The goal of any dyehouse is to deliver products that satisfy the shade requirements of its customers. The most common technique for shade approval employed in the past has been one in which the dyer compares the batch to the approved standard visually and, based on experience, decides whether or not the variation is acceptable. Batch to batch shade variation is impossible to eliminate completely, so an agreement must be reached between the dyer and the customer as to what represents acceptable shade variation. This type of agreement is based on the perception of each individual and may change day to day and shade to shade. Advancements in computer technology and programming have made it possible to remove the perception of the individual from the shade approval process and replace it with repeatable and reliable data that gives consistent pass/fail decisions.

Haphazardly establishing a program of computerized pass/fail tolerances can be a source of significant problems in any dyehouse. Understanding the advantages and disadvantages of color tolerancing formulas is essential in developing and implementing a successful computer pass/fail program. It is the purpose of this paper to describe some of the more common techniques used for computerized pass/fail programs.

**DISADVANTAGES OF VISUAL PASS/FAIL SYSTEMS**

The need for computerized pass/fail programs arises from the fact that visual evaluations of shade difference are not consistent when establishing the fine line between acceptable and unacceptable dyeings. A sample that is approved by one person may be rejected by another simply because they perceive color differently. This is true not only for the dyer and a customer, but for dyers on different shifts, and even for the same dyer day to day. The end result is delay in the decision making process, not to mention the uneasiness produced when a borderline shade is approved.

**REQUIREMENTS OF A COMPUTERIZED PASS/FAIL PROGRAM**

To successfully implement a computerized pass/fail program, several requirements must be met:

1. The program must be easy to understand with respect to both the software used to produce the pass/fail decision and the data that is generated. Operators will be reluctant to use a system that does not quickly produce the desired information.

2. Software results must correlate with the visual perception of those involved in initially establishing an acceptable pass/fail tolerance.

3. Pass/fail results must be reliable and repeatable day to day and shift to shift.

4. Once established, the program should lead to quicker pass/fail decisions, especially when a person typically
NUMERICAL BASIS OF COMPUTER PASS/FAIL DATA

All pass/fail formulas are calculated from basic colorimetric data generated by a spectrophotometer and appropriate software. It is not necessary to understand how the values are calculated to successfully interpret the data. For this reason, this paper will focus on the interpretation of results rather than on the calculations performed by a software package. All colorimetric values referenced in this paper are calculated using formulas as listed in AATCC Test Method 173-1992: "CMC: Calculation of Small Color Differences for Acceptability" (1). Other excellent references for calculation and interpretation of colorimetric data are "Principles of Color Technology, 2nd Edition" by Fred W. Billmeyer, Jr. and Max Saltzman (2) and "Practical Color Measurement" by Anni Berger-Schunn (3).

The basis of most pass/fail formulas are values known as CIE 1976 $L^*a^*b^*$ (CIELAB) coordinates. The values listed in Table I were recommended by the CIE (Commission International de l’Éclairage or International Commission on Illumination) to be used for general color description (4). A more useful transformation is the calculation of the differences between the CIELAB coordinates of a standard and a batch. This results in numerical values that describe the visual difference between the samples (Table II).

Table I: CIELAB Coordinates

<table>
<thead>
<tr>
<th>CIELAB Coordinates</th>
<th>Table II: CIELAB Color Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>L* Light - Dark</td>
<td>DL* (+) Light (-) Dark</td>
</tr>
<tr>
<td>a* Red - Green</td>
<td>Da* (+) Red (-) Green</td>
</tr>
<tr>
<td>b* Yellow - Blue</td>
<td>Db* (+) Yellow (-) Blue</td>
</tr>
<tr>
<td>C* Chroma/Brightness</td>
<td>DC* (+) Bright (-) Dull</td>
</tr>
<tr>
<td>h Hue Angle</td>
<td>DH* (+) Varies (-) Varies</td>
</tr>
</tbody>
</table>

The total color difference between two samples is termed DE and is equal to the square root of the sum of the squares of $DL^*$, $Da^*$, and $Db^*$.

PASS/FAIL TOLERANCES USING CIELAB $DL^*$, $Da^*$, $Db^*$

One technique commonly used in pass/fail programs is to establish boundaries for the values of $DL^*$, $Da^*$, and $Db^*$ between a standard and a batch. Batches that fall within these boundaries are approved while those falling outside are rejected. Figure 1 illustrates a typical $Da^*$/$Db^*$ tolerance block in $a/b$ color space within which acceptable batches must fall relative to a particular standard. Although the size may change, the acceptable area will always be rectangular when using $Da^*$ and $Db^*$ tolerances.

