JPMTR-2212
DOI 10.14622/JPMTR-2212
UDC 762:774.8-035.67-026.61

Research paper | 166
Received: 2022-06-03
Accepted: 2022-07-20

Characterizing the influence of white ink coating weight and print layer film type on chromaticity in gravure printed flexible packaging

Robert J. Eller and Gregory S. D'Amico

Department of Packaging and Graphic Media Science,
Rochester Institute of Technology, 69 Lomb Memorial Drive, Rochester, NY 14623

rjeppr@rit.edu
gdsppr@rit.edu

Abstract

When printing transparent substrates, a white ink underlayer is frequently required to reproduce saturated colors. Nevertheless, the cost of adding this underlayer makes it a potentially attractive cost reduction opportunity. The primary objective of this study was to investigate the influence of white underlayer coating weight (g/m^2) and print layer film type on the chromaticity of reverse printed structures representative of those found in gravure printed flexible packaging. To analyze the influence of white ink coating weight (Ctg Wt) and print layer film type on chromaticity, six design of experiments (DOEs) were conducted. Each DOE explored the relationship between three levels of white ink coating weight and three print layer film types for one ink (Magenta, Cyan, Yellow, Orange, Violet, or Black). The DOE results showed that both coating weight and film type have a statistically significant effect on chromaticity ($P < 0.005$). For Magenta, Cyan, Yellow and Orange inks, white underlayer coating weight had the dominant effect on chroma (the values of ΔC^*_{ab} typically between 4 and 7) while the effect of print layer film type was relatively minor (the value of ΔC^*_{ab} is typically < 1). For Violet ink, white ink Ctg Wt was still the dominant effect (the value of ΔC^*_{ab} was 7), but print layer film type had a more pronounced effect (the value of ΔC^*_{ab} was 3). The relationship between coating weight and chroma over the range from 0.49 g/m^2 to 1.95 g/m^2 was linear for all inks ($R^2 > 0.99$). Finally, when printing Magenta, Cyan, or Orange ink a coating weight reduction of 1 g/m^2 (from 1.95 g/m^2 to 0.98 g/m^2) resulted in a color shift of the ΔE_{00} ~2.5, and a 1.5 g/m^2 reduction (from 1.95 g/m^2 to 0.49 g/m^2) resulted in a color shift of ΔE_{00} ~3.5. Yellow, the weakest ink, was more affected (the ΔE_{00} ~4 for 1 g/m^2, and ΔE_{00} ~5 for 1.5 g/m^2), while Violet, a hue where the human visual system has less sensitivity to chroma differences, was less affected (the ΔE_{00} ~1.5 for 1 g/m^2, and ΔE_{00} ~2 for 1.5 g/m^2). For achromatic Black ink, lightness (L^*) was chosen as the response variable. Although white ink Ctg Wt and print layer film type had statistically significant effects on L^*, the differences attributable to these effects were at or below the threshold of visual detection.

Keywords: white ink underlayer, color saturation, ΔE_{00}, rotogravure

1. Introduction

In flexible packaging, reverse printed laminates are frequently used to package products such as potato chips, tortillas, extruded snacks, popcorn, and pretzels (InterFlex, 2021). A typical laminate is shown in Figure 1. In this laminate, a clear print web is reverse printed with directly applied chromatic inks. In many cases, these inks are subsequently overprinted with a white ink underlayer to enhance the saturation of the printed colors (Flexographic Technical Association, 2020). The use of the term "underlayer" reflects the fact that, from the viewpoint of the consumer, the white ink film underlays the chromatic inks. Finally, the finished bag structure is assembled by laminating a barrier web to the print web. In this structure, the colorfulness (chromaticity) of the graphic design is potentially affected by the interaction of the chromatic inks with the print web, and by the quality of the white underlayer (Flexographic Technical Association, 2020). Although a white underlayer is often required to achieve high levels of color saturation in eye catching graphics, the cost of adding white ink can be substantial, especially when graphic coverage is high. As a result, reducing white underlayer coating weight is a potentially attractive cost reduction opportunity for package printers.

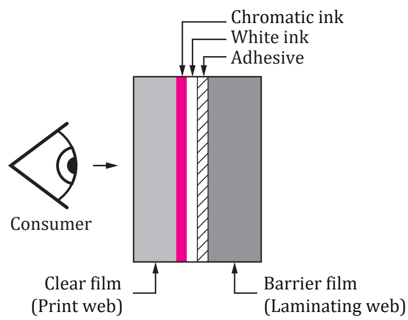

Figure 1: Typical flexible packaging laminate for salty snack bags

The principle problem associated with reducing white ink coating weight (Ctg Wt) is to ensure that the colors printed on the resulting underlayer retain their colorfulness (chromaticity). Chung and Hsu (2006) created a framework for optimizing the color gamut of gravure printed packaging, but the framework did not include optimizing a white ink underlayer. Other researchers have investigated the influence of substrate properties on printed colors (e.g. Valdec, Miljković and Auguštin, 2017) but their studies were restricted to opaque white substrates which do not require the use of a white ink underlayer. Finally, a number of other researchers have studied the properties of white ink underlayers (Argent, 2008; Rich, 2021), but always with a view toward optimizing the properties of the white ink layer (e.g. opacity, density, contrast) instead of optimizing the properties of chromatic inks backed by these underlayers. In fact, an extensive search of the literature failed to uncover any papers investigating how white underlayer coating weight affects the chromaticity of inks backed by the underlayer.

