The Effects of Carboxymethyl Cellulose and Polyacrylate on Coating Rheological Properties

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THE EFFECTS OF CARBOXYMETHYL CELLULOSE AND POLYACRYLATE ON COATING RHEOLOGICAL PROPERTIES

by

Tom Eugate Jr.

Advisor: Dr. Scheller and Dr. Janes

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ABSTRACT

The purpose of this thesis was to analyze and report rheological behaviors of a base coating formulation that will be altered by Carboxymethyl Cellulose (CMC) and polyacrylate and subjected to defects in the blade on a coating system. The coating formulations consisted of Hydrasperse clay, Dow 620-A SBR binder, and water. The control formulations will be at 58% and 63% solids. CMC and polyacrylate will be added to the coating formulations at 0.5 and 1.5pph, and 0.1 and 0.4pph based on parts dry pigment. A total of 10 formulations were ran on the Cylindrical Laboratory Coater (CLC). A defect was placed in the blade 0.4mm. wide and .25 mm. This was done to measure healing ability. High and low shear viscosities of the 10 formulations were tested using the Hercules and Brookfield viscometers. Water retention of the color was measured using the Abo Akademi Water Retention meter. A stylus profilometer was used to analyze the shapes of the defects in the dried coating. The image analyzer in the Western Michigan University Engineering Department was also be used to analyze the characteristics of the defects in the dried coating. Final properties such as gloss, opacity, Parker Print Roughness, and Parker Print Porosity were tested using the instruments in the pilot plant at WMU. Correlations were made between color rheology and water retention as affected by CMC and polyacrylate, the healing ability of the coating as affected by CMC and polyacrylate, and the solids levels of the color and addition amounts of CMC and polyacrylate to rheology, water retention, and healing ability of the coating.

It was determined that CMC raised Brookfield and Hercules viscosity considerably more than polyacrylate. Polyacrylate showed low Brookfield viscosities. It was shown that water penetration decreased as viscosity increased. CMC illustrated better water retention than polyacrylate. Healing ability showed to be dependent upon viscosity and viscosity offset water penetration effects. Increasing solids content increased viscosity and water retention and decreased healing ability. Flow modifier addition decreased gloss and porosity and increased roughness. An increase in solids to 63% increased gloss and decreased porosity. Brightness and opacity were unaffected by additives.
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INTRODUCTION

At present, blade coating is the predominant method of paper coating used in the paper industry. With trends of increasing coater speeds and lighter coat weights being applied, the importance of coater performance becomes even more critical.

Many properties of the coating color are very important to the performance of a blade coating system. To provide good coating quality the flow characteristics, or rheology, of a coating dispersion must be understood. To quantify color rheology, viscosity and water penetration of dispersions must be considered. In turn, rheological properties affect coater performance, or runnability.

The objective of this study will be to analyze the effects that different flow modifiers have on a control coating formulation when added in varying amounts at different coating color solids contents.

A clay-latex color will be used as the control formulation. Carboxymethyl Cellulose (CMC) and polyacrylate will be used as flow modifiers. The Cylindrical Laboratory Coater (CLC) will be used to apply the coatings to the base sheet. A defect will be implemented into the blade in order to assess healing ability. Although the defect will be larger than the defects on an actual coater they will give insight to the levelling characteristics or healing ability of the color.

By varying solids contents and addition amounts of flow modifiers a correlation between coating rheology, levelling, water retention, and final coated properties of the sheet will be made. Correlations will be made between: (1) color rheology and water retention as affected by CMC and polyacrylate, (2) the healing ability as affected by CMC and polyacrylate, and (3) solids levels of the color and addition amounts of CMC and polyacrylate to rheology, water retention, and healing.
BACKGROUND

The blade coating operation involves the application of coating color and metering away the excess with a blade. To understand the performance of a blade coating system, it is necessary to examine what affects blade coating. Coating color rheology and water retention and how these are affected by additives will be discussed in this portion of my thesis.

COATING COLOR RHEOLOGY

Coating colors are suspensions of minerals(pigments), binder particles, additives, and water. The rheology of a coating is affected by the pigment, additives, binder, and the total solids of the coating color. When the rheology of a color becomes 'poor' it will have a detrimental effect on coat quality(1).

