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INTERACTIONS BETWEEN COATING COLOUR AND BASE SHEET IN PIGMENT COATING

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ABSTRACT

The literature on the interactions between the coating colour and the base sheet during the pigment coating of paper is reviewed in the order to summarize the current knowledge within the area. The review is focused on the processes of forming and consolidation and on how the coating colour interacts with the base sheet during these processes, and how this interaction affects coating hold-out, roughness and coating mass distribution. A coating layer which stays on the surface of the base sheet and which has a uniform mass distribution is desired. The research world disagrees on whether coating hold-out is a relevant problem. The reason is that there is little direct evidence in the literature on coating penetration. However, there are numerous indications of an indirect character which suggest that coating penetration exists, both in blade coating and in coating with the metered size press. The pressure pulse to which the coating colour is subjected in the applicator nip during blade coating or in the transfer nip in metered size press coating and the permeability of the base sheet are factors which are said to control coating penetration. There is concordance in the opinion that the uptake of the aqueous phase of the coating layer is an extremely rapid process and that this uptake releases stresses in the sheet and plasticizes it. The release of stresses leads to roughening of the sheet whereas the plasticization makes it compressible and smooth in a compressed state

beneath the blade tip during the forming of the coating layer. Much attention has been given to the roughening and a number of extensive studies have been published about that. The studies on plasticization and sheet compressibility and how they affect the mass distribution of the final coating layer are fewer in number but non-existent. The roughening and plasticization of the sheet are reported to be different for woodfree and wood-containing sheets, due not only to the different types of fibres in the sheets, but also to their different densities. Woodfree sheets, which are generally the densest, are considered to be dimensionally the most stable. A number of researchers have reported that the pre-calendering has a great influence on the roughening. Studies have shown that the calendering builds in transverse stresses into the sheet and, in the case of wood- containing sheets, closes the lumen of thick-walled fibres. During the coating operation, when the sheet takes up the aqueous phase from the coating colour, these stresses are released and the lumen is opened. Several researchers have shown that all the smoothening effect of the pre-calendering can be lost during the coating process.

INTRODUCTION

Pigment-coated papers and paperboards are used as print carrier for multi-colour print when the demands on print quality are high. Magazines and consumer packages are two examples of such products.

The pigment coating is applied to the paper (for the sake of simplicity "paper" hereafter denotes both "paper and paperboard") in the form of a so-called coating colour, which consists of pigment, co-binder (thickener), and a latex binder suspended in water. Ground calcium carbonate (GCC) and kaolin clay are the two most frequently used pigments. Examples of frequently used co-binder are starch and carboxymethyl cellulose (CMC), and examples of frequently used latex binders are styrene-butadiene latex and acrylic latex. The dry solids content of the coating colour varies depending on its composition and on the coating technique used, but it is generally within the 60–65% range.

Blade coating is the most frequently used coating technique. In this technique, an excess of coating colour is applied to the paper to be coated, which is then metered to the target coat weight with a steel blade pressed against the paper, Figure 1. The coating layer is formed beneath the blade tip. There are

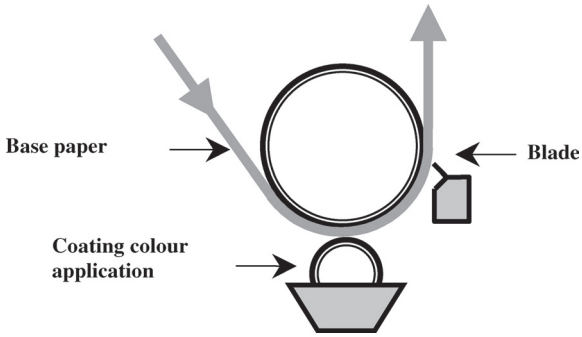

Figure 1 Schematic picture of a blade-coater with roll application of the coating colour.

different techniques for the application of the colour which differ in pressure in the application zone and in dwell time prior to the blade. The blade metering can take place according to two modes; bent blade and bevelled (stiff) blade.

Another coating technique which is gaining in popularity is the metered size press (MSP) technique. In this technique, the paper to be coated is passed through a nip between two rolls (transfer rolls) on which a pre-dosed amount of coating colour is applied with an application unit of some kind, Figure 2. The coating colour is transferred to the paper in the nip and both sides of the paper can be coated simultaneously.

Paper is a porous and hygroscopic material and the coating colour is water-borne. Therefore, paper and coating colour interact with each other and this

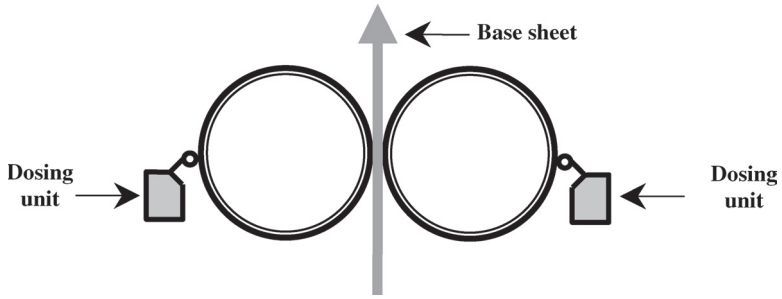

Figure 2 Schematic picture of a MSP-coater.

interaction starts immediately after the colour has been brought into contact with the paper and it continues during the whole process of consolidation. During this process, the coating colour may penetrate into the porous structure of the base sheet. This is undesirable because colour which has penetrated into the paper does not contribute to the coverage [1–10]. Moreover, the penetration is not uniform due to natural imperfections of the base sheet. Some areas are more absorbent than others and this may lead to a non-uniform composition and porosity of the coating layer [10–12]. A uniform coating layer with good coverability is a pre-requisite for superior printing properties [13].

The aqueous phase of the coating colour interacts with the fibres in the sheet [14–20]. This interaction, which includes fibre swelling, de-bonding and stress relaxation, leads to a movement in the base sheet beneath the wet coating layer during the consolidation. This movement makes the coated paper rough. After calendering, this roughness is transformed into non-uniformities in gloss, texture and porosity, which, as already mentioned, are detrimental for the printing properties. It should also be pointed out that the conditions during the forming of the coating layer are influenced by the interaction between the aqueous phase and the fibres in the base sheet [22–28] prior to the forming.

The objective of this paper is to review and discuss the interactions between the aqueous phase of the coating colour and the base sheet during the processes of application, forming and consolidation in blade coating and MSP-coating and their influence on the uniformity of the coating layer. The review is focused on the base sheet and coated sheet rather than on the fibres which build up these sheets. There are two reasons for making that priority. The first is that such a review is lacking and the second is that an excellent review of the general character of fibre-water interaction was presented at this symposium in 1993 by Salmén [29]. The review begins with a brief description of the uptake mechanism governing coating penetration and aqueous phase penetration. This is followed by a discussion of the different process stages.

UPTAKE MECHANISMS

Coating colour penetration

Paper is a porous material built of wood fibres. When an aqueous suspension, such as a coating colour, is applied onto such a material, the pores can take up the whole suspension or they can separate the aqueous phase from the solid phase. The solid phase will then stay on the surface and, in the case of a

coating colour, form the coating layer. Which of the uptake processes is the dominating one is dependent on the dimension of the pores in the base sheet and on the dimensions of the pigment particles or aggregates of pigment particles in the suspension. The pressure under which the uptake occurs is also important, since it governs the dimensions of the aggregates in the coating colour.

Coating colour penetration into the base sheet is assumed to take place under the influence of an external pressure during the application of the coating colour and during the metering beneath the blade tip in blade coating and in the transfer nip in MSP-coating. As long as the coating colour is fluid and no flow barrier (filter cake) has been developed, the rate of penetration per unit area, Q/A, can be described by Darcy's law:

$$\frac{Q}{A} = \frac{-K\Delta P}{\eta l} \tag{1}$$

where K denotes the permeability of the base sheet, ΔP the pressure drop across the sheet, η the coating colour viscosity and l the thickness of the sheet.

For a bed of packed spherical particles with a diameter of d_{eff}, the permeability K is given by the Kozeny-Carman equation:

$$K = \frac{\phi^3 \, d_{eff}^2}{36\kappa(1-\phi)^2} \tag{2}$$

where Φ denotes the pore volume fraction of the bed and κ the Kozeny constant (usually =5). Experimental studies of the relationship between the permeability and the porosity of filters and compressed mats made of Nylon, Dacron, glass and unbeaten sulphite have shown that Equation (2) is valid with reasonable accuracy [30, 31]. However, the permeability of paper differs from that of an ideal fibre network because of the effects of external fibrillation, fines and fillers [32].

Liquid penetration

The aqueous phase of the coating colour is taken up both by the pores in the sheet, so- called inter-fibre sorption, and by the fibres themselves, so-called fibre sorption. The former is governed by a capillary process whereas the latter is regarded as a diffusion process [33, 34]. The aqueous phase can also be taken up by surface diffusion or vapour phase diffusion ahead of the liquid front [35].

The capillary uptake is usually described using the Lucas-Washburn equation:

$$\frac{dh}{dt} = \frac{r\gamma \cos\theta}{4\eta h} \tag{3}$$

which after integration gives the more familiar expression:

$$h = \sqrt{\frac{r\gamma \cos\theta}{2\eta} t} \tag{4}$$

where h denotes the capillary rise and η and μ the viscosity and the surface tension of the liquid, respectively, θ the contact angle, r the pore radius, and t the time.

If an external pressure is influencing the capillary uptake, the Lucas-Washburn equation can be modified to account for this by including a term, ΔP, for the external pressure:

$$h = \sqrt{\left(\frac{r^2}{4\eta}\right)\left(\frac{2\gamma \cos\theta}{r} + \Delta P\right)t} \tag{5}$$

The corresponding expression for fibre sorption is Fick's second law which can be written:

$$\frac{dc}{dt} = D\frac{d^2c}{dx^2} \tag{6}$$

where c denotes the concentration at the depth x in the base sheet and D the diffusion coefficient.

Integrating twice with the boundary conditions $c = c_o$ for $t = 0$ and $c = c_o + k\sqrt{t}$ for $t > 0$ yields [36, 37]:

$$c = c_o + k\sqrt{\pi t}\left(ierf\frac{x}{Dt}\right) \tag{7}$$

where c_o denotes the concentration at the time of application and k a constant.

Common for both capillary penetration and diffusion is that they are both dependent on the square root of time. The difference between them is the

driving force and the opposing force for the uptake. For capillary uptake, the driving force is the capillary pressure and/or an external pressure. For diffusion, it is the concentration gradient over the interface between the base sheet and the wet coating layer. The opposing force for capillary penetration is the viscosity of the penetrating liquid and the rate of penetration decreases with increasing viscosity. Diffusion is not influenced by the viscosity of the liquid. Both capillary penetration and diffusion are relevant in coating.

Increasing the viscosity of the aqueous phase of the coating colour by the addition of thickener, for example CMC, reduces the uptake and improves the water retention of the coating colour only if the uptake is governed by a capillary process. If the uptake is governed by a diffusion process, the addition of thickener has only a marginal effect on the concentration gradient, and therefore the uptake and the water retention are affected only marginally by the addition. Knowledge of which process is governing the liquid uptake is vital when choosing a thickener for the coating colour. It is also crucial for the water retention test method to be used.

The time scales of the various phases in coating during which the aqueous phase of the coating colour interacts with the base sheet are in most cases extremely short. In blade coating at a machine speed of 1000 m/min, the residence time is approximately 3 ms in the applicator nip and approximately 0.035 ms beneath the blade tip. At the same machine speed, the residence time in the transfer nip in MSP-coating is approximately 3 ms. Bristow [38] has developed a device to study liquid sorption at short time scales. The device is known under the name Bristow-wheel and it is now widely used for absorption measurements at short times [e.g. 39–41]. Bristow [38] used this device in a systematic study of the influence of liquid and sheet properties on the liquid uptake in sized kraft paper. In Figure 3 the influence of the viscosity of two types of liquids; one hydrophobic (mineral oils of different viscosities) and one hydrophilic (water) is shown. The uptake mechanisms for these two liquids are different. The mineral oil is taken up solely by the pores, whereas the water is taken up both by the pores and the fibres themselves. For the mineral oils, the influence of the viscosity was in agreement with the Lucas-Washburn equation. This shows that oil absorption can be used to characterize the pore structure of paper.

The uptake of the water did not, however, obey the Lucas-Washburn equation. There are two reasons for this. The first is, as already mentioned, that water is taken up not only by the pores but also by the fibres. The second is that the water uptake of the fibres causes them to swell. This affects the pore structure during the course of uptake.

Salminen [42] has developed a device, based on the Bristow-wheel, with which liquid sorption at short times can be studied at elevated pressures and

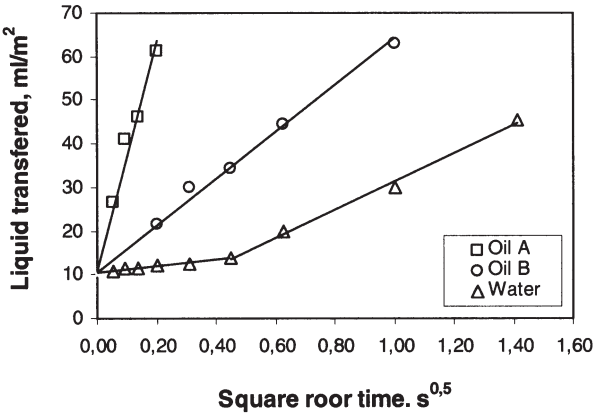

Figure 3 Liquid uptake as function of square root of time [38].

temperatures. This is interesting, since the application of the coating colour and the forming of the coating layer take place at elevated pressures and at temperatures above room temperature. In blade coating at a machine speed of 1000 m/min the pressure in the applicator nip in roll application is approximately 100 kPa [43] and beneath the blade tip it is approximately 1000 kPa [44, 45]. In MSP-coating at the same machine speed the pressure in the transfer nip is 400 kPa [46]. A typical temperature of the coating colour at the time of application is within the 50–60°C range.

Salminen [42] made an extensive study of water sorption of paper using this device which was presented in his thesis in 1988. These studies clearly demonstrated the importance of the external pressure on the water uptake and that the uptake for a given paper at pressures relevant for coating was solely governed by the external pressure, Figure 4. The work of Salminen [42] also confirmed that sized papers take up water by diffusion and that unsized papers take up water mainly by a capillary process. For capillary penetration at elevated temperatures, Salminen [42, 47] suggests that the liquid front in capillary penetration is preceded by a water vapour phase. At elevated temperatures, capillary condensation has also been suggested as a process governing the uptake [42, 47].