The primary objective of this study was to investigate the influence of white underlayer coating weight (g/m^2) and print layer film type on the chromaticity of reverse printed structures representative of those found in gravure printed flexible packaging.

2. Methods

To analyze the influence of white ink Ctg Wt and film type on chromaticity, six design of experiments (DOEs) were carried out using the materials and methods described below. Each DOE explored the relationship between three levels of white ink Ctg Wt and three print layer film types for one of six ink colors (Magenta, Cyan, Yellow, Orange, Violet or Black). Chroma (C^*_{ab}) was selected as the response variable for experiments involving chromatic inks (Cyan, Magenta, Yellow, Orange, and Violet). Lightness (L^*) was chosen as the response variable for the Black ink experiment since Black ink is designed to be as achromatic as possible.

2.1 Materials

Solvent based gravure inks supplied by Flint Group were used in the experiment. All inks were formulated to an efflux time of 19 seconds using a Zahn 2 cup before printing. Test swatches of each ink were printed on three films: 75 ga Oriented Polypropylene (75 OPP), 92 ga Cellophane (92 Cello), and 80 ga TIPA® 318 (80 TIPA) (the film thicknesses given in ga (gauge) correspond to 19 µm, 23 µm, and 20 µm, respectively). Swatches were printed using an RK Industries K Printing Proofer operating in direct gravure printing mode. The proofer used an electromechanically engraved plate (500 lpi, 37° compression angle, 130° stylus) to print 100 % solid color swatches. Three replicates of each ink / film type combination were printed for a total of 54 swatches (6 inks, 3 film types and 3 replicates). The inks and films used in the experiment are described in Table 1. For additional information, please see the weblinks associated with the references.

White underlayer samples were printed on a commercial gravure press using cylinders engraved to print nominal coating weights of 1.95 g/m^2, 0.98 g/m^2, and 0.49 g/m^2. All underlayers were printed on 75 OPP film. The coating weights used in the experiment

Table 1: Inks and films used in the experiment

Inks			**Films**	
Ink color	**Supplier**	**Grade**	**Film type**	**Supplier**
Cyan	Flint Group[1]	XCEL GS CF Blue	75 OPP	Tagleef Ind.[2]
Magenta	Flint Group[1]	2.2234R37CRLA2027 Bon Rubine	92 Cello	Futamura[3]
Yellow	Flint Group[1]	PluriBase V1 HS NC Yellow	80 TIPA	TIPA Corp.[4]
Black	Flint Group[1]	PluriBase Black		
Orange	Flint Group[1]	PluriStar RTV 37078 Orange		
Violet	Flint Group[1]	XCEL Carb Violet		

[1]Flint Group, Anniston, AL, USA (Flint Group, 2022)
[2]Tagleef Industries, Newark, DE, USA (Tagleef Industries, 2022)
[3]Futamura North America, Tecumseh, KS, USA (Futamura, 2022)
[4]TIPA North America, Jersey City, NJ, USA (TIPA, 2021)

were chosen to represent a typical white underlayer used in commercial printing (1.95 g/m^2), a half thickness underlayer (0.98 g/m^2), and a quarter thickness underlayer (0.49 g/m^2).

2.2 Data generation

Each DOE was a 3^2 full factorial design with three replicates. In this design, two variables (the exponent in 3^2) were evaluated at three levels (the base in 3^2) and replicated three times. Thus, each DOE consisted of three identical replicates printed using a single color of ink. Table 2 shows the design table for one replicate of the Magenta DOE.

Table 2: Design table for one replicate of the magenta ink experiment; the full experiment consists of three identical replicates

Run	Ink color	Film type	White ink Ctg Wt (g/m^2)
1	Magenta	75 OPP	1.95
2	Magenta	92 Cello	1.95
3	Magenta	80 TIPA	1.95
4	Magenta	75 OPP	0.98
5	Magenta	92 Cello	0.98
6	Magenta	80 TIPA	0.98
7	Magenta	75 OPP	0.49
8	Magenta	92 Cello	0.49
9	Magenta	80 TIPA	0.49

For each ink color / film type combination shown in this table, a sandwich consisting of the printed swatch and specified white underlayer was measured using a Techkon SpectroDens on an X-Rite black backing tile. In all cases, the swatch was placed print side down on a white underlayer positioned with its print side up. The resulting structure simulates a reverse printed flexible package (print film / chromatic ink / white ink / underlayer film). Figure 2 shows a test sample as printed and as sandwiched for measurement.

All measurements were collected using the following settings: D50 Illuminant, 2° Observer, No Polarization, Absolute Colorimetric, and M1 Measurement Condition. Nine sets of CIELAB values were collected from each test structure by superimposing a 3 × 3 grid on the printed swatch and taking one measurement in each grid square. The average of these values was used to represent the CIELAB values for the test condition specified in the design table. The response variables for the experiment, chroma (C^*_{ab}) for chromatic inks and lightness (L^*) for black swatches were calculated from the CIELAB values.

2.3 Statistical analysis

Three analyses were conducted to assess the influence of white underlayer coating weight (g/m^2) and print layer film type on chroma (or lightness in the case of Black ink). First, an analysis of variance (ANOVA) was conducted to assess the statistical significance of each variable in isolation and of the interaction between these variables. Second, regression models were created to predict chromaticity based on white underlayer coating weight for each film type. Finally, CIELAB data was analyzed to assess the visual impact of changing film type and/or coating weight in terms of ΔE_{00}. Each analysis is discussed in a separate section. For the ANOVA and regression analyses, the section opens with a detailed discussion of the Magenta analysis, followed by a discussion of how the remaining analyses (for Cyan, Yellow, Orange, Violet and Black) conform to or differ from the results discussed in the Magenta example.

