Formation and consolidation of a coating layer and the effect on offset-print mottle

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ABSTRACT: The literature on the formation and consolidation of a coating layer is reviewed, with emphasis on the occurrence of mottle in offset printing of coated paper. The review first defines and examines the press-related causes of mottle. The stain tests used to predict offset mottle are described along with their limitations. The main portion of the review is devoted to paper-related causes of mottle. The interaction between the coating color and the base paper during coating formation and consolidation is a focal point of discussion. Special attention is paid to factors influencing the distributions in mass, porosity, and binder content of the coating layer and their relation to mottle in the offset print. The role of calendering is also examined.

KEYWORDS: Bibliographies, coatings, consolidation, formation, layers, mottle, offset printing, printing.

Multicolor printing in magazines and advertisements is increasing substantially. Requirements for sharpness and brilliance are especially important for such prints, so coated paper is widely used *(1)*. Coated paper is the fastest growing paper grade *(2)*.

Pigment coating involves the application of a "coating color" to the paper. Such coating colors consist of pigment and binder suspended in water. Usually the pigment is kaolin clay, and the binder is a mixture of latex and starch. CMC (carboxymethyl cellulose) can be used instead of starch, but in smaller amounts. The total binder content is usually 10–15 parts per 100 parts of pigment. The solids content of a coating color of this type lies in the range of 45–60%, depending on the coating process. The water in the coating color that is applied to the paper is evaporated in a dryer. The dry coat weight varies, depending on the end use. The typical weight is about 10 g/m^2, which corresponds to a thickness of approximately 7 µm.

The coating improves the printing properties of the paper. However, this does not mean that print-quality problems are fewer and less serious with a coated paper. One of the most frequent problems, as well as the most serious, is mottling in an offset print *(3, 4)*. Mottle is an undesirable unevenness in print density, and it can have press-related or paper-related causes.

A great deal has been written about the paper-related causes of mottle. The general opinion is that mottle is caused by an uneven distribution of binder at the coating surface, the result of binder migration from the coating layer during the consolidation process. Uneven binder distribution can develop at the coating surface if a coating layer with an uneven distribution of mass is subjected to overly intense drying *(5–7)*. Another cause of uneven binder distribution is uneven transport of water from the wet coating layer to the base paper *(8–10)*. The literature about paper-related causes of mottle deals mostly with indirect results (stain tests) and focuses mainly on the effects of the drying operation.

The transport of water from the wet coating layer during the consolidation process is an important factor in determining coating properties. Besides influencing the binder distribution at the coating surface (and thus the mottle in the offset print), it also affects the conditions under which the coating layer is

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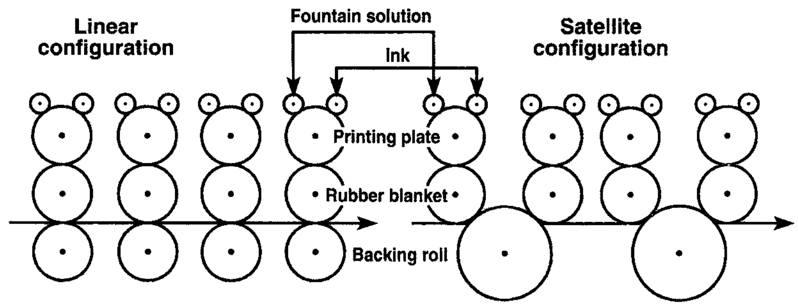
1. Two offset-press configurations: linear configuration (left) and satellite configuration (right)



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formed and thus the mass distribution of the coating layer. The distribution of mass determines surface roughness and other properties of the coated material that affect print mottle *(11–13)*. Calendering of a coating with an uneven distribution of mass also can alter the porosity distribution of the coating and thus contribute to mottle in the offset print *(14)*. Finally, transport of water to the base paper releases an interaction between the sheet surface and the wet coating layer *(11)*, and this interaction also can affect the printing properties of the coated material *(15)*.

This article reviews the literature within the area "paper coating—mottled offset print." The main body of the review deals with a series of papers by the author and co-workers, who focused on the causes of mottle in a wider sense while using direct methods to characterize the mottle and the coated material *(12–19)*. These papers are based on a series of experiments in which different types of base paper were coated on a pilot scale. The investigations sought to

1. Identify how the unit processes of forming, drying, and calendering affect the distributions of mass and porosity within the coating layer and the distribution of binder at the coating surface.
2. Establish relationships between these distributions and offset-print mottle.

The interaction between the base paper and the liquid phase of the wet coating layer was a principal focus of the studies.

Press-related causes of offset-print mottle

The essential feature of the lithographic offset-printing process *(20)* is that the nonprinting areas of the printing plate are hydrophilic and the printing areas are hydrophobic. Water is applied to the printing plate, where it adheres to the hydrophilic areas. When the ink is applied, it adheres to the areas not covered by water, i.e., the hydrophobic areas. The ink and water on the printing plate are first transferred to a roll covered with a rubber blanket and thence to the paper. In multicolor printing, the paper usually passes through four printing units in succession. The first printing unit typically prints black, with cyan in the second, magenta in the third, and yellow in the fourth. **Figure 1** illustrates two offset-press configurations.

A consequence of multicolor printing is that a printed area from a preceding printing unit will pass through one or more of the subsequent printing units, with the printed area contacting the rubber blanket in those units. Ink can be transferred from the print to the rubber blanket, and if this occurs unevenly, the print can become mottled. This is a frequent cause of a mottled offset print and is denoted "back-trap mottle" *(19, 20)*.

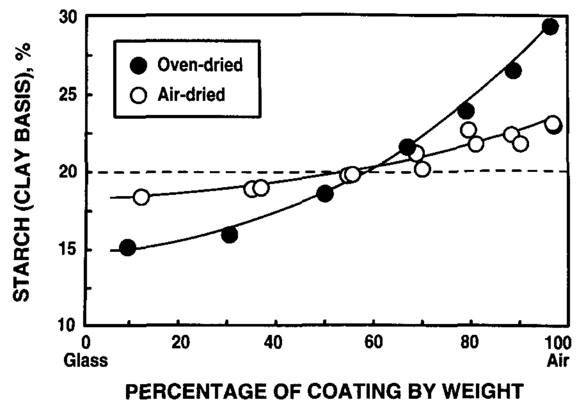
Mottle also frequently occurs when the water applied to the paper in one of the first printing units is not absorbed by the paper before it reaches a subsequent printing unit. This can lead to uneven ink transfer and a mottled print. Mottle from this source is denoted "fountain-water mottle" *(19, 20)*. This type of mottle is more frequent in satellite presses, where the distance between the printing units is shorter, than in presses where the printing units are arranged in a series.

When the fountain water on the printing form is transferred to the rubber blanket, it breaks up and forms droplets because of the hydrophobic character of the blanket *(21)*. This means that some groups of screen dots become surrounded by fountain water, whereas other groups are not. The dots surrounded by water are smaller when transferred to the paper, since they do not spread out to the same extent as those not surrounded by fountain water. This can lead to mottle in the halftone areas of the print, while the fulltone areas remain even *(19)*.

