Factors influencing the runnability of coating colors at high speed

Patrick A. C. Gane, Philip M. McGenity, and Philip Watters

The effective runnability of platey clay has been artificially suppressed by conventional practice based onan evolution of technology far removed from the physical requirements for higher speeds and shorter dwell times which began with the development of formulations designed for roll-applicator systems.

Blade coating is the dominant method for high-speed paper coating. As machine speeds in the last 10 years have increased, with current design capacity for up to 1600 m/min, there has developed an increasing problem of "runnability."

Although the speed issue is the major area of concern in Europe, worldwide the picture is more varied, with lower-speed fine paper and merchant-grade production suffering more traditionally encountered problems such as uneven coating and surface scratching.

Inevitably, the plethora of mill practices and breadth of discussion has led to conclusions, some of which are perhaps at best misleading. Of even more concern, these "conclusions," if stated over-clearly, can result in the industry complying and reacting accordingly. In some cases, these trends are being shown to be problematical. One such example is the unqualified implication that pigments that develop relatively high slurry viscosities are necessarily bad for runnability.

A reappraisal of the roles played by the components of a coating formulation and the effects of machine and base-paper properties on the coating color in the confines of the blade is essential to expanding our understanding of blade runnability. By isolating these various factors and recognizing the need to consider a coating color as an ensemble of discrete interactive entities rather than a fluid continuum suspended in an inhomogeneous environment, it is possible to propose a mechanism consistent with the observed phenomena of blade bleeding, stalagmite formation, etc.

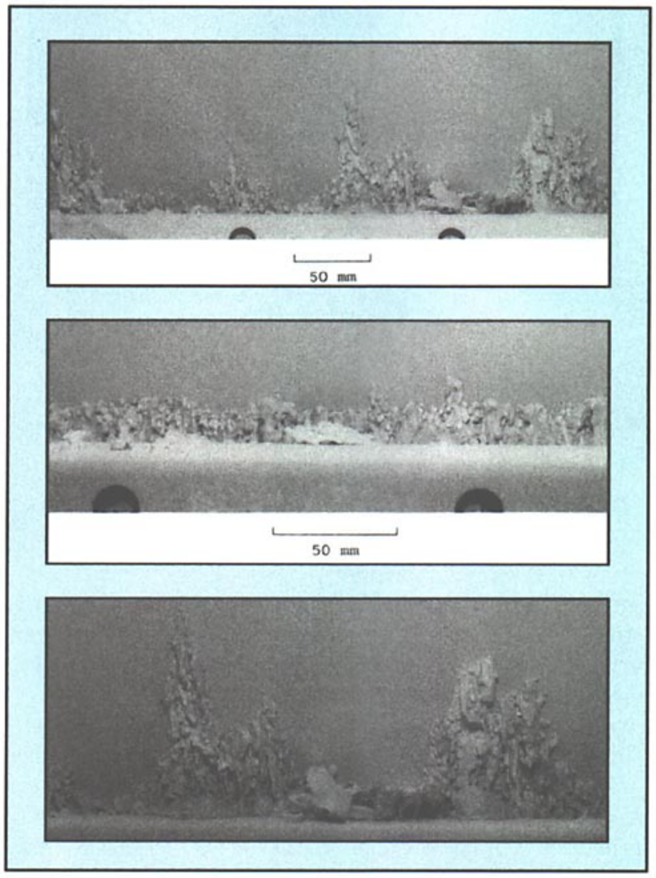
Practical experience is tending to support this model and illustrates clearly the advantages to be gained from a more considered approach to formulation design, particularly with respect to high-speed, short-dwell-time application.

Defining the problem

Blade coating at high speed suffers a physical breakdown in coating color application by a number of inter-related phenomena which, when considered singly, appear to be random. Collectively these constitute the problem of blade runnability.

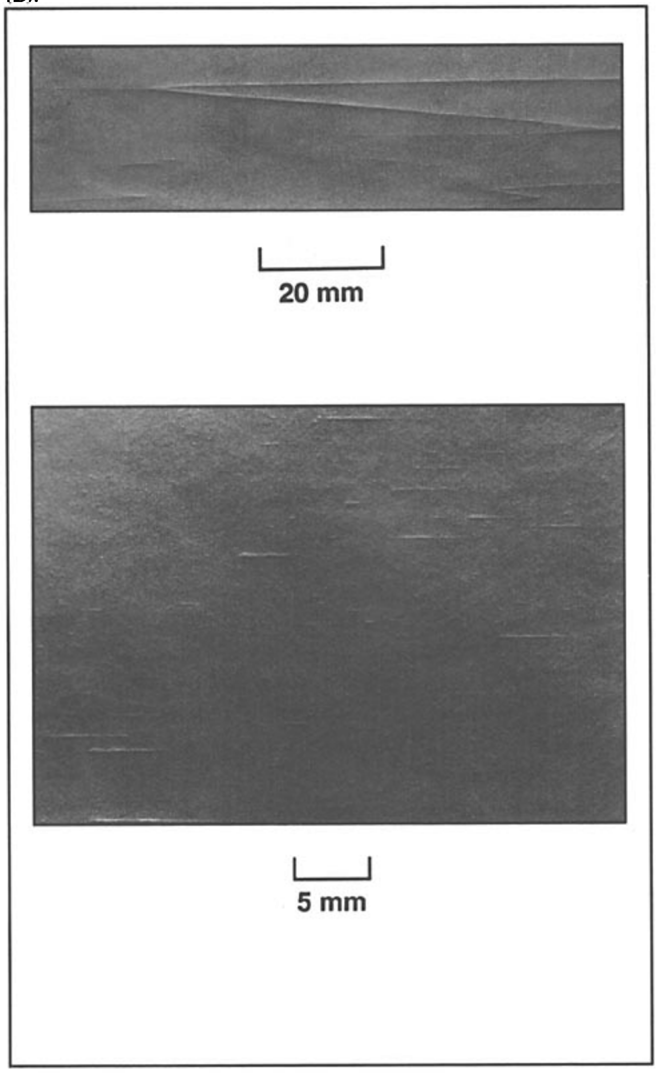
Gane is senior scientist and McGenity and Watters are scientists at ECC International Ltd., John Keay House, St. Austell, Cornwall PL25 4DJ, United Kingdom.

1. Typical semi-wet stalagmite formation

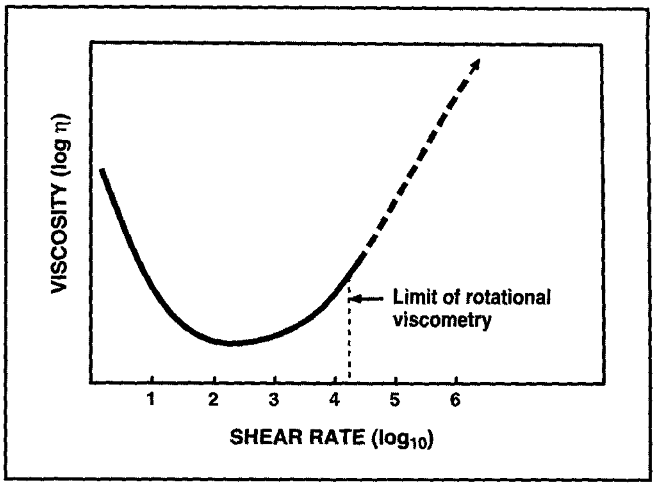


Manifestations of the problem include scratches, skips, streaks, spits, and "beard" growth at the exit from the blade nip. A typical example of stalagmite deposits or "beard" is shown in **Fig. 1** and illustrates a commercial application of a gravure formulation running at 1250 m/min. The severity of bleeding—the apparent extrusion of coating color ranging in solids content from "wet" to "dry"—does not necessarily immediately impinge on coater performance. Spitting of color, or "fleas," associated with the blade extrusion, leads to the deposition of a discrete quantity of excess coating on the paper

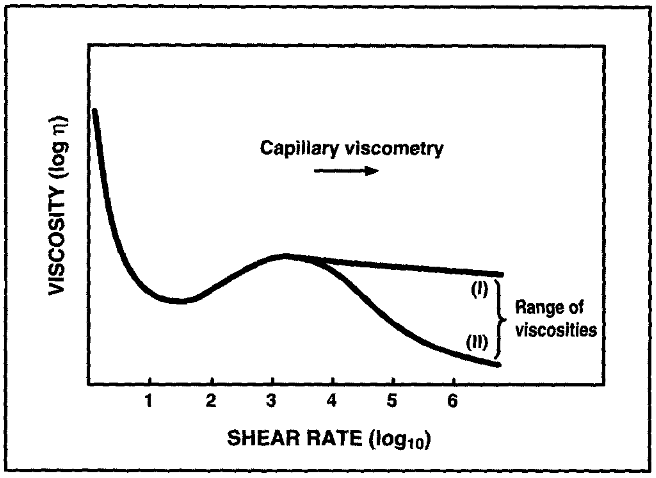
2. Excess coating can leave positive streaking (A) or spits and streaks (B).