Delay time

It is sometimes found that the water uptake did not start immediately after application but after a certain period time [33, 38, 40, 41, 48]. This time is

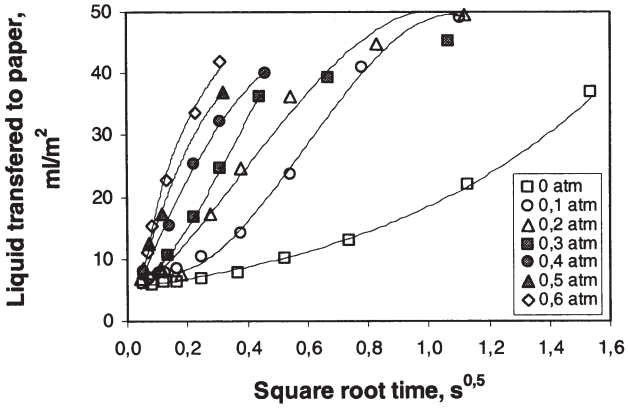

Figure 4 Liquid uptake at different pressures as a function of square root of time [47].

denoted "wetting delay". Bristow [38] has reported such a wetting delay for the uptake of sized kraft paper, cf. Figure 3. Lyne and Aspler [40, 41, 48] performed a systematic study on the wettability of wood-containing papers (newsprint) in the mid 1980's. They report e.g. that the wetting delay decreased with addition of surfactant to the water, Figure 5. The aqueous phase of coating colours contains surfactants.

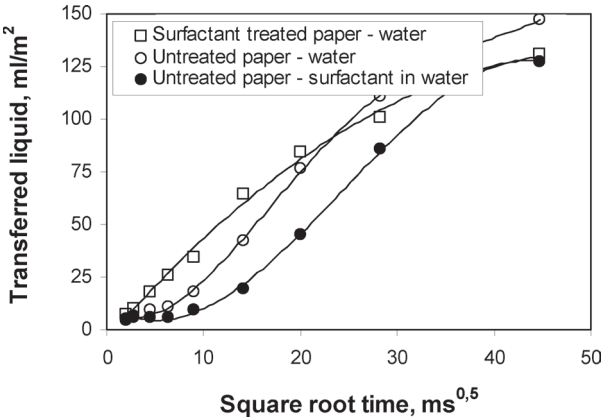

Figure 5 Liquid uptake as function of square root of time for surfactant treated and untreated newsprint [41].

Whether the wetting delay is real or due to an artefact caused by the way of representing the sorption curve has been the subject topic of discussion [49]. I shall not comment on this but it should be pointed out that there are no signs in the paper coating process that the uptake of the aqueous phase of the coating colour is delayed in any sense. On the contrary, all information available indicates that the uptake is an extremely rapid process.

Fibre swelling

The liquid taken up by the fibres causes them to swell and consequently the fibre network expands. This expansion affects the sorption rate and the sorption capacity of the paper. Bristow [14] has developed a technique with which the pore sorption and the fibre sorption of a paper can be estimated simultaneously, based on measurements of the liquid sorption and the thickness of the paper as functions of time. The liquid sorption is measured using the Cobb-method. The evaluation of the measurements, which is based on the relationship between the thickness increase and the liquid uptake, is briefly outlined in Figure 6.

Figures 7 shows measurements with water on sized and unsized sheets [14]. It is evident that the water uptake in the sized sheet was solely due to fibre sorption whereas the uptake in the unsized sheet was by both fibre sorption and pore sorption.

Coating colours contain Na^+ and Ca^{2+} ions which may influence the liquid uptake and the fibre swelling. Na^+ may originate from a number of different

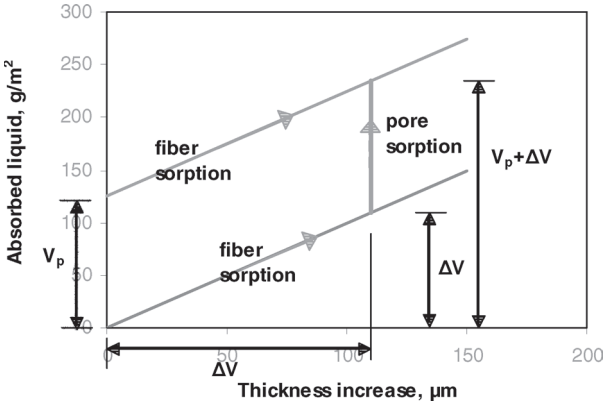

Figure 6 The principle for the evaluation of the relationship between the thickness increase and liquid uptake with respect to pore sorption and fibre sorption [14].

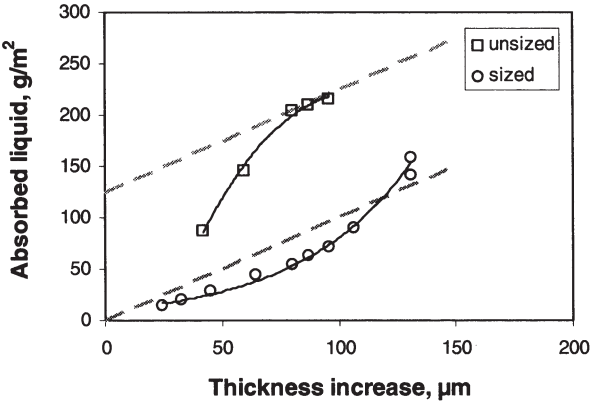

Figure 7 Water up take as a function of thickness increase for unsized and sized paper [14].

components or additives in the coating colour, e.g. Na-polyacrylate (dispersant) and Na-CMC (thickener). If the coating colour is based on GCC, which is common, it contains a significant amount of Ca^{2+}.

Bristow [50] has measured the uptake of aqueous solutions of NaCl, Na_2SO_4, and $BaCl_2$ in sized kraft papers using the Cobb-method and found that the uptake decreased linearly with increasing ion strength, Figure 8.

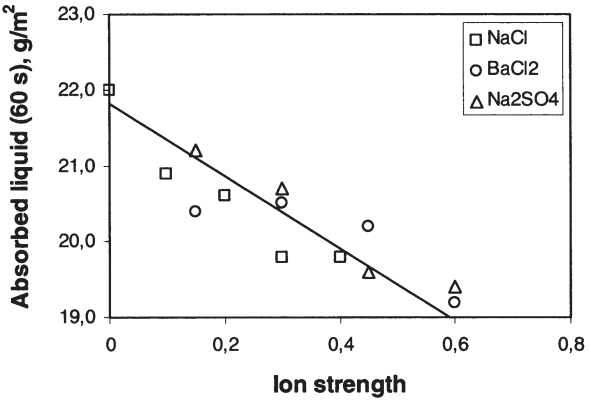

Figure 8 Absorbed liquid (Cobb-value) as a function of ion strength [50].

Since this type of paper takes up water mainly through fibre sorption [14], this suggests that the fibre swelling decreases with increasing ion strength. Work by Lindström [51] in which the influence of NaCl and pH on the water retention value (WRV) of pulps was studied, supports this conclusion

Several attempts have been made to account for the influence of the expansion of the fibre net-work on the water uptake [e.g. 33, 52]. In the previous symposium in 2001, Ketoja et al. [53] presented a paper in which they, with the help of numerical simulation, modelled inter-fibre and fibre sorption and fibre network expansion of a newsprint paper during the take up of 1.5 g/m^2 and 4.0 g/m^2 of water. A water uptake of 4.0 g/m^2 corresponds roughly to the liquid uptake during coating. The simulations were compared with experimental measurements of water uptake and network expansion using a device in which a CCD-camera monitors the change in opacity of the sheet during the sorption process followed by image analysis of the captured images. The simulations were in agreement with the experimental measurements. Ketoja et al. [53] also showed that 4.0 g/m^2 of water was taken up by the pore system within 20 μs. This is a rapid uptake. The fibre sorption was found to be a considerably slower process and it took 3 s to empty the pore system of 4.0 g/m^2.

Kinetics

Not only is the liquid uptake of paper an extremely rapid process. So are also the effects of the uptake on surface roughness and compressibility (plasticization). In coating there are numerous observations of an indirect character which support this, [e.g. 25, 27, 54].

Recently, Blohm and Borg [55] performed a study which confirmed those observations. They used STFI's pilot paper web research machine LINDA, Figure 9, which is equipped with a dampening unit with which water can be applied to a moving paper web. To measure the effect of the water application on the surface roughness and the compressibility, gauges for that purpose were installed in the machine. By varying the machine speed within the range of 14–300 m/min the dwell time could be varied within the range 56–1500 ms. The shortest dwell time is comparable with that between application and metering in high speed blade coating. Studied parameters included the type of base sheet (woodfree and wood-containing) and pre-calendering. The influences of these parameters are briefly discussed below.

The roughness of the uncaledered base sheets is shown as a function of dwell time in Figures 10 a and b, where it is evident that the roughening was considerable also at the shortest dwell time, which was 56 ms. This was true for both types of base sheets. The roughness of the pre-calendered base sheets

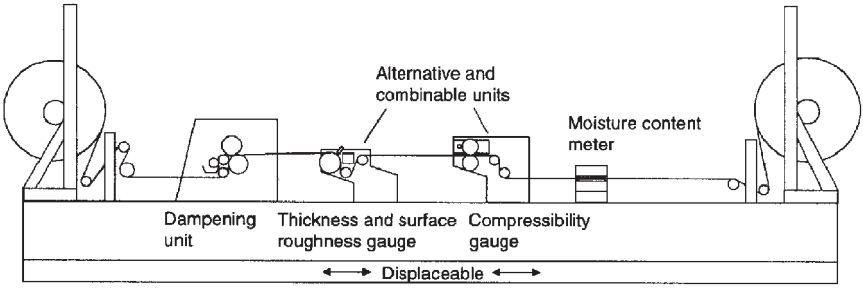

Figure 9 Schematic picture of STFI's pilot paper web research machine LINDA [55].

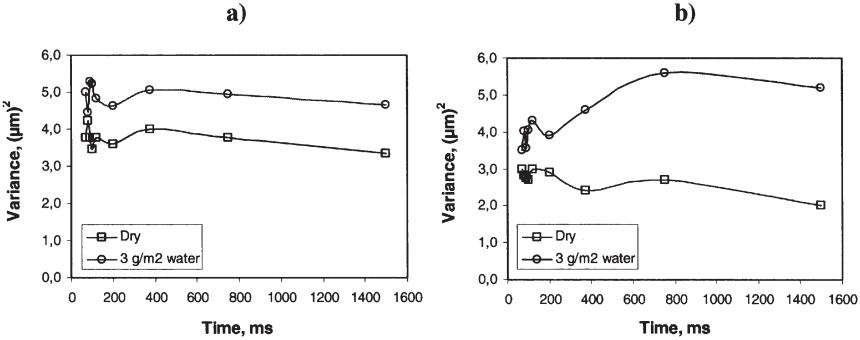

Figure 10 Variance in surface profile as function of time after water application for uncalendered base sheets, a) woodfree and b) wood-containing [55].

is shown as function of dwell time in Figures 11 a and b and, by comparing these figures with Figures 10 a and b, the effect of the pre-calendering can be assessed. This comparison shows that the pre-calendering reduced the roughening only for the wood-containing base sheet. This observation is in agreement with similar observations made by e.g. Engström and Morin [23] and Steffner et al. [56]. This means that the pre-calendering has a positive and stabilizing effect only on the woodfree, and not on the wood-containing sheets.

The compression of the uncalendered base sheets is shown as function of dwell time in Figures 12 a and b. The water plasticized the sheet and increased the compression, but only for the wood-containing base sheet, Figure 12 b. In that base sheet, a secured reduction of the compression was observed after a

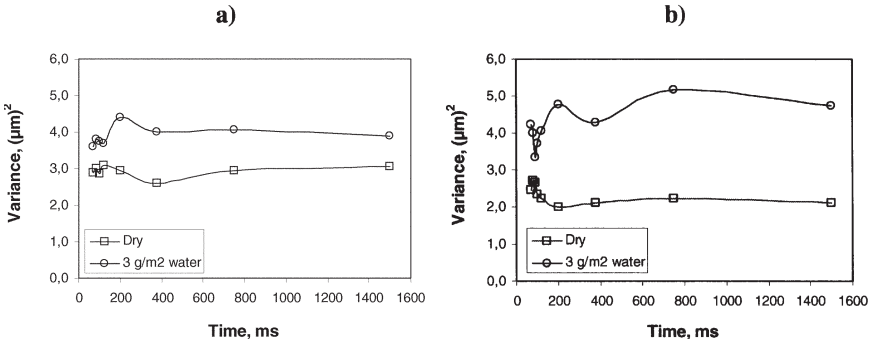

Figure 11 Variance in surface profile as function of time after water application for pre-calendered base sheets, a) woodfree and b) wood-containing [55].

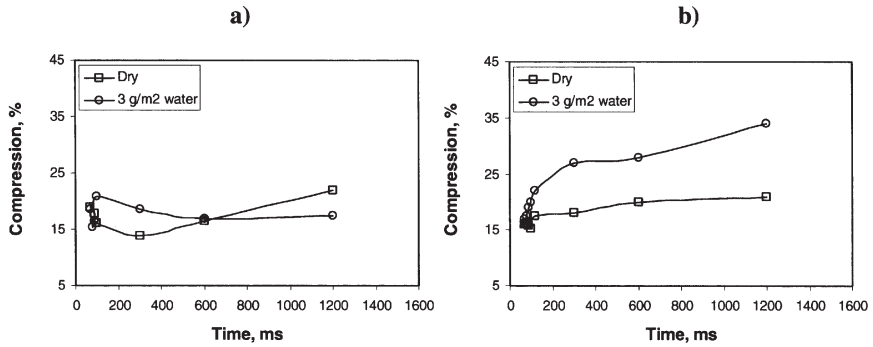

Figure 12 Compression as function of time after water application for the uncalendered wood- base sheets, a) woodfree and b) wood-containing [55].

dwell time of 100 ms. The reduction in the compression thus appeared later than the roughening. Blohm and Borg [55] believe that this is because the compression gauge used measured the bulk compression rather than the surface compression and that it takes time for the water to penetrate into the bulk of the sheet. For the woodfree base sheet, the compression was not affected whatsoever within the studied time interval, Figure 12 a.

COATING HOLD-OUT

Blade coating

The objective of pigment coating is to apply a uniform cover to the surface of the base sheet. To meet this objective, the coating must not penetrate beyond the surface of the base sheet. It must stay on the surface. However, paper is a porous material with a typical pore diameter within the range of 5–10 μm. Since most of the pigment particles in coating colours have a diameter which is below this pore diameter, it is taken for granted that the coating colour penetrates into the base sheet during the application and consolidation of the coating layer. Huang and Lepoutre [3] pointed out however that this opinion is not supported by studies on cross sections of coated material [57, 58].

The pigment diameter referred to here is that of the individual pigment particle. The effective particle size may, however, be larger due to aggregation caused by interaction between the pigment and binder system [59]. Numerical simulation of the flow in a wet coating layer during the consolidation on a porous substrate has also shown that the pigment particles tend to aggregate at the entrance of the pores and that these aggregates clog the pore openings [60], Figure 13. This also suggests that the pigment particles do not enter the pore in the form of particles but in the form of aggregates.

The first systematic study of coating hold-out was presented by Adams [2]. In that study the aim was to find out whether the surface treatment of the base sheet with a polymer affects coating penetration and coating hold-out. A base sheet was surface-sized with starch, CMC, styrene-maleic copolymer, and ketene dimer which are polymers which exhibit different film characteristics with respect to thier interaction with water. The surface-sized sheets were then blade coated with a kaolin-based coating colour and the coated sheets were tested with respect to common sheet properties. The results

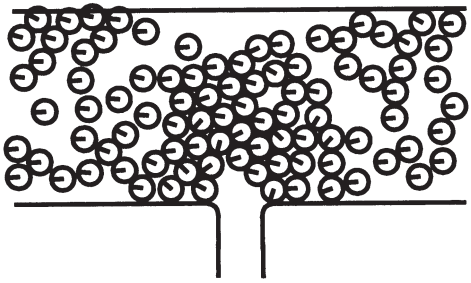

Figure 13 Flow in the vicinity of a pore opening [60].

suggested that surface sizing reduced coating penetration and that CMC was particularly efficient in that respect.