Viscosity, which is defined as the ratio of the shearing stress to the rate of shear applied to a given fluid, can be used as an indicator of rheology. This ratio is not constant for coating colors at different shear stresses and the colors apparent viscosity should be considered. Apparent viscosity is the ratio of shearing stress to rate of shear at a given point on its respective viscosity curve(2). From this it can be said that viscosity tests are limited in their application to industrial coating processes. The reason being that no known viscometers can simulate shear rates as high as those found on high speed coaters. They do, however, give a good indication of rheology.

Rheology of coating colors determines how they will behave on the coater. Rheology characteristics obtained from viscosity tests can be used to predict coater performance. For reasons stated earlier, however, they cannot be used to make absolute predictions. Many factors affect coater runnability. Some of these factors are: pigment size, shape, and distribution, and surface porosity and internal pore size of the pigment particles. Together all these factors play a role in how a coating releases its water during application(3). These factors affect the
immobilization point of the coating which is the point where the color solids attach to the base sheet.

The mixing order of ingredients in the coating formulation has an affect on its rheological properties. It was found that by mixing the same ingredients in different orders, it was possible to produce coating colors with totally different characteristics. Different structures were created just by changing the mixing order of the ingredients.

It is important to keep the pH of the formulation above 8.0 to prevent such problems as pigment shock. Pigment shock occurs from the adverse interactions of the ingredients in the coating formulation.

WATER RETENTION

Water retention is an important parameter affecting the runnability of a blade coater. Water retention is the ability of the coating formulation to retain its water without releasing it into the base sheet immediately after application. If water loss occurs into the sheet the binder will drain from the color. Coating formulations with low water retention may demonstrate patterning after application caused by rapid loss of water into the sheet. Surface smoothness may also suffer.

If water retention is poor there will be an increase in coating solids momentarily after application. With coatings of initially high solids, the coating film splits as the web leaves the applicator roll. This is caused by the increase of solids near the web resulting in an increase in resistance to flow.

Coating color rheology changes when water starts penetrating into the base sheet making rheology and water retention interdependent.

Binders affect water retention of a coating color. Various binders are used in the coating
process. They are: starch, synthetic latexes, and proteins. By using a larger amount of latex, the viscosity of the color at high solids can be reduced and a higher quality printing surface can be obtained. By increasing the amount of latex in the coating, the water retention of the coating is reduced(8). Protein and starch binders exhibit good water holding ability(6).

Various water-soluble polymers can be used to modify or increase water retention of a coating color. Some of theses polymers are: Carboxymethyl Cellulose, polyacrylates, sodium alginate, and starches. These polymers increase the viscosity of coating colors by forming flocculated or bridged structures with pigments and binders. This causes an increase in the water retention of the coating formulation.

**RHEOLOGY MODIFIERS**

The rheology of a coating formulation can be modified by the use of additives. Generally, these additives are used to increase or decrease the viscosity of the color(1). Rheology modifiers are mostly chemical flow modifiers which are added to coatings to control the viscosity of binders and regulate the flow and water retention of the coating formulation. By using flow modifiers a wider variety of coating formulation can be used on a single coater.

If the viscosity of the color is too low it can hinder optimum performance on the coater. A viscosity increasing modifier would be used to raise color viscosity. Several types of viscosity increasing agents are available. There are polyfunctional amines which act upon pigment, water-soluble natural or synthetic polymers which increase the viscosity of the aqueous phase of the color, and alkali-swellable latexes which combine the functions of binder and viscosity control. Each modifier has its own characteristics which must be accounted for when choosing it for use in a formulation. For reasons concerning this project, only water-soluble polymers will be discussed.
Also, when selecting a viscosity increasing flow modifier, water retention must be considered. Not all viscosity-increasing agents or thickeners are effective water retention agents. This is important because a certain amount of water retention is required, especially for formulations containing all latex binders and high solids, to provide high coat quality and good runnability(1). At high solids levels, if water is lost the application process may become quite difficult.

WATER-SOLUBLE POLYMERS

Sodium carboxymethyl cellulose (CMC) and sodium and ammonium polyacrylates are two common, water-soluble, high molecular weight polymers available to increase the viscosity of coating colors.

The water-soluble polymers increase the viscosity of the aqueous medium, and are generally effective in increasing the water retention of the coating. The polymers are available in various grades based on the molecular weight and degree of substitution of the polymer. Polymers of higher molecular weights are better thickening agents and require closer control of addition amount for a given viscosity increase. Also, since there is a lesser amount of a higher molecular weight polymer in the formulation, any degradation from shear tends to have a greater effect on the viscosity than with the lower molecular weight polymers. Larger amounts of lower molecular weight polymers provide easier control of the viscosity, better viscosity stability, and better water retention, but may impinge on the coated sheets ink holdout and porosity(1).