3. True dilatancy in coating color rheology



4. Observed rheology of typical coating colors



surface. The unwanted coating can be in the form of a positive streak (**Fig. 2A**) or a spray of droplets (**Fig. 2B**). Subsequent drying of deposits results in marking in the reels and surface damage of calender rolls.

Debate continues as to what might constitute a "safe" stalagmite. Inevitably, the conditions for developing stalagmites that remain benign and refrain from depositing spits and streaks will be a complex interaction between machine geometry, coating formulation, base-paper tension and relaxation, speed, etc. Approaches to the problem by attempting to form benign stalagmites may be a panacea in the mill context but are unlikely to create confidence in a long-term solution.

The traditional roll applicator system suffers from a number of drawbacks. The coating color applied at the roll must flow uniformly with no air entrapment or irregularity in deposition. The water loss under the application nip pressure and during the extended dwell time must be minimized. However, it is the very formation of an immobilized coating layer on the paper surface due to water loss prior to the metering blade that gives the roll application system a quality advantage under certain circumstances (*1*) and, importantly in this context, a method of controlling the stability of higher-coat-weight applications.

Unlike the roll applicator, the short-dwell applicator minimizes water loss prior to the blade compression region; therefore, the stabilizing coat-weight controlling mechanism is derived from the interaction between the impulse and viscosity-related forces generated as the excess color strikes the blade (*2, 3*) upstream from the tip without the formation of a preimmobilized layer. The impulse force, being related to the rate of change in momentum as the color impacts the blade, is strongly dependent on solids concentration. Color viscosity has traditionally dominated the debate surrounding blade bleeding. The desire for high-solids coating colors, based on criteria of coverage and efficiency of drying on high-speed lightweight papers, has led to a rapid movement toward fluid coating-pigment slurry viscosities. Unmanageably high viscosities will not run. If a fluid pigment is used, however, the viscous component is minimized such that a greater increase in solids concentration is required to balance the blade forces to achieve high-coat-weight applications (>9 g/m^2). This phenomenon is no more clearly exemplified than by the ample evidence in the industry that some of the greatest problems are associated with the higher-weight, short-dwell applications in lightweight coated papers (LWC).

The conclusions at this stage of the discussion, based purely on an analysis of practical experience, must be that:

- Classical continuum viscosity, per se, may not always be the underlying culprit. The cases where fluid pigment viscosity fails to achieve the desired coat weight, except under conditions of excessive color solids contents, indicate that blade bleeding relates more strongly to color solids levels than to viscosity.
- High blade pressure, for the application of the lowest coat weights, does not, in itself, develop the greatest occurrence of bleeding—albeit web breaks may be more common.

Pragmatically, the coating scientist is faced with developing a formulation which possesses sufficient continuous viscosity buildup with increasing solids content. The dilemma now exists in that those pigments typically associated with substantial color viscosity (e.g., platey clays) tend to develop bleeding at a lower solids content than that for fluid pigments, when used in traditional formulations.

The traditional continuum approach to coating color evaluation

Viscosity measurement

Coating colors have traditionally been described as a continuous fluid having a well-defined macrorheology derived from microinteractions between pigment particles and their fluid and chemical environment. Provided the color was free from macroscopic contaminants, such as extraneous paper fibers (*3*), debris, aeration, oversize mineral particles, or not subjected to destabilization through chemical invasion, ionic concentration, etc., the measurement of viscous components at varying shear rates and extended time scales provided the norm for coating color characterization.

In attempts to extend this approach to a level of sophistication sufficient to describe the phenomenon of fluid breakdown at the coating blade, through supposed classical dilatancy, even higher applied shear rates have been sought to match those assumed to exist under the blade tip. Capillary viscometry in particular has been frequently applied to coating formulations to extend the shear rates to $10^6\ s^{-1}$. This approach was supported by the onset of a dilatant behavior, particularly of pigment slurries, at shear rates typically in the region of 10^3–$10^4\ s^{-1}$. Immediate extrapolation of viscosity shear-rate plots, such as are shown in **Fig. 3**, were reasonably expected to follow the trend toward increasing viscosity. However, once attained, higher shear rates, when applied to many commercial coating colors, have invariably indicated (**Fig. 4**) either (a) a stabilization of the viscosity established at $10^4\ s^{-1}$ or, more commonly, (b) a further shear thinning region. Retrospectively, there existed prior evidence of such behavior from certain pigment slurries, which developed rapid shear thickening behavior at low shear or could be viscosity stabilized under shear at high solids (*4*).

Work by K. Walters *et al.*, supported by ECC International, at the University College of Wales, Aberystwyth, has confirmed previously published data (*5*) in that high shear rates per se do not result in any observed viscous behavior likely to be the prime cause of coating color breakdown.

It is reasonable to ask what measure of viscosity might actually be relevant. Certainly an equilibrium measure of continuum viscosity is on too long a time scale compared to the virtually instantaneous shear under the blade nip. Furthermore, the upstream flow and entrance geometry of a blade is different to the purely convergent geometry of a capillary rheometer. A rheometer design more realistic in these respects is urgently required.

Elastic behavior in coating colors

The stress components likely to contribute to viscoelasticity, elongational viscosity, or extensional viscosity have also been examined. Convergence of the flow toward the blade tip forms a classical geometry in which extensional viscosity would be manifest. The small dimensions and suspected high-shear flow between parallel boundaries under the blade nip would also be expected to generate viscoelastic behavior in terms of a force normal (perpendicular) to the flow velocity. However, at conventional color solids, high-shear continuum measurement has failed to indicate any elastic component (viscoelasticity or extensional viscosity) of the color rheology. This does not mean that induced color viscoelasticity might not be present under conditions of instantaneous shear or that the undoubtedly confirmed elastic components which are measurable at *low* shear rates do not contribute to extrusion or post-blade relaxation phenomena (*6*) which, in turn, could be used as indicators of likely blade bleeding. Therefore, the *possibility* of elastic behavior under the blade should not be ignored.

A revised approach

Runnability problems should be discussed in terms of coating color rheology only if the viscous behavior is studied using methods which:

- Truly represent conditions in a blade coater
- Consider the coating color to consist of discrete components with similar size to that of the gap under the blade, the interactions of which are likely to be discontinuous and not necessarily represented by conventional equilibrium rheological measurements (*2*).

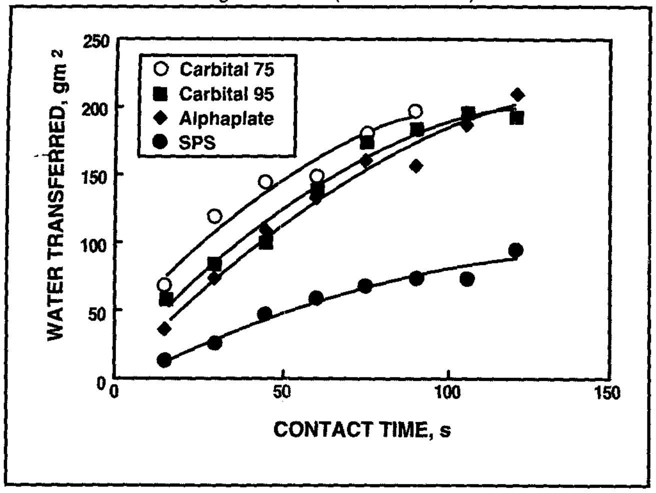
Coating color pressure dewatering

Work by Beazley and Climpson (*7*) and Windle and Beazley (*8*) clearly illustrated the likely migration of the fluid phase from coating colors under applied pressures. Lubrication theory was used to estimate a maximum pressure of 10^6–$10^7\ Nm^{-2}$ (10 bar) from the hydrodynamics of a wedge-shaped blade running at 600 m/min, assuming complete fluid transfer through the wedge.

