Color and Appearance Basics for Coatings

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INTRODUCTION

The two major functions of a coating are protection and decoration. Color and appearance are important in the coatings industry because they describe the decorative qualities that our customers seek from our products. Knowledge of color and appearance is important to personnel in all areas of the coatings industry. This tutorial will review the basics of color and appearance.

COLOR PERCEPTION

It is common to speak of a red car or a red light. In fact, color is not an intrinsic property of an object (car) or light. The notion of color applies only to the perception we have of the object or light but not to the object or the light itself.

Color perception begins with light. This light comes from a light source such as the sun or an incandescent tungsten filament light bulb.

Light is absorbed and scattered in the interior of the paint film. In the case of an opaque paint film, all of the light is absorbed or scattered and none of the light is transmitted through the film. Translucent paint films will transmit some of the incident light. When a translucent paint film is applied to a substrate, the transmitted light will be reflected back through the film and the color of the substrate will affect the color of the paint film.

The light observed by a colorist consists of light reflected from the front surface of the paint film (the film's gloss) plus the light scattered from the interior of the film and the substrate. Since light will be absorbed in the paint film, the color of the reflected light (its spectral distribution) will be different than that of the incident light. A colorist visually evaluating the color of a paint film usually positions the sample in such a way that the gloss of the sample is not seen. This is referred to as excluding the specular reflection. The geometry of the incident light illuminating the object and the angle of view of the light reflected from the object are important parameters that influence color and appearance. The gloss of an object is an often-overlooked aspect of color and appearance. The same object or colored material, treated to give different surface textures or gloss, appears different in color as well as gloss. Hence the old, but often-ignored, maxim—adjust the gloss of a batch of paint first and then adjust its color to match the color of the standard.

Light entering the eye is imaged onto the retina where light-sensitive receptors absorb the incident light and generate signals that are processed and sent to the brain. There are two kinds of receptors—rods and cones. Rods detect small amounts of light and are responsible for night vision. They are not sensitive to color and are inactive at higher light levels. Cones have a much lower sensitivity to light but become active at daytime light levels. There are three types of cones: S, M, and L cones. The spectral sensitivities of the cones overlap but are sensitized to wavelengths that roughly correspond to blue, green, and red light. The cones respond to the light incident upon them and reduce the entire spectrum of light into three signals—one for each type of cone. The rods and cones form a mosaic in the retina. The distribution of rods and cones varies throughout the retina with the cones distributed most densely in the center of the eye called the fovea. Each individual receptor interconnects within the retina to form receptive fields. In the receptive fields, impulses from the cone cells can either subtract from the other impulses or add together to produce signals that are sent to the brain. The receptive fields have different properties as a result of the varying distribution in the number and type of cones. The net result is the creation of black–white, red–green, and yellow–blue opponent signals. The brain interprets these signals as a color.

When two paint films are illuminated by the same light, and the light from those films produces the same set of signals, the two objects have the same color. If the same object is illuminated by a different light, and the light from those objects produces a different set of signals, the two objects will have different colors. When two objects match when illuminated by one light but no longer match when illuminated by a different light, we say that the films are metameric to each other. This usually occurs when the paint films contain different colored pigments.

The source of light, the reflectance characteristics of the object, the eye, and the processing of the sensory information by the neural system and brain all influence our perception of the color of an object.

When we speak of the color of light or an object in the remainder of this article, it is understood that we are speaking of the perception of the light or object by an individual with normal color vision (99.5% of women and 92% of men).

COMMUNICATING COLOR

One of the tasks faced by a worker in the field of color is communicating the description of a color to another individual, customer, or supplier. Each of us may have a good idea of what we mean by blue, green, yellow, red, etc., but what about fuchsia, salamander, coffee, etc.? Color naming can be very imprecise. As businesses become more global in their operations, the communication of color must become more precise and universal.

A color order system represents an orderly three-dimensional arrangement of colors. Color order systems arrange colors in three dimensions according to appearance. The most widely used color order system is the Munsell Color Order System. Albert Munsell was an artist who taught drawing and painting around the turn of the 20th Century.[1,2] Munsell named the three dimensions used in his system hue, value, and chroma. Hue is that attribute of color that distinguishes red from blue from green, etc. Value is a term artists commonly use to describe the lightness or darkness of a color. Light colors have a high value while dark colors have a low value. The most difficult of the three dimensions to understand is chroma—the difference of a color from gray. Some people call this attribute color strength or intensity. Consider a brick and a tomato that have the same hue, i.e., one is neither bluer nor yellower than the other, and are of equal lightness (value). The difference in color between them is the chroma, the tomato having a higher chroma (purer; more colorful) than the brick.