Stain tests

Various stain tests are often used to test a coated paper for its propensity to mottle during offset printing. K&N ink, which is gray–blue, and Croda ink, which is red, are the most common inks for these tests *(22)*. If the stain is uneven, this is interpreted as

2. Distribution of starch in air-dried and oven-dried coatings on glass plates



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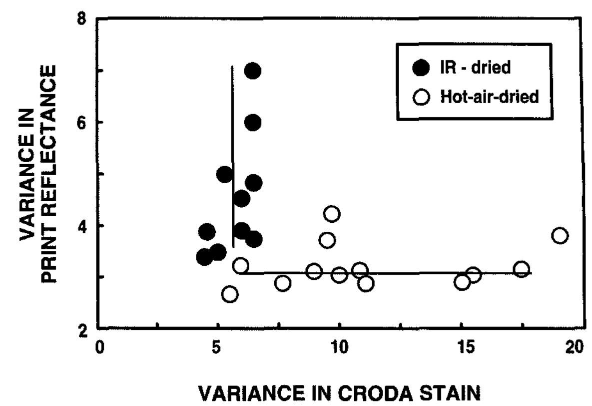
3. Variance in print reflectance (print mottle) in offset prints (black fulltone from first unit in a four-color press) as a function of variance in Croda stain (Croda mottle) for IR-dried and hot-air-dried sheets



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an indication that the offset print may be mottled *(19, 23)*.

Stain tests are also used as a basis for discussing the causes of mottle. The general opinion, based on such tests, is that the coated material should be dried at a low evaporation rate, thus preventing binder migration to the coating surface and subsequent mottle in the offset print. This opinion has its origin in a classical experiment by Dappen *(24)*, who coated glass plates with a coating color (kaolin clay and starch) and then dried them either at ambient conditions or in an oven at 105°C. He then determined the starch content in the *z*-direction by scraping off the coating layer gradually and determining the position and starch content of the scraped-off material. This experimental procedure required coat weights that were very high (47 lb or 230 g/m²). The results showed a greater concentration of starch near the surface of the oven-dried material, as seen in **Fig. 2**.

This experiment was followed up by other workers *(25, 26)*, who applied coatings to flat and etched glass plates and then dried them at ambient conditions or in an oven. The testing was limited to K&N stains. The stains were dark and even on the plates that were dried at ambient conditions, regardless of whether the plates were flat or etched. The K&N stains were pale on the coatings that were dried in the oven, and the stains on the etched glass plates were uneven. These results were linked with Dappen's result, and the following conclusions were drawn:

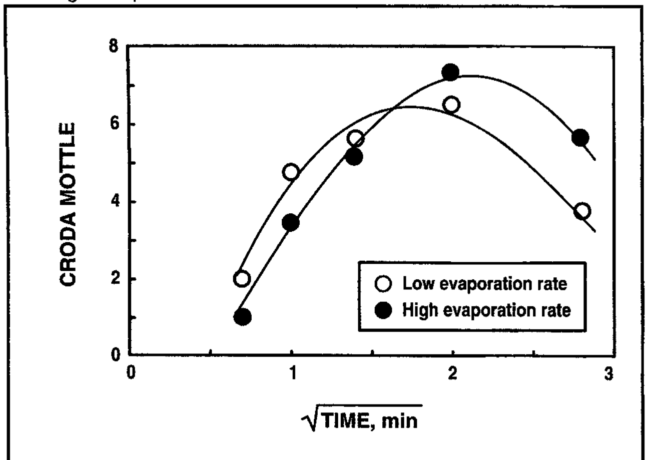
1. Binder migration towards the coating surface results in a pale K&N stain.
2. Uneven binder distribution results in an uneven K&N stain
3. Uneven binder distribution is caused by an uneven mass distribution of the coating layer in combination with overly intense drying.

Because an uneven K&N stain was also interpreted as an indicator of a mottled print, the logical conclusion was that print mottle could be minimized by drying coated materials at a low evaporation rate.

These conclusions seem to be consistent, but they suffer from several shortcomings. First, the unevenness in the stain is a poor indicator of mottle in the offset print *(19, 23, 27, 28)*. This is probably because the entire coating layer is saturated with ink during a stain test, with the ink often bleeding through the coating layer into the paper beneath it. This is a poor simulation of reality, where the printing ink penetrates only the outermost regions of the coating layer *(29)*. For obvious reasons, a stain test is also a poor indicator of fountain-water-induced mottle. Finally, the reduced intensity of the K&N stain is not necessarily the result of pore closure caused by binder migration to the coating surface at elevated temperatures. Such drying conditions also decrease the porosity of the entire coating layer *(30)*. Pore closure at both locations reduces the pickup of K&N ink.

Stain tests must be interpreted with great care. This fact was demonstrated in a coating trial in which different infrared (IR)-drying and hot-air-drying strategies were evaluated with respect to mottle in the offset print. Comparison of print mottle with the corresponding Croda-stain mottle showed that all the offset prints were more mottled and all the Croda stains were less mottled on the IR-dried material than on the hot-air-dried material *(19)*. Consequently, in this case, the Croda stains gave completely wrong information regarding the risk of mottle in the offset print, as seen in **Fig. 3**. However, results from another trial showed that the offset

4. Variance in Croda stain (Croda mottle) as a function of the square root of ink–paper contact time for coatings subjected to low and high evaporation rates