Water-soluble polymers each have different effects on color rheology, their sensitivity to pH, their compatibility with coating ingredients, and their susceptibility to bacterial attack(1).

NATURAL THICKENERS

Carboxymethyl Cellulose is a natural thickener. Its thickening ability is attributed to its
long polymer chains entangling and filling interparticle spaces. Natural thickeners are polysaccharide derivatives, with anhydroglucose units each containing three reactive hydroxyl groups. Substitution occurs by carboxymethyl groups at the hydroxyl groups. Because CMC contains negatively-charged carboxyl groups, this polymer tends to become surrounded by positive ions, which repel each other and straighten the chain backbone. This causes the cellulose chain to enlarge, giving space-filling capacity. The longer the polymer chains are, the greater the viscosifying power. This has a large effect on low shear viscosity.

POLYACRYLATES

Polyacrylates are sodium salts of polyacrylic acids. They are alkali-soluble synthetic polymers. The polyacrylate polymers are made by copolymerization of methacrylic acid and esters of methacrylic acids. The properties of the polyacrylates depend on the choice of the ester co-monomer, the acid/ester ratio, and the degree of cross-linking. Water solubility of these groups depends on the number of carboxylic groups present.

The properties of polyacrylates are similar to those of CMC.

COATER PERFORMANCE

Many factors affect blade coater runnability. Many studies have been done in the past to attempt to show correlation between rheology and coater performance. Rheology is strongly dependent on the microscopic state of the coating formulation. Various rheological tests have explained interactions in the coating color. Flow behavior of the color is complex. Factors contributing to this are: size and shape of pigment particles, pigment particle-to-particle interactions, solids content, and the shear-induced packing ability of the particles. The degree of interaction and strength of structures affect the rheological properties of coatings. Low values of viscosity are explained by weak pigment-polymer interactions and a low degree of structure
formation in the suspension. Low values of immobilization of solids demonstrates a strong pigment-cobinder interaction.

A mathematical model, developed by Turai(12), for the mechanism of coating streaks states: if the coating slurry loses water, and the clay concentration exceeds 70%, the clay will flocculate out of the slurry and clay particles can get lodged between the blade and streaks in the coating will occur from this. This is an example of the deleterious effect of poor water retention.

Sandras and Salminen(13) studied the effect of pigment-cobinder interactions and their impact on coating rheology, dewatering, and performance. They found that CMC and thickeners showed high interactions with the pigment, forming strong structures at low shear viscosity. As shear rate increases, the structure is broken down into individual aggregates or flocs. At high shear rates, these flocs give the color a pronounced shear thinning behavior. It was their opinion that the aggregates cause excessive high shear viscosity, having a negative effect of runnability. Runnability also diminishes with low water retention.

It was shown by Engstrom and Rigdahl(14) that defects may occur from the inability of a coating color to spread after the blade because elasticity slows levelling of the coating. Drying will freeze the defects on the sheet. This states the importance of healing in a blade coating system.

EFFECT of COATING RHEOLOGY on OPTICAL and SURFACE PROPERTIES

Pigments are porous and exhibit a large influence on a coatings optical and absorbency properties. Many variables influence the structural properties of a coating. These variables are: the size and distribution of pigment particles, orientation of the pigment particles, and addition level and type of binder used(15).

The most important property of a coated sheet is porosity. It affects ink absorption, water
absorption, and light scattering of the coating. Light scattering of the color affects opacity and brightness of the coated sheet. Porosity of the pigment is determined by the density of the pigment particles, particle size and shape, distribution of pigment particles, and binder level addition. Water retention also affects porosity.

Gloss of a coating is a measure of optical smoothness of the surface of the coated sheet. As pigment interaction increases, smoothness will suffer. Gloss is dependent on coating shrinkage, which causes microroughness. Shrinkage is influenced by the type and level of binder addition. It has been shown by Lee(16) that nonuniform shrinkage of the coating causes a reduction in gloss.

With a formulation containing clay, styrene butadiene latex, and CMC, Eklund(17) showed that gloss decreases with increased solids content. He suggested that this may be from a lower degree of orientation of the clay platelets during high solids application.

PREVIOUS WORK

Doug Bousefield, from the Chemical Engineering Department at the University of Maine, developed a model that correlates to leveling of a coating color. He concluded that the healing rate of a coating is dependent upon the rate of water penetration into the sheet. This model was not backed by in-depth testing so it could not be taken as 'absolute'.

