

Laboratory measurement of bleeding potential during blade coating

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WHEN COATING SPEEDS increase, problems happen. The biggest problem in high-speed coating—particularly by a blade coater—is a loss of color runnability because of bleeding (also known as “weeping” or stalagmite formation) on the blade edge. Bleeding occurs at high speeds, causing streaks or mottle on the coated paper surface. This article describes a laboratory test for investigating and predicting color runnability at high speeds.

Figure 1 is an SEM (scanning electron microscope) image of a typical stalagmite formation. The presence of stalagmites on the blade can lead to operational difficulties, poor paper quality, and calender roll damage. The factors that cause or contribute to bleeding include:

1. Coating conditions (coating speed, blade angle geometry, coat weight, and other mechanical factors) (1–7)
2. Coating color properties (high-shear viscosity, water retention) (1, 2, 6–15)
3. Base paper properties (sizing, pore structure, smoothness, modulus of elasticity, formation) (2, 6–9, 12).

Various researchers have provided theoretical descriptions of these findings. Turai (16), Modrak (9), Engström *et al.* (8), McGenity *et al.* (1, 4), and Bousfield (17) have developed hypotheses to explain the phenomena occurring under the

blade from rheological or dewatering perspectives, through simulation, or by other means. Others have employed direct observation of the bleeding phenomenon and then analyzed the results to obtain a means of improving coating runnability. Scriven, Vodnick, Takamura *et al.* (5, 13, 18, 19) used unique investigative approaches, including high-speed microscopic observation of weep on the blade, microanalysis of its structure and components, and observation of the coating process using a transparent blade.

Many of these and other studies indicate that low high-shear viscosity and high water retention are desirable color properties for good coating runnability (6, 10, 14, 15). In practical operations, however, coating colors with both of these properties do not always exhibit a high runnability, and several of these studies indicate that the viscoelasticity of the color is also a determining factor (7, 12, 15). Moreover, Gane *et al.* (20, 21) and Vaelimaeki *et al.* (22) have proposed the influence of relaxation-induced dilatancy in separable viscoelastic suspensions as a rheological phenomenon involved in the bleeding mechanism.

In all of these approaches, however, the final confirmation as to whether bleeding occurred at specified coating speeds was generally made using a pilot or a commercial coater, since no laboratory-scale equipment capable of reproducing the bleeding phenomenon was available. Such large-scale studies of coating runnability are costly, consuming

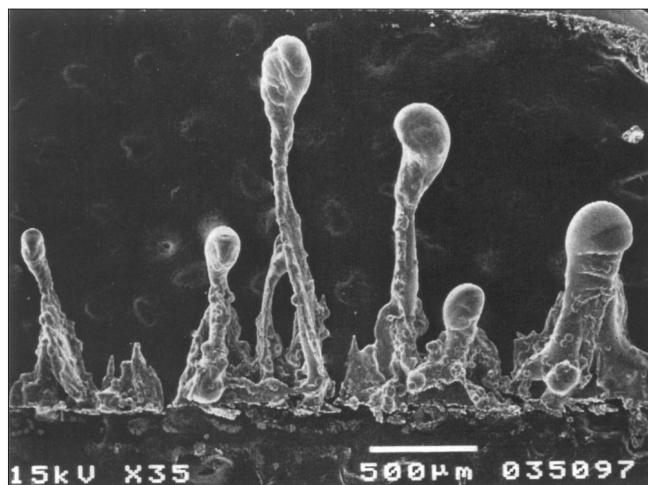
ABSTRACT

A laboratory-scale method for evaluating the susceptibility of coating colors to bleeding was developed and investigated. The proposed method can be used to estimate the critical coating speed—the speed at which bleeding occurs during coating—in a pilot or commercial coater. The reliability of the method is demonstrated by the close correspondence of laboratory results with results obtained on two pilot coaters. Because the laboratory method is a paperless test, the results must be adjusted to account for water absorption by the base paper, which affects the color solids under the blade. (Water absorption by the base paper can be determined by a separate dynamic water-retention test.) Analysis of the results confirms that high-shear viscosity and water retention for a given coating formulation are important factors in determining its bleeding susceptibility. However, the results also suggest the presence of a third, unidentified color property that influences bleeding potential. This factor is most likely related to changes in the color's viscoelastic behavior under shear. While the precise nature of this factor is unknown, its influence is included in the laboratory method, which provides a reliable means of evaluating color runnability.

Application:

A laboratory method for predicting bleeding susceptibility when blade coating a given combination of base paper and coating formulation. The method also can be used to research and analyze bleeding mechanisms.

a large volume of materials and resources, including base paper and color, labor, and time. Consequently, systematic investigation of the bleeding phenomenon has been limited, thus limiting the industry's ability to



1. Typical stalagmites (SEM image)

achieve a clear description and understanding of the factors responsible for bleeding.

As part of the effort to establish a method for evaluating coating runnability on a laboratory basis, we designed and constructed a laboratory-scale system for determining the susceptibility of coating colors to bleeding. There is no base paper used in the laboratory system. Rather, the color is applied directly to the backing roll, and the coating speed is increased until bleeding occurs at the blade edge. This "backing-roll coating" evaluation method (BC method) was found to provide the following advantages.

