Operational limits of blade coating associated with high aspect ratio pigments: Part II—cylindrical laboratory coater

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ABSTRACT: Process issues such as blade deposits, scratches, spits, and defects on the coating surface develop during blade coating of paper at high solids content and fast machine speeds. Coatings that contain high aspect ratio pigments display these issues at lower solids concentrations and slower web speeds than spherical or block shaped pigments. The shape of the pigment particles influences the characteristics of the coating formulation after drying, and high aspect ratio pigments can lead to high gloss surfaces that have good printing properties and are of interest in barrier coatings. The rheology, particle packing, and water retention are all functions of the pigment shape and size distribution. The base sheet properties of porosity, surface roughness, and permeability interact with the coating and the blade coater operating conditions. The possible causes of poor runnability are part of an interrelated and complex system.

A cylindrical laboratory coater (CLC) was utilized to determine the speed at which operational and quality issues begin at varying solids concentration for two pigments with different shape factors on two different paper surfaces with varying absorption rates. An operational window was developed for both pigments. Characteristics of the pigment suspensions were explored in order to find a relationship with the onset of operational problems. The high shear rate viscosity of these suspensions did not explain the operational windows. The difference between the solids concentration and the immobilization solids, which is a function of the shape factor, has a linear relationship to the runnability limits. This could be ascribed to the tight packing structure of the particles as the solids content approaches the immobilization solids.

Application: This research looked at how the aspect ratio of the pigments in a coating impacts the operational limits when using a cylindrical laboratory coater. An analysis of these potential causes behind runnability issues was conducted.

Problems during coating application develop during blade coating at high solids concentrations and fast web speeds. These problems include quality issues that affect the properties of the final product. These comprise scratches, streaks, and the non-uniformity of the coating layer. Also, operational issues can arise during the coating process. Deposits of coating on the backside of the blade and spits are common problems. Coatings consisting of high aspect ratio pigments exhibit these difficulties at lower solids contents and slower machine speeds than low aspect ratio pigments. Many theories on the causes behind this phenomenon have been suggested. The characteristics of the coating formulation, base sheet properties, and blade coater conditions all seem to play a role in the operational limits. While there has been much work on the topic of high-speed blade coating at high solids, there is still a lack of understanding of the basic mechanisms that limit the speed or solids of various formulations.

The shape of the pigment particles affects a wide array of the properties of the coatings. Water retention, packing structure, rheology, and particle orientation are all functions of the particle shape factor. Even in simple shear, it is well known that particulate suspensions that contain high aspect ratio particles will have higher viscosity than those with a more spherical shape at the same solids level. However, this behavior alone does not explain operational issues, because a high viscosity fluid should be able to be coated with blade coaters. The influence of particle orientation for a smooth coating application and the rotation of these high aspect ratio pigments during the coating process is thought to be linked to the formation of stalagmites and whiskers [1]. If the large particles flow parallel to the base sheet, no runnability issues occur. When the particles become misaligned to the paper surface, collisions between neighboring particles cause jams in the flow field to form, thus resulting in issues. As the shape factor of the particles increases, the more available space for rotation is required. While these mechanisms make sense, it is hard to study the actual high-speed operation and verify these mechanisms.

The orientation of the particles will also influence the packing ability and water holding capacity of the coating. How tightly the particles pack together is a function of the shape, size, and size distribution. Large aspect ratio pigments have the ability to pack in a very dense manner, but any disorientations could result in a loose packing structure. The rate of dewatering is affected by the shape and packing ability of the pigment. Tightly packed platy pigments will have an increased tortuosity and path length for pressure driven permeating flow [2]. As the solids concentration of the coating increases due to dewatering into the base sheet, the chances for defects in the coating layer are increased. The blade scraping across an immobile layer of particles could cause quality problems in the final product or operation issues [3]. When particles rotate in a shear field, collisions between the particles cause jams and particle structures form, which contribute to skipping and streaking defects [4].

The properties of the base sheet and the blade coater operating parameters can also affect the occurrence of runnability issues. The porosity and permeability of the substrate will alter the dewatering of the coating color as the coating contacts the substrate before the blade removes the excess coating. The surface roughness and compressibility of the base sheet have been speculated to increase a predisposition for stalagmite formation [5]. Blade coater operational settings can significantly impact the onset of runnability issues as well. Increasing the blade angle and using thinner blade thicknesses have diminished chances to promote the onset of blade buildup [6]. Gane and Coggon [7] found that by adjusting the blade angle, the packing structure of the clay could be controlled. The flow channel the blade makes with the base sheet has an impact on the runnability limits for a coating. The compressibility of the base sheet, the backing roll, and the blade angle will determine the flow channel [6]. The parameters that affect a coating's runnability are complex and interwoven.

Researchers have been using pilot scale coating equipment to study runnability limits for some time. Ghosh et al. [8] determined that runnability on a cylindrical laboratory coated (CLC) correlated with the critical stress of a coating at very small strains. Adding fine clay particles and altering the particle size distribution had a positive impact on increasing the immobilization solids and the water holding capacity of a coating, thus improving its runnability [9]. Dahlvik et al. [10] studied the influence of the rheological properties of clay based coatings on their runnability using a pilot scale coater: high viscosity corresponded to more operational difficulties and defects in the coating surface, but no clear relationship between the viscoelasticity and runnability could be defined. A slower rate of dewatering of a coating improved runnability [10].