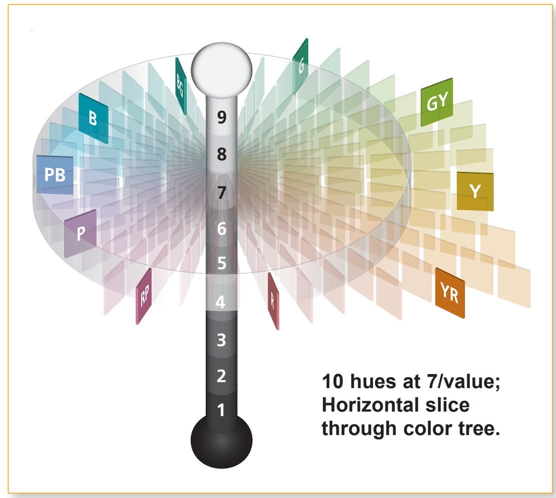

Figure 1—A horizontal slice from the Munsell Color Tree showing how colors of a single Munsell value vary around the hue circle by Munsell hue and radiate from the neutral axis by Munsell chroma. (Photo courtesy of X-Rite, Inc.)

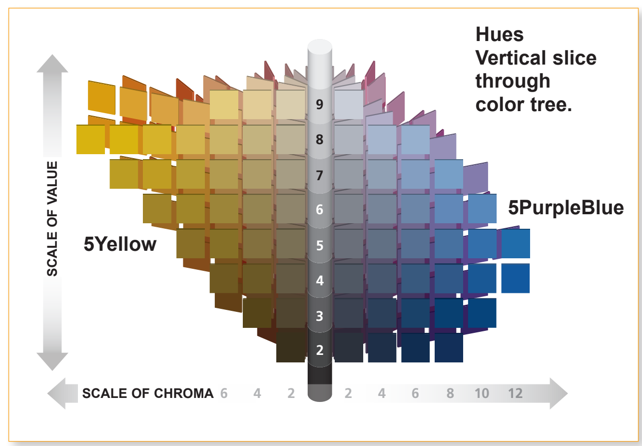

Figure 2—A vertical slice from the Munsell Color Tree showing how colors of two Munsell hues vary vertically by Munsell value and horizontally by Munsell chroma. (Photo courtesy of X-Rite, Inc.)

The three Munsell dimensions can be put together to form a color space in the shape of a cylinder.[3] The neutral grays (achromatic colors) form an axis in the center of the cylinder with the absolute white having a value of 10.0 and the absolute black having a value of 0.0. Chroma radiates outward from the central axis of this cylinder, and the hue varies in circles of constant chroma around the central axis.

If we take a horizontal slice out of Munsell color space (see *Figure 1*), the value (lightness) is constant and you can see the chroma radiating out from the center and samples of equal chroma forming concentric hue circles around the neutral core.

If we take a vertical slice out of Munsell color space (see *Figure 2*), the hue is constant and you

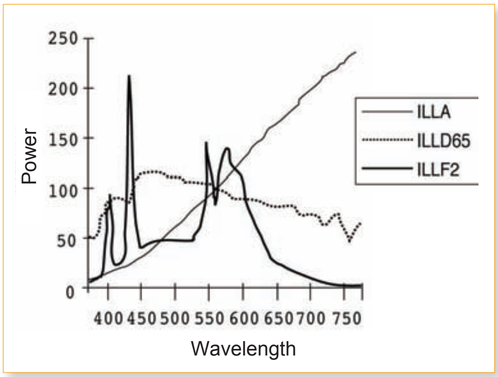

Figure 3—Relative spectral power distributions (SPD) of CIE Illuminants D65 (simulated daylight), F2 (cool white fluorescent light), and A (incandescent light). The SPD values of each illuminant have been set equal to 100 at a wavelength of 560.

can view the relationship between chroma and value for two complimentary hues.

Spacing within the Munsell system was designed to be visually equal. Thus, the color difference between two adjacent chroma steps will appear the same regardless of hue. Likewise two adjacent value steps will appear equally different, as will two hue steps.

Describing colors by their lightness (value), chroma and hue is natural and very precise.

COLORIMETRY AND THE CIE SYSTEM FOR MEASURING COLOR

Colorimetry, the measurement of color, attempts to standardize some of the variables associated with the perception of color and quantify that perception in terms of numbers. These numbers provide a way to communicate color and form the basis to express color differences between samples. Color perception requires a light source, a sample to be observed, and the eye and brain of the individual perceiving the color (the observer).

The pioneering work in color measurement was done by the scientists and engineers whose countries were members of the CIE (Commission Internationale de l'Éclairage — International Commission on Illumination).[4]

Standard Light Sources and Illuminants

The earth constantly receives electromagnetic radiation from space. Light is that part of the electromagnetic spectrum which the human eye sees. The CIE considers the wavelength range of visible light to be from 360 to 830 nanometers (nm). However, most color measuring instruments will not measure over such a wide range and the sensitivity of the eye at the wavelength extremes is minimal. For coatings applications, a more practical range of wavelengths is from 380 nm to 730 nm. When light of a single wavelength shines in the eye, it will appear to have color. The light from 360 to 500 will generally be described as shades of violet and blue, the light from 500 to 580 as shades of green and the light from 580 to 830 as yellow, orange, and red as the wavelength increases. Light from the sun is a mixture of light of different wavelengths. It can be separated into its individual wavelength components with a prism.

