Operational limits of blade coating associated with high aspect ratio pigments: Part I—bench top blade coater

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ABSTRACT: Operational issues, such as stalagmite formations, scratches, or spits, develop during blade coating of high solids coatings at high web speeds. Coatings that contain high aspect ratio pigments exhibit these difficulties at lower solids concentrations and slower machine speeds than coatings comprised of more spherical shaped pigments. There are a number of potential reasons behind this phenomenon, but a clear mechanism is not well established.

Using a bench top blade coater without a base sheet, the goal of this study is to understand the operational limits that occur due to the coating suspension interacting with the blade. Pigment suspensions are applied in excess in front of the blade. A camera mounted near the blade exit is used to detect defects and buildup on the backside of the blade. The machine speed at which deposits on the blade first appear was determined for three pigments having different shape factors and at varying weight fractions. A Newtonian fluid was also used in the coating device. A runnability window based on shape factor and solids content was developed. Small changes in the solids concentration displayed changes in the speed at which blade deposits begin to appear. No operational issues could be produced using the Newtonian fluid. Presence of the particles at solids concentration nearing their immobilization solids must be contributing to the development of runnability issues.

Application: This research looked at how the aspect ratio of the pigments in a coating impacts the opertional limits on a bench top blade coater.

High aspect ratio pigments, such as delaminated kaolins, have many beneficial properties that make them ideal for paper coating applications. Traditionally, kaolin is used to improve the printability of the final product with a smooth and excellent surface for ink receptibility [1]. The plate-like shape of kaolin particles is one of the most significant properties for achieving good base stock coverage in lightweight coating to enable high print quality to be reached [2]. However, there are often process issues during blade coating that are exhibited when coatings contain high aspect ratio pigments. These issues include stalagmite formation that is usually accompanied with wet bleeding, scratches, streaks, and spits. This constrains the applicability of coatings, comprising these pigments to lower solids content coating colors and slower machine speeds compared to those based on a more spherical shape pigment coating. This results in higher drying costs and lower quality coatings that decrease the overall efficiency of the process. This will also reduce the expected benefits of using high shape factor pigments in the coating.

Runnability is defined as the ease at which a coating is applied to a base sheet. Operational issues include blade bleeding, stalagmite buildup, streaks, and spits that limit the solids content and speed at which the coating can be applied. Many researchers have theorized on the factors that contribute to these problems, but the real mechanism behind the onset of these issues is not fully understood.

One of the initial indications of potential runnability issues is blade bleeding. This issue is related to the buildup of coating on the back side of the blade that has a wet viscosity consistency. Continued bleeding can lead to the formation of wet structures adhering to the blade tip, termed stalagmites. Alternatively, a drier structure can be observed directly forming a stalagmite without the wet bleeding appearance. Following this observation, there are three types of blade buildup: wet bleeding, which is the slow extrusion of coating with the properties of the coating before shear; the formation of a dry stalagmite; and lastly, a combination of both wet and dry stalagmite growth [3].

Stalagmite formation can be benign during the coating process. The formation of stalagmites does not always result in defects, but it does add some uncertainty into the long-term operation of that particular coating [4]. If stalagmites fall clear of the paper web, they do not cause any damage or defects to the product. When the stalagmites become detached from the blade and land on the surface of the coated paper, these deposits also have the potential to cause damage to equipment downstream from the coater [5].

Streaks have been defined as stripes of heavier coating thicknesses that run parallel with the machine direction and can be up to several centimeters to meters in length [6]. Spits are created when droplets of excess coating attach to the coating surface [5]. Besides streaks and spits, other defects such as scratches and skips are possible flaws that can appear on the final product. Skips on the paper surface are areas barren of coating that leave the final product with a patterned surface [4]. Scratches are indents on the final coating surface aligned with the machine direction [4,6]. The precise cause for these defects to occur is still a debated topic. Several theories have been developed to explain the operational issues that are exhibited by coatings that consist of plate shaped pigments. High aspect ratio pigments, narrow particle size distributions, low water retention, high viscosity, fast web speeds, and high solids are some the properties that haven been cited that seem to lead to more runnability issues [3,7,8]. There are many theories in which interactions between the coating, base stock and blade coating conditions are considered the main culprit in initiating runnability issues.