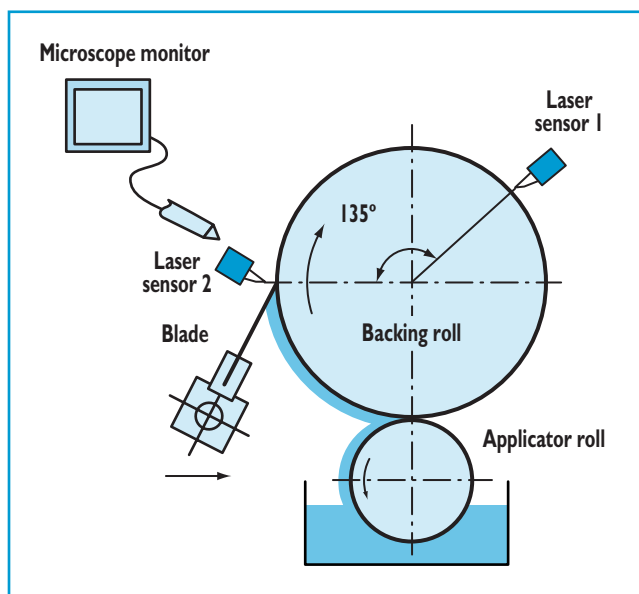
1. The method can be used to determine the susceptibility of coating colors to bleeding, excluding the influence of the water absorption by the base paper
2. The results can be applied to coating with a regular coater using base paper by adjusting for water retention as determined by the dynamic water-retention test.
3. The results reflect the influence of high-shear viscosity, which is commonly recognized for its effect on runnability, and also that of an additional unidentified color property that has not previously been recognized as an important determining factor.
4. As a small-scale experimental method, it greatly reduces material, labor, and time requirements. Consequently, the proposed method may help in promoting more systematic studies on coating runnability.

In this article we describe the laboratory BC method, present the results of experimental application, and correlate these results with those obtained on two pilot coaters.

EXPERIMENTAL

Color formulations

Table I describes the color formulations used in this study. The colors were prepared by dissolving sodium hy-



2. Configuration of laboratory test apparatus

dioxide and dispersant in water; adding ground calcium carbonate (particle size at least 90% < 2 µm); adding No. 1 kaolin while stirring and then stirring for 30 min; adding dispersed oxidized starch and stirring for 20 min; adding S/B latex and stirring for 20 min.

All S/B latexes were copolymers of styrene/butadiene/itaconic acid (57/40/3). Latexes A and B both had a particle size of 100 nm, but a special treatment was used in the processing of Latex B. Latexes C, D, and E had particle sizes of 70, 120, and 170 nm, respectively. Each color formulation had solids contents ranging from 62% to 69% and pH of 10–11.

Methods and apparatus

Laboratory tests—BC method. Figure 2 shows the schematic configuration of the laboratory BC apparatus, and Fig. 3 is a photograph of the apparatus. The laboratory device consists of a backing roll (rubber surface, 250-mm diam., 300-mm width, maximum peripheral speed = 540 m/min), an applicator roll, a blade (300-mm width, 0.508-mm thickness), and a manually driven coater head supporting the blade.

Color from the pan was spread onto the backing roll by the applicator roll, with the excess scraped from the backing roll by the blade. The blade region was monitored for the occurrence of stalagmites and weep via a microscope (Keyence) placed very close to the blade, and the images were videotaped at 50× magnification.

The coat thickness was measured by laser sensor 1 (Keyence), located 135° downstream of the blade edge. The thickness of the coating was determined from the angle of entry of a laser beam reflected into the detector from the target.

The bevel angle and the working angle (the angle between the blade and the backing roll, equal to bevel angle plus wedge angle) are given in Table II. The blade

angle and displacement at the blade edge were adjusted to obtain a blade wedge angle of 2°, and the blade pressure was adjusted to obtain a coat thickness of 10 µm as measured by laser sensor 1, with the blade displacement confirmed by laser sensor 2. The details are explained in Appendix A at the end of this paper.

The operation began with a peripheral speed of 100 m/min. If no bleeding was observed one minute after startup, the peripheral speed was increased by 50 m/min. This process was repeated until stalagmite or weep formations were observed along the length of the blade edge through the microscope monitor. These formations were taken as a manifestation of bleeding, and the peripheral speed at the time of their occurrence was taken as the critical coating speed (CCS), which served as the indicator of coating runnability during this study. Next, the solids content was decreased by 1% by adding water, and the CCS at that solids content was obtained using the same approach. The overall procedure is summarized by the flow diagram in Fig. 4.

To avoid any influence of blade wear, a new blade was installed for each color formulation. Figure 5 is a

Formulation	1	2	3	4	5	6	7	8	9	10
No. 1 kaolin	70	70	70	30	100	70	50	0	70	70
Ground calcium carbonate	30	30	30	70	0	30	50	100	30	30
Dispersant	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Alkali	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Oxidized starch	3	3	3	3	3	3	3	3	1	3
S/B latex										
A (100 nm)	11	...	...	11	...	...	...	...	...	...
B (100 nm)	...	11	...	...	...	...	...	...	...	...
C (70 nm)	...	...	11	...	...	...	...	...	...	...
D (120 nm)	...	...	...	...	11	11	11	11	11	...
E (170 nm)	...	...	...	...	...	...	...	...	...	11

I. Coating formulations (dry parts)

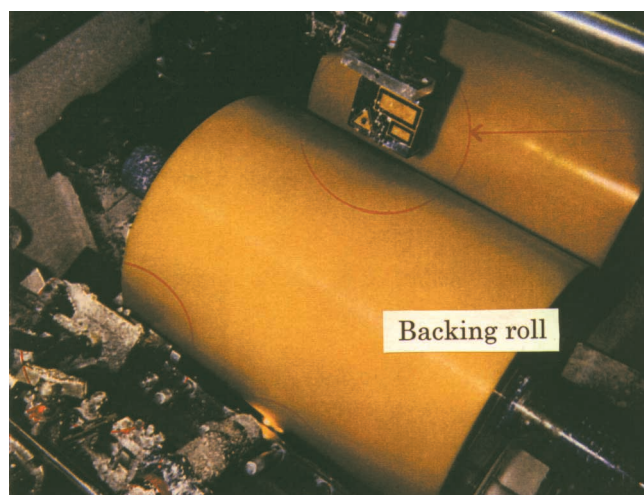
	PILOT COATERS		Laboratory BC method
	MHI	IHI	
Bevel angle, degrees	35	35	35
Working angle, degrees	37	37	37
Application	Fountain	Fountain	Flooded nip roll
Coating speed, m/min	100–1400	100–1400	100–540
Coat weight, g/m ²	10	10	10
Temperature, °C	35	20	20
Base paper	Wood free and wood containing	Wood free	None
Color formulations	1–4	6, 9, 10	1–10

