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Study of Metamerism and Inconstancy of Basic Color System Used in Wood Grain Laminates

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STUDY OF METAMERISM AND INCONSTANCY OF BASIC COLOR SYSTEM USED IN WOOD GRAIN LAMINATES

by

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In product gravure printing, many spot color inks are used. Because the use of spot colors tends to be customer specific, they are typically mixed in house by the gravure printer to satisfy the requirements of a specific customer order. Printers are often concerned about the best utilization of inks, and their recyclability, if possible, to make the production more sustainable. Spot colors may exhibit metameric behavior. This tendency causes problems in color matching, as these products are viewed in a standardized environment, using light source D_{50} or D_{65}, but are viewed under fluorescent lighting at the time of purchase. Therefore, it is necessary to assess their behavior under different light sources, which enables one to predict their performance. A comparative study has been carried out between metamerism indices and inconstancy indices of metameric color pairs. Two base color ink sets were compared for metamerism indices and inconstancy indices. Reflectance data readings were measured with a spectrophotometer and CIE L*a*b* color coordinates were calculated for D_{65}, A, F_2, and D_{50} illuminants. $D_{65/10}$ was chosen as the reference illuminant, with illuminants A, F_2, and D_{50} being considered as additional illuminants for calculating metamerism indices and color inconstancy indices The results show the importance of accounting for the change in perceived color when items are viewed under different lighting conditions.

TABLE OF CONTENTS

Table of Contents – Continued

CHAPTER

CHAPTER

LIST OF TABLES

LIST OF FIGURES

List of Figures – Continued

CHAPTER I

INTRODUCTION

In product gravure printing, spot colors are commonly used to produce products such as decorative laminates, wall coverings, and outdoor furniture fabrics[1]. Spot colors are used to achieve desired color effects. Usually, a color proof standard is sent to a color matching lab. The standard might be a printed shade, a Pantone number or even a piece of cloth. Currently, in many color matching centers, computer based software is used to create the spot color recipes. Colorant formulation software works on Kubelka-Munk theory[2]. Quality control is carried out with a spectrophotometer. Both 45/0 and 0/45 geometry instruments are used for measurement. However, a “specular included” mode of d/8 geometry can also be used as a helpful pass/fail decision making tool. Many spectrophotometers and quality assurance software programs are available with CIELAB colorimetry along with some advanced color difference formulas, such as ΔE_{CMC}, ΔE_{ab}, or ΔE_{2000}[3].

Usually, the pass/fail of shades is decided on the basis of acceptable tolerances of color difference values. Many times, metamerism index and color inconstancy index are not accounted for, while making the decision of pass/fail of a match[4]. Although spectrophotometers are used in the analysis of a match, the person performing the analysis will also give a visual approval of a shade. To-date, ΔE tolerances are the best known tools for maintaining consistency of color. CIELAB colorimetry provided in spectrophotometer software is less consistent because it fails to account for background and surrounding colors, and change in illumination level. These parameters are accounted for in color appearance models[5], which are mostly used in color management software. The color rendering index of illuminant and deviation of the observer's color matching function from standard CIE color matching function also lead to gaps in correlations between visual assessments and numerical pass/fail ratings. Currently, many color spaces are available, based on opponent color theory, which are claimed to be better than CIELAB 1976 color space. Generally, the specular gloss of measured color is often neglected in Quality Assurance/Quality Control, while deciding if a color is in an acceptable range of color difference. For all color standards, except metallic and pearlescent colors, the decision of an acceptance for a match should be based on metamerism and color inconstancy indices, along with color differences. This would result in more reliable acceptance/rejection decisions of a match being made.

Ideally, a color match should be selected on the basis of the closeness of the reflectance graph of a standard to the color of interest. Due to limitations in selection of colorants, it may not always be possible to generate unconditional matches. This leads to a need to account for metamerism and color inconstancy indices in deciding the acceptance or rejection of a particular shade. CIE colorimetry is useful for defined observer/illuminant conditions, but it fails to account for chromatic adaptation, lightness adaptation, luminance level, color of background, surrounding color and how all these factors affect the ultimate visual sensation of a particular color[5]. Again, as mentioned above, these factors contribute to color appearance phenomena, when visual matching of a spot color is important. When a numerical color difference is compared against a visual match, it is obvious that all color appearance phenomena are not accounted for, such as crispening, or spreading[5], and these may affect the visual match of a spot color. Thus, maintaining a colorimetric match against a visual correlation match becomes very difficult when a change in any single color appearance effect, like the Bezold-Brucke hue shift effect,[5] Abney effect[5], Helmholtz-Kohlrausch effect[5], Hunt effect[5], Stevens effect[5], or Bartleson-Breneman effect[5] occurs. Despite the limitations of CIE colorimetry, it is very useful to the average observer under average conditions and for maintaining color consistency in production. These phenomena are considered in color appearance models[5], where chromatic adaptation is emphasized.

CHAPTER II

LITERATURE REVIEW

In color perception, three components are important: 1) Light source 2) Object 3) Observer. So, in color measurement, it is important to consider all three factors so that illuminant and observer are accounted for. Color measurement is important for 1) Expressing color 2) Reproduction of color 3) Color communication and 4) Color control. During color reproduction, it is important to understand how accurately we can achieve a targeted color. To find the deviation from a target, a color difference calculation is necessary and for that it is necessary to plot the standard and color of interest in color space.

Color Spaces

Color Spaces[5]: The three dimensional space constructed using a geometrical expression of color is called a color space[6]. There are many color spaces available for colorimetric calculations. Color spaces are of two types: 1) Non-uniform color spaces 2) Nearly uniform color spaces. No perfectly uniform color space is available at this time. Color spaces based on opponent theory are considered here, because they are claimed to be more uniform[7]. According to opponent theory, red and green are opposite hues while blue and yellow are opposite colors[7]. The following, are color spaces available based on opponent color theory:

- AN Lab[8]

- Scofield 1943 Lab[8]
- Glasser, McKinney, Reilley, & Schnell 1958 - Lab[8]
- Hunter Lab 1966[9]
- MLab[10]
- CIE Lab 1976[8]
- K. Richter – LABNHU 19776[8]
- LLAB[5]
- RLab[5]
- ZLab[5]

These are modified color spaces that can be used for calculating color difference, and metamerism index (MI). But for convenience purposes, the CIELAB1976 model is used, even though further developed color spaces are claimed to be better. The formula used for CIELAB1976 color space is as follows:

CIELAB 1976 formula[8]

$$L = 116 f(Y/Y_r) - 16 \tag{1}$$

$$a = 500[f(X/X_r) - f(Y/Y_r)] \tag{2}$$

$$b = 200[f(Y/Y_r) - f(Z/Z_r)] \tag{3}$$

Where:

$$f(r) = r^{1/3} \qquad \text{for } r > 0.008856 \tag{4}$$

$$f(r) = 7.787r + 16/116 \qquad \text{for } r \leq 0.008856 \tag{5}$$

To calculate CIE XYZ the values from the following equations are used.

$$X = K \int_{380}^{730} \left(S(\lambda) R(\lambda) \overline{X}(\lambda) \right) \tag{6}$$

$$Y = K \int_{380}^{730} \left(S(\lambda) R(\lambda) \bar{Y}(\lambda) \right) \tag{7}$$

$$Z = K \int_{380}^{730} \left(S(\lambda) R(\lambda) \bar{Z}(\lambda) \right) \tag{8}$$

Where

XYZ- Tristimulus values

X_n, Y_n Z_n- Chromaticity coordinates of illuminant

$S(\lambda)$ – Illuminant emission data

$R(\lambda)$ – Reflectance data

$\bar{X}(\lambda)$, $\bar{Y}(\lambda)$, $\bar{Z}(\lambda)$- Color matching functions

$$K = \left[\frac{100}{\int S(\lambda)\, \bar{y}(\lambda)\, d\lambda} \right]$$

Cone Response Space

Cone Response Space[11]: Functions of this psychophysical color space are linear or logarithmic and denoted as R, G, B or L, M, S for long, medium & short wavelength responses of cones in the human eye. This space is used in chromatic adaptation transforms.

Illuminants

Illuminants[9,10]: An illuminant is set of numbers defined by the relative spectral power distribution that may or may not be physically realizable as a source[12]. All illuminant data are published by CIE. Some of CIE standard illuminants are mentioned below.

CIE Standard Illuminant A

CIE Standard Illuminant A[13]: An illuminant representing a tungsten lamp, for which absolute color temperature is 2856 K.

CIE Standard Illuminant C

CIE Standard Illuminants C[13]: An illuminant derived from illuminant A. It is an early daylight, or overcast sky, illuminant C has a correlated color temperature of 6774 K. According to CIE recommendations, illuminant C should be replaced with illuminant D_{65}, but the paper industry still uses C, as TAPPI standards have not been updated.

CIE 'D' Series of Illuminants

CIE'D' Series Illuminant[8]: Method of calculation of this series is based on a correlated color temperature. D_{65} is recommended by CIE as a standard illuminant with color temperature of 6500K. It represents noon day light. D_{50} has been adopted by the graphic art industry in the USA as a standard illuminant, and it represents direct sun light with color temperature of 5000K.

F2

F2[8]: It is a cool white fluorescent light with 4100 K correlated color temperature. This light source has a color rendering index (CRI) of 60.

Illuminant and light source are distinct concepts. An illuminant is defined by mathematical data, which are used in colorimetric calculations, while a light source is a physical source, which emits electromagnetic radiation in the visible region. Not all illuminants have physical light sources. Light sources are made by targeting illuminant data "*Color Rendering index is a measure of the degree of which the perceived colors of objects illuminated by the source confirm to those of the same objects illuminated by a standard source for specified conditions.*"[14]

Color Matching and Difference

Color Matching and Difference[6]: To calculate the difference between any two colors in a color space, a color difference formula is used. At least 24 color difference formulas in different color spaces are available. Even though extended color difference formulas are claimed to be "better" than the CIE1976 color difference formula[8], the CIE1976 formula is still widely used.

$$\Delta E_{ab} = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]^{0.5} \tag{9}$$

Where,

ΔE_{ab}- Is the color difference between any two colors.

ΔL- Difference between lightness value of standard and sample

Δa- Difference between an axis value of standard and sample

Δb- Difference between b axis value of standard and sample

When colors are matched, there are two types of matches that exist.

Invariant Match

Invariant Match[12]: When the standard and sample match under any illuminant/observer condition, the match is known as an invariant match. For matching a spot color, the first preference is an invariant match.

Conditional Match

Conditional Match[12]: It is very difficult to obtain an invariant match with the limited number of colorants available and cost limitations that exist for any job, so when matching conditions are defined and a "suitable" match is selected under such limiting conditions, it is known as a conditional match. Metamerism is often the greatest deficiency for such a match. When matching is carried out in this case, the decision of pass/fail is taken in a conditional way, agreed upon by customer and provider.

Acceptable Match

Acceptable Match[12]: Color difference limits, or acceptable color tolerance limits, are set for decision making. When the customer accepts a sample within specified tolerance limits, it is known as an acceptable match. This method is used for controlling consistency in production. If the visual difference between standard and sample is large, but the cost is much less, it may become an "acceptable" match. Here, the maximum acceptable color difference is defined and such a match is known as an acceptable match.[15]

Perceptible Match

Perceptible Match[12]: A shade is accepted by visual comparison, i.e. when it is perceived visually that the standard and the sample have less than just a perceptible difference, such a match is known as a perceptible match. In this method, the match is selected with the least perceptible difference. After getting customer approval, the color difference between the standard and sample is measured, and these used to set the tolerance limits, which are followed for color reproduction. A minimum perceptible match is always preferred, which is considered as "just a noticeable difference"[11].

Metamerism

"Metameric color stimuli have identical tristimulus values, but different spectral radiant power distributions"[8] If it happens with objects (reflection or transmission), then they are known as metameric objects. If it happens with illuminants, then they are referred to as metameric illuminants[16].

Types of Metamerism

Types of metamerism include illuminant, observer, field, instrument and geometric[17].

Illuminant Metamerism

When the standard and sample match under one illuminant but don't under another, it is called an illuminant metamerism. It is also known as a source metamerism.

Observer Metamerism

When standard and sample match under one observer, but don't for another observer, it is called an observer metamerism.

Field Metamerism

When standard and sample match under one field, but not under another, it is called a field metamerism. For example, if a standard and sample match under a 2° field but not under a 10° field, then it is known as a field metamerism.

Instrument Metamerism

When a standard and sample match under one instrument but not under another, it is called an instrument metamerism (see Table 1).

