OPTIMIZING SOLIDS AND RHEOLOGY IN BLADE COATING USING PIGMENT BLENDS - PART 1

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ABSTRACT
The paper industry has long known the potential advantages of running the highest possible coating solids from both a quality and economic standpoint. The limiting factor has always been blade runnability and coat weight control. The excellent rheology of calcium carbonate (GCC) has traditionally been used to increase the maximum solids level, but even with high levels of this material the coating solids becomes quite demanding when very/ultra fine types are used to produce glossy grades.

Work has been done using lab and pilot coater trials to evaluate the influence of pigment shape, size and particle size distribution on the upper solids limit of a coating formulation. The major impact of pigment packing once all other components in the formulation are optimized is theoretically characterized.

A numerical model has been developed to describe and better visualize the influence of GCC particle size on the maximum volume fraction of the dispersed pigments. A simple but effective concept of blending a suitable coarse GCC fraction into the matrix of the fine host pigment is described and practical results presented.

INTRODUCTION
Coated paper producers today face an immense challenge searching for business profitability whilst experiencing fierce market conditions. The crisis is affecting the graphic paper sector seriously, and to survive it will require a lot of creativity and initiative.

In recent years coating formulations have been significantly simplified, binder levels have been reduced and often more expensive pigments replaced by less costly types.

Alongside these important cost reduction measures, the producer of coated papers is continuously looking for new ways to further improve his process and above all to optimize cost efficiency.

It is therefore evident that the solids content of coating colors is currently regarded as one important option to further reduce production cost. In fact, the topic maximum dry solids content is continuously being addressed by many producers.

The potential advantages of higher dry solids are numerous in terms of economics, quality and environmental aspects (Bluvol et al., 2007).

• A better hold-out of the coating layer will improve the optical characteristics of the paper, in particular fiber coverage and sheet gloss when a large proportion of GCC is used in the pigment system. Fast setting of the coating favors good coverage.

• A more uniform binder distribution due to reduced migration into the base paper, and gentler drying contribute to better printability.

• Lower binder migration tendency due to faster immobilization and higher pigment packing (lower interparticle void volume) will positively affect binder demand.

• Higher intrinsic water retention/viscosity allows for reduction of additives, thickeners, etc.

• Better smoothness due to less re-swelling of fibers (greater surface stability and shrinkage reduction).

• Significant savings in drying energy or higher coater speeds possible when drying capacity limited.

• Lower level of biocides associated with reduced water in the system.

Figure 1 illustrates the drying demand in kWh/tonne coated paper in an off-line coater according to different solids contents and coat-weights. The values are calculated based on the
empirical assumption that 2 kWh/kg $H_2O$ are needed for removing the excess of water in off-line coating. For on-line coating the empirical assumption would be 1.5 kWh/kg $H_2O$.

The results show that a $\Delta$ solids of 3% represents a major savings in drying energy. In Figure 2 an economical quantification of the reduced drying energy is shown according to different energy prices (MWh).

The estimation of drying demand clearly shows the potential in cost savings when increasing the solids content. The figures show a cost reduction of approx. 1.8 USD/tonne coated paper when rising dry solids by 3% at 60 USD/MWh and 12 g/m²/side coat-weight.

Many producers of coated paper have continuously optimized their formulations to maximize solids. The maximum level being the threshold at which serious drawbacks for paper quality and process efficiency will trigger:

- excessive blade load for controlling the target coat-weight resulting in a higher number of web breaks and increased blade wear;
- rheology limitations or poor blade runnability leading to unacceptable scratching, bleeding, whiskering, etc.

Blade coating runnability is indeed a very complex subject where a myriad of interdependent parameters play a significant role (Gane, 1997; Gane, 1992). Figure 3 shows a summary of the main elements influencing manageable solids content in blade coating. The list above is certainly not complete. The effect of each single parameter is very difficult to assess. We believe, however, that the following dominant parameters influence mostly high shear viscosity/high strain rate rheology in blade coating:

- pigment system;
- coat-weight and coater speed;
- pulse dewatering under rapid rates of change of strain.

Figure 4 shows the calculated shear rate (coater speed (m/s) ÷ wet film thickness (µm)) according to solids content, coater speed and coat-weight. It is debatable whether these shear rates actually exist under the blade, since coating colors are viscoelastic, and the rapid rates of change of induced stress probably mean that the color is behaving more as an elastic solid and not sheared according to a uniform shear field. Effects such as boundary slip then account for phenomena such as bleeding, and the formation of elastically induced dilatancy likely account for scratching. Nonetheless, capillary viscometry is often used to represent the situation if uniform shear were assumed, and this can be adopted here to reflect the impact of changing various color parameters, albeit that they may well manifest themselves differently under the blade.

