WI 180804.04

T 524

DRAFT NO. 02 - SARG

DATE October 7, 2020

WORKING GROUP
CHAIRMAN Dennis Crawshaw

SUBJECT
CATEGORY Optical Properties

RELATED
METHODS See "Additional Information"

Color of paper and paperboard (45/0, *C*/2)

(Five-year review of Official Method T 524 om-13)

(no changes from Draft 1; editorial corrections incorporated)

1. Scope

1.1 This method specifies a procedure for measuring the color of paper or paperboard with tristimulus filter colorimeters or spectrophotometers incorporating directional (45/0) geometry and CIE (International Commission on Illumination) illuminant *C*.

NOTE 1: TAPPI T 527 "Color of Paper and Paperboard (d/0, C/2)" describes a similar procedure using diffuse illumination and normal viewing.

Approved by the Standard Specific Interest Group for this Test Method
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1.2 In the method, tristimulus values *X* (red), *Y* (green), and *Z* (blue), appropriate to the CIE-1931 (2°) standard observer, are calculated from reflectance measurements R_x, R_y, and R_z. or from *R* (λ) data. Color can then be expressed in various color space systems:

1. Hunter *L, a, b*
2. CIE *L**, *a**, *b**
3. *L**, *C**, *h*
4. Dominant wavelength, purity, luminosity
5. Color difference, [Δ*E*, Δ*E**, Δ*E**94, Δ*E* (CMC)]

1.3 Instruments equipped with microprocessors which give direct information relating to different color scale systems conform to this method only if the means of measurements and calculation conform to the descriptions herein.

2. Significance

2.1 The color appearance of paper and paperboard is important for its aesthetic value in marketing packaged products, as an aid to distribution of multi-ply forms, to differentiate pages or sections of published literature, in artwork, and in many other applications.

2.2 A numerical definition of color is essential to good quality control and to customer-producer relationships.

3. Definitions

3.1 *Dominant wavelength (of an illuminated object)*, the wavelength of spectrally pure energy which when mixed with the illuminant in suitable proportions will match the color of the specimen.

3.2 *Purity*, *excitation,* the ratio of the distance on a CIE chromaticity diagram between the achromatic point and the specimen point to the distance along a straight line from the achromatic point through the specimen point to the illuminant spectrum locus. The term "saturation" is also applied to this quantity.

3.3 *Luminosity*, the scale of perception representing a color's similarity to achromatic colors between black and white. This quantity is also known as "luminance" and "luminous reflectance."

3.4 *L*, *a*, *b*, *L**, *a**, *b**, these symbols are used to designate color values as follows: *L*, *L** represents lightness increasing from zero for black to 100 for perfect white; a, *a** represents redness when positive, greeness when negative; and *b*, *b** represents yellowness when positive, blueness when negative. When *a** and *b** are simultaneously zero, they represent grey.

3.5 *L**, *C**, *h*, *L** is as described in 3.4, *C** represents chroma, and *h* represents hue angle.

3.6 ΔE, ΔE^*, ΔE (CMC), the overall color difference values take into account lightness/darkness differences as well as chromatic differences. The intent is for a given value of ΔE, ΔE^*, ΔE (CMC), to represent the same visual perception of color difference anywhere in color space.

4. Apparatus

4.1 *Instrumental components*[1], consisting of a means for fixing the location of the surface of the specimen, a system for proper illumination of the specimen, suitable filters, gratings, or other optical components for altering the spectral character of the rays reflected from the specimen, photosensitive receptors to receive the reflected rays, and a means for transforming the receptor outputs to tristimulus functions.

4.2 *Spectral characteristics*

4.2.1 *Incident light.* The spectral power distribution of the light incident on the specimen determines the extent to which reflected light may be augmented by fluorescence. The product of the spectral power distribution of the source and spectral transmittance of the glass lenses and infrared absorbing filter in the incident system should correspond to the energy distribution given as a function of wavelength in Table 1. This relative spectral power distribution may be approximated by a select combination of a tungsten filament source, a heat absorbing filter, and UV trimming filter in the incident beam. If the paper or paperboard being measured by a spectrophotometer contains no fluorophores (fluorescent components, i.e., optical brightness), the spectral distribution of incident light will not affect the measurement of color, provided that sufficient energy is available at each wavelength of measurement.

4.2.2 *Light energy.* The light energy incident on the test specimen should not appreciably heat or fade the specimen during the measurement. An infrared absorbing filter (heat filter) in the incident beam will normally prevent overheating the specimen.

[1] Names of suppliers of testing equipment and materials for this method may be found on the Test Equipment Suppliers list in the set of TAPPI Test Methods, or may be available from the TAPPI Quality and Standards Department.