Lepoutre et al. [58] followed up the work of Adams [2] in a study the aim of which was to show the influence of coating penetration and void filling on the roughness and gloss of the final coated sheet. Coatings were performed on base sheets for LWC, which were pre-treated in different ways, using a puddle-type laboratory coater. The pre-treatments investigated were surface sizing with CMC and latex and internal sizing with ketene dimer. Since these pre-treatments with CMC and latex were applied in the form of an aqueous solution or dispersion a pre-treatment with water was also performed in the same way to enable the effect of the active component (CMC and latex) to be distinguished from that of water.

The results showed that neither hydrophobic sizing nor pre-treatment with CMC and latex had any effect on the super-calendered sheet properties. The interpretation of the results was that migration of coating components into the sheet was insignificant. This conclusion was qualitatively confirmed by examination of cross sections.

A study of the effect of the base sheet porosity, hydrophobicity and roughness on coating penetration was presented by Huang and Lepoutre [3]. This study constituted a part of Huang's thesis [61] presented in 1997. In the study, different base sheets were coated using a CLC-coater side by side, one unsized and one sized, see Table 1, to ensure identical coating conditions. The coating coverage was quantified using a burn-out test [24, 62], the reflectance and the standard deviation in reflectance of the sheets subjected to burn-out test being measured and evaluated using image analysis. The results, which are summarized in Table 1, showed that the reflectance was lower and the standard deviation in reflectance was higher, at the same coat weight, for the por-

Table 1 Effect of absorbency and roughness on coating uniformity – coated burn-out samples [3].

	Base sheet	Coat weight, g/m^2	Variance of grey level 0.5–1 mm	1–10 mm	Reflectance, %
Smooth	Dense unsized	8.3	10.1	31.5	44.2
	Dense sized	8.1	17.3	48.7	39.4
Rough	Dense unsized	8.7	15.7	30.8	49.9
	Dense sized	7.3	22.1	31.6	47.1
	Porous unsized	7.6	26.3	56.2	27.5
	Porous sized	6.9	26.9	62.3	25.6

ous sheets than for the dense ones, independent of hydrophobicity and surface roughness.

Since the mean reflectance of the burn-out is governed not only by the coat weight but also by the coat weight distribution due to the exponential relationship between reflectance and coat weight, according to the Kubelka-Munk theory, Huang and Lepoutre [3] analysed the data with the help of this theory. The result of this analysis showed that the lower reflectance of the porous sheets could not be explained by the non-uniform coat weight distribution whereas that was the case for the dense sheets. Therefore, it was concluded that the lower burn-out reflectance on the coated porous base sheet was caused by penetration of coating colour into the base sheet.

Metered size press

In coating with the MSP coating penetration can be assumed to be greater than in blade coating. This is due to that the pressure impulse during the forming of the coating layer is substantially larger than during the corresponding process in blade coating or during the application of the coating colour. The fact that the coat weight is restricted in coating with the MSP (< 8 g/m^2) also makes high demands on the coating coverage. This explains the extensive research which has been performed on coating coverage and coating penetration in MSP-coating [4–9] lately. Another reason is the great interest shown by the paper makers for this coating technique [63, 64].

In 2003, Forsström presented her thesis [65] entitled "Interaction between base sheet and coating color in metered size press coating". A question which was raised in the thesis and which Forsström studied and attempted to answer was: How much of the coating stays on the surface of the paper to be coated and how much goes beyond the surface. The thesis was based on five papers [4–8]. The papers [7, 8] dealing with double coating and a comparison between different techniques to measure coating coverage are not discussed here.

In the first paper [4], the aim was to identify the most important properties of the base sheet which affect the formation of the coating layer in the transfer nip and the coverage of the base sheet. The coverage was measured using a SEM-BSE method described by Kartovaara [27]. Three mill-made base sheets with different levels of porosity, surface roughness, hydrophobicity, and filler distribution were coated on a pilot scale. The coating colour used was based on a blend of kaolin clay and GCC and the viscosity of the aqueous phase of the coating colour was varied at two levels by varying the molecular mass of the CMC (low mw and medium mw) used as thickener. The solids content was the same for both coating colours.

The results showed that the coating transfer in the nip was directly linked to the porosity of the base sheet and that the transfer increased with increasing porosity of the base sheet. This increase was especially pronounced for the coating colour containing low mw CMC. This coating colour also yielded the most porous structure in the final dry coating layer. This porosity was also found to increase with increasing porosity of the base sheet. (The coating coverage was improved by increasing filler content in the surface of the base sheet). Neither the surface roughness nor the hydrophobicity of the base sheet affected the coating transfer or the coverage. Forsström et al. [4] claimed that the high coating transfer and the open structure of the final dry coating layer on the porous base sheet are indicative of coating penetration.

The first paper by Forsström et al. [4] was followed by a study in which the aim was to clarify the influences of roll hardness, machine speed, kaolin clay/GCC ratio, and solids content of the coating colour on the coating transfer and coating coverage [5]. The experimental approach was the same as that in the first paper [4] and two woodfree base sheets with different surface filler content were coated on a pilot scale. The trial was designed using the MODDE multivariate programme [66]. The results showed that the best coverage was obtained on the base sheet with a high surface filler content. A positive effect on the coverage was also obtained with a high fraction of clay in the coating colour and with a soft roll cover. The machine speed was not found to affect the coverage.

In order to confirm the results reported in the first paper [4] on a general level, a third study was performed. In this study [6], laboratory sheets with different porosities (air permeabilities) were produced by varying the type of wood fibre, softwood/hardwood – ratio, and the refining. A selection of sheets was also sized with AKD at three levels of addition. The filler content in the sheets was 20%. The sheets were taped into a reel and coated on a pilot scale with a kaolin clay/GCC-based coating colour. Besides assessing coating transfer and coating coverage, coating penetration was also evaluated on cross sections which were examined with the help of light microscopy. These examinations were performed in UV-radiation to separate pigment penetration from aqueous phase penetration. To achieve this, the coating colour used contained optical brightener.

There was a general correlation between the coating transfer and the permeability of the base sheets and also between the coverage and the permeability, regardless of the way in which the permeability was varied, Figures 14 a and b. This result, which confirms the interpretation of the results presented in the first paper [4], shows that the porosity is a parameter which governs these properties. The suggested interpretation of these results [6] was that

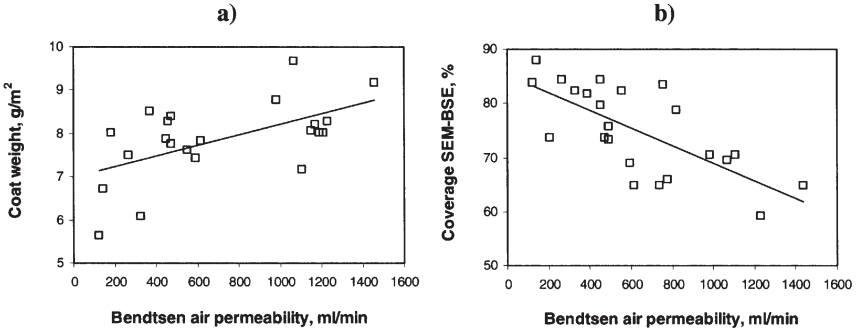

Figure 14 Coat weight (a) and coat weight (b) as a function of air permeability [6].

high coating transfer was caused by coating colour or coating colour components being pressed into the base sheet during the formation of the coating layer in the applicator nip, and that high coating colour penetration yields poor coverage.

The examination of the cross sections showed that the coating colour remained on the surface and formed a uniform layer on the dense base-sheets with air permeabilities less than 150 ml/min. For base sheets with air permeability values higher than 800 ml/min, the coating layer still appeared to be uniform but in some places the coating colour had penetrated deep into the base sheet. The aqueous phase (containing optical brightener) penetrated into the sheet in a similar way, i.e. deeper into the porous sheets than into the dense ones. It also penetrated deeper at low solids of the coating colour. These observations were taken as evidence that both the coating colour and its aqueous phase are pressed into the base sheet during the formation of the coating layer in the transfer nip – the aqueous phase in front of the coating colour.

The results of this study also confirmed that neither sizing nor surface roughness influence coating transfer or coverage, Figures 15 a and b. The fact that the surface roughness did not affect these properties was suggested to be because compression of the base sheet in the transfer nip yields a smooth surface. From blade coating it is known that a high compression of the base sheet beneath the blade tip during the forming of the coating layer leads to superior coverage [3, 67, 68]. Since the pressure pulse in the transfer nip is generally higher and longer than that beneath the blade tip, this explanation seems most likely. The compression of the base sheet during the forming of the coating layer in blade coating and its influence on the coating coverage

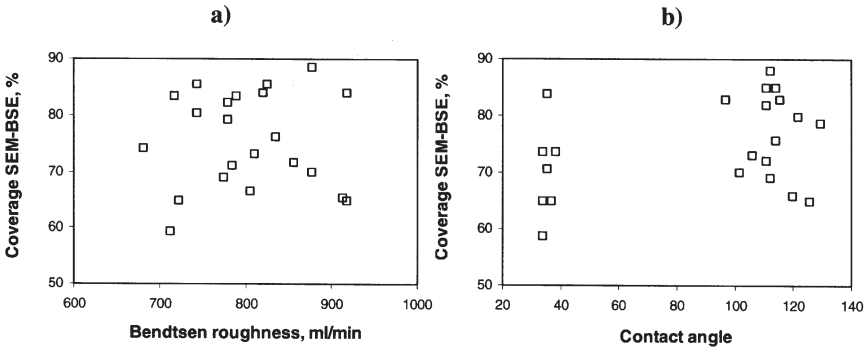

Figure 15 Coating coverage as a function of a) surface roughness and b) contact angle [6].

(coating mass distribution) is discussed in the section "Forming of the coating layer beneath the blade tip".

In the second paper [5], it was reported that soft rolls yielded somewhat better coverage than hard rolls. This was investigated systematically in another study by Forsström et al. [7] in which four woodfree base-sheets with different air permeabilities were coated on a pilot scale with a kaolin clay/GCC-based coating colour with two roll set-ups: 44/42 P&J and 88/84 P&J. The results showed that a better coverage was obtained with soft rolls and with denser base sheets. The roll hardness was also found to affect the oil absorption of the coated sheets (porosity of the coating layer) which was higher for the sheets coated with the hard roll. According to Forsström et al. [7] these results suggest that with hard rolls the layer was formed through simultaneous coating colour penetration whereas with soft rolls (longer nip) it was formed through filter cake formation.

PROCESS STAGES IN BLADE COATING

Solids increase in the circulation system

Figure 16 shows a schematic illustration of the circulation system in a blade coater. During coating, the level in the circulation tank is kept constant. It is well known that the solids content of the colour in the circulation tank, S_{ct}, is higher than that of the fresh coating colour, S_{in}, coming into the tank. This means that the composition of the coating colour metered by the blade has changed prior to the blade due to the loss of aqueous phase into the

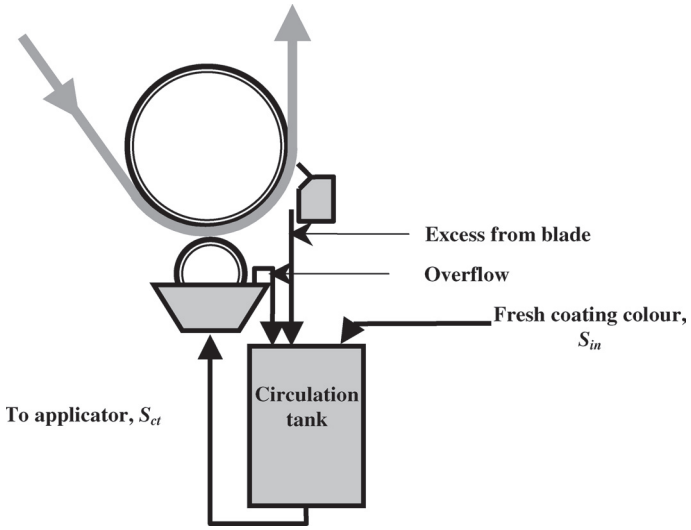

Figure 16 Schematic illustration of the circulation system in a blade coater.

base-sheet. An analysis of this change provides information as to how the coating colour interacts with the base sheet.

To explore this, Gagnon et al. [11] performed a trial in which a woodfree base sheet was blade coated with a coating colour based on a blend of kaolin clay and GCC with a binder system consisting of protein and latex. The trial started with fresh coating colour in the system. To monitor the change in composition of the coating colour, samples were taken from the circulation tank during the trial and analyzed with respect to solids content, viscosity, kaolin clay/GCC-ratio, pigment particle size distribution, total organic content and nitrogen content. The results, which are summarized in Table 2 and

Table 2 Composition of the coating colour in the circulation tank [11].

Time minutes	Solids %	Viscosity (Brookfield 20 rpm) mPas	Kaolin clay parts	GCC parts	Organic parts	Nitrogen (binder) parts
0	56.8	1700	45	55	21	6.0
80	58.5	1000	41	59	17	4.8
450	58.9	850	41	59	12	4.6
575	59.5	950	41	59	11	4.6

Figure 17, show a considerable loss of both latex and protein binder. The kaolin clay/GCC-ratio also changed as the particle size distribution decreased with time during the trial. This suggests a loss of fine material (preferentially kaolin) into the sheet.

The measurements reported by Gagnon et al. [11] clearly showed that coating material was lost into the base sheet prior to the blade. This loss reduces the amount of coating available for covering the base sheet and increases the porosity of the coating layer, due to the loss of fines which narrows the particle size distribution [69]. If the loss occurs non-uniformly due to non-uniform absorption of the base sheet, the porosity of the coating layer becomes non-uniform.

The uptake of water prior to the blade reduces the strength of the sheet. This may cause runnability problems in terms of web breaks because the sheet is not strong enough to withstand the forces to which it is subjected during the passage beneath the blade tip. The water uptake also increases the solids content and the viscosity of the coating colour metered by the blade. A higher blade pressure is needed to meet the target coat weight for a coating colour with a high solids content and a high viscosity [70, 71]. The higher blade pressure further increases the risk for web breaks. In addition, a high blade pressure may lead to problems in controlling the coat weight [72].

Blade scratches [73, 74] and blade bleeding [75, 76] are two other runnabilty problems in blade coating. They are caused by a too rapid loss of water prior to the blade which leads to a high solids content and a high viscosity of the coating colour during metering.

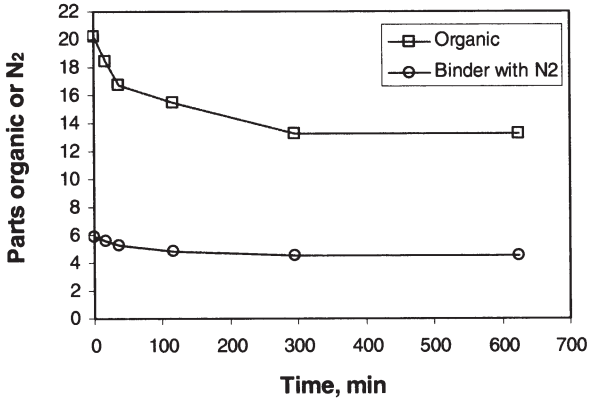

Figure 17 Depletion of binder during a run [11].