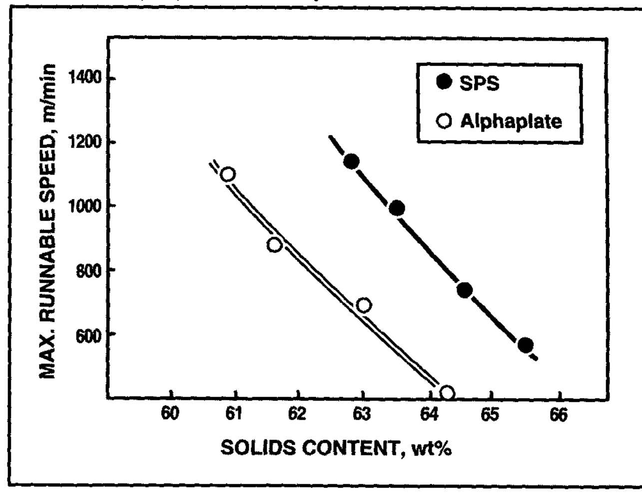
Later analyses by Eklund and Salminen (*9*) highlighted both the pressure regions in the roll applicator and at the blade. The time scales are recognized as short in all these references, e.g., 0.01-ms blade residence time at 1000 m/min. The latter authors, based on calculations by Kahila (*3, 10*) quote pressures in a roll applicator of 0.5–2.5 bar and under the blade of 4 bar.

A solids rise, therefore, occurring virtually instantaneously under high-pressure impulse forces of 1 μs duration, is a natural

5. Pressure dewatering of slurries (65 wt% solids)



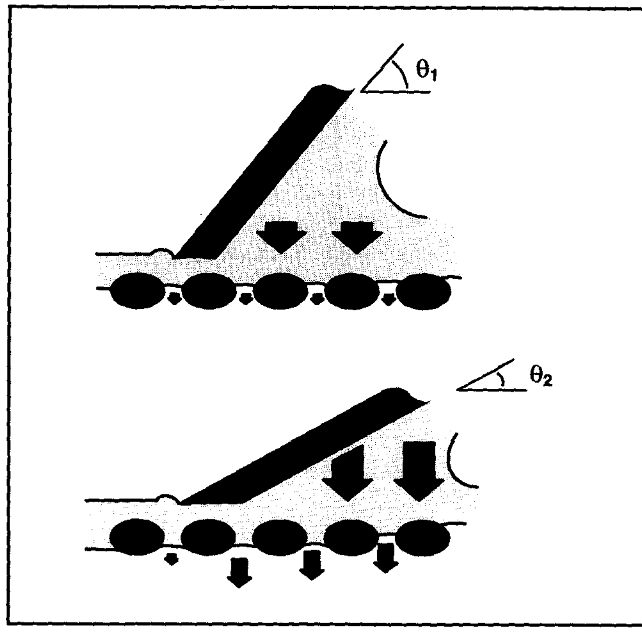
6. SPS and Alphaplate runnability without water retention aid



I. Base-paper properties

	Base 1	Base 2
Substance, g/m^2	42.00	50.00
Parker Printsurf (10 kgf), µm	5.05	6.00
Caliper, µm	69.00	70.00
Density, g/cm^3	0.61	0.71
Gurley porosity, s	88.00	70.00
Cobb, g/m^2	43.00	13.00
Ash, wt%	6.00	10.00
Burst, kPa	0.88	1.70

7. Pressure dewatering



consequence of high-speed, short-dwell blade coating and may lead to runnability problems.

The effects of pigment on preventing color pressure dewatering can be dramatic and due to a number of factors. Three main influences are suggested here.

Anisotropic color rheology

Despite the obvious need for high fluidity in the direction of blade shear, i.e., in the direction of web motion, a high degree of dilatancy in the *z*-direction (toward the web) would suffice to "lock" the color into a virtually solid form perpendicular to the base paper, thus retaining the fluid phase within the voids formed between the pigment particles and preventing penetration into the bulk of the sheet. This anisotropic viscous behavior ($\eta_{xy} << \eta_z$) will be a property of colors containing platey pigments in which the platelets are oriented parallel to the web motion.

Particle packing: tortuosity

Close packing of blocky pigment particles, such as fine calcium carbonates, creating a network of fine capillaries, tends to slow capillary dewatering of colors into absorbent base papers. However, under the external applied pressures at the blade, narrow capillaries alone are likely to be insufficient to resist water loss. Closely packed platey particles (*1*) introduce an added tortuosity which tends to resist the passage of fluid under pressure. Ultra-fine particles also, although detrimental to viscosity, do enhance the intrinsic water retention properties of coating colors (*11*).

Indications of the pressurized water retention properties of different pigments are afforded using the gravimetric Gradek (*12*) apparatus in which color or slurry is subjected to a constant external pressure and water loss into a filter paper monitored with time. Typical results are shown in **Fig. 5** in which pigment slurries of coarse and fine ground carbonates

(Carbital 75 and 95, respectively), a U.S. delaminated clay (Alphaplate), and English coating clay (SPS) have been pressurized to 0.25 bar. The English clay clearly manifests the highest level of intrinsic water retention.

Practical examples: English clay and U.S. delaminated clay

The consistent plateyness exhibited by English clay, particularly at the fine end of the size distribution, is seen as a fundamental property responsible for the differences between English primary and many U.S. secondary clays. In the context of runnability, the increased resistance of English clay to pressure dewatering of the color generally results in a higher maximum runnable speed compared with that of a similarly sized U.S. delaminated clay in the absence of water retention aid. The data in **Fig. 6** serve to illustrate this. The maximum runnable speed is here defined as the minimum speed at which stalagmites appeared during short-dwell-time applications onto a 42 g/m^2 offset base paper (**Table I**) at a given color solids content using the Valmet surface blade at the ECC International Technicentre at Lixhe in Belgium. The formulation of 11 parts by weight of styrene–butadiene offset latex based on 100 parts by weight of clay in the absence of any added water retention aid was applied using a beam angle of 45° with a 0.38-mm-thick blade with a free length of 18 mm at a constant tube pressure of 1.5 bar.

Particle packing under the blade

Anisometric particles, such as clay platelets, offer various resistance to passage in a shear flow depending on the orientation of the individual particles. In a simple analogy of posting a note under the door, one would ensure that the sheet of notepaper carrying the message was aligned with its straightedge toward the gap between the door and the floor. Similarly, a platey mineral particle will pass through the gap at the blade nip more easily if suitably prealigned. So, what could disrupt the alignment?

Obviously, contamination by extraneous debris, be it fiber or mineral (*13*), will prevent particle alignment.

Given sufficient color cleanliness, then particle alignment can depend on:

- Blade flow geometry
- Particle–particle and particle–formulation interactions
- Particle size and shape of formulation components (*14*)
- Fluid viscosity environment
- Major flow perturbations due to boundary condition fluctuations, typically basesheet roughness.

Blade geometry

The concepts of upstream blade flow geometry have been studied in detail (*2*), and the effects on coating structure, particularly gloss and light scattering, have been exemplified in pilot coating studies (*15, 16*). The lower the blade clamp angle, the more severe the directional change of the color flow being forced back from the blade tip (**Fig. 7**). The rapidity of change of flow direction of the excess color metered by the blade determines the rate of change of momentum of the color impinging on the upstream pressure zone of the blade. Severe impulse forces of this kind may disorient or tangle platey particles at high solids and create a large pressure-pulse effect in the region of the blade.

There exists, therefore, an optimum balance between solids content and blade geometry for a given coat weight and speed of application (*15*). Speed increase has an effect similar to either increasing solids content or decreasing the blade beam angle.

In summary, the worst conditions for blade bleeding are high solids in conjunction with low blade angle (stiff blade mode) and high speed. Furthermore the faster a machine runs, the greater will be the influence of the impulse pressure and the greater the likelihood of color dewatering and solids rise at the blade.

Low-angle (zero angle) bent-blade mode is traditionally used to apply high coat weights and to generate contour coating, predominantly in board applications, developing precoat uniformity, etc. The speed limitations due to the extended nip are based primarily on the film splitting phenomenon at the exit of the blade nip.

The effect of "water retention aids"

It is not within the scope of this paper to discuss the comparative properties of the many water retention aids. Many existing commercial offset formulations, however, contain from 0.3 pph to 1.0 pph carboxymethyl cellulose (CMC), even in short-dwell applications. Traditional concepts of water retention have been developed through long experience of roll applicator systems and the need to minimize static dewatering by base-paper imbibition following the initiating pulse at the roll. Recirculating systems have been designed around colors which have a low shear viscosity of 1000–2000 mPa·s at 30 s^{-1}.

