



*Pulp, paper and board*

## Basic equations for optical properties

### 0 Introduction

This SCAN-test guideline is a revision of SCAN-G 5:94. The major changes are:

- Consideration has been given to the fact that many SCAN-test methods have been withdrawn in favour of ISO Standards.
- The clause *Definitions* has been extended and the definitions are placed in a special annex, Annex A.
- Some of the symbols have been replaced in order to avoid the use of the same symbol for different quantities. One exception is  $k$  which is used in different meanings in Eqs. [2]–[5] and [12]–[13], and in Eqs. [22] and [24]. The symbol  $k$  is retained since it is established in both situations. Another exception is  $W$  which has different meanings in Eqs. [6]–[7] and in Eqs. [40]–[47]. The symbol  $w$  is used for grammage in Eqs. [17], [21] and [23] although it might be confused with the suffix  $w$  meaning white in the symbols  $T_w$ ,  $R_{gw}$  and  $R_w$ .
- For clarity, the use of suffixes has been extended.
- It is emphasised that reflectance factors, although they are often reported as percentages, are quantities on a scale from zero to unity for the perfect reflecting diffuser. The scale from zero to unity is also emphasised for opacity in Eqs. [14]–[15].
- The section on the calculation of tristimulus values now includes the calculation from reflectance factor values measured at 10 nm and 20 nm intervals.
- Weighting factors for the calculation of ISO brightness are now tabled also for  $\Delta\lambda = 20$  nm.
- The section on dominant wavelength and excitation purity has been rearranged in order to improve the clarity.
- The equations for the approximate calculations of dominant wavelength and excitation purity for fillers and pigments have been considered obsolete and have been excluded.

### 1 Scope

This SCAN-test guideline provides a summary of the equations used for determining the optical properties of pulp, paper and board. It should be used in conjunction with the particular Methods describing the determinations of the properties desired.

This guideline provides the information necessary for those engaged in development of software for computation of optical properties in accordance with current ISO standards and SCAN-test methods.

### 2 References

The following standards are normative in the application of this guideline:

ISO/CIE 10526:1999 CIE standard illuminants for colorimetry

ISO/CIE 10527:1991 CIE Standard colorimetric observers

ASTM E308:99 Standard method for computing the colors of objects by using the CIE system

CIE Technical Report 15.2 Colorimetry, 1986

This guideline is intended for use together with the ISO standards and SCAN-test methods listed in clause 16.

Note that within these ISO standards, ISO 2469 is considered to be the primary standard to which all the others are related.

### 3 Definitions

Important definitions are included in the clause where they belong. A comprehensive list of definitions that apply for the purpose of this guideline are found in Annex A. The definitions given are those published in the ISO standards or other documents indicated.

### 4 Colour appearance, tristimulus values

It is important to note that colour is a feature of human perception and cannot therefore be measured. Colour can however be described in terms of different attributes (lightness, redness, saturation etc). Psychometric scales and systems of alphanumeric notations have been developed purely on the basis of perceptual judgements to provide a means of locating colours in a three-dimensional colour space.

Physically, it is only possible to measure the intensity of the radiation which is the stimulus giving rise to the perception of colour. For pulp, paper and board, it is assumed that the sample is illuminated diffusely and that the viewing direction is normal to the surface of the sample. The stimulus, i.e. the spectral radiation flux  $\Phi_{\text{refl}}(\lambda)$ , reflected from the sample in the normal direction is proportional to the product of the incident spectral radiation flux  $\Phi_{\text{in}}(\lambda)$  falling upon the surface and the spectral reflectance factor  $R(\lambda)$  of the surface.

$$\Phi_{\text{refl}}(\lambda) = r \cdot R(\lambda) \cdot \Phi_{\text{in}}(\lambda) \quad [1]$$

where

$r$  is the ratio of the solid angle of the detection cone to the solid angle of the hemisphere ( $2\pi$  steradians).

In order to establish some connection with the visual experience, it is essential to realise that any colour percept may be produced by the mixing of three reference colour stimuli in a generalised colour matching experiment. A requirement is that the colour of none of the reference stimuli can be produced by mixing the other two. The values to which the fluxes of the reference stimuli have to be adjusted to make a perfect colour match of a test stimulus are described by the tristimulus values for the test stimulus. In colorimetry according to CIE (Commission Internationale d'Eclairage), the test stimuli are called  $X$ ,  $Y$  and  $Z$  or  $X_{10}$ ,  $Y_{10}$  and  $Z_{10}$ . These are adapted to colour matching experiments where the fields of view were  $2^\circ$  and  $10^\circ$  respectively. The tristimulus values for a specific test stimulus are evaluated for the CIE 1931 Standard Colorimetric Observer for the case of the  $2^\circ$  field of view and the tristimulus values are denoted  $X$ ,  $Y$ ,  $Z$ . Correspondingly, the CIE 1964 Supplementary Standard Colorimetric Observer is used in the case of the  $10^\circ$  field of view and the tristimulus values are denoted  $X_{10}$ ,  $Y_{10}$ ,  $Z_{10}$ .

The tristimulus values  $X$ ,  $Y$ ,  $Z$  for an object, which is reflective and may also be luminescent and which is illuminated by a chosen illuminant,  $S(\lambda)$ , are defined as:

$$\begin{aligned} X &= k \cdot \int R(\lambda) \cdot S(\lambda) \cdot \bar{x}(\lambda) \cdot d\lambda \\ Y &= k \cdot \int R(\lambda) \cdot S(\lambda) \cdot \bar{y}(\lambda) \cdot d\lambda \\ Z &= k \cdot \int R(\lambda) \cdot S(\lambda) \cdot \bar{z}(\lambda) \cdot d\lambda \end{aligned} \quad [2]$$

where

$$k = \frac{100}{\int S(\lambda) \cdot \bar{y}(\lambda) \cdot d\lambda} \quad [3]$$

and

$R(\lambda)$  is the spectral reflectance factor (or spectral radiance factor) of the material (on a scale from zero to unity for the perfect reflecting diffuser);  
 $S(\lambda)$  is the relative spectral power of the chosen illuminant;  
 $\bar{x}(\lambda)$ ,  $\bar{y}(\lambda)$ ,  $\bar{z}(\lambda)$  are the three colour matching functions of the CIE 1931 Standard Colorimetric Observer.

Note that the factor 100 in Eq. [3] is not a conversion to percentage units. It defines the scale for the tristimulus values.

If the material fluoresces and any type of fluorescence can be expected, the relative spectral power of the light source of the instrument and  $S(\lambda)$  have to be the same. However, in special cases, reliable measurements can be made although this is only approximately true. One such case is when the only fluorescent component is a Fluorescent Whitening Agent (FWA). Here the most important property of the light source is the relation between its energy in the excitation band (mainly UV radiation) and the emission band (blue end of the visible spectrum) of the FWA.