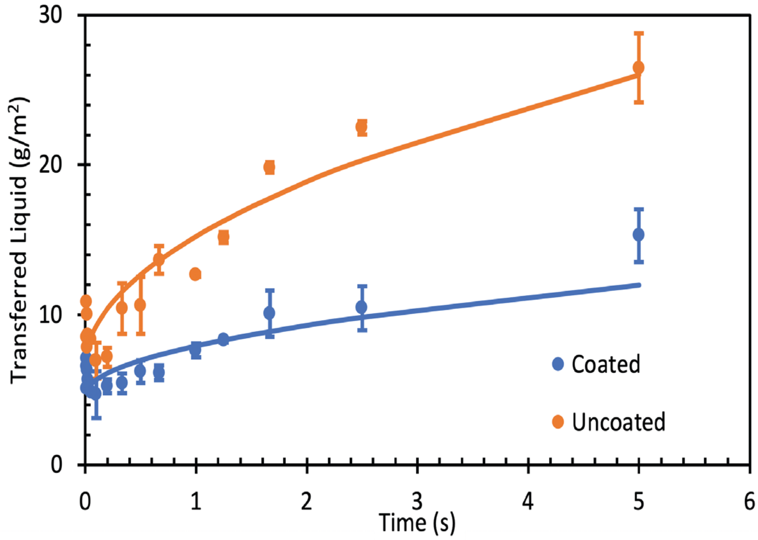
In this study, the effect of pigment particle shape on runnability using the CLC was examined. The effect of the roll speed on operational issues during coating and quality defects on the final product was assessed using two pigments with high and low shape factors over a range of solids. An exploration into the relationship between runnability and the characteristics of the pigment as a function of shape factor was conducted.

EXPERIMENTAL METHOD

Two pigments were used in this runnability study: AstraGlaze (Imerys; Paris, France) and XP01-6100 (Imerys). These pigments have average shape factors of 15 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 plate shaped particles. These pigments will be identified based on their aspect ratio or shape factor as either K15 or K90. Slurries of these pigments were prepared using a high shear mixer to ensure sufficient dispersion of the particles. The mass fraction of the slurries was determined by an infrared moisture analyzer (IR-35, Denver Instrument; Bohemia, NY, USA). In this runnability study, no other dispersants, additives or latexes were included in the suspension other than what was already added by the manufacturer, except for a small amount of a dye (<1% by weight). This dye helped color the white pigment to aid in the detection of quality issues in the final coating layer. This was done to limit the complexities of the suspension while focusing on the effect that particle aspect ratio has on the interaction with the coating equipment. The viscosity of the pigment suspensions at a shear rate of 10,000 s^{-1} and varying weight fractions was measured using a cup and bob rheometer (Hercules Hi-Shear Viscometer, Kaltec Scientific, Novi, MI, USA) using bob E ad a ramp time of 20 s. The data was fitted to the Mooney equation, which relates the viscosity to the volume fraction using two parameters to describe the sample, following a similar method as that outlined in Weeks et al. [11]. The viscoelasticity data of the slurries were determined using a Bohlin Gemini II rheometer with a 25 mm parallel plate geometry. An oscillatory test with a frequency sweep between 0.1 and 30 Hz at a constant strain of 0.01 was used. The immobilization solids were determined for each of the pigments by placing a small volume of the slurry onto a porous ceramic disk. Once the wet gloss from the surface of the slurries disappeared, the sample was removed, and the solids content determined.

The base sheet used in these tests was a paperboard coated on one side with a basis weight of 222 g/m^2. The coated side of the substrate was less permeable and had a smoother surface than the uncoated side. The base paper pore size distribution was characterized by mercury intrusion porosimetry. The porosity of the base sheet was found to be 0.25. The absorption rate of water was determined for each side of the paper by the Bristow wheel tester (Bristow Laboratory Apparatus). The results are shown below in **Fig. 1**.

The runnability tests were conducted on the CLC (CLC 6000, Sensor and Simulation Products; Tacoma, WA, USA). The pre-dry and the post-dry settings were kept constant for



1. Results from the Bristow wheel tests for the coated and uncoated sides of the substrate.

all trials at 5 s and 15 s at 50% power, respectively. The coat weight was also held steady at an average of 25 g/m² by adjusting the gap setting on the CLC. A small wireless camera (Hero 3+, GoPro; San Mateo, CA, USA) was attached to the bottom of the moving carriage. It was used to record any potential operational issues that occurred at the blade exit. A photo displaying the location of the camera with respect to the blade and pond is shown in **Fig. 2**. The solids concentration of each of the two pigments was varied, and the speed at which operational and quality issues begin to appear was determined.