Shambu Nath, a graduate student at Western Michigan University in 1994, did an in-depth project concerning the healing ability of coatings. He concluded that healing was dependent upon viscosity and viscosity offset effects of water penetration.

Conclusive data has not yet been established with concerns to the healing ability of coatings.
EXPERIMENTAL DESIGN and PROCEDURES

A wood-free base sheet was coated using the coating formulations shown in Table 1. All the coatings were tested for Brookfield viscosity, Hercules viscosity, and water retention.

Table 1
Coating Color Formulations

| Hydrasperse #2 clay - 100 parts |
| Dow 620-A SBR Latex Binder - 12 pph |
| Alcogum L-29 Polyacrylate - 0.1 pph |
| Alcogum L-29 Polyacrylate - 0.4 pph |
| Finnfix CMC - 0.5 pph |
| Finnfix CMC - 1.5 pph |

Coating formulations were prepared at 58 and 63% solids levels, and all the coatings were ran at 610 m/min. A defect was implemented into the blade to measure healing ability.

Coated paper was tested for the following properties: roughness (Parker Print Surf), porosity (Parker Print Surf), opacity, brightness, gloss, streak width, and slope of the streak.

Preparation of Coating Color

Hydrasperse #2 clay was dispersed at 72% solids without additional dispersant for 20 minutes. The dispersion was left at room temperature overnight. The proceeding morning the slurry was redispersed and cut into five equal parts approximately 2000 grams each. Dow 620-A SBR latex was added at 12 pph based on dry pigment. All coatings were prepared at 63% solids, ran on the CLC, and then diluted to 58% solids and ran on the CLC. Alcogum L-29 polyacrylate and Finnfix CMC were added to the coating color at 0.1 and 0.4 pph polyacrylate addition and 0.5 and 1.5 pph CMC addition. Coating pH was maintained just above 8.0 by addition of NaOH.
Coating Color Analysis

The coating colors were tested for viscosity at different shear rates by the following equipment.

**Brookfield Viscometer**

The viscosity was measured by submerging a rotating spindle into a color sample at 10, 20, 50, and 100 rpm. Brookfield viscosity is a measure of viscosity at low shear rates.

**Hercules Viscometer**

The Hercules viscometer is a cup and bob viscometer. Viscosity was measured using the E-bob at 4400 rpm with a ramp time of four seconds using the DV-10.

**Abo Akademi Water Retention Meter**

The principle for this testing procedure is based on a measurement that involve measurement of the quantity of water passing through a filter into an absorbing paper during controlled contact time and pressure.

The measuring instrument consists of a cylindrical metal tube into which the color sample is poured (approximately 10ml). The bottom of the tube is covered with a Milipore filter of pore size 5 microns and a Whatman 17 chr filter paper which is pressed against a rubber plate. The top of the tube is capped with a cover. An external pressure of .3 atmospheres is put into the tube which extracts the coating color through the filter and into the paper. The cover is removed after a set amount of time and the Whatman filter paper now containing water is weighed. The difference in pre-test to post-test weight is multiplied by 1250 to achieve water penetration as g/m².
Cylindrical Laboratory Coater

The CLC was used to apply the coatings at 9g/m² with a range of 1.5g/m². Coatings were applied at 610m/min to a wood free base sheet. Base sheet properties are given in Appendix 1. Blade run-in to maintain the required coat weight was recorded. Coat weight was measured using the microwave technique.

The CLC applies coating to the sheet in a helical pattern from a traversing head. It has been designed for a maximum speed of 1800m/min. It is accepted by industry for the study of coatings. The normal sequence of coating run is: tape paper to the drum, place the pond in the carriage and lock it in position, and fill the pond with coating. Close and lock the cover latch. After closing the cover latch the drum will gradually reach set speed. Depress start button and coating application begins. The paper will now be preheated, coated, and dried.

Induction of Blade Defect

A scratch of 0.4mm wide and .25mm deep was induced into the blade using a triangle file. The width of the resulting streak on the coated sheet could be measured for healing characterization.

Stylus Profilometer

This instrument was used to characterize the profile of the coating surface. A highly sensitive probe traversed the surface of the coated sheet and printed an image consistent with the surface profile on a grided sheet. From this grid, streak width could be measured because the grid blocks were uniform and of set value.