II. Coating conditions

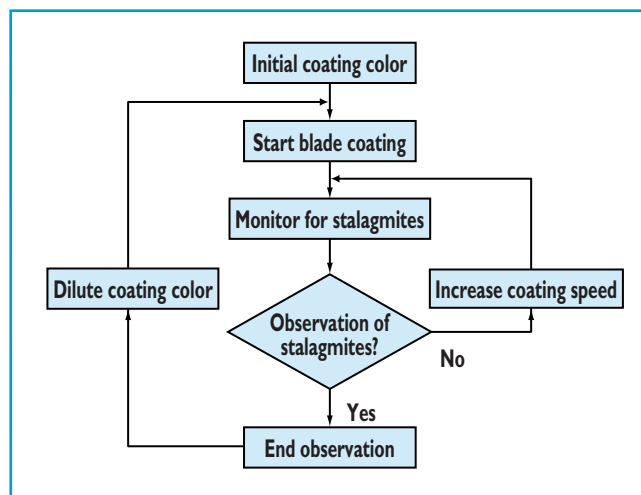
typical view of the images obtained in the microscope that was used to monitor the blade edge for the occurrence of stalagmites.

Laboratory tests—evaluation of dynamic water retention (23). When a base paper is being coated, the

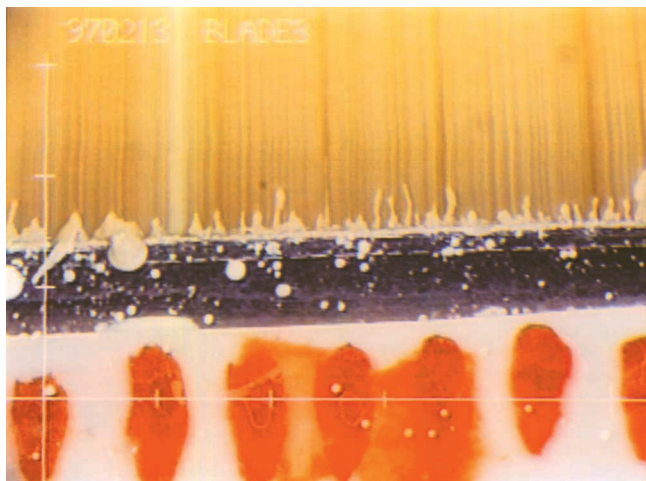
solids content of the color increases as water migrates from the color into the base paper. Using a laboratory bench coater, illustrated in Fig. 6, we measured the change in solids content in color that was scraped from the web downstream from the



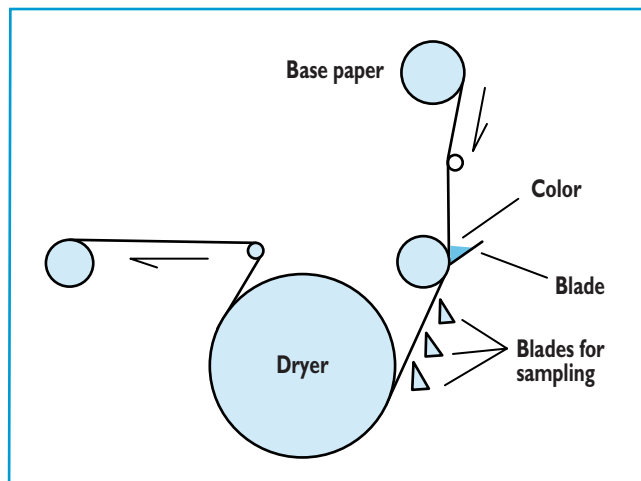
3. Laboratory test apparatus



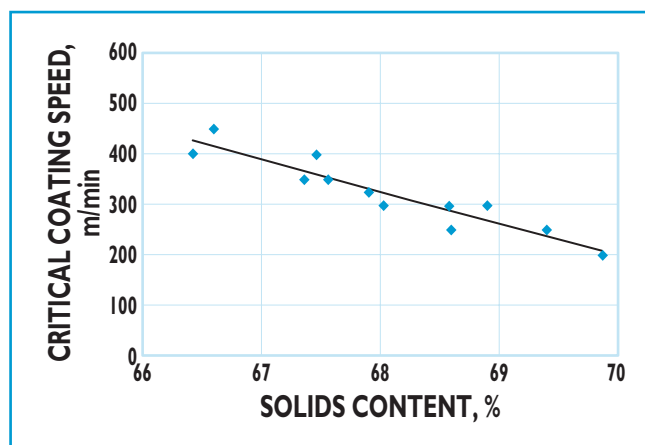
4. Flow diagram of laboratory test procedure



5. Image on microscope monitor



6. Configuration of dynamic water-retention test apparatus



7. Reproducibility of laboratory method

coater blade. The web was coated at a peripheral speed of 10 m/min, and color samples were removed twice at points 5–100 mm from the blade. The temperature of the color was 35°C.

Laboratory tests—capillary viscosity. The viscosity of each color formulation was measured at 20°C, at different solids contents and different shear rates, using a high-pressure capillary viscometer (Anton Paar).

Pilot coater tests. Pilot coater tests were conducted using commercial-scale pilot coaters at the facilities of Mitsubishi Heavy Industry (MHI) and Ishikawajima-Harima Heavy Industry (IHI). In these tests, the color was spread directly on the base paper. The conditions on the pilot coaters are listed in Table II.

Wherever possible, the pilot coater tests were conducted with a coating color temperature of 20°C, the corresponding temperature of the laboratory BC test. However, the tests at the MHI facility were conducted in midsummer, when coating temperatures were 35°C.