Pigment–CMC–latex interactions have been identified and reported in the literature (*17*). Further effects of CMC, such as color flocculation and sedimentation, are readily observable, and the possibility of shear-induced aggregation of binders in the presence of CMC should not be overlooked. Effects on coating coverage, base-paper roughening, and coating structure are well known, primarily evidenced by reduced gloss in certain circumstances.

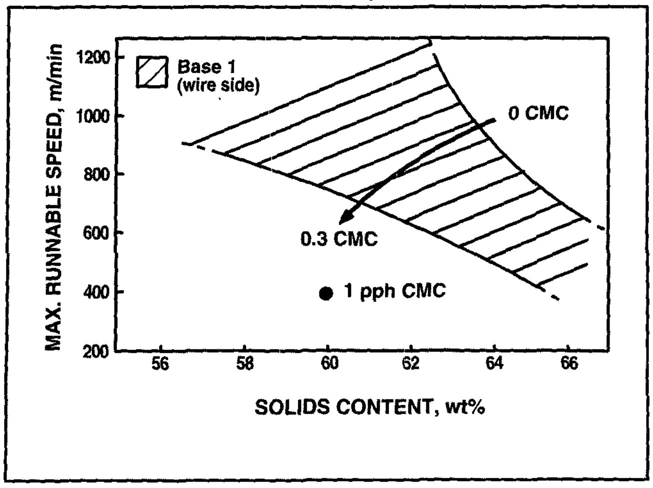
The viscous behavior of CMC in coating colors is also complex, with distinct evidence of color viscoelasticity at relatively low shear rates (*6*).

English clay with CMC

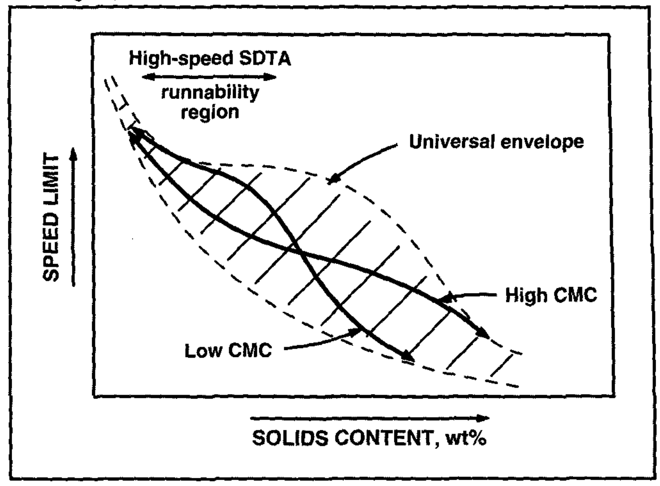
The effects of CMC on the runnability of short-dwell-time-applicator (SDTA) coating are clear even at small doses. **Figure** 8 illustrates this for a range of addition levels from 0 pph to 0.3 pph of a 30,000–40,000-MW CMC to the color described above [SPS + 11 pph styrene–butadiene–rubber latex (SBR)]. Again the base paper is 42-g/m^2 offset (Base 1).

The addition of CMC creates a runnability envelope. Figure 8 may be extended to include a complete range of runnabilities depending on solids and CMC dose by the following axiom: CMC as a water retention aid operates successfully by slowing base-paper imbibition during relatively long dwell times at slow coating speed. Thus, at high solids and low speed, there is a runnability benefit to be gained from using

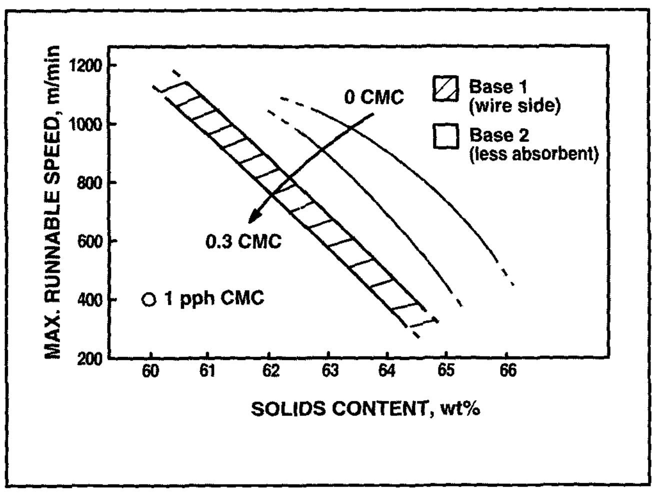
8. The effects of CMC on the runnability of SDTA coating



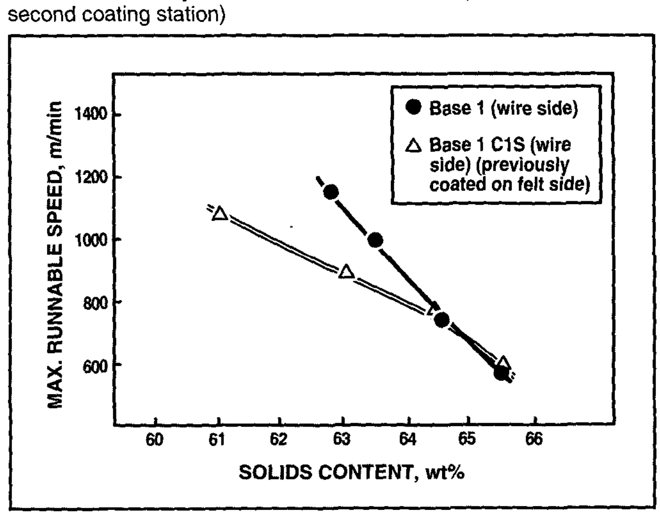
9. At high speeds, CMC can be detrimental.



10. Alphaplate universal runnability



11. SPS runnability without water retention aid (deterioration at the second coating station)



CMC. At high speed, CMC is apparently detrimental. There exists, therefore, a series of curves which cross over as the need for CMC reduces (**Fig. 9**). Naturally, the curves approach asymptotes at the limit of solids and of speed. A complete, closed envelope is defined by this family of curves. Practically, the area of concern at high speed is concentrated at, and to the left of, the mid-point of this envelope. Studying this runnability envelope enables the inter-related aspects of base-paper "absorbency" and dewatering from colors incorporating blocky particles to be understood.

U.S. delaminated clay with CMC

In contrast to SPS, the U.S. delaminated clay Alphaplate shows a less severe sensitivity to CMC on the Base 1 (**Fig. 10**). At first sight, it appears that the interactions are less strong between CMC and Alphaplate. This may be true. However, through closer examination of Alphaplate runnability by comparing the results on Base 1 with another much less "absorbent" base paper (Base 2, Table I), it becomes evident that the runnability envelope for CMC addition becomes broader than on Base 1 and thus must be affected by base-sheet absorbency. If U.S. clays are coated on very absorbent papers, then it is likely that the water retention properties of CMC at best equalize the detrimental interactive effects under the blade between the CMC and the pigment/latex.

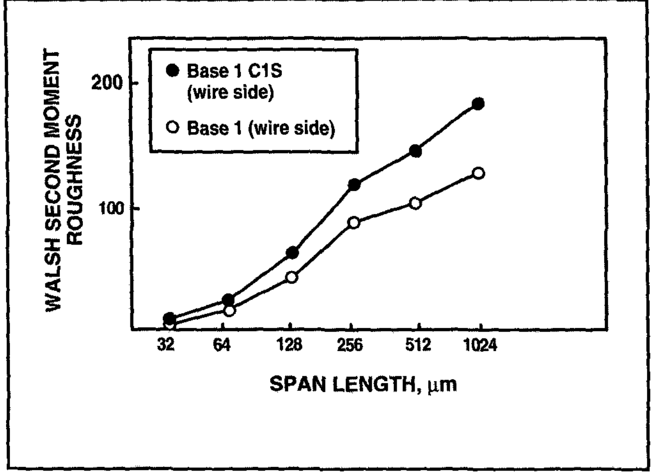
We must understand what is meant by base-sheet absorbency in more detail in conjunction with a range of roughness properties to appreciate the subtle combinations involved. Suffice it to say at this stage that the intrinsic runnability potential of the U.S. delaminated clay, in this formulation, appears to be more base-paper-dependent than the English clay of similar size distribution; this is identified by the reduced dynamic water retention of the coating color.