Table 1. Relative spectral energy distribution incident on the specimen

Wavelength, nm	*Relative energy, E*
320	0.1
340	2.4
360	7.9
380	14.3
400	22.0
420	30.9
440	43.6
460	58.9
480	78.3
500	100.0
520	121.8
540	144.7
560	169.7
580	188.4
600	200.8
620	204.6
640	199.8
660	187.3
680	169.2
700	144.4

Table 2. Tristimulus functions for CIE Illuminant *C*/2°

Wavelength, nm	$E_c\bar{x}$	$E_c\bar{y}$	$E_c\bar{z}$
360	-0.001	-0.000	-0.006
380	-0.011	-0.000	-0.054
400	0.089	-0.001	0.393
420	2.919	0.085	14.033
440	7.649	0.511	38.518
460	6.641	1.382	38.120
480	2.364	3.206	19.564
500	0.069	6.910	5.752
520	1.198	12.876	1.442
540	5.591	18.258	0.357
560	11.750	19.588	0.073
580	16.794	15.991	0.026
600	17.896	10.696	0.013
620	14.018	6.261	0.003
640	7.457	2.902	0.000
660	2.746	1.008	0.000
680	0.712	0.257	0.000
700	0.153	0.055	0.000
720	0.034	0.012	0.000
740	0.007	0.003	0.000
760	0.002	0.001	0.000
780	0.000	0.000	0.000
SUM	98.073	100.000	118.232

4.2.3 *Spectral response.* The overall spectral response of the instrument, as determined by the combination of the spectral distribution of incident light on the specimen, the absorption characteristics of the filters and other light altering optics, and the photosensitive response of the receptors to light reflected from the specimen, shall simulate the CIE color-matching functions weighted by the relative spectral energy distribution of CIE Illuminant *C*/2° given in Table 2. All color spectrophotometers conforming to this method, T 524, must use the integration tables contained in ASTM E308 (Table 5.6), "Standard Practice for Computing the Color of Object by Using the CIE System," for the computation of tristimulus values *X, Y,* and *Z.*

4.3 *Geometric characteristics.* The angle of viewing is required to be separated from the angle of illumination in such a manner that only rays reflected diffusely from the test specimen enter the receptor, thereby excluding specular reflectance from the reading. The illuminating beam shall be centered about an axis of 45 ± 0.5° from the normal to the specimen surface. The direction of viewing shall be perpendicular ± 0.5° to the specimen surface. The angle between the axis and any ray of either the illuminating or viewing beam shall not exceed 22.5°.

NOTE 2: Interchange of incident and viewing directions is allowed under this method.

4.4 *Photometric characteristics.* The photometric system must be linear over the entire scale to within 0.2% of full scale. Photometric linearity may be determined by following the procedure described in TAPPI T 1217 "Photometric Linearity of Optical Properties Instruments." The instrument must be sufficiently stable that the reflectance factor reading will not fluctuate by more than 0.1% of full-scale deflection while the measurement is being made.

5. Standards

5.1 *Primary reflectance standard*[1]. The primary reflectance standard (100%) is an ideal uniform diffuser with a perfectly reflecting and diffusing surface (the perfect reflecting diffuser).

5.2 *Calibration standards*[1]. Reflectance values assigned to calibration standards shall be traceable to an instrument calibrated in terms of the primary reflectance standard and having geometric and spectral characteristics consistent with this method.

5.3 *Specific calibration standards*[1]. Specific calibration standards, colored similar to the paper to be tested, may be used to minimize the effect of spectral and geometric differences between instruments whose results are being compared. The "specific calibration" values for these standards should be established by first exchanging paper samples of the type of paper to be compared. The paper sample and the ceramic standard must not form a metameric pair.

5.4 *Black standard* – a black cavity with a reflectance factor which does not differ from its nominal value by more than 0.2 reflectance units at all wavelengths.

6. Calibration

6.1 Check the calibration of photometric scales at reasonable time intervals (at least monthly) in a manner to insure linearity and accuracy over all ranges. Accomplish calibration by placing a series of neutral filters of known transmittance in the incident beam, or by measuring the reflectance factor of calibrated opaque specimens.

NOTE 3: Reference (*1*) describes procedures for use of a set of special test panels in calibration of major photometric, spectral, and geometric characteristics of the instrument.

6.2 Photometric linearity and proper spectral response of the instrument are key factors for determining accurate color measurements. Colored standards should be carefully measured and their results intercompared to assure color measurement accuracy of the apparatus.

NOTE 4: Clean ceramic or glass standards, if necessary, using the procedures provided by the supplier of the standards.

6.3 Place the black standard against the specimen aperture and adjust the zero setting of the instrument.

6.4 Replace the black standard with a white calibration standard and set the instrument to the calibrated reflectance value of the standard at each filter position or wavelength, as appropriate.