Image analyzer

The image analyzer is a powerful microscope that profiled a minute point on the streak in the coating. From the profile, the slope of the ridge in the streak could be measured and correlated to healing.
RESULTS AND DISCUSSION

Effect of Flow Modifiers on Color Rheology and Water Penetration

Viscosity of coatings at low shear rate and high shear rate was measured with the Brookfield and Hercules viscometers. The effect of polyacrylate and CMC addition on Brookfield viscosity for different coatings at 58% solids is shown in Figure 1. PA 0.1 and PA 0.4 showed the lowest viscosity, while CMC 0.5 and CMC 1.5 showed the highest viscosity. The reason for this is because of the better thickening ability of CMC at low shear viscosities. Brookfield viscosity at different rpm's is shown in Appendix 2.

![The Effects of Flow Modifiers on Brookfield Viscosity](image)

Figure 1. Effect of Flow Modifiers on Brookfield Viscosity at 10 rpm (@58% Solids).

Figure 2 shows the effect of flow modifier addition on Hercules viscosity at 4400 rpm. PA 0.1 and PA 0.4 showed the lowest viscosities and CMC 0.5 and CMC 1.5 showed the highest. CMC demonstrates a high level of interaction with the pigment particles, higher than that of polyacrylate. After exposure to high shear, the structures formed from thickeners and pigment are broken down into aggregates causing excessive high shear viscosity. It can be said that CMC interacts more with the pigment.
Figure 2. Effect of Flow Modifiers on Hercules Viscosity (@58% Solids).

Figure 3 shows the effect of flow modifier addition on water penetration as measured with the Abo Akademi water retention meter. CMC 0.5 and CMC 1.5 showed the lowest water penetration and PA 0.1 and PA 0.4 showed the highest water penetration. Note that water penetration is inversely proportional to water retention. It is clear the CMC gives the best water retention. Again, this agrees with CMC forming stronger flocculated or bridged structures with pigments. By doing this, viscosity is raised in the aqueous phase of the formulation. The increased viscosity causes the formulation to hang on to its water. Appendix 3 shows the effect of flow modifier addition on Hercules viscosity.

Figure 4 shows water penetration as a function Hercules viscosity. Water penetration decreased as the viscosity increased for all the flow modifiers. CMC showed the lowest level of water penetration (highest water retention). The data corresponds with the theory that as viscosity increases water retention increases. Appendix 4 shows the effect of flow modifiers on water penetration.
The Effects of Flow Modifiers on Water Penetration

Figure 3. Effect of Flow Modifiers on Water Penetration (@58% Solids).

Water Penetration as a Function of Hercules Viscosity

Figure 4. Water Penetration as a Function of Hercules Viscosity (@58% Solids).

Figure 5 shows blade run-in needed to maintain target coat weight as a function of Hercules viscosity. Blade run-in is the distance the blade is from the backing roll on the coater. In theory, blade run-in should increase with increasing viscosity. The graph shows blade run-in to lie on a straight line even as viscosity increases. Polyacrylate may demonstrate the same run-in as CMC because of its lower water retention values, causing immobilization of solids sooner and forcing the blade away from the backing roll.
Figure 5. Blade Run-in as a Function of Hercules Viscosity (@58% Solids).

Figure 6 shows the run-in needed as a function of water penetration. Run-in is expected to increase as water penetration increases because immobilization of solids increases the viscosity of the color under the blade and forces the blade away from the backing roll. The data contradicted this expected behavior. Appendix 5 shows the effect of flow modifiers on blade run-in.

Figure 7 shows streak width as a function of Hercules viscosity for all flow modifiers. Streak width was measured using the Stylus Profilometer, which was discussed in the Experimental Design and Procedures section. The addition of flow modifiers caused a decrease in streak width. As the viscosity of the modifiers increased, streak width decreased. Note that a larger streak width denotes better healing. The control showed the best healing followed by the polyacrylates and CMC. This figure illustrates that flow modifiers have a negative effect on healing. Water penetration was thought to play a major role in the healing ability of coating formulations. This data contradicts the theory and implies that viscosity offsets the effect of water penetration and plays the major role in healing.
Figure 6. Blade Run-in as a Function of Water Penetration (@58% Solids).

Figure 7. Streak Width as a Function of Hercules Viscosity (@58% Solids).

Figure 8 shows streak width as a function of water penetration. As the water penetration decreases, streak width decreases. Control showed the highest degree of healing followed by PA 0.1 and PA 0.4, and CMC 0.5 and CMC 1.5, respectively. This data indicates that viscosity plays a larger role in healing than water retention. This reasoning is based on the fact that at low water retentions, immobilization of solids occur quicker. Thus, the coating would be impaired from
healing. The data does not agree with this so viscosity must play the major role in healing.