Table 1. *Difference Between Instrumentation Parameters of Two Hypothetical Instruments*

Instrument specifications	Instrument 1	Instrument 2
Geometry	45/0	0/45
Range	380-730 nm	400-700nm
Internal sphere	6"	3"
Aperture	12mm	3.4mm
Splitting technique	Prism	diffraction grating
Chromating technique	monochromating	polychromating
Internal reading	2 nm	20 nm
Light source	Pulsed xenon	Tungsten
Filters	UV available	No filters

The instruments listed in Table 1 will provide different readings. Though they are calibrated, one instrument may pass a match while the other may fail it. If this occurs, then it is known as instrument metamerism. To avoid this situation, the same instrument manufacturer and model is recommended for use.

Geometric Metamerism

When viewing geometry changes breaks a match, it is called geometric metamerism. The chances of two colors being a geometric metameric pair are more prevalent for metallic and high gloss inks.

Degree of Metamerism

One can determine the degree of metamerism, which is also known as the magnitude of an effect for given pair of samples. Two ways of doing this are suggested, leading to the establishment of general and special metamerism indices.

General Metamerism Index, Bridgeman's Work

In the general metamerism index (Bridgeman's work[18]), the difference in spectral composition of a metameric pair is given, where $S_1(\lambda)$ & $S_2(\lambda)$ are the spectral power of the pair:

$$D = [\int_{380}^{780}\{S1(\lambda) - S2(\lambda)\}^2]^{0.5} \tag{10}$$

In this method, the differences in spectral emission composition are averaged. However, the difference needs to be appropriately weighted and must be dependent on the relative importance of different parts of the spectrum. In 1965 Nimeroff[19] suggested a weighted spectral power distribution curve to avoid overweighting the end of the spectrum by the CIE color matching function.

Nimeroff &Yurow's Recommended the following:[19]

$$MI(N+Y) = \int_{380}^{730}[\,(\bar{x}_{10}(\lambda)\Delta R\lambda)^2 + (\bar{y}_{10}(\lambda)\Delta R\lambda)^2 + (\bar{z}_{10}(\lambda)\Delta R\lambda)^2]^2 \quad .(11)$$

ΔR- Difference between reflectance data of standard and sample.

In Equation 11, the formula for CIE Color Matching Functions (CMF), are used as published in 1964 by CIE.

Instead of seeking a general index of metamerism, it is more justifiable to use different indices according to change in conditions.

Metamerism Index Based on Spectral Luminous Efficiency Function

Metamerism index based on spectral luminous efficiency function[20]: In this formula, the luminous efficiency function is weighted.

$$\mathrm{MI\ (P)} = \{\int_{380}^{730}(\, v_\lambda \Delta R_\lambda)^2\}^{0.5} \quad (12)$$

v_λ = spectral luminous efficiency function.

Special Metamerism Index

Special Metamerism Index[21]: When tristimulus values of a pair are identical under reference illuminant/observer, the metamerism index is equal to the color difference between two specimens computed under the test illuminant. The special metamerism index is referred to as "special" because it is only for changes in illuminant. This is also referred to as DIN 6172[21].

$$M_T^2 = (L_{1T}^* - L_{2T}^* + K_L)^2 + (a_{1T}^* - a_{2T}^* + K_a)^2 + (b_{1T}^* - b_{2T}^* + K_b)^2 \quad .(13)$$

$$K_L = L_{2B}^* - L_{1B}^*$$

$$K_a = a_{2B}^* - a_{1B}^*$$

$$K_b = b_{2B}^* - b_{1B}^*$$

	Under Reference Illuminant	Under Test Illuminant
Specimen 1	$L^*_{1B}\ a^*_{1B}\ b^*_{1B}$	$L^*_{1T}\ a^*_{1T}\ b^*_{1T}$
Specimen 2	$L^*_{2B}\ a^*_{2B}\ b^*_{2B}$	$L^*_{2T}\ a^*_{2T}\ b^*_{2T}$

$_1$ indicates specimen 1

$_2$ indicates specimen 2

$_B$ indicates under reference illuminant

$_T$ indicates under test illuminants

L*,a*,b* are CIELAB values

Apart from this formula, any extended color difference formula can be generally used for metamerism index calculations. If metamerism under illuminant 'A' is acceptable, then generally, a metamerism under another light source is acceptable.

Metamerism Index By Hunter for Change in Illuminant/CIE 15.2 Section 5.2 M.I. Formula

Hunter lab applies another type of special index[18,22] as follows:

$$MI(LABD) = [(\Delta L_{n1} - \Delta L_{n2})^2 + (\Delta a_{n1} - \Delta a_{n2})^2 + (\Delta b_{n1} - \Delta b_{n2})^2]^{0.5} \quad (14)$$

Where Δ indicates the difference between standard and sample and subscripts n1 and n2 indicate first and second illuminants, respectively. The L* a* b* values can be of Hunter or CIELAB color scale. This type of index does not distinguish between test and reference illuminants, but only the illuminant pairs. 0 to 0.5 MI is considered a perfect match and 0.5 to 1 MI is considered a doubtful match. Getting a perfect match for a fluorescent illuminant is difficult, so acceptable limits should be set on the higher side[23]. Note that Equation 14 reverts to Equation 13 for corresponding illuminants.

Metamerism Index for Change in Observer

A pair of samples, which match for one observer, but fail to match when an observer is changed, is called a change in observer[24] CIE metamerism index. This is because color matching functions vary for different observers for any field of view. For this index, as a rule, D_{65} is considered the standard illuminant. The procedure for calculating the observer metamerism index is as follows:

Step 1) Find the color matching functions for standard deviate observer by using following formula

$$\bar{x}_d(\lambda) = \bar{x}_s(\lambda) + \Delta\bar{x}(\lambda) \tag{15}$$

$$\bar{y}_d(\lambda) = \bar{y}_s(\lambda) + \Delta\bar{y}(\lambda) \tag{16}$$

$$\bar{z}_d(\lambda) = \bar{z}_s(\lambda) + \Delta\bar{z}(\lambda) \tag{17}$$

Where $\bar{x}_d(\lambda)$, $\bar{y}_d(\lambda)$, $\bar{z}_d(\lambda)$ are color matching functions of standard deviate observer for visible range. $\bar{x}_s(\lambda)$, $\bar{y}_s(\lambda)$, $\bar{z}_s(\lambda)$ are color matching functions of standard observer at any field (2° or 10°). $\Delta\bar{x}(\lambda)$, $\Delta\bar{y}(\lambda)$, $\Delta\bar{z}(\lambda)$ are deviation functions given by Ohta & Robertson[6].

Step 2) Calculate tristimulus values for both observers.

Step 3) Correct tristimulus values by paramerism method to avoid error.

Step 4) Then color difference is calculated as for the observer metamerism index as $M_{obs} = \Delta E$.

Generally, the CIE1976 color difference formula is used, but if another formula is used, then it should be mentioned. If the observer metamerism index is < 0.2 then it is good, if it is above 0.5 then it is poor.

Metamerism Index for Change in Field

When the field is changed, which breaks the metameric match, the index obtained is called metamerism index for change in field[6]. When the field is changed from 2° to 10°, or vice versa, the metameric match may break. In this calculation D_{65} is considered a standard illuminant. The procedure is as follows:

Step 1) Calculate Color coordinates for pair of samples under 2° & 10° fields

Step 2) Apply correction procedure of paramerism to color coordinates to avoid error.

Step 3) Calculate color difference by CIE1976 color difference formula. If any other formula is used then state so.

Berns and Billmeyer's Metamerism Index Based on Chromatic Adaptation Transform

The metamerism index based on chromatic adaptation transform by Berns and Billmeyer[25] can be calculated as follows:

Step 1) Calculate tristimulus values for all illuminants

Step 2) Calculate tristimulus values of primary illuminant using Nayatini's CAT model

Step 3) Apply Multiplicative correction

Step 4) Convert tristimulus values into CIELAB space

Step 5) Use color CIE1976 color difference formula for measuring MI

Step 6) Use same formula for Color Inconstancy Index (CII to be defined below)

$$MI\ (B+B) = [(L'_{STD} - L'^{C}_{SAM})^2 + (a^{*\prime}_{STD} - a^{*\prime C}_{SAM})^2 + (b^{*\prime}_{STD} - b^{*\prime C}_{SAM})^2]^{1/2} \quad (18)$$

Where C stands for correction for difference in tristimulus values under reference illuminant. STD represents the concern in color coordinate for the standard color and SAM represents the concern in color coordinate for the sample color. The corrections are made in tristimulus by paramerism.

Weighted Metamerism Index

$$MI_{weighted} = \frac{w_2 \Delta E^*_{ab,A} + w_3 \Delta E^*_{ab,F2} + \cdots}{w_2 + w_3 + \cdots} \quad (19)$$

When a metamerism index under several illuminants is calculated and grouped, the result is required at the time the weighted MI is calculated[9]. Selection of a weight factor is the matcher's choice and psychophysical experiments can be used to determine the W factor.

Where:

W- Weight factor

$\Delta E_{ab\ A}$- Color difference under illuminant A

$\Delta E_{ab\ F2}$- Color difference under illuminant F2

Paramerism

Paramerism[17]: When the metamerism index is calculated, the color difference between standard and sample must be zero at any illuminant/observer condition, i.e. $\Delta E = 0$ at any one illuminant/observer condition. But in practice, this difference is not zero and leads to error. To avoid error, a correction called paramerism[17] is calculated. Two types of corrections are available.

Multiplicative Correction

For illuminant/observer condition tristimulus values are:

$X_{11}\ Y_{11}\ Z_{11}$ illuminant/observer 1- Sample 1

$X_{12}\ Y_{12}\ Z_{12}$ illuminant/observer 1- Sample 2

Color difference is ΔE_1

Correction factor is calculated as follows.

$$f_X = X_{11}/X_{12} \qquad f_Y = Y_{11}/Y_{12} \qquad f_Z = Z_{11}/Z_{12} \tag{20}$$

then, tristimulus values of sample 2 after corrections are,

$$f_X X_{12} = X_{11} \qquad f_Y Y_{12} = Y_{11} \qquad f_Z Z_{12} = Z_{11} \tag{21}$$

For another illuminant observer condition, the following tristimulus values are calculated for the same pair of samples

$X_{21}\ Y_{21}\ Z_{21}$ illuminant/observer 2- Sample 1

$X_{22}\ Y_{22}\ Z_{22}$ illuminant/observer 2- Sample 2

The color difference is ΔE_2

If one corrects tristimulus values $X_{22}\ Y_{22}\ Z_{22}$ with factors of f_X, f_Y, f_Z, one get tristimulus values.

$$f_X X_{22} = X_{32} \qquad f_Y Y_{22} = Y_{32} \qquad f_Z Z_{22} = Z_{32} \tag{22}$$

Then the difference between $X_{21}\ Y_{21}\ Z_{21}$ and $X_{32}\ Y_{32}\ Z_{32}$ is converted into CIE1976 L*a*b* space for calculating the metamerism index.

Additive Correction

Calculation of corrected metamerism:

Calculate L* a* b* values for X_{11}, Y_{11}, Z_{11}, X_{12}, Y_{12}, Z_{22}

$L_{11}\ a_{11}\ b_{11}$ illuminant/observer 1- Sample 1

$L_{12}\ a_{12}\ b_{12}$ illuminant/observer 1- Sample 2

calculate correction factor

$$f_a = a_{11} - a_{12} \qquad f_b = b_{11} - b_{12} \qquad f_L = L_{11} - L_{12} \tag{23}$$

Calculate L* a* b* for X_{21}, Y_{21}, Z_{21}, X_{22}, Y_{22}, Z_{22}

$L_{21}\ a_{21}\ b_{21}$ illuminant/observer 2- Sample 1

$L_{22}\ a_{22}\ b_{22}$ illuminant/observer 2- Sample 2

Add correction factor to $L_{28}\ a_{28}\ b_{28}$ then it will become

$$f_a + a_{22} = a_{32} \qquad f_b + b_{22} = b_{32} \qquad f_L + L_{22} = L_{32} \tag{24}$$

Calculate the color difference between L_{21} a_{21} b_{21} and L_{32} a_{32} b_{32} and that is metamerism index.[17] Note that this yields the same value as Equations 13 and 14.

A Geometric Metamerism Index

Under a fixed illuminant and illuminating conditions, two goniochromatic objects are called geometric metamers. The geometric metamerism index[26] is then calculated.

GM=$\max_j \{\Delta E_j^G, \forall_j = \alpha; \alpha \geq 1\}$ T_k

$$\Delta E = \left[\sum \left(\frac{(\Delta T_k)j}{(T_k^s)_j}\right)^2\right]^{1/2} \tag{25}$$

Where,

$\Delta T_k \in [\,\Delta L,\ \Delta a,\ \Delta b,\ \Delta c,\ \Delta H], (T_k^s)_j, \in [L,\ a,\ b,\ c,\ h]$

Where $(T_k^s)_j$and $(T_k^s)_j =, (X_k^s)_j\ \forall_k$ represents the k[th] color-coordinate variations between the reference and the specimen panels, and the k[th] color-surrounding coordinate under the j[th] illuminant, respectively, and, the number of illuminants to be examined. For this formula L*a*b* values are measured by a goniophotometer.