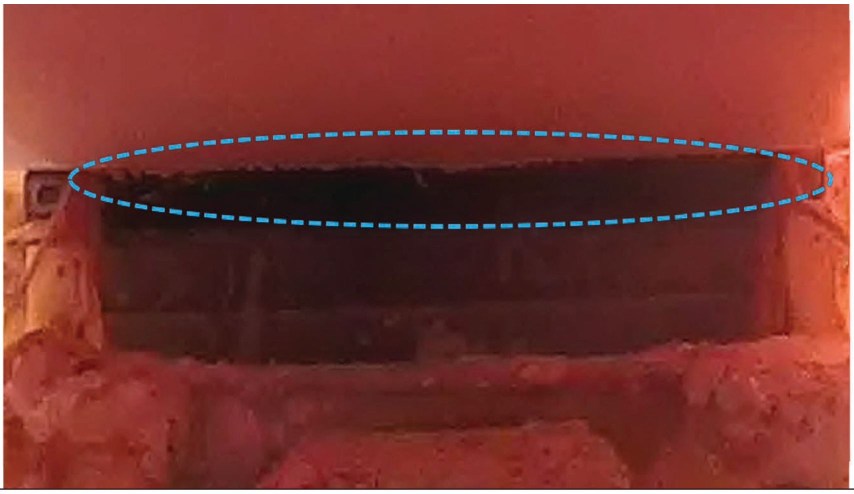
2. Photo showing the blade and pond (top arrow) and the location of the camera (bottom arrow).

RESULTS AND DISCUSSION

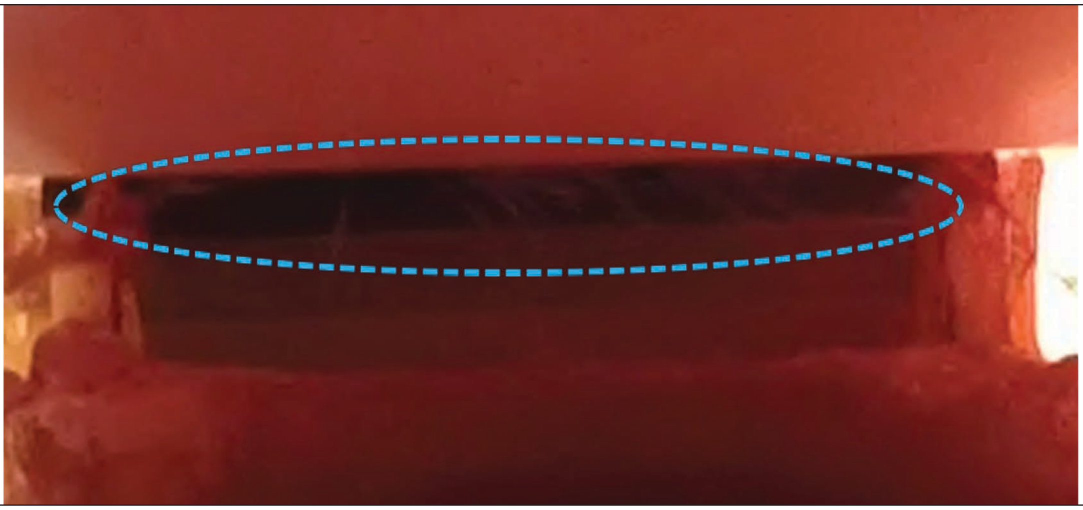
The runnability issues that arose during this study were classified into two categories: operational and quality. The most common observed quality issues were skip coating and scratches; these were determined by examination of the coated region. Operational issues included blade deposits or spits. These problems were observed during the coating application process. Determination of any operational issues was completed after analysis of the recorded video of the trial. Two operational defects were seen on the video. Blade deposits, shown in **Fig. 3**, are small amounts of coating that are extruded onto the backside of the blade. The second observed defect was spitting. **Figure 4** displays a large episode of spitting of coating from the blade nip.

The second runnability issue that was observed was quality problems with the coating layer on the substrate. **Figure 5** displays the two most commonly observed issues. On the left, deep scratches in the coating layer that run with the machine direction are shown. One of the most common quality issues was a non-uniform layer of coating on the surface of the substrate. There are sections of the substrate that are void of coating. This skip coating phenomenon is presented on the right of Fig. 5.

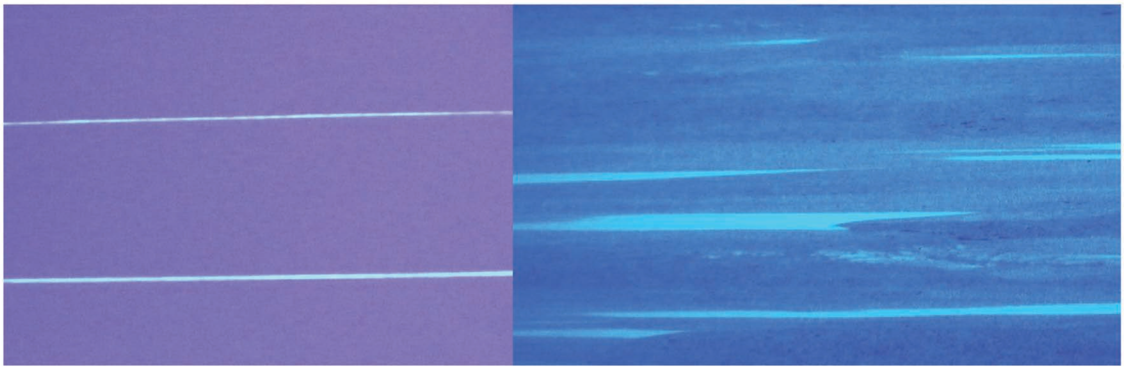
The results from the runnability study for K15 are shown in **Fig. 6**, where the solids content is given as mass fraction. There were only minor differences between the data with the uncoated and coated sides of the paper. Quality problems on the coating layer appeared at the same solids concentrations and roll speeds. The differences between the two sides of the paper are when blade deposits begin to materialize on the back side of the blade. On the uncoated substrate, operational issues begin to appear at slower machine speeds than