The base paper

Stability

The previous sections have already alluded to the fundamental dependence between good machine runnability and base-paper quality. Coating a water-based suspension of pigment and binder onto a natural network of cellulose fibers generates a vast number of physical responses. Included among

12. Base-sheet roughening after one-side coating



these--some of which might be implicated in poor runnability--are surface roughening, due to wetting and hydraulic impression (*1, 11, 18*), and fiber debonding and picking causing contamination of the coating color.

Examples of surface fiber instability and base-paper roughening abound in the literature (*19–22*), and refined mechanical pulps are particularly suspect (*23, 24*).

An example of base-sheet roughening, and its attendant reduction in runnability, is afforded by a test made on the back side of a coated-one-side (C1S) paper (Base 1). The paper is the same as that used in earlier examples of runnability but previously coated on one side. The application of SPS + 11 pph SBR latex produced the runnability curves shown in **Fig. 11**. The envelope produced on the C1S paper is clearly biased toward lower speeds for a given solids content. This result would correspond with a tendency for less-good runnability at the second coating station. We see that a plot of Walsh μ_2 against span length (*1, 24*) (**Fig. 12**), i.e., roughness over the lateral range from >2 μm to 1 mm, as measured by wave transform techniques applied to surface profilometry, reveals the back side of the sheet to be much rougher after the coating was applied to the front side.

Absorbency

Short-time-scale water sorption is difficult to measure. The relevant absorption mechanism by the base sheet on-machine occurs after an initiating external pressure pulse (*18*). In short-dwell-time applications, it is likely that a base paper which develops a significant resistance to hydraulic impression of the fluid phase will have an advantage over that which appears more "open," particularly when used in combination with pigments, which impart little or no intrinsic pressurized water retention to the coating color (Fig. 10).

Compressibility

The full effects of base-paper compressibility are not fully understood. It has been suggested that post-blade dewatering is likely to be enhanced by re-expansion of the compressed voidage in the base paper (*25, 26*). However, provided fiber pick strength is maintained, it is likely that a rough compressible base paper approaching the blade nip having been greatly compressed in the upstream pressure region (*3, 27*) should act in much the same way as an originally smooth incompressible base sheet. Indeed incompressibility of a sheet is known to create problems of coat weight control due to a fixed, predetermined, dynamic surface void volume (*3*)—yet another aspect of overall coater runnability! [A lack of compressibility of dynamic surface void volume tends to prevent effective use of constant-tip-angle blade tensioning mechanisms. Pressure tube devices, under which the rheological trap volume (*2*) at the entrance to the nip changes by constriction of the tip geometry (*14*), are often more effective in such cases.]

If elasticity of the base paper is to contribute to relaxation phenomena at the blade exit, then a measure of the dynamic roughness is likely to be appropriate, providing rates of deformation remain consistent with the very short period of the blade pressure pulse.

Phase separation: aggregation

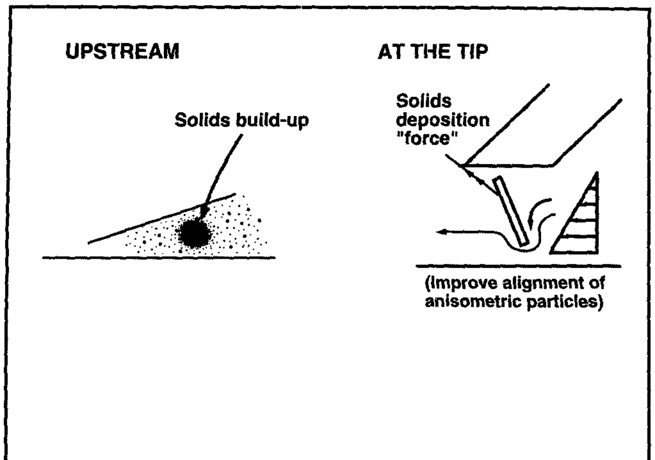
Stalagmite deposits vary widely in appearance from mill to mill and between machines and formulations. The various factors discussed so far, such as pulse dewatering, geometry, etc., undoubtedly contribute to these differences.

Analyses of stalagmite deposits often show that there is an absence of fiber or debris within the stalagmite. Neither do they suggest consistent differences in dry composition from the bulk color. It is not possible to identify a nucleation mechanism uniquely. Blade grooves are frequently cited as likely to deposit excess color or cause positive streaks. It is possible, however, to induce blade spitting under the most stringent conditions of cleanliness, suggesting that despite the well-proven connections with contamination in the recirculated color there exist other mechanisms which can be induced by or act in conjunction with, or independently of, "contaminants."

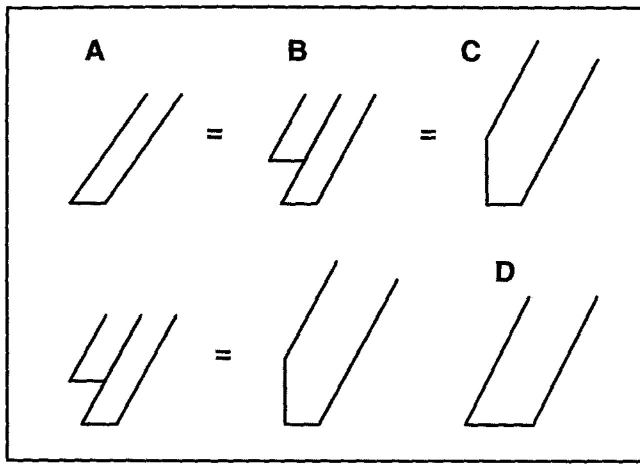
Deposits often appear on the upstream side of the blade after prolonged running times. The appearance of stalagmite growth at the exit or downstream side of the blade with time has implicated these upstream deposits. If this connection exists in some cases (although dry running of the blade prior to separation from the web may indeed be a practice responsible for instigating the upstream deposit), some mechanism involving phase separation, such as shear-induced flocculation, may be responsible (*28*). Continuous vortex circulation in the upstream flow could generate the necessary long-term shear for this to occur (**Fig. 13**). The upstream deposit in itself is not a necessary condition for poor runnability, but it is probably a manifestation of a process which ultimately is likely to lead to yet another mechanism based on contamination—in this case by large particles or aggregates.

The vortex intensity, found particularly in short-dwell coating heads, could conceivably lead to centrifugation and concentration of large particles both in the recirculating color and just prior to the blade nip. Vorticity in short-dwell chambers is a subject which has received much attention from researchers and machine manufacturers. Focus has been concentrated on achieving the minimum geometrical constraint for sustaining a single vortex or, conversely, preventing breakup of the circulation (*29*). It is important to remember

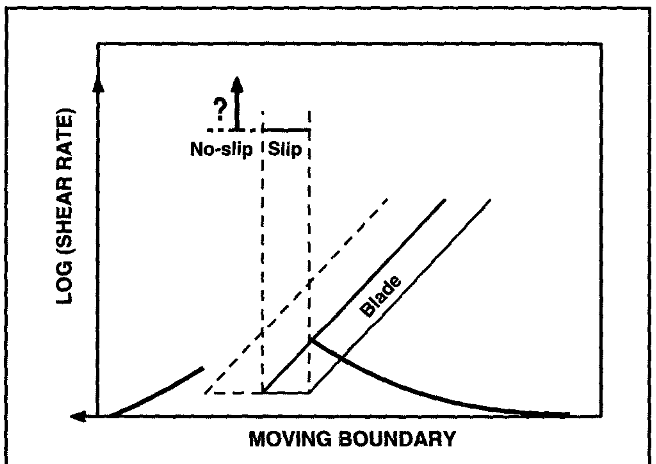
13. Phase separation upstream and at the tip



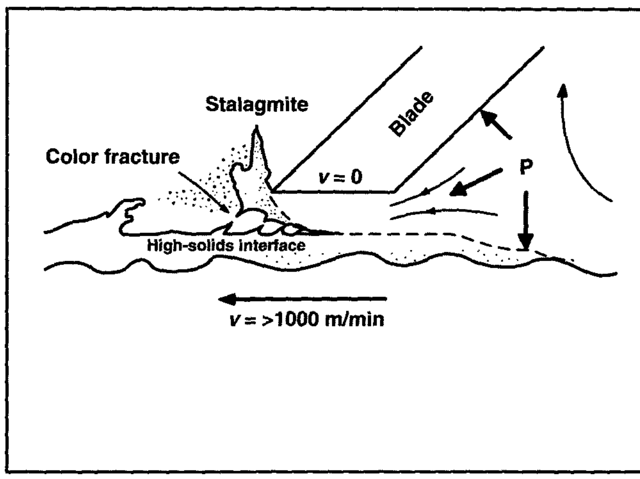
14. Blade bleeding appears not to depend strongly on blade tip pressure or geometry at the discontinuity but does depend on the length of the bevel or "land" area.