A light source emits visible light. An illuminant is a mathematical description of a light source. An illuminant or a light source is described by its spectral power distribution (SPD) which is the relative power emitted by the light source at each wavelength of interest. Illuminants and light sources are often confused. A light source is a real physical object that can be turned on and off to give light. Its SPD can be measured. An illuminant is a mathematical description of an SPD, which may or may not exist as a light source. It exists as a table or set of values as a function of wavelength.

The CIE recommended a series of daylight (D) illuminants. The most commonly used of these illuminants, D65, represents average daylight. The graphic arts community prefers illuminant D50, which is not quite as blue as D65. While these illuminants are recommended for color calculations, the CIE did not recommend light sources for these illuminants.

Fluorescent lights have achieved greater commercial use in recent years. The CIE has introduced a series of fluorescent (F) illuminants to represent commonly used fluorescent lamps.[4] Illuminant F2 represents a cool white fluorescent lamp.

Illuminants D65, A, and F2 are illustrated in *Figure 3*.

The Object

The reflectance factor is the ratio of light reflected from the object to that reflected from the perfect reflecting diffuser under the same geometric and spectral conditions of measurement.

A spectrophotometer is used to measure the reflectance factor of an object at each wavelength of light. The range of wavelengths from 360 to 830 nm is used in color measurement calculations but commercial spectrophotometers usually measure a narrower range of wavelengths such as from 380 to 730 nm. The measured reflectance factor of an object depends on the instrument used to make the measurements and the conditions under which the measurements are made.

The Standard Observer

The CIE standard observer simulates a human observer. The standard observers were derived from color matching experiments made by a panel of observers using a set of red, green, and blue lights.

The observer had to match monochromatic light projected on one half of the field by adjusting the intensities of a set of red, green, and blue lights projected on the other half of the field (see *Figure* 4). Monochromatic light consists of a very narrow band of wavelengths of light centering on a single wavelength. The experiment was performed over the visible spectrum. The amounts of the red, green, and blue lights required to match each of the spectral colors are called tristimulus values. Unfortunately, all colors could not be matched with the set of red, green, and blue lights used in the experiment. When this happened one of the lights was used to change the spectral color so that it could be matched with the other two lights, as shown in *Figure* 5. This resulted in negative tristimulus values. A set of tristimulus values was determined for each wavelength of monochromatic light. The sets of tristimulus values derived for an observer at all of the wavelengths of light is called the observer's color-matching functions. Since it is more convenient to use only positive tristimulus values in the calculations, the real red, green, and blue lights were transformed into a set of mathematical lights: X (representing red), Y (representing green), and Z (representing blue). Every color can be matched by using the appropriate amounts of X, Y, and Z (their tristimulus values). The CIE Standard Observers were derived by averaging the results of a number of observers.

The first CIE Standard Observer was recommended in 1931 and is commonly known as the CIE 2° Standard Observer. It was based on color matching experiments in which the observer viewed a small visual field subtending a visual angle of 2°, which is approximately the size of a dime viewed at arm's length (approximately 18 in.).

Vision researchers have learned that the visual system perceives color differently when viewing larger areas of color. The color matching experiments were repeated with a larger, 10° field, which is approximately the size a circle three inches in diameter viewed at arm's length. This new set of color matching functions is called the CIE 1964 Supplemental Standard Observer, which is commonly known as the CIE 10° Standard Observer. These functions are shown in *Figure* 6. Most colorimetric calculations are made using the 10° Standard Observer, which more closely approximates industrial viewing conditions.

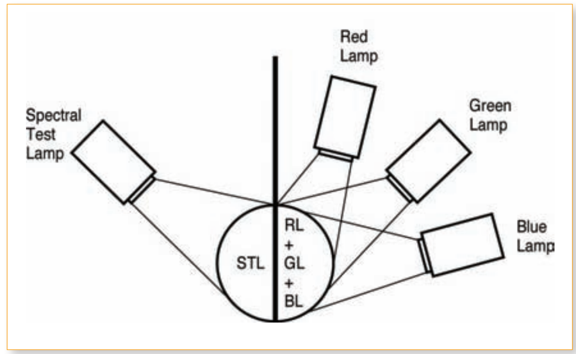

Figure 4—CIE standard observers were developed with the technique illustrated in this figure. A "single" wavelength of light was projected on one half of a circular area and the observer matched it with a combination of red, green, and blue lights.

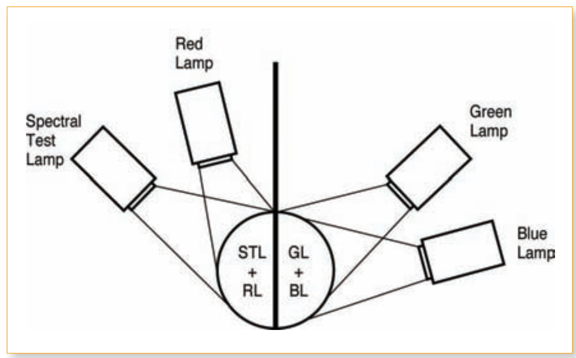

Figure 5—When a spectral light could not be matched by the observer with a combination of red, green, and blue light, one of the lamps had to be "added" to the spectral light. In this figure, when the combination of spectral light and red light was matched with a mixture of green and blue light; the amount of red light that had to be added to get a match was considered to be a negative amount.