Analysis of variance was used to assess the statistical significance of the relationships between sources of variation (coating weight, film type, coating weight × film type), and a response variable (chroma or lightness). In this analysis a linear model estimates the response variable as a function of source values. This permits the total observed variation of the response

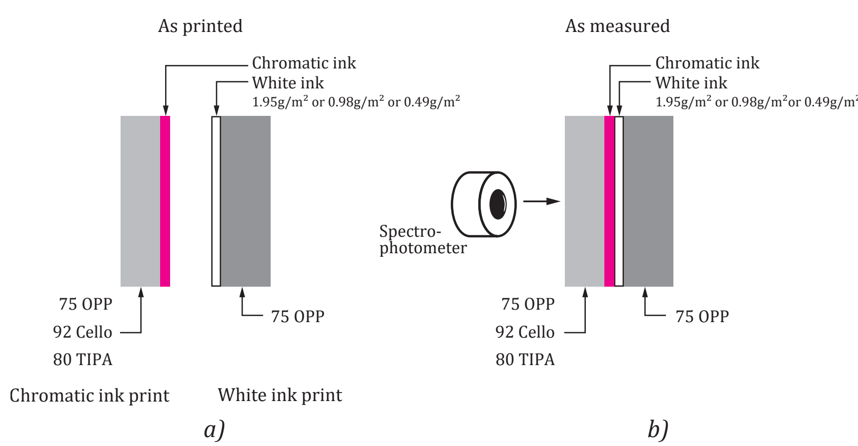

Figure 2: Test samples as printed (a), and as assembled for measurement (b)

variable to be divided into four components: 1) the amount due to changes in coating weight, 2) the amount due to differences in film type, 3) the amount due to the coating weight × film type interaction, and 4) residual error. Under the null hypothesis, coating weight, film type, and the coating weight × film type interaction have no effect on the response variable. An *F*-test is then used to compare the observed variation due to each source (film type, coating weight, and film type × coating weight) to the variation due to residual error. If *F*-value has a probability less than a critical value (0.05 in this study), we reject the null hypothesis and accept the alternative hypothesis that the source has a statistically significant effect on the response variable.

The ANOVA results are summarized in Tables 3 to 7. In these tables, the first column lists the sources of variation. The second lists the degrees of freedom (DF) associated with each source. As an example, the experiment as a whole has 26 degrees of freedom (the DF entry next to Total). In the experiment, 27 data points (3 film types, 3 coating weights and 3 replicates) are compared to the grand average to calculate the adjusted sum of squares (Adj SS). Once the grand average is calculated, only 26 datapoints are free to take on any value (the value of the 27^{th} datapoint must equal the grand average times 27 minus the sum of the first 26 values), so the experiment is said to have 26 degrees of freedom. Variance is proportional to the sum of squares of the differences between the group means and the datapoints in each group (Adj SS). In this context, "Adjusted" (Adj) means the sum of squares calculation is performed in a way that does not depend on the order in which the terms are introduced into the model. The next column, mean sum of squares, (Adj MS) divides Adj SS by DF to compensate for differences in group size. An *F*-statistic (*F*-value) is calculated by dividing the Adj MS value for the source by the Adj MS value of error. The *P*-value is the probability of getting the observed *F*-value when the null hypothesis is true. As stated above, we interpret *P*-values less than 0.05 as being statistically significant.

3. Results and discussion

3.1 Statistical analysis of the Magenta DOE

Table 3 summarizes the results of conducting an ANOVA on the Magenta DOE data.

Throughout the experiment, close attention was placed on reducing sources of random variation in the data. The resulting level of random error in the data reflects the effectiveness of these measures: less than 1 % of the total variation is attributed to random error. The majority of the observed variation is attributed to white ink Ctg Wt, with a smaller amount attributed to film type. When these effects were tested to determine their significance, the probability of obtaining the observed results through random chance (the *P*-value) was 0.000. Equivalently, the statistical significance of coating weight and film type on chroma exceeds 99.9 %. When the effect of the coating weight × film type interaction was tested, it was found to be statistically insignificant with a *P*-value (0.476) greatly exceeding the maximum *P*-value for a significant effect (0.05). The low level of random error in the experiment ensures that the signal (the interaction) is not being obscured by noise (error).

Main effects plots show the relative magnitude of each effect. Figure 3 is a main effects plot showing the relative impact of coating weight and film type on chroma. As expected, coating weight is the dominant factor with a total impact of ΔC^*_{ab} nearly 6, while film type contributes ΔC^*_{ab} to chroma variation a little less than 1.

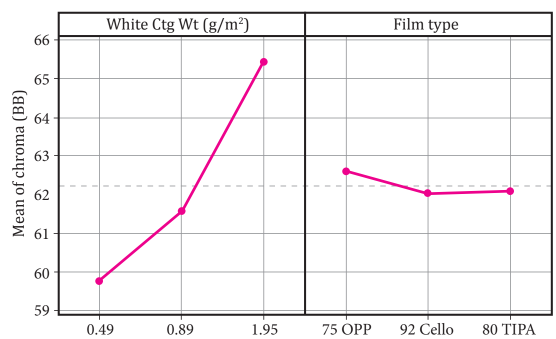

Figure 3: Main effects plot for magenta ink chroma measured with black backing (BB) vs white coating weight (Ctg Wt) and film type