According to the calculated shear rates, a coater speed increase of 250 m/min, whilst keeping the coat-weight constant, is nearly equivalent to a decrease of 2 g/m²/side coat-weight application at constant speed. Moreover, the calculations show also that an increase of 3% in solids has a lower impact on the shear rate for a given coat-weight than the speed reflected as a coat-weight change in the aforementioned steps. This is, however, clearly not a realistic scenario, as the solids content will additionally increase differently by the unavoidable change in partial dewatering of the coating color before the blade as the pressure pulse changes due to compensatory speed increase in blade load. In short, the coater type (application roll, jet), dwell time (coater type and speed), backing roll diameter and base paper characteristics (pulse dewatering related to sized/unsized, precoated, porosity, permeability, basis weight, etc.) will play a major role on the effective shear rate, or, more accurately described, rate of change of induced stress at the blade nip.

The ideal application solids in blade coating

Coating solids up-concentration between application and
metering, and certainly the much more relevant dewatering at the blade nip are responsible for many runnability issues and pose a limitation to the solids content of the coating color.

For every coating color there is a so-called immobilization point, which is the given solids point at which the color has lost any plasticity or deformation ability, and its viscosity increases abruptly to a very high value. This effect is even more pronounced as the elasticity of the color increases disproportionately to the viscous component, creating solidification as a function of strain rate applied.

Figure 5 shows schematically three possible scenarios of solids content in blade coating. Scenario 1 is not optimized and several disadvantages result from the low color concentration, such as poor hold-out, coating shrinkage and profile instability. Scenario 2 is the narrow operating window where the solids have been optimized and, therefore, the most advantageous for both quality and economics. Finally, scenario 3 illustrates too ambitious solids content where serious drawbacks should be expected in respect to machine runnability.

Note that region 2, which represents the ideal solids, is quite sensitive and will have very tight borderlines. Everyone familiar with coater trials knows that often a very small dilution solves troublesome runnability issues. We see also in Figure 5 that the immobilization point of any given coating formulation will determine along with all other “given” process variables the manageable optimized, respectively maximized, solids content. It is, therefore, in the nature of things to try to “extend” the immobilization solids as much as possible using all available means.

The present study focuses on how the utilized pigment(s) in the coating formulation will influence maximum solids content. As expected, the extensive number of trials has shown that the pigment system has a paramount effect on manageable dry solids once other formulation components are themselves optimized.

The theory of pigment packing – A pragmatic approach

Pigment particle size, particle size distribution and shape play the greatest role in determining the rheology of coating formulations at high shear rates. Figure 6 shows the impact of pigment type on viscosity according to solids content.

Both low and high shear viscosities depend very much on particle shape, size distribution and fineness, though low shear is also strongly dependent on dispersion and polymer components in the coating color. For optimally dispersed blocky pigments (GCC) at the same solids concentration, the viscosity is higher the narrower the particle size distribution and the greater the fineness. For platy pigments (clay) at constant solids, the viscosity increases dramatically with higher aspect ratio. Figure 7 shows the usual slurry solids for various coating pigments available in 2009 to coating paper mills in Europe.

Solids content up to 78% are common for relatively coarse to very fine GCCs. Ultrafine GCCs, on the other hand, are supplied at 75% solids. Steep particle size GCCs and PCCs merely reach 72% solids. Platy pigments like clay and talc can be made-down in some cases at only 60%-65% when the aspect ratio is very high. Fine high glossing clay can be delivered at 73% solids. These significant variations in slurry solids already give a clear indication about the influence of pigment packing depending on particle fineness, size distribution and morphology.

It is all about particle packing

Pigments with steep PSD (NPSD) will demand a higher volume of water in the dispersion than pigments with broad PSD (BPSD). The suspensions with BPSDs can pack tightly (more densely) due to fine particles filling the small voids between bigger particles, so that higher solids content can be attained.

Monodisperse systems (NPSD) produce much higher viscosities...
at same solids than polydisperse (BPSD) systems. The more “bulky” packing of NPSD pigments is however desirable for higher light scattering and better coating hold-out (opacity, hiding power, coverage). If compared to a coarser type, a finer GCC (BPSD) demands a higher volume in the dispersion due to the larger interspace required between the much more frequently occurring fine particles. A relatively coarse GCC of BPSD will, therefore, demand a lower volume in the dispersion for the same mass of CaCO₃. Figure 8 illustrates the volume demand of various GCCs and clays. Platy clays rotate to some extent on their axes demanding a significantly larger volume in the suspension. Finer clays having low aspect ratio are much closer to the isometric form and require, therefore, less free space (water) in the suspension to move unhindered. It should be noted, however, that partial alignment of platy pigments in the direction of flow means that the full spherical swept volume is only occupied by some particles.

Packing density thus depends upon the particle size distribution (PSD), the particle shape (and shape distribution) and also the fineness. In general, the following tendencies can be observed (Larsson, 2004).