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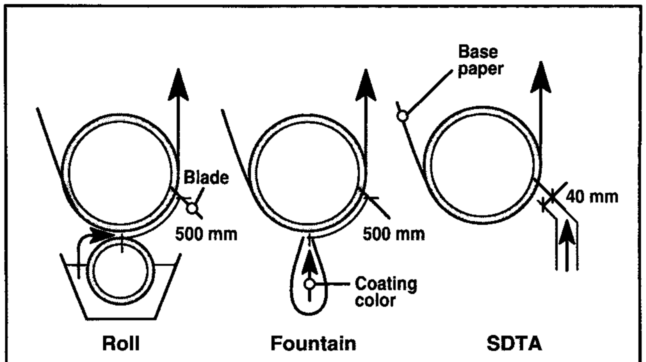
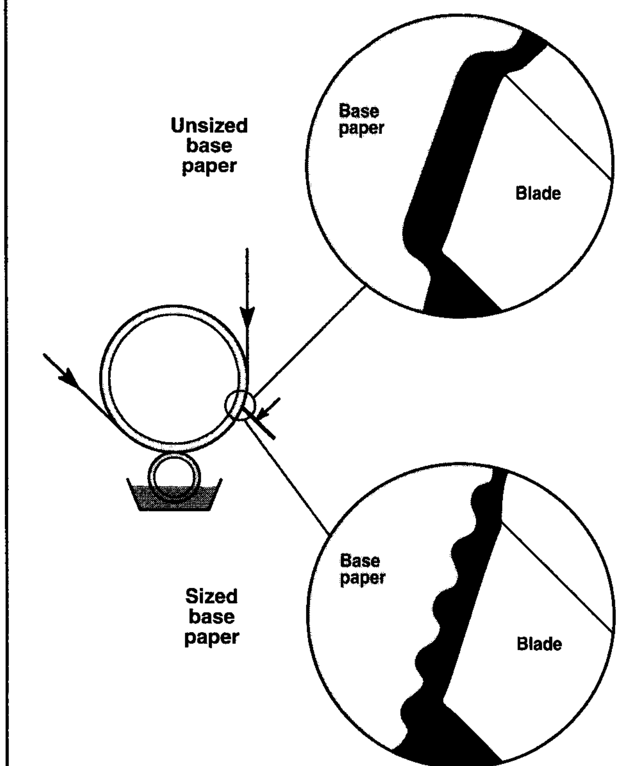
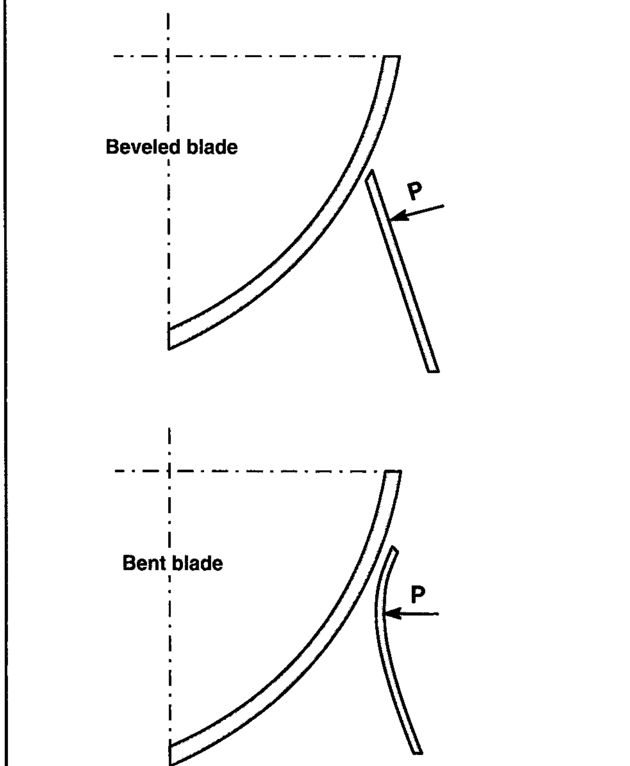
5. Three principles for application of coating color



6. Compression of sized and unsized base sheets under the coating blade. Unsized sheets are more compressible because of water uptake between coating application and the blade. Mass distribution of the coating layer is more uniform for compressible sheets.



7. Two configurations for blade coating



mottle rated in the same manner as the Croda mottle, provided the contact time between the Croda ink and the coated sheet was less than 2.5 min. This is illustrated in **Fig. 4**, where it is seen that the Croda stain is more mottled for material dried at the low evaporation rate at contact times less than 2.5 min. This rating is in agreement with the rating for mottle in offset print. If the contact time is longer than 2.5 min, the rating is the opposite *(16, 19)*.

Formation of the coating layer

The mass distribution within the coating layer is a key parameter determining many properties that—alone or in combination with one another—can affect mottle. Indeed, the mass distribution within the coating layer determines binder distribution, porosity distribution, and topography of the coating layer.

The mass distribution of the coating layer is determined by a complicated interaction of several factors, with the coating color, the base paper, and the coating process all playing important roles. However, the conditions during formation of the coating layer seem to be preeminent. These conditions are determined largely by the method used to apply the coating color.

Application of coating color

Coating color is applied with a roll, a fountain or jet, or SDTA (short-dwell-time applicator) unit, as illustrated in **Fig. 5**. Immediately following coating application, the base paper begins to pick up water from the wet coating layer.

If the coating color is applied with a roll, a substantial pressure pulse is developed in the nip between the applicator roll and the paper. Measurements on a pilot coater running at 1000 m/min showed that this pulse varied within the range of 1–2 kN/m, depending on the nip geometry *(31)*. It is reported that the water pickup by the base paper at these pressures appears to be of such magnitude that a filter cake develops in the bottom of the coating layer *(32)*. The same work also reported that the water pickup during the short residence time in the nip exceeds the pickup that occurs as the sheet travels from the applicator to the blade. The high pressure may also force the wet coating layer into the base paper, which has a negative effect on the printing properties of the coated material *(33)*.

The base paper is weakened by the water pickup that occurs between the applicator and the blade. In addition, an increase in water pickup by the base paper produces a corresponding increase in the solids content of the wet coating layer as it comes into the blade. The higher-solids coating exerts more pressure on the blade, so blade pressure must be increased to maintain constant coat weight. Both factors—the weakened sheet and the higher blade pressure—increase the risk of the paper sticking beneath the blade and tearing. SDTA coating produces fewer web breaks than conventional application of coating color because of the shorter contact time between the base paper and wet coating layer before it is scraped off by the blade *(34)*. The coating color is applied at a pressure only slightly higher than atmospheric pressure in the SDTA unit *(32, 34)*.

At the moment of forming beneath the blade tip, the mass distribution of the coating layer is determined by its two boundary surfaces *(35)*. Since the boundary surface at the blade tip is even and the boundary surface in contact with the base paper is uneven, the mass distribution of the coating layer at this stage is determined solely by the topography of the base paper. The base paper is compressed as it passes beneath the blade tip, which makes the surface smoother. Consequently, the topography that determines the mass distribution is that in the compressed state beneath the blade tip. The higher the blade pressure and the higher the compression, the more uniform is the mass distribution of the coating layer *(13, 14, 17)*. **Figure 6** shows sheet compression beneath the blade tip for an unsized base paper and a sized base paper. The unsized paper is more compressible because of the plasticizing effect of the water uptake from the coating color.

The blade pressure required to achieve a given coat weight is higher when the coating color is applied with a roll than with an SDTA unit. Thus it is not surprising to find that roll application gives the more even coating layer and the more even offset print *(13, 17, 36)*. Analogously, the mass distribution of the coating layer becomes more even at lower coat weights *(13, 17)*.