Figure 4 is an interaction plot for coating weight × film type. To interpret this chart, start with the chroma of a specific film type and coating weight combination. For example, the C^*_{ab} of the 75 OPP Magenta swatch measured on a 0.49 g/m^2 white underlayer was approximately 60. Now assume we change the film type to 80 TIPA and the coating weight to 1.95 g/m^2. Based on the main effects plot, a change from 75 OPP to 80 TIPA has an effect on ΔC^*_{ab} of approximately −0.5. Similarly, a change from 0.49 g/m^2 to 1.95 g/m^2 has an effect on ΔC^*_{ab} of approximately +6.0. In the absence of an interaction, the predicted result for 80 TIPA on a 1.95 g/m^2 white underlayer is simply the starting point plus the individual effects of ΔC^*_{ab} values: 60 − 0.5 + 6.0 = 65.5. Since this closely matches the observed result for 80 TIPA measured on a 1.95 g/m^2 white backing, we conclude that there is no interaction. If an interaction were present, the observed effect would be significantly larger or smaller than the starting point plus the main effects. On the plot in Figure 4, if all of the observed

Table 3: Analysis of variance for magenta ink chroma vs white coating weight and film type

Source	DF	Adj SS	Adj MS	*F*-value	*P*-value
Model	8	153.44	19.18	1 256.37	0.000
Linear	4	153.39	38.35	2 511.82	0.000
White ink coating weight	2	151.62	75.81	4 965.68	0.000
Film type	2	1.77	0.88	57.96	0.000
2-Way interactions	4	0.06	0.01	0.92	0.476
White ink Ctg Wt × Film type	4	0.06	0.01	0.92	0.476
Error	18	0.28	0.02		
Total	26	153.72			

effects closely correspond to the starting point plus the main effects, then the lines for the three film types will be approximately parallel. Turning our attention to Figure 4, we observe that this is the case. Thus, Figure 4 indicates that no interaction is present (which agrees with the ANOVA result that the coating weight × film type interaction is not statistically significant).

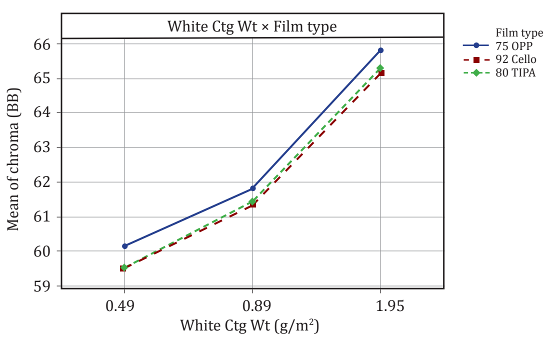

Figure 4: Interaction plot for magenta ink chroma measured with black backing (BB) vs white coating weight × film type

3.1.1 Statistical analysis of DOE data for the remaining experiments

The ANOVA results for the remaining chromatic colors (Cyan, Yellow, Orange, and Violet) are summarized in Tables 4 through 7. As the tables show, the results for these colors are strikingly similar to the results for Magenta. In all cases, random error accounts for less than 2 % of the total variation, again reflecting the high level of repeatability achieved in these experiments. White ink Ctg Wt is always statistically significant with a significance level exceeding 99.9 %. Film type is also a highly significant factor with a significance level exceeding 99.5 %. Finally, the *P*-value of the coating weight × film type interaction never comes close to the *P*-value required to be statistically significant (0.05).

The ANOVA results for Black are summarized in Table 8. Results for Black differed in several aspects from those just discussed. The response variable chosen for Black (an achromatic ink) was lightness (L^*). A perfect Black has an L^* value of 0. The combination of gravure printing and high quality Black ink yielded L^* values in the 5 to 6 range. The small magnitude of these L^* values (less than 10 % of the C^*_{ab} values just discussed) resulted in an exceedingly small total variation for Black: slightly more than 2 (compared to 65 to 260 for the chromatic inks). Since the magnitude of random variation for L^* values is similar to the magnitude for C^*_{ab} values (a fraction of a unit), random error in the Black ANOVA contributes 12 % of the total variation (compared to less than 2 % for the chromatic inks).

Despite this difference (which reduces the sensitivity of the analysis), *P*-values remained exceptionally low: 0.001 for coating weight and 0.000 for film type. This means that both factors are statistically significant at a level of 99.9 %. As with the chromatic colors, the coating weight × film type interaction is not statistically significant. On the other hand, the variation in L^* attributable to film type greatly exceeded the variation attributable to coating weight. This result is due to the fact that the 80 TIPA film has a distinct haze which significantly lightened the 80 TIPA samples compared to the other film types.

Figure 5 shows the main effects plots for Cyan, Yellow, Orange, Violet, and Black. The main effects plot for Magenta is repeated in the upper left position to facilitate comparison. Once again, the plots for the remaining chromatic colors (Cyan, Yellow, Orange, and Violet) bear significant similarities to the Magenta plot. In all cases, the effect of coating weight outweighs the effect of film type. The effect of film type on chroma, on the other hand, exhibits some differences between colors.

