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The influence of fine kaolin and ground calcium carbonates on the efficiency and distribution of fluorescence whitening agents (FWA) in paper coating

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KEYWORDS: FWA, Coating structure, Scattering, brightness, CIE whiteness, Microscopy

SUMMARY: Fluorescence whitening agent (FWA) distribution in paper coating is affected by paper and coating chemistry, coating and drying process. A pilot scale coating is a proper way to simulate a multi-layer coating. Fine kaolin blends with broad and narrow particle size distribution (BRD and NRW) ground calcium carbonates (GCC) were studied in top coat of double-coated paper from a high speed pilot coating. FWA efficiency was checked with TAPPI brightness and ISO CIE whiteness. Classic optical theory applications in light transmittance were further verified by another pilot scale coating with mixture design of experiment (DOE). This study found that when coating over a dark base stock containing no FWA, NRW GCC coating produced a higher light scattering coefficient, $\alpha_{\text{nrw}}$ as reflected in higher TAPPI brightness. However ISO CIE whiteness was lower than or equal to that of BRD GCC. An increase of $\alpha_{\text{nrw}}$ of NRW GCC coating to UV light is due to the larger pore volume density, $p$, and to a possible scattering cross-section, $\sigma(\lambda)$ increase as wavelength reduces. In either case, the combination of $p$, and $\sigma(\lambda)$ makes $\alpha_{\text{nrw}}$ larger in NRW GCC than in BRW GCC to attenuate short wavelength UV light more, i.e. a reduced UV efficiency. The results of this study suggest that for FWA efficiency and uniformity it is desirable to design a carbonate and kaolin pigment system to produce a gradient FWA distribution in thickness direction with the highest FWA concentration towards surface. If wood free or ground wood base paper and board contain FWA for the whiteness and uniformity from multi-scattering properties, BRD GCC with fine kaolin can further improve CIE whiteness by allowing more UV light to transmit to the pre-coat and base paper to generate more blue light and to be backscattered through it.

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Fluorescence whitening agents (FWA) are widely used in paper to increase whiteness. It is well known that a base paper containing wood fiber absorbs UV light and reduces the efficiency of FWA (Johnson 1991; Johansson 2000; e.g. Forsskål 2000). In paper coating, other factors are more critical as evidenced from a distyryl-biphenyl (DSBP) FWA lab study in the correlation of absorption and fluorescence, the yield between absorbed and emitted light, and the position of saturation point (Rohringer, Fletcher 1996). In a lab study of pre-moisturized pre-coat to prevent top-coat FWA from migrating into pre-coat, it was proposed to use FWA in top-coat and TiO$_2$ in pre-coat (Heikkilä et al. 1998). In a recent study of coating over glass, the reflectance was found in the range of 60-80%, and for kaolin somewhat higher in the visible region but lower in the UV-region (Fjellström et al. 2007a). The previous studies featuring lab-scale used kaolin and calcium carbonate separately without investigating the coating structure of fine kaolin and carbonates blend impacts on optical properties.

The FWAs used in paper industry are mainly sodium-salts, thus water soluble. The $\pi$-electrons in the conjugated chain absorb ultraviolet radiant energy in 300-360 nm wavelength and re-emit the energy mainly in 400-450 nm, blue light range. FWA distribution is affected by paper and coating chemistry, coating and drying process. A pilot scale coating is a proper way to simulate the complicated coating process. We conducted a pair-comparison pilot coating, then a pilot-scale design of experiment (DOE) to investigate kaolin and carbonate, and coating structure effects on FWA efficiency.

In an effort to describe the optical properties of highly scattering materials while reducing the computational difficulties, simplifying flux models have been designed for the radiative energy transport. A volume scattering medium consisting of a collection of scattering centers is described as homogeneous material characterized by effective scattering and absorption properties that are determined by its internal structure. In this approach, the fundamental equation of radiative transfer is based on the balance between the net flux change, the flux input, and flux continuing out in an infinitesimal volume. Assuming two diffusing components, a one-dimensional model based on plane symmetry for unit cross section was initially proposed (Schuster 1905). The model relates the phenomenological, effective scattering $S_{\text{eff}}$ and absorption $K_{\text{eff}}$ coefficients to measurable optical properties such as diffuse reflectance or transmittance. The most successful extension of this model is the so-called Kubelka-Munk (KM) theory (Kubelka, Munk 1931).