The coat weight was obtained from the difference in readings between the two β -ray thickness gauges in-

stalled before the coater and after the dryer. Coat weight was held at $10 \pm 0.5 \text{ g/m}^2$ (which corresponds to a thickness of 10 μm for this color as used in the laboratory BC test) by adjusting the coater head. The blade working angle (the angle between the blade and the base paper, equal to bevel angle plus wedge angle) was kept at $37^\circ \pm 0.5^\circ$ by adjusting the blade pressure. The coating speed was increased in increments of 50–200 m/min, and CCS was obtained in the same manner as in the BC method. The base papers were a wood-free paper (basis weight of 74 g/m^2 and a Stoeckigt sizing degree of 25 s) and a wood-containing paper (basis weight of 55 g/m^2 and a Stoeckigt sizing degree of 1 s).

RESULTS AND DISCUSSION

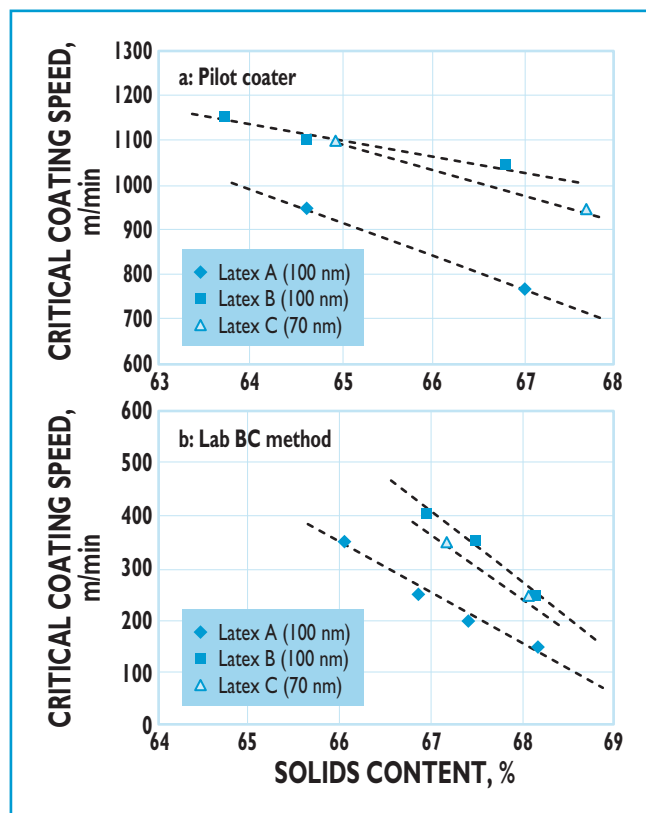
Reproducibility of laboratory evaluation

The reproducibility of the laboratory BC results was evaluated by conducting 12 tests over three days (four tests per day) using Formulation 1. The results are shown in Fig. 7. The mean deviation in CCS was $\pm 25 \text{ m/min}$, and the maximum deviation from the mean was 50 m/min. These results indicate effective control of color preparation, measuring, and other test conditions as well as good reproducibility.

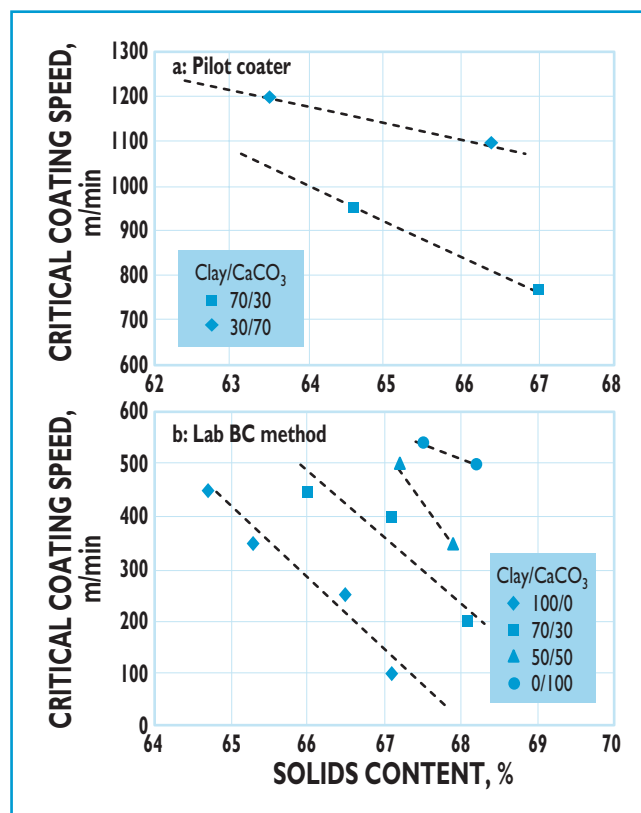
Comparison of laboratory and pilot coater test results

Laboratory BC evaluations were conducted using different color formulations and then compared with results from the pilot coaters. In the following figures, broken lines depict statistically unconfirmed tendencies suggested by a small number of data points. (Repetition or expansion of the experiments was not possible because of constraints in time and facility availability.)