Since  $S(\lambda)$  and the colour matching functions  $\bar{x}(\lambda)$ ,  $\bar{y}(\lambda)$ ,  $\bar{z}(\lambda)$  are defined for only a limited number of wavelengths  $\lambda_i$ , the tristimulus values are obtained by summation instead of integration. Equidistant  $\lambda_i$ -values are assumed. The wavelength pitch is denoted  $\Delta\lambda$ . For the CIE 1931 Standard Observer, Eq. [2] modifies to:

$$\begin{aligned} X &= k \cdot \sum_i R(\lambda_i) \cdot S(\lambda_i) \cdot \bar{x}(\lambda_i) \cdot \Delta\lambda \\ Y &= k \cdot \sum_i R(\lambda_i) \cdot S(\lambda_i) \cdot \bar{y}(\lambda_i) \cdot \Delta\lambda \\ Z &= k \cdot \sum_i R(\lambda_i) \cdot S(\lambda_i) \cdot \bar{z}(\lambda_i) \cdot \Delta\lambda \end{aligned} \quad [4]$$

where

$$k = \frac{100}{\sum_i S(\lambda_i) \cdot \bar{y}(\lambda_i) \cdot \Delta\lambda} \quad [5]$$

In the corresponding calculation of  $X_{10}$ ,  $Y_{10}$ ,  $Z_{10}$  for the CIE 1964 Supplementary Standard Observer (10° observer), the colour matching functions  $\bar{x}(\lambda_i)$ ,  $\bar{y}(\lambda_i)$  and  $\bar{z}(\lambda_i)$  in Eqs. [4]–[5] are replaced by  $\bar{x}_{10}(\lambda_i)$ ,  $\bar{y}_{10}(\lambda_i)$  and  $\bar{z}_{10}(\lambda_i)$ .

The bandwidth of the spectrophotometer is the wavelength interval surrounding the nominal wavelength of the monochromator within which the sensitivity of the instrument exceeds half the sensitivity at the nominal wavelength. In the ISO standards, the bandwidth is considered to be equal to the wavelength pitch  $\Delta\lambda$  and the sensitivity is considered to be a triangular function of wavelength.

For  $\Delta\lambda$ -values up to 5 nm, the CIE tables for  $\bar{x}(\lambda)$ ,  $\bar{y}(\lambda)$ ,  $\bar{z}(\lambda)$  and  $\bar{x}_{10}(\lambda)$ ,  $\bar{y}_{10}(\lambda)$ ,  $\bar{z}_{10}(\lambda)$  given in ISO/CIE 10527 shall be used, together with the tables for the appropriate illuminant given in ISO 10526 or CIE publ. 15.2. The tables are provided for  $\Delta\lambda$ -values of 1 nm and 5 nm. For other  $\Delta\lambda$ -values below 5 nm a proper table of interpolated values has to be calculated.

*Note* – Tables for the  $\Delta\lambda$ -value of 1 nm is available from CIE on disk (CIE Disk D001 and CIE Disk D002). The disks can be obtained from CIE Central Bureau, Kegelgasse 27, A-1030 Wien, Austria.

For  $\Delta\lambda$ -values exceeding 5 nm, the bandwidth of the spectrophotometer affects the shape of the  $R(\lambda)$  curve such that steep slopes cannot be rendered with sufficient precision. To neutralise this influence to some extent, ASTM has prepared tables of special weighting functions. To calculate the tristimulus values  $X$ ,  $Y$ ,  $Z$  and  $X_{10}$ ,  $Y_{10}$ ,  $Z_{10}$  for  $\Delta\lambda$ -values of 10 nm and 20 nm, the following equations shall be used:

$$\begin{aligned} X &= \sum_i R(\lambda_i) \cdot W_X(\lambda_i) \\ Y &= \sum_i R(\lambda_i) \cdot W_Y(\lambda_i) \\ Z &= \sum_i R(\lambda_i) \cdot W_Z(\lambda_i) \end{aligned} \quad [6]$$

and

$$\begin{aligned} X_{10} &= \sum_i R(\lambda_i) \cdot W_{10,X}(\lambda_i) \\ Y_{10} &= \sum_i R(\lambda_i) \cdot W_{10,Y}(\lambda_i) \\ Z_{10} &= \sum_i R(\lambda_i) \cdot W_{10,Z}(\lambda_i) \end{aligned} \quad [7]$$

where  $W_X$ ,  $W_Y$ ,  $W_Z$  and  $W_{10,X}$ ,  $W_{10,Y}$ ,  $W_{10,Z}$  are called tristimulus weighting factors, and the values tabled in ASTM E308:99 for different combinations of standard observers and standard illuminants shall be used. Note that  $R(\lambda_i)$  is on a scale from zero to unity for the perfect reflecting diffuser.

As an alternative to the determination from spectrophotometric data, the tristimulus values can be determined from measurements with a three-filter instrument such as the Zeiss Elrepho, where the combination of the spectral properties of the lamps, the optics, the filters and the detector are chosen by the manufacturer to give reflectance factors which are weighted averages over three broad wavelength bands. The measured values are designated  $R_x$ ,  $R_y$  and  $R_z$  and are on a scale from zero to unity for the perfect reflecting diffuser, although they are usually reported as percentages. Thereafter,  $X$ ,  $Y$  and  $Z$  are calculated as follows:

**C-illuminant, 2° observer**

$$\begin{aligned} X &= 78,321 R_x + 19,753 R_z \\ Y &= 100 R_y \\ Z &= 118,232 R_z \end{aligned} \quad [8]$$

**D65-illuminant, 10° observer**

$$\begin{aligned} X_{10} &= 76,841 R_x + 17,970 R_z \\ Y_{10} &= 100 R_y \\ Z_{10} &= 107,304 R_z \end{aligned} \quad [9]$$

The inverse relationships are

**C-illuminant, 2° observer**

$$\begin{aligned} R_x &= (X - 0,16707 Z) / 78,321 \\ R_y &= Y / 100 \\ R_z &= Z / 118,232 \end{aligned} \quad [10]$$

**D65-illuminant, 10° observer**

$$\begin{aligned} R_x &= (X_{10} - 0,16747 Z_{10}) / 76,841 \\ R_y &= Y_{10} / 100 \\ R_z &= Z_{10} / 107,304 \end{aligned} \quad [11]$$

**5 Reflectance factor, Y-value, opacity, transmittance**

5.1 *Reflectance factor, R* – Ratio of the radiation reflected by a body to that reflected by the perfect reflecting diffuser under the same conditions of illumination and detection (ISO 2469, ISO 5631).

*Note 1* – The reflectance factor is expressed as a percentage.

*Note 2* – The reflectance factor is influenced by the backing if the body is translucent.

In ISO 2469 and all other standards or methods to which this guideline is related, it is specified that the illumination shall be diffuse and that the direction of detection shall be perpendicular to the surface of the specimen. There is no or considerably reduced irradiation from directions close to the direction of detection, since a so-called gloss-trap is also specified.

It is a primary requirement of all optical measurements relating to pulp, paper and board that the reflectance factor measurements be traceable to the perfect reflecting diffuser, which is the absolute standard. ISO 2469 specifies that a calibration procedure shall be adopted in which an IR3 reference standard supplied by an ISO/TC6 Authorized Laboratory (cf. ISO 4094) is used. The values assigned to this standard shall be traceable to the perfect reflecting diffuser via an IR2 reference standard supplied by a Standardizing Laboratory.

Although Note 1 above explicitly mentions the custom of reporting reflectance factors as percentages, it must be emphasised that a reflectance factor of e.g. 80 % means that  $R = 0,80$ .

5.2 *Intrinsic reflectance factor,  $R_{\infty}$*  – Reflectance factor of a layer or pad of material thick enough to be opaque, i.e. such that increasing the thickness of the pad by doubling the number of sheets leads to no change in the measured reflectance factor (ISO 2469).

*Reflectivity* is synonymous with intrinsic reflectance factor.

