Predictive Modeling of Color Projection Quality II

Experimental Validation

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Introduction

For a given formulation, the color of a xerographic toner is dependent on the level of pigment dispersion. This is particularly evident for overhead projector (OHP) transparencies, since light scattered by the toner does not reach the projector lens and is lost. In Part I of this paper[1] we described a comprehensive Mie scattering model which predicted the transmission spectra of pigmented toner films from the pigment type, concentration, size and distribution in the toner, and the layer thickness. Here we compare those predictions with experimental results in terms of the Projection Efficiency and Projected Color of toner films.

Experimental

Seven toners, containing five different pigments, were selected for this study. These toners are listed in Table 1, showing the pigment type, concentration and dispersion level. In this paper, the abbreviations PR, PY and PB refer to the Color Index classifications Pigment Red, Pigment Yellow and Pigment Blue respectively. When the usual dry pigments were made into toners they produced a "good" to "very good" level of dispersion, except for two pigments (PR 81:3 and modified PB 15:3) which gave "poor" and "fair" dispersion levels respectively. For both these pigments, excellent dispersion was obtained by using them in the predispersed (flushed) state. All toners in this study used styrene-butadiene copolymer as the binder resin.

Transparency samples were made from these toners using a non-electrostatic powder-cloud development technique. In this method, the toner is placed in a small cylindrical container and a powder cloud is generated by a motor-driven stainless steel wire brush. Nitrogen gas at a controlled flow rate passes through the cylinder, carrying the toner cloud with it. The toner-laden gas rises up a small delivery tube and enters a larger settling tube. The gas flow rate is adjusted so that gas velocity in the small tube is adequate to carry individual toner particles up the tube, while agglomerates settle back into the cylinder. When the toner-laden gas enters the larger tube, the gas velocity falls by about 50X and is no longer adequate to carry the toner particles, which slowly descend while the clean gas continues upward and is vented. The toner particles eventually settle upon the substrate, which is placed horizontally on a slowly rotating turntable at the bottom of the larger tube. The entire turntable assembly is sealed to the bottom of the larger tube to prevent the nitrogen gas from escaping at that end.

Table 1. Summary of Experimental Toner Properties. Pigment volume fraction F_v was computed from resin and pigment density data. Data marked (b) had high uncertainty.

Toner No.	Pigment CI number	Pigment conc. (wt %)	Pigment form	Pigment dispersion (optical microscopy)	Particle Size (nm) & GSD (TEM)	Pigment volume fraction Φ_v
1	PR 81:3	5	flushed	excellent	108 ± 4 (1.8 ± 0.1)	2.94
2	PR 81:3	5	dry	poor	620 ± 60 (1.7 ± 0.2)	2.94
3	PR 122	5	dry	good	123(b) 2.6(b)	3.76
4	PY 97	5	dry	good	148 ± 5 (1.7 ± 0.1)	3.88
5	PB 15:3	2	dry	very good	83 ± 7 (2.0 ± 0.3)	1.32
6	modified PB 15:3	5	flushed	excellent	190 ± 10 (1.8 ± 0.1)	4.62
7	modified PB 15:3	5	dry	fair	490 ± 30 (1.6 ± 0.1)	4.62

The toner is deposited on the substrate uniformly and at a constant rate, which depends on the process conditions and can be experimentally determined. Thus a desired toner mass can be deposited by allowing the deposition to continue for the appropriate length of time. Samples with toner mass covering a range of at least 0.2 to 1.0 mg/cm^2 were prepared from all the toners. Xerox 3R2780 transparency stock was used as the substrate in all cases.

The toner films can scatter light from the bulk (pigment dispersion effects) as well as from surface roughness. In Part III of this paper[2] we discuss the sensitivity of transmitted light to surface ripple. Since only bulk scatter was to be evaluated for this study, much care was taken to make the surface as smooth as possible. The samples were initially fused on a color fuser running at high roll temperature and long dwell time (204°C, 100ms). They were then re-fused against a thin, smooth polyester film. This process enabled very smooth surfaces to be obtained, with gloss levels near 100 gu (75° TAPPI specular gloss) on most samples. It was, however, impossible to get adequately smooth surfaces on samples with very low toner mass.