Magenta, Cyan, and Yellow film type plots are virtually identical: the magnitude of film type's impact on chroma is small compared to the impact of coating weight, 75 OPP exhibits higher chroma than the other two films, and the chroma of 92 Cello and 80 TIPA are generally similar. Orange exhibits this pattern with the exception that 92 Cello chroma is closer to 75 OPP than 80 TIPA. Violet, on the other hand exhibits a different pattern. For Violet, the impact of film type on chroma

Table 4: Analysis of variance for cyan ink chroma vs white coating weight and film type

Source	DF	Adj SS	Adj MS	*F*-value	*P*-value
Model	8	67.49	8.44	127.42	0.000
Linear	4	67.46	16.86	254.72	0.000
White ink coating weight	2	65.33	32.67	493.38	0.000
Film type	2	2.13	1.06	16.07	0.000
2-Way interactions	4	0.03	0.01	0.12	0.972
White ink Ctg Wt × Film type	4	0.03	0.01	0.12	0.972
Error	18	1.19	0.06		
Total	26	68.68			

Table 5: Analysis of variance for yellow ink chroma vs white coating weight and film type

Source	DF	Adj SS	Adj MS	*F*-value	*P*-value
Model	8	215.89	26.99	158.39	0.000
Linear	4	215.74	53.94	316.57	0.000
White ink coating weight	2	231.18	106.59	625.61	0.000
Film type	2	2.57	1.29	7.54	0.004
2-Way interactions	4	0.14	0.04	0.21	0.931
White ink Ctg Wt × Film type	4	0.14	0.04	0.21	0.931
Error	18	3.07	0.17		
Total	26	218.95			

Table 6: Analysis of variance for orange ink chroma vs white coating weight and film type

Source	DF	Adj SS	Adj MS	*F*-value	*P*-value
Model	8	216.06	27.01	1 134.39	0.000
Linear	4	215.94	53.99	2 267.58	0.000
White ink coating weight	2	212.07	106.04	4 453.92	0.000
Film type	2	3.87	1.93	81.24	0.000
2-Way interactions	4	0.11	0.03	1.20	0.346
White ink Ctg Wt × Film type	4	0.11	0.03	1.20	0.346
Error	18	0.43	0.02		
Total	26	216.49			

Table 7: Analysis of variance for violet ink chroma vs white coating weight and film type

Source	DF	Adj SS	Adj MS	*F*-value	*P*-value
Model	8	262.80	32.85	974.24	0.000
Linear	4	262.78	65.70	1 948.37	0.000
White ink coating weight	2	227.56	113.78	3 374.40	0.000
Film type	2	35.23	17.61	522.33	0.004
2-Way interactions	4	0.02	0.00	0.11	0.978
White ink Ctg Wt × Film type	4	0.02	0.00	0.11	0.978
Error	18	0.61	0.03		
Total	26	263.41			

is much larger than for the remaining chromatic inks (ΔC^*_{ab} ~3 versus ΔC^*_{ab} ~1). In addition, there is a clear difference in the effects of the individual films on chromaticity: 75 OPP has the greatest effect, 80 TIPA has the least, and 92 Cello is almost exactly in the middle.

The Black main effect plot is much different than the plots for the chromatic colors (which is wholly consistent with the ANOVA results discussed previously). Unlike the chromatic inks, the impact of film type on lightness exceeds the impact of coating weight. In addi-

Table 8: Analysis of variance for black ink lightness vs white coating weight and film type

Source	DF	Adj SS	Adj MS	*F*-value	*P*-value
Model	8	2.0536	0.25670	16.75	0.000
Linear	4	2.0375	0.50937	33.23	0.000
White ink coating weight	2	0.3021	0.15103	9.85	0.001
Film type	2	1.7354	0.86772	56.60	0.000
2-Way interactions	4	0.0161	0.00403	0.26	0.898
White ink Ctg Wt × Film type	4	0.0161	0.00403	0.26	0.898
Error	18	0.2759	0.01533		
Total	26	2.3295			