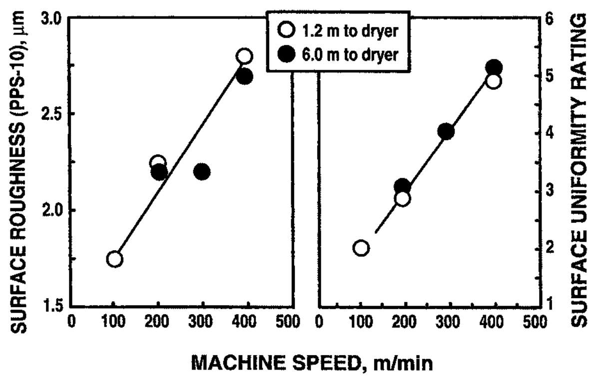
The inverse relationship between the mass distribution of the coating layer and the smoothness of the coated base paper has been established *(14)*. Nevertheless, a base paper coated with the SDTA coater exhibits the same smoothness as a sheet coated with roll application, despite greater unevenness of mass distribution within the SDTA coating layer *(13, 17, 36)*. Since coating smoothness is largely determined by the interaction between the base paper and the water in the wet coating layer *(11, 12, 13)*, it has been suggested that this interaction takes place solely after the formation of the coating layer in SDTA coating, but that it takes place both before and after coating formation in roll application *(36)*.

Leveling with a blade

During blade coating, excess coating color is scraped from the web and leveled out using either a beveled blade or a bent blade *(37, 38)*. **Figure 7** illustrates both principles.

When coating with a beveled blade, the blade is reported to ride on the peaks of the base paper surface, which would imply that the surface volume of the base paper

8. Surface roughness (left) and perceived surface uniformity (right) as functions of machine speed for a sized free sheet



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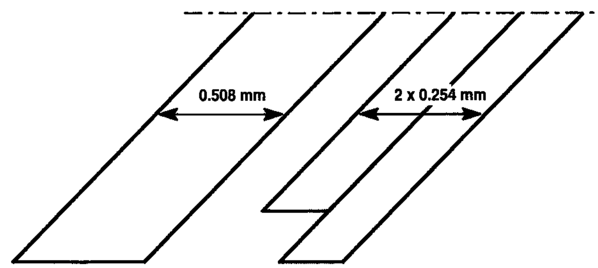
9. Blade configurations for tests: conventional 0.508-mm blade (left) and two 0.254-mm blades glued together (right)



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beneath the blade tip determines the coat weight *(37)*. From this perspective, coating with a beveled blade could be characterized as a coating method that fills the valleys in the surface of the base paper. However, it is also reported that coating with beveled blades results in a coating layer that is more reminiscent of a contour coating *(36)*. This opinion is based on ß-radiographic measurements of the mass distribution of the coating layer. If the blade really rests on the peaks in the base paper surface when the coating layer is formed, this means that the mass distribution is not affected by the conditions in the forming, i.e., on the blade geometry. In coating with a bent blade, it is reported that the blade rests on a coating film *(38)*.

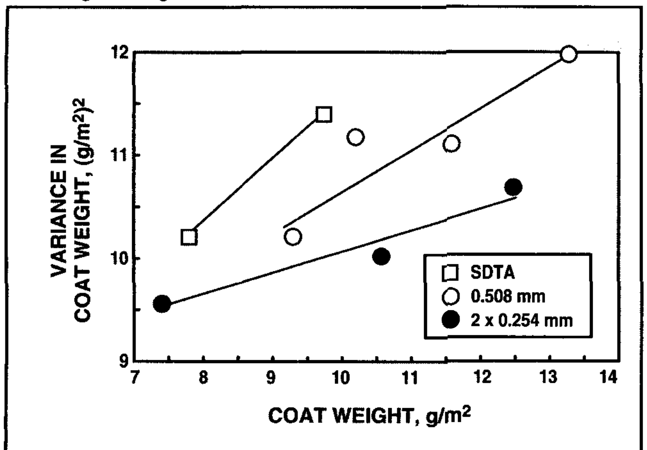
For sheets coated with a beveled blade, it has been found that both the surface roughness and the surface uniformity of the coated material increase with increasing machine speed *(13)*. This is illustrated in **Fig. 8**. The reverse behavior was observed for sheets coated with a bent blade *(12)*. The surface uniformity, which was rated visually, corresponded to the gloss distribution in the coating surface. The gloss distribution is reported to be governed by the mass distribution of the coating layer *(39)*.

Blade pressure must be increased when coating with a beveled blade and decreased when coating with a bent blade to keep the coat weight constant when the machine speed is increased *(40)*. Thus it can be concluded that high blade pressure produces a rough and uniform coating surface for both coating modes. A simple model of the blade-coating process was developed based on this observation *(13)*. This model proposes that when the blade pressure is increased, the compression of the base paper is increased as it passes beneath the blade tip, and that this evens out the surface roughness. Hence the coating layer will be more uniform in thickness or mass on a base paper that is compressed to a greater degree (cf. Fig. 6). When the compression is released after the blade, the base paper recovers in a movement that affects the coating layer. The greater this movement, the rougher the coating surface becomes.

Other investigations have found that the mass distribution of the coating layer as well as the offset print are more uniform for sheets that have been coated at higher blade pressures. For example, it has been reported that both the mass distribution of the coating layer and the offset print were more even when the blade pressure was increased (a) as a result of an increase in solids content of the coating color *(14, 41)* or (b) as a result of an increase in mass flow to the blade and in blade angle *(17)*.

To test the relevance of this model, a coating experiment was performed with two blade configurations *(13, 17)*, as illustrated in **Fig. 9**. One configuration involved the use of a single blade with a thickness of 0.508 mm. The other configuration consisted of two blades, each with a thickness of 0.254 mm, glued together with the tips displaced by approximately 1 mm. The blades in each configuration were of the same material and thickness, so they curved identically during the coating operation (i.e., the blade geometry was the same). However, the blades differed with regard to the contact area with the base paper, which was twice as large for the 0.508-mm blade. The relation between coat weight and blade pressure was the same for both the blades. Since the blade geometry was also the same, the pressure on

10. Variance in coat weight as a function of coat weight for coatings applied with an SDTA unit, a flooded-nip unit equipped with a 0.508-mm blade, or a flooded-nip unit equipped with two 0.254-mm blades glued together



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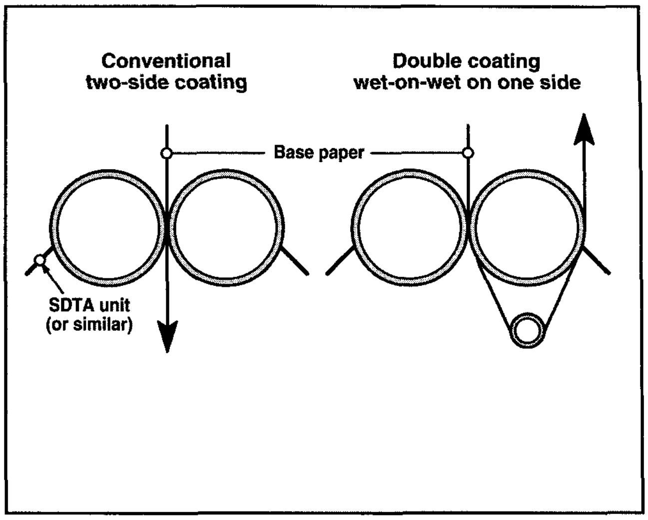
11. Two coating configurations



the base paper passing beneath the blade tip was twice as large for the 2 x 0.254-mm blade. The mass distributions of the coating layers were determined by X-ray radiography. As expected, mass distribution was more even on the material coated with the 2 x 0.254-mm blade, the result of the higher specific load and greater compression of the base paper when forming the coating layer. These results are shown in **Fig. 10** along with the results for a coating layer formed in the SDTA unit, which operates at low blade pressure. These results support the simple model of the blade-coating process presented here.

