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The Formation of Paper and the Measurement of Formation

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Abstract

In paper the evenness of planar distribution of mass in a small scale is called formation (or better: mass formation). Traditionally formation has been assessed visually, by looking the sheet of paper against transmitted light. Different kinds of optical testers are being used to obtain quantitative rankings that would be independent of the observer but would well correspond to the visual assessment. However, various raw-material and process factors do influence light transmittance in paper and do impair the correspondence between basis weight and the optical formation measurement (or visual assessment).

As the optical formation test methods do not incorporate an efficient calibration routine, the formation of the sophisticated paper grades of today the is rather difficult to measure optically and may lead to erroneous results. It may be concluded that the optical measurement is not suitable for paper grades with high filler content, coating, heavy calendering or that are made of heavily beaten pulp, nor does it apply for dyed or printed papers. For this reason, visual assessment and optical evaluation should be replaced with a measurement that gives reliable results independent on paper grade and manufacturing process.

Formation measurement based on beta radiation is suitable for all paper grades regardless to the material contents or process treatment. It is possible to measure even dyed or printed samples. Thanks to a simple and reliable calibration, the results are converted to real basis weight values that remain reliable even with time. The only beta tester commercially available is the AMBERTEC Beta Formation Tester.

Formation of paper does vary locally in the web. Typically there exists a formation profile, too, similarly to other properties of paper. Therefore, formation should always be expressed as a mean of a sufficient amount of parallel determinations. All formation measurements should be calibrated against basis weight.

What is formation ?

The quality requirements for modern paper grades do continuously increase. Therefore, a smooth formation of paper has become a desired property, as it, for instance results in high strength and good printing result. Formation does also vary locally in paper, even possessing a profile across the machine width, similarly to other properties of paper. Hence, there is an increasing demand for reliable formation measurement and control in paper mills.

Traditionally, paper makers judge formation visually, by viewing a sheet of paper against transmitted light, usually spread onto a light table. According to experience, this visual impression does quite well correspond to the true basis weight variation for uncalendered paper grades that are made of chemical or mechanical pulp only, without any filler or coating. The furnish composition and the process of the modern paper grades are very complicated and the evenness of material distribution cannot be reliably assessed any longer.

Today the traditional definition of paper formation ("you can see it") is no more generally useful. As it was earlier possible to visually estimate the evenness of material distribution it was quite natural not to make any difference between the true planar distribution of mass and the visual impression based on the distribution of light transmittance in the sheet and both were therefore called *formation*. Now this term is confusing and should be replaced for instance by "*mass formation*".

Mass formation is the evenness of planar distribution of mass in a small scale. There are several opinions on the scale but the most common one calls formation all basis weight variation shorter than 100 mm in wavelength. Based on research at the Helsinki University of Technology over decades, AMBERTEC has chosen 70 mm as the upper limit in wavelength: the scale should be chosen in such way that there exist several flocs in the area measured.

How formation should be measured ?

Direct gravimetric measurement

Because formation is defined as the evenness of planar distribution of mass the most straightforward method for formation measurement would be weighing tiny pieces of paper. Some gravimetric formation measurements have been carried out but this kind of a measurement, however, is very impractical: a newsprint paper specimen, 1 mm in diameter, weighs less than 50 micrograms and is extremely difficult to handle.

Indirect measurements

As it is practically impossible to measure formation gravimetrically, an indirect method must be used. There are two different principles available so far: one is based on the *transmittance of beta radiation* and the other on the *transmittance of light.*

The transmittance of beta radiation or light is used assuming that there exists an unambiguous correspondence between the transmittance and the basis weight of paper. This assumption is practically true for the beta radiation transmittance but poor in the case of light transmittance: many things do affect the optical behaviour of paper and therefore the correspondence between light transmittance and basis weight is often ambiguous.

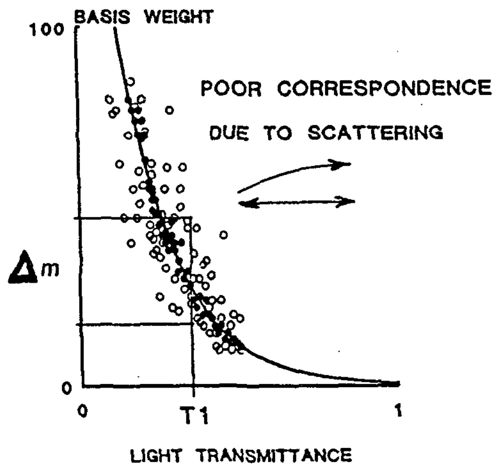

Figure 1. The correspondence between light transmittance and basis weight in paper. There always exists some variation of light transmittance in paper that is independent of basis weight variation. This impairs the correspondence. If the correspondence is poor, a single value of light transmittance no longer corresponds to a single value of basis weight but a broad range and the optical formation measurement is no longer useful.

