Pigment-cobinder interactions and their impact on coating rheology, dewatering, and performance

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ABSTRACT *Interactions between the pigment and cobinder in a coating formulation can affect coating rheology, dewatering, blade runnability, and coated-paper properties. These effects were examined in the laboratory using coatings containing English clay and one of the five cobinders chosen for study (polyvinyl alcohol, carboxymethylcellulose, starch, and two synthetic thickeners). Coating rheology was measured over a wide shear range and was found to be highly dependent on the choice of cobinder. The changes in rheology likely reflect differences in the shear resistance of the aggregates formed by the interaction of each pigment-cobinder combination. Simultaneous consideration of laboratory results for dewatering and rheology proved to be helpful in explaining differences in blade runnability on a high-speed pilot coater for the various coating formulations. Blade runnability appears to be diminished by the formation of strong aggregates in a coating dispersion and by coatings with poor water retention. Surface properties of the pilot-coated papers were evaluated, and the results showed correlation with coating-color parameters studied in the laboratory.*

KEYWORDS
Binders
Blade coating
Clay
Coatings
Pigment
Printing tests
Rheological properties
Viscosity

Pigmented coating dispersions, commonly referred to as coating colors, are subjected to a wide range of shear rates during the coating process. After mixing, the color is pumped, screened, and stored before it reaches the coating head. During these steps, the color is subjected to low-to-medium shear. At the coating station, shear rates can reach 10^4–10^5 s^{-1} during the application and 10^6–10^7 s^{-1} under the blade tip. After the blade, the coating color is subjected to zero shear. An additional complication is the penetration of the coating-color water phase into the base sheet during the coating process.

It is generally understood that coating rheology and dewatering must both be controlled if the coating is to be effectively applied using high-speed equipment. Research and industry experience suggest that rheology and dewatering are highly influenced by interaction between pigment and cobinder. This interaction can lead to formation of aggregates, and understanding the behavior of these aggregates at different rates of shear is a key consideration when evaluating the influence of a given cobinder on coating performance.

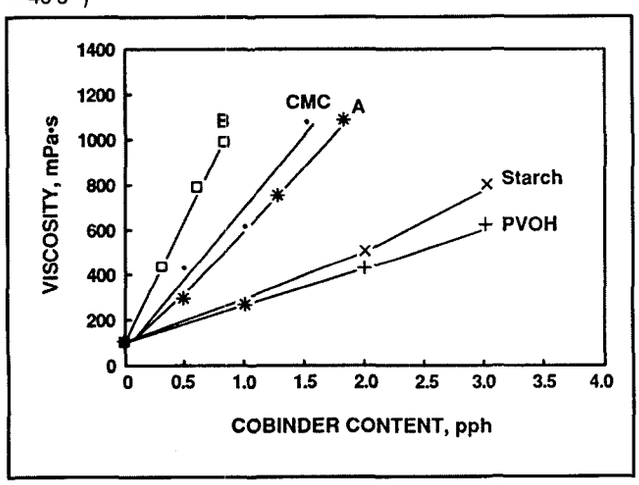
Several researchers have studied interaction phenomena and their effect on rheology and other color properties (*1–8*). In recent years, viscoelasticity measurement has been used as a tool to study the aggregation that occurs within a coating (*9–11*). These studies provide a broad basis for further investigations of interaction-controlled rheological and dewatering properties. However, most of these studies have been made at low shear rates, and the effect of the interaction phenomenon on the industrial coating operation has not been discussed. This study investigates the interaction between pigment (English clay) and various cobinders over a wide range of shear

I. Laboratory results for control coating (no cobinder) and five cobinders at three levels of addition*

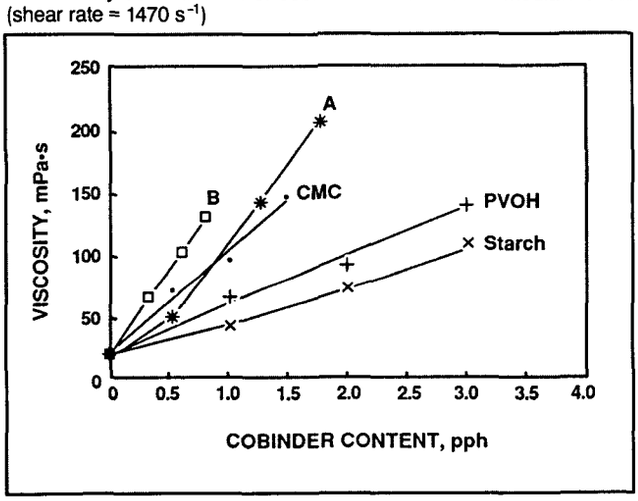
	Control	CMC, pph			PVOH, pph			Starch, pph			Thickener A, pph			Thickener B, pph		
		0.5	1.0	1.5	1.0	2.0	3.0	1.0	2.0	3.0	0.5	1.25	1.8	0.3	0.6	0.8
Brookfield viscosity (at 100 rpm), cP	105	680	1120	1960	420	740	1140	440	860	1470	440	1300	1880	700	1280	1720
Dewatering, g/m²	117.8	60.1	49.0	44.8	94.6	55.3	35.8	69.7	43.2	29.9	77.5	55.7	45.0	103.1	58.6	49.8
Viscosity, mPa•s																
at 46 s^{-1}	92	423	614	1070	264	431	627	263	511	811	284	752	1080	424	781	986
at 1470 s^{-1}	22	70.8	96.1	147.0	64.4	90.4	137.0	42.9	71.0	103.0	52.9	143.0	207.0	65.9	102.0	131.0
at 250,000 s^{-1}	32	41.5	51.5	58.5	54.4	77.7	90.0	42.5	64.1	82.6	35.8	57.8	72.4	41.0	51.5	61.1
Storage modulus, Pa	1.55	54.7	101	205	8.5	28.6	52.7	12.5	35.7	62.0	14.3	85.4	142	28.1	70.9	96.0
Loss modulus, Pa	1.01	7.2	11.9	19.5	2.5	5.0	8.4	3.0	6.5	11.2	4.0	11.5	18.9	3.4	7.8	11.2
Water-phase viscosity, cSt	1.00	2.03	3.54	5.70	2.01	4.10	7.91	2.73	8.31	25.0	6.32	18.5	33.4	5.94	13.9	23.0
Immobilization solids, %	78.2	76.0	75.2	75.0	74.6	74.6	74.4	76.7	76.3	76.1	76.3	74.4	73.3	75.9	74.6	74.4
Yield stress, Pa	7.4	23.2	33.6	60.8	16.2	20.1	32.3	15.6	28.3	41.9	8.5	44.6	60.8	16.9	31.0	54.2
Plastic viscosity, mPa•s	16.9	55.0	73.1	104.9	53.1	75.8	114.8	32.2	51.5	74.2	47.0	112.5	162.4	54.2	80.3	93.7