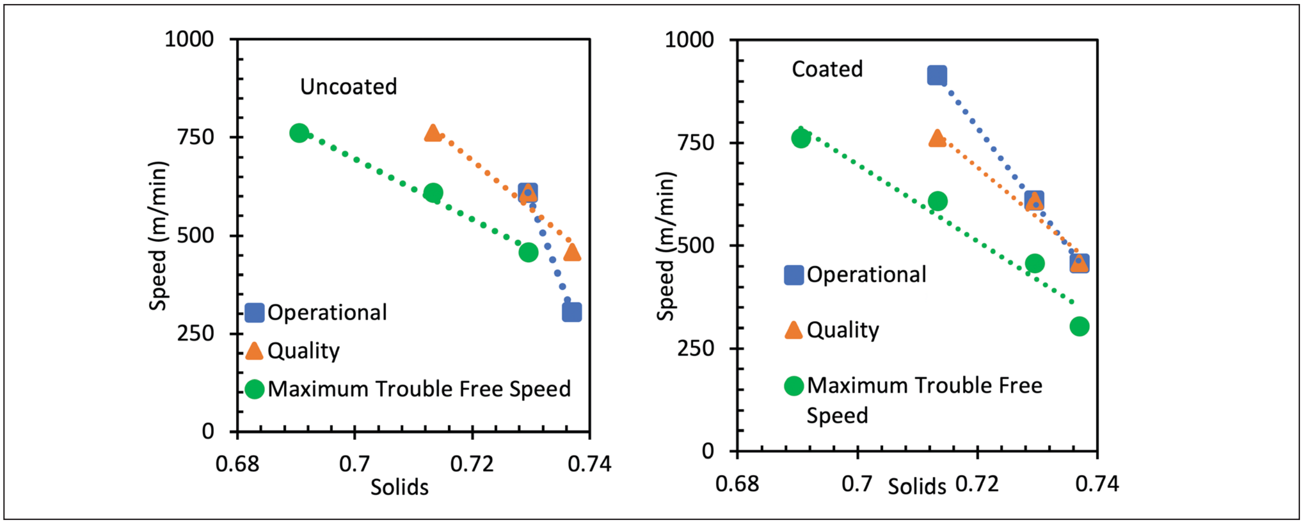
3. A frame taken from a video of K15 pigment at a solids content of 72.9% and roll speed of 609.6 m/min showing blade deposits on the backside of the blade. The blue dotted oval shows the key area of interest where the blade is touching the roll.



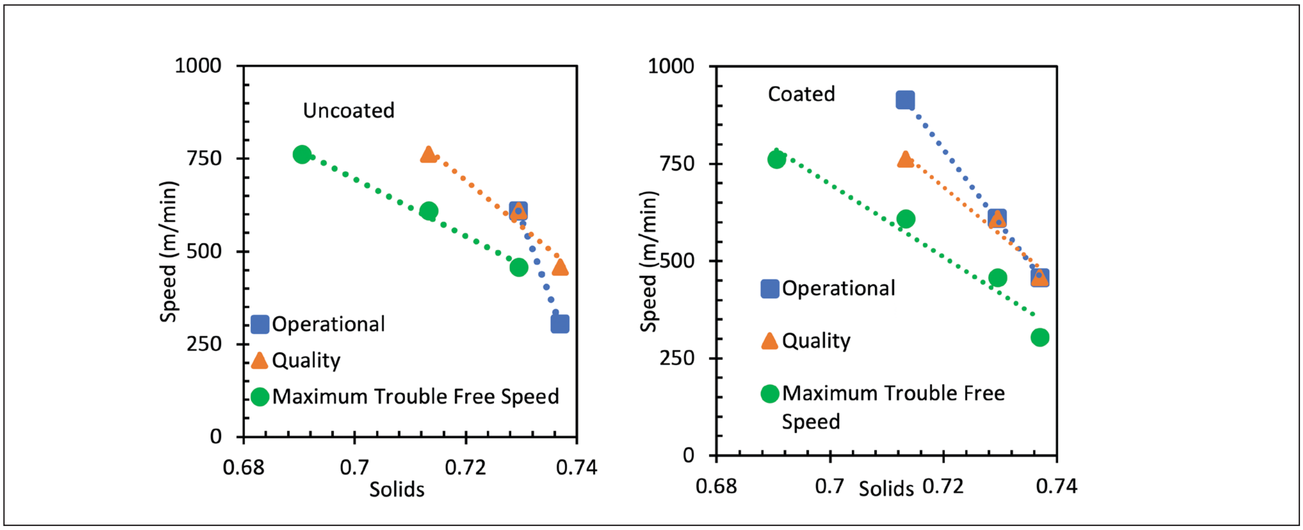
4. A frame taken from a video of K15 pigment at a solids content of 73.7% and roll speed of 457.2 m/min showing spitting from the blade. The blue dotted oval shows the spits.