In equation 25, $\Delta c,\ \Delta H$ are not necessary, as they are not independent of $\Delta a,\ \Delta b$ (equation 26 below) and therefor redundant.

Metameric Indices Based on Color Constancy Indices

For metameric pairs, each color has a different inconstancy index. So, the degree of metamerism can be measured as the ratio of difference in color constancy[27].

$$\mathrm{CCI\ (MC)} = \frac{[(\Delta L)^2 + (\Delta C)^2 + (2\Delta H)^2]^{0.5}}{(1+0.02C)} \tag{26}$$

ΔL- Difference between lightness of standard and sample.

ΔC- Difference between chroma of standard and sample

$$\Delta H = [(\Delta E)^2 - (\Delta C)^2 - (\Delta L)^2]^{0.5}$$

Here Δ indicates the difference in respective theoretical values of test color under test illuminant and those derived by nonlinear chromatic adaption transformations from the reference illuminant for equal color appearance.

Selection of color space, color difference formula & formula for MI & CII is totally dependent on experimenter's choice. No rules are available to compel one to select a particular formula or procedure. CIE provides only guidelines.

Dichroism

Dichroism[28]: "Refers to the ability of a material or substance to attain two different colors."[28] It occurs because of the following three reasons 1) Polarization of light 2) Angle at which light strikes the material and 3) Dye dichroism. It is a big problem in the measurement of dichromatic materials for colorimetric calculations. One should remember, dichroism and CII are different concepts. In CII the angle of viewing or concentration of material remains the same, but color appearance changes after changes to the light source. In dichroism, under the same light source, color appearance changes after changes in viewing angle or concentration of material. In this study, dichromatic materials are not considered for evaluation of CII and MI.

Color (In)constancy

Color (In)constancy[12]: Color constancy is nothing but perceiving the same appearance after changing the light source. An example of this is when our eye accepts that a paper looks white under many light sources. Ideally, color constancy does not exist, because if we look carefully, paper looks white under different light sources, but those whites are not all the same. So we need to see how much color change there is after changing the light source and that is color constancy. Color constancy is very important for printed gravure laminates, because they are viewed under several illuminants. When colors and recipes are selected, the criterion of color constancy is not usually considered. The color inconstancy index is very helpful for selecting recipes. Metamerism also has a close relation with color inconstancy. In metameric pairs, both samples have different color inconstancy indices. So the CII of a standard and recipe will help the matcher to select a recipe that has the lowest CII & MI indices. When a designer selects a shade, the shade with the lowest CII should be selected. A chromatic adaption transform is used in CII, but its purpose is not to predict the change in the appearance of the object, when illumination is changed. The chromatic adaption transform predicts the corresponding color with colorimetric values that are equivalent to the color under a standard illuminant. For example, if one color that is perceived as gray when illuminated under D_{65}, the chromatic adaption transform will predict a corresponding color with chromatic values that are equivalent to gray. Suppose a person has a wallpaper color patch they wish to match, as per current matching practice, matching is carried out under a D_{65} light source. But, when the illuminant is changed from D_{65} to another illuminant, the color appearance changes. Now, suppose the client standing at the light booth expresses that an 'A' illuminant is in the hotel where the wallpaper will be hung. Then it is important that the wallpaper be perceived under the 'A' as perceived under the D_{65}. For this example, a partitioned light booth is needed where the wallpaper colors can be viewed in both the D_{65} and 'A' illuminants. Only by this way can both be matched! In this case, chromatic adaptation transforms help in reproduction, but can't make them match visually when they don't.

Why Calculate CII?

When an observer perceives color under one light source, and then switches to another light source, the same patch is perceived differently, as the observer will compare the current perception with a previous one. In comparison, color memory and the speed of the changing light source affect the adaptation of color. If the light source is changed slowly and sufficient time is allowed to eyes for adaptation. Under those conditions it is difficult to compare a change in perception, because of loss of memory. For this phenomenon instrumental measurement and analysis method are reliable in colorant-recipe prediction. When the recipe for a colorant is predicted, if the CII is checked, attention should be paid to whether inconstancy occurs. The recipe with least CII should always be selected.

CII

When CII is calculated, the measuring conditions used should be mentioned. The procedure for calculating CII is as follows[13]:

Step 1) Measure/calculate tristimulus values of color under standard illuminant

Step 2) Use a chromatic adaptation transforms to calculate tristimulus values under test illuminant. Some will be discussed below.

Step 3) Calculate color difference between color coordinates under standard illuminant and calculated color coordinates under test illuminant.

CMCCON02[29] – The CMCCON02 formula is recommended with (Lightness: Chroma (l:c) is 2:2, see equation 29 below), but any other formula can be used, but it should be mentioned. In the CMCCON02 formula, the procedure is the same as above, but the CAT02 model should be used as the chromatic adaption transform and CMC (2:2) formula should be used for calculating color difference.

CMCCON02 Formula

The CMCON02 formula[29] can be calculated as follows:

Step 1) Calculate tristimulus values under source illuminant, CIE XYZ & L*a*b*c*h*.

Step 2) Use CAT02 formula and calculate CIE XYZ & L*a*b*c*h* values under destination illuminant

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M_{CAT02} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad M_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix} \tag{27}$$

M_{CAT02} is sharpened relative cone responsivities by matrix transformation under the assumption of complete chromatic adaptation.

$R_c = R[D(R_{Wr}/R_w) + 1\text{-}D]$

$G_c = G[D(G_{Wr}/G_w) + 1\text{-}D]$

$B_c = B[D(B_{Wr}/B_w) + 1\text{-}D]$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M^{-1}_{CAT02} \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix} \qquad M^{-1}_{CAT02} = \begin{bmatrix} 1.096124 & -0.278869 & 0.182745 \\ 0.454369 & 0.473533 & 0.072098 \\ -0.009628 & -0.005698 & 1.015326 \end{bmatrix} \tag{28}$$

Step 3) Calculate color difference by CMC(2:2) color difference formula.

$$\Delta E_{CMC} = \left[\left(\frac{(\Delta L)}{l S_L}\right)^2 + \left(\frac{(\Delta C)}{c S_c}\right)^2 + \left(\frac{(\Delta H)}{S_H}\right)^2\right]^{1/2} \quad (29)$$

Where:

$S_L = 0.040975L^*/(1+0.01765L^*)$ unless $L < 16$ when $S_L = 0.511$

$S_C = 0.0638C^*_{ab}/(1+0.0131C^*_{ab}) + 0.638$

$S_H = (fT + 1 - f)S_C$

Where:

$f = [(C^*_{ab})^4 / \{(C^*_{ab})^4 + 1900)\}]^{0.5}$

$T = 0.36 + |0.4 \cos(h_{ab} + 35)|$

If h is between 164 and 345 degrees when

$T = 0.56 + |0.2 \cos(h_{ab} + 168)|$

Where:

$S_L = 0.040975L^* / (1+0.01765L^*)$ unless $L < 16$ when $S_L = 0.511$

$S_C = 0.0638C^*_{ab} / (1+0.0131C^*_{ab}) + 0.638$

$S_H = (fT + 1 - f)S_C$

Where:

$f = [(C^*_{ab})^4 / \{(C^*_{ab})^4 + 1900)\}]^{0.5}$

$T = 0.36 + |0.4 \cos(h_{ab} + 35)|$

If h is between 164 and 345 degrees when

$T = 0.56 + |0.2 \cos(h_{ab} + 168)|$

In the above formulae

D - Discontinuity factor:- When switching from one light source to another, the degree of adaption is considered an adaption of complete discontinuity (D=1). This is the measure of degree is known as discontinuity factor.

XYZ - Tristimulus values

ΔL, ΔC, ΔH Defined above.

R_W, G_W, B_W - RGB response of illuminant

X_W, Y_W, Z_W- White point of illuminant

X_{Wr}, Y_{Wr}, Z_{Wr} – Tristimulus values of color under standard illuminant

R_{Wr}, G_{Wr}, B_{Wr} – RGB response of color under standard illuminant

R_c, G_c, B_c – RGB response under target illuminant

X_c, Y_c, Z_c – Tristimulus values under target illuminant.

Chromatic Adaptation Models

Chromatic Adaptation Models[16]: Chromatic adaptation is the process in which the light source is changed, and the eyes change sensitivity to adjust the color perception of the object to the same color the object had under the first light source. So a (human) memory matching concept comes into the picture in the chromatic adaptation phenomenon. So at full chromatic adaptation, the observer accepts a color constancy mechanism. An example of chromatic adaptation is that an apple looks red under fluorescent light and under daylight also, because the eyes adapt to change in illuminant. But when the color of an apple is compared by memory matching technique, the observer says the color changes slightly, but remains red. Fairchild explained this phenomenon[5]

"Color constancy is served by the mechanism of chromatic adaptation and memory color and can easily be shown to be very poor, when careful observations are made."

Chromatic adaptation models are used for calculating corresponding colors under different illuminants. Several chromatic adaptation models have been developed[16]. But the CIE recommendation is for the CIECAT02 model to be used in the calculation[5,16]. The CIECAT02 model is used in CIECAM02 and CMCCON02 calculations. Other models are:

1) von Kries[16]

2) Helson- Judd- Warren[5]

3) Nayatani Model[10]

4) Bartleson Transform[10]

5) Fairchild Model[5]

6) Hunt Model[5]

7) BFD Transforms[10]

8) Guth Model[16]

9) CIECAM97[29]

10) ZLAB[5]

11) ATD Model[10]

12) CIECAM02[5]

Chromatic adaptation models can be used to calculate metamerism index and color difference. It is claimed that color difference calculated by a CAM works better than conventional methods[30]. Also CAM can be used to calculate color differences when viewing conditions are different. So as per conventional methods, a color difference formula is only used to decide pass/fail of a sample. With modern techniques, use of CAM, metamerism index and CII to decide the pass/fail of a sample may give a better visual correlation than old techniques of colorimetry.

BFD

The Bradford transform is a modification of the von Kries model of short wavelength cone response[5,16]. Following are the steps used in its calculation:

Step 1) Calculate cone responses of reference illuminant, destination illuminant & color patch by using below equation

$$\begin{bmatrix} L_s \\ M_s \\ S_s \end{bmatrix} = M_B \begin{bmatrix} X_s/Y_s \\ Y_s/Y_s \\ Z_s/Y_s \end{bmatrix} \qquad M_B = \begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix} \tag{30}$$

Step 2) Use the following equations for calculating the destination cone response of the color patch.

$L_d = [F_D(L_{W,d}/L_{W,s}) + 1 - F_D]L_s$

$M_d = [F_D(M_{W,d}/M_{W,s}) + 1 - F_D]M_s$

$S_d = [F_D(S_{W,d}/S^{\tau}_{W,s}) + 1 - F_D]S_s$

$S^{\tau} = (S_{W,s}/ S_{W,d})^{0.0834}$

Step 3) from destination cone response calculate, tristimulus values under destination light source.

$$\begin{bmatrix} X_d \\ Y_d \\ Z_d \end{bmatrix} = M^{-1}_B \begin{bmatrix} L_d Y_s \\ M_d Y_s \\ S_d Y_s \end{bmatrix} \qquad M^{-1}_B = \begin{bmatrix} 0.9870 & -0.1471 & -0.1600 \\ -0.4323 & 0.5184 & 0.0493 \\ -0.0085 & 0.0400 & 0.9685 \end{bmatrix} \tag{31}$$

X_s, Y_s, Z_s – tristimulus values of color patch under source

X_d, Y_d, Z_d – tristimulus values under destination

L_s, M_s, S_s – Cone responses of color patch under source illuminant

L_d, M_d, S_d – Cone responses of color patch under destination illuminant

$L_{W,d}$, $M_{W,d}$, $S_{W,d}$- Cone responses of white point of destination illuminant

$L_{W,S}$, $M_{W,S}$, $S_{W,S}$- Cone responses of white point of source illuminant

F_D- Factor to discount illuminant difference

CAT02

To calculate CAT02, calculate the cone responses of reference illuminant, destination illuminant & color patch by using Equations 27 and 28. In the experiment, complete adaptation is considered if D=1, where D is the degree of adaptation. It ranges from 0 to 1 as 0 indicates no adaptation and 1 indicates complete adaptation of white point[31].

So different MI & CII are available and those can become helpful for making decisions regarding spot color approval. In this experiment, MI and CII will be used for approval of spot colors to understand the behavior of color under different illuminants, because in any color difference formulae this behavior is not accounted for.