A considerable body of work was dedicated to relate the KM parameters to microstructure and to incorporate both the single- and multiple-scattering effects. Refinements and higher order flux models were developed. A more accurate model that accounted for the usual condition of collimated incident radiation was elaborated (Reichman 1973). A four-flux model was developed that includes certain anisotropy of the scattered radiation (Maheu 1984). A six-flux model was implemented to incorporate the effect of particle shape and inter-particle correlation (Emslie 1973). In spite of the fact that it is based on empirical determination of

coefficients and that its range of applicability is rather unclear, the simple-to-implement KM theory gives a reasonably good description of experiments and has found applications in areas such as coatings, paper, paints, pigments, medical physics, and atmospheric physics.

Initially the internal reflection of photons at the medium’s boundaries was ignored. Later, the reflectance was included to show that by theory and experiment, the reflectance and absorption of a non-homogeneous specimen depend on the direction of illumination, whereas transmittance does not (Kubelka 1948, 1954). In addition to the assumptions mentioned already, the difficulties in using KM equation in this multi-layer coating study are that it does not have a wavelength parameter, the scattering coefficients of different layer cannot be experimentally determined from a coated whole sheet, and the scattering coefficients vary as thickness changes.

Assuming the normal incidence of a beam with irradiance \( I \) (Fig 1), the total flux transmitted through the slab is given by (Bohren, Huffman 1998)

\[
I_t = I(1 - R)^2 e^{-a h} (1 + R^2 e^{-2ah} + R^4 e^{-4ah} + \ldots)
\]  

where \( h \) denotes the thickness of the slab, the optical absorption coefficient \( \alpha = \frac{4\pi\sigma}{\lambda} \) denotes the incident wavelength, and \( k \) denotes the imaginary part of the complex refractive index of the material. The reflection coefficient \( R \) of an optically smooth surface is

\[
R = \frac{(n_i - 1)^2 + k_i^2}{(n_i + 1)^2 + k_i^2}
\]  

where \( n_i \) is the real part and \( k_i \) is the imaginary part of complex refractive indexes of the slab.

It is interesting to note that a heuristic criterion for smoothness is \( d < \lambda/8 \) where \( d \) is the height of surface irregularities (Beckmann, Spizzichino 1963). Glossy coated paper with fine kaolin and calcium carbonate has a typical roughness, \( \alpha_i = 15-40 \) nm as measured by near-field scanning optical microscopy (NSOM) (Dogaru, Carter 2006) and, therefore, satisfies this smoothness criterion.

The total transmittance through the slab is obtained by summing up the infinite series in Eq [1] to find

\[
T_{\text{slab}} = \frac{(1 - R)^2 e^{-a h}}{1 - R^2 e^{-2ah}}
\]  

A further approximation can be used to simplify Eq [2]. If the secondary reflection from the other side of the slab \( R^2 e^{-2ah} \) is small compared with unity, which is basically true for light transmittance in a very opaque pigment coating, then Eq [2] reduces to

\[
T_{\text{slab}} = (1 - R)^2 e^{-a h}
\]  

Though it includes the wavelength parameter, there are a number of practical aspects which are not accounted for in this representation. First, the coating layer has many small air voids of refractive index around unity (LePoutre 1989), which significantly increases the importance of scattering in comparison with absorption. Another complication arises in paper coatings that have random multiparticle orientation and packing, i.e. variety of optical dipoles with distributions from multi-ingredients, irregular air void size and shape distributions on both the surface and the inner layer of a coating. Moreover, optical interfaces are not homogeneous as assumed in this approximation. Due to variations in surface topography and dielectric properties along the interface, a confinement of evanescent waves occurs in the near-field of media random coating layer that may affect statistical properties of optical fields in the vicinity of interfaces (Apostol et al. 2006). More advanced optical scattering theories, such as T-matrix and coupled (discrete) dipoles approximation (CDA) etc. may be utilized to describe the scattering from inhomogeneous coating layers (Tsang et al. 2001).