Values of the intrinsic reflectance factor are often expressed as percentages.

5.3 *Luminous reflectance factor,  $R_v$*  – Reflectance factor defined with reference to the CIE illuminant C and the CIE 1931 colour matching function  $\bar{y}(\lambda)$ , and corresponding to the attribute of visual perception of the reflecting surface (ISO 2471).

This term is analogous to the CIE term "luminance factor", except that CIE does not define the illuminant.

The CIE definition refers to the  $V(\lambda)$  function which corresponds to the spectral sensitivity to light of the normal eye. This function is mathematically the same as the  $\bar{y}(\lambda)$  function for the CIE 1931 (2°) observer. To provide a value which takes into account the appearance of the material in daylight, the reflectance is thus weighted with respect to the energy distribution of the C-illuminant and the spectral sensitivity to light of the normal eye.

$$R_v = k \sum_i R(\lambda_i) \cdot S_C(\lambda_i) \cdot V(\lambda_i) \cdot \Delta\lambda \quad [12]$$

where

$$k = \frac{1}{\sum_i S_C(\lambda_i) \cdot V(\lambda_i) \cdot \Delta\lambda} \quad [13]$$

$S_C(\lambda_i)$  is the energy distribution of the C-illuminant;

$V(\lambda_i)$  is the visual efficiency function which is identical to the CIE 1931 colour matching function  $\bar{y}(\lambda_i)$  for the  $Y$  tristimulus value.

When the measurement is made with a single sheet of the material over a black cavity, the luminance factor is designated  $R_{v,0}$ . The *intrinsic luminous reflectance factor* is designated  $R_{v,\infty}$ . When it can be unambiguously deduced from the context,  $R_{v,\infty}$  may be designated  $R_{\infty}$ .

5.4 *Y-value (C/2°)* – Tristimulus value  $Y$  in the CIEXYZ-system of a layer of material of such a thickness that there is no change in  $Y$  when the thickness is increased.

This shall be interpreted as being the tristimulus value  $Y$  of a layer of material of such a thickness that there is no change in the value when the thickness is doubled. CIE illuminant C is used in the determination of the  $Y$ -value.

The  $Y$ -value was in the withdrawn SCAN-P 8 defined as a quantity to be reported per se. Now, reference is made to ISO 5631. The  $Y$ -value is related to the *intrinsic luminous reflectance factor* as  $Y = 100 R_{v,\infty}$ .

5.5 *Opacity,  $\Omega$*  – Ratio of the single-sheet luminous reflectance factor,  $R_{v,0}$ , to the intrinsic luminous reflectance factor,  $R_{v,\infty}$ , of the same sample (ISO 2471).

The single-sheet reflectance factor is defined as the reflectance factor of a single sheet of paper with a black cavity as backing.

The opacity is calculated as:

$$\Omega = \frac{R_{v,0}}{R_{v,\infty}} \quad [14]$$

However, opacity is usually expressed as a percentage, i.e.:

$$\Omega = \frac{R_{v,0}}{R_{v,\infty}} \times 100 \% \quad [15]$$

Note that the use of  $R_{v,0}$  and  $R_{v,\infty}$  means that the two reflectance factors involved are weighted with respect to the C-illuminant and the  $\bar{y}(\lambda)$  function for the CIE 1931 (2°) observer. If the sample contains a fluorescent whitening agent (FWA), the measurements are here recommended to be made under the UV(C) condition as described in Annex B.

If luminance factor data are available for a given grammage,  $w_1$ , it is possible to predict the opacity of a sheet of the same furnish and structure at another arbitrary grammage,  $w_2$ , by application of the Kubelka-Munk theory. The equation is:

$$\Omega_{w_2} = (A - 1) / (A - R_{v,\infty}^2) \quad [16]$$

where

$$A = \left[ R_{v,\infty} \left( 1 - R_{v,0,w_1} R_{v,\infty} \right) / \left( R_{v,\infty} - R_{v,0,w_1} \right) \right]^{w_2/w_1} \quad [17]$$

and the reflectance factors are on a scale from zero to unity for the perfect reflecting diffuser.

It may be necessary to make this correction if it is desired to calculate the mean opacity from measurements on a number of sheets having slightly different grammages.

5.6 *Transmittance,  $\tau$* , – Ratio of the transmitted to the incident flux.

*Transmittance from reflectance factor measurement,  $T$*  – Transmittance calculated from reflectance factor data determined under the conditions of illumination and detection specified in ISO 2469 (ISO 22891 in preparation).

The transmittance is calculated from  $R_0$  and  $R_\infty$  or from  $R$ ,  $R_0$  and  $R_w$  using one of the equations:

$$T = \sqrt{\left( \frac{1}{R_\infty} - R_0 \right) (R_\infty - R_0)} \quad [18]$$

$$T = \sqrt{\left( \frac{1}{R_w} - R_0 \right) (R - R_0)} \quad [19]$$

where  $R$  is the reflectance factor of a single sheet over a white backing with the reflectance factor  $R_w$ . All reflectance factors are on a scale from zero to unity for the perfect reflecting diffuser.

## 6 Diffuse blue reflectance factor (ISO brightness)

6.1 *Diffuse blue reflectance factor (ISO brightness),  $R_{457}$*  – Intrinsic radiance factor measured with a reflectometer having the characteristics described in ISO 2469, equipped with a filter or corresponding function having an effective wavelength of 457 nm and a width at half height of 44 nm, and adjusted so that the UV-content of the illumination incident upon the test piece corresponds to that of the CIE illuminant C (ISO 2470:1999).

The diffuse blue reflectance factor (ISO brightness) shall be calculated from reflectance factor data according to a special set of weighting factors, *Table 1*. The calculated brightness is usually designated  $R_{457}$ :

$$R_{457} = \frac{\sum_i R(\lambda_i) \cdot F(\lambda_i)}{\sum_i F(\lambda_i)} \quad [20]$$

The symbol  $R_B$  may be used instead of  $R_{457}$ . If the sample is non-fluorescent, the C-illuminant requirement can be relaxed.

*Table 1. Weighting factors for the calculation of ISO brightness. In ISO 2470, values of  $F(\lambda_i)$  for  $\Delta\lambda = 5 \text{ nm}$  are also given.*

Wavelength $\lambda_i$ nm	$F(\lambda_i)$ for $\Delta\lambda=10 \text{ nm}$ , arbitrary units	$F(\lambda_i)$ for $\Delta\lambda=20 \text{ nm}$ , arbitrary units
380	0,0	0,0
390	0,0	
400	1,0	1,0
410	6,7	
420	18,2	18,2
430	34,5	
440	57,6	57,6
450	82,5	
460	100,0	100,0
470	88,7	
480	53,1	53,1
490	20,3	
500	5,6	5,6
510	0,3	
520	0,0	0,0
Sum	468,5	235,5

6.2 *D65 diffuse blue reflectance factor (D65-brightness)  $R_{457,D65}$*  – Diffuse blue radiance factor measured when the UV-content of the irradiation has been adjusted as specified in ISO 11475 to correspond to the CIE standard illuminant D65.

For the determination of  $R_{457,D65}$ , the instrument must be adjusted so that the UV-content of the illumination matches the D65-illuminant. Thereafter the spectral radiance factor is measured and the D65-brightness is calculated using Eq. [20].

