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CORRELATION BETWEEN THE AREAL MASS AND OPTICAL DENSITIES IN PAPER

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Abstract

The aim of the present investigation is to find out those variables of the paper-making process that cause variation in the light transmission of paper, independently of basis weight variation. Furthermore, is intended to discover under what conditions and to what accuracy the distribution of areal mass (formation) can be characterised by the areal distribution of light transmittance. The study is carried out by measuring values of beta-ray transmission and light transmission at exactly the same points of paper samples using an aperture of 1 mm diameter and analysing the correlation of the results.

At this stage of the study the effects of furnish composition, beating, wet pressing, and calendering on the correlation between mass distribution and distribution of transmittance have been analysed. It can be seen that at least prolonged beating and heavy calendering change the distribution of transmittance in such a way that the optical formation measurement does not give a true picture of the distribution of mass.

Introduction

An even areal distribution of material on both large and small scale is a desirable property of paper from the viewpoint of production economy and of converting efficiency. Scale refers to wavelength of variation. Small scale variation means here variation on the scale that modern, commonly used optical formation testers investigate i.e. the wavelength range between 0.4 mm and 100 mm. The areal distribution of material in this range is generally called formation; the more even the distribution is, the better is the formation. The word formation, however, can cause confusion, because in England and in North America it traditionally stands for the impression one gets when looking at paper against light. In this paper this impression will be called look-through. ISO has defined formation as "the manner in which the fibres are distributed, disposed and intermixed to constitute the paper". Wahren proposed a definition, where formation equals variation coefficient of grammage and may thus have a numerical value[1].

Traditionally look-through has been used to judge the evenness of grammage distribution in paper and it is used even today for that purpose in paper-mills. Look-through gives a true picture of areal mass distribution in certain cases. In addition to that it is as such an important quality requirement for many paper grades.

In trying to construct a method for the characterisation of grammage distribution, in which the subjective evaluation of look-through could be replaced by a quantitative method, the measurement of light transmittance is used in most cases. This is practical because it describes exactly the same property of paper as look-through and because the measurement is easy to perform in comparison to beta-radiography and other methods that give a truer picture of grammage distribution.

For the practical measurement of formation it is important to define: (a) how the individual point by point measurement is carried out; what is the measuring aperture; how are the points situated relative to each other; what is the accuracy of individual measurements: and also (b) how the formation characteristic, or formation index, is calculated from the results of individual basis weight determinations.

The formation measurement is used to characterise the areal mass distribution in a quantitative manner that ranks papers within a paper grade according to the detrimental effects caused by the grammage variation to the end-use of the paper grade. Thus, the formation index may change with the end use purpose of the paper in question.

The scale of areal mass variation is of importance because it affects the degree of disturbance (caused by the variation of grammage), in the converting and end use applications.

The validity of the optical measurement may depend on the scale of the most significant part of the grammage variation. The matter of scale is not, in spite of its importance, discussed in this paper. Sara has studied the question of `scale´ in his work[2].

The most frequently used characteristics of the grammage variation are its standard deviation, coefficient of variation and power spectrum, though in certain applications some other quantity calculated from the measurements might better characterise the grammage variation. Our present understanding of the structure of paper does not allow the derivation of a better universal index of formation.

It is a recognised fact that optical measurement does not give a true picture of areal mass distribution on the small scale. Within a paper grade, however, the optical method is assumed to rank the samples in the right order of evenness of the grammage distribution. On the other hand, optical measurement is not reliable for grades that are heavily calendered.

A thorough study of the applicability of the optical method requires that it be possible to compare, point by point, the measured values of light transmittance and true grammage of the paper samples. It can be assumed that the true grammage can be estimated with sufficent accuracy by the absorption of beta-radiation. The measurements must be performed on exactly the same spots of the paper specimen to be useful in the comparison. The conditions of validity of the optical measurements have not, to the authors´ knowledge, been experimentally investigated. Some single comparisons between the light and beta-ray absorption methods have been reported[2-6].

Theoretical limitations of the optical method

According to current experience it is safe to state that grammage variations cannot be universally measured by the optical method. The requirements of the measurement vary according to the index of formation used to describe the variation. In order to apply the optical method, one must know the paper-making conditions under which the measured light transmittance values can be calibrated to the corresponding grammage values with sufficient accuracy. Under these conditions the variation of grammage of the paper samples can be compared using the variation of light transmittance as a basis for the formation indices selected. The optical method for formation evaluation should always fulfil the criterion that the observed formation index C^{WT} rank the paper samples studied in the same way as the `true´ formation index $C^{W}$ does. ($C^{W}$ is based on true areal mass density determinations ($w_i$) instead of the optical `areal mass density´ estimation $w_{T,i}$ used for C^{WT} measurements. C^{W} is calculated according to the same formula as C^{WT}.)

For each of the formation indices used, the optical method must fulfill various requirements, relating to, for instance, the sampling method, measured area, number of measurements and the locations of the measured points.

The validity of the optical `formation measurement´ can be examined by the correspondence of the two previously described formation indices and by the correspondence of the optical estimates of the grammage $w_{T,i}$ and the real grammage values w_i measured point by point.

If the values of light transmittance can be transformed to the values of grammage in such a way that the values of the correspondence points are pairwise equal, i.e.,

$$G(T_i) = w_{T,i} = w_i \tag{1}$$

the optical estimates, of course, will give equal values for any formation index to be used. For transformation purposes the functional relationship G between the light transmittance and the grammage has to be known and it has to be continuous and unambiguous.

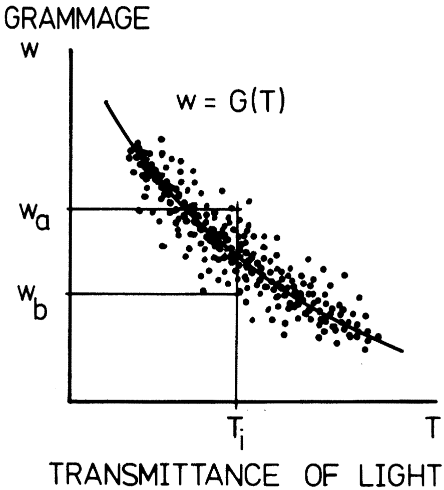

Fig 1—Relationship between light transmittance T and grammage w.

If the relationship G between light transmittance and true grammage varies, for instance because of local variations of the scattering coefficient, the obtained transmittance values will scatter around the hypothetical relationship of Eq.(1) i.e., w = G(T), (figure 1). The effect of this `incomplete fit′ is that the variance of the optical estimates of grammages (calculated on the basis of Eq. (1)) is lower than it would be if calculated from the true grammage values. The fit can be judged also on the basis of its effect on the formation index used, for instance on the variation coefficient.

Let us say that F and F′ represent the variation coefficients of grammage obtained by measurement of beta-radiation absorption and light transmittance respectively. The ratio F′:F can be used as a measure of the accuracy of the optical measurement. This ratio is

$$\frac{F'}{F} = \frac{s'_w}{\bar{w}'} \cdot \frac{\bar{w}}{s_w} = \frac{s'_w}{s_w} \qquad \text{since } \bar{w} = \bar{w}'$$

where $\bar{w}$ = mean of grammage and s_w = standard deviation of grammage.