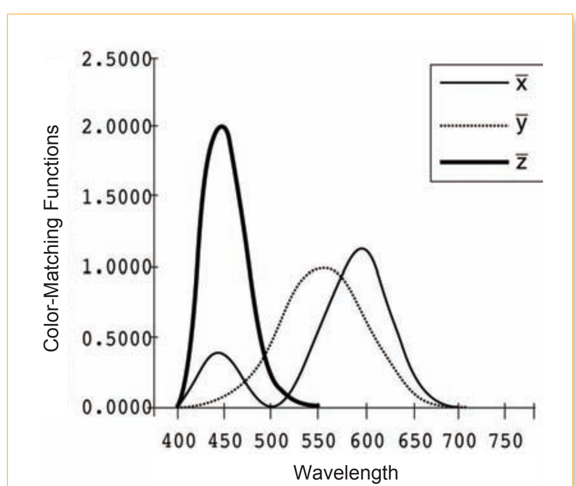

Figure 6—Color matching functions of the 1964 CIE Supplemental Standard Observer, commonly referred to as the 10° Standard Observer.

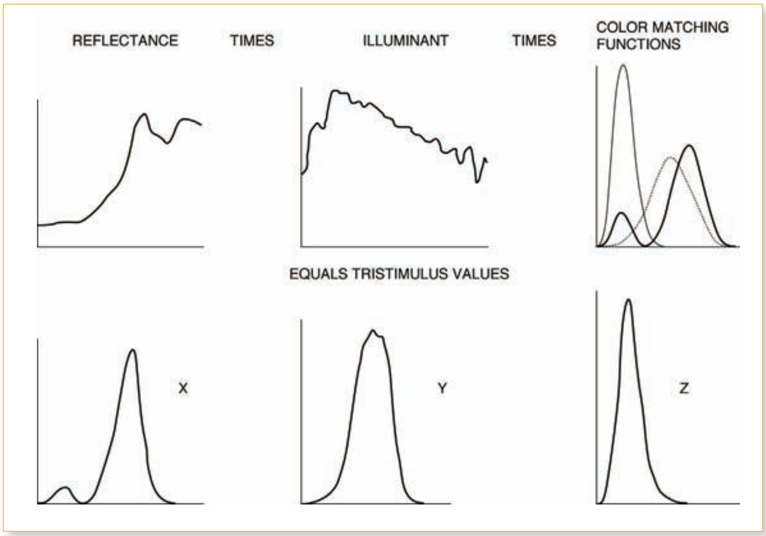

Figure 7—Tristimulus integration. The reflectance curve multiplied by the illuminant and multiplied in turn by each of the color-matching functions of the standard observer equals the tristimulus values. The areas under the curves are the numerical value of the tristimulus values.

Calculation of Tristimulus Values

The CIE tristimulus values for an object are calculated by combining the spectral power distribution of the illuminant with the reflectance factor of the object and the color matching functions of the observer.[4,5] Each tristimulus value is the integral of the product of the spectral power distribution, reflectance of the object, and appropriate color matching function of the observer over the visible wavelength region as shown in *Figure* 7. The integral is evaluated numerically as a sum over selected wavelengths in the visible region.

The following equations are used to calculate X, Y, and Z for a sample with reflectance values measured over the visible spectrum.

$$X = k\sum P(\lambda)\, \bar{x}(\lambda)\, R(\lambda)$$

$$Y = k\sum P(\lambda)\, \bar{y}(\lambda)\, R(\lambda)$$

$$Z = k\sum P(\lambda)\, \bar{z}(\lambda)\, R(\lambda)$$

where

$$k = \frac{100}{\sum P(\lambda)\, \bar{y}(\lambda)}$$

$P(\lambda)$ is the value of the spectral power distribution of the illuminant, $R(\lambda)$ is the reflectance factor of the sample, and the $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ are the CIE color matching functions for the standard observer at the wavelength, λ. The CIE recommends that the sums be taken over a set of equally spaced wavelengths from 360 nm to 830 nm at 1 nm intervals. For most practical purposes, however, they state that the sums can be taken over the wavelength range from 380 nm to 780 nm at 5 nm intervals. The factor *k* insures that the value of Y will be normalized to a value of 100 for the perfect diffusing reflector. Since many commercial instruments only measure at 10 nm intervals, ASTM International has published a set of weighting factors to be used with those instruments.[5]

Weighting factors are derived from the combination of the illuminant and observer data along with other adjustments based on the wavelength interval and range selected. The tristimulus values are computed by summing the product of the weighting factor and the reflectance at the same wavelength as indicated below.

$$X = \sum W_x(\lambda)\, R(\lambda)$$

$$Y = \sum W_y(\lambda)\, R(\lambda)$$

$$Z = \sum W_z(\lambda)\, R(\lambda)$$

A weakness of the CIE X, Y, and Z color space is its lack of visual uniformity. If two colors have the same X, Y, and Z values, they will have the same color. However, if two colors do not have the same X, Y, and Z values, it is very difficult to determine how different the colors would look. For example, if two green samples differed from two blue samples by the same amount of X, Y, and Z, the green samples would appear to have a smaller difference in color than the blue samples.