For the purpose of this discussion about coating pigments and structure influence on FWA efficiency within a porous paper coating, we treat the coating layer as a unit and use the extinction coefficient of a coating layer in an approximate equation in the form of

\[
T_{\text{coating}} = (1 - R)^2 e^{-a_{\text{total}} h} = (1 - R)^2 e^{-\frac{4\pi\alpha_{\text{ext}} h}{\lambda}}
\]  

where the \( \alpha_{\text{ext}} \) denotes extinction coefficient

\[
\alpha_{\text{ext}} = \alpha_{\text{abs}} + \alpha_{\text{scatt}} = \sigma(\lambda)\rho_v + \alpha_{\text{scatt}}
\]  

Eq [4] implies that high reflectance and thickness, as well as low wavelength reduce the light transmittance, \( T_{\text{coating}} \). In porous paper coating, the attenuation due to absorption, \( \alpha_{\text{abs}} \) remains relatively the same because it is primarily determined by the chemical composition and molecule structure of the coating chemicals i.e. both BRD and NRW GCCs are calcite carbonates. The attenuation due to scattering is measured by an averaged coefficient \( \alpha_{\text{scatt}} = \sigma p_v \) that is proportional to both scattering cross-section \( \sigma \) and the volume density of pores \( p_v \). Hence, the scattering coefficient is directly affected by the increase in pore volume fraction. As a result, the attenuation increases significantly due to the increase of \( \sigma \) and \( p_v \). We note that \( \alpha_{\text{scatt}} = \sigma(\lambda)p_v \) varies depending on wavelength, and is valid for a mono sized pore distribu-
tion, but in real coating one has an entire distribution of sizes. However, this would only make the result more specific to a particular coating composition, but will not affect the main conclusion that the increase in pore size and number leads to an increase in scattering. Also, it will not affect the statement about the wavelength dependence of attenuation that is not included in KM approximation. Another important observation relates to the wavelength dependence of the scattering cross section of an air pore. This is the origin of the spectral variations in both transmission and reflection from diffusing coatings.

**Experimental**

The first coating trial was run with paired-comparisons (Table 2). The second, a 3-factor DOE (the same pigments with different levels while all the other factors were the same as in the first trial), totaling eight trial points, was a mixture design and optimized with distance-based optimality. The DOE design and analysis was done with Minitab 15 statistics software (Minitab, USA).

Ground calcium carbonates (GCC) with broad size distribution (BRD) and with narrow size distribution (NRW) were from Omya AG. The fine kaolin was from KaMin LLC. The particle size distribution (PSD) was determined by sedimentation analysis (Sedigraph), and brightness and b-value by TAPPI T452 (Technidyne) at KaMin Laboratories, Macon, Georgia, USA (Table 1).

Table 1. TAPPI brightness and b-value, particle size distribution of pigments. BRD = broad particle size distribution, NRD = narrow particle size distribution.

<table>
<thead>
<tr>
<th>Pigment</th>
<th>TAPPI b-value</th>
<th>Cumulative particle size distribution, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Brightness</td>
<td>% &lt;5 µm &lt;2 µm &lt;1 µm &lt;0.5 µm &lt;0.2 µm</td>
</tr>
<tr>
<td>BRD GCC</td>
<td>95.3</td>
<td>0.42 96.6 94.1 70.6 42 20.3</td>
</tr>
<tr>
<td>NRW GCC</td>
<td>94.9</td>
<td>0.26 98.9 98.4 86.8 51.9 19.6</td>
</tr>
<tr>
<td>Fine Kaolin</td>
<td>90.9</td>
<td>2.19 99.1 97.2 93.7 79.7 44.1</td>
</tr>
</tbody>
</table>

Wood free base paper was from Fraser Papers, Canada: basis weight 62 g/m²; TAPPI brightness 85.4 and b-value 4.1.

**Preparation and properties of coatings**

Coatings with different combinations of pigments, designed to represent a range of coating compositions with variable porosities, were prepared. The coatings (Table 2) were prepared on pilot scale according to the pilot coating facility procedures (Ma et al. 2007).