5. Left: Two scratches running parallel with the machine direction in the coating sample from a trial using K90 pigment at 55.8% solids concentration and a roll speed of 914.4 m/min on the uncoated substrate. Right: Skips in the coating from a trial using K15 pigment at a 71.3% solids content at a roll speed of 914.4 m/min on the uncoated substrate. Both images are illuminated with a black light.



6. Runnability window developed for K15 pigment on both the uncoated and coated substrates.



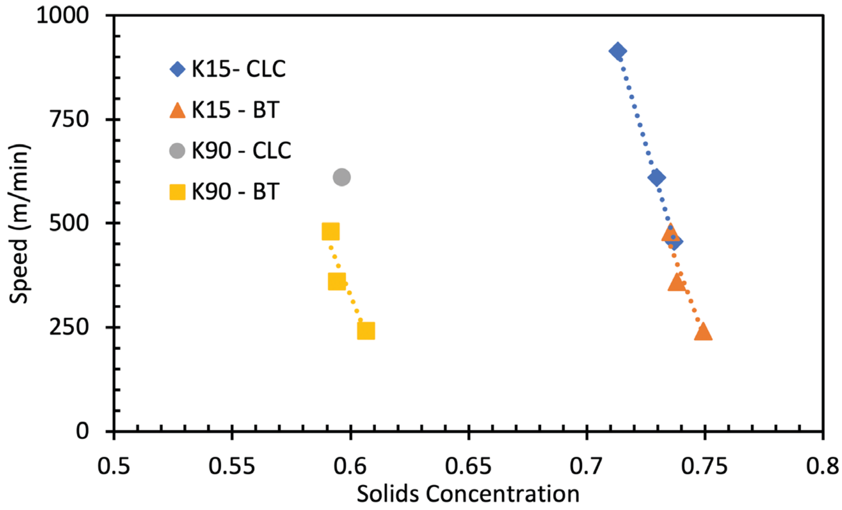
7. Runnability window developed for K90 pigment on both the uncoated and coated substrates.

problems with the quality of the coated product at the highest solids content. For the coated substrate, both operational and quality problems appear together for the highest two solids concentrations.

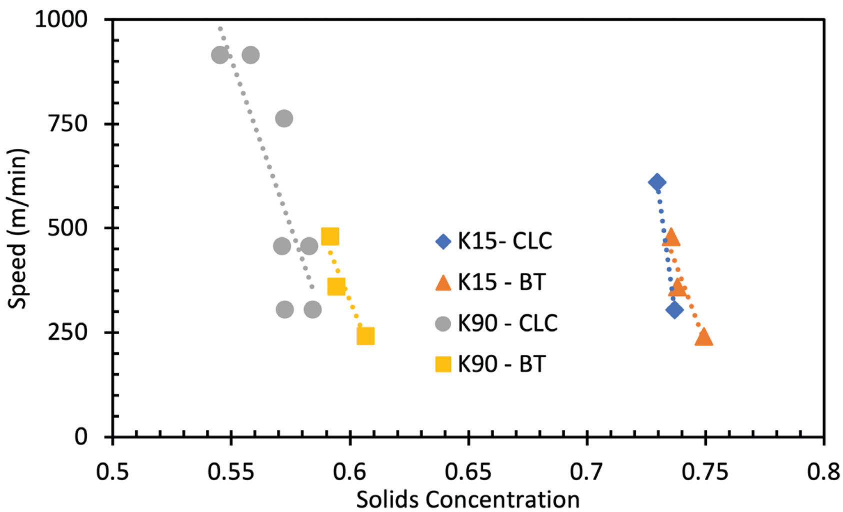
The results from the runnability study with K90 are shown in **Fig. 7** for both the uncoated and coated substrate. During the trials with the coated substrate, operational issues only developed once when reaching the highest solids tested. But during the tests with the uncoated base sheet, blade deposits were much more prevalent. The difference between these runnability windows could be attributed to the effect that the base sheet has on the coating process. The uncoated substrate has a higher permeability and could cause more dewatering of the coating than the less-permeable coated substrate.

The results from the runnability trials on the CLC were compared to the findings of the bench top blade coater discussed in Part I of this study [12]. Since the bench top blade coater did not employ a base sheet, only the onset of operational defects could be detected. The results of this comparison are shown in **Fig. 8**. The maximum speed of the bench top coater was similar to the lowest speed conducted on the CLC, and for K15, the onset of operational defects overlaps for the two devices. With the rubber roll covering of the bench top blade coater being smooth and non-absorbent and the coated side of the substrate sharing parallel qualities, the speed and solids concentration when blade deposits appear begin to line up. The results in Fig. 8 are important in that they show that the bench coater results do match well with the higher speed CLC results. The bench scale results likely could be used to predict the occurrence of operational issues at a high speed.