*Solids content for all coatings was 60.5%; pH was 8.8.

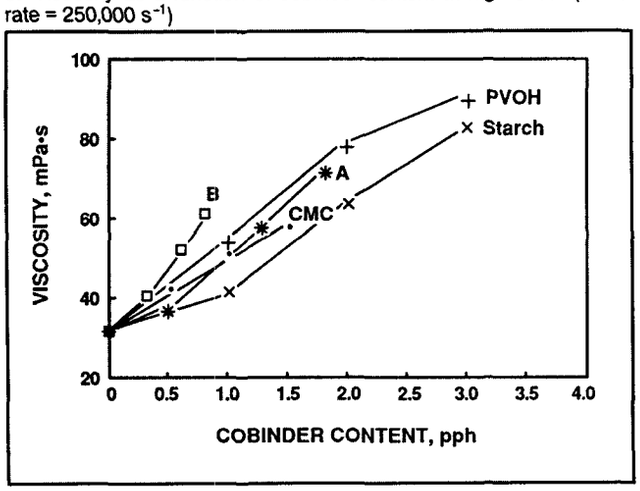
1. Viscosity as a function of cobinder content at low shear (shear rate = 46 s^{-1})



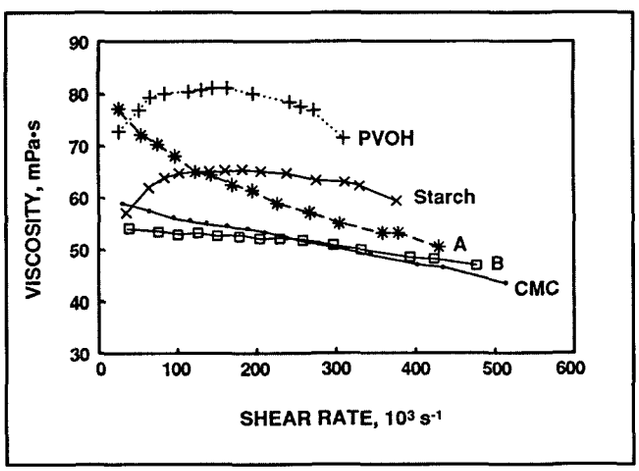
2. Viscosity as a function of cobinder content at intermediate shear (shear rate = 1470 s^{-1})



3. Viscosity as a function of cobinder content at high shear (shear rate = 250,000 s^{-1})



4. Viscosity of coatings at high shear (medium cobinder addition)



rates in an effort to gain insight into the practical implications of the pigment-cobinder interaction phenomenon. In the first part of this work, the rheological, immobilization, and dewatering properties of the coatings were studied in a laboratory environment. In the second part of this work, the various coatings were applied using a high-speed pilot coater. Our main objective was to attempt to correlate pilot results (blade runnability and coated-paper properties) with the results obtained in the laboratory.

Laboratory analysis

Experimental

The coating colors used in this study were all based on 100 parts English clay, to which 10 parts styrene-butadiene latex were added. Five different cobinders were studied: carboxymethylcellulose (CMC), polyvinyl alcohol (PVOH), two synthetic alkali-swellable cobinders (Thickeners A and B), and a cold-water-soluble starch. The coatings contained only one type of cobinder at a time, and the influence of each cobinder was studied at three levels of addition. Solids content was held constant at 60.5%, and pH was adjusted to 8.8 with NaOH.

For the rheological measurements, two rheometers were used. High-shear rheology (20,000-600,000 s^{-1}) was studied with an Eklund capillary viscosimeter; low-shear rheology (1-1500 s^{-1}) with a Bohlin VOR rheometer. The latter was also used in oscillation tests to obtain the storage and loss moduli of the coating colors at small deformations. (Storage modulus and loss modulus reflect the coating's elastic and viscous properties.)

The water retention of the coating colors was determined using a method developed at Åbo Akademi. The method is based on pressure filtration and involves gravimetric determination of the dewatered water phase. The contact time in these measurements was 2 min at 0.25-bar pressure. The apparatus used in this method is described in the literature (*12*). The immobilization-solids point was determined by the ceramic-plate method.