Many past studies have pointed to the rheology as the cause of the operational trouble. The particle shape has a sizable effect on the viscosity of the suspension. High aspect ratio pigments tend to have a higher viscosity at lower solids content than spherical pigments. Dahlvik et al. [9] concluded that a relationship exists between high shear rate rheology and runnability issues. In contrast, Suontausta [10] determined that viscosity of the coating had little effect on stalagmite formation. Others caution that the steady state rheology is not important but the response to the transient shear is the controlling mechanism [3,5,8]. The role of viscoelasticity during coating is one of the debated topics. It has been proposed that coatings, a multiphase dispersion, will have viscoelastic deformation when subjected to sudden changes in strain, thus leading to relaxation-induced dilatancy [3]. The combination of the pressure pulse underneath the blade and the elastic component in the z-direction of the coating will generate relaxation-induced dilatancy, where the suspending liquid is forced from the particle structure. As the web speed is increased, the velocity profile under the blade changes to plug flow with a slip plane against the blade [3]. When the slip plane moves away from the surface of the blade into the bulk, wet bleeding and extrusion of un-sheared coating will appear on the blade [3].

A high viscosity in itself should not be the only cause behind operational problems. If the viscosity increases at a certain shear rate, the blade may deflect in a way that is hard to predict. The alignment of the blade during coating has a large effect on a coating's runnability and the quality of the final product [11]. Also, the flow channel between the blade and the base sheet controls the rate of particle rotation. When particles are rotating through the shear field, collisions between the particles cause "log jams" and particle structures to form, which may contribute to skipping and streaking defects [12]. Although dilatant rheology alone does not explain operational issues, deflection of the blade and alterations in the flow channel could be a contributing factor.

The influence of particle orientation on runnability has been discussed in a number of publications [5,8]. The rotation of these plate-like particles during coating is thought to be linked to the formation of whiskers and stalagmites along with altering the packing ability and water retention of the coating layer. The development of stalagmites on blade coaters trigger the runnability issues at high production speeds [13]. While it makes sense that rotation of high aspect ratio pigments in the coating flow would disrupt the smooth flow of particles, a clear demonstration of this mechanism is lacking in the literature as well as established process limitations as to what solids can be applied for certain aspect ratios.

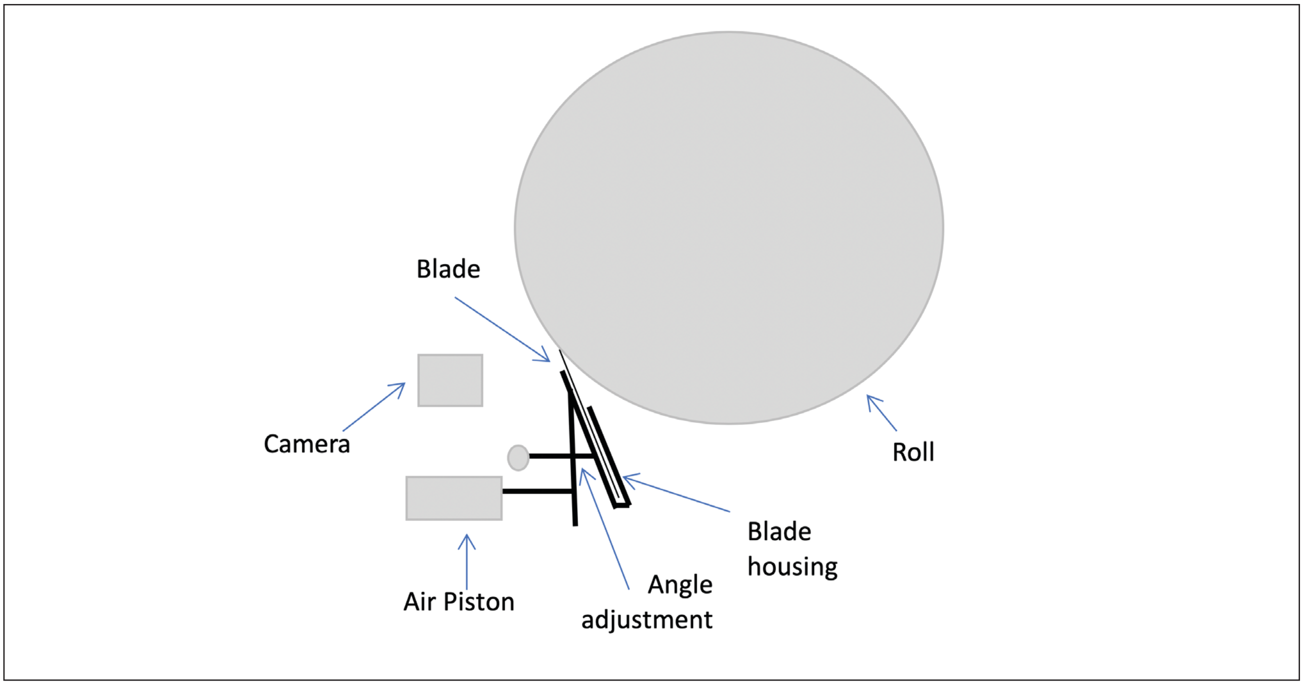
Characteristics of the coating formulation, base stock properties, and coater operation conditions have been linked to runnability issues. It is well known that if the solids of the coating increase or the permeability of the base sheet increases, the maximum coating speed decreases. Bousfield [14] proposed a model of blade coating that predicted the flow field and the buildup of a filter cake on the paper surface during the coating process: if the filter cake thickness approaches the gap between the blade and the paper, the filter cake will be scraped by the blade tip, leading to coating defects. This picture seems to explain some results, but it does not directly explain the runnability issues of high aspect ratio pigments. These plate shaped pigments may influence the filtercake solids in the model and the viscosity of the coating, and that could determine the growth of the filtercake.