## 7 Light-scattering and light-absorption coefficients

7.1 *Light-scattering coefficient,  $s$*  – The fraction of the diffuse light flux that is reflected on its passage through an infinitesimally thin layer of material. This may be related to a finite layer using the Kubelka-Munk theory which takes into account the grammage of the material, so that  $s$  has the units  $\text{m}^2/\text{kg}$  (ISO 9416).

$s$  is one of the two parameters of the Kubelka-Munk equations. When  $s$  is determined as a spectral quantity, it is denoted  $s(\lambda)$ .

It is determined according to ISO 9416 as a weighted average for the C illuminant and the colour matching function  $\bar{y}(\lambda)$  for the CIE 1931 ( $2^\circ$ ) observer, and is denoted  $s_v$ . If the information in the suffix can be unambiguously deduced from the context, the suffix may be omitted.

7.2 *Light-absorption coefficient, k* – The fraction of the diffuse light flux that is absorbed on its passage through an infinitesimally thin layer of material. This may be related to a finite layer using the Kubelka-Munk theory which takes into account the grammage of the material, so that  $k$  has the units  $m^2/kg$  (ISO 9416).

$k$  is one of the two parameters of the Kubelka-Munk equations. When  $k$  is determined as a spectral quantity, it is denoted  $k(\lambda)$ .

It is determined according to ISO 9416 as a weighted average for the C illuminant and the colour matching function  $\bar{y}(\lambda)$  for the CIE 1931 (2°) observer, and is denoted  $k_v$ . If the information in the suffix can be unambiguously deduced from the context, the suffix may be omitted.

7.3 *Conditions for the Kubelka-Munk theory* – The Kubelka-Munk theory is based on a number of assumptions. These may be summarised as:

- 1 The sample is a turbid medium forming a plane layer (perpendicular to the  $z$ -axis) of constant, generally finite, thickness and large enough for edge effects to be negligible
- 2 The sample is homogeneous in the respect that the optical inhomogenities (causing the scattering of the radiation) are incomparably smaller than the thickness of the layer and are uniformly distributed in the material
- 3 The medium of the material is the same as the medium from which the radiation enters the material (generally air)
- 4 One side of the layer is irradiated (the side having its normal in the  $+z$  -direction)
- 5 The reflected or transmitted radiation is not again reflected to the specimen unless a backing, reflecting the transmitted radiation in a defined manner, is used
- 6 Both irradiation and detection are monochromatic and of the same wavelength
- 7 The irradiation is perfectly diffuse or parallel having an angle of incidence of  $60^\circ$  from the normal
- 8 The scattering in the material is isotropic, i.e. it is independent of the angle between the incident and scattering directions.

It is required that these assumptions are not violated in such a way that the results are significantly affected. One example is that the irradiation need not be monochromatic provided that the sample is non-fluorescent. If the material contains a fluorescent whitening agent (FWA), it is a requirement of ISO 9416 that a 420 nm cut-off filter be placed in the light beam to ensure that the fluorescence effect is eliminated.

Two other requirements are: (i) the difference between the reflectance factors of the sample measured under different conditions, which are used in the equations below, must be sufficiently large, and (ii) the reflectance factor of the sample must be sufficiently high.

7.4 *Calculations of  $s$  and  $k$*  – In the Kubelka-Munk theory,  $s$  and  $k$  are calculated from reflectance data. However, in common practice the *reflectance factor* is used instead of the *reflectance*. This is often an acceptable approximation.

In Eqs. [21]-[26] all reflectance factors are on a scale from zero to unity for the perfect reflecting diffuser.

The spectral light-scattering coefficient is calculated as:

$$s(\lambda) = \frac{R_\infty(\lambda)}{w[1 - R_\infty^2(\lambda)]} \ln \frac{R_\infty(\lambda)[1 - R_0(\lambda)R_\infty(\lambda)]}{R_\infty(\lambda) - R_0(\lambda)} \quad [21]$$

where

- $s(\lambda)$  is the light-scattering coefficient, in square metre per kilogram;
- $w$  is the grammage of the conditioned sheet, in kilogram per square metre (*Caution:* Grammage is usually reported in *gram* per square metre);
- $R_0(\lambda)$  is the spectral reflectance factor (black backing);
- $R_\infty(\lambda)$  is the intrinsic spectral reflectance factor.

The spectral light-absorption coefficient is calculated as:

$$k(\lambda) = s(\lambda)[1 - R_\infty(\lambda)]^2 / 2R_\infty(\lambda) \quad [22]$$

where

- $k(\lambda)$  is the light-absorption coefficient, in square metre per kilogram.

The light-scattering and light-absorption coefficients are, as indicated in these equations, dependent on the wavelength. When non-spectral values are desired, the calculations are usually based on the luminance factors  $R_{v,0}$  and  $R_{v,\infty}$ , which means that the data are averaged over the visible spectrum using a product of a daylight irradiation spectrum (the C-illuminant) and the colour matching function  $\bar{y}(\lambda)$  for the CIE 1931 (2°) observer as weighting function. The light-scattering and light-absorption coefficients are calculated as:

$$s_v = \frac{R_{v,\infty}}{w(1 - R_{v,\infty}^2)} \ln \frac{R_{v,\infty}(1 - R_{v,0}R_{v,\infty})}{R_{v,\infty} - R_{v,0}} \quad [23]$$

$$k_v = s_v(1 - R_{v,\infty})^2 / 2R_{v,\infty} \quad [24]$$

If only a single sheet of paper is available, no value for  $R_\infty$  is available in Eqs. [21]-[24]. However, a value for  $R_\infty$  can be determined if measurements are made over two different backings, preferably black and white.  $R_\infty$  is then calculated according to the equation:

$$R_\infty = a - (a^2 - 1)^{1/2} \quad [25]$$

where

$$a = \frac{1}{2} \frac{(R_{gw} - R_{gs})(1 + R_w R_s) - (R_w - R_s)(1 + R_{gw} R_{gs})}{R_s R_{gw} - R_w R_{gs}} \quad [26]$$

and

- $R_{gs}$  is the reflectance factor of the black backing;
- $R_{gw}$  is the reflectance factor of the white backing;
- $R_s$  is the reflectance factor of a single sheet against the backing  $R_{gs}$ ;
- $R_w$  is the reflectance factor of a single sheet against the backing  $R_{gw}$ .

$R_{gs}$ ,  $R_{gw}$ ,  $R_s$  and  $R_w$  may be spectral reflectance factors or luminance factors.

In Eqs. [21]-[26], the difference between the reflectance factors measured under different conditions must be sufficiently large, depending on the accuracy required and on the noise level of the instrument. A satisfactory accuracy is usually obtained when the opacity of the sheet does not exceed 95 %. To lower the opacity of a dark pulp, the sheets must be made to a lower grammage than is usual. Very thin sheets are, however, sometimes too inhomogeneous, and in addition the requirement of the Kubelka-Munk theory that there shall be multiple reflections within the material may not be met. For mechanical pulp, the lower limit of grammage is about 30 g/m<sup>2</sup>, and for bleached chemical pulps, the lower limit is about 50 g/m<sup>2</sup>.

## 8 Chromaticity coordinates

The chromaticity coordinates  $x$  and  $y$  for the CIE 1931 Standard Observer are defined as:

$$\begin{aligned} x &= X/(X + Y + Z) \\ y &= Y/(X + Y + Z) \end{aligned} \quad [27]$$

The corresponding coordinate  $z$  is superfluous since  $z \equiv 1 - x - y$ .