![Streak Width as a Function of Water Penetration](image)

Figure 8. Streak Width as a Function of Water Penetration (@58% Solids).

Figure 9 shows the slope of the ridge in the center of the streak as a function of Hercules viscosity. An Image Analyzer was used to plot the profile of a small portion of the streak near its center. Note that slope is inversely proportional to healing. The control demonstrated the best healing ability, followed by PA 0.1, PA 0.4, CMC 0.5, and CMC 1.5, respectively. This was expected because of the correlation to differences in viscosity between the formulations. The lowest viscosities showed the best healing ability. This method of analysis for healing correlated well to streak width.

Figure 10 shows slope as a function of water penetration. From this figure, PA 0.1 and PA 0.4 showed better healing than CMC 0.5 and CMC 1.5. CMC 0.5 and CMC 1.5 showed similar healing. As mentioned earlier, water retention doesn't seem to play as major of a role in healing as viscosity does. This plot verifies that. See Appendix 6 for effect of flow modifier addition on healing.
Effect of Flow Modifiers on Optical and Surface Properties

Figure 11 shows the effect of flow modifier addition on gloss. From this figure, it can be said that gloss decreases with the addition of flow modifiers. This is because flow modifiers bridge to pigment particles forming structures that increase viscosity. After the coating is applied, shrinkage of the structures occurs upon drying causing microroughness on the coating surface.
Increasing microroughness will decrease gloss. See Appendix 7 for effect of flow modifier addition on optical and surface properties.

**The Effects of Flow Modifiers on Gloss**

Figure 11. The Effect of Flow Modifier Addition on Gloss (@58% Solids).

Figure 12 shows gloss as a function of Hercules viscosity. It is illustrated that as viscosity increases there will be a reduction in gloss. This holds true from the reasoning stated just above. Note that polyacrylate demonstrated higher gloss values than CMC.

Figure 13 illustrates Parker Print Roughness as a function of Hercules viscosity. Roughness increased as viscosity increased. CMC 0.5 and CMC 1.5 showed higher roughness values than PA 0.1 and PA 0.4. This is expected because CMC demonstrated the highest viscosities, which correlates to high structure forming and shrinkage.

Figure 14 is a plot of Parker Print Porosity as a function of Hercules viscosity. Porosity decreased as viscosity increased. PA 0.1 had the highest porosity and CMC 1.5 had the lowest porosity. The level of pigment and additive interaction is related to viscosity. As addition levels are increased the thickeners entangle pigment particles, increasing viscosity and diminishing void space in the structures. Thus, as viscosity increases porosity will decrease.
Figure 12. Gloss as a Function of Hercules Viscosity (@58% Solids).

Figure 13. Parker Print Roughness as a Function of Hercules Viscosity (@58% Solids).

Brightness and Opacity did not change appreciably with flow modifier addition. Brightness decreased slightly, but not observable trend was noticed. Opacity did the same.
Figure 14. Parker Print Porosity as a Function of Hercules Viscosity (@58% Solids).

**Effect of Solids Levels on Color Rheology and Water Penetration**

Figure 15 shows the effects of solids levels on Brookfield viscosity. An increase in solids levels caused an increase in viscosity. CMC 1.5 showed the highest viscosity while CMC 0.5, PA 0.4, and PA 0.1 respectively, had lower viscosities. CMC 1.5 and PA 0.4 showed to be most affected by the increase in solids content. It is surprising that PA 0.4 was more sensitive to solids content than CMC 0.5, but PA 0.4 still demonstrated a lower viscosity. The increases in viscosity can be largely attributed to pigment-pigment interaction.

Figure 16 shows the effect of solids levels on Hercules viscosity. CMC 1.5 had the highest viscosity and showed the largest increase, from 58-63% solids, of all the modifiers. Upon the increase in solids content, the controls viscosity increased considerably. A good deal of the viscosity increase can be attributed to pigment-pigment interaction or shear at the higher solids content. It can also be stated that the CMC demonstrated better thickening or entanglement of the pigment particles causing an increase in viscosity of the aqueous phase of the formulation.