The compression of the base paper during formation of the coating layer is determined not only by the blade pressure but also by the paper compressibility, which is increased by the water pickup between the applicator and the blade. This means that a sized base paper will have a negative effect on the evenness of the coating layer's mass distribution *(18, 36)*. Print mottle is also more pronounced on sized material. In addition, it has been reported that the compressibility of a base paper for LWC (lightweight-coated) grades should be high to obtain a uniform coating layer *(42)*.

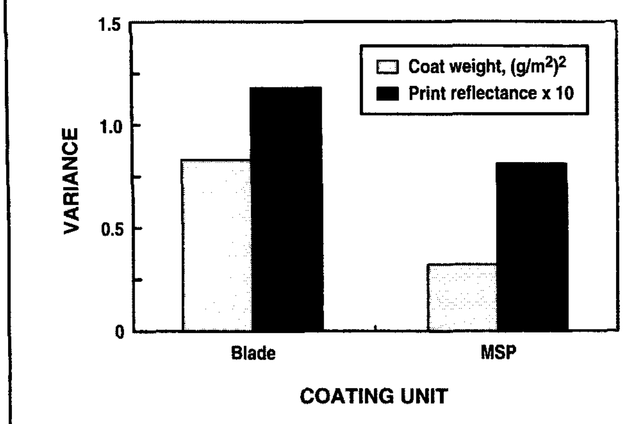
The coating layer is exposed to an extremely high shear rate when it is formed beneath the blade tip. This can lead to runnability problems, such as blade streaks, and the formation of stalagmites on the blade tip *(43)*. This high shear rate can also induce a flocculation in the wet coating layer *(12)* and an orientation of pigment particles *(44)*. Uneven distribution of pigment particles in the coating layer can lead to mottle in the offset print. The pressure pulse beneath the blade tip also may dewater the coating layer during its formation. Since the pressure pulse is short, the effect on the increase in solids content in the coating layer should be limited *(45)*, although it is reported that the pulse may squeeze out water from the base paper *(9)*.

Coating with the MSP unit

In the MSP (metering size press) coater, a preformed wet coating layer is transferred from a roll to the base paper in the nip between the paper and the transfer roll. This occurs simultaneously on both sides of the base paper, as seen in **Fig. 11** (left). As in roll application of the coating color in blade coating, a dynamic pressure develops in the transfer nip, forcing water into the base paper and increasing the solids content in the wet coating layer. The increase in solids content develops unevenly because of a natural variation in the rate of water pickup for the base paper, and the result can be an uneven transfer of the coating. At coat weights typical for fully coated materials, the MSP coating process reportedly produces a coating layer with an orange-peel-patterned surface that can result in print mottle *(46–48)*. Consequently, this coating process is used mainly for lightly pigmented coating or precoating. In these applications, the mass distribution of the MSP-coating layer is reported to be more even than a blade-coated layer *(14)*.

The MSP unit can be modified by installing a turning roll, as seen in Fig. 11 (right). With this configuration, it is possible to double-coat one side of the web wet-on-wet instead of simultaneously coating both sides of the web, as in Fig. 11(left) *(14)*. Coating in this manner reportedly eliminates the problem with the orange-peel pattern in the coating surface. As seen in **Fig. 12**, the mass distribution of the coating layer and the offset print obtained with this coating procedure are extremely even *(14)*. The mass distribution be-

12. Variance in coat weight and in print reflectance (print mottle) for blade-coated and MSP-coated (wet-on-wet double-coated) sheets. (Wavelength interval of variances = 4–8 mm; machine speed = 600 m/min.)



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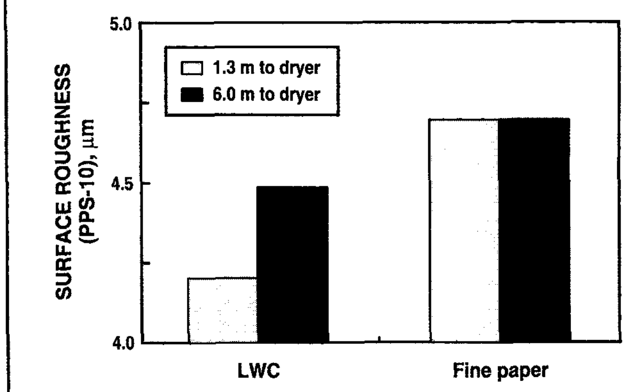
13. Surface roughness for LWC and sized free sheet for two distances between the blade and the dryer



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came more even at lower machine speeds. This indicates that mass distribution was affected more by the conditions in the transfer nip than by those during the consolidation, since extending the process of consolidation (by lowering the machine speed) had no negative effect on the mass distribution.

Consolidation of the coating layer

The kinetics of water transport from the coating layer during its consolidation process describes the rate of (a) water drainage from the wet coating layer into the base paper and (b) water evaporation from the coating surface until the coating layer immobilizes. It is generally accepted that these kinetics influence the properties of the dry coating layer, i.e., the porosity distribution of the coating layer and the binder distribution in the coating surface. These properties, in turn, govern the tendency toward print mottle in offset printing.

Unevenness in the porosity of the coating layer can arise both during its consolidation process and during the calendering of the coated material. In the first case, irregular porosity is caused by an uneven water absorption in the base paper. In the latter case, unevenness in porosity occurs because the coating layer is compressed more or less unevenly, depending on the topography of the coated surface.

Water removal from the wet coating layer between the coating unit and the dryer

The time during which the wet coating layer is in contact with the base paper can be divided into three intervals:

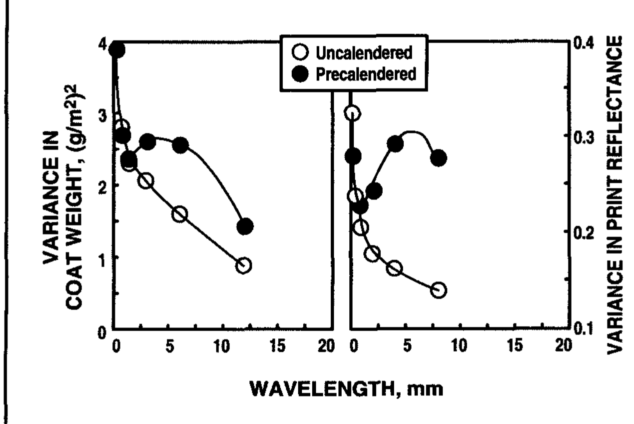
1. Time between applicator and forming unit
2. Time between forming unit and dryer
3. Time in dryer until immobilization of coating.