After fusing, the specular and diffuse components of transmittance were determined using a Match Scan II spectrophotometer over wavelengths of 380 to 700nm at 10nm intervals. Details of the measurement procedure have been published.[3]

In order to ensure that unwanted surface roughness effects were minimized, the samples were immersed in a liquid of matching refractive index. This was done in a small cell (50mm x 50mm × 0.5mm internal volume) constructed from optical-grade glass and shim stock, sealed with epoxy resin. Unfortunately, liquids which exactly matched the refractive index of the toner resin tended to dissolve the toner. The best compromise liquid was ethylene glycol (EG, refractive index = 1.432). The spectrophotometer was calibrated with the cell, EG and bare 3R2780 substrate in place.

Projection Efficiency and Projected Color Calculations

OHP transparency performance can be characterized in terms of two metrics, Projection Efficiency and Projected Color. Of these, the former is a useful process-evaluation metric, while the latter represents how the projected image actually appears to an observer. Both of these metrics can be calculated from the measured specular (P) and diffuse (N) components of transmittance of the toner films. Projection Efficiency (PE) was introduced by Dalal et al[3] in 1989. The computation procedure discussed in that paper was used here. The similar Haze metric was also calculated according to ASTM D1003-61.[5] The measurement geometry used here is slightly different from that specified by ASTM. While PE and Haze are similar, the former is the more useful process-evaluation metric because it is essentially independent of toner mass. When scattering is absent, Haze→0 and PE→100%. For completeness, the defining equations for Projection Efficiency and Haze are listed in equations (1) and (2).

$$PE = 100\% \left(\frac{ln\left[\frac{\sum_{\lambda=380}^{700} {}^{T}P+N^{(\lambda)}}{33}\right]}{ln\left[\frac{\sum_{\lambda=380}^{700} {}^{T}P^{(\lambda)}}{33}\right]} \right) \quad (1)$$

$$Haze = 100\% \left(\frac{\sum_{\lambda=380}^{700} S(\lambda)\left[T_{P+N}(\lambda) - T_P(\lambda)\right] y(\lambda)}{\sum_{\lambda=380}^{700} S(\lambda) T_{P+N}(\lambda) y(\lambda)} \right) \quad (2)$$

Projected Color was calculated in terms of the CIELAB color parameters L*, a*, b*, C* and h* according to the CIE procedure,[4] using only the specular (P) component of transmittance. The CIE 1931 (2°) standard colorimetric observer functions and CIE standard illuminant A were used. Illuminant A was chosen because most OHP projectors use incandescent lamps.

Results and Discussion

Figures 1 and 2 compare measured and predicted[1] Projected Color, PE and Haze values for the good and poor dispersions, respectively, of PR 81:3. Correlation between experimental and theoretical data is excellent, particularly at high toner mass. PE is the metric most sensitive to light scatter. Because it is impossible to get very smooth surfaces on samples with very low toner mass, this is where the greatest deviations occur.

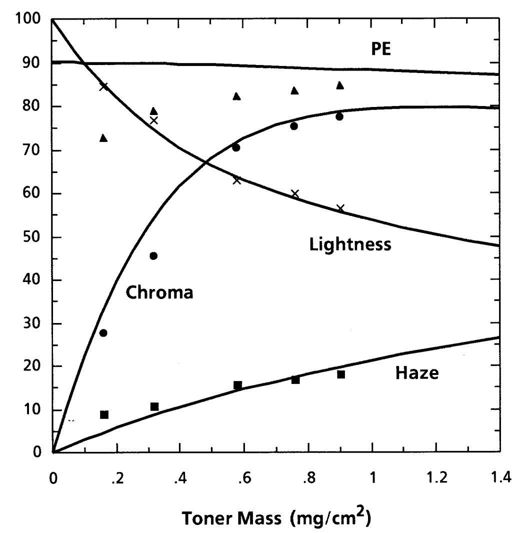

Figure 1. Trends in color metrics as a function of toner mass for well dispersed PR 81:3 pigment. The points are measured data in ethylene glycol cell, the lines theoretical predictions.