COATING COLOUR APPLICATION

De-watering mechanism

In blade coating, the coating colour is applied onto the base sheet in excess using a roll applicator, a jet applicator or a short dwell-time applicator (SDTA), Figure 18. The excess is metered with a blade to the target coat weight. These systems vary in two respects; the pressure during the application and the dwell time (time between application and metering), Table 3.

The work of Salminen [42, 47] clearly showed that liquid uptake at high pressures can be considerable even at short times. Assuming that the coating speed is 1000 m/min and that the pressure in the applicator nip and the dwell time are 0.5 atm and 3 ms, respectively, Figure 4 suggests that the liquid uptake in the applicator nip is greater than that during the dwell time between the nip and the blade. Based on this interpretation, Salminen [42, 47] put forward the hypothesis that the liquid uptake prior to the blade is governed by the pressure pulse in the applicator nip and not by the sorption potential of the base sheet. Since no external pressure is applied in the application zone in either jet application or SDTA application, the liquid uptake prior to the blade for these application systems is governed by the sorption potential of the base sheet.

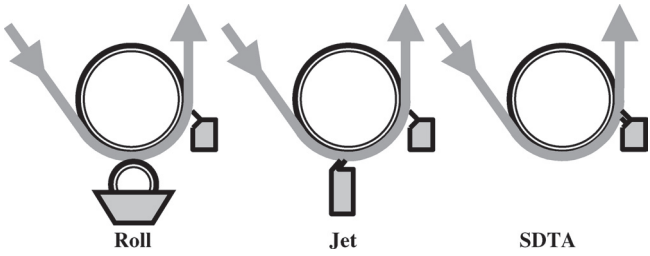

Figure 18 Schematic sketch of applicator systems in blade coating.

Table 3 Pressure in the application zone and dwell time prior to blade for applicator systems used in blade coating.

Applicator system	Pressure	Dwell time
Roll	High	Long
Jet	Atmospheric	Long
SDTA	Atmospheric	Short

The pressure pulse in the applicator nip is the driving force for the liquid uptake in roll application and the opposing force is the flow resistance of the filter cake formed when the coating releases liquid. To study the influence of the flow resistance, Sandås et al. [77] constructed a device for the purpose which is now recognized under the name Åbo Akademi Gravimetric Water Retention Tester (ÅGWRT). The TAPPI-Standard T 701 pm-01 for the measurement of water retention of coating colours is based on this device.

Using this device, Letzelter and Eklund [78, 79] performed a systematic study on a number of different coating colours. They measured, apart from the relationship between the liquid release from the coating colour and the pressure, the pore volume fraction of the filter cake formed and the viscosity of the aqueous phase. The aqueous phase was separated from the coating colour using centrifugation. The result showed that the liquid release, $V(t)$, could be described reasonably well with the help of the filtration equation, assuming an incompressible filter cake:

$$V(t) = A\sqrt{2\frac{\phi - \phi_0}{\phi_0}\frac{k(\phi)\Delta P}{\eta}t} \tag{8}$$

where ϕ denotes the maximum solid volume fraction, ϕ_0 the initial solid volume fraction, t the time, η the viscosity of the aqueous phase, $k(\phi)$, and ΔP the pressure difference.

It should be pointed out that Equation (8) implies that there is an immediate transition from filter cake to coating colour with both phases having a constant solids content (or solids volume fraction).

Eriksson and Rigdahl [80] performed a similar study on kaolin-clay-based coating colours containing CMC or starch as co-binder. They obtained the same results as Letzelter and Eklund [78, 79], but they questioned the existence of an immediate transition from filter cake to coating colour. Instead Eriksson and Rigdahl [80] suggested a smooth transition, a continuous gradient.

To assume an immediate transition from filter cake to coating colour, which is common in the research world, is a simplification and probably incorrect. A natural consequence of the fact that the solids content increases in the circulation tank is indeed that a gradient must exist. If the solids content of the metered coating colour is higher than that of the colour at the time of application, there is surely a gradient. If there were an immediate transition from filter cake to coating colour, the metered coating colour would have the same solids content as the colour at the time of application. Common wisdom says that this is not the case. If the blade was to meter not

only fluid coating colour but also a part of the filter cake, this would also result in a solids increase in the metered coating colour. This is, however, unlikely since it would cause blade scratches and a loss of product quality [11]. Experimental studies also confirm the existence of a gradient [37].

However, if the filter cake is assumed to be compressible, instead of incompressible as in the discussion above, a gradient will develop in the filter cake. This is shown in work on the theory of filtration presented by Tiller et al. [81], and Landman et al. [82]. Lohmander et al. [83] adopted this theory in filtration experiments of kaolin-clay-based coating colours with CMC as a thickener on ceramic plates. The moisture gradient which developed in the coating layer during the filtration was monitored using an NMR-technique. A continuous gradient was obtained and the shape of this gradient was identical with that of the calculated gradient according to the equation:

$$V(t) = A\sqrt{2\alpha\frac{\hat{\phi}-\phi_0}{\phi_0}\frac{k[\phi(0,t)]\Delta P}{\eta}t} \tag{9}$$

where α is a constant between (0 and 1) which is related to the concentration gradient of the filter cake at the surface of the filter (base sheet) and $k[\phi(0,t)]$ is the permeabilitity of the filter cake at the surface of the filter.

The findings of Lohmander et al. [83] confirmed two things: 1) Coating consolidation is a filtration process and 2) a continuous gradient is developed in the coating layer during this process.

Letzelter and Eklund [78, 79] took the works of Salminen [42, 47] and Sandås et al. [77] a step further and modelled the liquid release from the coating layer from the time of application until the point of immobilization. The modelling was based on data for the pressure in the applicator nip, the flow resistance of the filter cake, and the aqueous phase viscosity. The modelling confirmed the hypothesis of Salminen [39, 42] that the water release prior to the blade in high speed coating is determined by the pressure pulse in the applicator nip. It should be pointed out however, that the works of Letzelter and Eklund [78, 79] provide no evidence for this.

In 1997, the author performed a coating trial on a pilot scale in order to quantify the liquid release from the wet coating layer prior to and after the blade. The release prior to the blade was subdivided into release in the applicator nip and after the nip. The results of this trial have been confidential, but they have recently been released for publication and are presented and discussed briefly below.

In the trial, a base sheet for LWC was blade coated with a kaolin-clay-based coating colour using roll application. The pressure in the applicator nip

was varied by varying the machine speed and the applicator gap. The liquid release from the coating layer was measured by scraping off the coating at two positions after the blade and measuring the solids content of the scraped-off material. It should be pointed out that with this technique only the upper half of the coating layer is scraped off. Plotting the liquid release (solids content) against the square root of time after the blade yields a linear relationship [12, 84, 85] which is in agreement with the filtration Equations (8) and (9) and therefore supports the hypothesis that the consolidation process is a filtration process. The pressure pulse in the applicator nip was also estimated with the help of the Navier-Stokes equations.

The wet coating layer can only be scraped off from the base sheet in positions where the base sheet is supported. The pilot coater used offerd two such positions between the blade and the dryer, one against the backing roll 100 mm after the blade, and one against the turning roll 1350 mm after the blade, Figure 19. This restricts the number of data points for the estimation of the liquid release to two for every set of machine speed/applicator gap studied.

In Figures 20 a and b, the solids content of the scraped of material is plotted against the square root of time after the blade. Extrapolation of these lines to zero time yields the solids content of the coating layer at the exit from the blade. It is evident that this solids content is considerably higher than that at the time of application in coating at high speed and application using a narrow applicator gap. This confirms that the liquid release prior to the blade in high speed coating was controlled by the pressure in the applicator nip. The pressure distribution in the applicator nip is shown in Figure 21.

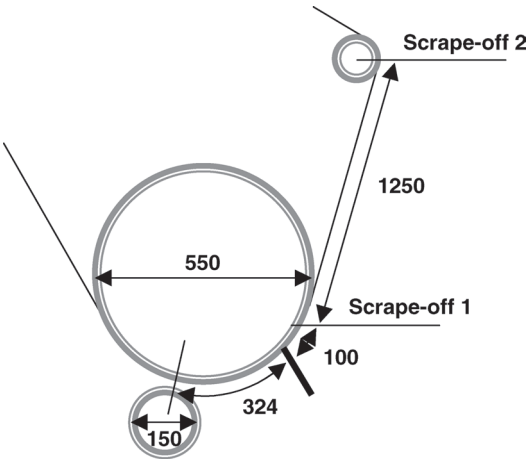

Figure 19 Scrape-off positions (distances in mm).

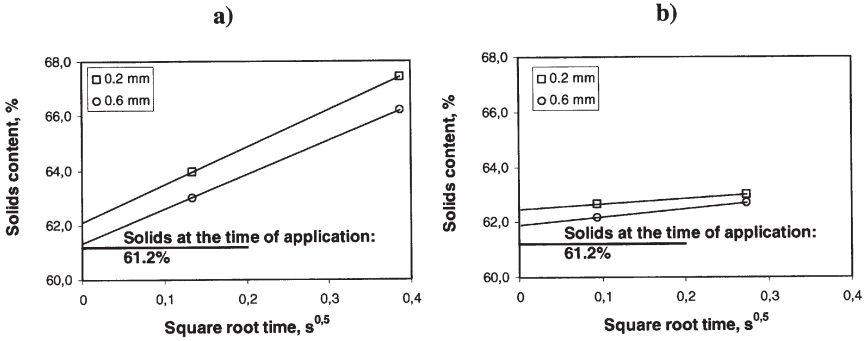

Figure 20 Solids content of scraped of material as a function of the square root of time after the blade a) at 500 m/min. and b) at 1000 m/min.

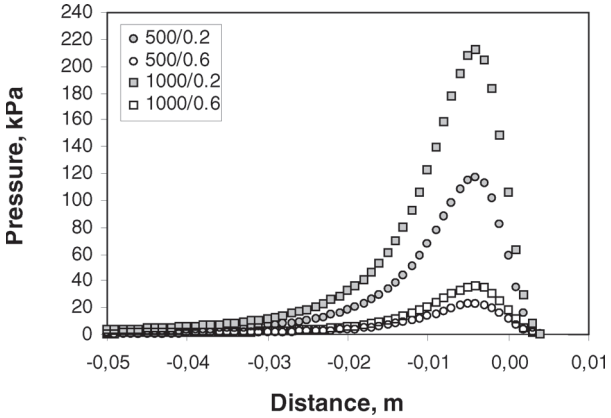

Figure 21 Pressure distribution in the applicator nip.

A natural reaction of the observant reader is, of course, to say that you cannot connect two data points with a straight line, as the author has done, and state that this straight line represents the course of liquid uptake. More data points are needed but, as already pointed out it was only possible to collect two data points. In order to state that the straight line which connects the data points line represents the course of liquid uptake, three conditions must be fulfilled: 1) the liquid release must theoretically be determined by a process dependent on the square root of time, 2) it must have been verified

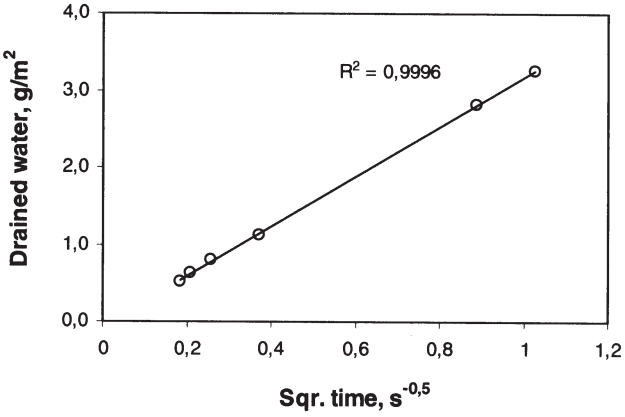

Figure 22 Drained water as a function of square root of time after the blade [12].

experimentally that the liquid release increases linearly with the square root of time and 3) the solids content of the scraped of material must have been determined with extreme accuracy. All three conditions are fulfilled. Conditions 1 and 2 are commented on above. The verification mentioned in condition 2 is shown in Figure 22 which is constructed from scrape-off data presented by Engström and Rigdahl [12]. Condition 3 is also fulfilled. Five scrape-off tests were made, and the solids content of the scraped off material was determined under controlled analytical conditions. The error in solids content was ± 0.025%-units.

A study similar to that of the author was recently performed by Jäder et al. [86]. In this study, the coating colour was applied with a jet-applicator in which the pressure in the applicator zone is close to atmospheric. No liquid release prior to the blade was observed in that study. It should be pointed out that the liquid release referred to here is that from the upper half of the coating layer.

Both Engström and Rigdahl [12] and Jäder et al. [86] found that the rate of liquid release was considerably higher at low machine speed than at high machine speed for certain coating colours. This behaviour was also true for the coating colour studied by the author, as is evident in a comparison of Figures 20 a and b. This behaviour has been explained in terms shear-induced aggregation which is more pronounced at high speeds and which changes the water retention properties of the coating colour [12]. Another possible explanation is that the absorption potential of the base sheet is affected by the pressure pulse beneath the blade tip [22, 26, 87] and that the sheet is

irreversibly compressed [88]. At high machine speeds, when the pressure is high, the irreversible compression becomes more significant. This reduces the porosity and the absorption potential of the sheet.

Influence on sheet properties

In the work of the author reported here, the final coated material was tested, among other things, with respect to coating coverage using the burn-out test and image analysis [24, 62]. The result of this analysis was reported in the form of a grey level mean value (GLMV) and a frequency-analyzed standard deviation about this value. The pressure pulse in the applicator nip affected both these measurers, as is evident in Figures 23 a, and b. The GLMV increased and the standard deviation decreased with increasing pressure. Figure 23 a shows that the coverage was reduced. There are two possible reasons for this: 1) the opacity of the coating had increased or 2) the coating was forced into the base sheet leaving a thinner coating on top of it. The latter of these alternatives is consistent with the interpretations of Forsström et al. [4, 6–8, 65] and of Huang and Lepoutre [3] of the influence of the pressure pulses on coating penetration in MSP-coating and in blade coating, respectively. The influence of the pressure pulse on the standard deviation of the GLMV will be discussed and commented on later in connection with the discussion of the process of forming of the coating layer beneath the blade tip.

Fifi and Arent [1] performed a pilot coating trial similar to the one performed by the author. They varied the applicator gap and measured the

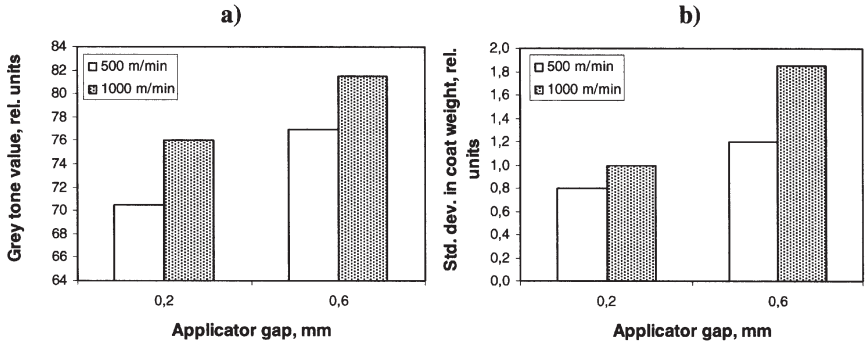

Figure 23 a) Coating coverage expresses as GLMV and b) coating non-uniformity expressed as standard deviation in GLMV at different pressures in the applicator nip.

aqueous phase penetration. The final coated and calendered material was tested with respect to a number of printing properties. The result of their study is consistent with that presented by the author and it showed that the penetration of the aqueous phase increased with decreasing applicator gap (increasing pressure). Reducing the applicator gap also had a detrimental effect on the printing properties measured.