The longest interval is the time between the coating unit and the dryer. Most of the water that the paper picks up from the wet coating is picked up during this stage *(49)*.

The ratio between the amount of water that is evaporated and the amount that is picked up by the base paper up to the immobilization point is a factor that determines the porosity of the coating layer *(12)*. This ratio is largely governed by the distance between the coating unit and the dryer, as well as by the rate of water pickup in the base paper and, to a lesser extent, by the conditions in the dryer *(49)*. The more water that evaporates from the coating layer up to the immobilization point, the more porous the layer will be *(12)*.

The distance between the coating unit and the dryer has an obvious effect on the amount of water pickup in the base paper. This distance can also affect the surface roughness of the coated material, with long distances contributing to greater surface roughness. This was shown in an experiment where an LWC base paper and a sized, wood-free base paper were blade coated. **Figure 13** shows that surface roughness increased with distance to the dryer for the LWC base paper but not for the sized, wood-free base paper *(17)*. This increase in surface roughness is caused by a movement released within the base-paper surface upon exposure to the water in the coating color. The movement of the paper affects the coating layer, leading to a roughening of the coating surface and a mottled offset print *(11, 13, 17)*.

14. Variance in coat weight (left) and in print reflectance (mottle) (right) as functions of wavelength for uncalendered and precalendered base papers



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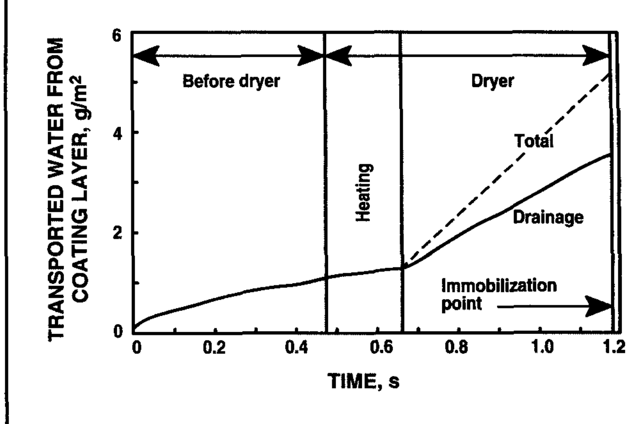
15. Water transported from coating layer as a function of time. Drainage accounts for most of the water transported from the coating layer up to the immobilization point. (Sized free sheet; evaporation rate = 20 kg water/m²·h.)



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The increase in the surface roughness of the base paper can also redistribute the mass of the wet coating layer during the consolidation process, thus causing mottle in the offset print *(13, 15, 18)*. Because the increase in surface roughness also increases the actual surface area of the base paper, the coating layer is stretched out during the consolidation process as it covers the larger area. It is stretched more over the fiber flocs and becomes thinner there, since the flocs expand more than the surrounding regions. This can be interpreted as a redistribution of the mass of the coating layer *(13, 15)*.

The interaction between the base paper and the water and its effect on the increase in surface roughness and in paper thickness have been thoroughly studied *(11, 50–53)*. This research has shown that the irreversible increase in surface roughness of a freely dried and uncalendered sheet was practically zero when water was applied to the sheet if the sheet was based on mechanical pulp, and only marginally larger if it was based on chemical pulp *(52)*. In another study, the same researchers showed that the swelling pressure was rated in an identical manner *(51)*. The swelling pressure is related to the sum of the reversible and irreversible increase in surface roughness, provided the latter is linked to the increase in thickness, which is usually the case.

The situation was different for calendered sheets *(51, 52)*. Both the irreversible increase in surface roughness and the swelling pressure were markedly higher and highest for the sheets based on mechanical pulp. For these sheets, the increase in surface roughness upon exposure to water was so large that all the calendered reduction in surface roughness vanished. Similar results are reported elsewhere *(14, 54)*. **Figure 14** shows the results of a coating experiment performed on uncalendered and precalendered base papers. Evenness for the mass distribution of the coating layer (left) and the offset print (right) was greater for the uncalendered sheets. The greater evenness of the uncalendered sheets was ascribed to the fact that the precalendered base paper experienced a greater increase in surface roughness when it was exposed to the water in the coating layer *(15)*.

The surface profile of the base paper beneath the coating layer can be calculated from the mass distribution and surface profile of the coating layer *(14)*. If this calculated surface profile is compared with the surface profile of the base paper before coating, information is obtained regarding the increase in surface roughness of the base paper during the coating operation. This calculation procedure has been applied to both coated uncalendered and precalendered base papers. According to these calculations, the surface profile of the uncalendered base paper beneath the coating layer was not affected by the coating, whereas the surface profile of the precalendered base paper increased to the same level as it had before being calendered *(14)*. Consequently, the entire effect of the precal-endering on the surface profile or surface roughness disappeared when that paper was exposed to the water in the coating color.

Drying

In the dryer, the base paper continues to pick up water from the wet coating layer even as water starts to evaporate *(49)*. This is demonstrated by the results presented in **Fig. 15**. The transport of water to the base paper ceases when the coating layer reaches its immobilization point, which occurs at a solids content of approximately 75% for ordinary kaolin-based coating colors. Watanabe and Lepoutre *(55)* call this immobilization point the FCC (first critical concentration). Their work showed that at the FCC, a pigment matrix has developed within the wet coating layer. Within this matrix, the liquid phase remains mobile up to a solids content of 90%, which they call the SCC (second critical concentration).

After the immobilization point or FCC, the fine-capillary pigment matrix is emptied of its water solely by evaporation. Capillary forces draw the matrix together, and the coating layer shrinks. The degree of shrinkage depends on the stiffness of the latex binder. The greater the stiffness, the less is the shrinkage of the coating layer and, consequently, the greater its porosity. The porosity is also higher if the coating layer is dried at a low temperature *(30)*, since the latex binder is then stiffer and is not deformed to such a great extent by the capillary forces *(56)*. The glass-transition temperature, T_g, of the latex is a commonly used measure of its stiffness.

It has been shown that the mass of the coating layer can be redistributed during the drying process and that the mass becomes more evenly distributed at higher evaporation rates *(18)*. The offset print was also reported to be more even on coatings dried at higher evaporation rates. One explanation for this is that the higher rate of evaporation shortens the time of interaction between the base paper and the water within the coating layer, thus reducing the magnitude of the movement released in the surface of the base paper beneath the coating layer. As already mentioned, this movement can redistribute the mass of the coating layer during the consolidation process. IR-drying of the coated material is reported to give a coating layer with a less-uniform mass distribution than hot-air drying and thus a layer that is more prone to mottling *(13)*.