Correspondingly the chromaticity coordinates  $x_{10}$  and  $y_{10}$  for the CIE 1964 Supplementary Standard Observer are defined as:

$$\begin{aligned} x_{10} &= X_{10}/(X_{10} + Y_{10} + Z_{10}) \\ y_{10} &= Y_{10}/(X_{10} + Y_{10} + Z_{10}) \end{aligned} \quad [28]$$

## 9 Dominant wavelength, excitation purity

9.1 *Dominant wavelength*,  $\lambda_D$  – Wavelength of the monochromatic stimulus which can be additively mixed with a chosen achromatic stimulus so that the mixed stimulus matches the stimulus from the sample (cf. CIE publ. 17.4, 845-03-44).

In *Figure 1* the loci of the sample stimulus and an achromatic stimulus have been plotted in the CIE  $xy$  chromaticity diagram. Since additive colour mixings are represented as straight lines in this diagram, the definition means that the locus of the dominant wavelength is found if a straight line from the achromatic locus  $(x_n, y_n)$  through the stimulus locus  $(x_s, y_s)$  is extended to the spectral locus  $(x_D, y_D)$ . The wavelength having the coordinates  $(x_D, y_D)$  is  $\lambda_D$ .

Stimuli with a purplish appearance have no dominant wavelength. For these samples the complementary wavelength  $\lambda_C$  may be used.  $\lambda_C$  is defined by the point of intersection of the spectral locus and the line used to determine the dominant wavelength but extended in the opposite direction. In order to obtain accurate values of  $\lambda_D$  (and  $\lambda_C$ ) the chromaticity coordinates of the stimulus must differ significantly from the chromaticity coordinates of the achromatic stimulus.

9.2 *Excitation purity*,  $p_e$  – Ratio of the distance from the point representing the achromatic stimulus  $(x_n, y_n)$  to the colour stimulus considered  $(x_s, y_s)$  to the distance from the point representing the achromatic stimulus  $(x_n, y_n)$  to the point on the spectrum locus representing the dominant wavelength  $(x_D, y_D)$  (cf. CIE publ. 17.4, 845-03-48).

$p_e$  is thus defined in terms of figure 1 as  $p_e = d_1/d_2$ , where  $d_1$  is the distance between  $(x_n, y_n)$  and  $(x_s, y_s)$  and  $d_2$  is the distance between  $(x_n, y_n)$  and  $(x_D, y_D)$ . The excitation purity is usually reported as a percentage.

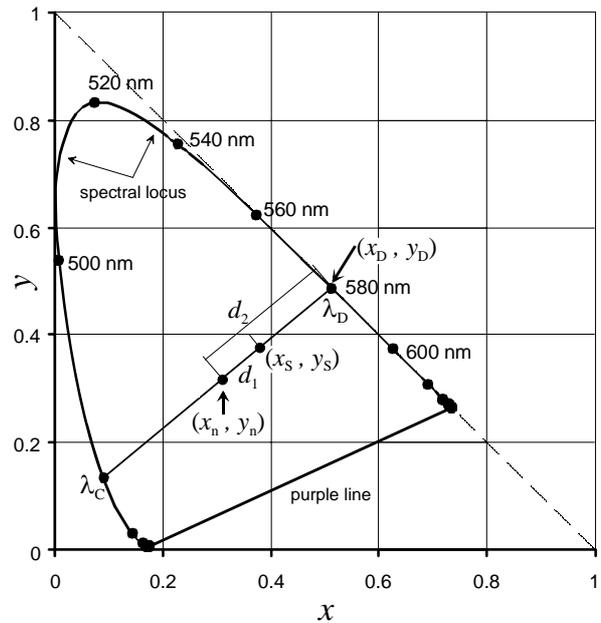


Figure 1. The CIE  $xy$  chromaticity diagram. In the diagram are shown the loci of CIE illuminant  $C$   $(x_n, y_n)$ , a sample  $(x_s, y_s)$ , the dominant wavelength  $\lambda_D$  of the sample at the coordinates  $(x_D, y_D)$  and the complementary wavelength  $\lambda_C$ .

9.3 Calculation of  $\lambda_D$  and  $p_e$  – Within SCAN-test and ISO/TC 6 there is no standardized procedure for how to calculate  $\lambda_D$  and  $p_e$  for an arbitrary  $\lambda_D$  within the visible spectrum. Section 9.4 presents approximations used for newsprint shade. These approximations have been developed in order to adapt to the limited computer capacity of older instruments. In the future this special case will be replaced by a general calculation procedure. Newer instruments usually calculate  $\lambda_D$  and  $p_e$  for an arbitrary  $\lambda_D$ .

9.4 Approximation used for newsprint shade – CIELAB colour ( $C/2^\circ$ ) coordinates (see clause 10) are recommended for the reporting of newsprint shade, but the  $(Y, \lambda_D, p_e)$ -values of the sample may also be used. The following equation was recommended in the now withdrawn SCAN-P 71:95 for dominant wavelengths in the narrow range from 570 nm to 580 nm. Other  $\lambda_D$ -values must be calculated according to the definition above.

$$\lambda_D = A + B M + C M^2 + D M^3 \quad [29]$$

where

$$M = (y_s - y_n) / (x_s - x_n) \quad [30]$$

and

$x_s$  and  $y_s$  are the  $C/2^\circ$  chromaticity coordinates of the newsprint sample;

$x_n$  and  $y_n$  are the  $C/2^\circ$  chromaticity coordinates of the perfect reflecting diffuser.

Numerically  $x_n$  and  $y_n$  are:

$$x_n = 0,31006; y_n = 0,31615$$

In order to obtain  $\lambda_D$  in nm, the following constants are used:

$$\begin{array}{ll} A = & 601,075 \\ B = & -35,4710 \end{array} \quad \begin{array}{ll} C = & 14,4225 \\ D = & -2,41788 \end{array}$$

Eq. [30] is not valid if  $x_s = x_n$ . The condition that these constants shall only be used within the range of  $\lambda_D$  from 570 nm to 580 nm means that  $1,7803 \geq M \geq 0,84199$ .

In the same situation, the recommended equation for excitation purity is:

$$p_e = \frac{\sqrt{(x_s - x_n)^2 + (y_s - y_n)^2}}{E + F \lambda_D + G \lambda_D^2 + H \lambda_D^3} \quad [31]$$

If  $\lambda_D$  is given in nm, the constants in this equation when the dominant wavelength is in the relatively narrow region from 570 nm to 580 nm are:

$$\begin{array}{ll} E = & 40,4558 \\ F = & -0,130132 \end{array} \quad \begin{array}{ll} G = & 8,95164 \times 10^{-5} \\ H = & 2,65050 \times 10^{-8} \end{array}$$

Note – The excitation purity is here given on a scale from zero to one for the pure spectral colour. If it is desired to express it as a percentage, the value given by Eq. [31] must be multiplied by 100.

## 10 CIELAB colour space coordinates

10.1 CIELAB colour ( $C/2^\circ$ ),  $(L^*, a^*, b^*)$  –  $L^*$ ,  $a^*$  and  $b^*$  values of the sample according to the CIELAB 1976 system, evaluated according to the CIE 1931 Standard Observer and the CIE illuminant C.

If the sample is fluorescent, the UV condition of the instrument must be adjusted to correspond to the CIE illuminant C, as described in ISO 2470.