15. Moving boundary



16. Dominance of $v = 0$ blade boundary condition predicts nonslip condition (color must film split). At high solids, dilatant fracture occurs. A wet stalagmite indicates early fracture, a dry one indicates late fracture.



that not all existing coating heads conform to ideal conditions. Internal baffles can cause a propensity for air entrapment and unstable flow conditions, examples of which reinforce the absolute necessity for uniform upstream flow, especially when using platey pigments. Even symmetrical flow constraints do not ensure uniform flow in cylindrical circulating flows; it may become the realm of chaos theory to account for the instabilities observed and commented on in the recent literature (*30*).

Theoretical modeling of molecular dynamics in a shear flow suggests that particles in a shear field tend to migrate toward the flow boundary (*31*). A simplistic view can be afforded by considering the pressure drop on the downstream side of a particle in a velocity field. Figure 13 illustrates this effect for a large clay platelet as the high-velocity stream lines become compressed in the flow between the particle and the base paper. A resultant acceleration of the solid material to the low-velocity boundary has the effect of raising the solids content in the color in contact with the blade. Clearly the cross-sectional area of the particle presented to the flow is an important factor in such a mechanism. Disordered platelets will pose a greater problem than either ordered, thin platelets or fine, spherical particles.

The clear evidence that stalagmite growth may coexist in many cases with a satisfactory coating on the paper is perhaps the key to understanding the mechanism of blade bleeding. It is the continuity in contact with the base-paper boundary that unequivocally points to the discontinuous behavior being located at the blade boundary. These concepts crystallize into a working hypothesis when viewed in relation to the effects of blade thickness in the following section.

The blade boundary: forming a stalagmite

The properties of the color in contact with the base paper induced in the flow region upstream from the blade nip has been the preoccupation of our discussion so far. The sampling region which reveals this prehistory is at the blade nip.

A simplistic calculation of shear rates in the nip based on laminar flow suggests shear rates of 10^6 s^{-1}. Is there time for these shear rates to be established in the flow, and, if so, what are the relaxation mechanisms involved in the storage and release of the energies involved? These questions arose previously when considering the relevance of classical equilibrium rheometry. If we accept the uncertainty of whether continuum fluid mechanisms are relevant, a new question immediately arises concerning the definition of the flow boundary conditions at the blade. If, on the micro scale, we break down the continuum into a model of particles and their fluid and particulate surroundings, then the concept of a fixed velocity boundary flow must also become suspect. One way of investigating this is to adjust the time that a given boundary condition is applied. In the context of flow under the blade nip, this is a simple matter of adjusting the blade thickness.

Changing blade thickness alone would change the effective blade pressure due to the flexure of the blade, so a number of variants were tested to encompass both the thickness and pressure as independent parameters. These are illustrated in **Fig. 14** and may be summarized as:

- A thin blade (Fig. 14A)
- A thin blade with another thin blade used as a backing but not in contact with the paper (Fig. 14B)—after the method of Kuzmak (*32*) and illustrated by Gane and Coggon (*2*)
- A thick blade of approximately twice the thickness of the thin blade (Fig. 14D)
- The thick blade honed to a land area equivalent to that of the thin blade (Fig. 14C).

The first onset of blade spitting was at the same speed for all the shorter tip lengths, i.e., blades A, B, and C. The base chosen was relatively incompressible, and the change in pressure between the single blade and the stiffer comparisons made little difference to the initial speed limit. The runnability of the thick blade (D) with the greater nip length was markedly inferior. For example, SPS at 63 wt% solids in an offset formulation of 11 pph SBR latex and 1 pph CMC had a maximum runnable speed reduction of 400 m/min on going from the thinner to the thicker blade (0.3 mm and 0.54 mm thickness, respectively).

By considering the greater tip length as having a higher probability of establishing a zero velocity boundary condition due to the increased residence time, it is conceivable that the discontinuous behavior at this boundary is one of slip/nonslip. The shorter the boundary contact length, the less likely is the zero-velocity boundary condition to become established. Freedom from blade spitting is, therefore, likely to be associated with a plug flow phenomenon in which slippage at the blade boundary predominates (**Fig. 15**) at high speeds.

In further support of an hypothesis based on a slip/nonslip mechanism at the blade boundary are three observations.

First, if flow adjacent to the blade truly satisfied a zero-velocity boundary condition, then blade wear would be reduced since abrasive particles would not have any motion relative to the blade. These effects could account for the variety of blade wearing reported from various mills and serve also to provide greater evidence for regarding large particulate matter as bridging the small gap between blade and paper and contributing to the breakdown of idealized continuum flow (*33*).

Second, replacement of a worn blade or use of a nonwetting material such as PTFE can eliminate bleeding, i.e., an unwetted blade encourages boundary slippage and plug flow.

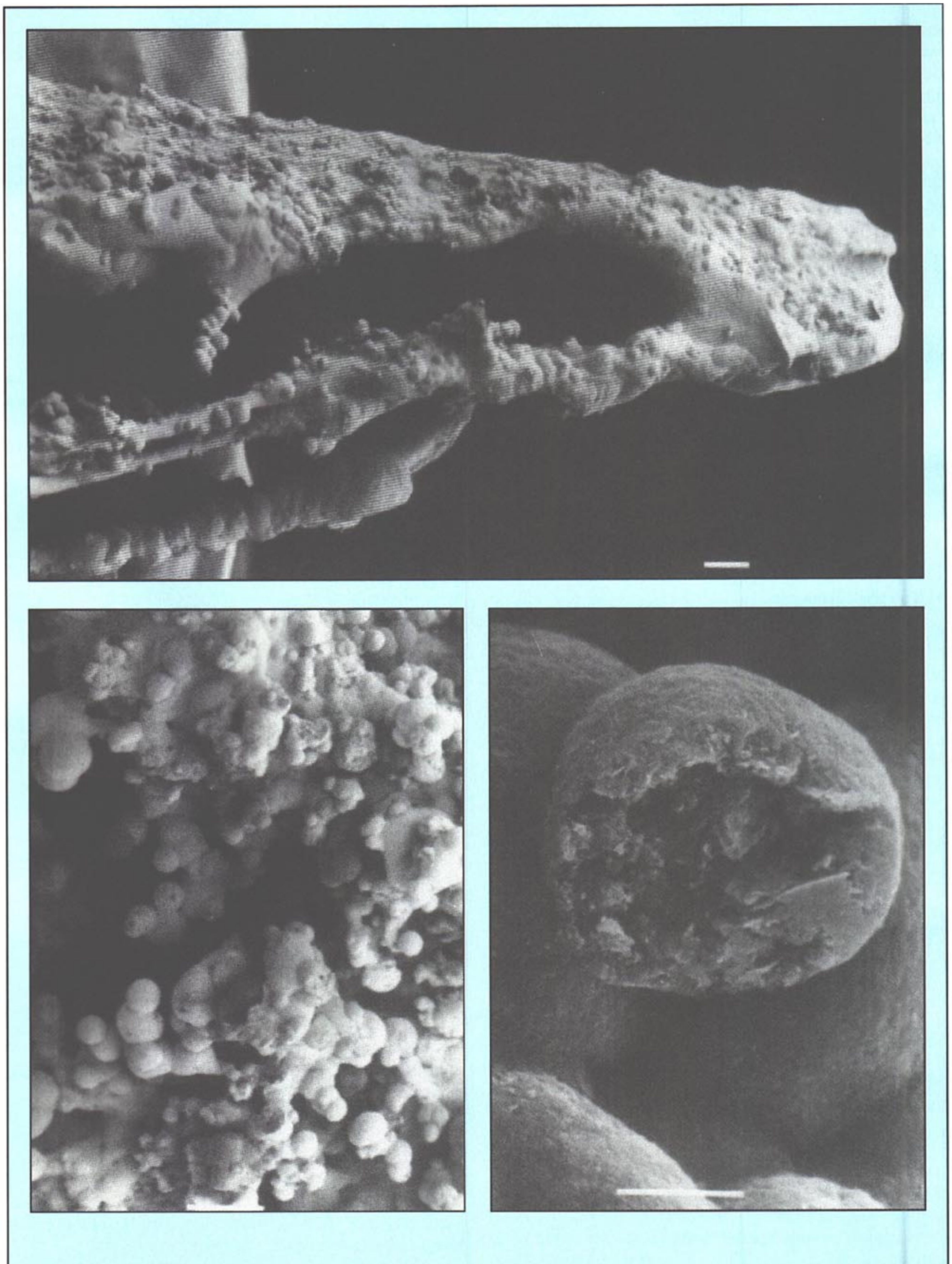
Finally, a low-viscosity fluid medium is known to encourage phase separation at the flow boundary, forming a layer of fluid adjacent to that boundary. In the context of blade coating, this would encourage effective plug flow of the solids-concentrated suspension with a velocity profile defined by that of the relatively rough, moving base-paper boundary rather than the stationary blade. This effect of forming a low-viscosity layer could be particularly relevant to some of the benefits seen from removing CMC, i.e., a reduction in fluid-phase viscosity and improved boundary slippage (*34*).