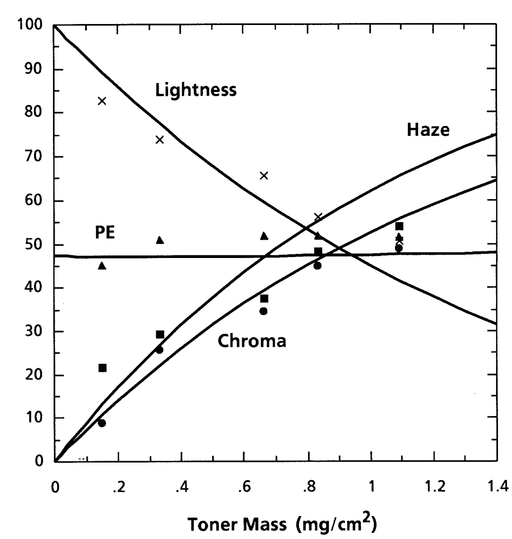

Figure 2. Trends in color metrics as a function of toner mass for poorly dispersed PR 81:3 pigment. The points are measured data in ethylene glycol cell, the lines theoretical predictions.

PE values for the poor dispersion are much lower than those for the good dispersion. Chroma, or color saturation, is correspondingly reduced. Note that PE is almost independent of toner mass, but Haze increases significantly with toner mass.

Predictions for the other toners are of similar quality. The corresponding plots for the other toners are not included here because of space considerations.The prediction errors for the other toners are, however, summarized in Table 2.

Table 2. RMS Prediction Errors for Projected Color, PE and Haze. No adjustable parameters are utilized in the prediction.

Toner number (see Table 1)	No. of samples	RMS Prediction Error from Mie Scattering Model				
		ΔE*	ΔL*	ΔC*	PE (%)	Haze (%)
1	5	6.3	1.3	4.9	9.9	2.3
3	5	4.1	2.2	1.3	7.8	4.7
4	4	7.4	4.8	4.3	19.5	10.3
5	5	7.3	5.0	5.3	11.2	5.6
6	5	7.9	1.8	4.5	3.2	6.8
Average of Good Dispersions	24	6.7	3.3	4.3	11.1	6.3
2	5	18.5	6.2	4.1	4.0	8.2
7	5	22.1	6.0	3.1	14.3	11.7
Average of Poor Dispersions	10	20.3	6.1	3.6	9.2	10.0

The CIELAB color difference ΔE*, and the lightness and chroma components ΔL* and ΔC*, were calculated from the difference between the measured and predicted Projected Color according to the CIE method.[4] The values listed in Table 2 are the root mean square (RMS) values of all the samples (over a wide range of toner mass) for each toner. The average ΔE* for all the well-dispersed toners (toners 1, 3, 4, 5 and 6) was only 6.7 CIELAB units. (By way of comparison, most color reproduction technologies, including photography, generally produce larger errors in the reproduced color.)

Conclusion

Mie theory has been shown to be an excellent predictor of light scattering from pigment particles in color xerographic toners.

References

1. A. J. Paine, E. N. Dalal, S. E. Blaszak and I. D. Morrison, Predictive Modeling of Color Projection Quality. I: Absorption and Scattering of Light by Pigment Particles in Toner Layers, *Proc. IS&T 47th Annual Conf.*, Rochester, May 1994; (see page 354, this publication).
2. H. Mizes, Predictive Modeling of Color Projection Quality. III: Surface Roughness Effects on Transparency Projection Efficiency, *Proc. IS&T 47th Annual Conf.*, Rochester, May 1994; (see page 350, this publication).
3. E. N. Dalal, S. E. Blaszak and P. C. Swanton, Projection Efficiency of Color Xerographic Transparencies, *Proc IS&T Fifth Intl. Congress on Non-Impact Printing Technologies*, San Diego, November 1989.
4. *International Commission on Illumination*, "Colorimetry," 2nd ed., Publication CIE No. **15**.2, Central Bureau of the CIE, Vienna (1986).
5. American Society for Testing and Materials, "ASTM Standards on Color and Appearance Measurement," *ASTM*, Philadelphia (1987).