$L^*$  is a measure of lightness. In the CIELAB representation,  $a^*$  is an approximate measure of the component on the red-green axis ( $a^* > 0$  is reddish and  $a^* < 0$  is greenish) and  $b^*$  is an approximate measure of the component on the yellow-blue axis ( $b^* > 0$  is yellowish and  $b^* < 0$  is bluish).

10.2 CIELAB colour ( $D65/10^\circ$ ),  $(L^*, a^*, b^*)$  –  $L^*$ ,  $a^*$  and  $b^*$  values of the sample according to the CIELAB 1976 system, evaluated according to the CIE 1964 Supplementary Standard Observer and the CIE standard illuminant D65.

If the sample is fluorescent, the UV condition of the instrument must be adjusted to correspond to the CIE illuminant D65, as described in ISO 11475.

10.3 Calculations – In the CIELAB system, the coordinate system is chosen so that  $a^* = 0$  and  $b^* = 0$  represent achromatic stimuli. If at the same time  $L^* = 100$ , then the stimulus corresponds to the perfect reflecting diffuser under the illuminant chosen. To achieve this, the tristimulus values for the perfect reflecting diffuser under the chosen illuminant have to be incorporated into the equations. These values are denoted  $X_n, Y_n, Z_n$  and  $X_{n,10}, Y_{n,10}, Z_{n,10}$  for the respective standard observers. The equations below are given for the  $2^\circ$  observer. The corresponding equations for the  $10^\circ$  observer are obtained by replacing  $X, Y, Z, X_n, Y_n$  and  $Z_n$  by  $X_{10}, Y_{10}, Z_{10}, X_{n,10}, Y_{n,10}$  and  $Z_{n,10}$ .

The CIE lightness  $L^*$  is calculated as:

$$L^* = \begin{cases} 116 \cdot (Y/Y_n)^{1/3} - 16 & Y/Y_n > 0,008856 \\ 903,3 \cdot (Y/Y_n) & Y/Y_n \leq 0,008856 \end{cases} \quad [32]$$

The  $a^*$  and  $b^*$  values of the CIELAB system are calculated as:

$$\begin{aligned} a^* &= 500 \cdot [f(X/X_n) - f(Y/Y_n)] \\ b^* &= 200 \cdot [f(Y/Y_n) - f(Z/Z_n)] \end{aligned} \quad [33]$$

where

$$f(\xi) = \begin{cases} \xi^{1/3} & \xi > 0,008856 \\ 7,787 \cdot \xi + 16/116 & \xi \leq 0,008856 \end{cases} \quad [34]$$

where  $\xi$  is  $X/X_n$ ,  $Y/Y_n$  or  $Z/Z_n$ . The required values of  $X_n$ ,  $Y_n$ ,  $Z_n$  and  $X_{n,10}$ ,  $Y_{n,10}$ ,  $Z_{n,10}$ , the tristimulus values for the perfect reflecting diffuser, for different illuminants are:

A-illuminant:	$X_n = 109,850$	$X_{n,10} = 111,144$
	$Y_n = 100$	$Y_{n,10} = 100$
	$Z_n = 35,585$	$Z_{n,10} = 35,200$
C-illuminant:	$X_n = 98,074$	$X_{n,10} = 97,285$
	$Y_n = 100$	$Y_{n,10} = 100$
	$Z_n = 118,232$	$Z_{n,10} = 116,145$
D65-illuminant:	$X_n = 95,047$	$X_{n,10} = 94,811$
	$Y_n = 100$	$Y_{n,10} = 100$
	$Z_n = 108,883$	$Z_{n,10} = 107,304$

The chromatic information in the  $a^*$  and  $b^*$  coordinates may also be expressed in polar coordinates  $C^*_{ab}$  and  $h_{ab}$  where the CIE 1976  $a$ ,  $b$  chroma  $C^*_{ab}$  is a correlate of chromaticness and is analogous to the excitation purity, and the CIE 1976  $a$ ,  $b$  hue-angle  $h_{ab}$  is a correlate of hue and is analogous to the dominant wavelength.  $C^*_{ab}$  and  $h_{ab}$  are calculated as:

$$C^*_{ab} = \sqrt{(a^*)^2 + (b^*)^2} \quad [35]$$

$$h_{ab} = \begin{cases} \arctan\left(\frac{b^*}{a^*}\right) \cdot \frac{180^\circ}{\pi} + \phi & a^* \neq 0 \\ 90^\circ & a^* = 0 \quad b^* > 0 \\ 270^\circ & a^* = 0 \quad b^* < 0 \\ \text{undefined} & a^* = 0 \quad b^* = 0 \end{cases} \quad [36]$$

where

$$\phi = \begin{cases} 0^\circ & b^* \geq 0 \quad \text{and} \quad a^* > 0 \\ 180^\circ & b^* \geq 0 \quad \text{and} \quad a^* < 0 \\ 360^\circ & b^* < 0 \quad \text{and} \quad a^* > 0 \\ 180^\circ & b^* < 0 \quad \text{and} \quad a^* < 0 \end{cases} \quad [37]$$

Since the value of the arctangent function corresponds to an angle in radians, the factor  $180^\circ/\pi$  has been inserted to convert to degrees which is the unit in which  $h_{ab}$  is

reported. The chosen values for  $\phi$  mean that  $h_{ab}$  has its zero value at the  $a^*$ -axis and that  $h_{ab}$  increases in the counter-clockwise direction. Mathematically  $h_{ab}$  is undefined when  $C^*_{ab} = 0$ . It is however recommended to report  $h_{ab}$  as undefined when  $C^*_{ab}$  is so small that the stimulus cannot be perceptually distinguished from an achromatic stimulus having the same  $L^*$ -value.

## 11 Colour differences in CIELAB

11.1 *Introduction* – Several colour-difference equations exist. However, none of these are standardized in any SCAN-test method or ISO standard within the pulp and paper sector. Here the most important equation is mentioned, but other colour difference measures such as the CIE 1994 ( $\Delta L^*$ ,  $\Delta C^*_{ab}$ ,  $\Delta H^*_{ab}$ ) colour-difference model,  $\Delta E^*_{94}$ , may be considered.

11.2 *CIELAB colour difference,  $\Delta E^*_{ab}$*  – Distance in the CIELAB colour space between two colour stimuli.

The CIELAB colour systems is constructed to be approximately uniform with respect to colour differences. However, it has to be noted that it is an approximation and allows neither for large colour differences nor exact comparisons of colour differences in different parts of the colour space.  $\Delta E^*_{ab}$  is used for applications in which the CIELAB system can be considered to be sufficiently uniform. The colour difference  $\Delta E^*_{ab}$  between two stimuli ( $L^*_1, a^*_1, b^*_1$ ) and ( $L^*_2, a^*_2, b^*_2$ ) is defined as

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad [38]$$

where

$$\begin{aligned} \Delta L^* &= L^*_2 - L^*_1 \\ \Delta a^* &= a^*_2 - a^*_1 \\ \Delta b^* &= b^*_2 - b^*_1 \end{aligned} \quad [39]$$

## 12 CIE-whiteness

12.1 *CIE-whiteness,  $W$*  – Measure of whiteness derived from the CIE tristimulus values determined under specified conditions, and expressed as whiteness units (ISO 11475, ISO 11476).

Under proper viewing conditions, CIE-whiteness is a correlate to perceived whiteness.