Laboratory results are presented in **Table I**.

Results and discussion

Development of coating viscosity with increasing cobinder addition is shown in **Figs. 1-3** at conditions of low, intermediate, and high shear, respectively. At low shear, the five cobinders fall into two groups, as seen in Fig. 1. CMC and the two synthetic thickeners (A and B) had a strong viscosifying effect, while PVOH and starch had a weaker effect. As the shear rate increases to 1470 s^{-1}, the difference between the two groups decreases, as seen in Fig. 2. At 250,000 s^{-1}, no separation into groups can be made, as seen in Fig. 3. Such behavior indicates that the coatings with PVOH and starch had a less-pronounced shear-thinning flow than did the coatings containing CMC or Thickeners A and B. This applies especially for the coatings with PVOH, which showed the lowest viscosity at low shear rates and one of the highest viscosities at high shear rates, clearly demonstrating the importance of carrying out rheology measurements over the widest possible range of shear rates. The high-shear capillary viscosities of the coatings, shown in **Fig. 4**, provide further evidence of differences in flow behavior between the two groups.

Relative color viscosity as a function of water-phase viscosity is shown in **Figs. 5-7**, at conditions of low, intermediate, and high shear, respectively. (Relative color viscosity is defined as the ratio of color viscosity to the viscosity of the dispersing medium.) Water-phase viscosity was determined by mixing polymer solutions at the same concentrations used in the coating colors, assuming that no polymer is adsorbed on the pigment particles. At low shear rates (Fig. 5), the addition of CMC produced a high relative viscosity, indicating a strong interaction between CMC and the pigment. At intermediate shear rate (Fig. 6), the colors containing PVOH showed a relative viscosity of the same magnitude as the CMC-containing colors. At high shear rate (Fig. 7), the PVOH colors displayed the highest relative viscosity. The relative viscosities of the colors containing starch also rose to a level comparable with CMC and higher than the synthetic thickeners. This behavior indicates that pigment interaction with PVOH or starch is different from that with CMC or the synthetic thickeners.

The interaction between the pigment and the various cobinders was studied using oscillation measurements to obtain the storage and loss moduli. The storage and loss moduli at 1 Hz vs. water-phase viscosity are shown in **Figs. 8 and 9**, respectively.

Figure 8 shows that the storage modulus of the colors containing CMC is an order of magnitude greater than the storage moduli of the other colors. This indicates a strong interaction between CMC and the pigment particles at small deformations. The high storage modulus may be due to a flocculation of the clay-CMC system. If so, then the flocculation structure appears to be strong enough to withstand the forces at low shear rates (as demonstrated by the oscillation measurements) but tends to break down as the shear rate increases (as seen in the previous figures).

Figure 9 shows that the colors containing CMC also had a high loss modulus, possibly the result of a breakdown of some of the "bonds" in the structure, thus giving a viscous instead of an elastic response. It has been proposed (*9*) that some coating colors can be regarded as a nonlinear viscoelastic material, i.e., a material whose elasticity is dependent on the degree of deformation. This nonlinearity may be due partly to the breakdown of the bonds in the structure as the shear rate increases. The oscillation measurements do not, however, explain the high relative viscosity at high shear rates for the coating colors containing PVOH.

It has recently been reported that the "elastic floc model" of Hunter (*13*) can be applied to clay-latex dispersions (*14*), and it is used in this study to model colors that also contain cobinders. The model is based on Bingham plastic flow behavior for the dispersions studied.

$$\tau = \tau_B + (\eta_p/\dot{\gamma})$$

where

τ = measured stress

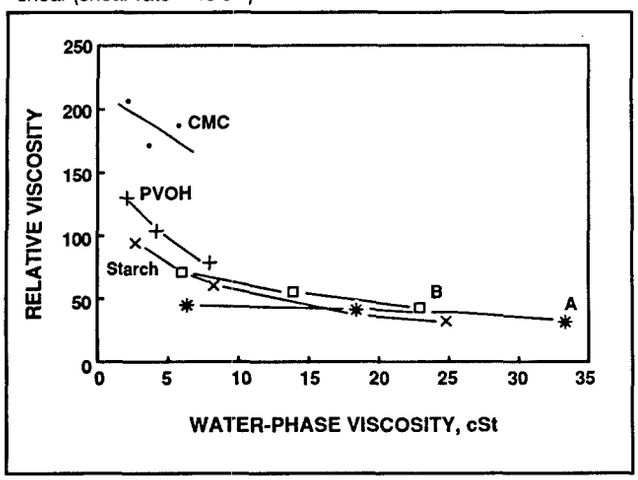
τ_B = Bingham yield stress

η_P = plastic viscosity

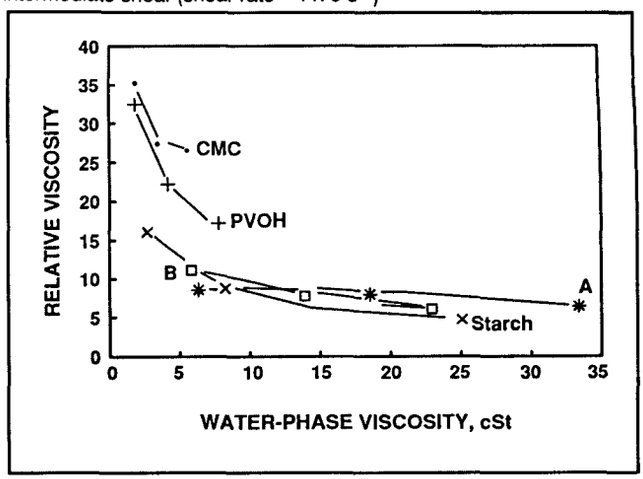
$\dot{\gamma}$ = shear rate

Above a certain shear rate, the shear stress varies linearly with shear rate over a relatively wide range of shear rate. After plotting shear stress against shear rate, the yield stress can be determined by extrapolating the linear region to zero shear rate. The