The square of s'_w/s_w (s'^2_w/s^2_w) is the same as the proportion of explained variance, and s'_w/s_w equals the correlation coefficient between basis weight sequences from beta-measurement and light measurement. Assuming a correlation coefficient r = 0.90

(proportion of explained variance = $100.r^2$ = 81 %) the variation coefficient will be estimated 10 % smaller with the optical method than using the beta-absorption method. Generally the variation coefficient measured with the optical method will be smaller than that measured by the beta-absorption method, if this type of transformation is used. The square root of the proportion of the explained variance indicates how large this difference is[2].

Because the dependence of grammage on the light transmission may vary greatly from sample to sample, it is advisable to check the accuracy of the transformation G, Eq.(1), each time the structure of the paper investigated is expected to have changed. This transformation procedure also gives a good indication of the accuracy of the optical measurement in such cases.

If the formation index used requires good or perfect local correspondence between light transmittance and true grammage, the optical method cannot be used in such cases where the optical results scatter around the functional dependence of Eq. (1). Such a formation index would for instance be the gradient of the grammage variation on the floc edge.

Norman and Wahren[3] have examined the relationship between the grammage and light transmittance on the basis of the Kubelka equation:

$$A = \ln(1/T) = \ln(I_o/I) = \ln((a/b)\sinh bsw + \cosh bsw), \quad (2)$$

where a and b are parameters containing the reflectivity of the sheet, R_∞.

This equation was derived for a homogeneous, diffusing plate with even surfaces and for diffuse illumination. Thus the equation is not accurately valid for paper that is always more or less heterogeneous and uneven on its surfaces. The relationship between transmittance T and scattering power sw is presented in figure 2.

Equation (2) has been used assuming the scattering coefficient s and the reflectivity R_∞ to be constant within the sheet to be measured. By placing the sheet in contact with a backing material with an equal reflectance R_b to the reflectance

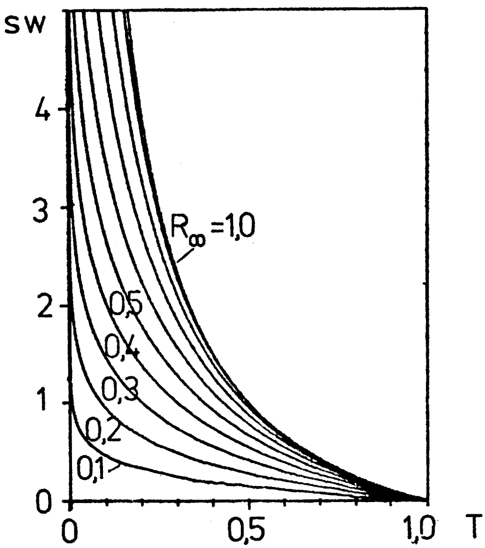

Fig 2—Kubelka relationship between light transmittance T and scattering power sw with increasing R_∞.

of the sheet, $R_b = R_\infty$, Eq. (2) reduces to

$$A = bsw \qquad (3)$$

Sensitivity to the variations of the scattering coefficient can be reduced by adjusting the distribution of wavelength in a way that the ratio k/s is made as high as possible (R_∞ made as small as possible) for the sheets inspected.

The linear relationship between the grammage and the light transmittance given by Equation (3) is not valid if

a) the scattering coefficient varies as a function of the grammage

b) the scattering coefficient varies independently of the grammage for instance because of an uneven distribution of different material components of paper.

If the incident light is not diffuse non-linearity can also be caused.

c) if the reflectance of the surface of paper varies with the grammage: for example if the smoothness of heavy spots differs systematically from that of the light spots,

d) if the reflectance of the surface varies independently of the grammage,

e) if the incident light is not diffuse, the light spots of paper appear to be too heavy because the direct incident beam of light will become diffuse very quickly when progressing through the sheet.

Factors a), c), and e) change the shape of the relationship between the grammage and the light transmittance, the factors b) and d) decrease the accuracy of the transformation expressed by Eq. (1).

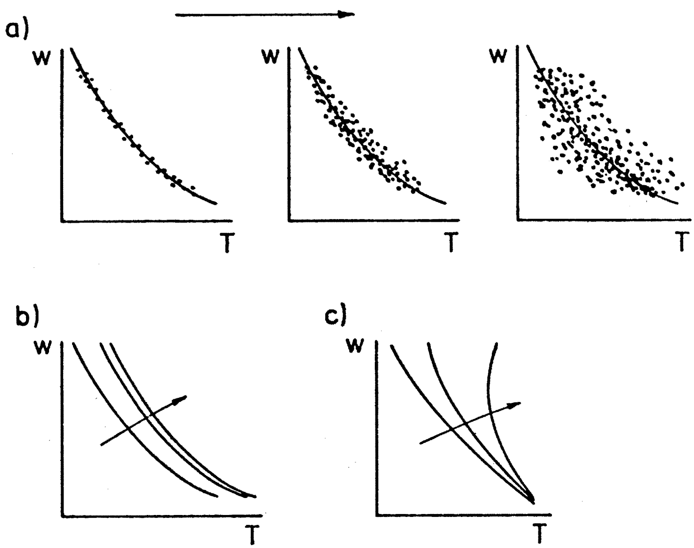

Fig 3—Examples of possible changes induced by calendering in the relationship between light transmittance T and grammage w. Calendering pressure increases in the direction of the arrow.

For instance calendering may cause the following changes in the relationship between the light transmittance and the grammage (figure 3):

a) The relationship w = G(T) does not change, but its accuracy decreases.

b) The shape of the relationship does not change, but the level changes, i.e., w = K + G(T), where K = constant.

c) The shape of the relationship changes; w = G"(T).

The change may also be a composition of all the mentioned changes at the same time.

It can be assumed that the local reflectivity of light varies at least in sheets made from several material components with different optical properties. The scattering coefficient may vary because of uneven fines distribution or because of local variation of the bonding degree of fibres. Furthermore, it can be assumed that wet pressing and calendering cause variation of scattering coefficient as a function of the grammage, because the local values of pressure will be high on the heavy spots of paper in comparison to the surroundings. Because of this the light scattering coefficient decreases on heavy spots of paper in heavy calendering (calender blackening) and the unambiguity of the relationship between the grammage and the light transmittance disappears: grammage is not

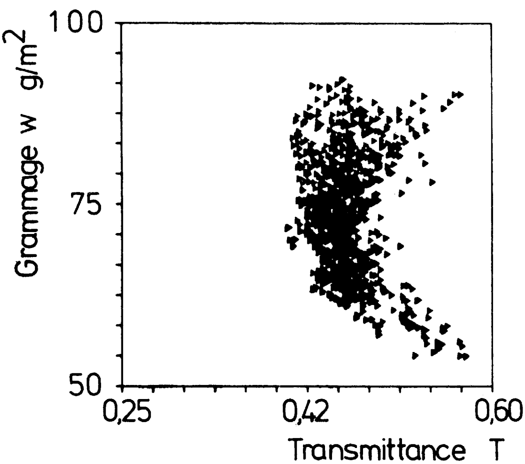

Fig 4—An example of the effect of heavy calendering on the relationship between light transmittance T and grammage w /6/.

now a single valued function of transmittance (see figure 4)[6].

In his work Sara found that the correlation between measured values of grammage and light transmittance was best in the case of sack kraft paper (r = -0.92) and lowest in the case of coated and calendered art paper (r = 0.06). SC magazine paper had a correlation coefficient of -0.89 before the calendering and -0.68 after ordinary supercalendering treatment[2].