### The concept of volume fraction

The concentration of slurries and coating colors is normally expressed in terms of “solids content” or mass fraction. It gives a clear idea about the mass relationship between solids and vehicle (water). Solids content can easily be determined using a suitable scale combined with drying (IR/microwave heaters). The rheological characteristics of a suspension do not depend, however, on the mass concentration, but rather on the required “volume” of the dispersed solids. Therefore, we need to introduce another variable, “the pigment density”, in order to better understand the pigment effect on slurry and coating color concentration.

The simple relationships below illustrate the difference between mass and volume fraction:

\[
\text{mass fraction} = \frac{m_{\text{solids}}}{m_{\text{solids}} + m_{\text{water}}} \times 100 = \text{solids content}
\]

\[
\text{volume fraction} = \frac{V_{i}}{\sum V_{i}} \times 100 = \text{volume solids content}
\]

Where \(V_{i}\) is the volume of the specified component, and \(\sum V_{i}\) is the volume of all components prior to mixing (including water).

The volume fractions are related by density to the masses of the solids being considered. Evidently, rheology will be influenced by the volume the solids occupy in the dispersion in relation to the fluid volume (volume relationship of solids to the continuous phase). The examples in Figure 9 illustrate how various products will differentiate rheologically more distinctly when the solids are expressed in volume fractions:

Note that at the same solids content (78%) the volume fraction of GCC (0.57) is 24% higher than the volume fraction of TiO₂ (0.46). At the same volume fraction of GCC at 78% solids, TiO₂ would reach 85% solids content!

\[
\text{solids content} = \frac{850}{850 + 150} \times 100 = 85\% \\
\text{volume fraction} = \frac{850/4.23}{850/4.23 + 150/1} = 0.57
\]

### The rheology of GCC pigments

We have already seen that the particular morphology of GCC, a blocky, almost spherical pigment, facilitates very dense pigment packing (rheological behavior) making it predisposed for high solids coating. The coated paper industry has long ago identified this advantage and continuously tries to maximize this benefit to the utmost limit. In fact, we have seen a continuous movement towards higher solids in the last twenty years.

The particle packing of GCC depends on PSD and fineness. These two characteristics not only determine viscosity, but also the water retention, immobilization point (time) and immobilization solids. Figure 10 shows the water retention characteristics of various GCCs. (Gradek instrument; 0.5 bar; 9 sec.; 10 mL).

Among other important factors like mineral type and characteristics, dispersant type and level, etc., water retention is also a function of particle fineness and distribution (specific surface). The finer the pigment, the higher the water retention will be for polydispersed types (BPSD). Steep particle distribution (NPSD) decreases water retention due to the much lower number of ultrafine particles and therefore pronounced permeability typical of monodispersed pigments. High permeability results in high dewatering under pressure.

The results in Figure 10 relate to identical coating formulations using different GCCs at a solids content of 66%. The use of a

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**Figure 8.** Particle shape, size distribution and fineness; influence on solids content and runnability according to volume swept out by the rotation of the particles

**Figure 9.** Solids content and volume fraction; density (\(\rho\)); GCC = 2.7 g/cm³; clay = 2.6 g/cm³; latex = 1.03 g/cm³; TiO₂ (rutile) = 4.23 g/cm³

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suitable water retention agent at an appropriate level is needed for maintaining stable solids over time if pressure or dwell time induce excessive dewatering, therewith ensuring trouble-free blade runnability (extends the immobilization time).

Figure 11 shows the immobilization point of various GCCs with BPSD; an ultrafine UF BPSD\textsuperscript{1}, a fine F BPSD\textsuperscript{2} and a relatively coarse C BPSD\textsuperscript{3}. In addition, the behavior of a very fine NPSD GCC VF NPSD\textsuperscript{4} is displayed. The C BPSD\textsuperscript{3} needs a much longer time to reach the immobilization point, this in spite of its lower water retention. VF NPSD\textsuperscript{4} immobilizes much faster than all BPSD pigments. Figure 12 shows the immobilization solids of the aforementioned GCC types. Note that the measurement of final solids is not very accurate due to solids gradient in the filter cake formed during the determination of the immobilization point. Variability of up to \(\pm 5\%\) in immobilization solids results has been detected. The displayed data averages the results of three measurements.

The tendency is clear, the relatively coarse GCC C BPSD\textsuperscript{3} will immobilize at much higher solids than the ultrafine UF BPSD\textsuperscript{1} type, thus explaining the longer time to reach the immobilization point shown in Figure 11. In contrast, the VF NPSD\textsuperscript{4} immobilizes at clearly lower solids due to its spatial configuration adverse to flow at high concentrations (higher volume demand).

The differences in immobilization time and solids content between the different GCC types are also critical for film coating. The initial solids of the coating color must be selected accordingly, so that runnability issues like dry build-up, misting and dusting remain controlled (Gane, 2001; Gane et al., 1997).

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REFERENCES