CIE L* a* b* Color Space

To improve the visual uniformity of the CIE system, the CIE transformed the tristimulus values into color coordinates, the CIE 1976 L* a* b* (abbreviated as CIELAB) color space.[4] The CIE also defined the chroma, C^*_{ab}, and hue angle, h_{ab}. In the coatings industry the CIELAB color space has gained widespread acceptance by manufacturers, customers, and suppliers. The values of L* for lightness, a* for redness–greenness, and b* for yellowness–blueness are calculated from the tristimulus values according to the following equations:

$$L^* = 116\ f(Y/Y_n) - 16$$

$$a^* = 500[\,f(X/X_n) - f(Y/Y_n)]$$

$$b^* = 200[\,f(Y/Y_n) - f(Z/Z_n)]$$

where

$$f(Y/Y_n) = (Y/Y_n)^{1/3}$$

for values of (Y/Y_n) > 0.008856 and

$$f(Y/Y_n) = 7.787(Y/Y_n) + 16/116$$

for values of (Y/Y_n) equal to or less than 0.008856. Similarly defined are $f(X/X_n)$ and $f(Z/Z_n)$. In addition, X_n, Y_n, and Z_n are the tristimulus values of the illuminant being used in the calculation.

$$C^*_{ab} = [a^{*2} + b^{*2}]^{1/2}$$
$$h_{ab} = \arctan[b^*/a^*]$$

The CIELAB system is illustrated in *Figure* 8. The a* axis runs from right to left with more negative values showing the shift toward green and more positive values showing the shift to red. On the b* axis, more negative values shift toward blue and more positive values shift toward yellow. The L* or lightness axis is perpendicular to the diagram. The L* axis goes from a perfect black (L* = 0) to a perfect white (L* = 100) with all of the grays in between. Colors are commonly shown on an a*b* diagram. In an a*b* diagram the center is a perfect gray and the lightness value is constant over the a*b* plane. Circles on the a*b* diagram represent constant chroma. The hue angle is zero along the +a* (red) axis and increases in a counter clockwise direction around the diagram with the +b* (yellow) having a hue angle of 90°, the -a* axis (green) having a hue angle of 180°, the -b* axis (blue) having a hue angle of 270°.

This transformation of the tristimulus values gives improved correlation with visual color perception. The Munsell hue circle would be a perfect circle in a visually perfect color space. *Figure* 9 shows a Munsell hue circle plotted on an a*, b* chromaticity diagram. Although there is a significant improvement over X,Y,Z color space, the CIELAB color space is still not perfect. For some purposes, CIELAB may be close enough to a visually uniform system, but the search continues for a more perfect system.

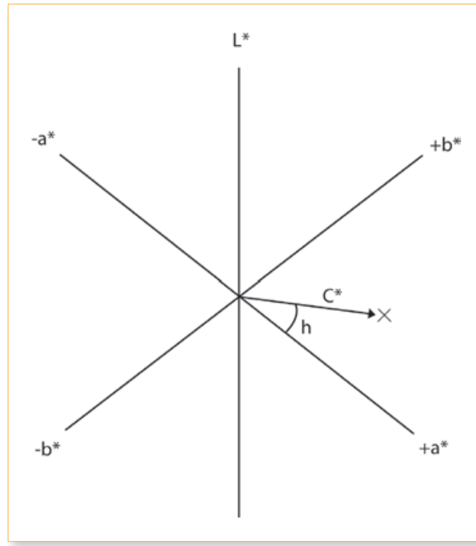

Figure 8—A point in CIELAB color space can be described either by its L*, a*, and b* coordinates or by its L*, C*, and h coordinates.

COLOR DIFFERENCES AND TOLERANCES

Much of the effort spent on color in the coatings industry involves describing color differences. These may be the differences between two lots of pigments, the concept color and the laboratory match, the product standard and the production batch, or the product standard and the final coated product. Describing the differences in color is essential and being able to put numbers on the difference or otherwise quantify it is extremely useful.

In dealing with color differences, it is important to distinguish between perceptibility and acceptability. A color difference between two samples is perceptible if you can see the color difference between them. While two samples may be perceived to be different in color, the difference in color may still be acceptable to the user or consumer. Color tolerances tell us how great the color difference between the sample and the standard can be and still be acceptable on the coated product.

Color differences can be evaluated visually or by instrumental measurements. The words used to describe color differences should be specific. The terms the author recommends using are lightness, chroma, and hue. The sample is either equal in lightness to the standard or it is darker or it is lighter. The sample may have the same, a higher or a lower chroma than the standard. Hue differences are usually described in terms of redness, yellowness, greenness, or blueness. A red or