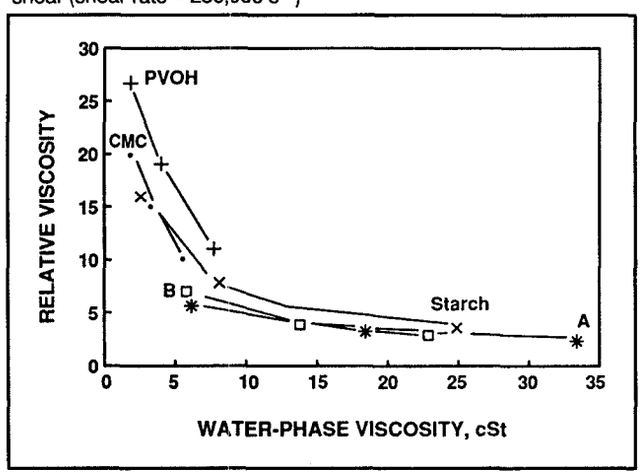
5. Relative viscosity as a function of water-phase viscosity at low shear (shear rate = 46 s^{-1})



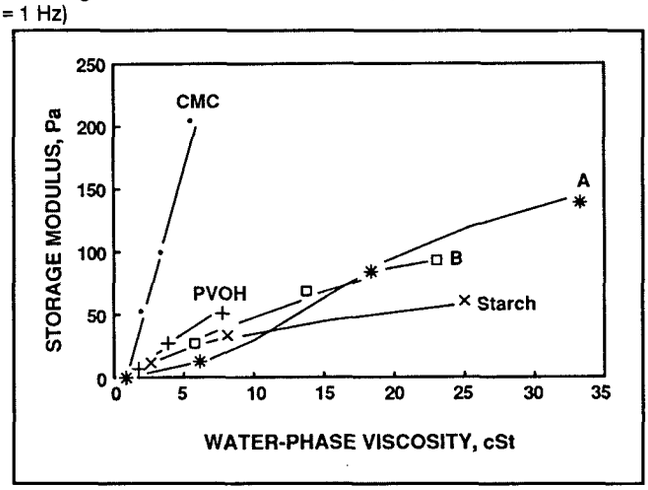
6. Relative viscosity as a function of water-phase viscosity at intermediate shear (shear rate = 1470 s^{-1})



7. Relative viscosity as a function of water-phase viscosity at high shear (shear rate = 250,000 s^{-1})



8. Storage modulus as a function of water-phase viscosity (frequency = 1 Hz)



plastic viscosity is given by the slope of the linear region.

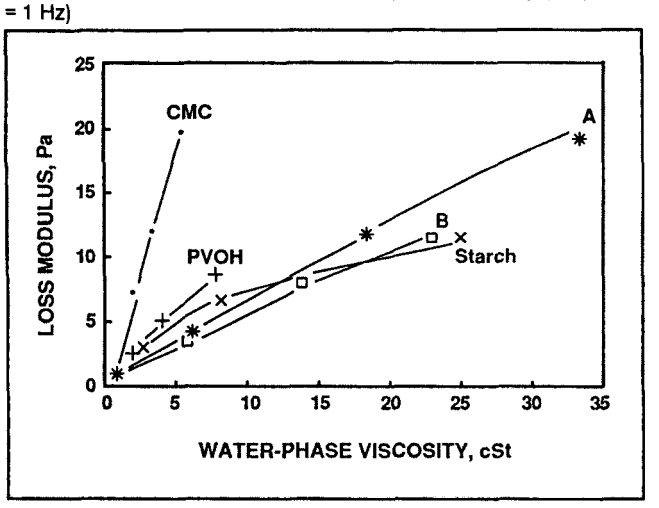
According to the elastic floc model, the plastic viscosity describes the size of structural units, called flocculi, that are able to trap some of the dispersing medium. The bonds in these flocculi are continually disrupted by the flow field, which also causes new contacts to occur, resulting in an equilibrium where the volume ratio of flocs and particles is constant. The yield stress reflects the interactive force in the dispersion at rest and is thus expected to correlate with the storage modulus.

The Bingham yield stress and plastic viscosity as functions of water-phase viscosity are shown in **Figs. 10 and 11**, respectively. The calculations were made using flow curves (shear-rate range 0-1470 s^{-1}). Yield stress for the colors containing CMC was found to be higher than for the other colors. This implies that more energy is required to get the CMC colors to flow, indicating that they have a stronger structure that must be broken down. Comparison of Figs. 8 and 10 shows the expected correlation between storage modulus and yield stress. A similar correlation has also been reported by Fadat *et al.* (*10*). Since the storage modulus and the yield value are both studied at very small deformations, and since both reflect the strength of the structure, a high storage modulus often predicts a high yield-stress value and vice versa.