Table 2. Pigment compositions of first pilot coating, in parts by weight. In addition, all coatings contained 0.15 parts dispersant Dispex N-40 (Ciba Chemicals, Switzerland), 12 parts latex XU31301 (Dow Chemicals, USA); 0.5 parts carboxymethyl cellulose Finnfix10 CMC (CpKelco, Finland); 0.7 parts fluorescence white-enhancement agent Blankophor P FW A (Bayer, Germany); 0.7 parts lubricant Devflo 50C (Devoden, USA) and 0.3 parts cross linker Bermet 2720 (Bercen, USA). Water retention value (WRV) was measured with one bar and two minutes (AA-GWR, USA).

<table>
<thead>
<tr>
<th>Topcoat</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine kaolin</td>
<td>40</td>
<td>20</td>
<td>40</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BRD GCC</td>
<td>60</td>
<td>80</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NRW GCC</td>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Solids of coating, %</td>
<td>65.2</td>
<td>65.7</td>
<td>65.0</td>
<td>65.0</td>
<td>65.0</td>
<td>65.2</td>
</tr>
<tr>
<td>WRV, g/m²</td>
<td>119</td>
<td>134</td>
<td>153</td>
<td>164</td>
<td>183</td>
<td>211</td>
</tr>
</tbody>
</table>

The coatings were applied on a wood free base paper using a pilot coater in Trois-Rivières, PQ, Canada. The pilot coater was run at 1400 m/min. Jet applicator + blade coating station were used (Metso Paper, Finland). Moisture and coat weight profiles were on-line measured by infrared and X-ray but manually controlled. The base paper was precoated with 100% coarse ground calcium carbonate with 12 parts of latex, 0.7 parts CMC, and 0.5 parts FWA. The coat weight was 12 g/m² and run at 66% solids. The pre-coat formulation and process were kept constant for all coating trial points. The top coating solids target was 65% with no on-line dilution. Drying automation was used to control the zone of first immobilization point and machine-direction temperature profile. An accurate control of 12 g/m² top coat weight with σ = 0.2-0.4 is essential for even coating layer thickness.

**Optical measurements of coated samples**

The coated paper samples were prepared and conditioned according to TAPPI standard T402. TAPPI brightness was determined with 457 nm wavelength light (light source A standard, Fig 2) by TAPPI T452. ISO CIE whiteness was measured with diffused light source (light source D_65 standard with more UV than TAPPI brightness standard, Fig 2) according to ISO 11475:2000. Whiteness is defined as the reflectance of light across the visible spectrum including color components in the measurement. Brightness is defined as the reflectance of light at the wavelength of 457 nm without color in the measurement. Due to this difference, whiteness becomes important in paper industry (e.g. Lekelä 2000).

Fig 2. Spectral energy distributions of standard illuminants A, C, and D65 (e.g. Crawford et al. 1996).

For the analysis of FWA distribution in thickness direction, paper samples were embedded in epoxy resin. A cross section of 5 µm thickness was sliced with a dry diamond knife. A cooled digital camera was used to capture the image under Zeiss Axioplan UV-light microscope in reflective mode with a fluorescence filter. To keep constant light intensity, 20 ms exposure time was used for each sample, respectively (KCL Oy, Espoo, Finland).
**Result and Discussion**

**Coating pore structure of coated samples with fine kaolin and carbonate**

The coating pore structures of coated paper samples were characterized with mercury intrusion (Ma et al. 2007). When blended with 20 and 40 pats of fine kaolin, NRW GCC generated higher pore volume than BRD GCC with the same pore diameter ranges (Fig 3). This was also true for 100 parts of GCCs (not shown here). Based on Eqs. [4,5], a larger pore volume density, \( \rho \), increases the light scattering coefficient, \( \sigma_{\text{scatt}} \), and consequently reduces the light transmittance \( T_{\text{coating}} \).

**GCC type and kaolin level influence on TAPPI brightness and CIE whiteness**

As the base paper and pre-coat were kept constant, the effect of brightness difference of coated paper was more determined by the top-coat pigment brightness and packing. The increase of kaolin level led to lower brightness in blends with either BRD GCC or NRW GCC (Fig 4). The pigment brightness and b-value of BRD were 0.4 and 0.16 (less blue) points higher than those of NRW GCCs, respectively (Table 1). However, compared to BRD GCC, NWR GCC generated higher coated paper brightness (Fig 4). This is expected from discussions on optics and coating pore structure. The coated paper brightness is increased by the high scattering power of NRW GCC coatings that can hide the dark base paper better.