Doi et al. [15] mapped out the critical coating speed as a function of clay and calcium carbonate composition, as well as latex type; a laboratory coater with a base sheet was used to find the critical coating speed before defects were observed. They found that the speed at which defects first appear was always lower for coatings containing clay compared to ground calcium carbonate. The latex size also can have an influence on the critical coating speed. The authors did not find a correlation between high shear viscosity and the critical coating speed but could explain some pilot scale results with the laboratory device if they considered dewatering. An unknown "third" factor may be needed to explain this, but the mechanism behind this third factor was not clear.

In this study, an examination of the critical coating speed is undertaken for three pigments, each with different shape factors. The experiments are similar to those described by Doi et al. [15], except here the influence of just the pigment aspect ratio is isolated. An operating window based on the shape factor and the solids content was developed. Also examined is the effect that high viscosity and blade alignment has on the runnability of pigment slurries.

EXPERIMENTAL METHOD

This study focused on three kaolin pigments: Astra-Glaze (Imerys; Paris, France), XP10-6003 (Imerys), and XP01-6100 (Imerys). These pigments have on average shape factors of 15,



1. Schematic of the bench top blade coater.

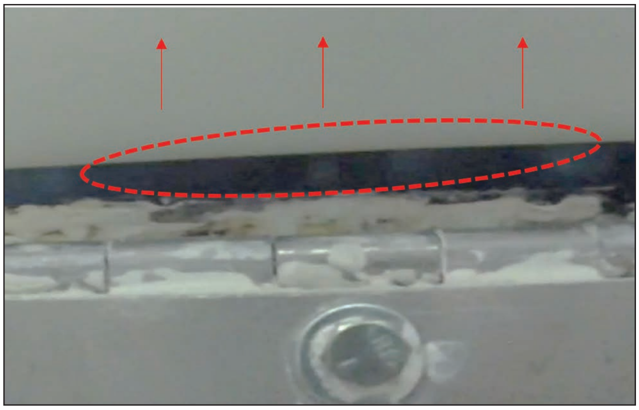
35, and 90, respectively, as reported by the supplier. Shape factor is defined in a specific manner by the supplier, but can be taken as an average aspect ratio of the plate-like particles. These pigments will be identified based on their aspect ratio or shape factor as KXX. For instance, the kaolin pigment with a shape factor of 35 is identified as K35. Slurries of these pigments were prepared using a high shear mixer to ensure adequate dispersion of the particles. The mass fraction of the slurries was ascertained by a dry weight method. In this work, no other dispersants, additives, or latex was added to the suspension other than what was already included by the manufacturer. This was done to limit the complexities of the suspension while focusing on the affect that particle aspect ratio has on the interaction with the blade coater.

A bench top blade coater was used in this study. A schematic of the device is shown below in **Fig. 1**. It consists of a rubber covered roll with a diameter of 10.16 cm and length of 24.13 cm. The turning speed is computer controlled and variable up to a roll surface speed of 1200 m/min, but is usually operated at speeds less than 600 m/min. The runnability study was conducted with a stiff steel blade with a bevel angle of 45°. The loading force for the blade was applied by two low static friction air pistons using compressed air. The blade angle was determined from the tangent of the point of contact between the roll and the blade. Proper alignment of the blade is crucial, since running on the heel is known to induce runnability issues. The pressure of the compressed air entering the piston was kept constant at 8 psi for all runnability trials. This corresponds to a blade loading force of 11.2 N/m. This blade coater does not include any base sheet. The absence of the base sheet will remove the effect of dewatering of the coating layer into the substrate, and thus eliminate one of the possible causes of runnability issues.