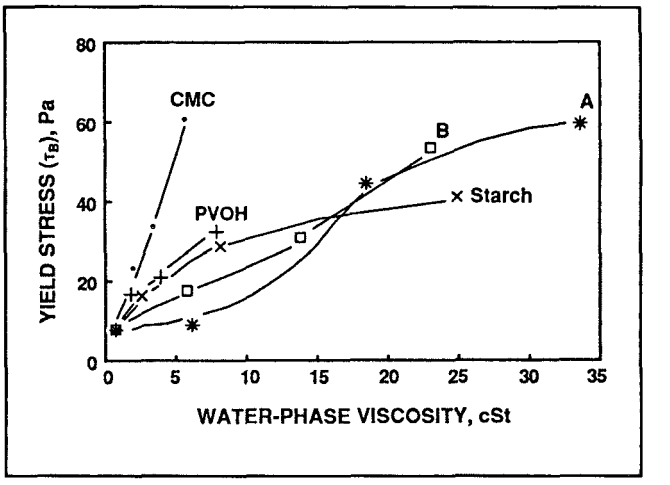
Plastic viscosity is high for both the CMC colors and the PVOH colors, as seen in Fig. 11. These colors are thus expected to be able to form relatively strong flocculi that can withstand shear forces at least up to a shear rate of 1500 s^{-1}. Since the storage moduli and the yield stress for these colors clearly differ from each other, it can be assumed that the interaction between CMC and the pigment is different from that of PVOH and the pigment.

The CMC colors have a strong three-dimensional structure at very low shear rates, which breaks down into relatively strong flocculi as the shear rate increases. The PVOH colors, on the other hand, have a weak, or no, macrostructure at very low shear rates but form strong flocculi that possibly could withstand even very high shear forces. This would explain the high relative viscosity for PVOH colors observed at 250,000 s^{-1}, as seen in Fig. 7. Since the relative viscosity of the CMC colors is lower than for the PVOH colors at 250,000 s^{-1}, and since the shear-thinning flow is more pronounced, it is possible that the CMC-clay flocculi tend to break down

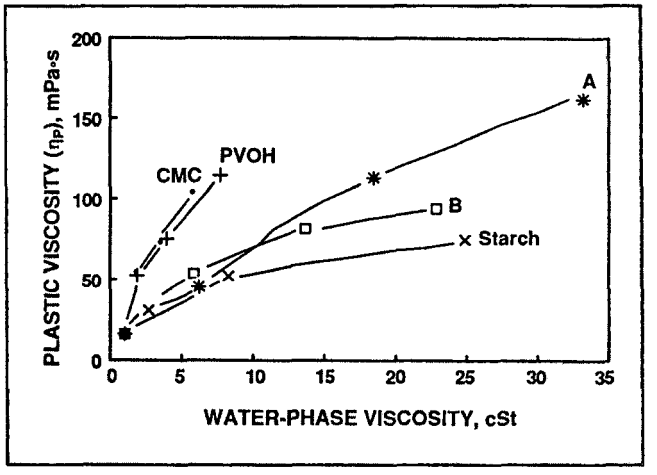
9. Loss modulus as a function of water-phase viscosity (frequency = 1 Hz)



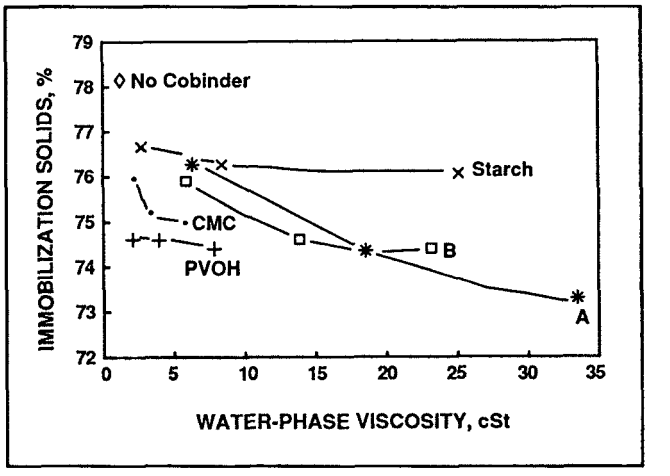
10. Yield stress as a function of water-phase viscosity



11. Plastic viscosity as a function of water-phase viscosity



12. Immobilization solids as a function of water-phase viscosity



more easily than the PVOH-clay flocculi.

The location of the CMC molecules in the flocculi structure is not clear, but it is likely that the aggregates are of a more open and loose structure than with PVOH. The high internal strength of the PVOH-clay aggregates suggests the possibility that the aggregates are held together by a bridging mechanism. PVOH is a nonionic molecule, but it has a high density of hydroxyl groups that are able to interact and even form hydrogen bonds with the silanol groups on the surfaces of the clay particles (*2*).

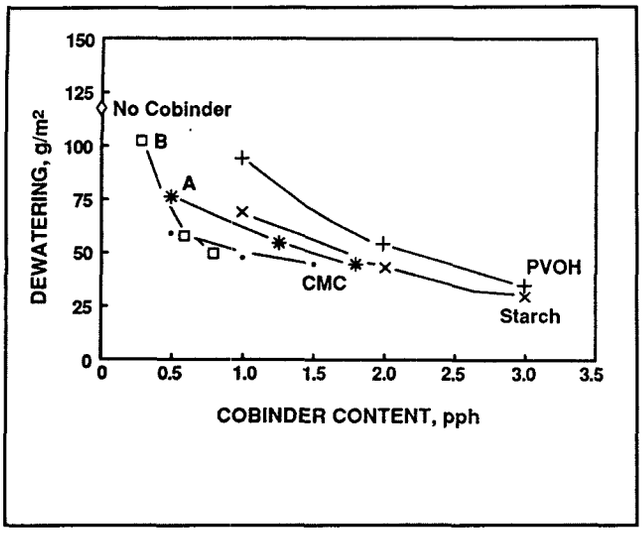
This may explain the observed differences in the rheological behavior of the CMC and PVOH coating colors. The CMC-clay interaction probably results in the formation, at rest, of a three-dimensional structure. As the shear rate increases, the structure breaks down into flocculi that are present up to at least 1500 s^{-1} but which break down at high shear rates. The PVOH colors, as noted, show no tendency to form a three-dimensional structure throughout the whole color system, since the yield stress and storage modulus values are relatively low. The relative and plastic viscosities, however, indicate the presence of relatively strong flocculi. The potentially high bond density between PVOH and clay particles can explain the strength of the PVOH-clay flocculi.