UPTAKE BETWEEN APPLICATION AND METERING

In the roll application of the coating colour, the liquid uptake in the applicator nip is controlled by the pressure developed by the flow through the nip. In that sense the uptake can be regarded as a pressure-driven capillary process cf. the Lucas-Washburn Equation (5). In pressure-driven dewatering, the liquid taken up by the base sheet is the aqueous phase of the coating colour. This phase contains the soluble components in the colour, of which the most important is the co-binder. The function of the co-binder is to control the viscosity of the aqueous phase and thereby the water retention of the coating colour.

Between the application and the metering as well as in the application zone in jet application and SDTA, the liquid uptake occurs under atmospheric pressure. Without external pressure, the liquid uptake is governed by the absorption potential of the base sheet. Under these circumstances the liquid uptake can be a capillary process or a diffusion process or a combination of both, Bristow [14], Hoyland [33], and Salminen [47]. The driving force for the liquid uptake in diffusion is the concentration gradient over the interface between the base sheet and the coating colour (aqueous phase). This gradient is not governed by the viscosity of aqueous phase but by its concentration. Although normal adjustments of the co-binder level may have a significant influence on the viscosity of the aqueous phase, the same adjustment has only a marginal influence on the concentration gradient. In the selection of co-binder to control the water retention of the coating colour it is therefore important to clarify what determines the liquid uptake; is it a pressure-driven process or is it a diffusion process? The same holds for the selection of test method for the water retention of the coating colour. This method must simulate the dominant liquid uptake process in question.

The existence of the two uptake mechanisms and the relevance of knowing which mechanism controls the uptake was demonstrated by Ahlroos [89] and later by Eriksson and Rigdahl [80]. This was done in experiments in which the water retention of kaolin-clay-based coating colours containing different amounts of CMC was measured using the Warren Water Retention Tester

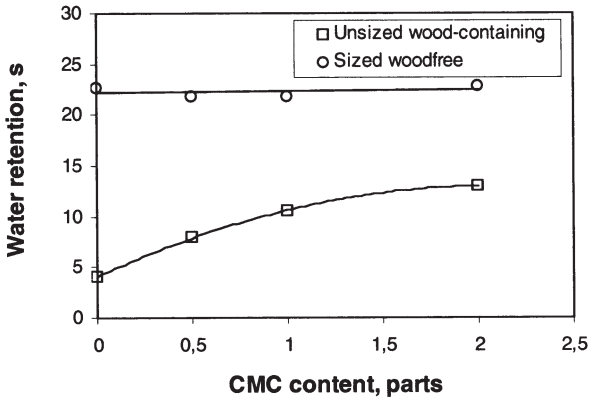

Figure 24 Water retention of kaolin clay-based coating colours as a function of CMC-content measured using the Warren method on a sized woodfree base sheet and an unsized wood-containing base sheet [89].

[90]. The measurements were performed on two base sheets: 1) a wood-containing sheet for LWC on which the liquid uptake can be assumed to be controlled by a capillary process and 2) a woodfree sized fine paper on which the uptake can be assumed to be a diffusion process [14, 33, 47]. The result is shown in Figure 24 and it is evident that the water retention increased with increasing CMC-content (viscosity) for the unsized wood-containing base sheet for LWC whereas the CMC-content or viscosity hardly influenced the water retention at all on the woodfree sized base sheet. This suggests that the coating colour was dewatered by a capillary process on the unsized sheet and by a diffusion process on the sized sheet.

The fact that the dewatering of coating colours can be controlled by a diffusion process is supported by works of Lepoutre et al. [91] and Inoue and Lepoutre [92] who studied the setting (dewatering) of water soluble and dispersion adhesives on unbleached board. They report that the setting was governed by a diffusion process for both the types of adhesive.

Sheet properties

The effect of the dwell time between application and blade on the sheet properties has been studied by several research groups, e.g. Fujiwara et al. [93], Leino and Veikkola [94], Kuni and Lares [95], and Ahlroos et al. [96]. All these groups report that an increase in dwell time yields a coating layer with more uniform mass and binder distributions. The mass and binder

distributions are factors reported to influence the mottling in lithographic offset printing [13, 67, 97–100]. The reason why a long dwell time yields a more uniform coating layer will be discussed in detail in the next section.

FORMING AND CONSOLIDATION OF THE COATING LAYER IN BLADE COATING

The interaction between the base sheet and the aqueous phase of the coating colour plasticizes and roughens the base sheet. These processes start immediately after the application of the coating colour and continue during the forming and consolidation. The uptake of the aqueous phase ceases when the immobilization point or the First Critical Concentration (FCC) [101] is reached.

Three techniques have been used to quantify the surface profile and the roughening of the base sheet beneath the coating layer: 1) microscopy on cross sections [25, 26, 102–104], 2) removing the base sheet from the coating layer and measuring the surface profile of the uncovered surface [105], and 3) measurements of the mass (thickness) distribution of the coating layer and the surface profile of the coated sheet [23].

In the microscopy technique approximately 10 mm long samples are embedded in epoxy resin. The cross section to be studied is polished and examined using light microscopy (incident light) and the captured image is evaluated using image analysis. This analysis yields data about the surface profile of the base sheet beneath the coating layer and the coated paper, respectively and of the coating thickness variation, Figure 25. Comparing the surface profile of the base sheet before the coating with the surface profile beneath the coating layer in the final coated uncalendered sheet gives a basis for the evaluation of the roughening. Due to the rather short length of the sample this technique yields information about variations on a short length scale.

In the second technique, the base sheet is removed by dissolving it in concentrated sulphuric acid. After rinsing with de-ionized water, the bottom side of the coating layer is measured with respect to the surface profile. As in the microscopy technique, comparing this surface profile with that of the base sheet prior to the coating provides a basis for an evaluation of the roughening.

The third technique is based on measurements of thickness distribution and surface profile. This technique yields not only data of the surface profile of the base sheet in the dry final coated uncalendered sheet, but also data of the surface profile of the base sheet in a compressed state beneath the blade

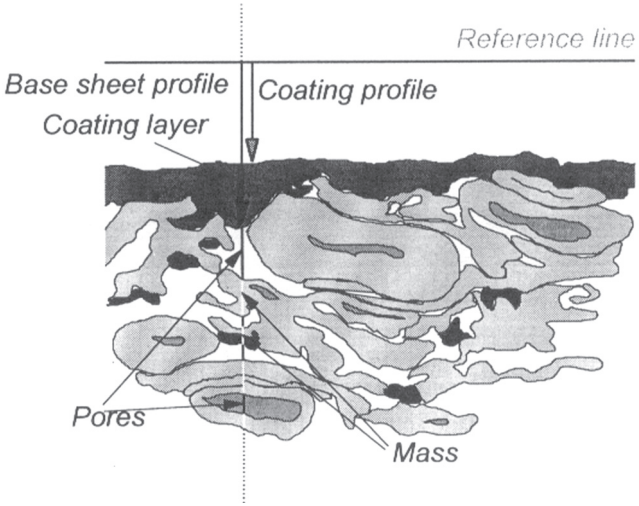

Figure 25 Schematic cross section with the measured surface profiles inlaid [102].

tip during the forming of the coating layer. The compression is influenced by the interaction between the base sheet and the aqueous phase prior to the blade, which plasticizes the base sheet. Engström and Morin [23] used a burn-out test and image analysis for the measurement of the thickness distribution and a stylus instrument for measurement of the surface profile. This technique will now be discussed in more detail.

Evaluation of burn-out-test and surface profile measurements

The evaluation of the burn-out test and the surface profile measurements includes a frequency analysis of the measured data. The result of the analysis is reported in the form of a standard deviation in grey-tone or profile height in eight spatial wavelength bands within the range from 0.0625 to 12.0 mm.

The effect of levelling on the coating thickness distribution can be ignored on a length scale identical to that of the fibre flocs. On that length scale, the surface profile of the coated paper can be assumed to be in phase with the surface profile of the base sheet. Experiments performed by Allem and Uesaka [102] and by Tomimasu et al. [106] support this assumption. A typical length scale of a fibre flocs is 4–8 mm. With the assumption that all the variation within that interval can be placed at its centre of gravity, i.e. $(4\times8)^{0.5} \approx 5.66$ mm, the surface profile of the upper and lower boundary surfaces of

the coating layer H_{s1} and H_{s2}, respectively, can be written in the form of sinusoidal time series:

$$H_{S1} = h_0 + \sqrt{2}\sigma_{S1} \sin\frac{2\pi}{5.66} x \tag{10}$$

$$H_{S2} = \sqrt{2}\sigma_{S2} \sin\frac{2\pi}{5.66} x \tag{11}$$

where h_0 denotes the mean thickness of the coating layer, σ the standard deviation of the surface profile and the subscripts s_1 and s_2 the upper and lower boundary surfaces respectively of the coating layer, and x the distance, see Figure 26. s_2 is also identical with the surface profile of the base sheet beneath the coating layer.

For a sinusoidal, time series the relationship between the amplitude A and the standard deviation σ is given by the expression:

$$A = \sqrt{2}\sigma \tag{12}$$

By analogy the thickness profile, T_c, of the coating layer can be written:

$$T_c = \delta_c \sqrt{2}\sigma_c \sin\left(\frac{2\pi}{\lambda} x + \pi\right) \tag{13}$$

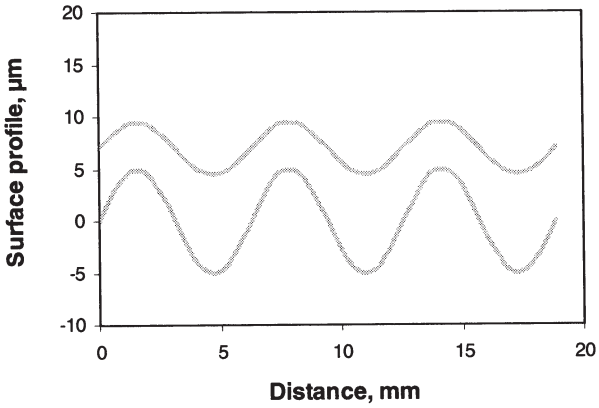

Figure 26 Schematic cross section of a coated paper.

where δ_c denotes the density of the dry coating layer and σ_c the standard deviation in coat weight. The phase shift of π is due to the fact that the surface profiles of the upper and lower boundary surfaces of the coating surfaces are assumed to be in phase, as is illustrated in Figure 19 which means that the coating thickness T_c will attain a maximum when the surface profile H_{s1} attains a minimum, and vice versa.

The thickness distribution of the coating layer, T_c, is given by the difference between the upper boundary surface, H_{s1}, and lower boundary surface H_{s2}:

$$H_{s1} - H_{s2} = h_0 + \sqrt{2}(\sigma_{s1} - \sigma_{s2}) \sin \frac{2\pi}{5.66} x \tag{14}$$

$$\text{where} \quad -\delta_c \sigma_c = (\sigma_{s1} - \sigma_{s2}) \tag{15}$$

Since δ_c, σ_c, and σ_{s1} are known quantities, the surface profile of the base sheet beneath the coating layer in the final coated sheet, σ_{s2}, can be calculated.

This analysis can be taken a step further to calculate the surface profile of the base sheet in a compressed state beneath the blade tip. This calculation is based on the same assumption as above, viz. that the mass distribution of the coating layer is not changed during the process of consolidation because levelling during this process can be ignored on a length scale equal with 4–8 mm. The standard deviation in mass of the coating layer beneath the blade tip is thus, expressed in dry coat weight, identical with that of the final dry coating. The standard deviation in thickness is not however the same, but it can easily be calculated knowing the solids fraction S and the density δ_{wet} of the coating colour using the relationship:

$$\sigma_{wet} = \delta_{wet} \frac{\sigma_c}{S} \tag{16}$$

During the forming of the coating layer beneath the blade tip, the upper boundary surface of the coating layer is given by the blade, which is straight, Figures 27 a and b. This means that the standard deviation in surface profile of the upper boundary surface σ_{s1} is equal to zero and that the surface profile of the base sheet in a compressed state beneath the blade tip is given by the calculated standard deviation in wet coating thickness:

$$\sigma_{wet} = \sigma_{s2,wet} \tag{17}$$

The solids fraction S in Equation (16) can be assumed to be identical with

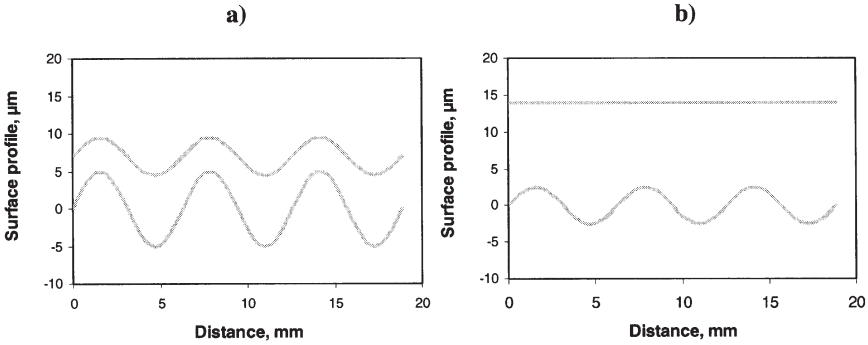

Figure 27 Schematic cross section of a) dry final coated paper b) base sheet with wet coating beneath the blade tip.

that at the time of application and the density of the coating colour at the same solids fraction, δ_{wet}, can easily be measured. Moreover, the mass distribution of the dry coating layer, σ_c, is known from the burn-out test. Thus, $\sigma_{s2,wet}$ can be calculated since all parameters are known.

Forming of the coating layer beneath the blade tip

In blade coating, the coating layer is formed beneath the blade tip and the conditions there govern the mass distribution of the final dry coating layer. As is evident in Equation (17), this mass distribution is determined by the surface profile of the base sheet, but this surface profile is not identical with that of the base sheet prior to coating but with that in a moist and compressed state. This is because the base sheet has taken up aqueous phase from the coating colour prior to blade, which swells and plasticizes the fibre network. This in turn, affects the compressibility of the base sheet and the blade pressure needed to control the coat weight.

Engström and Morin [22] used the technique described above on a material produced in a pilot coating trial in which a base sheet for LWC was blade coated with a kaolin-clay-based coating colour. Their analysis of the surface profile of the base sheet in a compressed state beneath the blade tip showed that it was considerably smoother than prior to the coating. This was interpreted as being due to compression of the base sheet beneath the blade tip. This can also be expressed by saying that the compression dominated over the roughening prior to the blade and that the compression controlled the surface profile of the sheet beneath the blade tip.