Using this coating device, the critical coating speed was obtained by determining what speed runnability issues first appear at varying weight fractions. Since there was no dewatering of the coating and no additives in the slurry, the solids content of the sample was higher than a traditional coating formulation in order to generate any runnability issues. A small camera (GoPro Hero 3+) was positioned near the exit of the blade to record any defects that might occur during the trial.

One of the factors suggested to influence the onset of runnability problems is the high viscosity of the high aspect ratio pigments. To examine if high viscosity of the pigment slurries per se is potentially one of the factors behind the observed stalagmite formations, high fructose corn syrup, a Newtonian fluid with a comparable viscosity of 1.5 Pa s at 226 s^{-1}, was coated using the bench top blade coater. The critical coating speed was determined for this fluid using the same conditions as the pigment slurries.

The viscosity of the slurries at a shear rate of 10000 s^{-1} and varying weight fractions was found using a cup and bob rheometer (Hercules Hi-Shear Viscometer; Kaltec Scientific, Novi, MI, USA) using bob E and a ramp time of 20 s. The data was fitted to the Krieger-Dougherty equation, which relates the viscosity to the volume fraction using two parameters to describe the sample, following a similar method as outlined in Weeks et al. [16]. The low shear viscosity of each of the slurries used in the runnability study was determined using a Bohlin Gemini II rheometer (Malvern Panalytical; Malvern, UK) using a 25 mm diameter parallel plate geometry with a gap of 1 mm. All measurements were conducted at room temperature and completed in triplicate. The immobilization solids were determined for each of the pigments by placing a



2. A frame taken from video of K90 at a solids content of 58% and roll speed of 480 m/min showing no deposits or stalagmites on the blade. Red arrows show the roll surface motion. Red dotted oval shows the key area of interest where the blade is touching the roll.

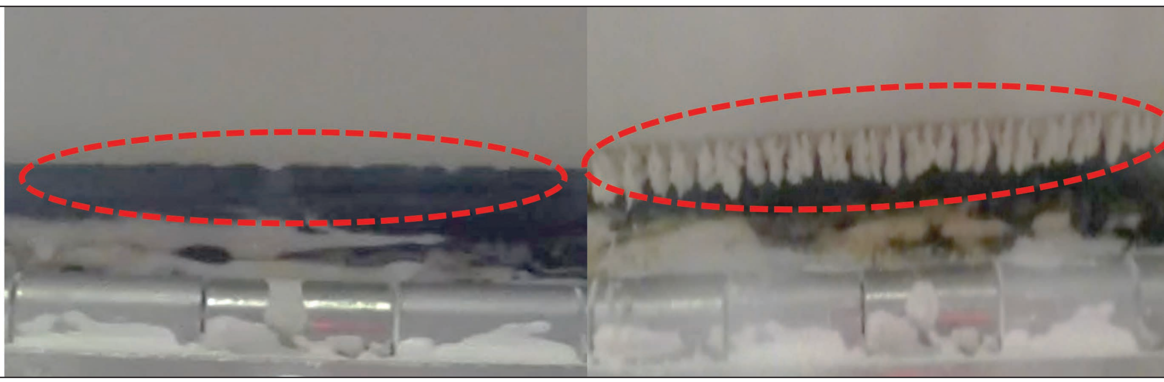
small volume of the slurry onto a porous ceramic disk. Once the wet gloss on the surface of the slurries disappeared, the sample was removed, and the solids content determined.

RESULTS AND DISCUSSION

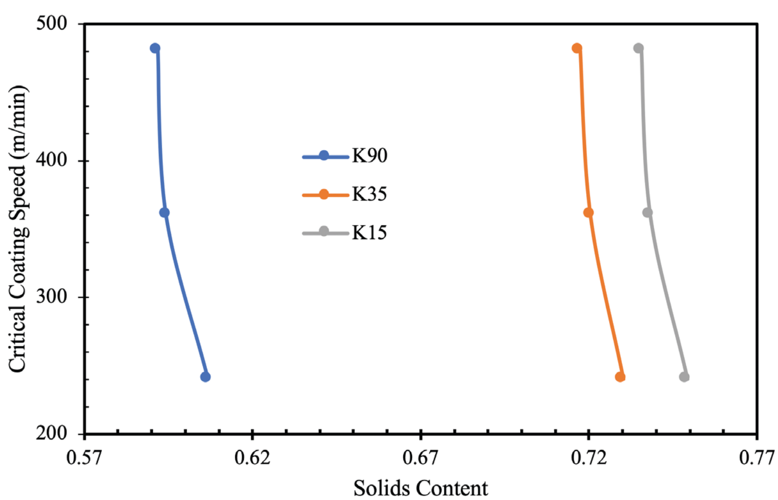
In preparation for the runnability test, pre-trials were completed on the bench top blade coater to confirm the device's ability to apply a clean and uniform layer of coating. **Figure 2** is a still image taken from a video of a K90 slurry trial showing no runnability issues or defects.

