on handsheets, formed either on a Noble and Woods Sheet Former, British handsheet mold, or the Formette Dynamique, using the IPST Formation Tester, briefly described below.

The Formette dynamique gives a unique, but high level of formation depending on the furnish used. It supposedly comes closest to the ideal of forming a random network of fibers. It also has the possibility to form handsheets with a nonrandom fiber orientation.

After formation the sheets were wet pressed and dried under full restraint using the IPST press and dryer combination. The sheets were made on a British sheet mold, and TAPPI recommended procedures were followed.

The IPST Formation Tester is shown in Figure 1. It has the capability of making light transmission and reflectance measurements in the wavelength range of 400-700 nm, as well as, beta particle absorption measurements. An aperture of 1 mm x 1 mm is used for both light transmission and beta measurements.

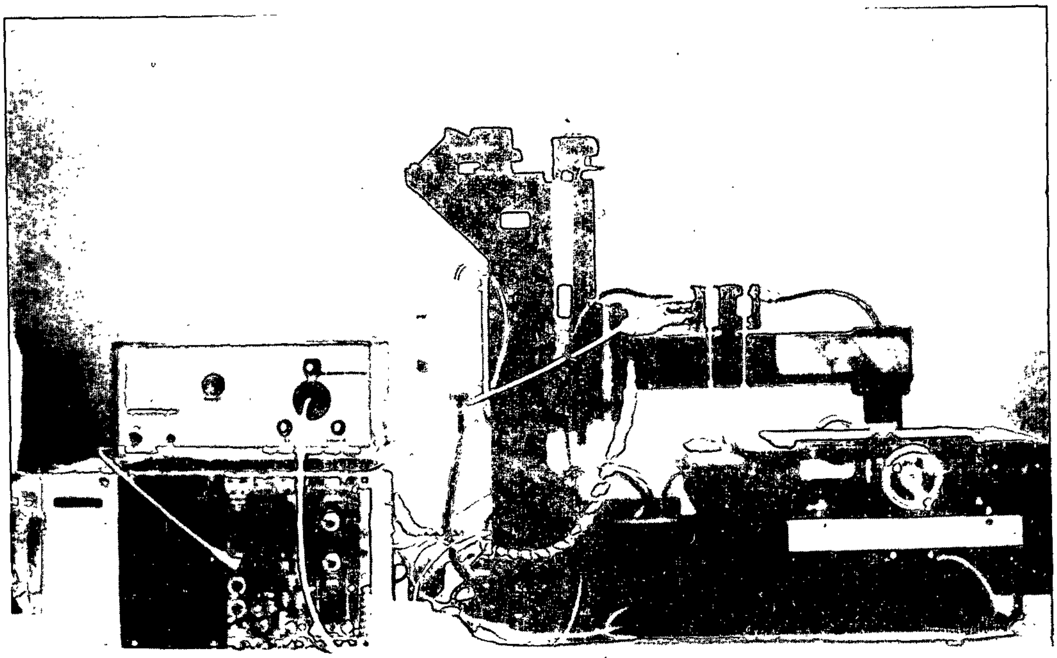

Figure 1. IPST Formation Tester.

Formation samples of various sizes can be used, and are held in place on the x-y table by magnetic clamps. User-friendly software has been developed for the x-y table to transport the sample so that formation measurements can be made over the area selected.

The incident illumination is a 100-watt quartz halogen lamp transmitted through a fiber optic cable, and a bifurcated cable is used when reflectance measurements are made. The beta emitter used is a 50 mCi promethium source mounted on a 5 mm diameter aluminum disc with a 2 micron silver window (obtained from Amersham International).

Optical measurements can be made continuously; however, when mass density measurements are being made, the discontinuous mode is used with delay times varying from 1 to 30 secs depending on the average grammage.

The objective in software development was to have a user-friendly system with a variety of options for formation measurement and information presentation, including CV(W), CV(T), FFT, and Spatial Gray Level Dependence Method.

RESULTS AND DISCUSSION

The coefficient of variation of mass density CV(W) with inverse square root grammage, i.e., $1/(W)^{1/2}$, is shown in Figure 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 equation (1). Figure 3 shows that as formation deteriorates, i.e., CV(W) increases, tensile strength decreases. When forming handsheets at constant grammage on the Formette Dynamique, we have found tensile strength to be invariant with forming consistency over the range of 0.1% to 2.0% (9).