When the results from the bench top blade coater are compared to the onset of operational issues on the CLC using the uncoated substrate, a small reaction to the absorption of water into the base sheet is seen. This phenomenon can be



8. Comparison of the results for the onset of operational problems for both K15 and K90 on the cylindrical laboratory coater (CLC) with the coated substrate (CLC) and the bench top blade coater (BT).

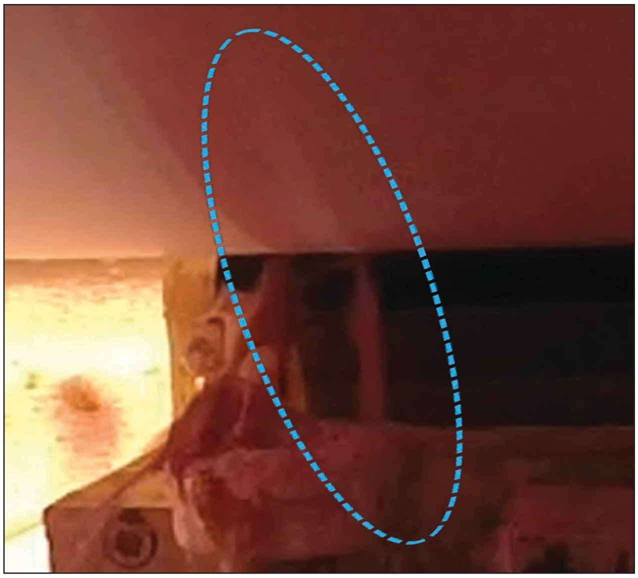


9. Comparison of the results for the onset of operational problems for both K15 and K90 pigments on the CLC with the uncoated substrate (CLC) and the bench top blade coater (BT).

seen in **Fig. 9**. For K90 at the same machine speed, defects begin to appear at lower solids concentrations on the CLC than with the non-absorbent bench top blade coater. With K15, the comparable solids concentrations displayed blade deposits at differing machine speeds. Blade deposits were seen at slower roll speeds on the CLC with the uncoated substrate than with the bench top. There is, therefore, a minor effect of dewatering and absorption occurring during the coating application process when the coating is applied to the uncoated side of the substrate on the CLC.

During the examination of the recorded video taken throughout the runnability trials, evidence of slip plane breakage during coating became evident. **Figure 10** shows still images taken from the video. Coating is being extruded from the blade nip. Also, a non-uniformity in the coating layer on the substrate is visible. This phenomenon could be related to a similar event seen on the bench top blade coater. A slip plane forms between the blade and the coating layer due to relaxation-induced dilatancy. Something causes that slip plane to move from the surface of the blade to the interface between the coating and the substrate, thus allowing the coating to be extruded from the nip and causing a defect on the surface of the final product. Further investigation into the potential causes of the movement of the slip plane will be required.

In the quest to determine the causes behind the onset of runnability issues, an analysis of the characteristics of the coating at the solids concentration that developed operational issues was undertaken using both the results from the bench top blade coater and the CLC using only the coated substrate. Only the coated substrate data was used, due to the effect that dewatering of the more porous and permeable uncoated substrate has on the runnability limits. Many past studies indicated a relationship between runnability and the viscosity. The viscosity of each slurry at high solids level was estimated after fitting Mooney's equation, shown in Eq. 1, to the experimental data collected. The more common Krieger-Dougherty equation could not be used because the solids content of some of the tested slurries was above the maximum flowing fraction found by fitting the data at various solids. Fitting the data to the Mooney equation results in larger maximum flowing fractions than the Krieger-Dougherty equation. The calculated viscosities for all the tested slurries are displayed below in **Fig. 11**. The viscosity of the slurries calculated are not comparable. The viscosity for the highest solids concentration for K15 is the about the same viscosity for lowest solids content of K90:



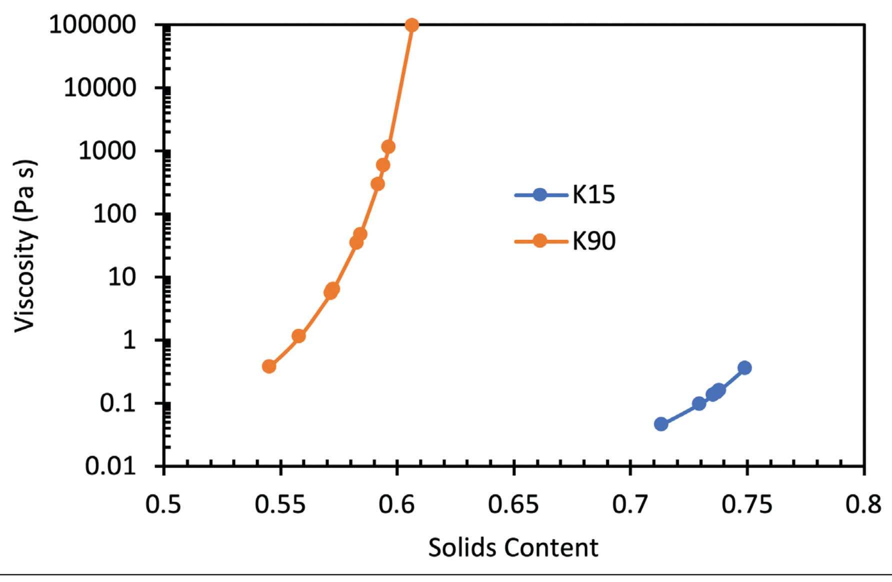
10. Image taken from a video of K15 pigment at 73.7% solids content and a roll speed of 457.2 m/min displaying a spit from the blade and defect on the substrate surface.