A similar pilot coating trial was performed by Jäder and Engström [87] in which a woodfree base sheet was blade coated with coating colours of different water retentions and different rheologies. The rheology affected the blade pressure needed to achieve the target coat weight. In this study, the base sheet was found to be rougher beneath the blade tip than it was prior to the coating, i.e. the opposite of that which was true for the base sheet for LWC. For the woodfree base sheet, the surface profile in a compressed state beneath the blade tip was controlled by the roughening prior to the blade.

The fact that the base sheet for LWC, which is a wood-containing paper, was smoother in a moist and compressed state whereas the opposite was true for the woodfree base sheet shows that the former sheet was markedly more compressible. This observation is in line with the work of Skowronski et al. [107] on the swelling pressure of sheets having different fibre compositions. They reported that papers based on chemical pulp develop a high swelling pressure when exposed to water and that sheets based on TMP-fibres develop practically no pressure at all. A high swelling pressure can be assumed to oppose compression. Swelling pressure is discussed in more detail in the section "Swelling pressure".

The influences of the dwell time, the water retention, and the blade pressure (rheology) on the surface profile of the base sheet in a compressed state beneath the blade tip were also clearly demonstrated in the work of Jäder and Engström [87]. A long dwell time in combination with a coating colour having a poor water retention as well as a poor rheology (high blade pressure to meet the target coat weight) yielded the smoothest surface profile. This shows that the uptake of the aqueous phase prior to the blade plasticized the sheet and made it compressible. The greater the uptake, the more compressible was the base sheet.

The compression of the base sheet beneath the blade tip is governed by the blade pressure (compressive load) and by the compressibility of the base sheet in a moist state. The compressibility is governed by the interaction between the aqueous phase of the coating colour and the fibre material in the base sheet and by the accompanying fibre swelling in two ways: 1) the fibres and the fibre network which build up the sheet are plasticized 2) the pressure (swelling pressure) that is build up in the fibres and the fibre network. The former makes the base sheet compressible, the latter may have the opposite effect.

In a trial on a pilot scale in which a base sheet for LWC was coated, Engström et al. [54] also found that the coating mass distribution was considerably more non-uniform for SDTA than for roll application. They showed that this was due to less compression of the base sheet beneath the blade tip during the forming of the coating layer in SDTA. In another pilot trial,

Engström et al. [108] coated a base sheet for LWC, a sized woodfree base sheet and an unsized wood free base sheet. The two woodfree base sheets were produced on the same paper machine and they were thus identical except for the sizing. The coating was carried out under identical conditions. A comparison of the mass distribution of the coating layer on the two woodfree base sheets clearly showed that it was considerably more uniform on the unsized base sheet. This shows that this base sheet was more compressible than the sized one. Whether this is due to a higher water uptake and plasticization prior to the blade or to a softer network cannot be answered on the basis of these results.

Roughening of the base sheet during the process of consolidation

The roughening of base sheets for LWC has been studied by Gane et al. [25, 26], by Engström and Morin [23], and by Allem and Uesaka [102]. All these groups report a significant roughening of the base sheet during the coating. Studies of Jäder and Engström [87] have shown that the same is true for a woodfree base sheet. Jäder and Engström [87] also quantified the surface compression of the sheet beneath the blade tip and roughening after the blade, they and found a smooth relationship between these two parameters. The relationship is shown in Figure 28, and it is evident in the figure that the

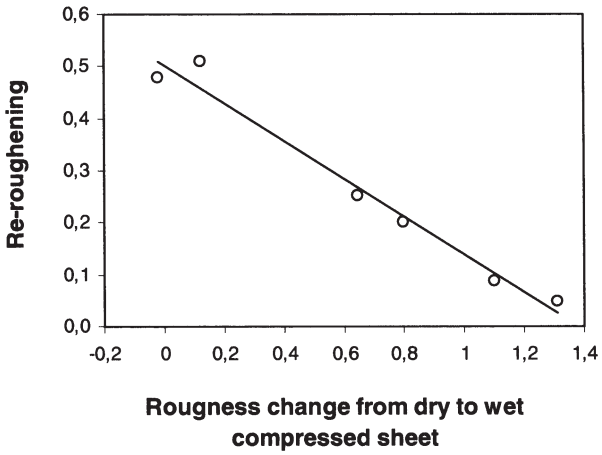

Figure 28 Compression of the base sheet beneath the base sheet as a function of roughening after the blade [87].

smoothening caused by the compression decreases with increasing surface compression. This shows that the pressure pulse beneath the blade tip causes a permanent (plastic) deformation of the base sheet.

Gane et al. [26] report similar results from a study in which the influence of the fibre composition (TMP and pressure groundwood) was investigated. With 100% TMP the base sheet beneath the coating was rougher than prior to the coating. Replacing TMP with PGW resulted in a more stable base sheet which was smoother than it had been prior to the coating. It also resulted in a coating layer with a more uniform thickness distribution. The fact that the base sheet beneath the coating layer was smoother than prior to the coating was reported to be due to a "calendering" effect of the passage beneath the blade tip.

The influence of pre-calendering on the roughening of a base sheet for LWC has been studied by Gane et al. [25] and by Engström and Morin [23]. Both research groups obtained the same result showing that the roughness of the uncalendered base sheet was not affected by the coating and that all the smoothening effect of the pre-calendering was lost during coating, i.e. the roughness of the paper beneath the coating was the same for uncalendered and pre-calendered base sheets. It should nevertheless be pointed out that the coated pre-calendered base sheet exhibited a significantly lower roughness than the coated uncalendered base sheet. This is true both for the base sheet studied by Gane et al. [25] and the one studied by Engström and Morin [23].

The effect of pre-calendering on the mass (coat weight) distribution and the mottle in a lithographic offset print on the final coated and printed material has been studied by Engström and Lafaye [24] on LWC paper produced on a pilot scale. The mass distribution and print mottle (back trap) was measured using the same image analysis techniques on burn-out images and 100% cyan prints printed in the second printing unit in the printing press.

Figure 29, shows the frequency analyzed mass distributions. Two facts are evident in the figure: 1) the variance was lower for the uncalendered sheet and 2) the variance exhibited a maximum within the 4–8 mm range for the pre-calendered sheet. This range corresponded to the size of the fibre flocs in the base sheet. The first observation clearly shows that a more uniform coating mass distribution was obtained on the uncalendered sheet. The interpretation of the latter observation was that fibre flocs which are pressed down during pre-calendering "pop up" when exposed to the aqueous phase in the coating colour.

A comparison between the frequency-analyzed mass distribution and the frequency-analyzed print reflectance (mottling) shows that these curves have the same shape, Figure 30. This, in turn, shows that non-uniformities in the mass of the coating layer are transferred to the print which becomes mottled.

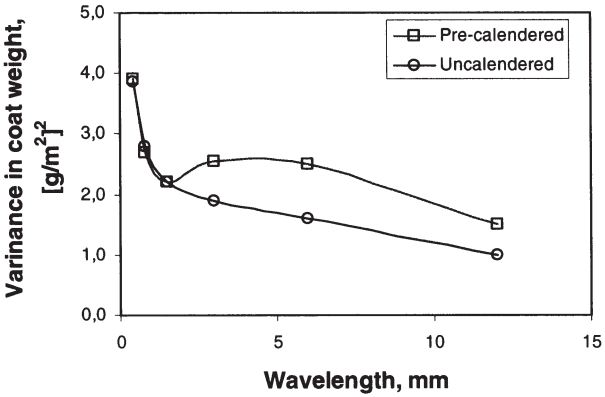

Figure 29 Frequency-analyzed coat weight distribution [24].

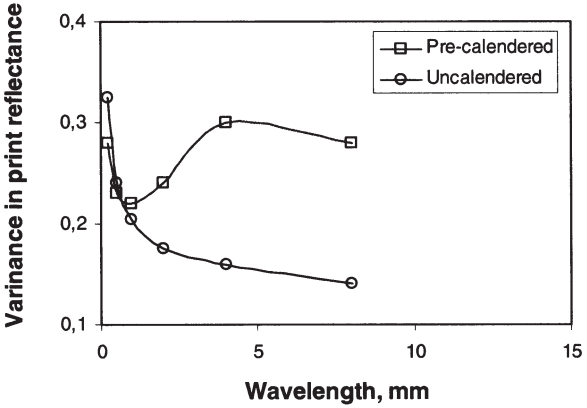

Figure 30 Frequency-analyzed coat weight distribution and frequency-analyzed print reflectance (mottling) [24].

Moreover, this shows that a uniform coating mass distribution is a prerequisite for a print without mottling. As already mentioned, the mass distribution is governed by the surface profile of the base sheet in a compressed state beneath the blade tip, and this compressibility is governed by the interaction between the base sheet and the aqueous phase of the coating colour prior to the blade.

Gane el al. [25] studied not only the effect of pre-calendering on the roughening during coating but also the effect of the water retention of the coating colour and of the applicator system used on the coating mass distribution. The material studied was blade coated LWC produced on a pilot scale using STDA and roll application. The base sheet was the same in all the experiments.

The water retention of the coating colour, which was varied by varying the particle size of the kaolin clay in the coating colour, had a marked effect on the roughening. The coating colour with the poorest water retention yielded the highest roughening, but the roughening was not influenced by the coat weight which was varied within the range 5–9 g/m^2. For a coating colour with good water retention, however, the roughening increased with increasing coat weight. These observations show, according to Gane et al. [25], that both the magnitude of the aqueous phase uptake and the time for interaction between the aqueous phase and the base-sheet affect the roughening.

The comparison between roll application and SDTA showed that roll application led to more sheet roughening. In accordance with the interpretation of the influence of water retention and coat weight, Gane et al. [25] ascribed this to the longer dwell time in roll application.

The influence of the applicator system on the roughening has also been studied by Kartovaara [27]. The material studied was produced in a pilot coating trial in which a base sheet for LWC and a sized woodfree base sheet were blade coated at coat weights within the 5–22 g/m^2 range. The surface roughness of the coated material was measured in terms of the thickness associated with the roughness volume using the Bristow-wheel (1 cm^3/m^2 = 1μm) [38]. The roughness volume is plotted against the coat weight in Figures 31 a and b. For the sized woodfree sheet the thickness of the roughness volume decreased with increasing coat weight in the same manner for both applicator systems. Moreover, for the sized woodfree sheet, the thickness of the roughness volume was lower than for the base sheet for LWC. This was true over the entire coat weight range studied.

The wood-containing base sheet behaved differently, the thickness of the roughness volume being markedly higher for the SDTA coated papers. For STDA, the thickness of the roughness volume was also higher than for base sheets at coat weights below ca. 9 g/m^2.

The roughness volume of the final coated paper is governed by the roughness of the base sheet and by the degree of void filling. These two factors oppose each other. The solid material in the coating fills in the voids and makes the base sheet smoother. Simultaneously, the aqueous phase makes the sheet rougher. Kartovaara [27] discusses how these factors differ between roll

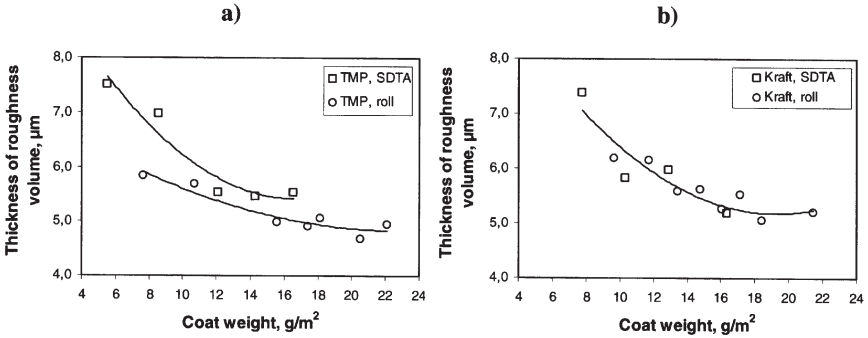

Figure 31 Thickness of the roughness volume as a function of coat weight for a) LWC and b) a sized woodfree base sheet [27].

application and SDTA and how this difference influences the thickness of the roughness volume of the final coated paper. Briefly, the essence of this discussion is: that, if the base sheet roughens mainly prior to the blade, as is the case in roll application, then the void filling is efficient and it controls the thickness of the roughness volume. If on the other hand the roughening prior to the blade is less, as is the case for SDTA, then the void filling is less efficient and the thickness of the roughness volume is controlled mainly by the interaction between the aqueous phase and the base sheet and the subsequent roughening after the blade.

The studies of Gane et al. [25] and Kartovaara [27] both yield information about coat weight variations on a sub-millimetre level. Variations on this length scale may not necessarily coincide with variations on a longer length scale; e.g. on a fibre floc level. This is evident in a study by Engström and Norrdahl [54] in which roll application was compared with SDTA, and in which the variations in coat weight were measured using the burn-out test [23, 62] which yields data of the coat weight variations on a fibre floc level. The results of Engström and Norrdahl [54] showed that SDTA yielded poorer coverage than roll application. This is in agreement with the results reported by Gane et al. [25] and Kartovaara [27].

INTERACTION BETWEEN BASE SHEET AND WATER

Roughening of the base sheet in contact with water

The water taken up by the fibres and the accompanying fibre swelling expands the fibre network and roughens the paper. In a series of papers published in

1985–90 [18, 19, 20, 107], Skowronski and Lepoutre at PAPRICAN, Canada, presented the first systematic work on this theme.

In the first two first papers [18, 19], three commercial papers, two newsprints and one base sheet for LWC, which all were delivered with both low and high water-sorption capacity, were coated with a kaolin-clay-based coating colour and with water alone using a laboratory puddle-type blade coater. In the first paper [18] the effect of the water-sorption capacity on the roughening and the hold-out was studied. The second paper [19] deals with the relationship between internal stresses and roughening.

All the tested sheets became rougher after coating with water. The most roughened was the newsprint based on TMP, followed by the newsprint based on groundwood, and the least roughened was the base sheet for LWC which was based on chemical pulp and double-screened groundwood pulp. The air permeance increased in a similar way. According to the authors, this result suggested that mechanical fibres causes a higher roughening than chemical fibres and that TMP fibres are worse than groundwood fibres in this respect. The differences between the low-sorption and the high-sorption papers were small.

The magnitude of the roughening was however affected by the water-sorption capacity of the base sheet. This conclusion can be drawn from Figure 32, where the volume of coating colour applied is plotted against the surface roughness of the base sheet in a compressed state beneath the blade tip. This roughness was measured at a clamp pressure which was identical with the blade pressure and it was assumed that the water uptake prior to the

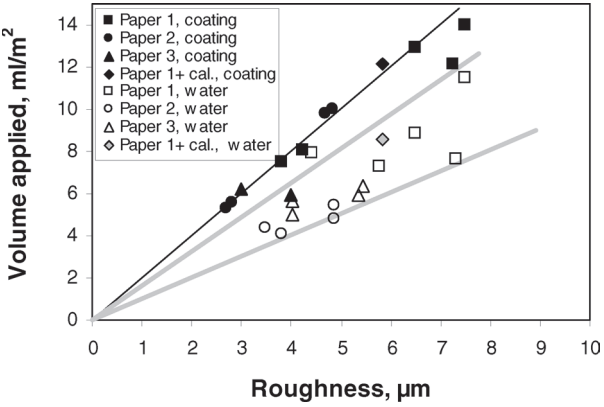

Figure 32 Volume coating applied as a function of the roughness of the base sheet measured in a compressed state equivalent to the compression beneath the blade tip [18].

blade had not affected the compressibility of the paper because the dwell time in the puddle-type coater used was extremely short. For the low-sorption base sheet there was a linear relationship between the volume of coating colour applied and the surface roughness. For the high-sorption base sheets, the data points scattered somewhat, but the roughness values of these papers at a given applied volume coating were always higher than those of the low-sorption papers.