Depending on the solids of the slurry and the speed of the roll, the defects observed were varied. They ranged from small stalagmites beginning to form at specific locations on the blade to large extrusions or stalagmites building up across the entire backside of the blade. **Figure 3** shows the varying number of defects observed during the trials. Spitting was observed during the cases when considerable stalagmites were present.

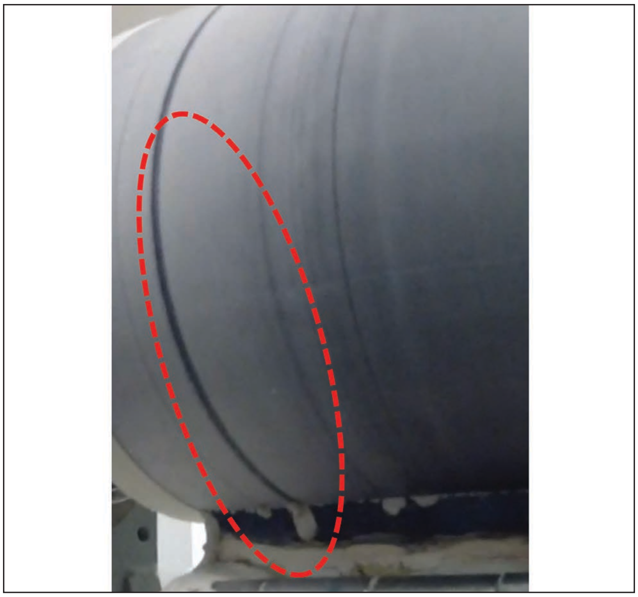
The results of the runnability tests are displayed below in **Fig. 4**, where the solids content is given as mass fraction. For solids content less than that recorded in the plot, no runnability issues were seen at the maximum speed of the tests (480 m/min). Minute changes in the solids concentration altered the critical coating speed. On average, there was only 1.4% difference in the solids concentration between the critical coating speed at 240 m/min versus at 480 m/min. K15 and



3. Left: Small stalagmites on the backside of the blade with K90 at 59.43% solids and a roll speed of 360 m/min. Right: Large stalagmites across length of blade with K90 at 58.7% solids and a roll speed of 480 m/min.



4. Critical coating speed based on the solids content for each of the three tested pigments.



5. Wet bleeding with possible slip plane failure at the roll surface with K90 at a solids concentration of 59.43% and a roll speed of 360 m/min.

K35 displayed the onset of stalagmite formation at weight fractions of 73.6% and 71.7%, respectively. K90 displayed runnability issues at a solids concentration of only 59.2%. These weight fractions are higher than what would be used in an industrial setting, but these suspensions did not have latex or additives. These experiments show that similar defects occur for all pigments and that these defects did not require absorption or roughness from a paper surface to occur.

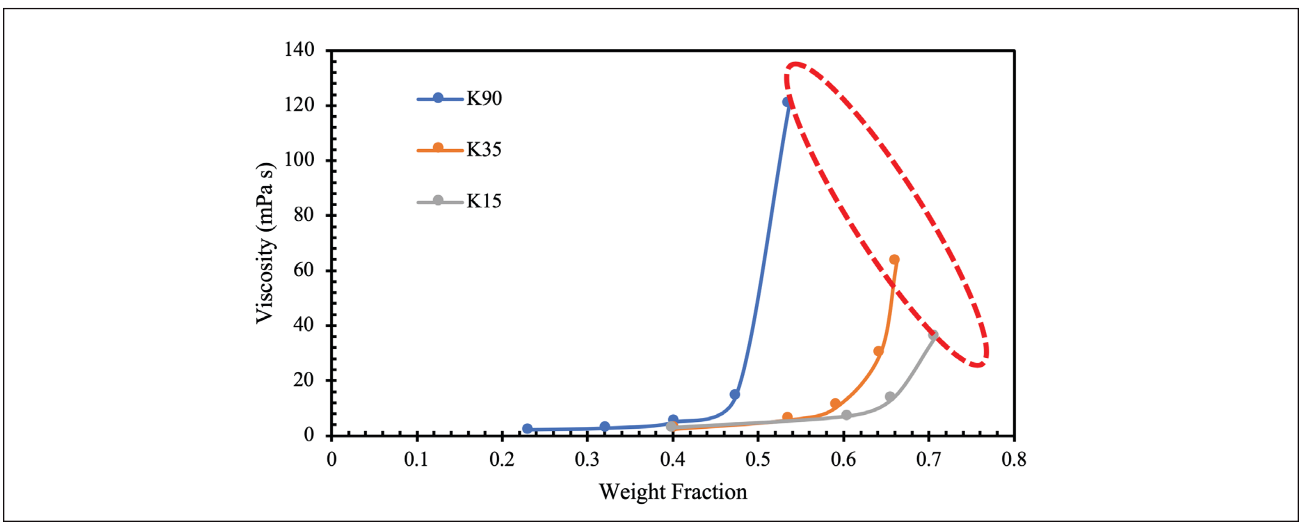
While examining the videos taken during the runnability study, there was evidence of wet bleeding in some cases. **Figure 5** is taken from one video that displays an occurrence of wet bleeding. All coating was being removed from the rubber roll and extruding out and collecting on the backside of the blade. This observation supports the theory of the relaxation-induced dilatancy with a slip plane. The slip plane moved from the surface of the coating against the blade to the interface between the roll and the coating. The interactions between the coating, the backing roll, and the blade material would be a contributing factor to potential operational issues.