The thickness of the measured sheet affects the ratio between the effective measuring aperture and the nominal measuring aperture in the optical measurement, because the light beam is scattered as it progresses through the paper. The thicker the sheet and the higher the scattering coefficient, the larger becomes the area outside the nominal aperature size about which the transmitted light beam gathers information. The maximum resolution is limited by the ratio of the nominal aperture to the sheet thickness. If the diameter of the aperture gets smaller than the thickness of the sheet, light scattering and absorption information collected outside the nominal aperture will start significantly to affect the results. Based on the results of Norman and Wahren[3] one may conclude that with a measuring aperture about 1 mm in diameter the error caused by the light scattering will be extremely small on ordinary papers (grammage below 60 g/m^2).

Measuring Apparatus

In trying to examine the relation between the light transmittance and the beta-ray absorbance, (here used as an estimate of the true grammage) it is essential that both of the measurements are done on exactly the same spot and that the resolution of the intensity of variation is adequate. The measuring equipment used in this study has been developed from an earlier semi-micro analyser of paper properties. This, however, was insufficiently accurate to study the applicability of the optical `formation method´[4].

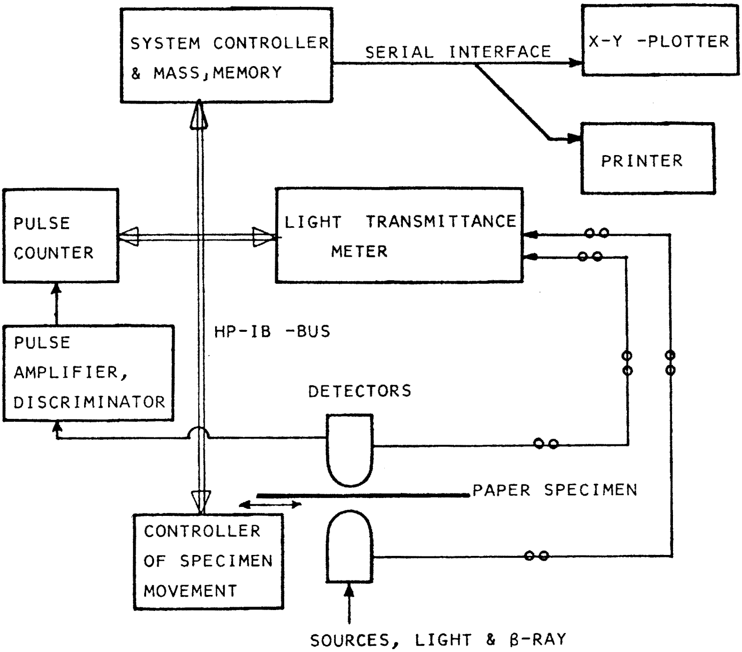

Fig 5—Block diagram of the measuring apparatus.

The schematic block diagram of the measuring system is shown in figure 5. The equipment works automatically under supervision of a system controller (HP 9835A computer). Both the control of the movement of the specimen and the transport of the measured results are done via the HP-IB databus. The results are stored for calculation on a magnetic tape cassette, which also acts as mass memory for the system controller. Simultaneously the results can be plotted on an x-y plotter for controlling the function of the equipment. The system controller is capable of carrying out all the calculations required in analysing the data.

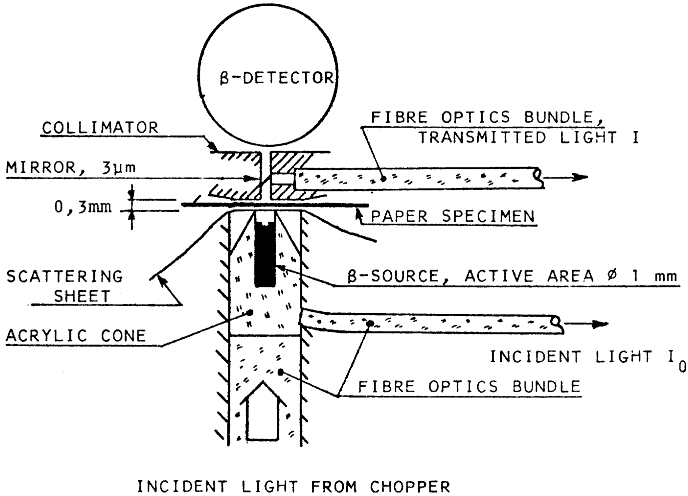

Fig 6—Radiation sources and detectors of the apparatus.

Both the light transmittance and the beta-ray transmittance measurements are performed coaxially through the same aperture. The specimen is motionless during the actual measurement (figure 6). Thanks to this the measured areas of both measurements are as equal as possible in size and location. The beta-radiation source (1 mCi Pm^{147}) is about 0.7 mm below the sample. The active diameter of the source is 1mm. The light source used can be either a HeNe-laser that emits monochromatic (630 nm) light or an iodine incandescent lamp that emits white light. The wavelength distribution of the latter can be modified with appropriate filters. The light is brought from the chopper equipment in a glass fibre bundle (diameter 10 mm) and then concentrated onto the area of the measuring point with a truncated plastic cone. With this arrangement it is possible to obtain adequately even and high intensity of illumination on the entire measuring area.

Above the acrylic cone is situated a filled HDPE sheet (12 g/m^2) which ensures that the incident light beam is well diffused while, at the same time, affecting the intensity of beta-radiation as little as possible.

The gap between the scattering layer above the radiation source holder and the detector collimator is fixed at 0.3 mm. The paper sample is pressed against the collimator with a spring loaded teflon ring. Thus the sample cannot move in the measuring gap in the z-direction during the measurement.

The length of the collimator is 5 mm and the orifice in the centre of it is 1 mm in diameter. Because the sample is pressed against the underside of the collimator during the measurement, the aperture always has this diameter. The light transmitted through the sample is turned through 90° with a thin mirror fitted in the middle of the collimator at a 45° angle. The mirror is polyester coated with a monomolecular layer of aluminium. (The thickness of the mirror is 3 μm and its grammage is 4 g/m^2.) Both the sample of the incident light I_o and the transmitted light are led to the detectors through a fibre optic bundle.

The incident beta-radiation is transmitted through the paper according to the well established formula(7):

$$T = n/n_o = e^{-\mu w} \tag{4}$$

where n and n_o are the numbers of particles of incident and transmitted radiation, μ is the absorption coefficient, and w the grammage.

The absorption coefficient of beta-radiation is known, constant and nearly equal for all the different components of paper. The measurement of beta-transmittance is based on pulse counting(8): a constant number of pulses (usually 50,000) is counted at each point and the time needed for that is recorded. Using this method the standard error of the measurement is the same at each point, $(\sqrt{n}/n)$, regardless of the value of basis weight. It is valuable to know this, when the point by point relationship between the optical and beta measurements is examined.

By counting 50,000 pulses per measured point the coefficient of variation at a transmittance level, $T_b = 1$, ranged from 0.45% to 0.46%, which agrees well with the theoretical value of 0.45%.

The activity of the beta-radiation source is quite low. Because of this the gap between the beta-source and the proportional counter tube used as the detector should be as small as possible. Otherwise the time needed for pulse counting will become too long to be reasonable. (A single measurement on 50g/m^2 paper takes about 70 s.) For the same reason the basis weight of the mirror and the scattering layer must be as low as possible.