Water does not begin to evaporate from the wet coating layer until the coating is heated to a temperature corresponding to the wet-bulb temperature of the surrounding air. The time required to achieve this temperature is called the heating time. In an IR dryer, this time is negligible and evaporation begins immediately. In a hot-air dryer, on the other hand, the heating time can be 0.2–0.35 s (Fig. 15) if the coating color and base paper are at ambient temperature, as is the case when the first side of the paper is coated in an off-line coater *(49)*. When the reverse side is coated—or when coating takes place in line with a warm coating color and base paper—the heating time is substantially shorter.

When the evaporation rate increases, the immobilization point is obviously reached earlier. However, if the evaporation rate in a hot-air dryer is increased by raising the temperature of the impingement air, the temperatures of both the coating layer and the base paper also increase simultaneously. This leads to a faster water transport into the base paper. As a result, the ratio of the amount of water picked up by the base paper to that evaporated up to the immobilization point remains constant and consequently is independent of the evaporation rate *(49)*. It is not possible to reduce the amount of water pickup by the base paper by increasing the evaporation rate. Temperature in an IR dryer is substantially higher than in a hot-air dryer, and this may increase the rate of water transport to the base paper.

Redistribution of binder

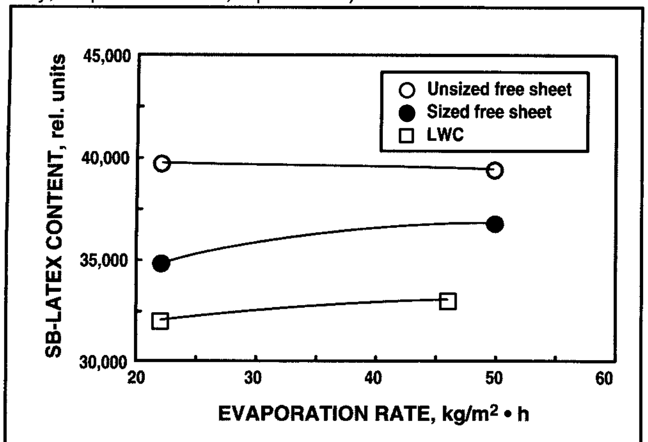
Some of the binder accompanies the water that is picked up by the base paper from the wet coating layer, and some accompanies the water transported to the coating surface, where the water evaporates. This leads to a redistribution of the binder during the consolidation process of the coating layer, with binder being concentrated at the coating surface and at the boundary between the coating and the base paper *(1, 5)*. It is generally accepted that the migration of binder to the coating surface increases the likelihood of print mottle.

Of course, the rate of water pickup by the base paper is important in this context. The more water that is picked up from the wet coating layer, the greater is the binder concentration in the region close to the base-paper surface *(5)*. Analogously, the same authors found that the base-paper surface was less enriched with binder when coated with a coating color of high solids content or high water retention.

The mechanism of water pickup is different for sized and unsized papers *(57, 58)*, and this affects the redistribution of the binder. This also has been recognized by Krishnagopalan and Simard *(59)*, who showed that the transport of binder toward the base paper is substantially higher in unsized papers. The binder content in the base paper can be enriched only if both water and binder in the liquid phase are picked up. This implies that the mechanism of water pickup is a capillary process for unsized paper and a diffusion process for sized paper. However, the mechanism of water pickup is dependent not only on the type of base paper (sized or unsized) but also on the conditions under which the pickup takes place. Water pickup for sized papers has been found to be a capillary process when the sheet is under high hydrostatic pressures *(58)*, as in the applicator nip, beneath the blade tip, or in the transfer nip in the MSP coater *(32)*.

The common consensus is that binder migration can be avoided by drying the coated material at a low evaporation rate. This has been confirmed in model experiments. As already mentioned, Dappen's experiments with coated glass plates *(24)*

16. Styrene–butadiene-latex content at coating surface as a function of evaporation rate in the first and second air hoods for unsized free sheet, sized free sheet, and LWC (Coating color: 100 parts clay, 10 parts SB latex, 1 part CMC)



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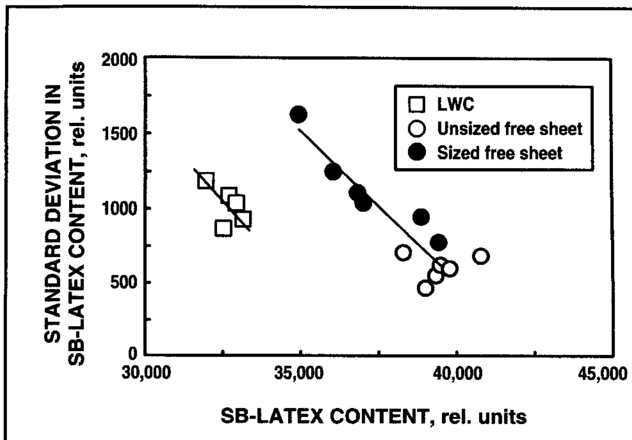
17. Standard deviation in SB-latex content at coating surface as a function of SB-latex content for unsized free sheet, sized free sheet, and LWC (Coating color: 100 parts clay, 10 parts SB latex, 1 part CMC)



Reprinted from Ref. *18*, courtesy of TAPPI

showed that the binder content in the coating surface was highest for oven-dried plates (105°C). However, experiments performed under more realistic conditions in a high-speed pilot coater indicate that the binder content in the coating surface is independent of the evaporation rate *(16, 18)*. Results from these experiments are presented in **Fig. 16**.

Binder migration to the coating surface increased when the coat weight was increased and when the distance between the applicator and the dryer was decreased, i.e., when the amount of water available for evaporation increased *(16)*. The binder content in the coating surface is higher in material dried with IR than in material dried with hot air *(16)*. This may be due to the greater amount of water available for evaporation when IR-drying is used, since such dryers are usually installed prior to an existing hot-air dryer. Note that in cases where IR-drying has been reported to reduce binder migration, the migration has been measured indirectly using stain tests.

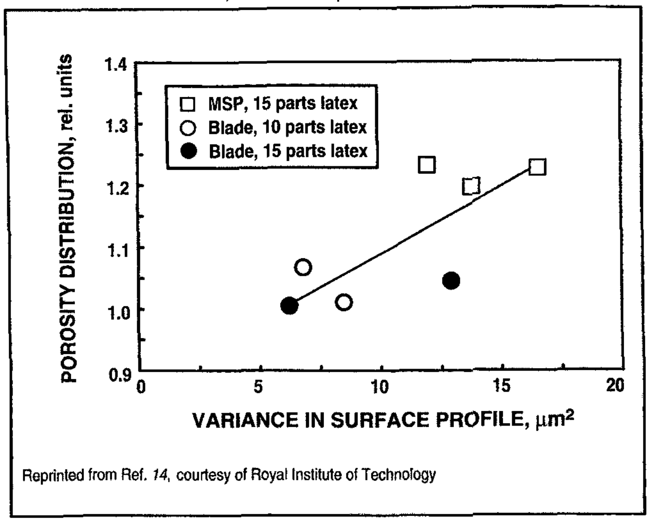
Since binder migration is considered to be the cause of mottle, it is generally recommended that the evaporation rate be minimized to avoid mottle. As already mentioned, this opinion is based on indirect results from stain tests. However, investigations of a direct character suggest that this is an incorrect drying strategy for coated paper *(16, 18, 27, 60)*. These investigations have shown that the evaporation rate can be high before the immobilization point, but that the evaporation rate after the immobilization point must be low if mottle is to be avoided. This can be accomplished by shutting down a hood in the hot-air dryer or by interrupting the evaporation for a short period immediately after the immobilization point. Shutting down a dryer hood results not only in a less mottled print but also in a higher binder content in the coating surface *(16)*.