- An addition of fines, filler or into the furnish does decrease the light transmittance of the sheet and the curve moves left.

- Beating and wet pressing increase the bonding degree and hence, light transmittance and the curve moves to right.

- Calendering increases the light transmittance of the heaviest spots of the sheet; with increasing nip load the upper end of the curve bends to right.

- Both beating and calendering increase the amount of basis weight -independent variation of light transmittance in the sheet (i.e. the scattering across the curve).

If there is an unambiguous correspondence between basis weight and transmittance (see the curve in Fig. 1) a single measured transmittance value does correspond to a ***single value*** of basis weight. However, if the correspondence is ambiguous, i.e. if there exist transmittance variation that is independent of basis weight variation in paper (see the points scattering across the curve in Fig. 1) a single transmittance value no longer corresponds to a single basis weight value but a ***range***. The range depends on the degree of ambiguity (i.e. the scattering across the curve).

Beta formation measurement

The absorption of beta radiation with suitable energy is very closely the same for all material components of paper. Therefore, the correspondence between basis weight and beta radiation transmittance is unambiguous. The ***measurement based on beta radiation is excellent in accuracy*** and it may well be compared to gravimetric determination. As the transmittance of beta radiation in paper is a function of mass only, even coloured or printed samples can be reliably measured.

Direct beta formation measurement

So far the only commercially available beta formation tester is based on direct measurement of beta radiation transmittance. The device, AMBERTEC Beta Formation Tester, is designed for continuous, automatic formation measurement at paper mill laboratories.

The beta radiation measurement is easy to calibrate against the true basis weight variation of the sample (Fig. 2). As all material components of paper do possess practically the same absorption coefficient when using Promethium-147 sources, the results from a beta measurement are independent of furnish composition, filler type and amount, colour, coating and all of the process variables including beating, wet pressing or calendering. Therefore it is possible to measure samples made of heavily beaten pulp as well as samples that are thick, calendered or even printed ones. This is very useful: if formation is suspected to be the cause for poor printing results it may be directly measured from the poorly printed area.

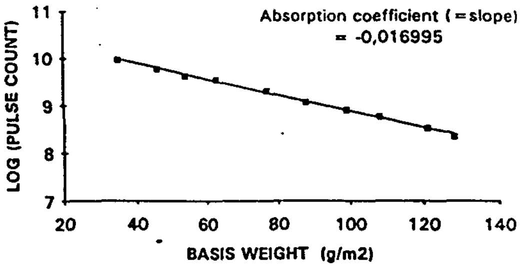

Figure 2. Typical calibration of a Beta Formation Tester. A set of mill made papers with different furnishes and basis weight are measured (black squares). With a sufficient number of sheet even the effect of slight errors in the basis weight of the sheets is negligible. The slope of the regression line gives the absorption coefficient of beta radiation in paper.
Calibration is to be carried out over the entire basis weight range used for formation measurements. A similar calibration routine may be used for different speciality sheet materials (polymer, glass, etc.)

Direct beta measurement is very easy today and is almost as fast as the optical off-line measurement. For example, the AMBERTEC Beta Formation Tester may be run 24 hours per day without operator supervision as it is possible to load up to 200 sheets at a time into the tester. As the tester can also be connected to the mill laboratory data computer network the formation test results can be automatically transmitted to the laboratory test database.

Beta radiography

A measurement based on beta radiation transmittance may also be carried out indirectly, through radiography. In beta radiography a beta radiograph of the sheet is first exposed onto a X-ray film and the film will then be measured optically, usually using image analysis.

The resolution of beta radiography is very high (down to 0.1 mm in aperture) and it allows the use of even very complicated indices. However, the exposure of the radiograph as well as the measurement is rather time consuming, complex and sensitive to errors in the development process and therefore it is mainly used at research institutes only. The method allows the measurement of samples up to slightly above 100 g/m^2 (when using the most common Carbon-14 source of radiation).

Optical measurement

In principle, the correspondence between basis weight and light transmittance may change in three different ways: the position, the slope or the amount of scattering across the curve may change. When the amount of fines or filler in the furnish is increased the light transmittance of the sheet decreases and the curve of correspondence moves left towards the origin (Fig. 1). The addition of dye increases the light absorbency and the curve moves left again. Wet pressing and beating increase the bonding degree and the curve moves right with the increasing light transmittance.