The degree of interaction between clay particles and the various cobinders seems to affect the immobilization-solids content of the colors, as shown in **Fig. 12**. The addition of CMC and PVOH lowers the immobilization solids noticeably more than the addition of starch. A strong interaction between the pigment particles and the cobinder often results in a less-ordered packing of the particles. The storage modulus, yield stress, and plastic viscosity of the colors with starch as cobinder (Figs. 8, 10, and 11, respectively) indicate a weak interaction between this type of starch and clay. This could explain the relatively high immobilization-solids level of the starch-containing colors.

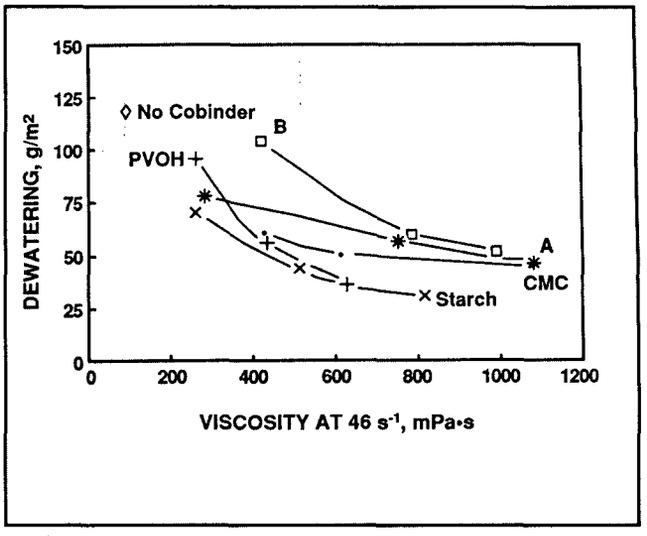
Immobilization solids were determined using the method described by Reinbold and Ullrich (*15*), i.e., gently stirring the color with a glass rod on an unglazed ceramic plate until the color immobilized and stuck to the rod. This method proved to be reproducible within tenths of a percentage point and can be used to study relative differences between different colors.

The degree of dewatering as a function of cobinder addition level is

13. Dewatering as a function of cobinder content



14. Dewatering as a function of viscosity at low shear (shear rate = 46 s^{-1})



shown in **Fig. 13**. It can be seen that all systems show increased water retention with higher cobinder addition levels. A practical upper limit for the addition level of cobinder as water-retention agent is, however, set by the coating-color viscosity. A better measure of the water-retention contribution of various cobinders is therefore obtained by comparing the degree of dewatering with the coating-color viscosity, depicted in **Fig. 14**. It can be seen that cold-water-soluble starch provides the lowest dewatering rate. This can be explained by low interaction between the starch and the pigment, leading to high water-phase viscosity and compact structure of the immobilized coating layer.

The water-phase viscosity and the structure of the immobilized coating layer at the paper-coating interface have been identified elsewhere as important factors in the dewatering mechanism (*16*). At low shear rates, PVOH also shows a low dewatering rate in relation to coating-color viscosity. At high shear rates, however, the PVOH is probably not an efficient water-retention agent, as evidenced by the low shear-thinning character of the PVOH colors. Not surprisingly, the synthetic cobinders, especially Thickener B, show high dewatering rates. This is probably a result of the relatively high degree of interaction between the pigment and the synthetic cobinders, indicated by the rheology measurements.

II. Coating formulations used in the pilot-coater study*

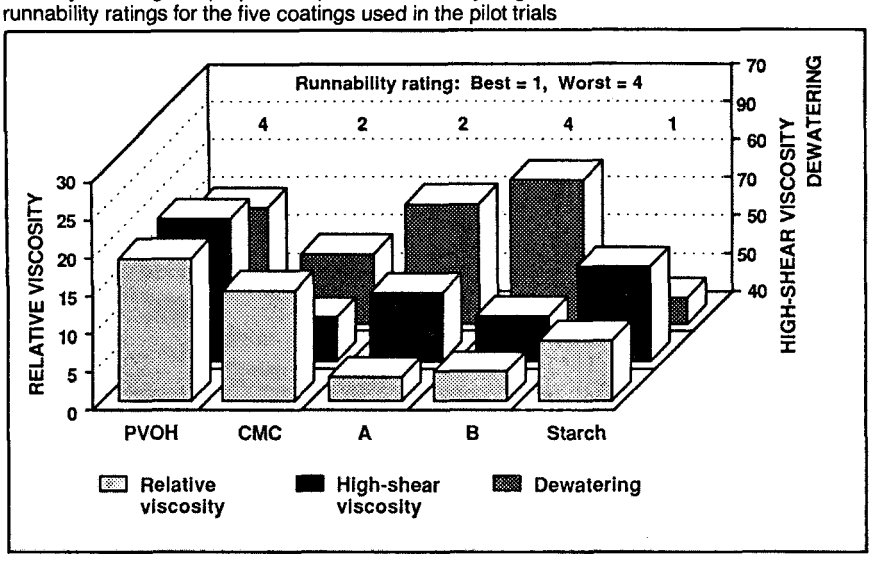
	CMC	*PVOH*	*Starch*	*Thickener A*	*Thickener B*
Cobinder content, pph	1.0	2.0	2.0	1.25	0.6
Solids content, %	59.8	60.0	60.4	60.0	60.5
Brookfield viscosity (at 100 rpm), cP	1620	1200	1250	2260	1600
pH	8.5	9.0	8.6	8.7	8.6
Coat weight, g/m²	11.8	11.0	11.1	11.1	11.2