Increase in coating viscosity is cited as one of the most common theories for runnability issues. An analysis of the viscosity of each of the pigment slurries at varying weight fractions was conducted on a Hercules Hi-Shear viscometer. **Figure 6** displays the viscosity-weight fraction relationship between the three pigments; the viscosity was recorded at 10000 s^{-1} shear rate. The Krieger-Dougherty equation, shown below in Eq. 1, was fit to the data using a least squares regression method. This equation calculated the viscosity based on the volume fraction and two parameters characterizing the suspension. One of the parameters is the maximum flowing fraction. The shear rate used in the test can have some impact on the calculated value of the maximum flowing fraction. It has been shown that this value is on average 10% lower than the immobilization solids content and likely linked to the volume fraction at which unhindered particle movement in the suspension has become restricted [16]:

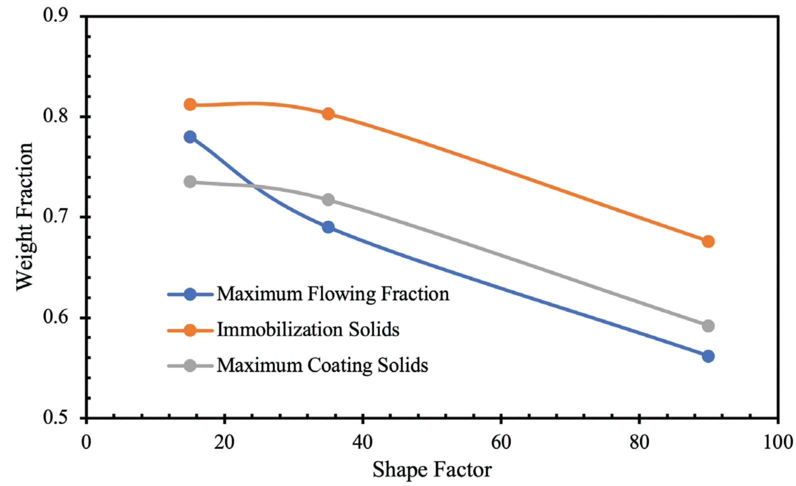
$$\mu = \mu_s \left(1 - \frac{\phi}{\phi_m}\right)^{[\mu]\phi_m} \quad (1)$$

where μ_s is the viscosity of the fluid phase, $[\mu]$ is the intrinsic viscosity, and ϕ and ϕ_m are the volume fraction and maximum packing fraction of the particle phase, respectively.

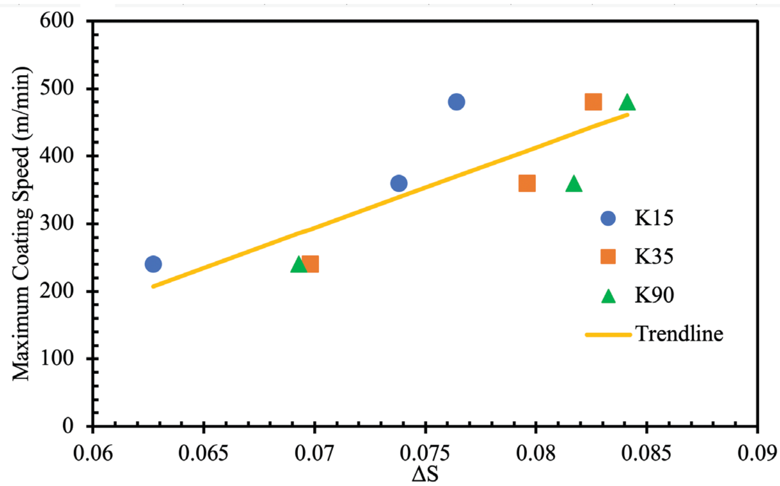
The solids concentrations used for the bench scale lab coater were actually higher than the maximum flowing solids obtained from fitting the viscosity-solids behavior to the Krieger-Dougherty equation. The red oval in Fig. 6 highlights the range of weight fractions that was used. All slurries had a higher solids content than what was testable on the Hercules Hi-Shear viscometer. The slurries quickly over torqued the