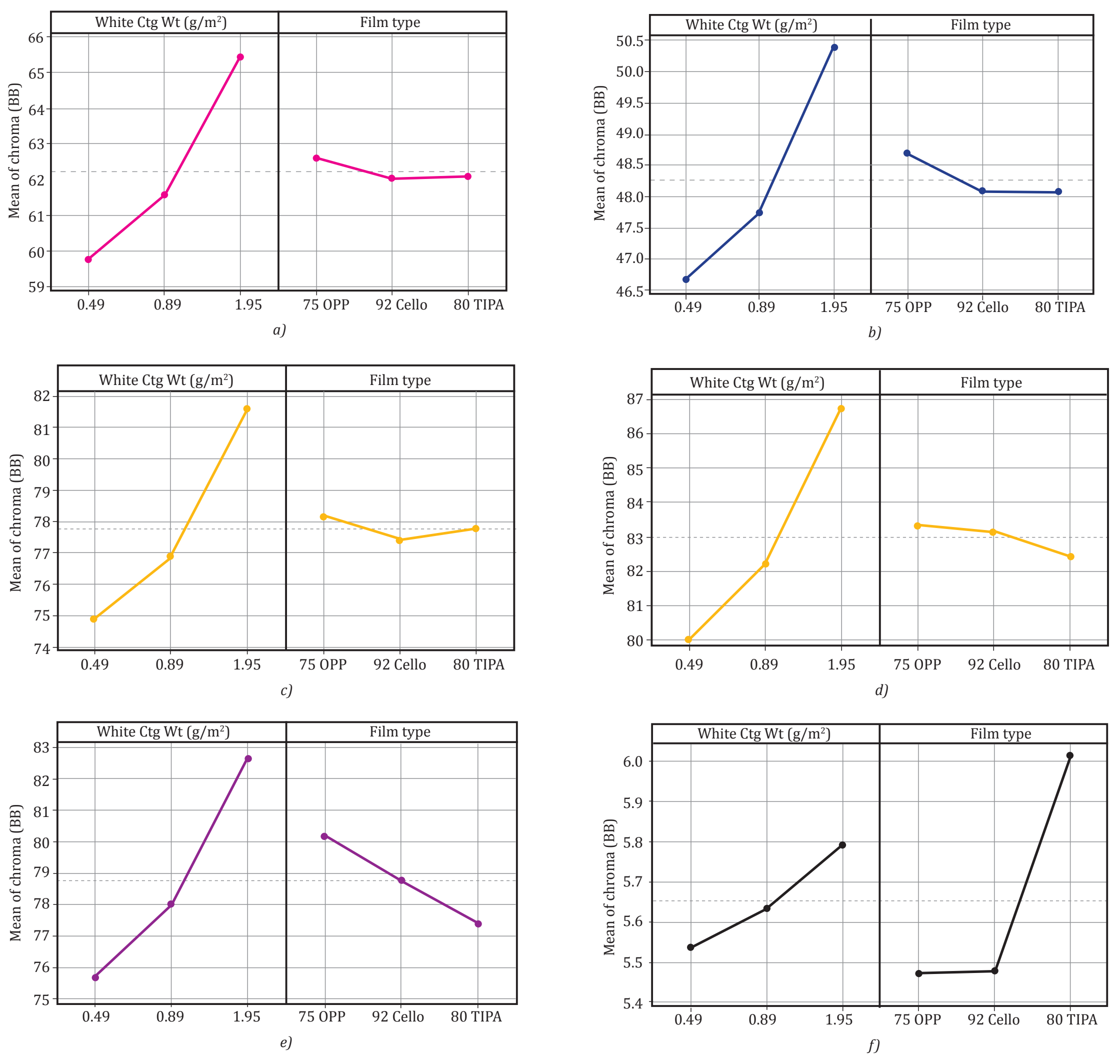

Figure 5: Main effects plots for all inks: a) Magenta, b) Cyan, c) Yellow, d) Orange, e) Violet, and f) Black, measured on black backing (BB)

tion, 80 TIPA stands apart from 75 OPP and 92 Cello in its impact on lightness. It should also be pointed out that lightness differences among the black samples are either visually undetectable or at the very threshold of detectability. This contrasts strongly with the chromatic inks where chroma differences are highly visible.

3.2 Regression analysis of experimental data

Having established that the relationships between coating weight, film type, and chromaticity parameters are statistically significant (i.e. real and repeatable), the next step is to develop quantitative, predictive models for chromaticity. To realize this end, linear and nonlinear regression models were used to develop quantitative relationships based on the data collected.

3.2.1 Regression analysis of Magenta data

For purposes of generating regressions, the chroma values of the replicates were averaged and the average was used as a single data point representing the film type / coating weight combination. In addition to the data presented in the previous section, chromaticity was measured on unprinted 75 OPP. Table 9 shows the Magenta dataset used for the regression analysis.

Table 9: Magenta chroma versus film type and coating weight

	Chroma (C^*_{ab})		
White ink Ctg Wt	**75 OPP**	**92 Cello**	**80 TIPA**
1.95 g/m^2	65.79	65.11	65.40
0.98 g/m^2	61.82	61.36	61.44
0.49 g/m^2	60.14	59.52	59.52
0.00 g/m^2	25.31	25.87	25.27

A separate regression model (chroma as a function of coating weight) was created for each film type. A logarithmic transformation of the data resulted in a regression models that fit the data reasonably well. The result for 75 OPP is shown in Figure 6.

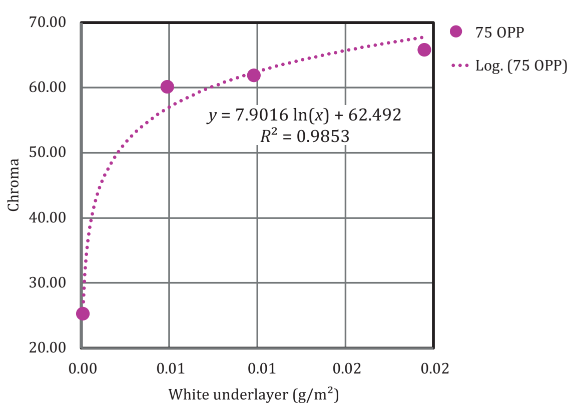

Figure 6: Logarithmic regression of chroma vs white underlayer coating weight for Magenta ink on 75 OPP film

Although the logarithmic regression curve has an R^2 of 0.9853, it still significantly underestimates the chroma value of the 0.49 g/m^2 underlayer and overestimates chroma of the 1.95 g/m^2 underlayer.

Since the plot points in the region of interest (0.49 g/m^2 to 1.95 g/m^2) look approximately linear, the next step was to assess the fit of a linear regression to these points. Figure 7 shows the results.

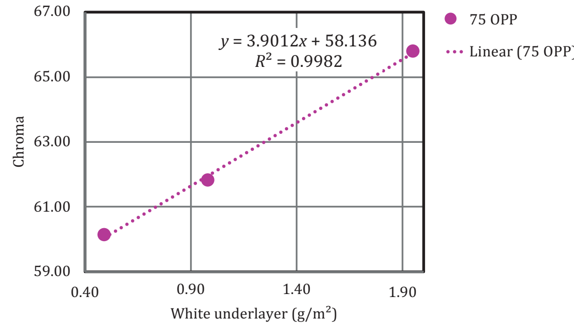

Figure 7: Linear regression of chroma vs white underlayer coating weight for Magenta ink on 75 OPP film

As the figure shows, a linear regression with an intercept C^*_{ab} of 58 and a slope C^*_{ab}/g/m^2 of 3.9 is a near perfect fit with an R^2 of 0.9982. The intercept, slope, and R^2 are the key results of this analysis. To save space, the remaining regressions are presented in tabular form and graphs are omitted. Table 10 presents the Magenta regression results. Intercept data shows that the swatches printed on 75 OPP are slightly more chromatic than those printed on the other films. The slopes (chroma gain per 1.0 g/m^2 increase in coating weight) are grouped around C^*_{ab}/g/m^2 of +3.9. Finally, R^2 values of 0.99+ demonstrate that between 0.49 and 1.95 g/m^2 coating weight, the regression is a near perfect fit to the data.