*All formulations contained 100 parts English clay and 10 parts styrene-butadiene latex.

III. Blade runnability during pilot-coater trials

Cobinder	*Blade load*	*Blade runnability*	*Runnability rating (1 = best)*
CMC	11.8	Some dry and medium wet stalagmite formation	2
PVOH	24.0	Very strong dry and wet stalagmite formation	4
Starch	16.4	Minor dry stalagmite formation, some "pearling"	1
Thickener A	15.4	Some dry and medium wet stalagmite formation	2
Thickener B	12.6	Some dry and extreme wet stalagmite formation	4

15. Key rheological properties (relative viscosity, high-shear viscosity, dewatering) and runnability ratings for the five coatings used in the pilot trials



Pilot-coater trials

Further work with a pilot coater was carried out to explore the practical implications of the pigment-cobinder interaction and its effect on rheological and dewatering properties. The pilot trials focused on how the various cobinders influenced blade runnability and coated-paper properties.

Experimental

A wood-containing lightweight-coated-grade base paper was coated at a speed of 1200 m/min using the coating formulations listed in **Table II**. A flooded-nip application unit, with a blade angle of 35°, was used. The coating was dried using five infrared units followed by sufficient air-foil drying to obtain a final moisture-content target of 6%.

Although the low-shear viscosity for the various systems is somewhat higher than in the laboratory experiments, the differences between the systems reflect those observed in the laboratory environment. This suggests that the rheology, dewatering, and interaction data observed in the laboratory can be used to qualitatively characterize the coating colors used in the pilot-coater study.

Blade runnability was assessed visually during the trial by monitoring streaks as well as dry and wet stalagmite formation. In addition, the blade load required to achieve a coat weight of 11 g/m^2 was recorded. The paper properties were tested according to TAPPI test methods and other (*17*) procedures.

Results and discussion

Blade runnability. The runnability results for the various coating colors are summarized in **Table III**. A comparison between the runnability results and the previously discussed laboratory data shows no simple relationship. However, a simultaneous consideration of dewatering and rheological data, as shown in **Fig. 15**, provides insight into some of the reasons for the differences in blade runnability.

The favorable runnability achieved with starch is in line with the low dewatering value. The excellent water retention of the starch coating seems to compensate for the relatively high high-shear viscosity. The colors containing CMC or Thickener A were rated as providing moderate runnability. This is not surprising, since the laboratory results showed low-to-moderate values for dewatering and high-shear viscosity. Blade runnability was equally poor for the colors containing PVOH or Thickener B. However, the possible explanations for their poor performance are different. The unfavorable runnability of the PVOH color is probably explained by the very low shear-thinning character (high relative and high-shear viscosity), whereas Thickener B provided the lowest water retention of all systems under laboratory conditions.

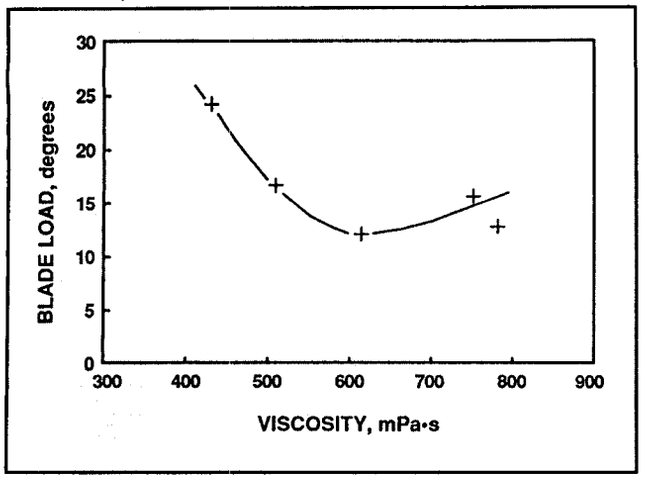
In summary, this study suggests that blade runnability is diminished by pigment-cobinder interactions that create strong, permanent structures at high shear rates. Blade runnability is also negatively affected by interactions that result in a high dewatering rate. These results thus support the previous findings of Hirsch and Laun (*18*), who recognized the need to include dewatering data as well as rheological measurements in laboratory prediction of blade runnability.

Figures 16 and 17 show the blade load required to obtain the coat-weight target as functions of low-shear and high-shear viscosity, respectively. Even though the theoretical relationship between viscosity and coat-weight development is extremely complex, the results seem to indicate that viscosity measurements at low shear rates provide only limited information regarding the required blade load. The high-shear viscosity, however, shows good linear correlation with the required blade load. Again, this suggests that the ability of the interaction-induced structure in a coating color to withstand shear has a significant influence on the practical coating process. Clearly, it is important to measure rheology at high shear when evaluating the effect of pigment-cobinder interactions on the industrial coating process.