CHAPTER III

PROBLEM STATEMENT

Color reproduction is carried out under certain conditions. When conditions change, tracking change in behavior is important. It is important to predict change in appearance to define color reproduction tolerances. When one basic color set is expected to be replaced by another, comparing them under different viewing conditions is necessary. But comparing a way of change in behavior can become a significant factor for accepting. Many spot colors change their dominant appearance under different light sources. Furthermore, two spot colors, which match within tolerances, may change differently from one another under different light sources. The first is characterized by CII, while the second is characterized by MI. In order for ink suppliers and printers to provide acceptable colors to their customers, it is necessary to understand and predict the above mentioned phenomena.

CHAPTER IV

EXPERIMENTAL

A white coating was printed onto a special gravure paper supplied by Omnova solutions. Inks used by them in the printing of wood grain laminates were printed onto the pad coated paper using a 150 LPI plate and a gravure K-proofer[32]. The properties of the inks used are provided in Table 2. After drying, reflectance measurements were taken using an X-Rite–i1. The conditions under which the measurements were taken are described below. From these measurements, the color difference, metamerism index and color inconstancy index were calculated.

Table 2. *Ink Description*

Ink Code	Color	Viscosity [Sec] by Zahn cup 2
314	Red	36
349	Red	35
357	Yellow	33
385	Yellow	32
347	Blue	35
2314	Red	35
2349	Red	35
2357	Yellow	32
2385	Yellow	33
2001	Blue	36

Measuring and Calculation Parameters

- Geometry of Instrument – 45/0
- Illuminant – D_{65}, D_{50}, A, F_2 etc.
- Observer – CIE1964
- Field- 10°
- Color Space – CIE L*a*b* 1976
- Aperture- 4mm
- UV component- without UV filter
- Pass/Fail Limits – At just perceptible difference
- Paramerism method- Multiplicative
- MI formula- CIE 15.2 sec 5.2
- CII formula- CMCCON02, CMC 2:2
- $\Delta E - \Delta E_{CMC\ 1:1}$

Selection of Formula

1) For color difference calculation D65/10 and CMC1:1 was used as recommended by OMNOVA Solutions
2) For metamerism index formula recommended by CIE in section 15.2 was used along with multiplicity correction method.
3) For CII recommended CMCCON02 formula was used.
4) For pantone D50/2 was used as in digital Pantone library CIEL*a*b* values are available only in D50/2 and as no standard/sample condition exist for symmetry ΔE_{ab} formula is used.

CHAPTER V

RESULTS AND DISCUSSION

For comparing two basic color series K-proofer draw-downs were taken at an ink viscosity window of 32-36 seconds by Zahn cup 2 on a 150 lpi plate. As one ink set was designed similarly to the other, similar shades generate pairs of sample and standard. Similar colors were printed at the same time side by side for comparison as shown in Table 3. Results show that some pairs have less color difference and less metamerism index, so to understand behavior of spot colors, reflectance graphs need to plotted and analysis to be carried out.

Table 3. *Color Difference $\Delta E_{CMC\,(1:1)}$ Between Standard and Sample Inks*

Standard Ink Number	Sample Ink Number	$\Delta E_{CMC\,(1:1)}$
314	2314	1.37
349	2349	2.20
357	2357	0.96
385	2385	5.47
347	2001	5.90

The pair 357 – 2357 shows the least color difference and pair 347- 2001 shows the largest color difference. Among the five pairs shown in Table 3, pair 357-2357 and pair 314-2314 have acceptable color differences, while the color difference of pair 349-2349 is borderline acceptable. Pair 385 – 2385 and pair 347-2001 both have unacceptable color differences. For these calculations the CMC (1:1) color difference formula was used.

Table 4. *Metamerism Index*

Ink 1	Ink 2	$D_{65}\rightarrow A$	$D_{65}\rightarrow D_{50}$	$D_{65}\rightarrow F_2$
314	2314	2.36	0.61	2.88
349	2349	0.20	0.11	0.43
357	2357	1.38	0.29	1.89
385	2385	3.03	0.70	2.58
347	2001	2.66	0.65	3.40

From Table 4, the $D_{65}\rightarrow D_{50}$ MI was least for all pairs and highest for the $D_{65}\rightarrow F_2$ illuminant condition. The 349- 2349 pair had the lowest MI for all illuminant conditions but its color difference was borderline acceptable.

Table 5. *Inconstancy Index*

Inks	$D_{65}\rightarrow A$	$D_{65}\rightarrow D_{50}$	$D_{65}\rightarrow F_2$
357	1.90	0.26	7.06
2357	2.11	0.89	7.65
385	3.16	0.75	9.85
2385	2.71	0.62	8.46
314	3.19	0.84	3.24
2314	3.51	1.50	3.14
349	1.99	0.48	4.47
2349	1.74	0.43	5.27
347	5.61	1.77	10.87
2001	3.92	1.14	8.61

Table 5 shows the 314 ink to have a balanced CII in A & F2. The $D_{65}\rightarrow D_{50i}$ condition had the highest CII and MI for all inks. Ink 357 has the least CII in A and 2314 has least CII in F_2.