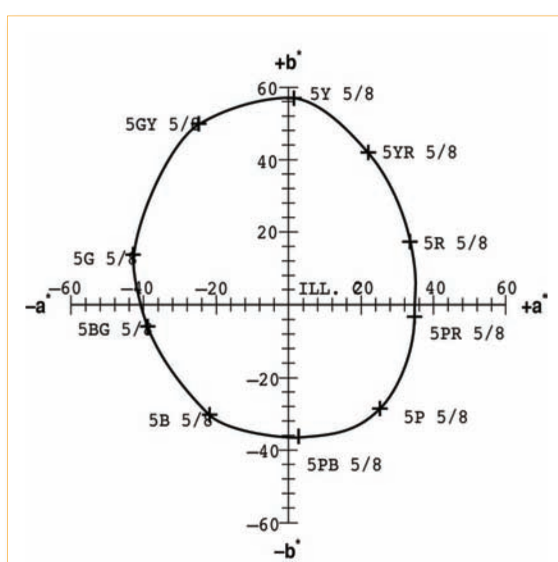

Figure 9—A Munsell hue circle plotted on a 1976 CIE CIELAB a*b* diagram. The Munsell hue circle is closer to being a true circle in this diagram. CIELAB space, however, is still not a totally uniform color space.

green sample may be yellower or bluer than the standard, and a yellow or blue sample may be redder or greener than the standard. For example, a red sample may be moderately yellower, slightly darker, and lower in chroma than the standard.

Before instrumental measurements are made, color and gloss differences between a standard and a sample should be evaluated visually. The standardization of visual examination has greatly improved the uniformity of products and the accuracy of color matches.[6-9]

Instrumental evaluations of color difference yield numerical values that can be expressed as lightness, chroma, and hue differences between sample and standard. Instruments can measure color differences that cannot be perceived by a human observer. In setting color tolerances with instruments, care must be taken not to set color tolerances below the threshold of human color perception. Instrumental measurements correlate best with visual evaluation when standardized visual evaluation methods are used and when the standard and sample have the same gloss and texture.

Color Difference Equations

An ideal color-difference equation would provide a single-number pass/fail equation for evaluating the small to medium color differences that are typical in the surface color industries. A number of equations exist for calculating color differences from instrumental measurements. Several of the equations are discussed below. Consult ASTM D2244 Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates for all of the mathematical details of the equations.[10]

CIELAB: The CIE recommended the CIELAB $L^*a^*b^*$ uniform color space and color difference equation in 1976. Its popularity increased through the 1980s and it became the most commonly used equation in the coatings industry. Below are the equations used to calculate the CIELAB color difference:

$$\Delta L^* = dL^* = L^*_{sample} - L^*_{standard}$$

$$\Delta a^* = da^* = a^*_{sample} - a^*_{standard}$$

$$\Delta b^* = db^* = b^*_{sample} - b^*_{standard}$$

$$\Delta E^* = dE^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

$$\Delta C^* = dC^* = C^*_{sample} - C^*_{standard}$$

$$\Delta H^* = dH^* = [(\Delta E^*)^2 + (\Delta L^*)^2 + (\Delta C^*)^2]^{1/2}$$

A negative value of ΔL^* indicates that the sample is darker than the standard. A positive value of Δa^* indicates that the sample is redder than the standard. A negative value of Δa^* indicates that the sample is greener than the standard. A positive value of Δb^* indicates that the sample is yellower than the standard. A negative value of Δb^* indicates that the sample is bluer than the standard. A positive value of ΔC^* indicates that the sample has a higher chroma (cleaner) than the standard. A negative value of ΔC^* indicates that the sample has a lower chroma (dirtier) than the standard. ΔH^* is the hue component of the color difference. The sign of ΔH^* is taken as positive if the hue angle of the sample is greater than that of the standard and is negative if the hue angle is less than that of the standard. Reference 10 proposes an alternative method for calculating the hue component of the color difference.

Although the CIELAB color difference formula was a significant advance over those developed previously, there was still a need for improvement. Color difference research on acceptable textile samples produced ellipsoids when plotted in CIELAB color space rather than the spheres that would be expected in a uniform color space. Ellipses close to neutral colors are the smallest. The ellipses increase in size as the chroma is increased. Most ellipses point towards the neutral point except those in the blue region.

CMC(l:c): To improve the agreement between visual evaluations and instrumental color differences, the Color Measurement Committee of the Society of Dyers and Colorists of Great Britain modified the CIELAB color difference equation to improve its uniformity.[11] This resulting equation is called the CMC(l:c) equation and became a British Standard.[12] Although originally developed for textile applications, the CMC(l:c) equation has become the most popular color difference equation used in the coatings industry. Below is the equation for calculating the CMC(l:c) color difference:

$$\Delta E_{CMC} = \left[\left(\frac{\Delta L^*}{lS_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{cS_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{S_H}\right)^2\right]^{1/2}$$

The CMC(l:c) equation allows the user to change the emphasis of the lightness difference to the chromaticity difference by changing the weighting factors l and c. The textile industry prefers an l:c weighting of 2:1. Different weightings may be appropriate to different industries. The factors S_L, S_C, and S_H the size of the ellipsoidal acceptance region in color space to compensate for the lack of visual uniformity of the CIELAB color space.

Although the CMC equation was a considerable improvement over CIELAB, its development was based on the acceptability of textile color matches rather than perceptibility criteria. Its primary application has been to establish acceptability tolerances.

When the standard and trial are reversed, different CMC(l:c) color differences are calculated even though their visual difference is perceptually the same. Because of that phenomenon, the CMC(l:c) equation is more properly referred to as a color tolerancing equation rather than a color difference equation.