Vanderhoff and Bradford *(61)* have discussed possible mechanisms for binder migration. One of these mechanisms assumes that a pore system is developed in the coating surface early during the consolidation of the coating layer. In this pore system, the liquid phase from the bulk of the coating layer is transported to the surface, where the binder is deposited when the water evaporates. If the rate of evaporation is higher than the rate of transport in the pores, no binder will be transported to the coating surface, since the evaporation front will then be within the coating layer. Binder will be enriched in the coating surface only when the transport of water to the coating surface equals the evaporation rate. This may explain why the binder content in the coating surface increased when a dryer hood was shut down *(16)*.

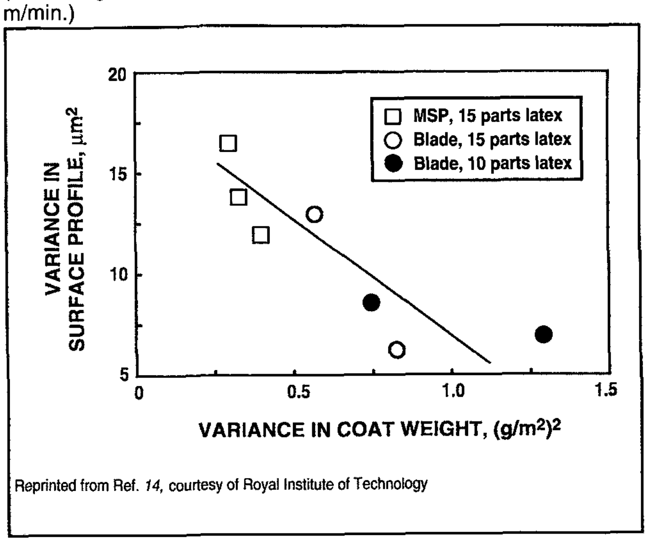
There are obvious similarities between the consolidation process described by Watanabe and Lepoutre *(55)* and the effect of shutting down a dryer hood on the binder content in the coating surface. The evaporation rate can be high up to the FCC, the point at which a pigment matrix is formed in the wet coating layer. However, the evaporation rate must be low between the FCC and the SCC, when the liquid phase is removed from pores in the pigment matrix.

The belief that binder migration is associated with an uneven binder distribution in the coating surface is based on the results of stain tests. Direct measurement of the binder distribution requires access to advanced equipment, and such measurements had not been performed until recently. These measurements

18. Porosity distribution of supercalendered coating layer as a function of variance in surface profile of coated sheet before supercalendering for MSP-coated and blade-coated sheets. (Wavelength interval of variances = 4–8 mm; machine speed = 600 m/min.)



19. Variance in surface profile of coated sheet as a function of variance in coat weight for MSP-coated and blade-coated sheets. (Wavelength interval of variances = 4–8 mm; machine speed = 600 m/min.)



(18) show that an increase in binder content at the coating surface

1. Increases the uniformity of the binder distribution at the coating surface
2. Reduces mottle in offset printing.

Figure 17 shows that the standard deviation of SB (styrene–butadiene) latex content at the coating surface decreases as the SB latex content at the coating surface increases.

It has been suggested that an uneven mass distribution of the coating layer leads to an uneven binder distribution in the coating surface and thus to a mottled offset print. Direct measurements of mass distribution and binder distribution have confirmed this hypothesis. However, a closer study of the relationships between mottle and both mass distribution and binder distribution indicates that there are additional factors that affect the mottle in the offset print *(18)*.

The question of how the mass distribution of the coating layer is affected by the type of base paper and the conditions during formation of the coating layer was discussed under the heading "Application of the coating color." Analogously, the binder distribution in the coating surface was found to be more even on

1. Unsized paper than on sized base paper *(18)*
2. MSP-coated material than on blade-coated material *(14)*.

It also has been reported that the binder distribution becomes more uneven with IR-drying than with hot-air drying *(62)*.

Calendering

Despite the comprehensive volume of literature relating to coated paper and print mottle, no work has been reported on how calendering of coated paper affects offset-print mottle. This subject has been treated to some extent for uncoated paper.

When a sheet is calendered, its porosity becomes unevenly distributed because the peaks in the paper surface are compressed more than the valleys. Kajanto *(63)* supercalendered and soft-calendered two uncoated papers of different grammages to different surface roughness levels (Bendtsen smoothness) within the range of 100–400 mL/min. After calendering, the papers were test-printed, and the mottle in the print was determined. Print mottle increased or remained unaffected when surface roughness was reduced by supercalendering. In the case of the soft-calendered material, on the other hand, print mottle decreased with decreasing surface roughness. These results were ascribed to the greater evenness of porosity distribution for the soft-calendered sheets. Porosity is reported to be more even because the softer nip follows the topography of the paper to some extent. It was also reported in the same work that the prints were less mottled on a well-formed sheet.

Analogous behavior has been established for coated papers *(14)*, where it was shown that calendering produced greater unevenness in a coating layer that followed the surface contour of the base paper than in a coating layer that merely filled the valleys. As seen in **Fig. 18**, the porosity distribution of the coated sheets after supercalendering was lowest for the sheets with the smoothest surface (uneven mass distribution of coating layer) and highest for the sheets with the roughest surface (even mass distribution of coating layer). **Figure 19** shows that a coating layer with an even surface profile has an uneven mass distribution and vice versa. The topography of the coating layer had the same effect on the gloss distribution of the coating surface.

The porosity distribution was indirectly quantified by means of the ratio of the variance in scattering power, sw, of the calendered to that of the uncalendered material. For uncalendered material, s is constant, whereas s for the calendered material is determined by the local porosity of the coating layer. The variable w denotes the coat weight.

Final remarks

Coated paper will show a low tendency to mottle during offset printing if the coating layer is even, both in structure and in chemical composition. The coating's evenness is governed by

1. The processes of coating-layer formation and consolidation
2. The interaction between the liquid phase of the coating color and the base paper during formation and consolidation.

While our knowledge of the mechanisms governing the development of mottle remains incomplete, it has increased substantially during the last decade. Therefore, there is cause to be optimistic about the future, since a more thorough understanding of the coating process and of the coating-color–base-paper interaction can be foreseen. This will open new possibilities to control print mottle by producing coated papers with superior printing properties. TJ

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