Table 10: Regression results for the chroma of magenta ink printed on 75 OPP, 92 Cello, and 80 TIPA measured on white underlayers with coating weights between 0.49 g/m^2 and 1.95 g/m^2

Film type	Intercept	Slope	R^2
75 OPP	58.1	3.90	0.9982
92 Cello	57.6	3.83	0.9999
80 TIPA	57.5	4.03	0.9999

3.2.2 Regression analysis of the remaining data

Table 11 compares the regression results for the remaining chromatic colors. Magenta results are included for ease of comparison. As Table 11 shows, linear regressions provide near perfect fits to the data (R^2 values between 0.9947 and 0.9999) for all combinations of chromatic inks and film types. The intercept data is consistent with the main effect analyses for film types: choice of film type has a minor effect on chroma ($C^*_{ab} \leq 1$) for all inks except Violet, where film type has a C^*_{ab} effect of 3. Slopes are closely grouped within each ink, but vary significantly between inks. The slope (% intercept/g/m^2) adjusts for this difference by dividing the slope (in C^*_{ab}/g/m^2) by the value of the intercept (in C^*_{ab}). After making this

Table 11: Regression results for chroma of chromatic inks printed on 75 OPP, 92 Cello, and 80 TIPA measured on white underlayers with coating weights between 0.49 g/m² and 1.95 g/m²

Ink	Film type	Intercept	Slope (C^*_{ab}/g/m²)	Slope (% Intercept/g/m²)	R^2
Magenta	75 OPP	58.1	3.90	6.7 %	0.9982
	92 Cello	57.6	3.83	6.6 %	0.9999
	80 TIPA	57.5	4.03	7.0 %	0.9999
Cyan	75 OPP	45.7	2.60	5.7 %	0.9996
	92 Cello	45.3	2.42	5.3 %	0.9971
	80 TIPA	45.0	2.74	6.1 %	0.9963
Yellow	75 OPP	73.0	4.54	6.2 %	0.9947
	92 Cello	72.0	4.67	6.5 %	0.9983
	80 TIPA	72.5	4.66	6.4 %	0.9997
Orange	75 OPP	78.0	4.67	6.0 %	0.9999
	92 Cello	78.0	4.50	5.8 %	0.9992
	80 TIPA	77.0	4.69	6.1 %	0.9994
Violet	75 OPP	74.7	4.79	6.4 %	0.9998
	92 Cello	72.1	5.47	7.6 %	0.9895
	80 TIPA	71.8	4.81	6.7 %	0.9997

adjustment, we can observe that all slopes fall between 5.3 % and 7.6 % per 1.0 g/m² increase in white ink Ctg Wt with two thirds of the slopes falling between 6.0 % and 6.9 % per 1.0 g/m². Black results have been excluded from this analysis since the L^* (lightness) differences among the black samples are visually insignificant and a predictive model is, therefore, meaningless.

3.3 Relationship between chroma loss and CIEDE2000

Chroma is only one aspect of color perception. To understand the visual impact of changing coating weights and film types, CIEDE2000 color difference values were calculated from the underlying CIELAB data. The CIELAB values of ink swatches printed on 75 OPP and measured on a 1.95 g/m² white underlayer were used as color references since 75 OPP is a standard packaging film and 1.95 g/m² is a standard white ink Ctg Wt.

Unlike the previous two sections, Magenta results will not be discussed separately. Instead, it is more instructive to examine the results for all colors, film types, and coating weights simultaneously. Table 12 summarizes the results of the ΔE_{00} analysis. Black ΔE_{00} values are all less than 1 (i.e. visually undetectable or barely detectable). Thus, Black results have been excluded from the table since they have no visual significance.

Table 12: CIEDE2000 color differences vs reference CIELAB values for each ink (i.e. CIELAB values of each ink printed on 75 OPP and measured over a 1.95 g/m² white underlayer); values below 2 ΔE_{00} are shown in normal text, values between 2 and 3 ΔE_{00} are italicized, values above 3 ΔE_{00} are italicized and shown in bold

Ink	Film type	ΔE_{00} on 1.95 g/m² White	ΔE_{00} on 0.98 g/m² White	ΔE_{00} on 0.49 g/m² White
Magenta	75 OPP	0.00	*2.48*	***3.41***
	92 Cello	0.55	*2.58*	***3.86***
	80 TIPA	0.27	*2.34*	***3.53***
Cyan	75 OPP	0.00	*2.34*	***3.42***
	92 Cello	0.38	*2.64*	***3.71***
	80 TIPA	0.37	*2.56*	***3.53***
Yellow	75 OPP	0.00	***3.50***	***5.10***
	92 Cello	0.93	***4.35***	***5.41***
	80 TIPA	0.24	***3.66***	***5.39***
Orange	75 OPP	0.00	*2.46*	***3.65***
	92 Cello	0.10	*2.31*	***3.50***
	80 TIPA	0.23	*2.35*	***3.56***
Violet	75 OPP	0.00	1.21	1.80
	92 Cello	0.35	1.57	*2.17*
	80 TIPA	0.60	1.69	*2.27*