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

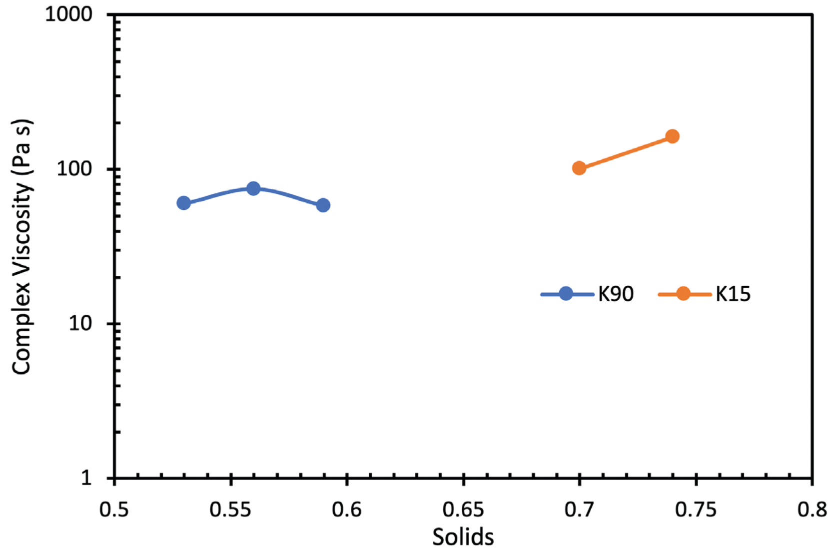
where μ is the viscosity of the coating suspension, μ_s is the viscosity of the fluid phase, $[\mu]$ is the intrinsic viscosity, and ϕ and ϕ_m are the volume fraction and the maximum flowing fraction of the particulate phase, respectively.

Many of the clean operating conditions on the bench top blade coater and the CLC are at larger solids levels than what can be measured in the concentric cylinder rheometer. This result indicates that a dynamic effect is at play in the blade coaters, where the suspension experiences the shear field for a short amount of time. The short duration shear event under the blade may not give time for some type of disordered structure to develop compared to the concentric cylinder situation. This short duration allows the suspension to be applied with the blade at solids larger than what would be expected from the steady shear behavior.

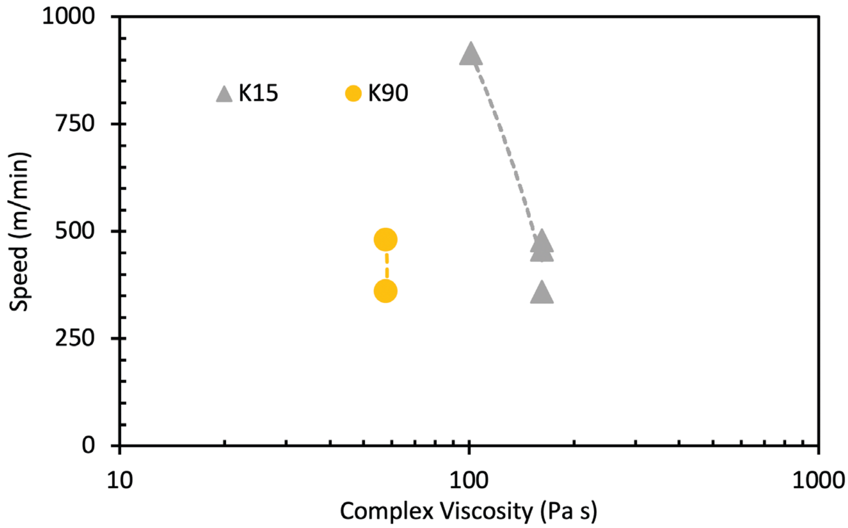
With the steady shear viscosity unable to determine a correlation with the onset of operational problems, exploration into the complex viscosity was conducted; the complex viscosity is not the same as a dynamic viscosity but may give a



11. Calculated viscosity (Pa s) from the Mooney equation for K15 and K90 pigments at the solids content used in the runnability studies.