CCS for different latexes. Figure 8 shows that the laboratory BC and pilot coater tests yielded the same relative ranking of the latexes on the basis of their respective CCS values, even though the two tests yielded quite different CCS values for a given solids content. For example,



8. Effect of latex type on critical coating speed



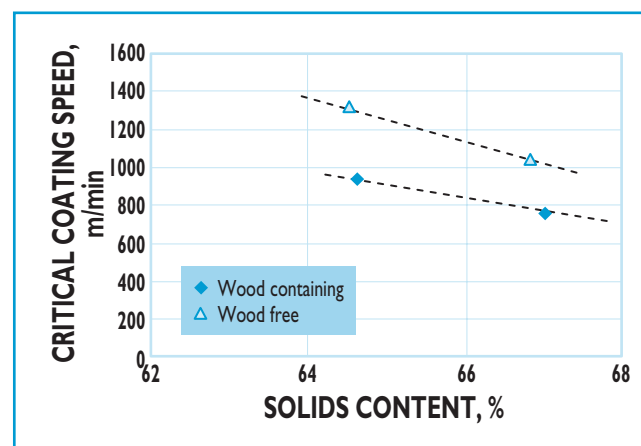
9. Effect of clay/calcium carbonate ratio on critical coating speed

Latex A (67% solids content) had a CCS of 250 m/min for the laboratory BC method (Fig. 8b) and 780 m/min for the pilot coater (Fig. 8a). This difference is partly attributable to the different color temperatures. Confirmation that the different temperatures used in these experiments did not affect the relative ranking will require further investigation. The difference in hardness between the BC roll and the base paper may have had an effect on runnability, and the roughness and porosity of the base paper also could have affected the bleeding propensity.

CCS for different ratios of clay/calcium carbonate. Figure 9 shows the changes in CCS with changes in the clay-to-calcium carbonate ratio as obtained by the pilot coater and BC tests. In both tests, the CCS increased with increasing calcium carbonate ratio. This is because calcium carbonate particles have a small aspect ratio (i.e., close to spherical), so the high-shear viscosity decreases with increasing ratio of calcium carbonate.

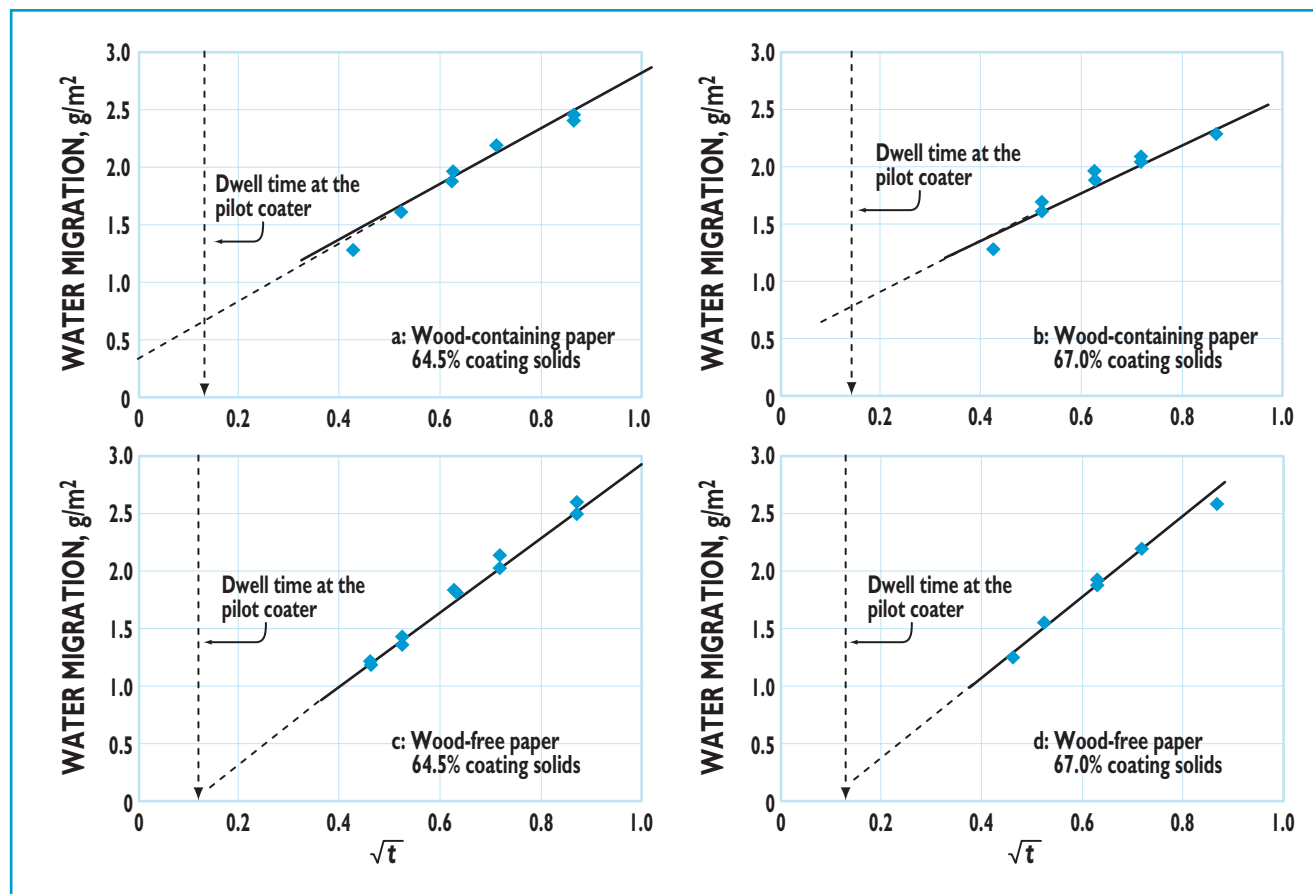
Estimation of CCS for commercial coater

We investigated the relationship between water retention and susceptibility to bleeding under commercial coating conditions by using wood-containing and wood-free base papers on the MHI pilot coater. Figure 10 shows the results of this pilot coater test. The CCS was lower for the wood-containing paper than for the wood-free base paper, presumably because of the greater water absorption by the wood-containing paper, leading to a higher solids content just under the blade.