CIE94: Based on visual perceptibility evaluations on a large data set that included glossy paint samples, The Industrial Color-Difference Technical Committee (TC 1-29) of the CIE recommended a new color difference equation, CIE94, modeled after the CMC(l:c) equation.[13] The Committee retained some features of the CMC(l:c) formula but felt that others did not contribute to its success. The CIE94 formula has the same form as the CMC(l:c) formula with different weighting factors. The CIE94 equation is also a color tolerancing equation.

$$\Delta E^*_{94} = \left[\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{k_C S_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{k_H S_H}\right)^2\right]^{1/2}$$

The parametric factors k_E, k_L, k_C, and k_H are normally set equal to unity for the reference viewing conditions specified as D65 illuminant against a neutral background with L*=70. They may be varied like the CMC equation weighting factors for other viewing conditions. They take into consideration effects influencing color difference judgments. The S factors correct for CIELAB's lack of visual uniformity.

CIEDE2000: In 2001, the CIE recommended an improved color difference equation, CIEDE2000, that outperforms the CMC(l:c) and CIE94 equations in uniformity.[14,15]

$$\Delta E_{00} = \left[\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_t\left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)\right]^{\frac{1}{2}}$$

The CIEDE2000 equation includes an additional term that rotates the ellipsoids in the blue region when plotted in L*a*b* space.

Tolerances

The most important question to ask when setting a tolerance is not "Is there a color difference between the standard and the sample?" but rather "Is the color of the sample acceptable?" Tolerances should be determined visually and based on the use of the color.

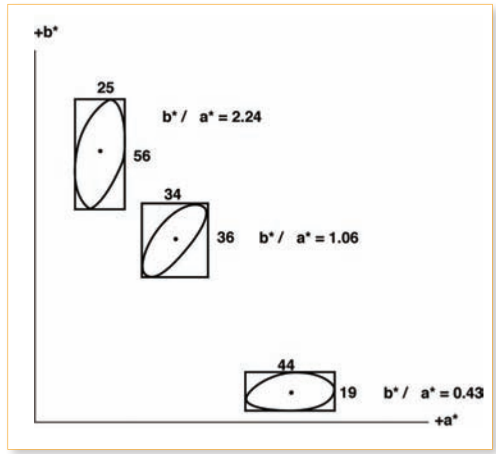

Figure 10—Setting tolerances in CIELAB color space using the differences in a* and b* coordinates do not match some acceptability tolerances very well.

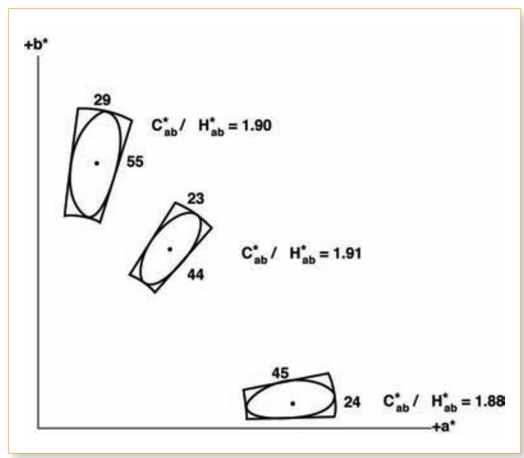

Figure 11—Setting tolerances in CIELAB color space using differences in C* and H* fit acceptability tolerances better than the differences in a* and b*.

Instrumental color measurement and calculated color differences can be used to supplement visual evaluation and provide a quantitative ruler for judging color.[16] This ruler is quite useful since most samples will have a perceptibly visible color difference. The major problem with instrumental tolerances is the tendency to want the total color difference to be 0.0. This is unrealistic since the instrument can detect differences that a human cannot. For example, color differences below about 0.4 CIELAB color difference unit will not generally be seen.

Another method of setting tolerances would be to assign them in terms of the differences of the components of a color difference equation. The amount of difference allowable is ideally determined from measurements of samples previously found to be acceptable. Sometimes approximations are made based on similar samples and colors. Unfortunately, sometimes a tolerance will be picked without reference to the application.

CIELAB color differences can be broken down either into lightness (Δ L*), red–green (Δ a*), and yellow–blue (Δ b*) components or into lightness

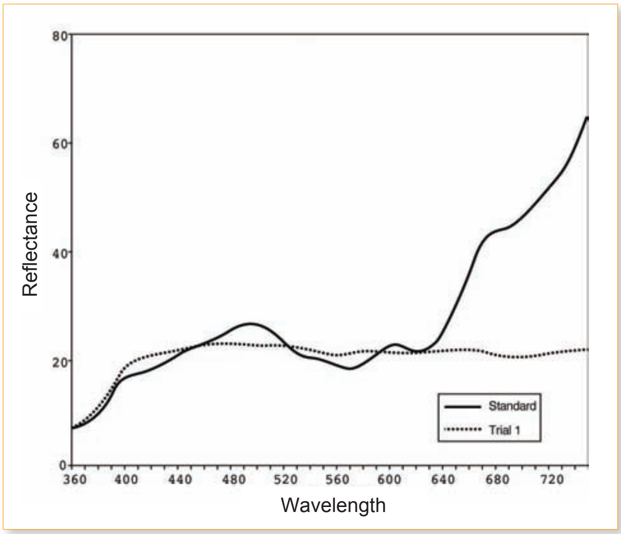

Figure 12—Illuminant metamerism is when two samples having different spectral reflectance curves, such as those shown in this figure, match when viewed by a normal observer with one light source but no longer match when viewed by the same observer with a different light source.