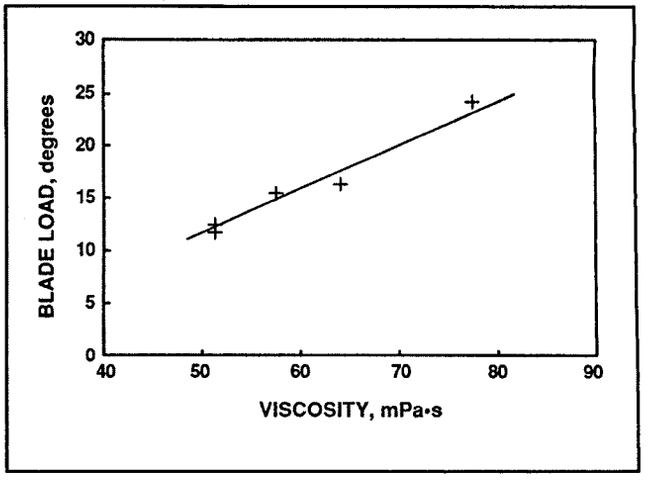
Surface properties of coated papers. Key surface properties of the papers coated on the pilot machine are listed in **Table IV**. The results are in line with the influence the various cobinders are generally thought to have on the properties of a coated paper. A comparison between the paper properties and the interaction data obtained in the laboratory provides some additional explanations for the differences in paper properties.

The very high values for dry- and wet-pick resistance for the PVOH system are probably related to the strong pigment-PVOH interaction observed in the wet coating color. Starch was found to have a low interaction with the pigment and hence to provide high immobilization solids. This results in a compact coating structure and may thus contribute to the high ink gloss and

16. Required blade load as a function of viscosity at low shear (shear rate = 46 s^{-1})



17. Required blade load as a function of viscosity at high shear (shear rate = 250,000 s^{-1})



ink set-off values. A characteristic property of the synthetic-thickener-coated papers seems to be a high coating porosity, leading to improved rotogravure printability (heliotest). The low immobilization-solids and reasonably high storage-modulus values for the synthetic binders (Table I) indicate that the good heliotest performance is probably a result of the high degree of interaction in the coating-color system at the low deformation rates after the blade.

IV. Surface properties of pilot-coated papers

	CMC	PVOH	Starch	Thickener A	Thickener B
Brightness, %	69.6	70.4	69.9	70.1	70.6
K & N, %	7.3	6.5	5.3	6.4	8.4
IGT, cm/s	36	43	38	16	36
Heliotest, mm	17	18	15	21	22
Wet pick, %	43	26	64	59	70
Ink set-off, s					
15	0.87	0.88	0.96	0.64	0.39
30	0.68	0.84	0.82	0.48	0.32
60	0.32	0.50	0.58	0.21	0.11
120	0.08	0.26	0.23	0.04	0.02
Ink gloss, g/m²					
0.8	76.0	81.5	85.1	76.7	78.5
1.6	83.5	82.7	87.4	82.5	83.3
3.5	86.9	88.5	90.0	87.9	86.2

Conclusion

A study of the influence of pigment-cobinder interaction on rheology, dewatering, and coating performance showed that the cobinder had a profound effect on the rheology of the coating colors. No single rheological property can adequately describe the type and extent of the interaction or predict the size and strength of the aggregates formed in the colors. However, several conclusions can be drawn by combining rheology data obtained at low, intermediate, and high rates of shear. The five cobinders used in this study can be divided into three main categories:

Category I (CMC, Thickeners A and B). Cobinders in this category show a high interaction with the pigment, forming a strong three-dimensional structure at low shear rates. At low viscosity, the colors show a high stiffness and high relative viscosity. As the shear rate increases, the structure is broken down into individual aggregates or flocs. The strength of these flocs is not, however, sufficient to withstand the shear forces at high shear rates, giving the colors a pronounced shear-thinning behavior. The immobilization-solids level is reduced by the interaction, i.e., by the formation of aggregates.

Category II (PVOH). Cobinders in this category also show a high interaction with the pigment, but it does not lead to formation of a three-dimensional structure at low shear rates. However, strong individual aggregates are formed with enough strength to keep the colors aggregated up to very high shear rates. Coating colors containing this type of cobinder thus have a less-pronounced shear-thinning nature. As in the case of Category I cobinders, the immobilization-solids level is reduced by the interaction.

Category III (starch). Cobinders in the third category show at most only weak interaction with the pigment. The rheology is thus mainly that of the pigment dispersion and the cobinder solution. The shear-thinning behavior is less pronounced than for Category I cobinders, since there is no structure to be broken down. The immobilization-solids level is not noticeably lower than that of the color without cobinder.

From the pilot coater trials, it was apparent that simultaneous consideration of laboratory dewatering and rheological data can be helpful in explaining differences in blade runnability. Formation of strong aggregates in the coating color causes excessive high-shear viscosity, which has a negative influence on runnabil-

ity. Poor water retention also diminishes blade runnability.

The pilot trials also showed a good correlation between the high-shear capillary viscosity and the required blade load. In addition, it was found that the pigment-cobinder interaction affected coated-paper properties.

It can be concluded that the interaction between pigment and cobinder has a major influence on coating rheology and, thus, on blade runnability and coated-paper properties. Laboratory techniques and measurements can be useful in predicting commercial performance as well as increasing the knowledge of the complex rheology of coating colors.□

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