$W$  is usually derived from the CIE tristimulus values determined under the conditions specified in ISO 11475 or ISO 11476. The two ISO standards differ in that ISO 11475 prescribes an adjustment of the UV-content in the illumination to match the CIE-illuminant D65, a UV(D65) adjustment, together with a D65/10° computation, whereas ISO 11476 prescribes a corresponding adjustment to the CIE-illuminant C, a UV(C) adjustment, and a C/2° computation. If it cannot be unambiguously deduced from

the context, the observer and illuminant shall be specified as a suffix, e.g.  $W_{D65/10}$ . If the sample is fluorescent, the UV condition of the instrument must be correctly adjusted.

$W_{D65/10}$  with a UV content in the light source corresponding to illuminant D65 is recommended as outdoor daylight conditions (ISO 11475).  $W_{C/2}$  with a UV content in the light source corresponding to illuminant C is recommended as indoor daylight conditions (ISO 11476).

For more details concerning the UV-conditions, see Annex B. The CIE-whiteness value  $W$  is defined as:

$$W_{10} = Y_{10} + 800(x_{n,10} - x_{10}) + 1700(y_{n,10} - y_{10}) \quad [40]$$

for the 10° observer and

$$W = Y + 800(x_n - x) + 1700(y_n - y) \quad [41]$$

for the 2° observer, where  $x_{n,10}$ ,  $y_{n,10}$ ,  $x_n$  and  $y_n$  are the chromaticity coordinates for the perfect reflecting diffuser under the illumination considered and for the 10° observer and the 2° observer respectively. Values are given in Table 2.

The material is considered to be white provided that  $W$  lies within the limits given by:

$$40 < W_{10} < (5Y_{10} - 280) \quad [42]$$

or

$$40 < W < (5Y - 280) \quad [43]$$

12.2 *Green/red tint, CIE tint,  $T_w$*  – Measure of deviation from whiteness towards the green or red region, and expressed as tint units (ISO 11475, ISO 11476).

Under proper viewing conditions, a correlate to the perceived deviation from whiteness of the material towards the greenish or reddish regions.

Two tint values exist, analogous to the two whiteness values for D65/10° and C/2° conditions. If it cannot be unambiguously deduced from the context, the observer and illuminant should be specified as a suffix, e.g.  $T_{w,D65/10}$ .

The CIE green/red tint value is calculated for the CIE 1964 and 1931 Standard Observers according to:

$$T_{w,10} = 900(x_{n,10} - x_{10}) - 650(y_{n,10} - y_{10}) \quad [44]$$

or

$$T_w = 1000(x_n - x) - 650(y_n - y) \quad [45]$$

where the values for  $x_{n,10}$ ,  $y_{n,10}$ ,  $x_n$  and  $y_n$  are given in Table 2.

A positive  $T_w$ -value indicates a greenish tint and a negative value a reddish tint. The primary purpose of the tint value calculation is not to provide a colorimetric parameter but to provide a limit for the applicability of the whiteness equations. The material is considered to be white only if the tint value lies within the limits given by:

$$-3 < T_w < 3 \quad [46]$$

Table 2. Data for  $x_n$ ,  $y_n$ ,  $x_{n,10}$  and  $y_{n,10}$  for two illuminants.

For the C-illuminant:	$x_n = 0,31006$	$y_n = 0,31615$
	$x_{n,10} = 0,31039$	$y_{n,10} = 0,31905$
For D65-illuminant:	$x_n = 0,31273$	$y_n = 0,32902$
	$x_{n,10} = 0,31382$	$y_{n,10} = 0,33100$

### 13 Fluorescence component of CIE-whiteness

13.1 *Fluorescence component (of CIE-whiteness),  $W_F$*  – Measure of the extent to which the whiteness of the material is affected by excitation of the added fluorescent whitening agent (FWA) under the conditions specified in the relevant International Standard (ISO 11475, ISO 11476).

It is calculated as the difference between the whiteness measured using a source of light having a UV-content corresponding to the chosen illuminant and the whiteness measured with a source without radiation in the excitation band. Thus,

$$W_F = W - W_0 \quad [47]$$

where

$W$  is the whiteness value under D65 or C conditions;  
 $W_0$  is the whiteness value when the fluorescent effect has been fully eliminated.

It is not sufficient merely to eliminate the UV-component of the illumination since the added Fluorescent Whitening Agent is to some extent excited by visible light. The instrument shall be equipped with a sharp cut-off, UV-absorbing filter having a transmittance not exceeding 5,0 % at and below a wavelength of 410 nm and not exceeding 50 % at a wavelength of 420 nm. The cut-off filter shall have characteristics such that a reliable reflectance factor value is obtained at 420 nm. The reflectance factor value obtained at 420 nm shall then be considered for computational purposes to be the value which applies at all lower wavelengths at which it is not possible to make any measurements.

## 14 Yellowness index

14.1 *Yellowness index, J* – A measure of the extent to which a nearly achromatic stimulus deviates in yellowness from an achromatic stimulus having the same Y-value.

The yellowness index is calculated (cf. DIN 6167) as:

$$J = 100(R_x - R_z)/R_y \quad [48]$$

For the C/2° illuminant-observer condition, the yellowness index is therefore calculated as:

$$J = \frac{1,277X - 1,059Z}{Y} 100 \quad [49]$$

and for the D65/10° illuminant-observer condition the yellowness index is calculated as:

$$J = \frac{1,301X - 1,149Z}{Y} 100 \quad [50]$$

## 15 Metamerism index

15.1 *Metamerism* – Phenomenon that object colours appear the same although the stimuli are spectrally different (cf. CIE publ. 17.4, 845-03-05).

Two such stimuli are called a *metameric pair* or *metamers*. A problem related to the phenomenon of metamerism is that two objects having the same perceived colour in one illumination may have different perceived colours in another illumination.

Colorimetrically metameric colour stimuli are defined as colour stimuli having the same tristimulus values but different spectral reflectance factor distributions. This definition also implies that the CIELAB colour difference  $\Delta E^*_{ab}$  between these stimuli is zero.

15.2 *Metamerism index,  $M_{II/I}$*  – Colour difference  $\Delta E^*_{ab}$  between two samples, which are metamers under a reference illuminant/observer condition, determined under a different set of illuminant/observer conditions.

The metamerism index is the difference in colour between two samples with regard to the secondary illuminant/observer conditions II when they are the same in the primary illuminant/observer conditions I. If the  $\Delta E^*_{ab}$ -value of the two samples is exactly zero in condition I then the metamerism index is given by:

$$M_{II/I} = \Delta E^*_{ab,II} \quad [51]$$

where  $\Delta E^*_{ab,II}$  for the two samples is calculated using Eq. [38] for condition II.

If, in the primary condition, the  $\Delta E^*_{ab,I}$ -value is not exactly zero, a correction can be made to take into account this deviation. The corrected metamerism index is then given by:

$$M_{II/I} = \left( (\Delta L^*_{II} - \Delta L^*_{I})^2 + (\Delta a^*_{II} - \Delta a^*_{I})^2 + (\Delta b^*_{II} - \Delta b^*_{I})^2 \right)^{1/2} \quad [52]$$

where  $\Delta L^*$ ,  $\Delta a^*$  and  $\Delta b^*$  are defined in Eq. [39]. Eq. [52] may only be used to correct for small variations in samples which are basically metameric pairs.