7. Test specimen

From each test unit of the paper obtained in accordance with TAPPI T 400 "Sampling and Accepting a Single Lot of Paper, Paperboard, Containerboard, or Related Product," cut the sample to be tested into pieces large enough to extend at least 0.25 in. (6.35 mm) beyond all edges of the instrument aperture. Assemble the pieces into a pad which is thick enough so that doubling the pad thickness does not change the test readings. (With creped or other bulky papers care must be taken to avoid pillowing of the pad into the instrument by too much pressure.) Do not touch the test areas of the specimens with the fingers, and protect them from contamination, excessive heat, or intense light.

8. Procedure

8.1 Operate the instrument in accordance with the manufacturer's instructions. Allow adequate warm-up time to ensure stable results.

8.2 Calibrate the instrument as described in Section 6.

8.3 Place the opaque pad of sample sheets with the side to be measured against the specimen aperture and with the machine direction parallel to the light beam, and obtain the reflectance values R_x, R_y, and R_z and/or the reflectance spectra.

8.4 Move the uppermost test piece to the bottom of the pad and obtain the reflectances of the newly exposed specimen. Repeat this process until five specimens have been tested.

NOTE 5: Some materials may yield a different result, depending on whether the sample is illuminated from "upstream" or "downstream" with respect to the machine direction. In those cases, tests should be made for both orientations and the results averaged.

8.5 Recheck the instrument calibration and retest the sample if any of the calibration reflectances show a drift greater than 0.1% full scale.

9. Calculations

NOTE 6: The use of the three-filter system may result in small to significant differences from the values obtained using the full function for the tristimulus value *X* depending upon the spectral characteristics of the sample (*4*).

9.1 Calculate the tristimulus values *X*, *Y*, and *Z* for each specimen from:

$$X = 0.78341\ R_x + 0.19732\ R_z$$
$$Y = R_y$$
$$Z = 1.18232\ R_z$$

or by using the integration tables in ASTM E308, "Standard Practice for Computing the Color of Object by Using the CIE System," for a spectrophotometer.

9.2 Calculate color in one of the following color space systems: (most instruments are equipped with microprocessors which do the necessary computational work).

9.2.1 Hunter *L*, *a*, *b*. Calculate Hunter color values from:

$$L = 100\ (Y/Y_0)^{1/2}$$
$$a = K_a\ (X/X_0 - Y/Y_0)/(Y/Y_0)^{1/2}$$
$$b = K_b\ (Y/Y_0 - Z/Z_0)/(Y/Y_0)^{1/2}$$

Constants for the above equations for illuminant *C*/2 are $X_0 = 98.073$, $Y_0 = 100$, $Z_0 = 118.232$, $K_a = 175.0$, and $K_b = 70.0$.

If desired, calculate color difference from:

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

9.2.2 *CIE L*, a*, b** (*CIELAB*). Calculate CIELAB color values from: (preferred)

$$L^* = 116\ (Y/Y_0)^{1/3} - 16$$
$$a^* = 500\ [(X/X_0)^{1/3} - (Y/Y_0)^{1/3}]$$
$$b^* = 200\ [(Y/Y_0)^{1/3} - (Z/Z_0)^{1/3}]$$

where: X/X_0, Y/Y_0, and $Z/Z_0 > 0.01$. The constants X_0, Y_0, and Z_0 are given in paragraph 9.2.1. If desired, calculate color difference from:

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

9.2.3 L*, C^*, h. Calculate CIELAB color values as in paragraph 9.2.2. Then calculate chroma (C^*) and hue angle (h) from:

$$C^* = (a^{*2} + b^{*2})^{1/2}$$
$$h = \arctan (b^*/a^*)$$

If desired, calculate color difference from:

$$\Delta E^* \text{ (CMC)} = \text{cf}[(\Delta L^*/lS_L)^2 + (\Delta C^*/cS_c)^2 + (\Delta H^*/S_H)^2]^{1/2}$$

where:

l = 2.0 (other values of l may be required, for best correlation with visual assessment, in cases where the surface characteristics differ or for dark samples; see ref. *2*).

for $L^* > 16$: $S_L = 0.040975\ L^*/(1 + 0.01765\ L^*)$
for $L^* \leq 16$: $S_L = 0.511$
$S_C = [(0.0638\ C^*)/(\ 1 + 0.0131\ C^*)] + 0.638$
$S_H = (FT + 1 - F)\ S_C$
$\Delta H^* = [\Delta E^{*2} - \Delta C^{*2} - \Delta L^{*2}]^{1/2}$
For small color differences away from the achromatic axis: $\Delta H^* = 2[C^*_{std}C^*_{sam}]^{1/2}\sin[\Delta h/2]$

cf is a "commercial factor" (*5*) which adjusts all axes of the CMC volume to create a volume of acceptance for commercial use. After such adjustment, all ΔE^* (CMC) values equal to or less than 1.0 are considered to be commercially acceptable.