As this table shows, white ink Ctg Wt is the dominant factor influencing the observed ΔE_{00} values with print layer film type having a secondary effect, a finding that is consistent with the ANOVA results. The range of variation due to film type is less than ΔE_{00} of 1 for all ink color / Ctg Wt combinations. The white ink Ctg Wt, on the other hand, has a pronounced effect on perceived color. For Magenta, Cyan, and Orange inks, cutting white ink Ctg Wt from 1.95 g/m² to 0.98 g/m² results in a ΔE_{00} of ~2.5 color difference; a further reduction to 0.49 g/m² results in a ΔE_{00} of ~3.5 color difference. For Yellow, color difference is magnified. Reducing white ink Ctg Wt to 0.98 g/m² results in a ΔE_{00} of 3.5 – 4.5 color difference, and further reducing coating weight to 0.49 g/m² results in a ΔE_{00} of 5.0 – 5.5 color difference. This effect is attributable to the fact that Yellow has the least blocking power of all inks. As a result, Yellow is more dependent on the white underlayer to block background colors (in this case the black backing) than the remaining inks. Violet, on the other hand, shows less sensitivity to reductions in white ink Ctg Wt. In this case, a 0.98 g/m² white underlayer is a ΔE_{00} of ~1.5 color difference versus a 1.95 g/m² underlayer, while a 0.49 g/m² underlayer results in a ΔE_{00} of ~2.0 color difference. This effect is most likely attributable to the fact that the human visual system is less sensitive to chroma changes in the Blue-Violet region than in other color regions. The ΔE_{00} calculation introduced a rotational factor to account for this difference and improve the agreement between ΔE values and human color judgements (Habekost, 2013).

4. Conclusions

The results of six DOEs assessing the impact of white underlayer coating weight and print layer film type on the chromaticity of gravure printed Magenta, Cyan, Yellow, Orange, and Violet swatches showed that both coating weight and film type have a statistically significant effect on chromaticity ($P < 0.005$). For Magenta, Cyan, Yellow, and Orange inks, white underlayer coating weight had the dominant effect while the effect of print layer film type was relatively minor. Violet ink followed this general pattern, but the difference between the effect of white ink Ctg Wt and print layer film type was less pronounced. The relationship between coating weight and chroma over the range from 0.49 g/m² to 1.95 g/m² was linear for all inks ($R^2 > 0.99$). Finally, when printing Magenta, Cyan, or Orange, a coating weight reduction of 1 g/m² (from 1.95 to 0.98 g/m²) resulted in a color shift ΔE_{00} of ~2.5, and a 1.5 g/m² reduction (from 1.95 to 0.49 g/m²) resulted in a color shift ΔE_{00} of ~3.5. Yellow, the weakest ink, was more affected, while Violet, a hue where the human visual system is less sensitive to chroma differences than it is when judging other hues, was less affected.

For achromatic Black ink, lightness was chosen as the response variable. Although white ink Ctg Wt and print layer film type had statistically significant effects on L^*, the differences attributable to these effects were at or below the threshold of visual detection.

Acknowledgement

The authors would like to recognize their graduate assistants, Nhung Pham and Yash Dhote, for their outstanding diligence and attention to detail during the preparation and measurement of the samples used in this project. The remarkably low error levels obtained bear testimony to the quality of their work.

References

Argent, D., 2008. Opacity & white ink. *Paper, Film and Foil Converter.* [online] Available at: <https://www.pffc.online.com/print/5759-opacity-white-ink-0101> [Accessed 3 April 2022].

Chung, R. and Hsu, F., 2006. Gravure process color gamut optimization. In: *2006 TAGA Proceedings: 58th Annual Technical Conference. Va*ncouver, Canada, 19–21 March 2006. Sewickley, PA, USA: TAGA.

Flexographic Technical Association, 2020. *A holistic approach to white ink laydown*. [online] Available at: <https://www.flexography.org/industry-news/a-holistic-approach-to-white-ink-laydown/> [Accessed 8 July 2022].

Flint Group, 2022. *Flexible packaging inks – gravure lamination*. [online] Available at: <https://www.flintgrp.com/en/products/packaging-and-narrow-web/packaging/north-america/gravure/gravure-lamination/> [Accessed 6 July 2022].

Futamura, 2022. Cellophane. [online] Available at: <https://www.futamuragroup.com/en/divisions/cellulose-films/products/cellophane/> [Accessed 6 July 2022].

Habekost, M., 2013. Which color differencing equation should be used. *International Circular of Graphic Education and Research,* 6*,* pp. 20–33.

InterFlex, 2021. *Flexible packaging for salty snacks*. [online] Available at: <https://www.interflexgroup.com/salty-snacks-packaging/> [Accessed 4 July 2022].

Rich, D.C., 2021. Consistent determination of the contrast ratio of white inks. *Journal of Coatings Technology and Research,* 18(6), pp. 1501–1509. https://doi.org/10.1007/s11998-021-00515-8.

Tagleef Industries, 2022. *Non food packaging.* [online] Available at: <https://www.ti-films.com/en/non-food-packaging-films/products> [Accessed 6 July 2022].

TIPA, 2021. *Tipaclear.* [online] Available at: <https://tipa-corp.com/portfolio/packaging-by-reel/tipaclear/> [Accessed 6 July 2022].

Valdec, D., Miljković, P. and Auguštin, B., 2017. The influence of printing substrate properties on color characterization in flexography according to ISO specifications. *Tehnički glasnik,* 11(3), pp. 73–77.