Spectral Reflectance Graphs

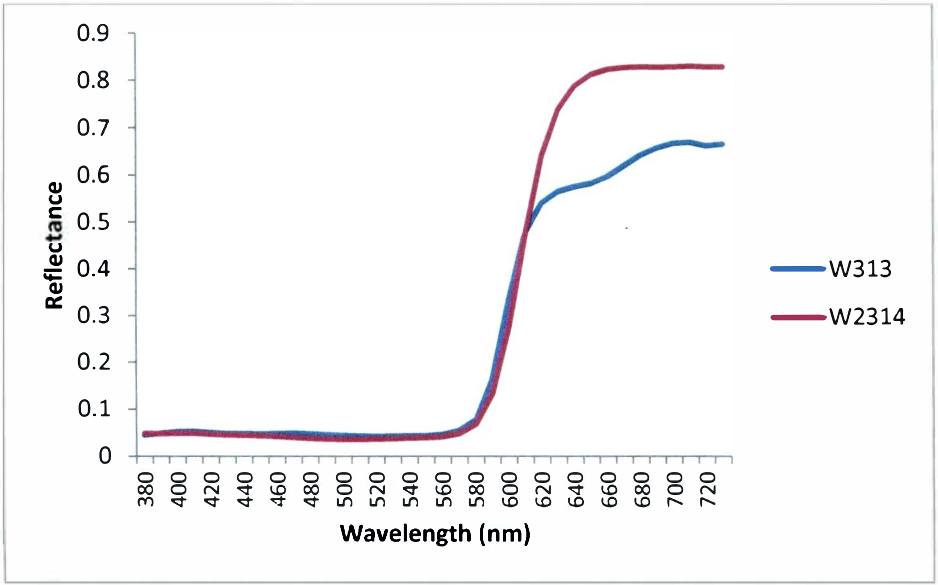

Figure 1. Reflectance Graph of 314 and 2314 Series of Inks

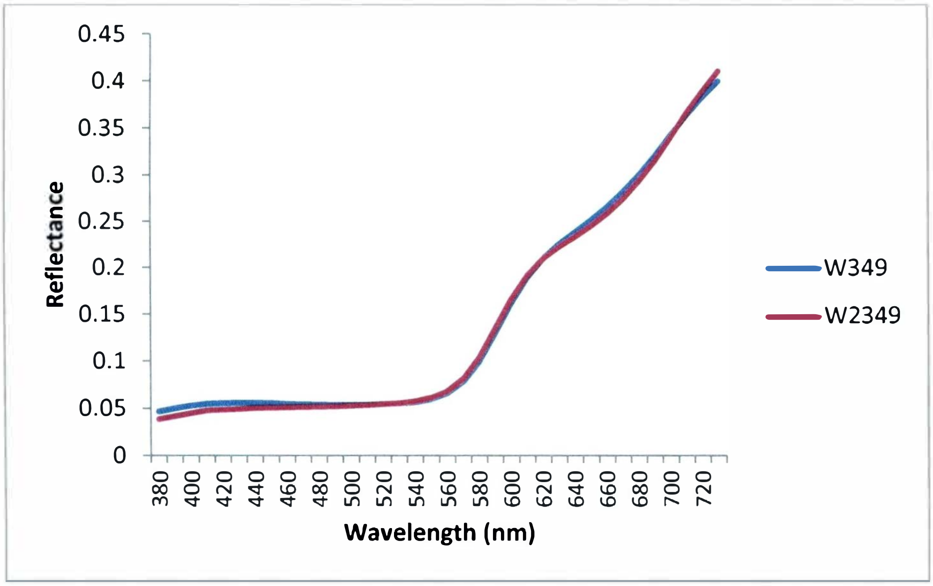

Figure 2. Reflectance Graph of 349 and 2349 Ink Series

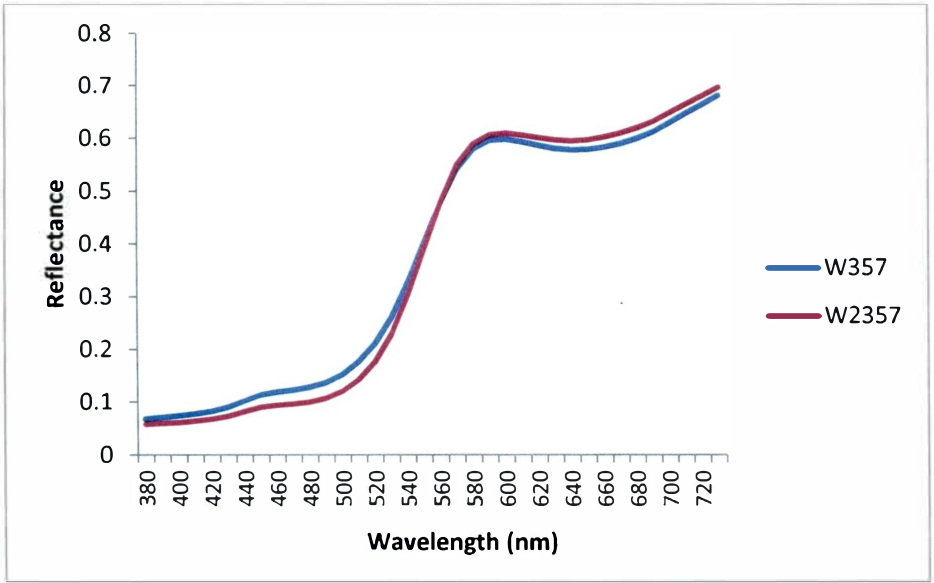

Figure 3. Reflectance Graph of 357 and 2357 Ink Series

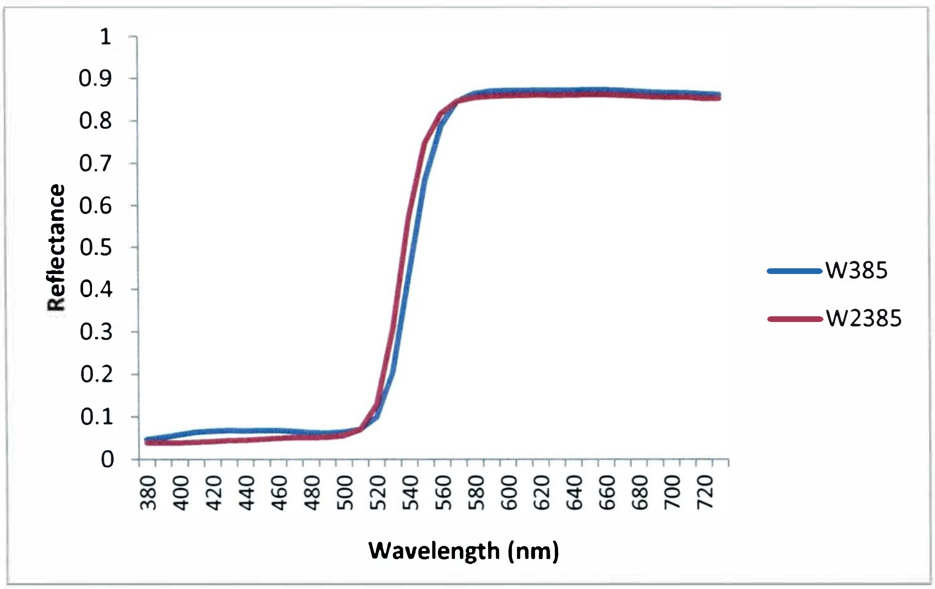

Figure 4. Reflectance Graph of 385 and 2385 Ink Series

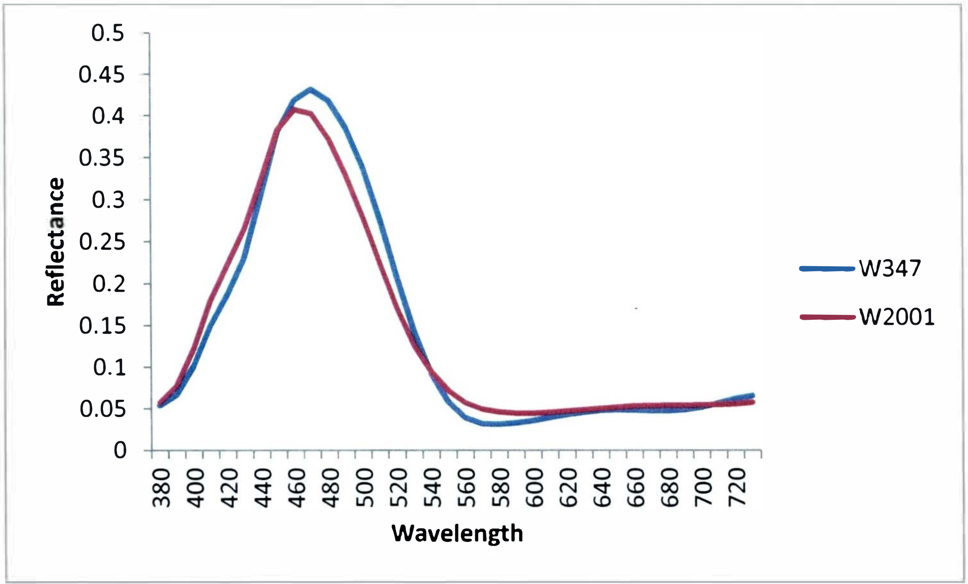

Figure 5. Reflectance Graph of 347 and 2001 Ink Series

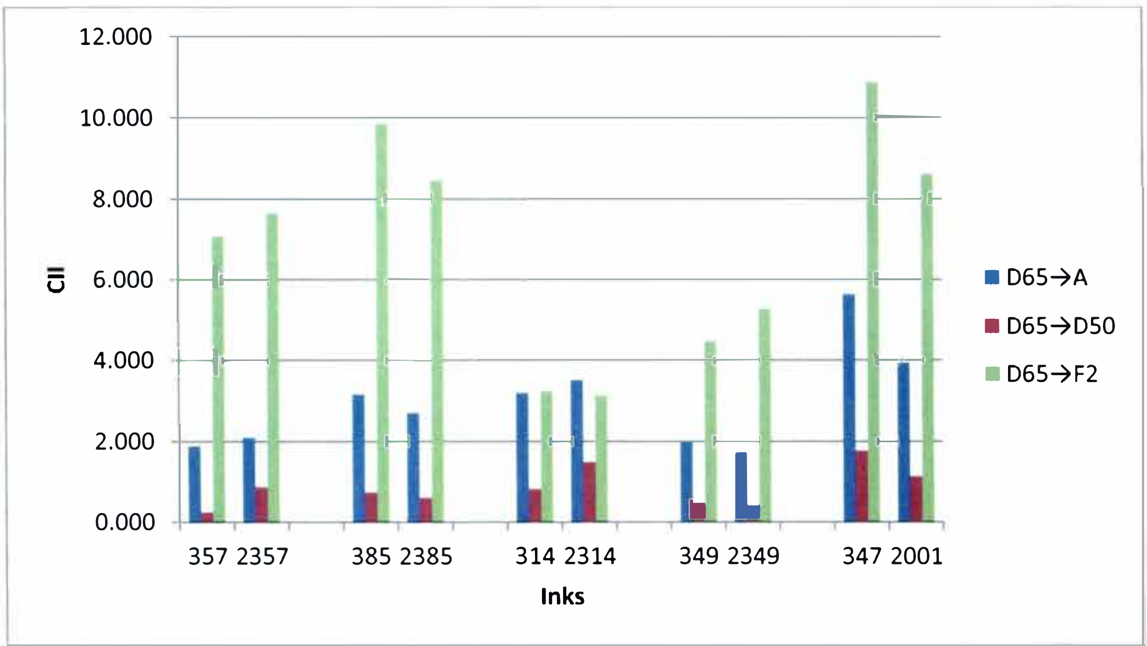

Figure 6. CII of Inks Under Different Light Sources

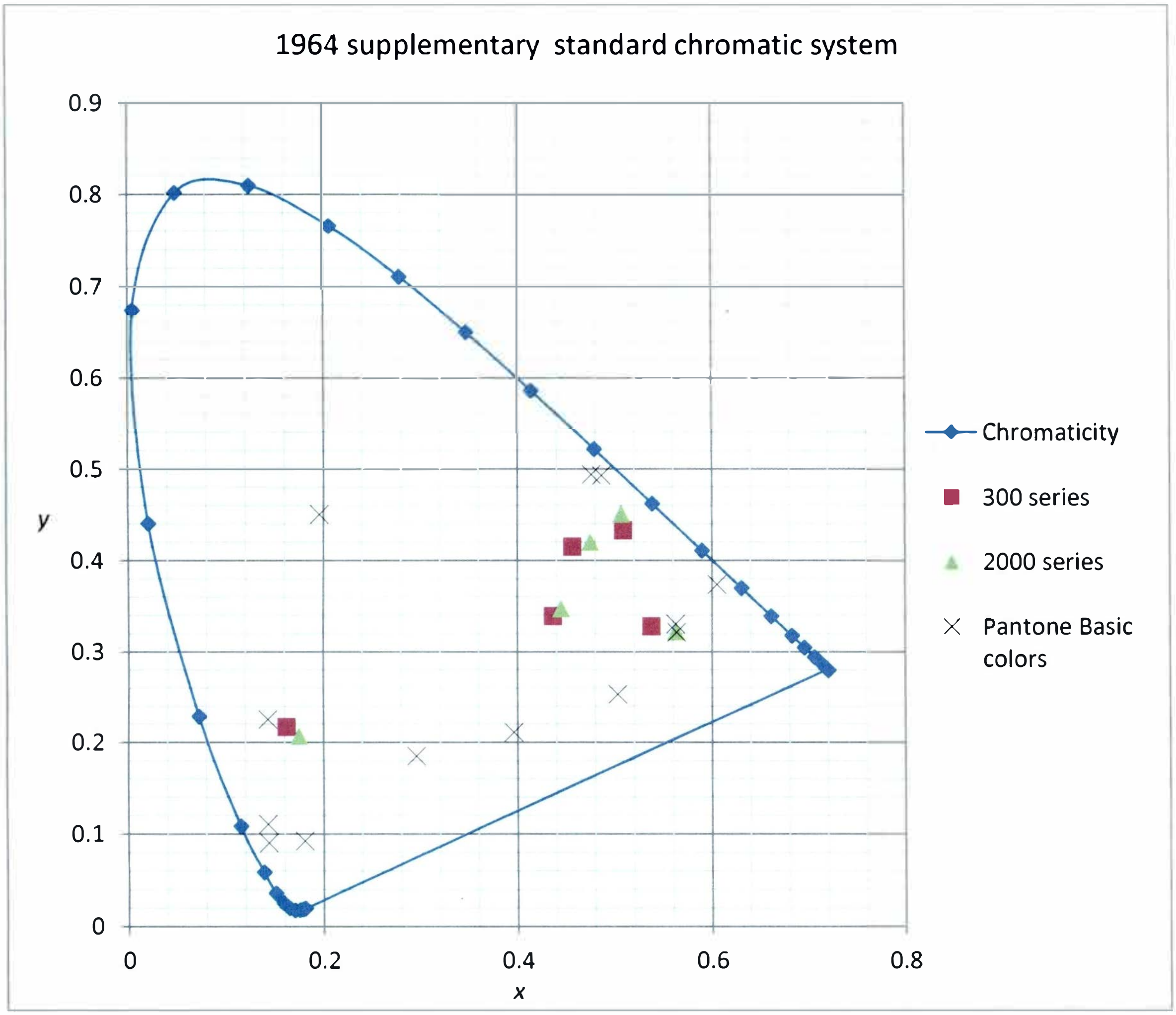

Figure 7. Plot of Base Colors in Chromaticity Diagram

In Figure 7, x and y are chromaticity coordinates calculated by[8]

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \tag{32}$$

Where, XYZ are tristimulus values[8].

Color inconstancy indices (CII) for all inks are illustrated in Figure 6. CII for illuminant change D_{65} to A was found in the range of 1.74 to 5.61, the smallest was found for 2349, being 1.74, and the largest for 347, being 5.61. CII for illuminant change from D_{65} to D_{50} were in the range of 0.26-1.7, the smallest was found for 357 (0.26) and largest for 347, being 1.77. As expected, the largest CII was found in illuminant change D_{65} to F_2, which was in the range of 3.14 to 10.87, the largest being for 347. The 347 and 2001 pair has large color difference, large MI and CII, which therefore is not an acceptable pair.

To summarize, considerable spectral color difference was found between 347 and 2001 inks, along with considerable MI, but also high CII values. In the case of 349 and 2349, they show low metamerism and moderate color difference, but acceptable CII along with similar spectra, and therefore the 2349 shade can be accepted. The 357 and 2357 pair shows the least color difference, but doubtful MI and large CII values, and therefore, the proposed replacement shade may not be acceptable for changes in light source conditions. 357and 2357 shades show similar reflection spectra, but the two colors have acceptable ΔE values, along with less MI in illuminant A, as well as unacceptable CII under illuminant F_2. Thus, the substitute shade becomes unacceptable for the required situation. Just as Omnova Solutions has its own proprietary basic color set, Pantone has a basic color ink set widely used in industry. So it is interest to compare CII and MI of Omnova's ink set with PMS[33] inks.

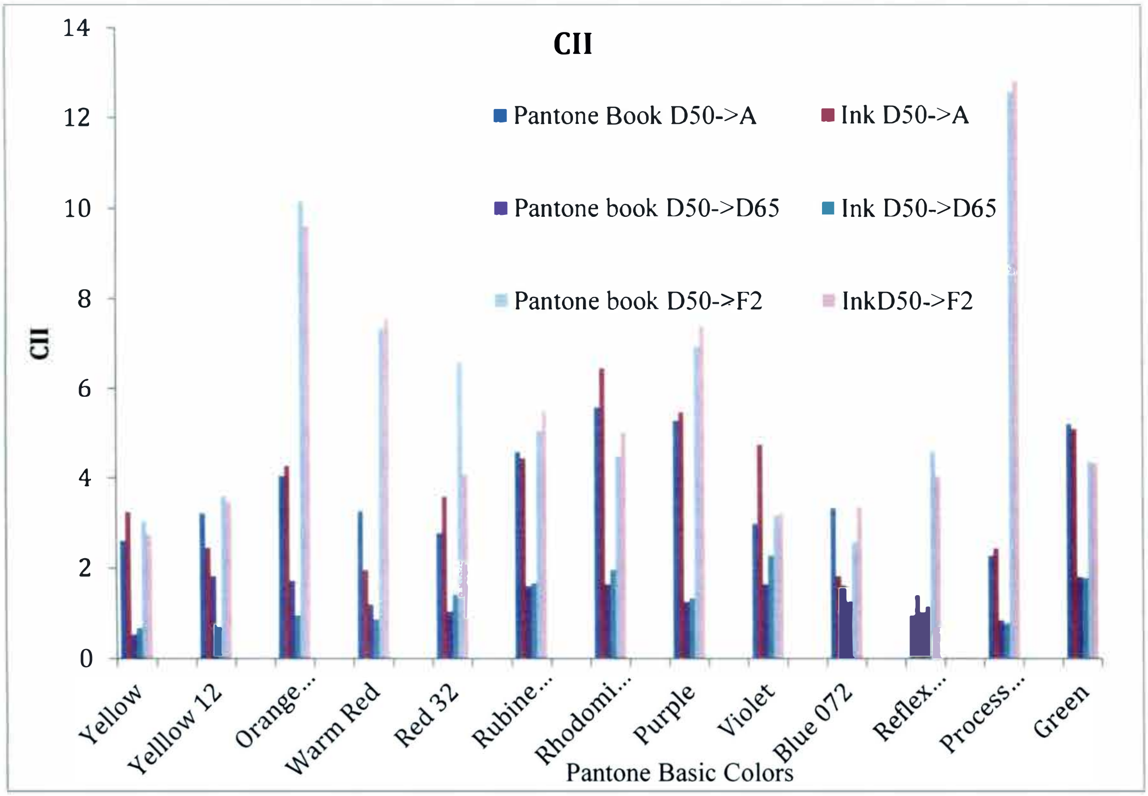

Figure 8. CII of Pantone® Basic Colors

The Color Inconstancy Indices are summarized in Table 5.