where:

$F = [(C^*)^4/(C^{*4} + 1900)]^{1/2}$
$T = 0.36 + \text{abs}\ [0.4 \cos (35 + h)]$

unless h is between 164° and 345°, then

$T = 0.56 + \text{abs}\ [0.2 \cos (168 + h)]$

For ΔE^*94, use the following:

$$\Delta E^*_{94} = \left[\left(\frac{\Delta L^*}{K_L S_L} \right)^2 + \left(\frac{\Delta C^*_{ab}}{K_C S_C} \right)^2 + \left(\frac{\Delta H^*_{ab}}{K_H S_H} \right)^2 \right]^{0.5}$$

Weighting functions S_L, S_C, S_H adjust the total color difference equation to account for variation in perceived color difference magnitude with variation in the color standard location in color space.

$S_L = 1$

$S_C = 1 + 0.045C^*_{ab}$

$S_H = 1 + 0.015C^*_{ab}$

Parametric factors K_L, K_C, K_H are correction terms for variation in perceived color difference component sensitivity with variation in experimental conditions. These parametric factors may be defined by industry groups to correspond to typical experimental conditions for that industry.

9.2.4 *Dominant wavelength, purity, luminosity*. Calculate the trichromatic coefficients for each specimen from:

$x = X/(X+Y+Z)$ and $y = Y/(X+Y+Z)$.

Using Hardy's "Handbook of Colorimetry" (*3*) or equivalent computer program, determine the dominant wavelength and excitation purity from the trichromatic coefficients. Luminosity is equal to the *Y* value.

10. Report

10.1 Report the average values and standard deviations for the color system used.

10.2 Report that the tests were made in accord with this method.

10.3 Identify the sample type and surface tested (top or bottom).

10.4 Identify the standard used by its source, number, and reference primary standard. Also report the color scale values for the standard used.

10.5 Identify the instrument used by manufacturer's name and model number.

10.6 Report the value of cf coefficient used when ΔE^* (CMC) is reported.

11. Precision

11.1 The repeatability and reproducibility values listed below are derived from reports 45 through 52 of the Collaborative Reference Program on Color and Appearance conducted by Collaborative Testing Services, Inc., using near-white papers. Approximately 30 laboratories participated and each laboratory reported results for 8 individual tests.

	Repeatability within laboratories	*Reproducibility between laboratories*
L	0.43	1.83
a	0.32	0.91
b	0.43	1.26
ΔL		0.68
Δa		0.45
Δb		0.61

11.2 The repeatability values for luminosity, dominant wavelength, and purity are based on results for three different papers tested at five laboratories. Those for reproducibility are for three papers tested at 45 laboratories.

	Repeatability within laboratories	*Reproducibility between laboratories*
Luminosity,%	1.5	2.5
Dominant wavelength, nm	2.0	5.0
Purity,%	1.0	2.0

11.3 Repeatability and reproducibility are estimates of the maximum difference (at 95%) which should be expected when comparing two test results from materials similar to those described above under similar test conditions. These estimates may not be valid for different materials or testing conditions. The reader should be cautioned that these values are based on actual/mill/laboratory measurements with procedures which may not conform to this method. This information is given as an estimate of the variation in 45/0 color testing that exists across the industry.

12. Keywords

Paper, Paperboard, Color, Spectrometer, Photometers, Tristimulus values, Reflectance, Dominant wavelength, Luminosity, Colorimetry

13. Additional information

13.1 Effective date of issue: To be assigned.

13.2 Previous issues of this method may have permitted more than one geometry, may have limited the method to white or near-white papers, or may have defined only one or two color space systems. This revision restricts the method to instruments having the geometry characteristic defined in paragraph 4.3, eliminates restrictions based on sample color, and defines all of the presently common color space systems.

13.3 The 2002 revision provided numerous enhancements, adds the CIE delta E* 94 equations, and corrects the CMC color difference. This version contains a revision to the description of calibration standards. The 2013 version contains only editorial changes.

Literature cited

1. Hunter, R.S., “Tests for uniformity of 45°0° Reflectometers,” *J. Opt. Soc. America* **53**:390-393 (1963).
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5. AATCC 173 “CMC: Calculation of Small Color Differences for Acceptability.”

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TAPPI T 1215 “The Determination of Instrumental Color Differences.”

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Your comments and suggestions on this procedure are earnestly requested and should be sent to the TAPPI Standards Department.

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