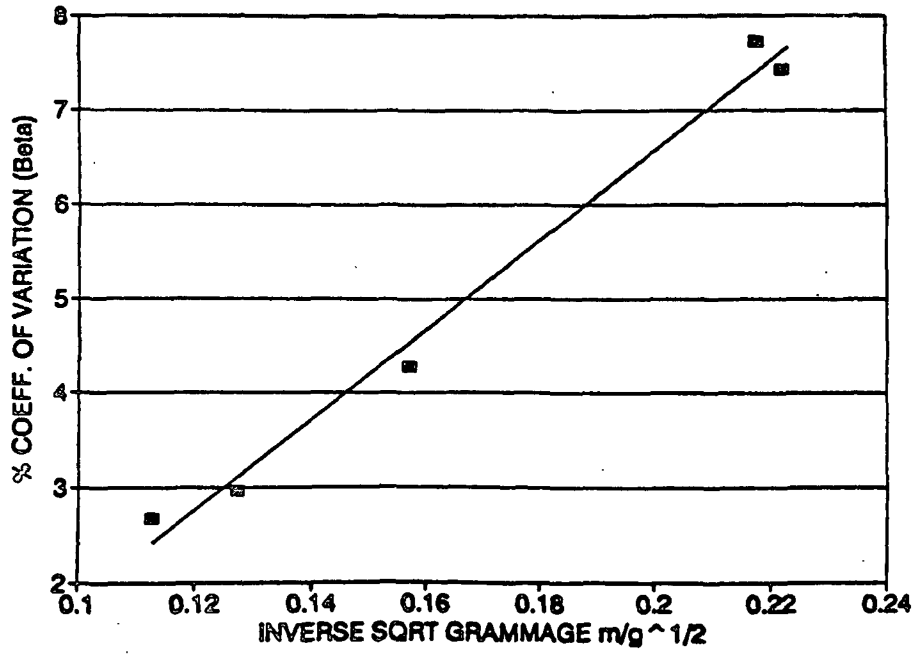

Figure 2. Variation of Specific Tensile Strength with Cofficient of Mass Density CV(W).

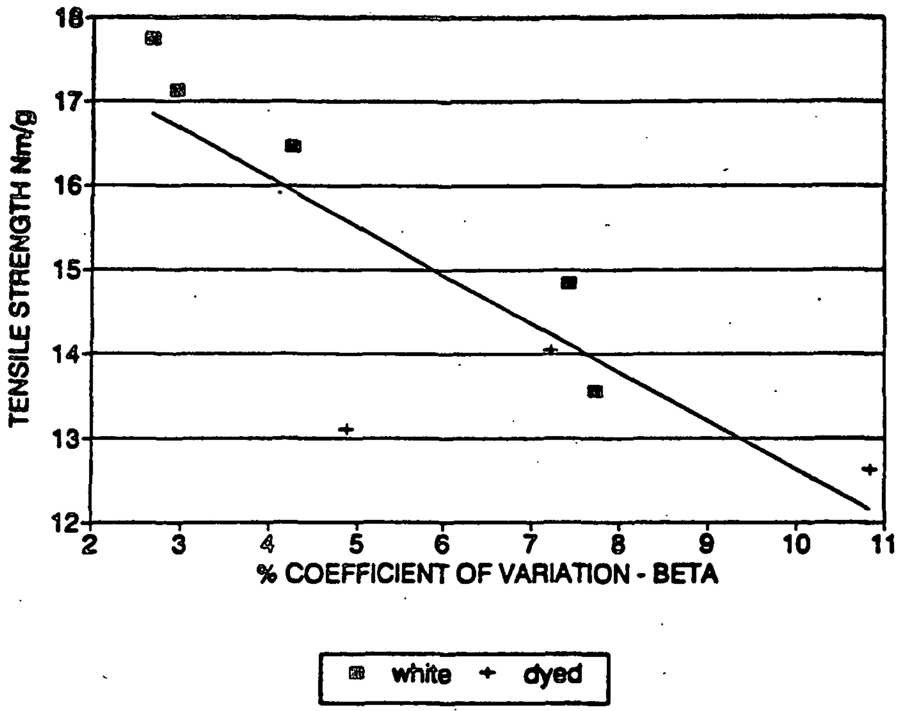

Figure 3. Variation of the Coefficient of Variation of Mass Density CV(W) with Inverse Square Root Grammage.

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 $CV(W)_{pred}$ given in the final columns are calculated using equation (1) and measured values of coarseness and fiber length. The latter was used to estimate the value of the fiber length factor k (5). In these experiments, very little change in fiber coarseness and length was found with PFI refining.

Table 1. **Effects of Furnish and Refining on Formation.**

BLEACHED EUCALYPT KRAFT

PFI Refining REVS	CSF ml	CV(T) %	CV(W) %	$CV(W)_{pred}$ %
0	580	2.79	2.58	2.05
500	476	2.87	2.60	1.98
1500	341	3.38	3.15	2.23
3000	134	3.24	2.66	2.15
5000	79	4.48	3.23	2.27

BLEACHED NORTHERN SOFTWOOD KRAFT

PFI Refining REVS	CSF ml	CV(T) %	CV(W) %	$CV(W)_{pred}$ %
0	623	5.38	5.43	3.85
2500	406	5.49	2.60?	3.70
5000	224	7.78	5.14	3.64
7500	84	10.21	4.95	3.70
10000	41	25.27	15.63	3.61

As one would expect, on the basis of fiber length and coarseness, the hardwood sheets show better formation than the softwood sheets. It is interesting to note that at the highest level of refining the formation shows significant deterioration, particularly for the softwood handsheets. This is attributed to the longer drainage time which occurs at low freeness levels, i.e., allowing more time for flocculation to occur. It was found with this work, which was part of a class assignment in paper physics at IPST, that tensile strength also fell at the highest level of refining. There are a number of instances in the literature concerned with pulp evaluations where the tensile strength falls off at high levels of refining, and clearly formation could be responsible for this.