Skowronski and Lepoutre [18] made the assumption that the volume of coating colour applied is controlled by the roughness volume of the base sheet in a compressed state beneath the blade tip. They were than able to state that the linear relationship for the low sorption sheets shows that the roughness volume was not changed prior to the blade for these sheets. By analogy, the deviation from a straight line and the fact that these base sheets accepted more coating than was predicted by the relationship for the low sorption papers suggests that the roughness beneath the blade tip blade was higher than that of the uncoated base sheet prior to the coating. A sheet of high roughness requires more coating to fill the surface voids (roughness volume). The fact that the roughening took place prior to the blade shows that this is an extremely rapid process.

The studies of Skowronski and Lepoutre [18, 19] have shown that the sorption capacity of the base sheet has a marked influence on the roughening. Therefore it was natural for these researchers to continue their work with a study of the influence of sizing on roughening. In this study [20], a base sheet for LWC was sized with a ketene dimer (AKD), which was applied to the sheet from a hexane solution to avoid structural changes. It was observed that the sizing did not cause any structural changes and that the surface roughness, the gloss, and the air permeability of the sheet also remained unaffected by the sizing. The sizing made the sheets totally water-repellent.

The sheets were coated both with a coating colour and with water in the same way as before [18, 19]. The sheets were also tested in the same way with respect to surface roughness and gloss. The result was very clear. Neither the surface roughness nor the gloss of the coated sheets was affected by the sizing of the base sheet. This was true both for the pigment-coated sheets and for the water-coated sheets.

The ketene dimer sizing affects the capillary sorption but not the fibre sorption. Therefore the magnitude of the fibre sorption can be assumed to be the same for both the sized and unsized sheets. These results confirmed the hypothesis that fibre sorption is responsible for the structural changes in the sheet when it is exposed to water and that these structural changes cannot be suppressed by blocking capillary penetration. Moreover, the results suggested that the absorption of coating components by capillary movement was

improbable. This was qualitatively confirmed by inspection of optical cross-section micrographs [19].

As already mentioned, studies by Gane et al. [26] and by Engström and Lafaye [25] have shown that the effect of pre-calendering on the roughness of the base sheet is lost during coating. There are different techniques for pre-calendering such as conventional hard-nip calendering and temperature gradient (TG) calendering. A question was whether these techniques affect the roughing differently. Skowronski [20] studied the effect of these techniques and of press drying on the roughening of handsheets based on TMP and kraft pulp. The handsheets were taped onto a roll and coated with water using the same technique as previously [18,19].

The results showed that the water coating affected neither the surface roughness nor the thickness of the uncalendered or press-dried sheets [20]. This was true for both types of sheets. On the pre-calendered sheets, the roughness and the thickness increased. This increase was approximately the same for both the calendering techniques, but the increase was significantly higher for the TMP-sheet. All the smoothening effect of the calendering was not however lost after water coating.

The studies of the researchers at PAPRICAN have been continued at PFI, Norway, within the framework of a PhD-project. The thesis entitled "Moisture-induced roughening of mechanical pulp" [109] is based on five papers [15–17, 110, 111].

In reference [110], a study is presented which deals with the influence of fines and wet pressing on the moisture-induced roughening of calendered and uncalendered handsheets based on TMP-pulp. Fines and wet pressing influence the bonding in the sheet and the objective of the study was to explore their influence on moisture-induced roughening. The sheets were tested with respect to surface roughness (PPS). The bonding in the sheets was also tested by measuring the tensile strength and the light scattering coefficient. These measurements showed that increased wet pressing increased the bonding in the sheet.

The results are summarized in Figure 33, where the roughness of the sheet is plotted against the wet pressing pressure. It is evident in the figure that increased bonding (wet pressing pressure) reduced the roughening only marginally. Moreover, it is evident in the figure that the quantity of fines did not affect the roughening at all. They only affected the level of the roughness.

Increased beating, which like increased wet pressing also increases the degree of fibre bonding in the sheet has, however, been found to reduce the roughening [26]. However, this reduced roughening might be caused by increased fibre flexibility which reduces the number of lumen expanded fibres in the sheet [112].

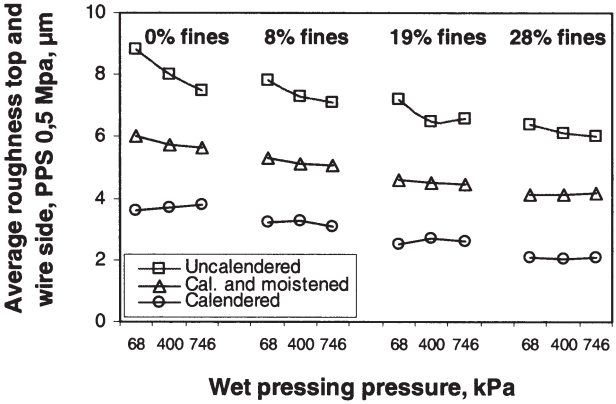

Figure 33 Surface roughness as a function of wet pressing pressure [110].

In reference [111], the length scale of the roughening was determined. This study was performed on a SC-paper, prior to and after moistening and re-drying using profilometry and FTT-analysis of the recorded signal. The measuring area was 250 µm × 250 µm. The results were presented in the form of power spectra. A comparison of these spectra for the sheet prior to and after moistening showed that most of the roughing occurred at wavelengths corresponding to typical fibre widths. Engström and Lafaye [24] have studied roughening using a similar technique, but on a significantly larger measuring area of 25400 µm × 25400 µm. Engström and Lafaye [24] observed that most of the roughening occurred on a length scale which was identical with the dimensions of the fibre flocs in the sheets. If the roughening is governed by an irreversible moisture-induced thickness expansion, it is quite logical that the fibre-rich areas of the sheet, i.e. the fibre flocs, expand more than the surrounding fibre-poor areas.

As already discussed, pre-calendering of the base sheet and its influence on the roughening has caught the attention of several researchers e.g. Engström and Lafaye [24], Gane et al. [26], Skowronski [20]. In reference [17], Forseth and Helle have studied the effect of pre-calendering on the roughening in blade coating with water. The base sheets studied consisted of a sized and an unsized newsprint paper, a SC-paper, and a base sheet for LWC, all machine-made, which prior to the coating were calendered at one of two line pressures, termed "mild" and "hard" using a laboratory calender. The coatings were performed on a CLC 6000 coater, equipped with IR-drier, at a machine speed of 800 m/min. The surface roughness of the sheets was measured prior to and after the coating.

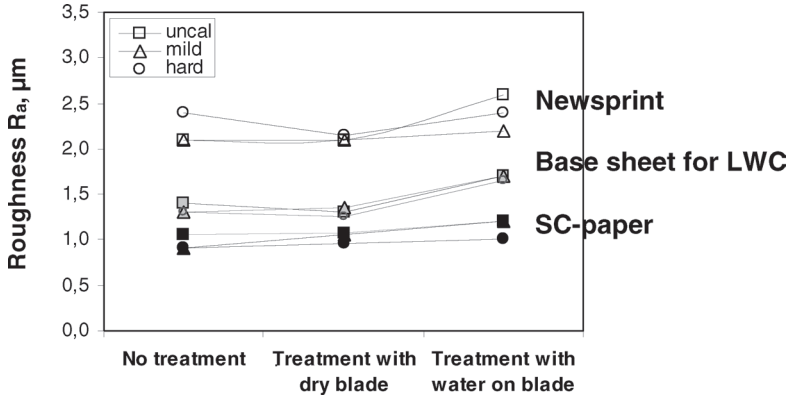

Figure 34 Roughness of different sheets prior to coating and after coating dry and coating with water [17].

"Coating" dry, at the same blade pressure as with water, reduced the roughness of the sheet, for all the sheets studied. This shows that the sheets were compressed beneath the blade tip and that the recovery (spring back) after the blade was not complete. Coating with water influenced the roughness of both the calendered and uncalendered sheets. The roughening, however, was for more pronounced for the calendered sheets. However, it should be pointed out that after coating with water, the pre-calendered sheets were also significantly smoother than the uncalendered ones. The sizing did not influence the roughening. This is in agreement with the studies of Forsström et al. [6] and of Skowronski and Lepoutre [18]. The results are summarized in Figure 34.

Compressibility

The compression of the base sheet beneath the blade tip during the forming of the coating layer has been discussed in the section entitled "Forming of the coating layer beneath the blade tip", where it was stated that high compression yields a coating layer with uniform thickness (mass) distribution. This compression is determined by the pressure to which the sheet is subjected beneath the blade tip and the compressibility of the sheet. A measure of the compressibility is the elastic modulus, and for an anisotropic material like paper, this is different in the three directions of the material. An example which shows this is given in Table 4 taken from a work by Xia et al. [113].

Remarkable and worth pointing out in Table 4 is the low value for the

Table 4 Elastic module for a board based on unbleached kraft pulp [113].

Direction	Elastic modulus, MPa
Machine (MD)	3000
Cross-machine (CD)	1000
Thickness (ZD)	20

ZD-modulus which is two orders of magnitude less than that of the modulus in the plane. Similar values of the ZD-modulus are presented by Provatas and Uesaka [114] and Rättö [115]. These researchers have also studied the effect of the surface roughness on the compressibility and they have shown that the surface compression is significantly greater than the bulk compression. This is because the load is not uniformly distributed over the surface but is concentrated onto the peaks. Provatas and Uesaka [114] also showed that a smooth sheet with a less compressible bulk structure can be rougher under compression than a rougher and more compressible sheet, Figure 35. They also pointed out that a consequence of this is that pre-calendering, which reduces both the roughness and compressibility, may not necessarily lead to a smoother sheet under compression. The possibility of such behaviour has been confirmed in a study by Endres and Tietz [116] in which blade coating, coating with the MSP and curtain coating were compared with each other with respect to sheet structure. It was found that the curtain-coated material,

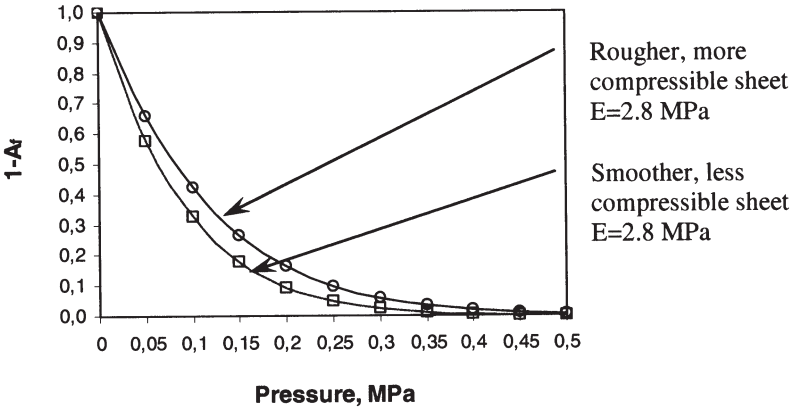

Figure 35 The non-contact areas ($1\text{-}A_f$) of simulated papers under pressure [114].

in spite of the fact that is was the roughest, exhibited the largest contact area under pressure using the LCSA-technique (Local Contact and Stress Analyser) [117]. The larger contact area was attributed to the fact that the base sheet was not compressed during the coating, in contrast to the base sheets for blade coating and coating with the MSP. The density (uncalendered) of the curtain-coated sheet was 720 kg/m^3 and that of the blade and MSP coated sheets was 790 kg/m^3. Curtain coating is a non-contact coating method [118].

It is well known that the elastic modulus in the plane of paper decreases considerably with increasing moisture content [e.g. 119–121]. Figure 36,

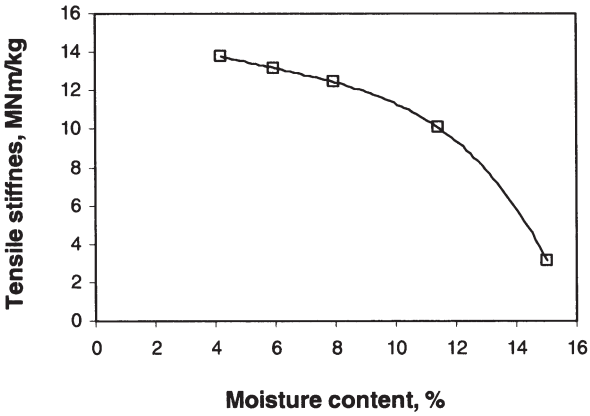

Figure 36 Tensile stiffness (MD) versus moisture content for a linerboard [121].

which is taken from the thesis of Nordvall [121], shows the tensile stiffness (specific modulus) in MD of a linerboard as a function of the moisture content. The decrease in the tensile stiffness was marginal up to a moisture content of approximately 8%. Above 8%, the decrease was considerable. This suggests that tensile stiffness of the base sheet can be reduced significantly during coating when the sheet is brought into contact with the coating colour, because the moisture content of the surface of the sheet can be assumed to exceed 8%.

The modulus in ZD is affected in approximately the same manner as the modulus in MD. This was demonstrated in a study by Engström and Morin [122] in which a base sheet for LWC was compressed in a platen press at three moisture contents within the 5–12% range. The pressure was 30 MPa and the length of the pressure pulse was 20 ms. Figure 37 shows the compression as a

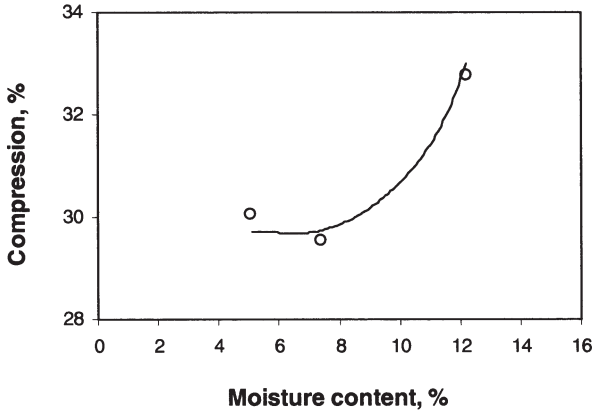

Figure 37 Compression as s function of moisture content for a base sheet for LWC. Platen press experiment at a pressure of 30 MPa and a pulse length of 20 ms [122].

function of moisture content. Work by Bergh et al. [123] has shown that coating layers on compressible base sheets exhibit a uniform thickness (mass) distribution.

Engström and Morin [122] also reported that the recovery (spring back) after that the load was released decreased when the moisture content increased. This means that the permanent compression was greater at higher moisture contents.

Swelling pressure

The compression of the base sheet beneath the blade tip is determined by the pressure on the sheet and by its compressibility. The compressibility referred to here is that of the sheet in a moist state which is influenced by the uptake of the aqueous phase from the coating colour prior to the blade. This process plasticizes and swells the fibres in the base sheet and the fibre swelling increases the thickness of the sheet [14, 33]. If the thickness is kept constant during the liquid uptake, the swelling will create a pressure, the swelling pressure, in the sheet. Skowronski et al. [107] have constructed a device to measure this swelling pressure.