6. Viscosity at varying weight fractions for three pigments at a shear rate of 10000 s^{-1} with highlighted range of slurries tested.



7. Weight fraction for the maximum flowing fraction, immobilization solids, and the maximum coating solids based on the shape factor of the pigment.

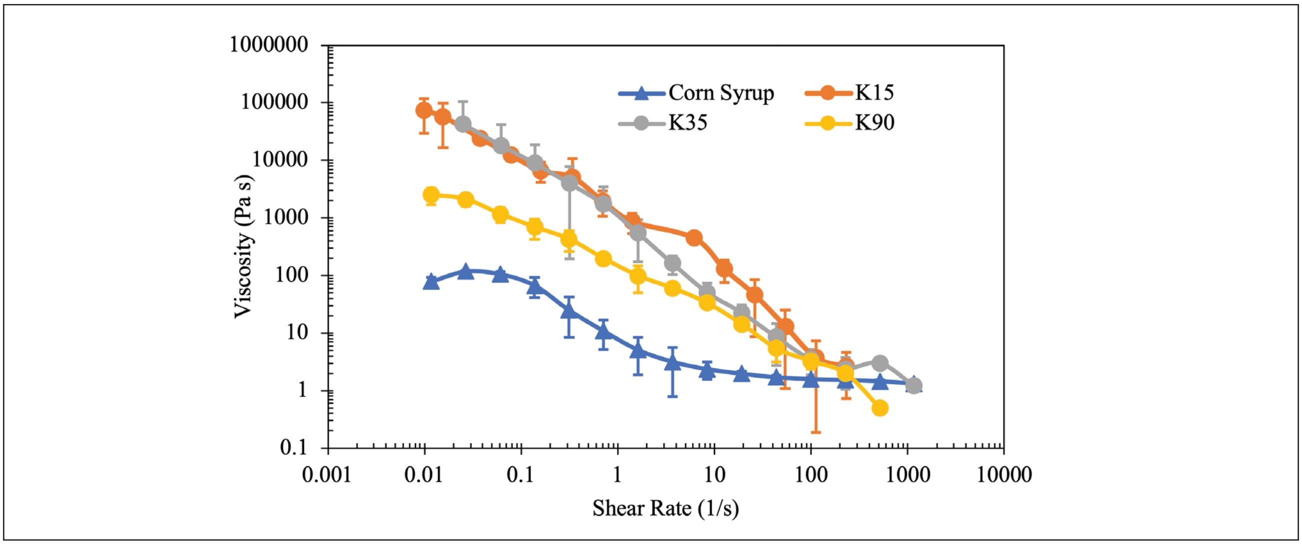


8. Linear relationship between ΔS and the critical coating speed for K15, K35, and K90.

limits of the device. This equipment uses a cup and bob geometry that applies steady shear while ramping to a high shear rate and back down again. During the coating process, a large and sudden shear force is exerted on the suspension. This would suggest that the dynamic response of the pigment slurry to the instantaneous force is important for coating runnability. K15 and K35 showed a similar viscosity to weight fraction relationship. The viscosity begins to increase at similar solids concentrations. This grouping resembles the trends observed in the runnability window.

A comparison between the maximum flowing fraction, immobilization solids, and the maximum coating solids, which is weight fraction of the slurry with a critical coating speed of 480 m/min, is shown in **Fig. 7**. All three parameters are functions of the shape factor of the pigment. For K90 and K35, there is a large difference between the maximum flowing fraction and the immobilization solids. There is a much smaller difference, however, between those values for K15. The maximum coating solids fall between the maximum flowing fraction and the immobilization solids. This result does not hold true for the lowest shape factor pigment. All weight fractions used in the runnability study for K35 and K90 were above the maximum flowing fraction, while K15 are below. It could be tentatively concluded that the rotational freedom of high aspect ratio pigments is indeed a critical factor in respect to high shear rheology and the instantaneous response under a coating blade.