10. Effect of base paper on critical coating speed (pilot coater)

To estimate the solids content under the blade, we conducted a dynamic water-retention test to ascertain the rate of water migration from the color to the base paper. Because of the difficulty of obtaining good reproducibility under the high speeds employed in the pilot coater—and because the product of the pressure and the time under the blade is virtually constant under given conditions (and thus unaffected by the difference in coaters)—we used the bench coater for this test. (See Appendix B at the end of this paper.) At low coating speeds, scraping was readily performed, and the



11. Pihl-Olsson plots for wood-containing and wood-free base papers

reproducibility of the water migration volume measurements was excellent; at high coating speeds, uniform scraping became difficult and reproducibility was poor.

We applied Pihl-Olsson's equation (Eq. 1) to calculate the rate of water migration from the color to the base paper during blade coating. We then plotted the water migration quantities (as determined by the dynamic water-retention test) against the square root of time, with line fitting by least squares. The results show a linear relationship for the wood-containing and the wood-free papers, as seen in Fig. 11. The point where the color initially contacted the base paper was taken as $t=0$, and the scraping points for sample gathering were 20–115 mm downstream.

$$h = \left[\frac{(2r\gamma \cos\theta + pr^2)t}{4\eta} \right]^{0.5} \quad (1)$$

where

h = water migration quantity

r = mean radius of pores in base paper

γ = surface tension of water

θ = contact angle

p = pressure applied under the blade

t = time

η = viscosity of color under high shear

In pilot coater tests, the dwell time was calculated from dwell length (30 cm) at the critical coating speed for each solids content. The y -values at the dwell times indicate the quantity of water migrating to the base paper up to the region under the blade. For the wood-containing base paper, the water migration was 0.58 g/m² and 0.78 g/m² for color solids contents of 64.5% and 67%, respectively (Figs. 11a and 11b). For the wood-free base paper, water migration was 0.08 g/m² and 0.15 g/m² for color solids contents of 64.5% and 67%, respectively (Figs. 11c and

11d). These results clearly imply that the actual solids content just under the blade is higher than the nominal solids content.

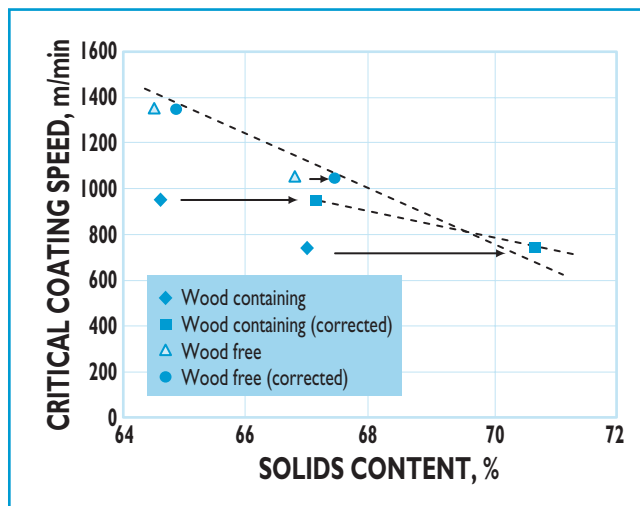
We next corrected the CCS for the wood-containing base paper based on this estimated water migration. The results shown in Fig. 12 indicate that differences in CCS between the base paper types resulted entirely from the difference in water absorption. The water migration to the wood-free base paper under the blade was almost nil, the same as that to the rubber roll. This suggests that the CCS for the wood-containing base paper in commercial coating can be estimated by obtaining the CCS by the BC evaluation method and correcting the results for water migration as measured by the dynamic water-retention test.

More precise estimates may well require a further correction to compensate for differing color applica-

tion methods. Since fountain application was utilized in the pilot coater and pond application in the bench coater, the application pressure was presumably higher on the pilot machine, resulting in greater water migration and thus higher solids content in the region under the blade. The color application pressures were not measured in the present investigation, so clarification of their degree and influence awaits further study.

Causes for bleeding—comparison with capillary viscosity

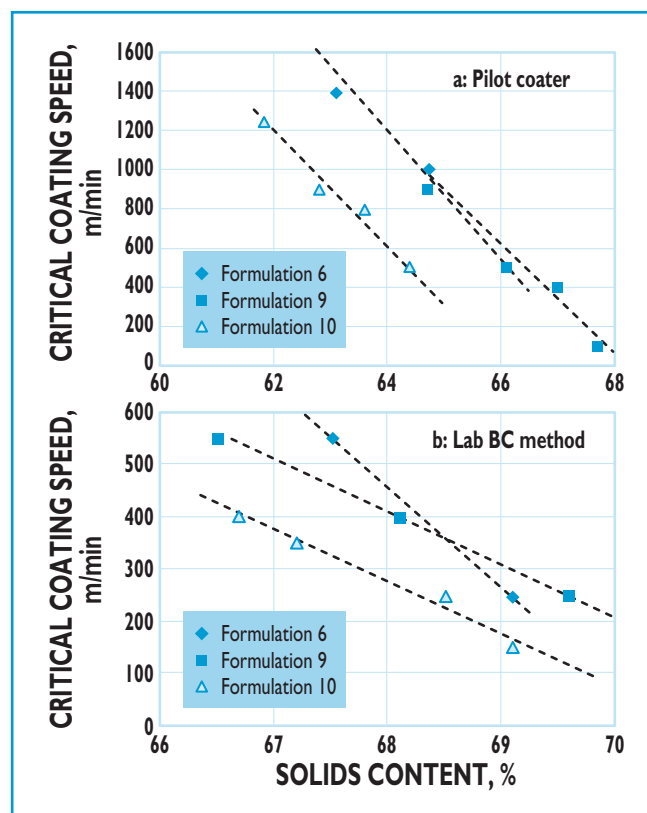
It is generally recognized that bleeding decreases with decreasing high-shear viscosity and with increasing water retention within the color. To further investigate these relationships, we compared the results obtained on the IHI pilot coater, as shown in Fig. 13a, and the corresponding BC method test, as shown in Fig. 13b. In both cases, Formulation 10 (containing 170-nm S/B latex) had a lower critical coating speed at a given solids content than Formulations 6 and 9 (containing 120-nm S/B latex). The critical coating speed was not affected by the change of starch content in these three formulations. (Formulation 9 contained one part of starch, while Formulations 6 and 10 contained three parts starch.) Increasing starch content generally results in greater water retention, and thus a higher critical coating speed might