12. A plot of the relationship between the complex viscosity and the solids content for K15 and K90 pigments.

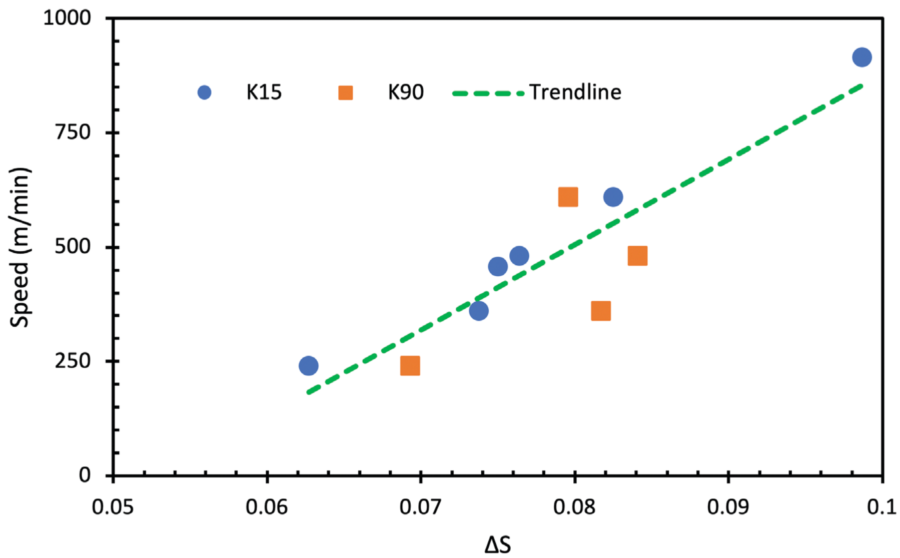


13. Plot showing the relationship between the complex viscosity and the maximum coating speed for K15 and K90 pigments.

sense of the effective viscosity at short times. **Figure 12** displays the complex viscosity at the solids content that was used in the runnability studies. The value shown in the figure is the average complex viscosity over the frequency range of 10 to 30 Hz. There was a substantial amount of noise in the data. The complex viscosities at different solids concentrations are of similar values while in steady shear there are orders of magnitude difference in viscosity. As the solids concentration increases, there is only a small change in the complex viscosity.

Because the complex viscosities are of the same magnitude for the two pigments, there might be a relationship with the runnability of the suspension. **Figure 13** displays the relationship between the complex viscosity and the machine speed where operational issues developed during the runnability studies. There may be a trend that could be used to predict when a coating might begin to exhibit operational issues. Currently, it is not able to predict when a pigment will exhibit runnability issues. This suggests, however, there might be potential to provide information on the dynamic response of the particles during blade coating. Additional research into the area will be needed to determine this potential relationship.

Operational difficulties began to appear at high solids concentrations approaching the immobilization solids for the pigment. Recall that the immobilization solids concentration



14. Linear relationship (R^2 = 0.7998) between ΔS and the roll speed at which operational issues appear for both K15 and K90 pigments.

is a function of the shape, particle size, and size distribution of the pigment. The difference between the immobilization solids and the solids content of the tested slurry, which will be called Δ*S*, was calculated for all tests. There seems to be a connection between Δ*S* and the runnability window. **Figure 14** displays the relationship between these two parameters. As the Δ*S* increases, the slurry was able to run at higher speeds before blade deposits were visible. As the solids concentration approaches the immobilization solids, Δ*S* thus heads towards zero, and operational problems start at very low speeds. The relationship appears to be linear, with a slope of 18684 m/min. K15 data points are closer to the predicted trend. There does seem to be a bit more scatter with the K90 data points.

While the results are for only the two pigments used in this study, the data does seem to collapse onto a single line. If this relationship holds true for other pigments of varying shape factors, the maximum operational speed could be quickly calculated. A simple test to determine the immobilization solids would be necessary to estimate the maximum coating speed for the desired solids concentration. The immobilization solids will take into account the particle shape and size distribution. This relation would prove to be very useful for many applications

CONCLUSIONS

The coating window using the CLC was determined for two pigments of varying shape factors using two substrates. Operational and quality issues were observed, and the onset of problems occurred around the same operating conditions. The effect of the permeability differences between the two base sheets was minor. The results obtained from the bench top blade coater and the CLC did show correlation. The solids content of all the slurries was high and approaching the immobilization solids.

These suspensions could be applied at solids higher than the maximum flowing solids value obtained by fitting the Krieger-Dougherty equation. The operational limits did not correlate with the viscosities predicted from the Mooney equation. Operational limits occurred at steady shear viscosities that were orders of magnitude different, but for the complex viscosities they were similar; this result indicated that the operational issues must relate to a dynamic response of the suspension. The runnability limits did correlate with Δ*S*, the difference in solids between the immobilization solids and the coating solids. This parameter seems to have a linear relationship with the operation limits. This relationship could be attributed to the lack of available space for particle motion in the high shear field underneath the blade and may be of some value in predicting operational limits of other systems. **TJ**

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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. This research focused on the effect that pigment particle shape has on the operational limits.

During this study, it was interesting to find that it took more paper and coating materials to run a large runnability study on the cylindrical laboratory coater (CLC) than what had been estimated. It was also interesting to see how the difference between the solids content and the immobilization solids displayed a relationship for the onset of runnability issues.

This research provides insight for mills on the behavior differences between pigment shapes. The next step is to expand the number of pigments analyzed and experiment with various coating color formulations.

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