The measurement of `parallel´ light transmittance is based on the equally well-established formula of Lambert-Beer[9]:

$$T = I/I_o = e^{-\gamma w} \tag{5}$$

Here the value of the generalised absorption coefficent γ varies depending upon the optical properties of the sheet (scattering and absorption). It also exhibits local variations within a specimen due to reasons discussed earlier. (The variation of the generalised absorption coefficient γ as a function of different variables in the paper-making process is one of the main things to be examined in this study).

Both the sample of the incident light and the transmitted light are converted to voltage signals using semiconductor photodiodes. The frequency of the chopped light, and thus of the square waves with alternating amplitude, is 103 Hz. The voltages are converted to frequencies proportional to them. These frequencies are divided (f/f_o) and thus directly calibrated values of light transmittance will be obtained (figure 7).

With this arrangement the accuracy of the light transmittance measurement can be made as high as to 5 significant digits. The accuracy of the light transmittance measurement is superior to that of the beta-radiation measurement. Because of the AC-principle of operation the optical measurement is insensitive to all other frequencies but the chopper frequency and its

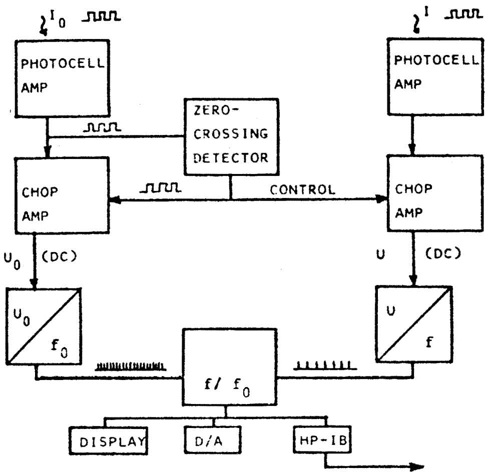

Fig 7—Schematic block diagram of the light transmittance measurement.

harmonics. Thus it is in practice totally insensitive to the illuminating conditions of the surroundings. Because both the incident and transmitted light are measured, possible fluctuations in the intensity of the light source are automatically compensated. The stability of the optical measurement is excellent in both short and long terms; on transmittance level 1 the standard deviation of 1,000 measurements taken over 15 hours was 0.00004, giving a coefficient of variation of 0.004 %.

The sample is moved with stepper motors. During the time of the areal optical and mass density measurements the specimen is motionless. Thus any electrical time constants of the meters do not affect the results. The motor system is triggered by the system controller having received the results from the measuring instruments. The sample is moved in the plane of the sheet. The system is capable of scanning a maximum area of 30 x 150 mm in steps of between 0.3 and 18.9 mm.

The track of the movement is repeatable to an accuracy of 0.05 mm, and the positioning of the specimen in the specimen holder to an accuracy of 0.1 mm.

The variation of humidity of the ambient air is a potential source of error for the described measurements of very high accuracy. A 10% change in the relative humidity of the measuring room can be easily recognised in the results. Because of this the apparatus is installed in an air-conditioned room.

The apparatus is described in more detail elsewhere(10).

Results from earlier experiments

It is known from earlier research[2,6] that, for instance, heavy calendering, beating or filling decrease the correlation between light transmittance and grammage considerably. Earlier results have shown that the contribution to light transmittance variation which is independent of grammage variation, can be so high within one specimen, that it will not be possible to construct true formation indices based only on the optical measurement (see Eq. (1)).

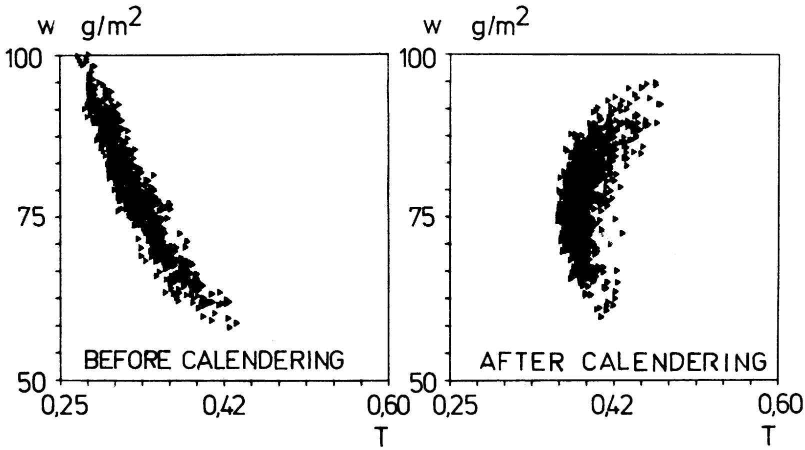

Fig 8—Effect of calendering on the relationship between light transmittance T and grammage w for uncalendered and calendered laboratory handsheets /6/.

The effect of heavy calendering on the relationship between grammage and light transmittance is shown in Figure 8[6]. Two laboratory handsheets of basis weights 77 and 78.5 g/m^2 were measured. The furnish was a fully bleached kraft pulp with clay as a filler, ash content 6.5 %. Before filtration the stock was kept after mixing for 40 seconds in the mould to degrade the formation. One of the sheets was calendered in a laboratory calender using hard rolls with a pressure of 70 kN/m, in an atmosphere of 50 % RH, 25° C.

As a result of calendering new optical contacts were formed at the thick, heavy spots in the uncalendered sheet. Because of the new optical contacts these spots are now optically more transparent.

The linear correlation between the transmittance values and the values of grammage on the uncalendered sheet was - 0.93 and that on the calendered sheet was -0.18. In the latter case the unambiguity of the relationship between grammage and light transmittance has disappeared. This means that a particular transmittance value corresponds to two different grammages. The transmittance has changed dramatically from the expected inverse relationship at the `heavy end´ values of grammage. In a case like this the use of optical formation measurement is, of course, no longer possible(6).

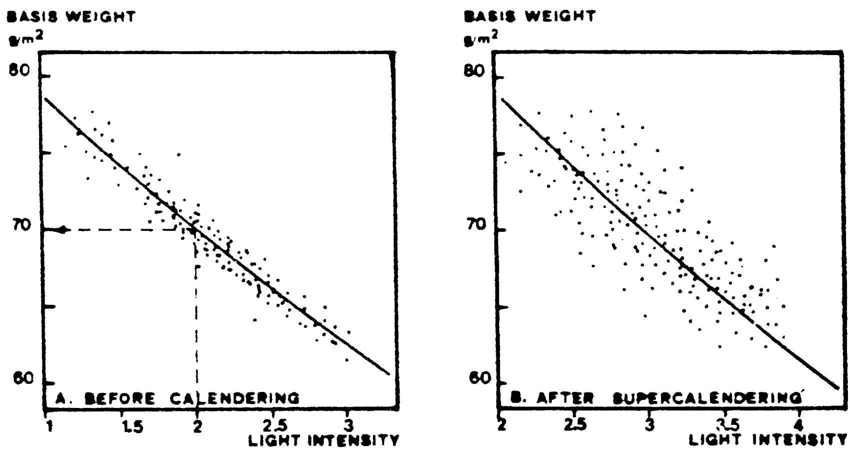

Fig 9—Effect of production scale supercalendering of SC magazine paper on the relationship between light transmittance T and grammage w /2/.