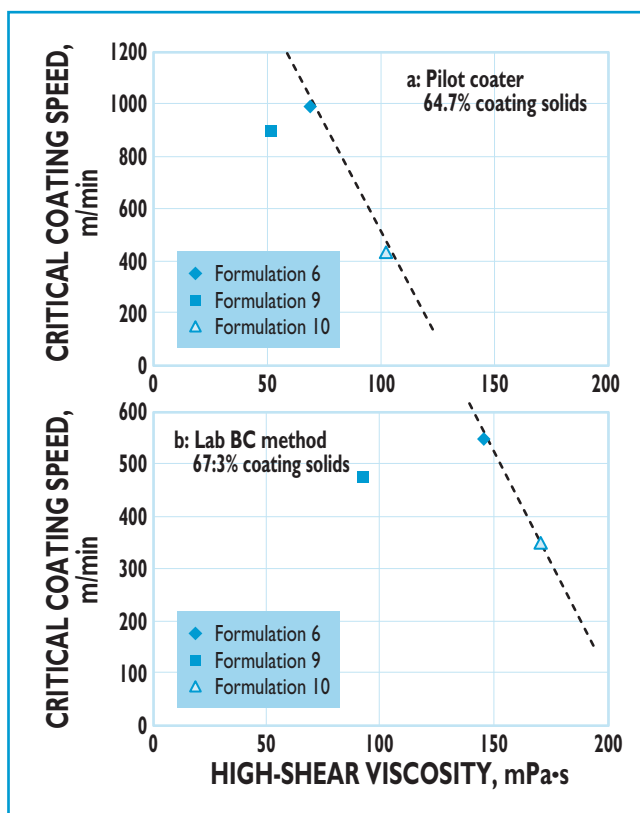
12. Correction of CCS for water migration

be expected for Formulation 6. However, the IHI pilot coater test used wood-free base paper with little water migration, and the BC method used the roll itself with nil water migration. Consequently, the greater water retention in Formulation 6 had no observable effect in these tests.

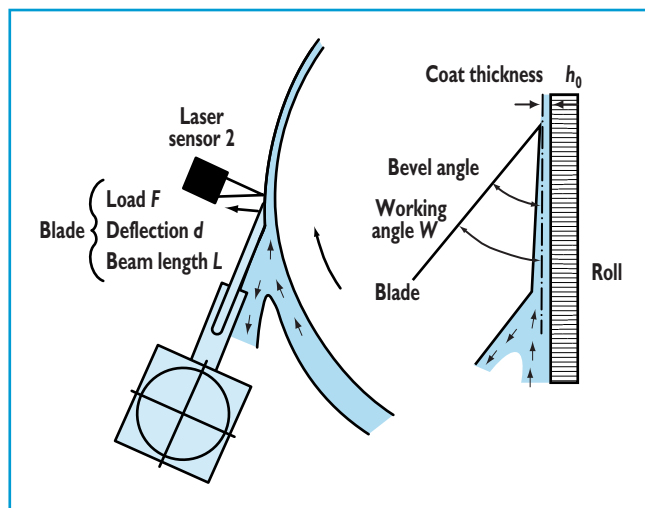
We obtained the capillary viscosity for each color formulation at various solids contents and shear rates. We then plotted the values of their high-shear viscosity at



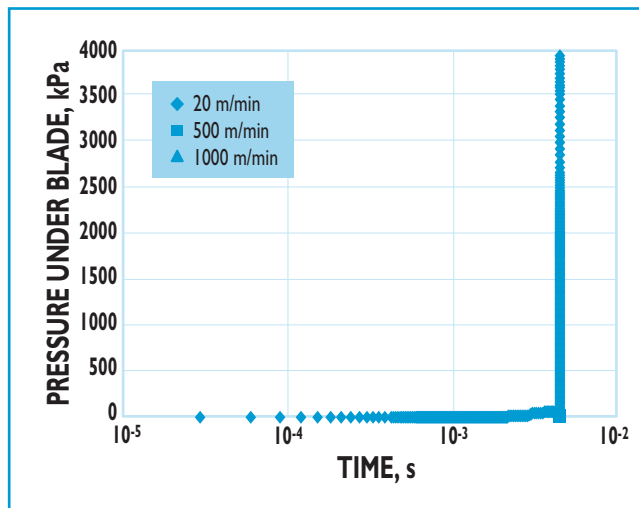
13. Effect of color formulation on critical coating speed



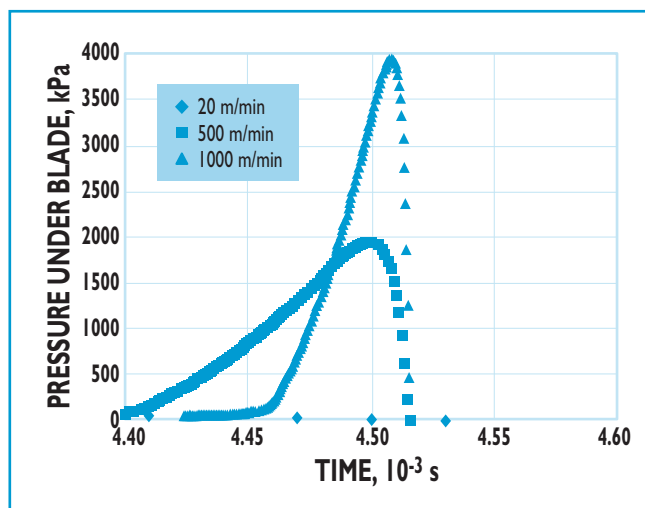
14. Correlation between CCS and high-shear viscosity at CCS



15. Compensation for deflection of coater blade during laboratory test coating



16. Pressure distribution under the coating blade at three machine speeds



17. Pressure distribution under the coating blade (detail of Fig. 16)

one solids content—at the shear rates at which the critical coating speed was obtained—against the CCS values, as shown in Fig. 14.