CII- Pantone® book and Ink draw downs

Table 6. *Color Inconstancy Index Calculated From Pantone® Book and Ink Drawdowns for D_{50} to D_{65}, F_2 and A*

	$D_{50}\rightarrow A$		$D_{50}\rightarrow D_{65}$		$D_{50}\rightarrow F_2$	
Color	Pantone® book	Ink	Pantone® book	Ink	Pantone® book	Ink
Yellow	2.61	3.25	0.54	0.68	3.05	2.76
Yellow 12	3.21	2.45	1.82	0.71	3.59	3.46
Orange 021	4.03	4.27	1.72	0.96	10.14	9.60
Warm Red	3.26	1.96	1.19	0.87	7.32	7.54
Red 32	2.78	3.59	1.04	1.41	6.56	4.06
Rubine Red	4.57	4.43	1.59	1.67	5.04	5.49
Rhodamine Red	5.56	6.44	1.64	1.96	4.47	5.01
Purple	5.26	5.45	1.25	1.33	6.94	7.38
Violet	2.98	4.73	1.64	2.27	3.15	3.20

Table 6 — Continued

Color	$D_{50} \rightarrow A$ Pantone® book	Ink	$D_{50} \rightarrow D_{65}$ Pantone® book	Ink	$D_{50} \rightarrow F_2$ Pantone® book	Ink
Blue 072	3.32	1.82	1.61	1.26	2.56	3.35
Reflex Blue	0.96	1.40	1.02	1.16	4.56	4.031
Process Blue	2.27	2.43	0.84	0.77	12.56	12.81
Green	5.18	5.07	1.80	1.78	4.33	4.33

Color inconstancy is an inherent property of the behavior of color, when viewed under different light sources. It was found that PMS yellow, yellow 12, Red 032, violet, blue 72 have less inconstancy, while PMS process blue and orange 21 show unacceptable color inconstancy for the required criteria. Acceptable limits of color inconstancy index can be decided by psychophysical experiments or by the contract proof method. This limits selection of these basic colors, or shades, in various product-printing conditions. The important point to notice from Figure 8 is that large CII for some illuminant changes shown in Figure 6 are not that unusual, since similar behavior is shown for inks used to print PMS books. Thus, the two ink sets discussed here are not necessarily "bad" or unusual, but some light sources create more artifacts under light source changes than others.

Figure 9 shows that color difference of the same Pantone® color between different color libraries is unacceptable except for green and orange. The L*a*b* values are shown in Table 6.

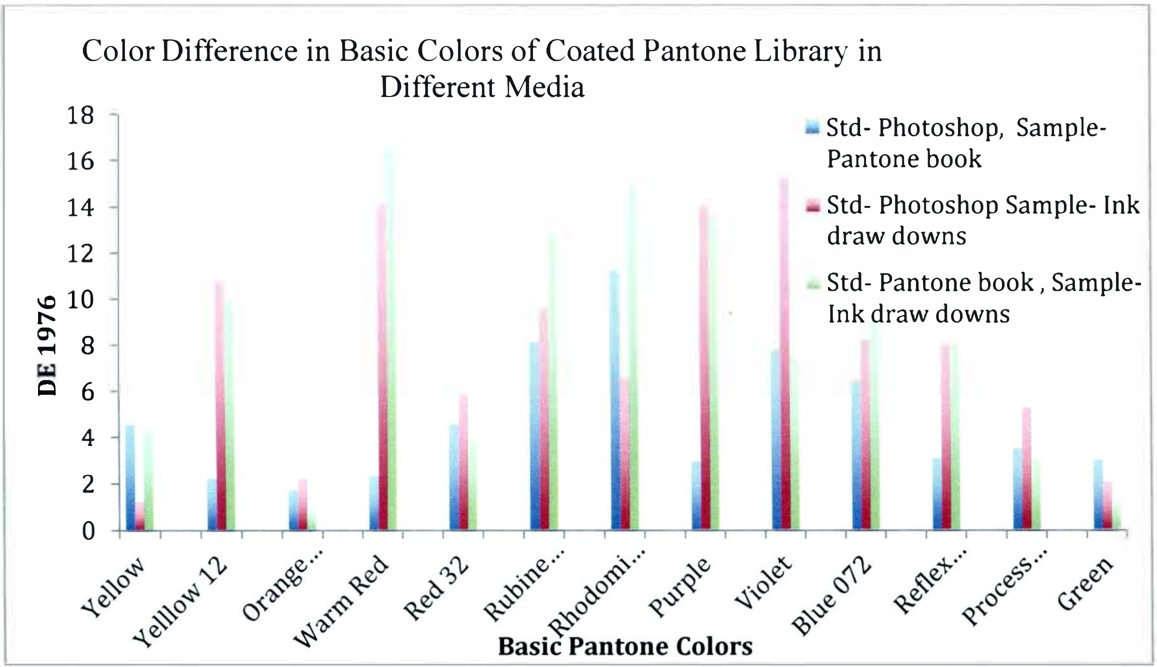

Figure 9. Color Difference ΔE 1976 Between Pantone® Basic Colors in Different Media

Table 7. *CIEL*a*b* Values and Color Difference of Pantone® Basic Colors in Different Libraries*

	CIEL*a*b* values in different libraries			Color Differences by 1976 formula		
Pantone Color	Photoshop® Library (1)	Printed Pantone® book (2)	Ink draw downs (3)	Sample 1 Sample 2	Sample 2 Sample 3	Sample 1 Sample -3
Yellow	89, -3, 112	89.12, -1.2, 107.81	88.13, -2.15, 111.83	4.56	4.25	1.22
Yellow 12	87, 4, 114	87.78, 2.05, 113.29	95.84, 4.42, 107.89	2.22	9.99	10.76
●range 021	64, 62, 86	61.07, 64.75, 84.76	60.35, 64.31, 84.51	1.73	0.86	2.24
Warm Red	58, 70, 50	58.41, 69.95, 47.70	54.64, 72.65, 63.47	2.34	16.44	14.14
Red 32	54, 74, 46	54.57, 71.95, 41.97	52.57, 74.92, 40.34	4.56	3.92	5.9
Rubine Red	44, 77, 9	38.74, 70.79, 8.27	41.55, 78.45, 18.18	8.17	12.84	9.62
Rhodamine Red	52, 77,-16	43.84, 69.26, -15.36	49.50, 82.95, -17.17	11.27	14.93	6.56
Purple	48, 65, -42	50.06, 65.63, -44.03	41.75, 74.08, -50.78	2.96	13.64	14.1
Violet	24, 46, -66	19.51, 51.74, -68.79	15.31, 57.77, -70.33	7.8	7.5	15.26
Blue 072	20, 38, -78	15.62, 42.46, -76.41	16.48, 35.35, -71.05	6.45	8.93	8.22
Reflex Blue	19, 26,-68	16.98 27.93, -66.65	13.86, 32.16, -67.54	3.1	8.03	8.03

Table 7 – Continued

Pantone Color	Photoshop® Library (1)	Printed Pantone® book (2)	Ink draw downs (3)	Sample 1 Sample 2	Sample 2 Sample 3	Sample 1 Sample -3
	CIEL*a*b* values in different libraries			Color Differences by 1976 formula		
Process Blue	49, -33, -54	45.55, -33.61, -54.11	44.31, -31.55,-56.01	3.51	3.06	5.3
Green	58, -77, 2	59.28, -79.18, 3.63	59.34, -78.39, 2.72	3.01	1.2	2.07
Average color difference				4.74	8.11	7.96

Orange and green have lower color differences for all shades. Rhodamine and Rubine Red have very high color differences among all libraries. The difference between Photoshop® libraries and ink draw downs in Yellow and Yellow 12 is acceptable. The average color difference between Photoshop® libraries and the Pantone® book is the least among color differences between different libraries. Large differences in lightness values account for much of the color difference, in many cases. In the case of Yellow 12 the lightness difference between Photoshop® values and ink draw down is very high, so it shows a large color difference, but lightness difference between Photoshop® and printed Pantone book is less, which results in less color difference. Warm red and Green show similar results. Warm red has the highest color difference between the printed Pantone® book and ink draw-downs. The Metamerism Indices are given in Table 6.

Table 8. *Metamerism Index of Pantone® Basic Colors Under Different Illuminants*

Metamerism Index			
Std: Pantone book	Sample: Ink draw downs		
Color	$D_{50} \rightarrow A$	$D_{50} \rightarrow D_{65}$	$D_{50} \rightarrow F_2$
Yellow	2.7	1.06	0.73
Yellow 12	1.86	0.43	0.76

Table 8 — Continued

Metamerism Index

Std: Pantone book	Sample: Ink draw downs		
Orange 021	0.85	0.33	0.79
Warm Red	1.47	0.68	1.61
Red 32	2.53	1.02	1.41
Rubine Red	1.39	0.59	1.67
Rhodamine Red	2.72	1.06	1.19
Purple	4.72	1.53	3.19
Violet	4.78	1.84	1.03
Blue 072	1.6	0.4	0.74
Reflex Blue	1.6	0.44	1.25
Process Blue	1.59	0.52	0.66
Green	0.44	0.18	0.3
Average	2.17	0.74	1.17

Table 6 shows significant metamerism in $D_{50} \rightarrow A$. The least metamerism is found in Green, which is 0.44. In $D_{50} \rightarrow F_2$ five colors shows metamerism index < 1. The least metamerism is found in $D_{50} \rightarrow D_{65}$. Rhodamine, Purple and Violet show large metamerism. The reason for high metamerism could be their dominant and complementary wavelength nature, because they lie on the purple line of the chromaticity diagram. For that, analysis of the spectral reflectance graph is necessary.

Spectral Reflectance Curves of Basic Pantone® Colors

Reflectance spectra are helpful for understanding matches and behavior of color, irrespective of illuminant and observer. Thus, spectral reflectance curves of Pantone® inks and Pantone® book colors were plotted from 380 nm to 730nm (Fig.10-22).