![Figure 1: CIE L*a*b* Tolerances](www.techexchange.com)

The question that arises is whether or not this system produces pass/fail decisions that correlate with actual visual analysis. In Figure 2, a series of batches have been plotted that are considered to be acceptable matches to the
standard. If a ring - or ellipse - is drawn around these acceptable batches as in Figure 3, it can be seen that some of the batches fall inside the ellipse, but outside the square. These batches would be visually

![Figure 2: Acceptable Batches](image1)

![Figure 3: Acceptability Ellipse](image2)

acceptable, but would be failed by the CIELAB $L^*a^*b^*$ tolerancing program. In the same manner, batches that fall inside the square but outside the ellipse will be passed by the program even though they are visually unacceptable. If we examine standards located throughout the positive $a^*/b^*$ quadrant, we find that the sizes of the ellipses representing acceptable shade variation change (Figure 4), indicating that most observers are more sensitive to shade variation in some colors than in others. If CIELAB $L^*a^*b^*$ tolerances are used for the standards represented by the ellipses, a different set of tolerances will be required for each standard as can be seen in Figure 5. Depending on the tolerances selected, there will be many instances in which computer pass/fail decisions do not agree with visual evaluation. For this reason, CIELAB $DL^*$, $Da^*$, and $Db^*$ tolerances do not meet the requirements for an acceptable pass/fail program as stated earlier.

![Figure 4: Acceptability Ellipses](image3)

![Figure 5: CIELAB Tolerance Blocks](image4)

**PASS/FAIL TOLERANCES USING CIELAB $DL^*$, $DC^*$, $DH^*$**

Reexamining Figure 5 above indicates that the ellipses representing visually acceptable batches align themselves with the center of the $a^*/b^*$ color space. This spherical nature of color is described numerically using the concepts of chroma ($C^*$) - the distance of a sample from the center of color space - and hue ($h$) - the angle formed by the positive $a^*$ axis and a line connecting the sample to the center of color space. Although pass/fail tolerances can be established using the differences in $C^*$ and $h$ ($DC^*$ and $DH^*$), the same problems will be encountered as when using $Da^*$ and $Db^*$ tolerances. (Figure 6).
Batches that fall outside the ellipse but inside the square will produce incorrect pass/fail decisions from the computer system. Note that the tolerances can be modified as indicated by the dashed lines in Figure 6, but there will still be areas of incorrect pass/fail decisions. Because different pass/fail tolerances would be required for different colors and because the computer pass/fail decision will not always agree with visual assessment, CIELAB $DL^*$, $DC^*$, and $DH^*$ tolerances do not meet the stated requirements of a successful pass/fail program.

**PASS/FAIL TOLERANCES USING CIELAB $DE^*$**

As stated previously, $DE^*$ is a value that describes the total color difference between a standard and a batch. A pass/fail system based on a single value rather than on three values would be much easier to understand, an important factor of the requirements for an acceptable pass/fail program. Two samples have been plotted in Figure 7. Assume that the values for $DL^*$ and $Da^*$ are both 0.00 and the only difference is in the sign of $Db^*$. Solving the $DE^*$ formula with these values of $DL^*$, $Da^*$, and $Db^*$ gives the following results:

\[
DE^*(\text{Batch 1}) = \sqrt{DL^* + Da^* + (-Db^*)} = Db^* \\
DE^*(\text{Batch 2}) = \sqrt{DL^* + Da^* + (+Db^*)} = Db^*
\]

The above formulas show that the $DE^*$ values of the two batches will be equal even though there will be a significant difference in the color of the batches when compared to each other. If a pass/fail tolerance was established based on Batch 1, Batch 2 would also pass because it has the same $DE^*$ value. The ellipse in Figure 7 indicates that Batch 2 is visually unacceptable due to a large hue variation, leading to the conclusion that a pass/fail program based solely on CIELAB $DE^*$ will often produce unacceptable results.

Unique values for $DE^*$ would be required for each color family as well due to the variations in the sizes of the acceptability ellipses previously discussed.
The examples discussed thus far have all dealt with pass/fail programs based on CIELAB calculations. It should be apparent from these examples that any pass/fail program based on CIELAB will require separate tolerances for different colors or color families and will not always agree with visual color difference evaluations. This will lead to a lack of confidence in the results from the pass/fail program and a tendency to depend on visual shade assessment.

PASS/FAIL TOLERANCES USING THE CMC FORMULA

For a computer system to accurately generate pass/fail decisions, there must be a way to describe the ellipses that represent visually acceptable color difference, and for a tolerancing program to be simple and accurate, it must be possible to describe each ellipse using the same number.