Figure 17 shows water penetration as a function of Hercules viscosity at different solids levels. As solids increase, viscosity increases and water retention increases. Note that as water penetration increases, water retention decreases. It should be observed that CMC 1.5 had a viscosity increase of over 100%, but its water retention increased by only 19%. The polyacrylates
showed larger increases in water retention than did CMC upon solids increases. It may be concluded that water retention does not change linearly with respect to viscosity. Note that Hercules viscosity is not plotted on a linear scale. This figure was shown to illustrate a trend on a general basis.

Figure 15. Effect of Solids Levels on Brookfield Viscosity.

Figure 16. Effect of Solids Levels on Hercules Viscosity.
Figure 17. Water Penetration as a Function of Hercules Viscosity at Different Solids Levels.

Figure 18 shows water penetration as a function of Hercules viscosity at different solids levels using a point graph. This figure is similar to Figure 17 except that Hercules viscosity is plotted on a linear scale. This shows a better correlation between solids levels. Bold print denotes 63% solids.

Figure 18. Water Penetration as a Function of Hercules Viscosity at Different Solids Levels.
Effect of Solids Levels on Coater Performance

Figure 19 illustrates blade run-in as a function of Hercules viscosity at different solids levels. Note that bold print denotes 63% solids. From 58 to 63% solids, the amount of run-in needed to hit target coat weight increased two-fold. This can be explained by reasoning that at higher viscosities blade pressure can be reduced because the pressure exerted on the blade by the color increases. Note that all flow modifiers demonstrated similar run-in. At lower viscosities, water penetration causes immobilization of solids under the blade quicker. Thus, viscosity increases under the blade. Hence, run-in is similar for all flow modifiers.

Figure 19. Blade Run-in as a Function of Hercules Viscosity at Different Solids Levels.

Figure 20 shows blade run-in as a function of water penetration at different solids levels. This figure clearly shows that blade run-in is dependent upon water penetration at low viscosities and viscosity at higher viscosities. Run-in shows to be dependent upon solids content, which in turn will increase viscosity. Note that bold print denotes 63% solids.

Figure 21 illustrates streak width as a function of Hercules viscosity at different solids levels. Streak width is considerably less at higher solids. This indicates less healing. Streak width
was measured in the same manner as discussed earlier. CMC showed poorer healing than polyacrylate. From this data, water penetration effects seemed to be offset by viscosity. Viscosity was concluded to be the controlling factor concerning healing. Note that Hercules viscosity is not plotted on a linear scale. This figure was shown to illustrate a trend on a general basis.

**Blade Run-in as a Function of Water Penetration**

![Blade Run-in as a Function of Water Penetration](image)

Figure 20. Blade Run-in as a Function of Water Penetration at Different Solids Levels.

**Streak Width as a Function of Hercules Viscosity**

![Streak Width as a Function of Hercules Viscosity](image)

Figure 21. Streak Width as a Function of Hercules Viscosity at Different Solids Levels.

Figure 22 shows streak width as a function of Hercules viscosity at different solids levels.
using a point graph. This figure is similar to Figure 21 except that Hercules viscosity is plotted on a linear scale. This shows a better correlation between solids levels. Bold print denotes 63% solids.

Figure 22. Streak Width as a Function of Hercules Viscosity at Different Solids Levels.

Figure 23 shows streak width as a function of water penetration at different solids levels. It is evident that as streak width decreases (less healing), water penetration decreases. Again this shows viscosity to be the controlling variable concerning healing. Note that water penetration was not plotted on a linear scale. This figure was used to show a trend on a general basis.

Figure 23. Streak Width as a Function of Water Penetration at Different Solids Levels.
Figure 24 shows streak width as a function of water penetration at different solids levels using a point graph. This figure is similar to Figure 23 except for water penetration is plotted on a linear scale. This shows a better correlation between solids levels. Bold print denotes 63% solids.

Figure 25 shows slope as a function of Hercules viscosity at different solids levels. The slope of the ridge was measured in the same manner as discussed earlier. Note that a lesser slope signifies better healing. As the viscosity increases, there is an adverse affect on healing. Again, viscosity is determined to be the controlling factor concerning healing ability. Note that Hercules viscosity was not plotted on a linear scale. This figure was used to show a trend on a general basis.

Figure 24. Streak Width as a Function of Water Penetration at Different Solids Levels.
Figure 25. Slope as a Function of Hercules Viscosity at Different Solids Levels.

Figure 26 shows slope as a function of Hercules viscosity at different solids levels using a point graph. This figure is similar to Figure 17 except that Hercules viscosity is plotted on a linear scale. This shows a better correlation between solids levels. Bold print denotes 63% solids.