Sara compared in his study(2) a magazine paper before and after supercalendering. Normal calendering treatment with soft rolls decreased the correlation between light transmittance and basis weight from its original -0.88 to -0.68. Thus the optical method may give erroneous results even for ordinary SC magazine papers depending on the formation index used (figure 9).

The effect of beating on this relationship is illustrated in figure 10(6). A specimen of 55 g/m^2 greaseproof paper (made from a furnish of highly beaten spruce sulphite pulp) was measured. Because of beating the amount of interfibre bonding has increased, the paper has become optically more homogeneous, and its transmittance has increased. The correlation between basis weight and light transmittance was -0.47. Here too, the use of optical measurement would not lead to strictly valid results for grammage variance.

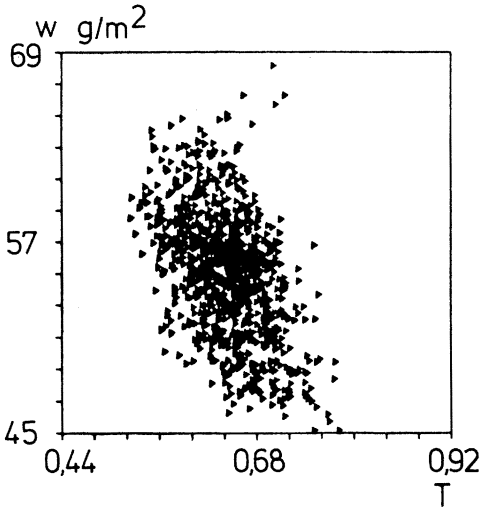

Fig 10—Relationship between light transmittance T and grammage w for highly beaten spruce sulphite pulp /6/.

Preliminary experiments to select relevant paper-making variables

In the present study the objective is to find out the limits of the various paper-making process variables which determine the applicability of the optical formation measurement technique and to examine the changes in the relationship between grammage and light transmittance as these variables are altered.

The purpose of the preliminary tests (phase 1) was to find out the relevant variables for systematic experiments. The following variables could potentially affect the relationship between the grammage and the light transmittance:

1.	Sheet structure:	Degree of formation Basis weight
2.	Raw material variables:	Type of fibrous material Filling Dyeing
3.	Process variables:	Beating Wet pressing Calendering

Variable	Range of variation
Formation	Delay time in the sheet mould before filtration; 10, 25, 40, 55, 70 seconds
Grammage	50, 100, 150, 200 g/m^2
Fibre type	100 % kraft, 70/30 kraft/GW, 50/50, 30/70, 100% GW
Filling	TiO_2; ash content 0 and 20 %
Dyeing	Will be carried out as a separate test. The sheet will be immersed in a coloured, non-polar liquid after measurements on undyed sheet. The same points of the sheet will be measured every time.
Beating	Valley hollander; load 5500 g, time 10, 30, 60, 90 min, (approximate drainage resistance 15, 20, 50, 80 ^{o}SR)
Wet Pressing	Laboratory press; pressure 0, 500, 1000, 1500 kPa
Calendering	Laboratory calender; constant speed 10 m/min, constant (ambient) temperature and humidity (50 % RH, 23^{o}C), hard rolls, four nips. Pressure 0, 20, 40, 80 and 160 kN/m.

Table 1
The range of variables studied in the preliminary tests

In the preliminary tests one of the variables in addition to formation was varied at a time, while the others remained constant. Semi-bleached pine kraft pulp was used as fibre material. In checking the effect of fibre type, ordinary groundwood pulp was used as well. The range of the variables studied is shown in Table 1.

In these tests the coefficient of variation was used as a formation index

$$F = 100(s_w/\bar{w}) \tag{6}$$

Another index of formation, calculated in another way, might better characterise the nature of areal mass distribution. Such an index might be, for example, the wavelength distribution that was used by Norman and Wahren(3) and Sara(2) in interpreting their radiograms, or even some new index describing the steepness of the floc edge. On the basis of our present knowledge, however, it is not possible to derive a formula for calculating a quantity like this in order to characterise better the end-use potential of a certain paper.

The results obtained show that there is an excellent linear dependence between the transmittances of light and beta-radiation in many cases. The results exhibit a much better correlation between the optical and the beta-measurements than any reported earlier(2-6). While the highest correlation reported by Sara was -0.92 on sack kraft paper (beta-radiation based grammage vs. light transmittance), in our results the correlation between the same quantities for laboratory handsheets has been -0.99 in many cases. Some results referring to constant formation conditions are presented in Table 2. For these sheets the coefficient of variation of grammage was about 9.5%. This was achieved by keeping the stock in the sheet mould for 70 s before filtration.

The results shown here are based upon measurements of one to three separate sheets per test point only. Thus it is too early to make any statements regarding the levels of various paper-making variables within which the optical formation measurement technique may be used.

TABLE 2. CORRELATION BETWEEN TRANSMITTANCES OF LIGHT AND BETA-RADIATION FOR SOME LABORATORY HANDSHEETS (50 g/m^2)

Fibre furnish kraft /groundwood	Drainage resistance	Pressure in wet pressing [kPa]	Ash content (TiO_2) [%]	Calendering load [kN/m]	Bendtsen roughness [ml/min]	Density [kg/m^3]	Coefficient of variation, transmittance of beta-radiation	Coefficient of variation, transmittance of light	Correlation between transmittances of beta-radiation and light
100/0	SR 15	490	20	0	-	-	9.4	10.4	0.95
0/100	"	"	0	"			7.0	8.9	0.97
70/30	"	"	"	"			10.0	8.4	0.98
100/0	"	"	"	"			9.6	7.7	0.98
"	"	0	"	"		330	10.2	8.3	0.99
"	"	500	"	"		509	9.6	7.6	0.98
"	"	1000	"	"		529	9.0	6.9	0.97
"	"	1500	"	"		557	8.1	5.8	0.95
"	"	490	"	20	480		10.7	6.9	0.98
"	"	"	"	40	145		9.8	5.5	0.95
"	"	"	"	80	53		9.7	3.6	0.84
"	"	"	"	160	24		9.9	2.6	0.52
"	SR 29	"	"	0			9.4	7.3	0.98
"	SR 58	"	"	"			9.1	7.6	0.97
"	SR 82	"	"	"			9.1	7.4	0.93
"	SR 92	"	"	"			10.6	7.5	0.91

Neither have the interactions between several simultaneous variables been studied so far. However, the results obtained do indicate the directions of the effects. The suitability of the optical measurement technique could possibly be assessed if the production history of the sheet to be measured were known.