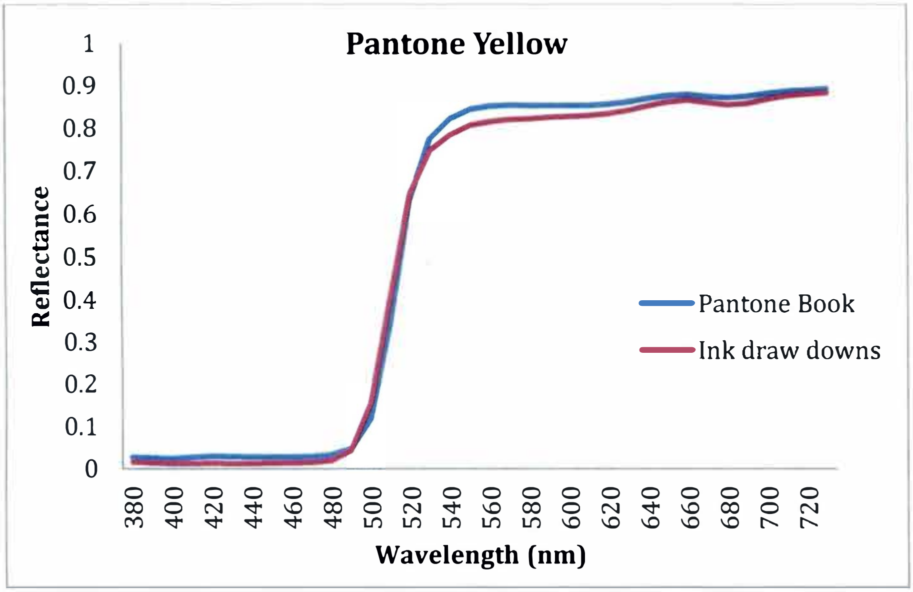

Figure 10. Reflectance Graph of Pantone® Yellow

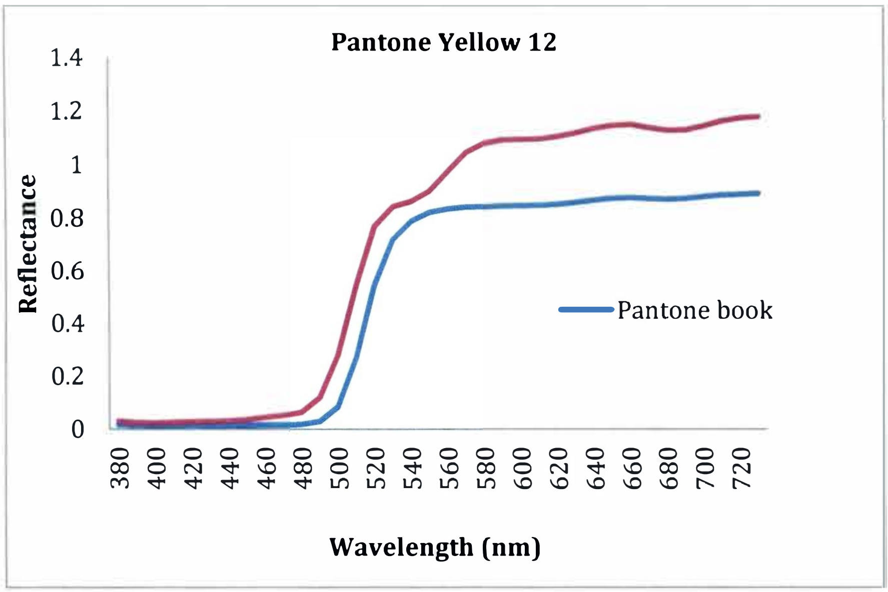

Figure 11. Reflectance Graph of Pantone® Yellow 12

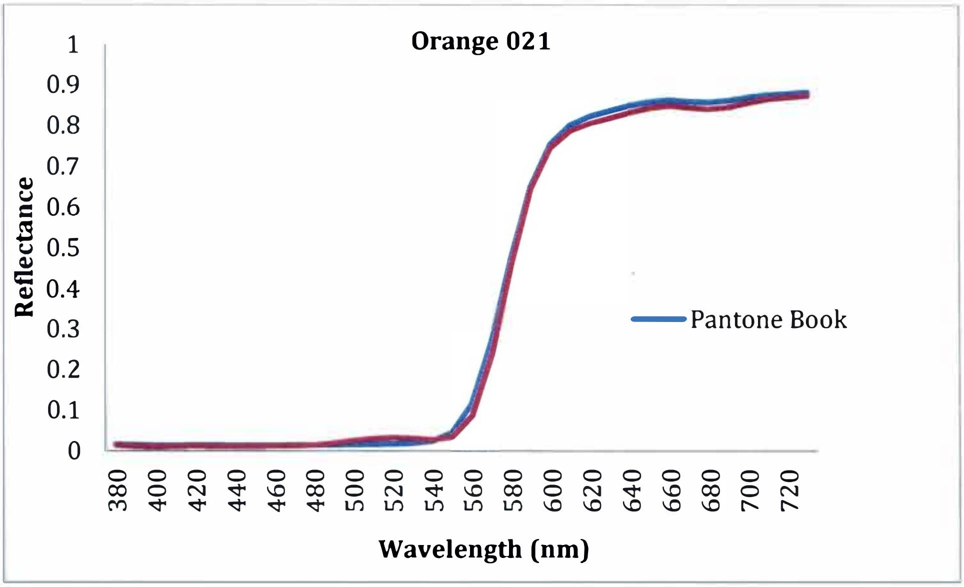

Figure 12. Reflectance Graph of Pantone® Orange 021

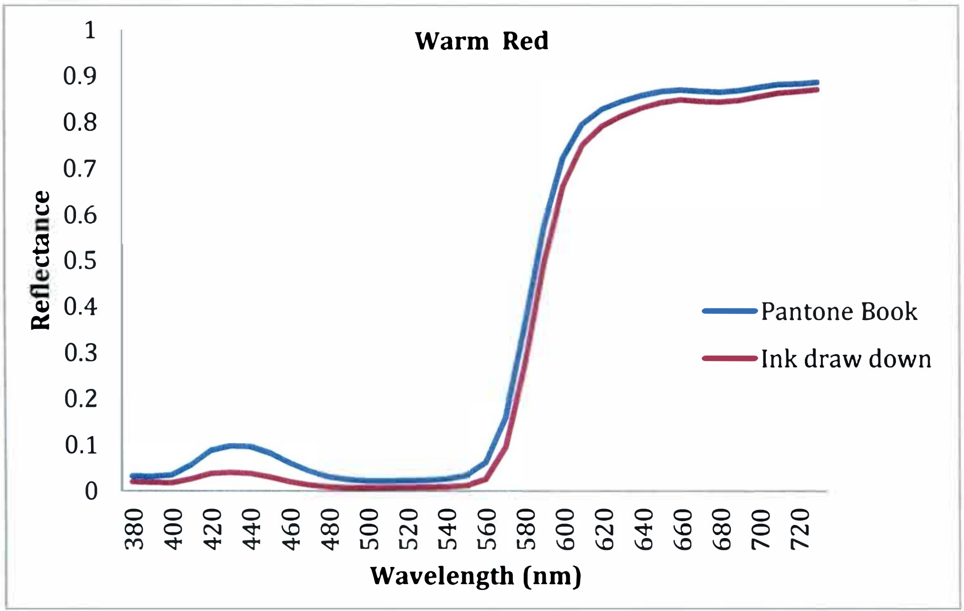

Figure 13. Reflectance Graph of Pantone® Warm Red

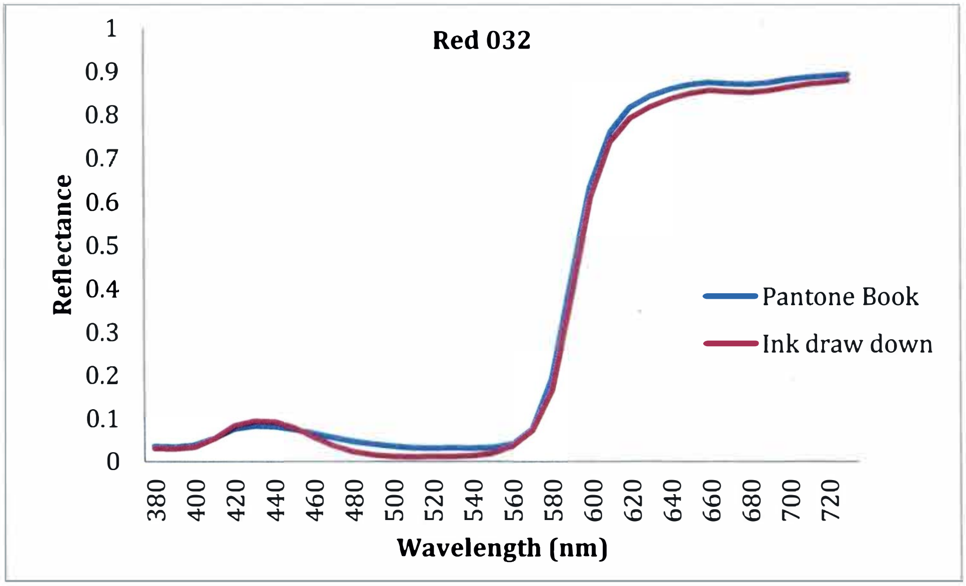

Figure 14. Reflectance Graph of Pantone ® Red 032

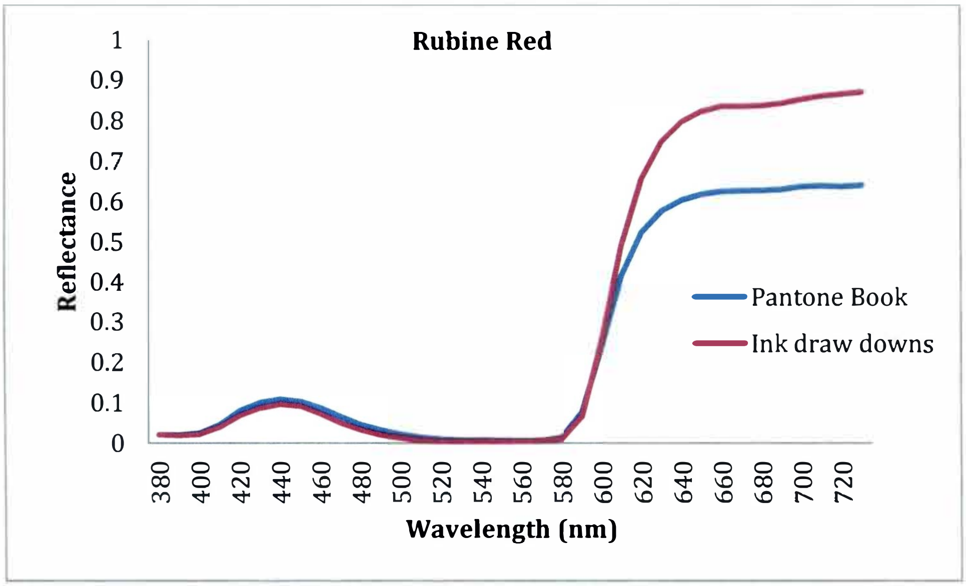

Figure 15. Reflectance Graph of Pantone® Rubine Red

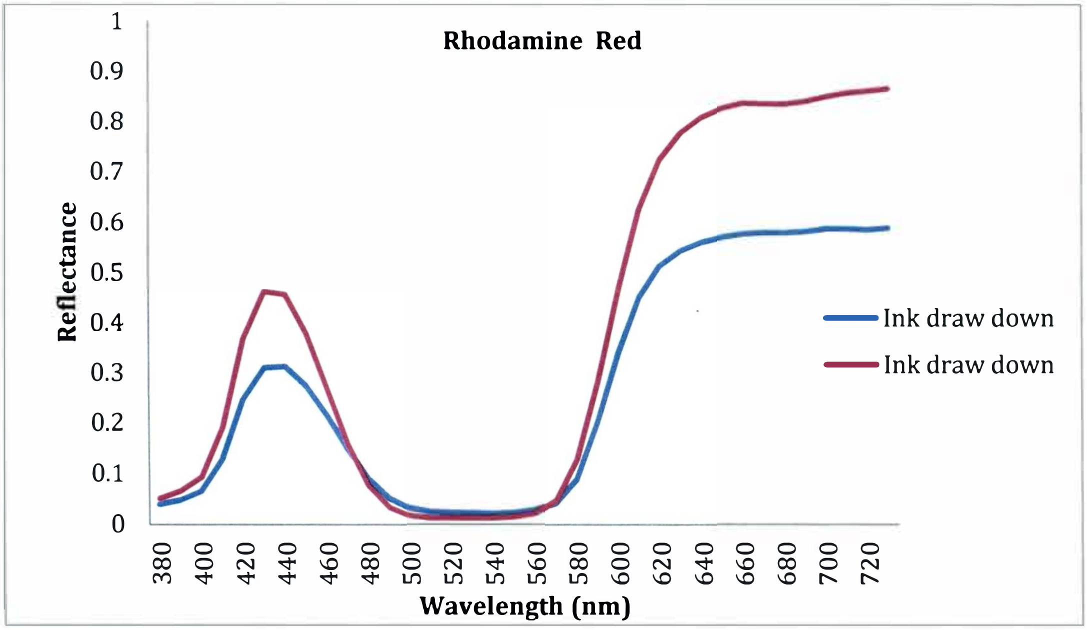

Figure 16. Reflectance Graph of Pantone® Rhodamine Red

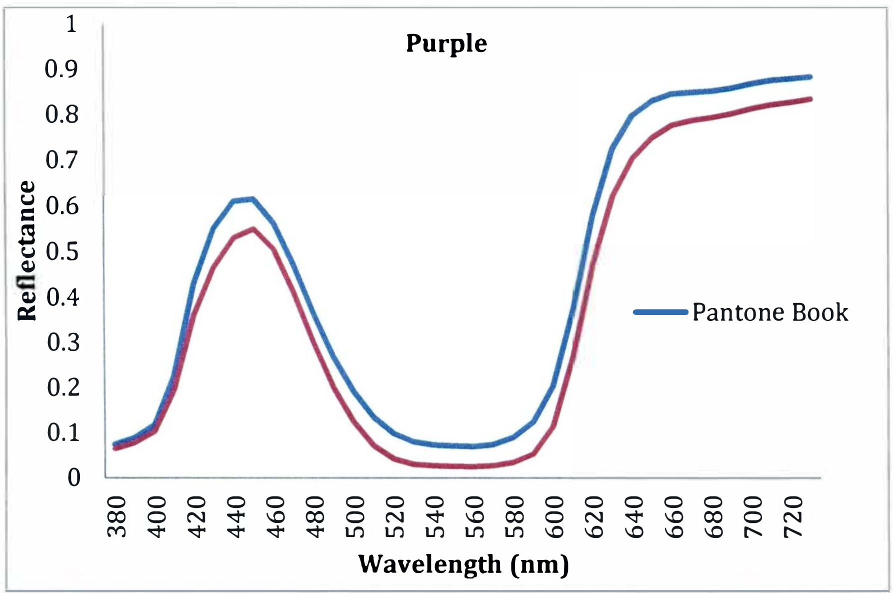

Figure 17. Reflectance Graph of Pantone® Purple

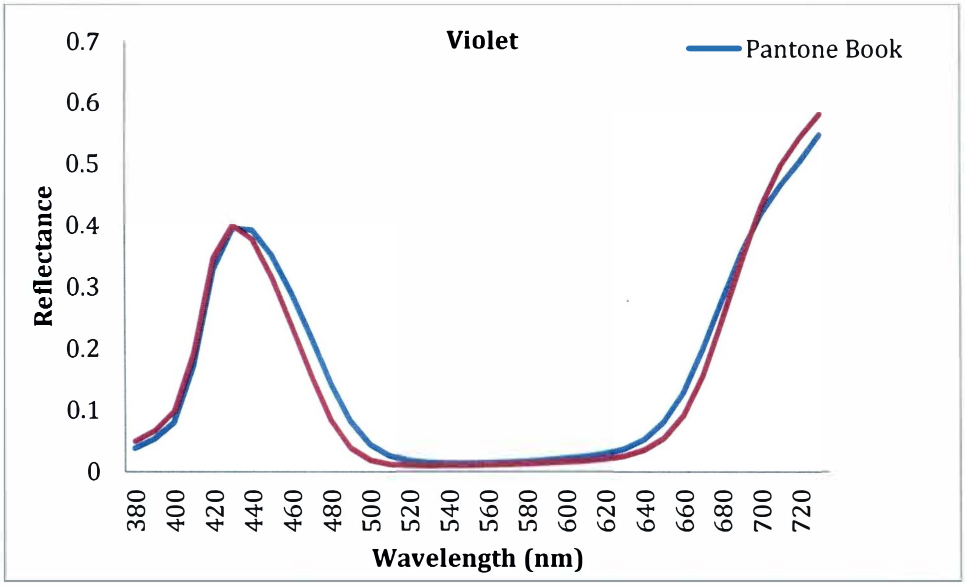

Figure 18. Reflectance Graph of Pantone® Violet

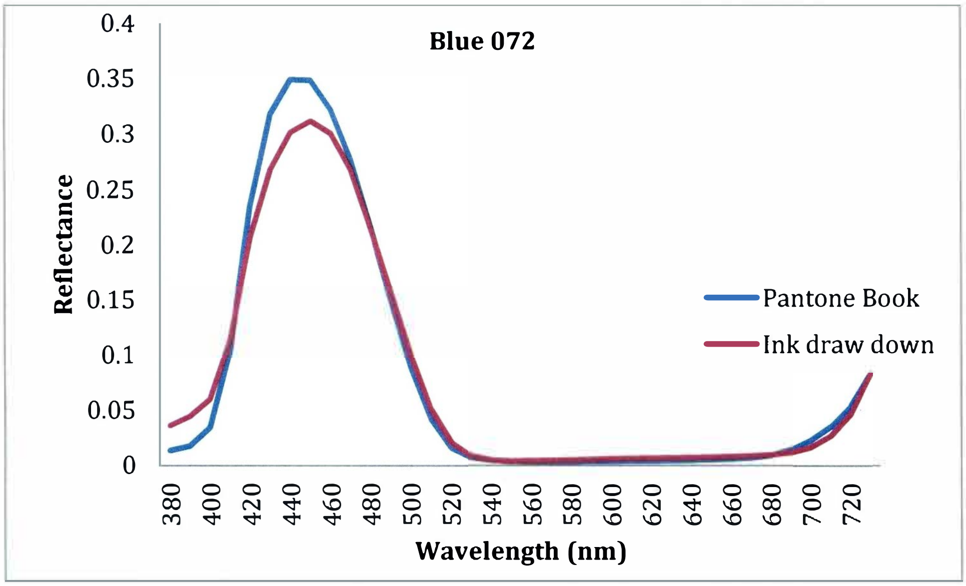

Figure 19. Reflectance Graph of Pantone® Blue 072

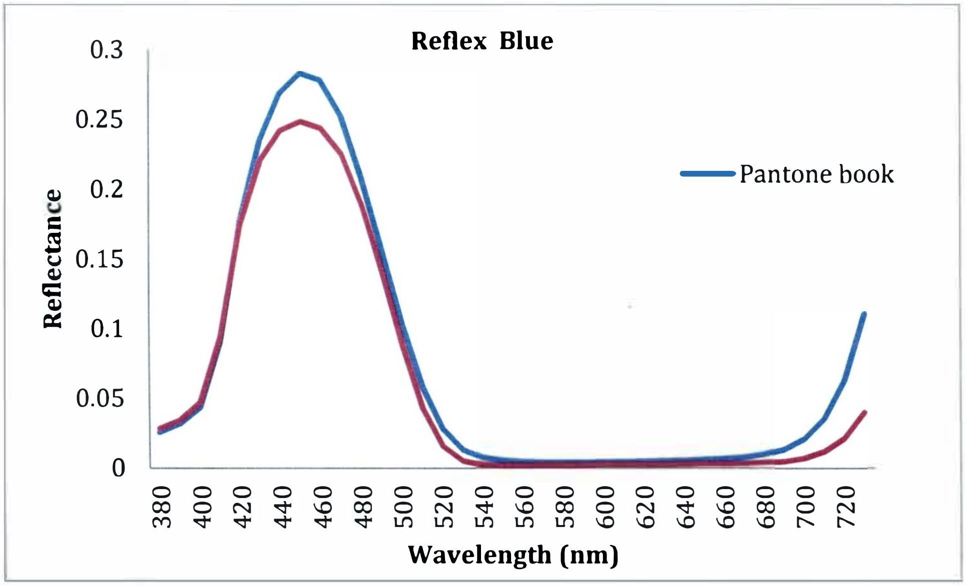

Figure 20. Reflectance Graph of Pantone® Reflex Blue

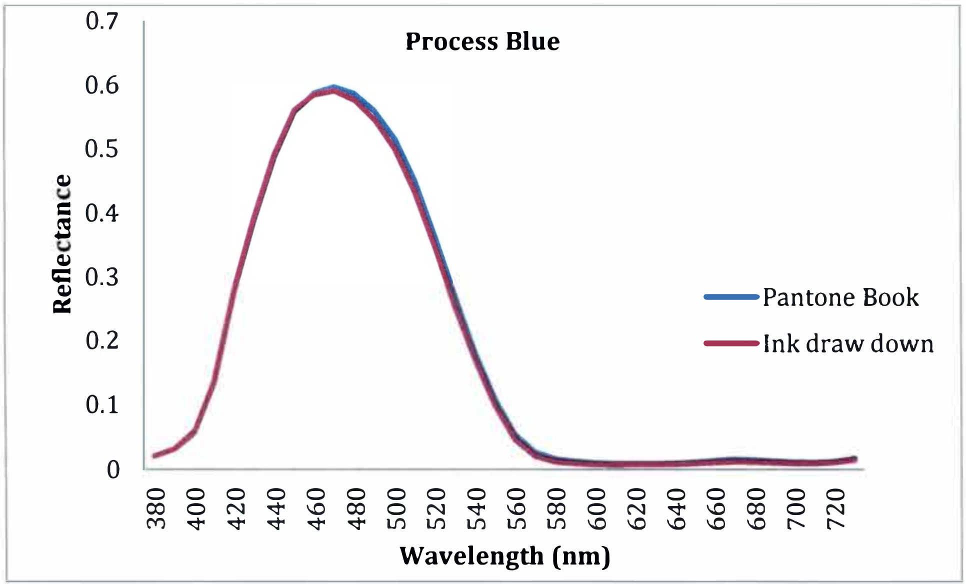

Figure 21. Reflectance Graph of Pantone® Process Blue

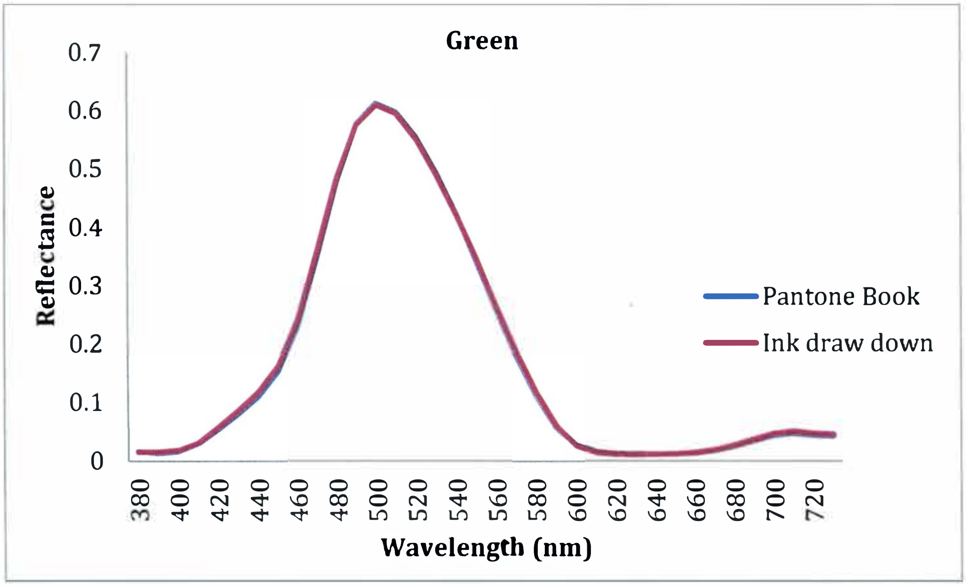

Figure 22. Reflectance Graph of Pantone® Process Green

Figures 10-22 show that only Green is a nearly perfect spectral match and no metamerism under incandescent or fluorescent light occurs. In the Orange and Process blue spectra, the sample graph follows the nature of the standard spectrum. The reflectance spectra of standard and sample cross each other in Red 032, Rubine Red, Violet, Rhodamine Red, and Blue 072 colors. As metameric inks have different inconstancy indices, so the color inconstancy index of Pantone® basic colors from the Pantone® book and ink draw-downs were calculated and compared. Reflectance graphs of ink draw-downs and printed Pantone® book have the same nature and a considerable difference in CII was not found.

When the nature of the reflectance graphs of the standard and sample is similar, the color difference is lower. If the pair is metameric, then there will be no significant difference in color inconstancy indices, too. The data show that when there is a large difference between printed Pantone® book and ink draw downs, there is no match in spectral graphs. This leads to slight metamerism in these pairs as well. The color inconstancy indices of the investigated colors in the printed Pantone® book and ink library are similar, because the difference is negligible considering the high values of inconstancy indices.

CHAPTER VI

CONCLUSION

Perception of color depends on the light source used to illuminate it. In wood grain laminate industry at the time of printing the sheet is viewed under standard light source like D_{65}. However, at customers' end any different light source may be used, so it not always possible to use light source at customers' end for viewing. In some cases, it may not be known. So, at the time of first matching, it is important to know how much perception of shade will change when it will be viewed under different light sources. Also, it is important to know if it is related to metamerism. And when two basic ink sets are compared, does the change in perception for both ink set remain the same?