If such a model is accepted, in which stalagmite formation is associated with the momentary establishment of a zero-velocity boundary condition at the blade nip, contributing to an instantaneous shear flow superimposed on an otherwise virtually unsheared plug flow, then it is possible to visualize a simple mechanism for deposition of color at the blade exit. **Figure 16** shows the necessary film split as material retained with the blade has to separate from that transported downstream by the web. Since separation of color from the blade tip involves separation of particles through a fluid medium, reduction of the viscosity of the fluid medium, by whatever means, will reduce the likelihood of stalagmite formation. The suspected viscoelastic forces, extensional viscosity, and possible dilatancy developed by the shear forces experienced during the separation can all be invoked to describe the form taken by the stalagmite.

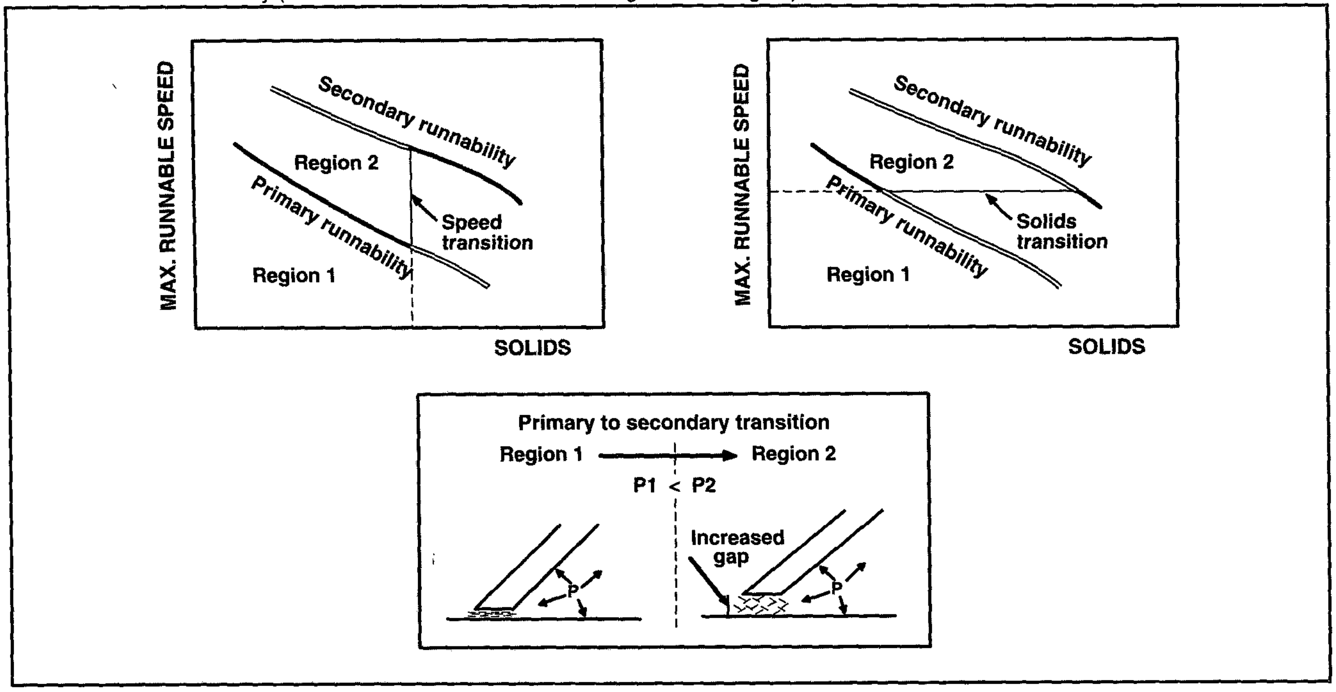
Frequently, the deposition of material onto the stalagmite structure is by addition of spherical droplets along its length and at the tip (**Fig. 17**). Filamentation and subsequent droplet formation is characteristic of a film split phenomenon, and relaxation of the filament section attached to the blade will regain the likely orientation of the exit flow from the nip, i.e., forming a small but definable angle to the web. Speed, viscosity, and solids content will be some of the factors defining this angle, hence the comments concerning benign versus malignant stalagmites, depending on the probability of detachment and subsequent damaging deposition on the web which will necessarily be a function of stalagmite hardness and angle relative to the web. The effect of film splitting in the context of roll coating is well known, and the mechanisms of filamentation and cavitation suggested here are not dissimilar (*35–37*).

Wet and dry bleeding, too, can be explained in terms of rapid film splitting. A formulation which forms a thick zero-velocity boundary layer adjacent to the blade, with good intrinsic water retention, will produce a more continuous wet extrusion with an early film split forming in the body of the color between the blade and the paper. Conversely, a formulation which encourages phase separation (dewatering) or exhibits dilatancy during extension and filamentation, or both, will contribute to a dry bleed prior to a wet bleed under more severe conditions. Much the same observation can be made of the formation of solids deposits oriented radially in a rotational cone and plate viscometer following the onset of dilatancy and subsequent color fracture.

17. Electron micrograph of stalagmite. Note the growth through droplet addition.



18. Flexible blade runnability (transitions occur for SPS at coat weights of 9–10 g/m^2)



Blade pressure and coat weight control

The previous section discussed the relationship between stalagmite formation and the length of blade adopted in the nip. In the context of a relatively incompressible base paper, blade tip pressure, as such, is not a primary determining factor for runnability, provided excess pressures are not applied with resulting web breakage or rapid wear. The emphasis should be given to the pressure balancing forces upstream from the blade tip (*2*, *3*), as, indeed, controversy will continue as to whether any force actually exists at the tip; probably the answer is "sometimes," depending on transient viscoelasticity, lubrication, convergent flow, etc.

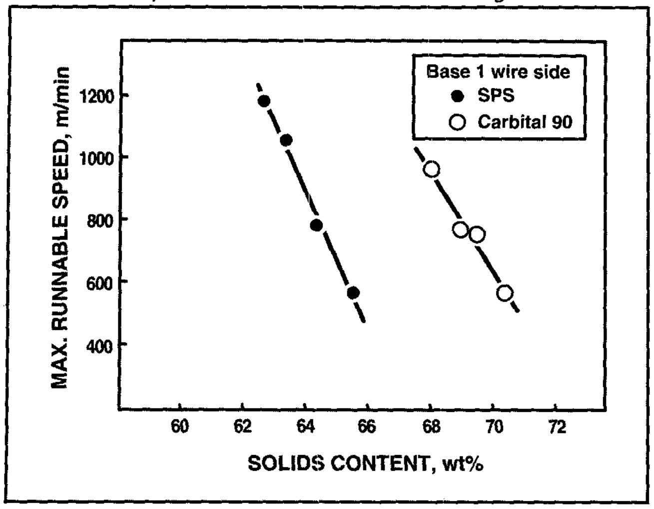
The upstream pressure balance has been discussed as being responsible for pulse dewatering of the color and for the coat weight controlling property of the rheological trap volume of the nip entry geometry. It has also been emphasized that the dynamic surface voidage and compressibility of the base paper must be considered as contributing to the upstream dynamics and gap defined under the blade. If these forces are to be balanced in such a way as to control coat weight, the blade must be of sufficient stiffness. Herein lies a problem if a thin blade is adopted for reasons of preventing stalagmite formation.