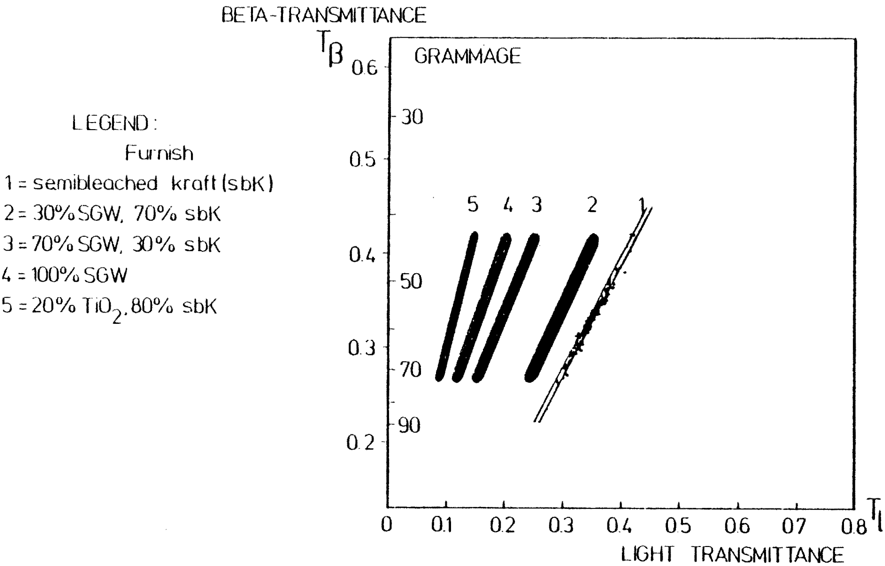

Fig 11—Effect of furnish composition on the relationship between transmittances of light T_l and beta-radiation T_β for laboratory handsheets.

The effect of furnish composition on the relationship between transmittances of light and beta-radiation is shown in figure 11.

For a pure semi-bleached kraft furnish the actual measured points are shown together with the lines of ± one standard deviation, determined from the linear regression relation obtained. In the other cases on this figure, as in the following figures, only the envelopes containing most of the measured points are shown.

An increase in the percentage of non-bonding furnish component, for instance substituting filler for a part of the long softwood fibre component, causes both the mean and standard deviation of the optical transmittance to decrease considerably. The results also show a very slight increase in light transmittance variation coefficient with increasing percentage of groundwood or filler. The increase in the slope of the correspondence between the transmittances of light and beta radiation will make accurate estimation of grammage more difficult with an increase in the proportion of groundwood or filler.

Increased refining causes both the mean and standard deviation of the optical transmittance to increase, thus decreasing the slope of correspondence between this quantity and the beta transmittance. In other words, although refining causes the sheet to be more even when inspected visually, the opposite is observed in the measurements (see figure 12). However, the relative range of scatter (coefficient of variation) of the light transmittance seems to remain roughly constant in refining.

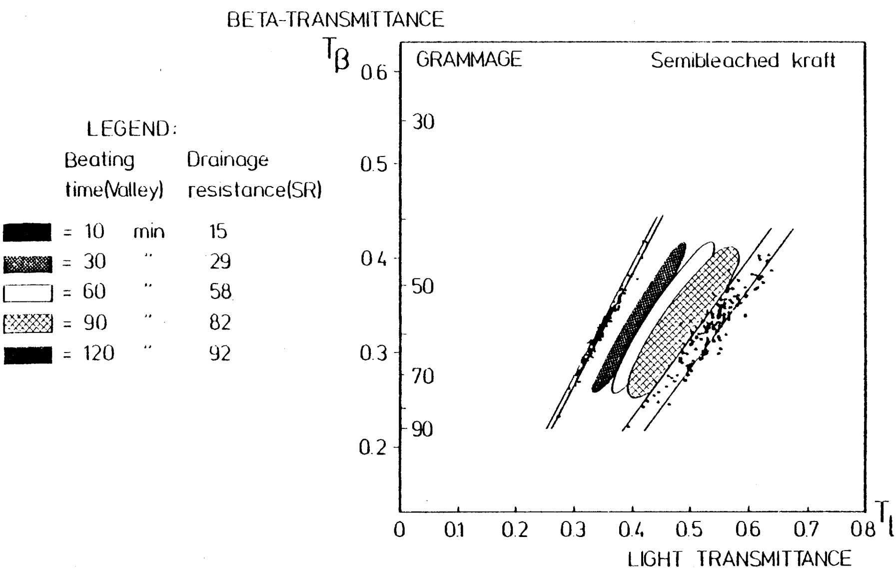

Fig 12—Effect of beating on the relationship between transmittances of light T_l and beta-radiation T_β for laboratory handsheets.

The effect of wet pressing on the relationship between the transmittances is shown in figure 13. An increase in wet pressing pressure very slightly decreases the deviation of light transmittance (the slope) and changes its mean. The slope of the correspondence does not seem to be sensitive to wet pressing at normal sheet densities.

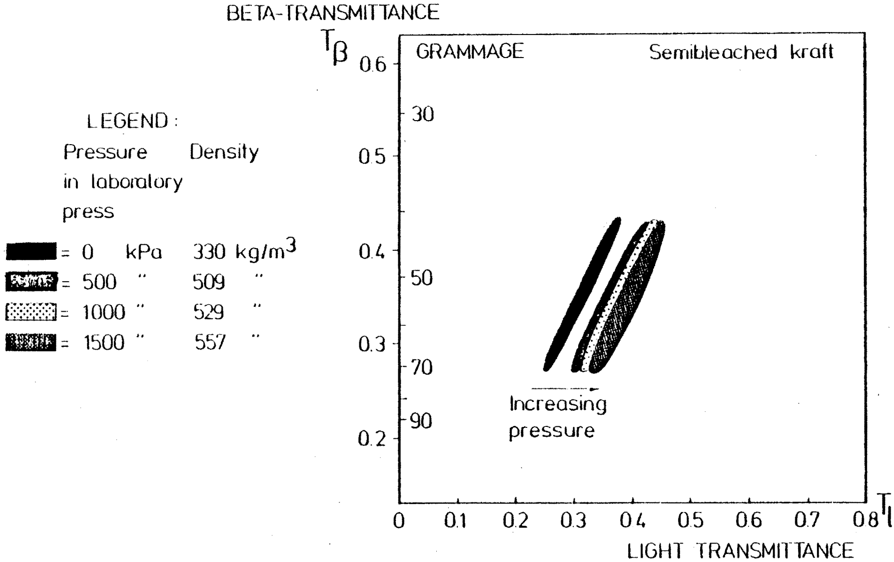

Fig 13—Effect of wet pressing on the relationship between transmittances of light T_1 and beta-radiation T_β for laboratory handsheets.

Calendering causes the density of the sheet to increase, at first in the thickest spots. This effect is observable even at relatively low calendering loads, while the thinnest spots on the sheet remain almost unchanged (figure 14). The optical transmittance of the thick, heavy spots increases with an increase in the calendering load, causing the standard deviation of the light transmittance to decrease drastically. Finally the correlation between the transmittances disappears completely and the slope of correspondence approaches infinity as the calendering load increases. Thus two spots of the sheet with entirely different grammage values may show the same light transmittance, because the number of transparent fibre crossings in the heavier, originally thicker spot has increased strongly. This means that the optical method becomes less accurate for characterising the actual formation of a calendered sheet.