If spectral reflectance data of two colors match, then the two color stimuli match under all conditions. If one tries to express the match of color under one set of conditions, then use of spectral reflectance curve is not sufficient. It was found that expressing perfectness of match is not sufficient under only one set of conditions. So relative differences between conditional matches are expressed by metamerism, but it requires pairs of matches, because perception of color has impact of all components in viewing conditions. Change in viewing condition is not accounted for in metamerism, but is accounted for in color inconstancy indices. Data show that if color difference is low and metamerism index is also low, this pair could still have large inconstancy indices. For example, 349 and 2349 have lower MI but their CII is larger than 2314 and 314 under D_{65}-> F_2 condition as 2314 and 314 has higher MI than 349 and 2349 under F_2. But a metameric match has differences in color inconstancy indices. As 347 and 2001 has the highest MI, so its CII has a difference under F_2, the same way 385 and 2385 pair has a high metamerism index, so it shows that their CII are different.

Selection of color space and color difference formula is always experiment performer's choice. Using a different color difference formula does not affect analysis because each formula has its own range of acceptance and rejection so ultimately it does not affect concussion. In gravure printed wood grain laminates, viewing is carried out in standard viewing condition. Shades are matched and metamerism indices are checked in general practice matching, with small color difference and metamerism difference is selected, but this study shows if metamerism index is small then samples follow the nature of the reflectance graph of standard colors. In this work it was shown that ink pair 347 and 2001 has a large metamerism index, but small inconstancy index.

This study confirmed that the spectral reflectance curves of ink pairs, along with metamerism indices are not sufficient measures for finalizing a shade match, especially when the printed jobs are exposed to different light sources. Combination of spectral reflectance graph matches, MI and CII help to select the best ink shades for the job, especially for wood grain laminates. If a selected ink pair is metameric and the sample has less CII than the standard then it is an acceptable match. Basic inks of 2000 and 300 series have difference in in colorimetric characteristics, so one can't replace the other.

Both ink sets were compared with the Pantone® basic colors set. It was found that the Pantone® basic color set covers a larger area in chromaticity diagram than 2000 and 300 basic color sets. Inconstancy of Pantone® basic colors is compared with 300 and 2000 series. The comparison shows that Pantone® yellow has less CII than 2000 and 300 series. Pantone® shades are recognized by numbers and are available in different media forms including digital and printed book. Its consistency was checked under different libraries of the same condition, this shows large unacceptable color differences, large metamerism indices and reflectance graphs of the same color between different color libraries. It showed no consistency in shade between libraries for color communication by using specified number or name. Thus, it is not reliable to communicate shades by Pantone® number for the Pantone® basic colors. This result places doubt on using other Pantone® color numbers as well.

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