Interestingly, an apparent metastable running condition can occur with such a blade, particularly when used with platey pigments. This may be manifest in a runnability curve such as that shown in **Fig. 18**. As the solids content of the color or speed increases, so does the coat weight. A point is reached at which the particle packing of clay platelets may become disordered, and the first signs of spitting and dilatancy become apparent under the nonslip condition. However, further increase in solids or speed has the effect of increasing the blade gap further—hence the importance in relation to thin, flexible blades—such that disordered platelets can pass unhindered under the blade, possibly under the boundary slip condition. An apparent improvement in runnability is observed, though not necessarily a return to the same paper properties as seen prior to the first runnability limit due to a likely change in coating structure. Furthermore, higher coat weights can be achieved without a decrease in blade pressure, thus avoiding a return to the "dilatant" condition previously associated with the effective narrowing of the blade gap when the nonslip condition was re-established. Effectively, the model proposed would suggest that under suitable conditions, further increases in speed or solids content, or both, if associated with the necessary viscous properties, could take the industry beyond this metastable condition, and, therefore, through the present runnability barrier into a higher speed regime.

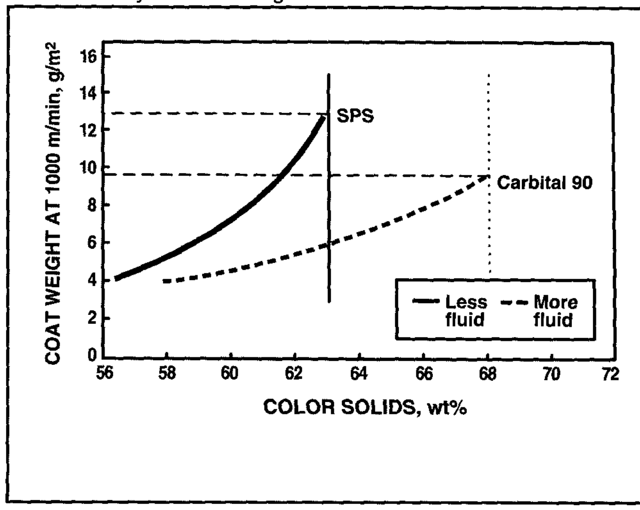
These observations account for many of the apparent anomalies of bleeding appearing and disappearing as blade pressures change and describe well the very area of difficulty encountered most frequently in the mill, i.e., that of achieving the higher coat weight range in LWC (9 g/m^2) using high-speed, short-dwell machines. The higher coat weights may well lie beyond the first runnability region. The solids content and speed combine to develop the necessary blade gap, but may be just sufficient to cause initial stalagmite growth before the required gap is attained. Further increases in solids or speed then result in runaway coat weights as the gap continues to increase, perhaps into a bleed-free region, but at too high a coat weight.

The coarser particles in the size distribution of SPS and U.S. delaminated clay are typically 5 µm in diameter, closely corresponding to the necessary coating film thickness for 10 g/m^2. The tendency to a critical solids, coinciding with this coat weight region, therefore may not be surprising. An associated drop in quality at these coat weights for platey clays, if

19. Maximum speed and solids for bleed-free coating



20. Runnability and coat-weight limits



used in random packing, is also predictable (*16*).

Blocky pigments

Quality lightweight coatings require the maximum coverage for the minimum coating film thickness. Platey clays can satisfy this criterion. For runnability under conditions prevailing today, however, the fluidity of fine U.S. clays and ground calcium carbonates appears superficially attractive.

As speeds increase, the aspects of pulse dewatering and coat-weight control are likely to become ever more important, and the relatively open packing of blocky particles will prove detrimental to good water retention. Greater upstream forces result in greater penetration of fluid colors into the base paper with even further reductions in quality. The speed limit for calcium carbonate runnability is proven to be higher for a given weight solids concentration than for most existing platey clays, as is clearly shown from the pilot coater data for Carbital 90 plotted in **Fig. 19**. It is necessary, however, for blocky pigments to be coated at high solids (a) to gain maximum coverage at the lowest coat weights (<7 g/m^2) and (b) to attain the higher coat weights (>9 g/m^2). A contradiction arises since solids contents below that suitable for maximum coverage are necessary to achieve low coat weight, and the high solids may fail to produce the upper coat-weight range prior to the onset of blade bleeding. For example, the carbonate coatings shown in **Fig. 20** did not exceed 9 g/m^2 before the onset of bleeding in a conventional formulation, whereas SPS coat weights can rise to >12 g/m^2 under similar conditions.

The open packing, characteristic of blocky pigments, is less sensitive to many of the disrupting influences discussed previously such as formulation component particle size, blending, etc. and exhibits a far greater tolerance of machine operating conditions. However, the cross-sectional area of a blocky particle presented to a shear flow is greater than that of an aligned platelet, so, especially under conditions of poor dispersion or in the presence of ionic contaminants, blocky particles will suffer a greater probability of shear-induced aggregation (*28*) compared with platelets run under conditions of complete orientation. Furthermore, there occur many more platelets per unit volume at a given solids content defined by weight (depending on platelet thickness) than in a formulation containing blocky particles of similar size distribution determined under conditions of sedimentation. Thus, in terms of particles per unit of time passing under the blade, high-aspect-ratio pigments present the greater number per unit solids content.

Conclusions

High-speed coating develops intense pressure gradients upstream from the blade tip. The blade confinement geometry must be adjusted to minimize the hydraulic impression of coating color into the base sheet and to prevent excessive vorticity, which can act detrimentally in developing a flow environment that is likely to favor a shear-induced aggregation and poor particle packing.

The conditions for improved blade runnability devised from this work fall into four main areas.

First, a single conceptual view of the ideal pigment for improved LWC runnability and quality should include the following criteria:

1. The pigment must develop sufficient color fluidity in the plane of shear to allow passage under the blade.
2. It should create a high level of intrinsic water retention under the influence of external pressure pulses.
3. It should exhibit an anisotropic rheology such that flow perpendicular to the plane of shear, i.e., into the base paper, should be resisted.

There also must be a formulation environment developed in which the runnability of this idealized pigment can be optimized, namely:

- The particle size (or distribution of sizes) in the color formulation must be considered as a whole and not according to the individual components.
- The use of polymeric additives including starch binders should be avoided unless proven *not* to be detrimental.

- The fluid-phase viscosity should be minimized.
- The latex-pigment-polymer combination must be stable under shear.
- The coating mix must be free from debris, oversized particulate matter, and chemical contamination.

The third condition is that coating should be applied to a base sheet that is relatively nonabsorbent and nonporous, has a low level of uniform surface roughness, exhibits stability against fiber pick and debris, and freedom from roughening due to fiber swelling, debonding, etc. during wetting and hydraulic impression.

A whole area of study is still wanted here to understand further the mechanism of base-paper interactions and may fall more specifically in the realm of the papermaker. It is, however, essential to identify when problems are caused by the base rather than the coating, and to this end it is necessary to pursue the methodology for characterizing base papers through experiment, equipment, and observation.

Finally, the application environment should be designed to minimize dwell time for color in contact with the base paper, to have a stable flow regime at the blade, with a precise control mechanism for adjusting blade beam and tip angle independently to adopt a chosen geometry best suited for the chosen pigment, with the adoption of a very thin or possibly a nonwetting blade tip, to eliminate contamination and air entrapment, and for controlled color, base paper, and applicator temperature and humidity.

These proposals are by no means exhaustive; many areas remain to be investigated, for example, backing roll hardness, web take-off, geometry at the blade exit, vibrational effects, materials science—the list goes on and on! They do, nonetheless, together with the model of stalagmite formation proposed here, provide the means for evaluating suitable pigment, formulation, and machine technology with a vision of the targets for the future of blade coating. It is also vital when recognizing deviations from these ideals to adopt the flexibility needed for a variety of solutions, each specific to a particular mill context or coating philosophy, and to use this as a means of exploiting the uniqueness of each pigment type.

It is becoming apparent that the effective runnability of platey clay has been artificially suppressed by conventional practice based on an evolution of technology far removed from the physical requirements for higher speeds and shorter dwell times which began with the development of formulations designed for roll-applicator systems. This evolutionary philosophy of developing fluid pigment systems tends to be based on a number of misconceptions:

1. It ignores the evidence that fluidity tends to accompany low-aspect-ratio pigments, which have intrinsically poor pressurized water retention properties in the color.
2. It fails to recognize the role played by viscosity in controlling coat weight, particularly at the upper levels of LWC applied with short-dwell coaters.
3. It encourages pressure penetration of the color into the base sheet and roughening of the base-sheet profile. □

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