In calendering the 'hill-top' (heaviest) places of the sheet first bear the nip load and the light transmittance at these spots strongly increases; the upper end of the correspondence curve bends strongly to right (Fig. 3). Finally there might be places in paper that simultaneously possess both higher basis weight and higher light transmittance than the rest of the sheet. This can be shown through a simple experiment: if a sheet with watermark is calendered with increasing nip load, at a certain load the watermark totally disappears!! This is due to the increase of light transmittance (due to increased bonding of the fibres in the sheet): the transmittance level of the (lower basis weight) watermark will be reached.

Especially calendering and beating strongly increase the amount of basis-weight--independent variation of light transmittance (the scattering across the curve in Fig. 1) that finally makes the optical measurement impossible.

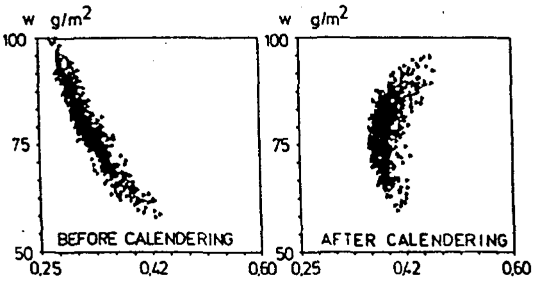

Figure 3. The effect of calendering on the correspondence between basis weight and light transmittance (laboratory fine paper furnish handsheets). In calendering the thickest spots of the sheet do bear the nip load and the light transmittance does strongly increase due to increased bonding degree. In these kind of cases the optical measurement will give totally misleading results.

Fig. 4 shows the correspondence between grammage and light transmittance for some mill made papers. The best correspondence will be obtained for uncalendered paper grades made of chemical or mechanical pulp without filler or coating. Supercalendering of SC base paper (#1 to #2 in Fig. 4) strongly increases the slope. The only difference between the MF lightweight papers (#4 and #5) was in the dye shade, the one was yellowish and the other slightly greenish; the difference in correspondence is remarkable, however. In the bible paper (#3) the correspondence is clearly curvilinear. In glassine (#6) the effect of prolonged beating and in release papers (#7 and #8) the effects of both beating and heavy calendering are clearly visible.

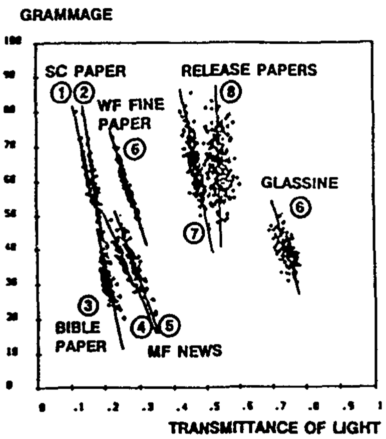

Figure 4. ***The correspondence between basis weight and light transmittance for some mill made papers. Calendering (#1->#2) strongly affects the slope as does even a slight addition of dye (#5->#4). The optical measurement is not at all applicable for papers that are highly filler loaded (#3), made of heavily beaten pulp (#9) or heavily calendered (#7 and #8).***

It is easy to understand that for most of these mill made paper grades a *typical optical formation measurement* does only give more or less random number test results as a single value of light transmittance may equal to the entire basis weight range of the sheet. The result obtained from an optical formation measurement is not reliable because it does depend on the furnish composition, manufacturing process and thickness variation of the sheet. Also, it strongly depends on the spectral properties of the light source as well as of the detector. If the spectrum is monochromatic (e.g. like for a laser) the test results will be rather sensitive to sample colour variation.

Obviously the formation of printed samples cannot be measured optically - the tester would merely read the print ink variations.

Typically the optical testers are fast and a big number of points per determination will be measured.

In theory a small measuring aperture may be used in the optical formation measurement - but only in theory, as the sheet thickness variations do cause large variations in the actual measuring aperture due to light scattering in the sheet.

The correspondence between basis weight and light transmittance does strongly vary with time, due to changes in the furnish and process (1). Therefore, the optical testers even should be separately calibrated for each sheet to be measured. Without exception ***the optical testers cannot be reliably calibrated against basis weight.*** Even a proper calibration can only remove the effect of furnish composition but it cannot remove any effects of basis weight-independent variation of light transmittance, due to process variables. Many users of optical formation testers have been disappointed to see that even the same paper grade gives different readings from day to day or that as the formation was made today to the same numerical levels as yesterday, the sheet looks very different. A properly calibrated beta formation tester always gives true basis weight variation figures.