Figure 26. Slope as a Function of Hercules Viscosity at Different Solids Levels.
Effect of Solids Levels on Optical and Surface Properties

Figure 27 shows gloss as a function of Hercules viscosity at different solids levels. An increase in viscosity caused gloss to decrease. This can be attributed to a larger number of structures formed between flow modifier and pigment at higher viscosities. Upon drying, these structures shrink causing microroughness to appear on the sheet surface lowering gloss. As solids was increased, gloss increased. This was due to better fiber coverage. CMC showed lowered gloss values than polyacrylate. This was due to higher viscosities. Bold print denotes 63% solids.

Figure 28 shows Parker Print porosity as a function of Hercules viscosity at different solids levels. As viscosity increased porosity decreased. This can be attributed to more entanglement and thickening of the color causing a less porous final coated sheet. CMC showed the lowest porosity values. At higher solids porosity decreased even more. This can be attributed to more pigment in the coating structure filling void space. Bold print denotes 63% solids.

Figure 27. Gloss as a Function of Hercules Viscosity at Different Solids Levels.
Figure 28. Porosity as a Function of Hercules Viscosity at Different Solids Levels.

Brightness and Opacity were virtually unaffected by an increase in solids levels. It is expected that opacity would decrease upon solids addition due to less void volume in the coating structure, but this trend was not observed from the data.
CONCLUSIONS

I. CMC raised Brookfield and Hercules Viscosity considerably more than polyacrylate.
   Polyacrylate showed low Brookfield viscosities.

II. Water penetration decreased as viscosity increased. CMC showed better water
    retention than polyacrylate.

III. Healing ability was dependent upon viscosity. Viscosity offset water penetration
     effects with concern to healing. The colors with the highest viscosity showed less
     healing.

IV. Increasing solids content increased viscosity and water retention. Healing was reduced.

V. Flow modifier addition decreased gloss and porosity and increased roughness. An
   increase in solids to 63% increased gloss and decreased porosity. Brightness and
   opacity were unaffected by additives.
RECOMMENDATIONS

I. Adjust addition levels of flow modifiers to achieve matching low shear viscosities. Analyze effects on color properties and coater performance.

II. Research why viscosity offsets water penetration with concern to healing.

III. Coat base sheets with different absorbencies to determine effects of water penetration and viscosity on healing.

IV. Analyze streaking of the final sheet, not just from the implemented defect, and correlate to healing.


9.) Young, L.V. and Hickman, A.D., *Efficiency of Various Thickener Types, Natural and Synthetic, as Viscosity Builders in Paper Coating Formulations*, Dow Sales Literature, (1992).


APPENDIX 1

Base Sheet Properties
Base Sheet Properties

Basis Weight - 55g/m^2

Hercules Size Test - 24 sec.

Brightness - 76.74%

Opacity 87.23%

Gloss - 5.80%

Parker Print Roughness - 5.9 microns

Parker Print Porosity - 513ml/min.
APPENDIX 2

Effect of Flow Modifier Addition on Brookfield Viscosity
Effect of Flow Modifier Addition on Brookfield Viscosity

<table>
<thead>
<tr>
<th>Sample</th>
<th>% Solids</th>
<th>Brookfield Viscosity (cp)</th>
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APPENDIX 3

Effect of Flow Modifier Addition on Hercules Viscosity
Effect of Flow Modifier Addition on Hercules Viscosity

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<th>Hercules Viscosity (cp)</th>
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APPENDIX 4

Effect of Flow Modifier Addition on Water Penetration
Effect of Flow Modifier Addition on Water Penetration

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<th>% Solids</th>
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APPENDIX 5

Effect of Flow Modifier Addition on Blade Run-in
### Effect of Flow Modifier Addition on Blade Run-in

<table>
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<tr>
<th>Sample</th>
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<th>Blade Run-in (thousandths of an inch)</th>
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APPENDIX 6

Effect of Flow Modifier Addition on Healing
### Effect of Flow Modifier Addition on Healing

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<th>Sample</th>
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<th>Streak Width (mm.)</th>
<th>Slope</th>
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APPENDIX 7

Effect of Flow Modifier Addition on Final Sheet Properties
Effect of Flow Modifier Addition on Final Sheet Properties

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<tr>
<th>Sample</th>
<th>% Solids</th>
<th>Gloss</th>
<th>Brightness</th>
<th>Opacity</th>
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<th>Porosity</th>
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