(Δ L*), chroma (Δ C*), and hue (Δ H*) components. *Figure* 10 shows an example of setting tolerances in terms of CIELAB Δ a* and Δ b*. As you can see in the diagram, there are areas in which the sample can fall within the Δ a* and Δ b* limits but be outside the acceptability ellipse. This is particularly true when the color is away from the a* or b* axes. *Figure* 11 shows an example of setting tolerances in terms of CIELAB Δ C* and Δ H*. By setting tolerances using those components, there is less chance of the color being within the measured tolerance limits but outside the acceptability ellipse. The Society of Automotive Engineers, SAE, recommended setting instrumental tolerances for automotive products using CIELAB ΔL^*, ΔC^*_{ab} and ΔH^*_{ab}.[17] One way to help avoid the error of having the color inside each measured limit but outside the ellipse is to also include a tolerance based on the total color difference.

The CMC tolerancing system based on the CMC color difference equation has gained acceptance in many applications. The CMC color difference is calculated and is used as a single measure of acceptability. Acceptable and unacceptable color matches are determined by visual examination. The samples are arranged in order of increasing CMC color difference. A CMC color difference is determined below which a sample will be an acceptable color match. This defines an acceptable CMC color match ellipsoid in color space. Samples with CMC color differences located at the boundary of the acceptance ellipsoid may or may not be acceptable matches and must be evaluated visually for acceptance. Samples with color differences outside the boundary of the ellipsoid are unacceptable matches and are rejected. The ellipsoid represents the volume of acceptance in color space and automatically varies in size depending on its position in color space. A commercial factor cf is sometimes used to change the size of the acceptability ellipsoid to accommodate different classes of customers. Similar tolerancing methods can be set up using the CIE94 or CIEDE2000 color difference formulas.

Indices of Metamerism

Metamerism occurs when two colored samples match under one light source to an observer but cease to match if the light source is changed. Two samples are also metameric if they match to one observer but not another under the same light source and viewing conditions. Metamerism is a major problem in color matching paints. Since metamerism can originate from a number of causes the subject deserves some additional discussion. Several types of metamerism are recognized and must be dealt with by the color matching laboratory.

Illuminant metamerism is when two samples having different spectral characteristics match when viewed by a normal observer under a given illuminant, but no longer match when viewed by the same observer using the same illuminating and viewing geometry but with a different illuminant. *Figure* 12 shows the spectral curves of two specimens displaying illuminant metamerism. This type of metamerism often occurs when a color match is made using colorants that are different than those present in the target to be matched. This situation can occur when attempts are made to color match a coating to ceramic, plastic, textile, or printed material since the colorants used in these materials often differ from the colorants used in coatings. This type of metamerism can also occur in color matching a coating if the available colored pigments are different than those in the submitted target.

Observer metamerism is when two samples having different spectral characteristics match when viewed by one observer, but do not match when viewed by a different observer under the same conditions. This type of metamerism can be very difficult to deal with unless the individuals involved are aware of their color perception differences and have some understanding of the color perception process. Testing individuals for color perception and their ability to distinguish color differences is important for individuals involved in color decisions.

A measure of metamerism can be defined as the color difference between the match and standard under a reference illuminant/observer combination in which the pair match and a test illuminant/observer combination in which the degree of metamerism is evaluated. A typical reference combination is CIE illuminant D65 and the 1964 10° standard observer and typical test combination is illuminant A and the 1964 10° standard observer. The CIE metameric index,[4] MI, is the total color difference between the metameric pair under the test conditions.

Any color difference equation can be used. Other reference and test conditions may be chosen but it is assumed that a metameric pair matches exactly under the reference condition. This index is known as the special index of metamerism, change of illuminant.

A special index of metamerism, change in observer can also be calculated. The standard and reference conditions use the same illuminant but different observers, for example the 10° and 2° standard observers.

The CIE defines two samples as metamers if their spectra are different in the visible region and have identical tristimulus values for a single condition of illuminating and viewing. Samples that approximately match under a reference condition and vary in color under other test conditions are not metamers according the CIE definition. The ASTM refers to these samples as paramers. This common situation is still referred to as metamerism by many industrial color matchers. The DIN6172 Metamerism Index[18] is a useful means to characterize these almost matching, functionally metameric samples.

CONCLUSION

Color and appearance are important to the coatings industry because color sells products. When all other aspects of two coatings are nearly the same, it is color that the purchaser uses to make his/her final decision. This tutorial covers only the bare basics of color. Space restricted the inclusion of many other aspects of color that are important in the coatings industry. References 19 through 25 provide sources of more general information about color. CT

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