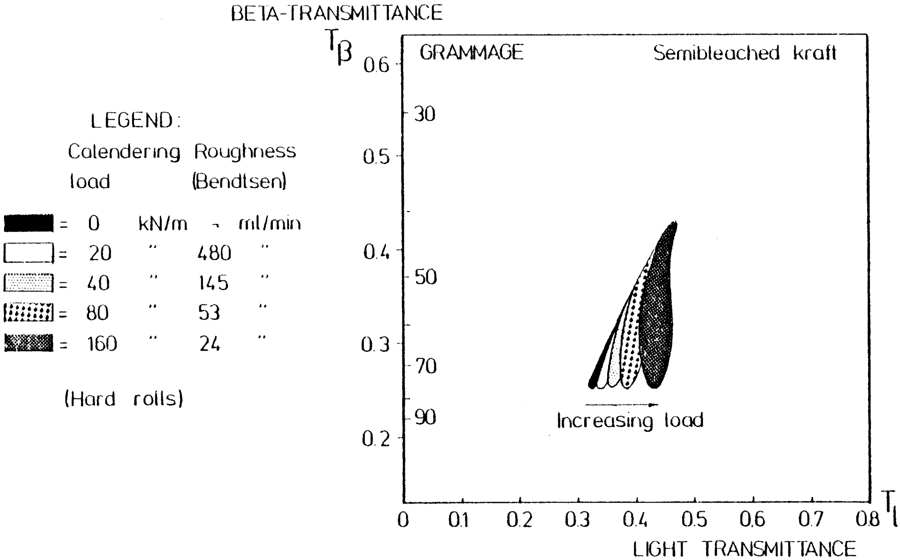

Fig 14—Effect of machine calendering on the relationship between transmittances of light T_1 and beta-radiation T_β for a laboratory handsheet.

The low activity of the available beta-radiation point sources limits the weight of sheet measurable to about 100 g/m^2. For point by point comparisons the accuracy of grammage measurement must be the same at every point, which is achieved in this experiment by counting always an equal number of pulses. With increasing grammage the counting time per measurement becomes too long to be practicable.

In figure 15 the effect of grammage variation on the relation between the transmittances is shown, for mean grammages between 40 g/m^2 and 90 g/m^2. In this range the relationship is linear so that it may be assumed that the results obtained from the 50 g/m^2 sheets will apply, to both lighter and heavier sheets.

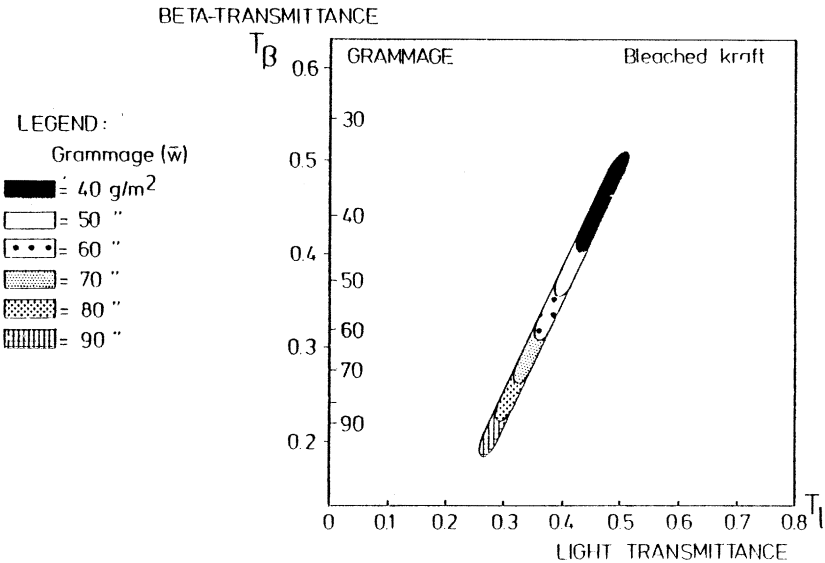

Fig 15—Effect of grammage variation on the relationship between transmittances of light T_1 and beta-radiation T_β for laboratory handsheets.

Table 3 shows some results for machine-made papers. Here grades have been chosen for which the optical measurement could possibly lead to erroneous results. The correlation between transmittances is considerably poorer than for the results in table 2. The relationships obtained are shown in figure 16.

Grade	Basis weight g/m^2	Variation coefficient T	Variation coefficient T_b	Correlation T *vs*. T_b
SC magazine paper	65	8.6	6.2	0.90
LWC (rotogravure)paper	65	3.4	3.4	0.52
Release paper	72	4.2	1.1	0.46
Greaseproof paper	40	5.6	3.9	0.79
Opaque greaseproof	40	6.2	2.9	0.81

Table 3.

Correlation between transmittances of light (T) and beta-radiation (T_b) for some machine made papers.

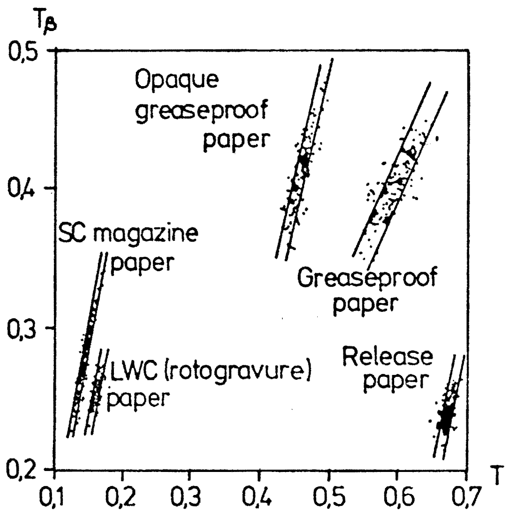

Fig 16—Relationships between transmittances of light T_1 and beta-radiation T_β for some machine made papers (measured observations are shown in addition to the lines of $\pm$ std. deviation calculated from the regression line).

Conclusions

In this study a unique formation measuring apparatus has been developed that offers the possibility of studying a little known property of paper, namely the relationship between its optical transmittance and true grammage.

Though the work is still in progress, the results obtained so far ensure that there is a good chance of verifying the validity of the optical method of formation measurement. However, it is still too early to consider publishing any guidelines on its use.

The results confirm the recognised fact that optical measurement does not give a true picture of areal mass distribution on the small scale. The information gained by optical measurement seems in many cases to be insufficient to predict the effect of small scale grammage variations on the behaviour of paper in, for example, the converting and printing processes. Depending on the formation index used, the optical method may however give reliable results, even though the point-by-point correlation between optical transmittance and grammage be not perfect.

NOMENCLATURE

A	Absorbance of light
a	$1/2(1/R_\infty + R_\infty)$
b	$1/2(1/R_\infty - R_\infty)$
C^W	Formation index based on true grammage values
C^{WT}	Formation index based on grammage estimations transformed from light transmittance values
F	Coefficient of variation, used as a formation index
G	Functional relationship between the grammage and the light transmittance used to transform the light transmittance values to estimations of grammage
I	Intensity of the light beam transmitted through the sheet
I_o	Intensity of the incident light beam
k	Absorption coefficient of the sheet
n	Number of beta-particles transmitted through the sheet
n_o	Number of incident beta-particles
R_∞	Reflectivity of the sheet
s	Scattering coefficient of the sheet
s_w	Standard deviation of grammage
T	Transmittance of light
T_b	Transmittance of beta-radiation
w_i	A true grammage value
$w_{T,i}$	An estimate of true grammage value obtained by the transform $w_{T,i} = G(T_i)$
$\bar{w}$	Mean of grammage
γ	Generalised absorption coefficient; combined effects of absorption and scattering of light
μ	Absorption coefficient of beta-radiation

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The authors wish to express sincere thanks to Mr. Pertti Aaltonen of the Laboratory of Paper Technology of the Helsinki University of Technology for his valuable advice and comments during the work.

Mr. Ilkka Niemelä has done an excellent work in designing and constructing the sensitive and accurate light transmittance meter. The personnel of the instrument workshop of the laboratory carried out the construction of the mechanical parts of the apparatus very skillfully.