Using this device, the swelling pressure was monitored as a function of time for handsheets based on TMP and on a bleached kraft pulp. The sheets were prepared using a standard wet pressing procedure but, in order to obtain sheets with the same density, kraft sheets were also made with wet pressing. A

set of the sheets was also calendered. Prior to the application of water, the sheets under test were compressed under an initial pressure of 17 kPa.

The swelling pressure curves for the sheets tested are shown in Figure 38. The swelling pressure measured is an effect of 1) sheet structure collapse caused by the plasticization effect of the water and 2) fibre swelling. For the low density sheets, the swelling pressure was negative indicating that the sheet structure collapsed when these sheets were supplied with water. For the dense sheet, a positive pressure was monitored showing that the swelling pressure was controlled by the fibre swelling.

For the uncalendered sheets which were wet pressed in the same way, the sheets based on TMP developed no swelling pressure whatsoever in contrast to the sheets based on kraft pulp which exhibited a very high swelling pressure. The influence of the sheet density on the swelling pressure explains the difference in swelling pressure between the sheets based on TMP and kraft pulp. For the calendered sheets, both the sheets based on TMP and the sheets based on kraft pulp exhibited a swelling pressure. However, it should be pointed out that the calendered and uncalendered sheets based on kraft pulp developed the same swelling pressure.

The fact that the uncalendered sheet based on TMP developed no swelling pressure and that the calendered sheet did was discussed by Skowronski et al. [107]. They suggested that the lumen of the fibres in the sheet was collapsed during the calendering and opened when the sheet was exposed to water, and that this lumen opening was responsible for the swelling pressure.

The swelling pressure can be used to discuss the surface profile of the base

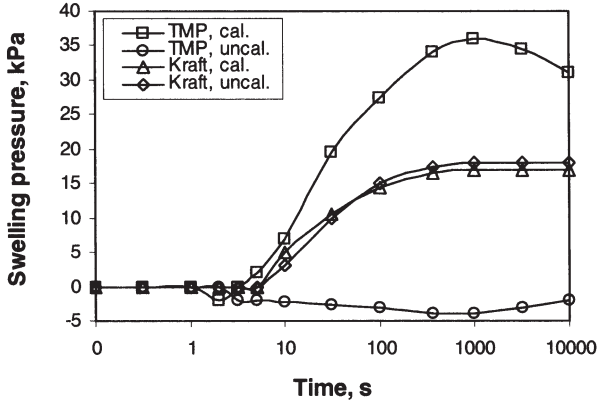

Figure 38 Swelling pressure curves for different sheets [107].

sheet in a compressed and moist state beneath the blade tip during the forming of the coating layer. This surface profile determines the mass distribution of the coating layer, which is a key property in a print quality context. The coating mass distribution must be uniform to obtain a high quality print. To meet the demand for a uniform mass distribution, the surface profile must be smooth. A sheet which collapses under pressure meets this demand, i.e. a sheet which exhibits a negative swelling pressure. The opposite is also true, i.e. sheets which do not collapse under pressure will be rough in a compressed state, i.e. sheets exhibiting a high swelling pressure. The swelling pressure explains why the mass distribution is more uniform on LWC than on fine paper [27, 108] and why it is more uniform on an uncalendered than a on precalendered base sheet [24, 26].

Internal stresses

Wood fibres are curled and twisted. When a sheet built up of such fibres is strained during drying, stresses are built into the sheet. A number of researchers, e.g. Htun [124], have studied restrained drying and the influence of shrinkage during drying on the in-plane mechanical properties of the sheets, and they have found that these parameters are related. Restrained drying and low shrinkage give a high modulus of elasticity and high strength levels. In 1964, Johanson and Kubat [125] developed a method for measuring the in-plane stresses built in into the sheet during drying.

Lindem [126] has developed an instrument in which wet paper sheets can be dried under controlled stress or controlled shrinkage. Using this instrument, Lindem [126] studied the influence of the shrinkage on the surface properties of handsheets based on mechanical pulp and on chemical pulp. The results showed that the surface roughness increased and the gloss decreased with increasing shrinkage during drying. The changes in roughness and gloss occurred in the same way and to the same extent for both the pulps, Figure 39. Lindem [126] suggested that the smoother surface obtained at low shrinkage was caused by a straightening of fibre segments between the fibre bonds in the sheet. Lindem [126] also showed SEM-images of sheets which were dried in a restrained state and in a free state. These images clearly showed that the sheets dried under restraint were smooth and that those freely dried were rough. The texture of the surfaces also agreed with the images presented by Forsberg and Lepoutre [127], which show dry and wetted paper surfaces captured using ESEM.

Skowronski and Lepoutre [18, 19] discussed the causes of the roughening and mentioned irreversible fibre swelling, de-bonding and stress relaxation as possible causes. In their second paper, Skowronski and Lepoutre [19] studied

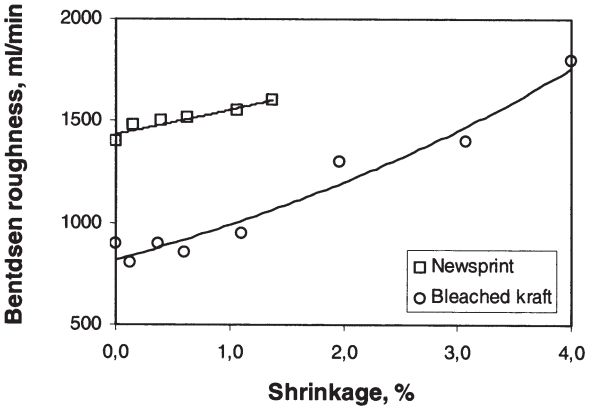

Figure 39 Surface roughness as function of shrinkage during drying [126].

stress relaxation in the base sheet during the coating of sheets with low and high sorption capacities. The stress relaxation was measured using the technique developed by Johanson and Kubat [125]. In the high sorption sheets, all the stresses were released during coating with coating colour as well as with water. In the low sorption sheets, the stresses were only partly released. For these sheets, Skowronski and Lepoutre [19] report a fair correlation between the release of internal stresses and the roughening.

Addition [128] followed up the work of Skowronski and Lepoutre [18–20] with a study on hand sheets based on never-dried kraft hardwood pulp beaten to different freeness levels. The sheets were exposed to 97% relative humidity for one week. Although the stresses in the sheet decreased considerably during the long exposure time (24–38% depending on the freeness of the pulp), the roughness remained constant. Enomae et al. [21] have reported similar results.

Similar results were also obtained by Sasaki et al. [129] in an experiment in which they soaked a sheet of a commercial fine paper in water and then dried it. The sheet became rougher and the internal stresses were reduced. They then calendared the water-treated sheet and soaked again it in water. The roughness increased to the same level as it had prior to the water treatment, while the internal stresses remained unaffected. This is an example of roughening without the reduction of the in-plane internal stresses. Thus, the works of Addition [128], Enomae et al. [21] and Sasaki et al. [129], do not confirm the hypothesis that the release of in-plane stresses in the sheet causes roughening.

Enomae et al. [21] pointed out that internal stresses must be anisotropic

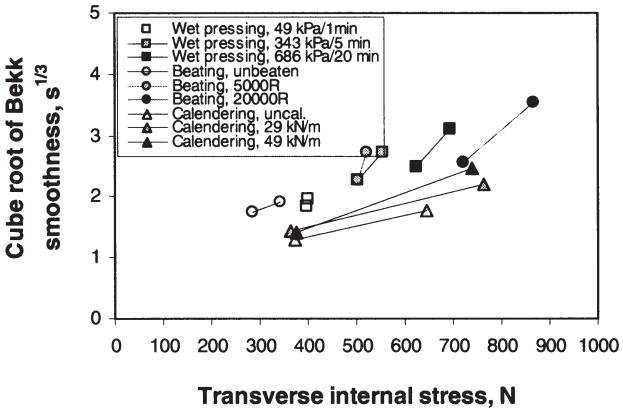

Figure 40 Bekk-smoothness as a function of the transverse internal stress [21].

because the stresses to which the paper is exposed during production are anisotropic. It is therefore reasonable to believe that compressive stresses, like those exerted in calendering, should build up stresses in the sheet. Engström and Lafaye [24] have expressed the same idea. To test this hypothesis, Enomae et al. [21] modified the method of Johanson and Kubat [125] for measurement in the compression mode and studied the influence of the release of transverse stresses on the roughness for handsheets based on kraft pulp in which freeness, wet pressing and filler content constituted the experimental parameters. The influence of calendering was studied on a commercial wood-containing paper. The roughness and the thickness of all the sheets studied increased, whereas the transverse internal stresses decreased, when the sheets were soaked in water. Figure 40 shows the relationship between the Bekk-smoothness and the transverse internal stress. The lines connecting each pair of points show the changes caused by exposure to water.

The effects of calendering, conditioning, dampening, and drying on the microscopic surface properties of sheets based on groundwood pulp and on kraft pulp have been studied by Retulainen et al. [130] using confocal microscopy. Their observations indicated that fibre bonds were broken during the calendering and that some of the compression remained on the peaks in the sheet after wetting and drying. This suggests that broken fibre bonds may have contributed to the roughening observed. Only very little lumen collapse due to dampening and re-drying was observed, and in most cases the aspect ratio of the fibres remained unaffected. Z-directional movement and bending of fibres were also observed. The authors claim that this is as an important

alternative mechanism of sheet densification during calendering. This mechanism is reminiscent of that proposed by Lindem [126] for the effect of shrinkage during drying on sheet density and roughness.

Lumen opening

Forsberg and Lepoutre [127] have studied the effects of moisture uptake and moisture release (drying) on the surface roughness of SC-papers and LCW-papers using an environmental SEM technique. They observed that mechanical fibres expanded in thickness when moistened and that these fibres retained the expanded thickness after drying. The chemical fibres behaved differently. These fibres expanded when moistened, but during the drying they shrank and recovered their original thickness.

Forseth and Helle [15–17, 110, 111] continued on this track and studied dimensional changes of the fibre cross-section caused by calendering and moisture (24 h at 97% R.H.) with the help of light microscopy on cross sections of SC-paper. Their results showed that the lumina of most fibres (mechanical) were open in the uncalendered sheet and closed in the calendered sheet. Moistening of the calendered sheet opened the lumina. These results agree with those presented by Forsberg and Lepoutre [127].

Unfortunately, there are no direct studies, comparable to those performed by Forseth and Helle [15–17, 110, 111] on how the fibres in sheets based on 100% kraft pulp respond to calendering and moistening. However, there are good reasons to believe that the lumina are closed in the uncalendered sheets, and that they remain closed after calendering and moistening, as suggested by the results of Forsberg and Lepoutre [126]. Other results which support this are that moistening/drying increases the thickness of sheets based on mechanical fibres whereas it has no effect on sheets based on chemical fibres [19].

The thickness increase caused by the moistening is dependent on the thickness of the fibre wall, and thick-walled fibres expand more than thin-walled ones Forseth and Helle [15–17, 110, 110]. Similar results have been reported by Norman and Höglund [131].

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Transcription of Discussion

INTERACTIONS BETWEEN COATING COLOUR AND BASE SHEET IN PIGMENT COATING

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Joseph Aspler PAPRICAN

Your last point raises two interesting questions:

1. With the increased use of mechanical fibres how do you think we can get less irreversible swelling?
2. Do you think the increased use of de-inked fibre would give non-roughening or less-roughening due to fibres during coating?

Gunnar Engström

That is a good question and it is true that recycled fibres are more stable than mechanical and chemical fibres. But I think that some of the difference between wood-free and wood-containing base papers also stems from the difference in density between these papers. It is much easier to compress a low density wood-containing paper. So it is an advantage to have a low density, but what is better: wood-free papers or wood-containing papers? This is a question which is difficult to answer, because there are so many aspects to consider. It is not only a matter of the type of fibres, but also a matter of how the fibres behave in the different process stages in the paper production process and how this behaviour affects the sheet properties. And this behaviour is different for different types of fibres. So, I do not know, and I do not dare to speculate either, but it might be that recycled fibres have an advantage. I do not know, but it might be so.

Discussion

Tetsu Uesaka Mid Sweden University

Thank you for the very nice review. My question concerns the pre-calendering effect. You mentioned that essentially the pre-calendering effect disappears during coating due to roughening. However, as you may be aware, over the last several years there have been quite a few studies done in this regard and in fact pre-calendering did improve coating uniformities in spite of all our beliefs. Do you have any comment on this?

Gunnar Engström

Yes, that is also what I have seen, but only for wood-free papers. I have never seen any positive effect of pre-calendering for wood-containing papers.

Tetsu Uesaka

Wood-containing papers also show the same effect.

Gunnar Engström

As I already have said I have only seen a positive effect for wood-free papers, not for wood-containing papers. For wood-containing papers I have studied how different types of calendering technique affect the paper – hard nip, hot soft nip with different temperatures – but I have never seen any positive effect of pre-calendering. But it might be that disagreement between our experiences depends on the scale we are looking at. In my studies I have concentrated the evaluation on a length scale similar to that of the fibre floc structure.

Richard Bown IMERYS Minerals Ltd

Just a point on that last comment. The kinetics of this process are quite important and the data you are showing about the roughening effect, which you attribute to being roughening under the blade, could well be roughening shortly after the blade. So if you are coating a pre-calendered sheet you can be coating onto something which is quite smooth and then it roughens shortly after the blade. So you get something more like contour coating in that type of instance which then does give you a different quality of paper, and which may well be what some people observed.

Gunnar Engström

What you do when you pre-calender a base paper is that you compress it. That makes it less compressible. That means that the roughness in the paper is not that easily compressed away beneath the blade tip. It seems that the effect of the densification of the paper during the pre-calendering on its compressibility remains during the formation of the coating layer beneath the blade tip. So when the paper comes to the blade tip it is stiff, but rough. When the same uncalendered paper comes to the blade tip it is also rough, but since it is compressible the roughness is compressed away by the blade pressure.

We have seen similar effects with curtain coating which is a contour coating technique. During the forming of the coating layer in this technique the base paper is not compressed because curtain coating is a contact-free coating method. That means that the paper is compressible when it comes to the calender. So in spite of a rougher coated paper, which is a consequence of the contour coating, the final coated and calendered paper will be smoother and the coating layer will be more uniformly compressed, because the deformation occurs mainly in the base paper beneath the coating layer. That is interesting.

Murray Douglas McGill University

There has been much written about the role of the delay time between coating and drying on the quality of the coated sheet. Those are very interesting curves that you have presented and discussed about the time evolution of roughness and plasticization. Do those results give you some insight as to the role of the coating-to-drying delay time?

Gunnar Engström

Yes, the dwell time prior to the blade. There are coaters, which differ in dwell time. The coaters I have discussed are regular coaters in which the distance between the application and the blade is approximately one metre. The coaters with longer dwell time are called long dwell time coaters and for these coaters the dwell time is approximately 2 to 3 times longer. The long dwell time coaters produce a perfectly uniform coating layer in terms of thickness. This is due to the fact that the water uptake prior to the blade plasticizes the base paper so when it comes to the blade, the blade smoothes the paper which in turn results in a coating layer with uniform thickness.