We note that even at the higher levels of freeness measured values of formation are higher than the predicted values. This is presumed to reflect a deviation from an ideal random network of fibers. We also see that as formation deteriorates, the difference between optical and mass density measurements increases.

The effects of different forming conditions are illustrated in Table II. In the first part of Table II, the effects of delay time before sheet formation, addition of a cationic wet strength agent (kymene 557H), and forming consistency on elastic properties and their variability are shown. As expected, increases in these variables lead to a deterioration in formation. Interestingly, the average values of in-plane elastic properties are maintained, while there is an improvement in the out-of-plane elastic constant. However, there is a significant increase in the variability of those measurements, particularly for the out-of-plane elastic constant.

Also shown in Table II are results for Formette handsheets made using the same furnish for two levels of fiber orientation R ($=E_{md}/E_{cd}$). The Formette made handsheets are slightly better than the best formed Noble and Woods handsheets, but now we note a small improvement in formation with increased delay time. In the case of the Formette, the delay time is the time between network formation on the 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, and if anything, formation is improved slightly with increasing fiber orientation, at least as judged by the light transmission measurements, i.e., CV(T). 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 and Woods handsheets. On the basis of these results, it appears that fiber orientation does not have an inherently adverse affect on formation. However, it is clear that in creating a nonrandom fiber orientation on the paper machine, i.e., by changing the difference in jet-to-wire speed, this does have an adverse affect on formation.

Table II. Characterization of Handsheets Having Various Levels of Formation.

NOBLE & WOODS HANDSHEETS

CONSIST. %	t_D secs	PAE %	GRAMMAGE g/m^2	DENSITY g/cm^3	CV(T)	CV(W)	V^2 $(km/s)^2$	CV(V^2) %	V_z^2 $(km/s)^2$	CV(V_z^2) %
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	70.4	30.78	7.74	12.4	0.167	31.5

FORMETTE HANDSHEETS

CONSIST. %	t_D secs	R	GRAMMAGE g/m^2	DENSITY g/cm^3	CV(T)	CV(W)	V^2 $(km/s)^2$	CV(V^2) %	V_z^2 $(km/s)^2$	CV(V_z^2) %
0.400	0	1.12	67.4	0.773	5.61	6.78	8.79	1.8	0.188	4.4
0.400	5	1.15	70.2	0.769	5.53	6.54	9.05	2.0	0.184	2.1
0.400	0	3.46	68.1	0.830	5.34	6.70	8.13	2.9	0.195	5.3
0.400	5	3.22	72.0	0.808	5.34	6.25	8.13	2.5	0.185	3.4

t_D dwell time in headbox or delay time before drainage on Formette
R $= (Vx^2/Vy^2)$
V^2 geometric mean in-plane elastic constant
V_z^2 out-of-plane elastic constant or modulus
PAE Kymene 557

The impact of refining and wet pressing on the strength properties of paper was recently examined by Bither and Waterhouse (10). In addition, we have examined the effects of network consolidation by refining and wet pressing on formation, and the results are summarized in Table III. The formation of the handsheets, which were made on the Formette Dynamique, is improved by refining and wet pressing. 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. The limit of course would be the densification of the sheet to a nonvoidal continuum with a CV(W)=0.

Table III. The Effects of Refining and Wet Pressing on Formation.

CSF ml	Wet-Pressing psig	Density g/cm^3	CV(T) %	CV(W) %
-	0	0.300	6.86	5.21
741	40	0.810	5.72	4.72
155	0	0.791	4.49	4.00
157	40	0.880	5.38	3.70
270 Cl.	0	0.740	4.42	3.86
270 Cl.	40	0.874	5.36	3.67

We also note that there is a small improvement in formation at constant density or void volume. This implies that the average pore size and its distribution must be different, and we have actually found this to be the case (10). Our formation results seem to be consistent with this idea. The reader might expect a similar trend to appear in the results given in Table I, i.e, as refining is increased, formation should improve. In discussing Table I, we have already noted that no significant change in average fiber length or coarseness was observed; however, it is believed that the increased drainage time may be responsible for negating the above effect.

CONCLUSIONS

The influence of a number of papermaking variables on sheet formation has been examined. It has been shown that the coefficient of variation of mass density CV(W) is inversely proportional to the inverse square root of grammage as predicted by theory.

The formation of TAPPI handsheets can deteriorate at low freeness levels, due to an increase in drainage time, and may be responsible for the drop off in tensile strength, sometimes found in pulp beating evaluations.

Flocculation effects produced by a delay in drainage, cationic strength additives, and increased forming consistency, were found to have an adverse affect on formation, and although the mean values of in-plane and out-of-plane elastic constants were not changed, their variability increased significantly.

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