The users of optical testers therefore should be well aware of the different factors (e.g. the colour variations of the sample) affecting the test results and they should know for which paper grades the tester can be reliably used. This is rather easy to verify using different kinds of mill made papers or laboratory handsheets that will be suitably coloured or calendered.

Based on the above facts, visual assessment and optical formation measurement cannot be recommended for most of the modern paper grades. Instead, the ***beta formation measurement should be used as it is superior in accuracy and can be used for all paper grades - and even printed papers!***

Formation indices

The usefulness of the test result strongly depends on the index of formation used. A good index is both single and unambiguous, it does not depend on the basis weight level but depends in a known manner on the sheet properties. Also the index should describe the end use properties of the sheet. All of these requirements are rather controversial.

This kind of an index is practically impossible and therefore usually only simple and easy-to-understand indices are used. These include the standard deviation and the coefficient of variation of basis weight and light transmittance. Despite of the simplicity the standard deviation is a very good one: it has been shown for example, that there is a very high correlation, up to 0.7-0.9 between the offset print unevenness and the standard deviation of basis weight, obtained from beta formation measurement (2,3).

The interpretation of more complex indices like the power spectrum, is not easy and unambiguous in terms of a few figures only. Therefore, they are not widely used in the formation testers aimed for routine operation or quality control.

Various testers do produce different types of floc maps. In a multi-colour or multi-shade map the different colours/shades refer to different transmittance levels alike the height isolines on a topographic map. The interpretation of these maps is difficult, however.

Ideally, an index simultaneously would tell the user both the intensity and the nature of the basis weight variation and possibly even certain special features of the variation like streaks or defects. This kind of an index is not available, yet.

Sampling for the measurement

Formation does possess a profile like other paper properties, too (Fig. 5). This should be kept in mind when taking samples for formation measurement. According to vast experience the formation even between rolls, side by side at the winder may vary extensively: one might be excellent as the other may cause reclamation. Therefore the measurement should not be carried out of a single sheet per sample only - in either optical or beta method! Parallel determinations are required for all other paper properties and that should apply for formation, too.

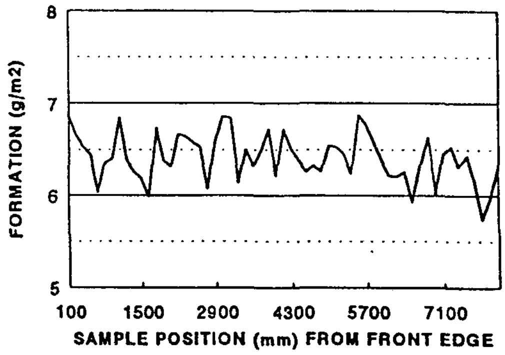

Figure 5. A typical cross directional formation profile. Formation (standard deviation of basis weight) = 6.4±0.1 g/m² (95% confidence limits). Each single value represents a 400 point measurement over an area of 70 mm x 70 mm, taken at 140 mm intervals in cross direction of the web. Maximum value 6.9 g/m². Minimum value 5.7 g/m².

Along with the test result also a measure for the reliability of the result should be given e.g. in the form of 95% confidence limits. This gives reference for reliable comparison of formation readings. Low confidence limit figures suggest that the formation is even over the sample width or that the sample sheets were taken from one machine directional position of the web only. In direct beta formation method the 95% confidence limits for a measurement consisting of 4-7 parallel determinations usually are 0.1 - 0.2 g/m^2, e.g. for wood containing printing papers with a smooth formation profile.

Conclusions

All furnish component and paper process variations do change the correspondence between *basis weight and light transmittance* through the sheet. However, the correspondence between (Pm-147) *beta radiation transmittance and basis weight is practically constant* for all furnish components of paper and is not affected by process variables either (and not even by printing). Therefore, the **beta radiation based method is the only reliable formation measurement** for the modern paper grades containing fillers, coating, dye (or multi-colour fibres) and especially for those ones that are calendered or made of heavily beaten pulp.

All formation testers should be regularly calibrated. Otherwise the changes is electronics, detectors, lamps or radiation sources may unexpectedly affect the results. All other test instruments in paper industry are being calibrated, why not formation testers, too!

Formation of a web is not constant but does strongly vary from point to point and it even does possess a profile. Therefore, **formation should never be measured from a single sheet per sample only** but preferably from at least 4 (preferably 7) specimen, taken from different locations over the web if only possible.

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