This anomaly with K15 was noticed during the completion of the runnability tests. Following the trends set by the other two pigments, it was hypothesized that the maximum coating solids of the K15 slurries would be between the maximum flowing fraction and the immobilization solids. When slurries



9. Low shear viscosity profiles for corn syrup, K15 (73.82%), K35 (72.04%), and K90 (59.43%).

of K15 were tested in that expected solids range, the rubber roll could not turn at the set speed. These slurries were of the same consistency as the K90 and K35 slurries as determined by simple hand mixing. The slurries were viscous and difficult to stir and pour. The solids content of K15 was diluted by 5% before it was able to be run in the blade coater. At this lower solids concentration, the slurry was very easy to stir and pour. It was surprising that defects were still observed on the coating device at this solids concentration because it was below the maximum flowing solids. While K15 could be coated at the high solids, the concentration was lower than the maximum flowing solids, while the other two pigments were able to be applied at solids above the maximum flowing solids. The reason for this behavior is not clear, but it must relate to a dynamic response of the suspension.

Blade deposits appeared when the solids content of the slurry was close to the immobilization solids for the pigment. The difference between the immobilization solids and the solids content of the tested slurry, which will be called ΔS, was calculated for the all trials. There does seem to be a trend developing. **Figure 8** displays this relationship. As the solids concentration of the slurries decreases, thus ΔS increases, and higher machine speeds were possible before any operational issues developed. This relationship appears to be linear, with a slope of 12000 m/min. This result is quite interesting and valuable in that for a wide range of particle aspect ratios, the maximum coating speed follows this simple relationship. While other rheological parameters to predict this maximum speed may be possible and based on physics, this simple relationship is only based on the solids content of the coating and the immobilization solids of the system.

A Newtonian fluid, high fructose corn syrup, with a viscosity that is comparable to the test pigment suspensions, was used in the bench top blade coater. The viscosities of the three pigment samples and the corn syrup are shown in **Fig. 9** and were determined using a controlled stress rheometer with a cone and plate geometry. Only the viscosity profiles for the solids content with a critical coating speed of 360 m/min are shown. The viscosity profiles for each of the three weight fractions are similar. As the shear rate increases, the viscosity for all the fluids becomes more closely aligned. During the runnability test using the corn syrup, no runnability issues could be produced and a uniform layer of syrup was applied to roll at the highest testable speeds. This observation leads to the theory that the presence of the particles in the coating is key to cause of runnability issues. The packing interactions between the particles are affecting the way the pigment slurry behaves and potential induced interparticle interactions may give rise to operational issues. Therefore, a full understanding of this area is paramount to discovering the causes behind runnability issues.

Blade deposits began to appear when the solids concentration of the slurry neared the immobilization solids of that pigment. At these high solids, interactions between the rotating particles could be causing disruptions in the flow field and the packing structure. The collision of particles could arise from disrupting the arrangement of particles, which contributes to the formation of skipping and streaking on the final product [12]. Higher aspect ratio pigments required more available space for rotation than spherical pigments. They are capable of causing larger instabilities in the packing structure with little movement.

CONCLUSIONS

The coating window was characterized for pigment suspensions as a function of solids and pigment shape factor. As expected, the higher shape factor of the pigment had a lower maximum coating solids compared to the low shape factor pigments. The onset of coating operation issues occurs within a solids range of around 1.5%. With the absence of a base sheet, formulation latex, or other additives and binders, blade deposits were still generated. The inability to produce any runnability issues when coating with either a Newtonian fluid or a low solids concentration establishes that coating near the immobilization solids is required to create blade deposits with a non-absorbent base sheet and at the tested machine speeds. At high solids, the interactions between rotating particles could be disrupting the structure and causing jams in the coating layer during shear. These disruptions could be contributing to the onset of runnability issues. **TJ**

ABOUT THIS PAPER

Cite this article as:
Weeks, L., Gane, P., Lyons, T., and Bousfield, D., *TAPPI J.* 18(2): 123(2019).
https://doi.org/10.32964/TJ18.2.123

DOI: https://doi.org/10.32964/TJ18.2.123

ISSN: 0734-1415

Publisher: TAPPI Press

[About this journal]

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ABOUT THE AUTHORS

This research is a portion of my (Weeks) Ph.D. work in examining the operational limits of blade coating with high aspect ratio pigments and what can cause runnability issues. Using past research as a foundation, this research investigates some of the main theories behind runnability issues, while focusing on pigment particle shape.

It was interesting that the small changes in weight fraction result in large changes to the operational window. And it was definitely interesting to note that coating with corn syrup makes one huge, sticky mess!

For mills, this research offers insight into the behavioral differences between pigment shapes. The next step for this research is to expand the number of pigments analyzed and experiment with varying coating color formulations.

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