BRD GCC generated CIE whiteness higher than or equal to that of NWR GCC across the levels studied (Fig 5). The addition of kaolin reduced CIE whiteness regardless of GCC types. Besides the features of TAPPI reflective vs. ISO diffused lights, TAPPI light source has a very low level of UV light while the CIE whiteness light source \( D_6 \) is similar to outdoor daylight that contains higher level of UV light (Fig 2). Coating structure has influence on light scattering. The higher scattering power of narrow distribution pigment packing affects not only the attenuation of the forward scattering but also the backscattering when the light is multi-scattered before it exits either side of coated paper. Furthermore, various particle size and shape distributions have different light scattering and absorption efficiencies (e.g. Bohren, Huffman 1998).

**GCC and kaolin packing influence on CIE whiteness**

The samples (Table 4) of second pilot coating trial run on a mixture DOE design were analyzed to statistically predict the coating structure influence over brightness and CIE whiteness.

The quadratic regression with \( p \)-value =0.021 shows that TAPPI brightness was affected by the pigment types

<table>
<thead>
<tr>
<th></th>
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<th>TAPPI Brightness, %</th>
<th>CIE Whiteness, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>75.5</td>
<td>87.3</td>
</tr>
<tr>
<td>Prob. of</td>
<td></td>
<td></td>
<td>72.6</td>
<td>109</td>
</tr>
<tr>
<td>linear coefficient</td>
<td>0.021</td>
<td>0.006</td>
<td>0.3</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Table 4. Analysis of Variance (ANOVA) for TAPPI brightness and CIE whiteness of coated paper samples (component proportions) with the estimated regression coefficient.
and PSD with NRW GCC having the highest brightness contribution. However, the whole regression cannot be calculated linearly ($p$-value = 0.3). The regression coefficients with $p$-value = 0.006 for CIE whiteness shows the equality of NRW GCC and fine kaolin while BRD GCC had the highest contribution to CIE whiteness. The probability of linear coefficient $p$-value =0.07 allows a linear regression with 90% confidence level. This DOE based trial statistically confirmed the TAPPI brightness and CIE whiteness results of the first pilot trial. Moreover, the lower regression linear coefficient pointed to the weak compatibility of high brightness NRW GCC with FWA when compared with BRD GCC (109 vs. 133). The surface response (Fig 6) shows that to have high CIE whiteness, the level of NRW GCC needs to be increased. Furthermore, the response surface of different pigment systems has its uniqueness for regional optimization.

The DOE statistical prediction of this coating study reveals that for visual wavelength lights a high $\alpha_{\text{FWA}}$ is needed to reduce light transmittance and to cover the dark base paper. It also, however, shows that for UV light that is attenuated more in the coating ($Eq [4]$), a low $\alpha_{\text{FWA}}$ is needed to increase UV light transmittance and to generate more blue light from FWA. An increase of $\alpha_{\text{FWA}}$ to UV light is due to a larger $\rho_v$, and to a possible $\sigma(\lambda)$ increase as wavelength decreases (it is also possible to have a case of $\sigma(\lambda)$ decrease but its magnitude must be in the range to give a net increase of $\alpha_{\text{FWA}} = \sigma(\lambda)\rho_v$). In either case, the combination of $\rho_v$ and $\sigma(\lambda)$ makes $\alpha_{\text{FWA}}$ larger in NRW GCC than in BRW GCC to attenuate short wavelength UV light more as reflected in low CIE whiteness, i.e. a reduced UV efficiency. While the $\alpha_{\text{FWA}} = \sigma(\lambda)\rho_v$ contribution to $T_{\text{FWA}}$ in a multi-coating is discussed, a complete evaluation of $Eq [5]$ requires that the thickness, $h$ impact, i.e. FWA distribution in the thickness direction be further investigated.