A project to develop a formula that met these criteria was undertaken by the Color Measurement Committee of The Society of Dyers and Colorists, Great Britain. After visually and instrumentally evaluating a significant number of samples, the Color Measurement Committee produced a new formula that modified the CIELAB equation in such a way that the ellipses that represented acceptable shade variation could be described with one value called DE(CMC). Using the CMC formula, the total volume of each ellipse can be calculated and is equal to a DE(CMC) of 1.0. As the region of color space changes, the size of the ellipse changes with regard to visual perception, but the DE(CMC) remains 1.0. It is therefore possible to use a single value for DE(CMC) as a pass/fail tolerance for all shades. DE(CMC) is typically written as CMC(2:1), where (2:1) are values used in the CMC formula corresponding to the variables (l:c). With these values of (l:c), the ratio of lightness, chroma, and hue are fixed in the CMC equation so that they correlate with visual assessment of textile samples. These values should be held constant at (2:1) unless actual results indicate the need for modification (5).

Because the CMC formula allows for the use of a single tolerance for all shades, a pass/fail program based on CMC will not be difficult to implement or understand. The CMC tolerance will also correlate with visual assessment regardless of the color being evaluated, making CMC an ideal choice for a computerized pass/fail program.

IMPLEMENTING CMC PASS/FAIL

The first step in successfully implementing a CMC pass/fail program is to develop a repeatable sample measurement technique. If sample measurement is not repeatable, color difference data will not be reliable and results of pass/fail calculations will vary significantly. Proper measurement technique will include determining the proper sample conditioning, sample thickness, sample placement at the spectrophotometer, and number of measurements. Once the correct technique is established, all standards and batches must be measured in the same manner. The spectrophotometer must also be maintained and calibrated according to manufacturer specifications to insure accurate sample measurement.

After establishing the correct measurement technique, an appropriate DE(CMC) tolerance must be selected. A value of 1.0 is an excellent starting point for DE(CMC), but this may vary depending on end-use of the material. The best technique for determining an appropriate DE(CMC) - or commercial factor (cf) - is to evaluate batch history information. The commercial factor that is selected should be a value that will generate a passing decision for visually acceptable batches and a failing decision for visually unacceptable batches. Again, this value may not be 1.0 depending on how critical color is for the product being dyed. Materials that have less stringent shade requirements might be successfully evaluated using a commercial factor of 1.25 or 1.50. The reverse is true in that some products may require a cf of less than 1.0.

After establishing a starting point for the DE(CMC) commercial factor, this value must be confirmed through trial using an assortment of colors in the production environment. If the tolerance selected does not provide pass/fail data that correlates with the visual assessment of the majority of observers, the value should be modified. Once the correct value is established, all observers should agree to accept the results of the pass/fail program.

SPECIAL CONSIDERATIONS

Although a pass/fail program based on DE(CMC) will provide data on the acceptability of a batch compared to a
standard, it will not provide data indicating how a current batch compares to previous batches. In Figure 8, the two batches presented are within the acceptability ellipse, indicating that they both pass when compared to the standard, but there is a significant difference between the two batches when compared to each other. Even though both batches pass, the customer may object to the batch to batch variation if these batches are delivered together or in succession.

![Figure 8: Batch Variation](image)

To insure that a customer receives batches with limited variability, run charts similar to the ones in Figure 9 should be employed. A run chart will indicate the performance of many previous batches in regards to values such as DL, DC, and DH as calculated with the CMC formula. This will give the dyer essential information in determining the acceptability of a new batch relative to previous batches. Run charts are also helpful in determining if a process is out of control.

As a particular color is dyed on a regular basis, it may become obvious that the approved batches are all located in a specific area of color space relative to the standard. The batches may be skewed to the red side or the bright side similar to the batches depicted in Figure 10. As new batches are dyed, it is preferable that they also fall into this localized area. To insure that only batches in this new region are judged as passing, it will be necessary to modify the CMC acceptability ellipse to include only this region. The dashed ellipse indicates a transformation of the CMC formula using special software and a significant number of visually acceptable batches. When this modification is utilized, only batches that fall within the new boundaries will be passed. Batches falling outside this area, even though they may be within the original CMC tolerance, will be failed. This modification will be applicable only to specific standards used in the calculation and will have to be repeated for other standards.

![Figure 9: DL Production Run Chart](image)
CONCLUSIONS

A reliable pass/fail program is an essential part of establishing accurate shade communication between dyer and customer. Although there are several color space options available for implementing a pass/fail tolerance program - none of which are absolutely uniform - results of observations indicate that tolerances based on DE(CMC) produce computer pass/fail decisions that most closely duplicate visual assessment. To insure that the tolerance formula that is actually implemented is accurate, it should be based on batch history gathered using repeatable techniques. Once an accurate pass/fail tolerance has been established, much of the guess work may be taken out of day to day shade assessment.

REFERENCES