Figure 14a shows the results obtained on the IHI pilot coater at 64.7% solids content. The results do not show a straight-line relationship between CCS and high-shear viscosity. Formulation 6, which contained 120-nm latex particles, had a lower high-shear viscosity and a higher CCS than Formulation 10, which contained 170-nm particles. Formulation 9 contained the same size and type of latex particles as Formulation 6 and had less starch than the other coating formulations. Nevertheless Formulation 9 had a lower CCS despite its lower high-shear viscosity. Since the base paper used in this investigation was wood-free paper with almost no water migration, we inferred that the differences in the CCS values were not attributable to different water retentions of the colors.

To test this inference further, we performed BC evaluations using the same color formulations at 67.3% solids content and compared the results. As seen in Fig. 14b, the results of the BC test were similar to those obtained on the pilot coater, with Formulation 9 plotting substantially below the line connecting the CCS for Formulations 6 and 10. Any bleeding that may have occurred during the BC evaluation was free from any influence of water absorption by the base paper and, thus, from any effects of differing water retentions by the colors. Consequently, the low CCS at low high-shear viscosity for Formulation 9 clearly suggests the presence of a third factor.

Starch, which is a water-soluble polymer, interacts with clay, calcium carbonate, latex, and other substances dispersed in the color liquid, adsorbing to or desorbing from them to maintain equilibrium. Upon exposure to the high-shear stress imposed by the applicator, the equilibrium is temporarily disrupted, but the color recovers its original rheological structure after the stress is removed. The results in Fig. 14 suggest that the degree to which the rheological structure has recovered by the time the color reaches the point just under the blade may have a close relation to the occurrence of bleeding. If that is the case, this would be a third factor affecting runnability, in addition to high-shear viscosity and water retention. This third factor may be viscoelasticity, but we have not yet obtained enough evidence to state this with certainty. Note also that the BC evaluation detects bleeding under the condition of nil water migration to base paper, so this “third factor”—at least as manifested in these experiments—must be explained without direct involvement of water migration to paper. Although this third factor has not yet been identified, its effect is included in the laboratory BC method, which also includes the effect of color high-shear viscosity.

CONCLUSIONS

The laboratory "backing-roll coating" (BC) method provides a reliable means of evaluating the susceptibility of coating colors to bleeding. In this system, the color is applied directly to the backing roll, and the coating speed is increased until bleeding occurs at the blade edge.

The study revealed several interesting findings:

1. For base sheets that resist water migration from the color, the BC test can indicate the relative susceptibility to bleeding for different coating formulations. The BC results showed good agreement with results obtained on a pilot coater.
2. For base sheets that absorb water from the color, the results for the BC test must be adjusted to ac-

count for the water migration from the color to the sheet. This is done by applying the results of a separate dynamic water-retention test to account for the increase in solids under the blade.

3. A third color property—in addition to high-shear viscosity and water retention—is also apparently involved in the occurrence of bleeding. While this third property has not yet been identified, its effect is captured by the laboratory BC method. **TJ**

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Press impulse, Pa·s

Coater speed, m/min	
20	112.7
500	114.3
1000	115.9

III. Area under pressure–time lines for coatings applied at different speeds and pressures

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The authors thank Hidekazu Ishimura, Shuzo Mitani, Shinji Goto, and Junichi Shishido for their theoretical and experimental expertise and assistance in support of this study.

Received for review Feb. 6, 1998.

Accepted Sep. 30 1998.

APPENDIX A

When a blade installed at a working angle of W_0 is pressed toward the backing roll to remove excess color, a deflection of d is generated at the blade edge, making the actual working angle W a little less than the original angle. We measured d with laser sensor 2, as illustrated in **Fig. 15**, and adjusted the blade pressure to maintain W constant.

If the blade is regarded as a cantilever beam, the deflection d and the angle of deflection P can be expressed by the following formula (24).

$$d = \frac{F L^2}{2E I_z}$$

$$P = \frac{F L^3}{3E I_z}$$

and then

$$P = \frac{3}{2} \frac{d}{L}$$

where

F = concentrated load

L = span of blade (blade beam length)

E = modulus of elasticity of blade

I_z = geometric moment of blade section

Accordingly, the working angle W during coating can be obtained from P and W_0 by the following formula.

$$W = W_0 - P$$

With this approach, the critical coating speed on the laboratory apparatus was obtained at the same coat weight and wedge angle used during pilot coating.

APPENDIX B

During high-speed coating (i.e., on a pilot coater or a commercial coater), a high pressure is generated just under the blade for a short period of time. On the other hand, during low-speed coating (i.e., on a bench coater), a lower pressure is generated for a longer period of time.

We made the following assumptions:

1. The high-shear viscosity was nearly the same in both cases,

since the shear rates of both the bench coater (coating speed, 10 m/min; shear rate, approx. 10^4 L/s) and the pilot coater (coating speed, 1000 m/min; shear rate, approx. 10^6 L/s) fall within the second region of Newtonian flow.

2. The coater blades were sufficiently similar to be considered as having virtually the same geometry in the area of interest.

We calculated the pressure under the blade against time at three ma-

chine speeds, as shown in **Fig. 16** and in greater detail in **Fig. 17**. As shown in **Table III**, the time integral of the pressure, i.e., the area under the pressure–time line, was nearly the same in all cases and thus independent of speed. On this basis, it follows that the water migration just under the blade can be considered to be equivalent for the pilot and the bench coaters, despite the differences between these two coater types.

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