**FWA distribution in coatings with different kaolin levels**

For all the microscopy illuminated with UV light (Fig 7), the FWA of 100 parts of coarse GCC pre-coat mostly concentrates at the interface of pre-coat and base paper (since base paper does not have any FWA, it appears black in the image). Though the CMC level was higher in pre-coat (0.7 vs. 0.5 parts of top-coat), the blade pressure and capillary adsorption combined with porous coating of coarse GCC caused rather severe dewatering that brought FWA to the interface and anchored there, and left very little FWA to migrate towards surface during drying of post pre-coating. It is interesting to note that the FWA concentration at the interface of pre-coat and top-coat is much lower than at top surface (Fig 7C). This indicates that in this high speed coating with jet applicator and bevel blade the dewatering from top-coat into the pre-coat is much weaker than from pre-coat into base coat. For all the top coatings (the interface of top and pre-coat can be located at an even split of total coating thickness as shown in Fig 7B), the 100 parts NRW GCC (Fig 7A) has a rather uniform intensity of FWA in thickness direction. When 20 parts of fine kaolin (Fig 7B) was added at the expense of NRW GCC, the FWA concentrates more toward surface, and this becomes even more evident when 40 parts fine kaolin (Fig 7C) was added. Digital imaging analysis for the top 1/3 of coating layer thickness of the cross section produced 183, 151, 125 blue levels (it is based on 2^1 = 256 blue level, the larger number the brighter) for sample D, E, F, respectively (Adobe, Photoshop® USA).

Recalling the discussions above, Eqs [4,5] and Fig 7, one can make several observations. For high efficiency, FWA should be concentrated near the top surface because this is where the short wavelength UV light is the least attenuated, and most exposed to the backscattered UV light from the coatings. The FWA of pre-coat concentrates at the interface (approximately 20 $\mu$m of an average thickness) of pre-coat and base paper. The high $\alpha_{\text{FWA}}$ and $h$ at the interface produces the less UV transmittance based on $Eq [4]$, making the FWA of pre-coat the least efficient. This note about FWA distribution can be extended to single blade and film coatings where the FWA distribution is affected by the same mechanism as pre-coat, i.e. through the interactions between base paper and coating. If a wood free or ground wood base paper and board contain FWA for the whiteness and unifor-

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**Figure 7 (A)** has 100 parts of NRW GCC in top-coat; **(B)** 80 parts NRW GCC and 20 parts of fine kaolin in top-coat; and **(C)** 60 parts of NRW GCC and 40 parts of fine kaolin in top-coat. Coated paper cross section of microscopy illuminated with UV light. The dark middle layer is the base paper that has no FWA. FWA of pre-coat heavily concentrates at the interface of pre-coat and base paper while the FWA of top-coat concentrates more at top surface with the addition of fine kaolin at the expense of NRW GCC.
mity from multi-scattering properties, BRD GCC with fine kaolin can further improve CIE whiteness by allowing more UV light to transmit to the pre-coat and base paper to generate more blue lights and to be backscattered through it. Kaolin has lower brightness and absorbs more UV light than carbonates (e.g. McComb, Stickler 1995). This study shows that this can be partially compensated by the fine kaolin ability of retaining and allowing the migration of FWA towards the surface to make FWA more efficient. If a wood free base paper has high yield pulp, kaolin containing coating layer can more effectively screen UV to reduce light-induced brightness reversion of high yield pulp (Yuan et al. 2006). We suggest that for FWA efficiency, uniformity and UV screening it is desirable to design a carbonate and kaolin pigment system to produce a gradient FWA distribution in thickness direction with the highest FWA concentration towards the surface.

Conclusion

This study found that increasing fine kaolin level at the expense of NRW GCC made FWA concentrate more towards the surface as shown by cross sections of microscopy under UV light. Pigment coating structure affects the FWA efficiency mainly in the ways of light scattering and FWA distribution in thickness direction. The combination of pore volume density, \( \rho_v \) and scattering cross-section, \( \sigma_c(\lambda) \) makes \( \sigma_c(\lambda) \) larger in NRW GCC than in BRW GCC to attenuate short wavelength UV light more, i.e. a reduced UV efficiency. It is desirable to design a carbonate and kaolin pigment system to produce a gradient FWA distribution in thickness direction with the highest FWA concentration towards the surface. While its brightness and whiteness are lower than carbonates (e.g. McComb, Stickler 1995), it is desirable to design a carbonate and kaolin pigment system to produce a gradient FWA distribution in thickness direction with the highest FWA concentration towards the surface.

Literature


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