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REFERENCES

1. Wahren, D., `Proposed definitions of some basic papermaking terms´, Svensk Papperstidn., 1967, **70**(21), p. 725-729
2. Sara, H., `The characterization and measurement of paper formation with standard deviation and power spectrum´, Helsinki 1978, Helsinki University of Technology, Dissertation, 162 p.
3. Norman, B. and Wahren D., `Mass distribution and sheet properties´, in `The fundamental properties of paper related to its uses´, Ed. F.M. Bolam, Tech. Sect., B.P.&B.M.A., London, 1976, p. 7-70
4. Aaltonen, P. and Simola, J., `An automatic measuring device for semi-micro scale analysis of certain paper properties´, Paper & Timber (Finland), 1971, **53**(9), p. 479-488
5. Miller, C and Kallmes O., `A practical formation tester based on mass variations´, Pulp & Paper Mag. Can., 1978, **79**(2), p.79-82
6. Komppa A., `An apparatus for measurement of transmittances of light and beta-radiation simultaneously point by point´, Helsinki, 1978, Helsinki University of Technology, Forest Products Department, Thesis work (M.Sc), p. 86

7. Evans, R.D., `The atomic nucleus´, McGraw-Hill, New York, 1955, 972 p.

8. Herdman, P.T. and Corte, H., `Comments on the distribution of mass density in paper´, Pulp & Paper Mag. Can., 1980, **81**(10), p.68-71.

9. Andersson, O., `Properties and measurements of paper reflectance fluctuations´, Svensk Paperstidn., 1965, **68**(13), p.465

10. Komppa, A., `Apparatus for measuring paper formation coaxially with light and beta radiation´, To be published.

APPENDIX

In the preliminary tests the light and beta-ray transmittance measurements were performed on specimens of size approximately 100 mm x 30 mm such that the distance between two successive points is 4.5 mm. The number of measurements performed for one specimen is thus 150. Assuming that the variation of the grammage is distributed normally, the accuracy of the estimate of standard deviation can be calculated as follows:

For a normally distributed variable the quantity ns^2/σ^2 is X^2_{n-1} distributed, where

n = number of observations
s^2 = estimate of variance
σ^2 = the variance of the population

The relationship between the number of observations and the ratio s/σ is shown in figure I-1. Assuming that the variation of the grammage on the measured area is equal to the variation of the entire population the accuracy of the estimate of variance s^2 increases very slowly after a sample size of 150 observations. Using a sample size of 150 observations $s = \sigma \pm 11\%$ with a probability of 95 %(2).

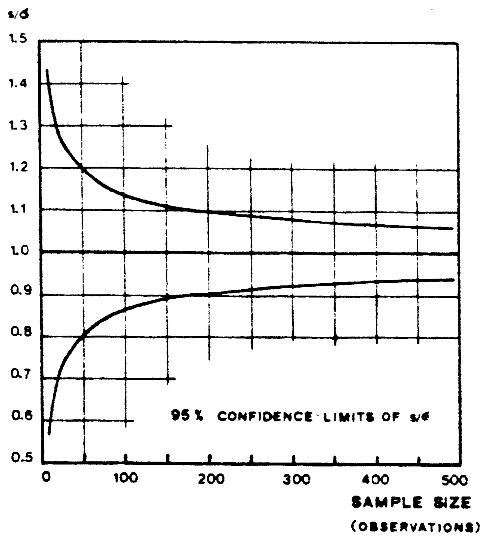

Fig I-1—Relationship between the sample size and confidence limits of s/c at 95% confidence level.

Transcription of Discussion

Discussion

Discussion following paper 6.1 by Mr. A. Komppa and Prof. K.I. Ebeling

Dr. R.F. Edgar, Infrared Engineering, UK

Firstly, do you make any effort in your experimental arrangement to destroy the coherence of the laser light? I would worry that if you don't continuously vary this, you might get noise, over and above the formation noise, as a result of optical coherence effects.

Secondly, have you considered making use of the reflected light as well as the transmitted light in order to eliminate scatter? By doing so, I think you could make the optical system work a lot better, and perhaps improve the correlation with grammage.

Mr. A. Komppa, Helsinki University of Technology, Finland

To answer your first question, we no longer use a laser: our light source is a white halogen lamp. Secondly, we used to make use of reflected light in our previous apparatus to improve the correlations, but the results obtained did not give much useful information. In the present apparatus there's no room for reflectance measurement.

Dr. J. Colley, APPM Ltd, Australia

I would like to comment on the importance of the density distribution on printability. In particular, I would like to suggest that of the three examples shown earlier, that with the worst apparent formation would have the worst printability, despite the fact that all three formations were actually the same. Would you comment on this?

Prof. K.I. Ebeling, Helsinki University of Technology, Finland

Thank you, you are absolutely correct. Formation alone will not determine printability. The response of the printing press is much more governed by surface properties than by bulk properties. Printability is very much influenced by density distribution, and I do not think we shall go on to consider density distribution.

Mr. A. Ibrahim, AccuRay, USA
You have selected two variables, calendering and beating, to investigate. Have you considered trying to investigate the influence of other paper-making variables more under the operator's control, for example headbox efflux ratio, jet impingement angle, forming board distance and headbox consistency, on the agreement between paper opacity and its grammage?

Mr. A. Komppa
That's not the aim of this study. Because of the wide range of the parameters studied we had to work entirely in the laboratory. Thus we're not able to investigate the influence of all the paper machine variables. Of course the parameters you mention do have an important effect on formation.

Prof. K. I. Ebeling
I would like to point out that our prime concern was to compare the optical properties of the paper with its grammage, so that the variables you mention, though of importance in determining the formation of the paper, are not necessarily relevant to our investigation.

Dr. W. C. Rutledge, Mead Corporation, USA
Is the response of your photo-diodes and electronics fast enough that your equipment could be used to measure density variations on the machine? One of the draw-backs of beta gauges is their inability to respond fast enough to see micro-density variations.

Mr. A. Komppa
Possibly, but because we are aiming for the highest possible precision our response time is quite long.

Prof. K.I. Ebeling

The beta gauge is so slow that to do point-to-point correlation, as we are doing, the sample must be stationary for the measurement. But, as you all know, one of the great advantages of the optical method of grammage determination is its high speed.

Dr. H. Corte, Wigins Teape, UK

Did you move your samples continuously or discontinuously?

Prof. K. I. Ebeling

Discontinuously.

Dr. H. Corte

And the average number of particles was 50,000? That's what you give in the text.

Prof. K. I. Ebeling

The results presented here are based on counting 20,000 pulses. (This was amended after the symposium to 50,000. ed.)

Dr. H. Corte

20,000. Did you use a scintillation counter to detect the elctrons?

Mr. A. Komppa

No, it was a Philips proportional tube detector (ionisation chamber) we were using.

Dr. H. Corte

You realise of course that in that case you were not measuring the individual electrons because there is a continuous energy spectrum. You are only measuring a signal related to the number of beta particles transmitted through the paper. We have found, that although the half-life of the beta decay of Promethium is 2.6 years, the half-life of the accompanying gamma radiation is much longer. This means that, though after 2.6

years you will still have half the original number of electrons emitted from your source, your signal- to-noise ratio will be considerably worse. Have you noticed that?

Mr. A. Komppa

Yes, we have noticed this. However, because of the low activity of the Promethium point sources available, we have to change our source about once a year anyway.