## 16 Literature

16.1 CIE Publication 17.4, CIE International Lighting Vocabulary, 4th Ed Geneva 1987

16.2 ISO 2469 Paper, board and pulps – Measurement of diffuse reflectance factor

16.3 ISO 2470 Paper, board and pulps – Measurement of diffuse blue reflectance factor (ISO brightness)

16.4 ISO 2471 Paper and board – Determination of opacity (paper backing) – Diffuse reflectance

16.5 ISO 5631 Paper and board – Determination of colour (C/2°) – Diffuse reflectance method

16.6 ISO 9416 Paper – Determination of light scattering and absorption coefficients (using Kubelka-Munk theory)

16.7 ISO 11475 Paper and board – CIE whiteness, D65/10° (outdoor daylight)

16.8 ISO 11476 Paper and board – Determination of CIE whiteness, C/2° (indoor illumination)

16.9 ISO 22891 *In preparation*

16.10 ISO 4094 Paper, board and pulps – International calibration of testing apparatus – Nomination and acceptance of standardizing and authorized laboratories

16.11 SCAN-P 72 Papers and boards – Colour (D65/10°)

16.12 DIN 6167:1980-1 Beschreibung der Vergilbung von nahezu weißen oder nahezu farblosen Materialien

16.13 Wyszecki, G. and W.S. Stiles, Color Science – Concepts and methods, quantitative data and formulae. 2nd ed. 1982, New York: John Wiley & Sons. 950 p

## Annex A – Definitions

For the purpose of this guideline the following definitions are relevant:

A.1 *Reflectance* – Ratio of the reflected radiant or luminous flux to the incident flux.

*Note 1* – Unless otherwise specified, the reflected flux in all possible reflection directions is meant, which gives the total reflectance.

*Note 2* – It is sometimes convenient to divide the total reflectance into the sum of the specular and the diffuse reflectance.

A.2 *Reflectance factor,  $R$*  – Ratio of the radiation reflected by a body to that reflected by the perfect reflecting diffuser under the same conditions of illumination and detection (ISO 2469, ISO 5631).

*Note 1* – In the context of ISO 2469 and related standards, the irradiation is diffuse and the direction of detection is perpendicular to the surface of the specimen.

*Note 2* – A gloss trap ensures that there is no or considerably reduced irradiation from directions close to the direction of detection.

A.3 *Spectral reflectance factor,  $R(\lambda)$  or  $R(\lambda_i)$*  – Reflectance factor expressed as a function of wavelength.

*Note 1* – In this guideline, a wavelength-specific reflectance factor is indicated as  $R(\lambda)$ . In computational contexts, the reflectance factor variable is denoted  $R(\lambda_i)$ .

A.4 *Intrinsic reflectance factor,  $R_\infty$*  – Reflectance factor of a layer or pad of material thick enough to be opaque, i.e. such that increasing the thickness of the pad by doubling the number of sheets leads to no change in the measured reflectance factor (ISO 2469).

*Note 1* – *Reflectivity* is synonymous with intrinsic reflectance factor.

A.5 *Radiance factor,  $R$*  – Ratio of the radiant flux reflected and emitted by a body to that reflected by the perfect reflecting diffuser under the same conditions of illumination and detection (cf. ISO 11475, ISO 11476).

*Note 1* – The radiance factor is analogous to the reflectance factor except that it takes into

consideration all radiation not merely reflected radiation. For non-fluorescent samples, the radiance factor is also the reflectance factor. For fluorescent samples, the radiance factor is different from the reflectance factor.

*Note 2* – The radiance factor is often denoted  $\beta$  instead of  $R$ .

A.6 *Spectral luminous efficiency function,  $V(\lambda)$*  – Function describing the sensitivity to light of the human eye at different wavelengths. It is mathematically defined as: ratio of the radiant flux at wavelength  $\lambda_m$  to that at wavelength  $\lambda$ , when the two fluxes produce the same photopic sensation under specified photometric conditions,  $\lambda_m$  being chosen so that the maximum value of this ratio is unity (CIE publ. 17.4, 845-01-22).

*Note 1* – The data of  $V(\lambda)$  apply to the CIE 1924 Standard Photometric Observer for Photopic Vision.

*Note 2* –  $\lambda_m = 555 \text{ nm}$ .

*Note 3* – Photopic vision is light-adapted vision, i.e. the eye response is the response of the cones in the retina.

*Note 4* – For computational purposes, the  $V(\lambda)$  function is identical with the  $\bar{y}(\lambda)$  function for the CIE 1931 (2°) standard observer.

A.7 *Luminous reflectance factor, Luminance factor,  $R_v$*  – Reflectance factor defined with reference to the CIE illuminant C and the CIE 1931 colour matching function  $\bar{y}(\lambda)$ , and corresponding to the attribute of visual perception of the reflecting surface (ISO 2471).

*Note 1* – The CIE term "luminance factor" is a wider term since it does not define the illuminant.

A.8 *Intrinsic luminous reflectance factor, Intrinsic luminance factor,  $R_{v,\infty}$*  – Luminous reflectance factor of a layer or pad of material thick enough to be opaque, i.e. such that increasing the thickness of the pad by doubling the number of sheets results in no change in the measured reflectance factor.

A.9 *Opacity,  $\Omega$*  – Ratio of the single-sheet luminous reflectance factor,  $R_{v,0}$ , to the intrinsic luminous reflectance factor,  $R_{v,\infty}$ , of the same sample (ISO 2471).

The single-sheet reflectance factor is defined as the reflectance factor of a single sheet of paper with a black cavity as backing.

A.10 *Transmittance*,  $\tau$  – Ratio of the transmitted to the incident flux.

A.11 *Transmittance from reflectance factor measurement*,  $T$  – Transmittance calculated from reflectance factor data determined under the conditions of illumination and detection specified in ISO 2469 (ISO 22891 in preparation).

A.12 *Tristimulus values* – A triplet of numerical values describing the strengths of three reference colour stimuli when these match the colour of a test stimulus in a well specified colour matching situation.

A.13 *CIE tristimulus values*,  $X, Y, Z$  – Tristimulus values for a colour stimulus evaluated for the CIE 1931 Standard Colorimetric Observer ( $2^\circ$  observer).

A.14 *CIE tristimulus values*,  $X_{10}, Y_{10}, Z_{10}$  – Tristimulus values for a colour stimulus evaluated for the CIE 1964 Standard Colorimetric Observer ( $10^\circ$  observer).

A.15 *CIE colour matching functions*,  $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$  – Functions describing the tristimulus values  $X, Y, Z$  for monochromatic colour stimuli of equal radiance and where the wavelength  $\lambda$  is a variable.

A.16 *CIE colour matching functions*,  $\bar{x}_{10}(\lambda), \bar{y}_{10}(\lambda), \bar{z}_{10}(\lambda)$  – Functions describing the tristimulus values  $X_{10}, Y_{10}, Z_{10}$  for monochromatic colour stimuli of equal radiance and where the wavelength  $\lambda$  is a variable.

A.17 *Y-value* ( $C/2^\circ$ ) – Tristimulus value  $Y$  in the CIEXYZ-system of a layer of material of such a thickness that there is no change in  $Y$  when the thickness is increased.

*Note 1* – This shall be interpreted as the tristimulus value  $Y$  of a layer of material of such a thickness that there is no change in the value when the thickness is doubled, see A.4.

*Note 2* – The irradiation is here CIE illuminant C.

A.18 *Dominant wavelength*,  $\lambda_D$  – Wavelength of the monochromatic stimulus which can be additively mixed with a chosen achromatic stimulus so that the mixed stimulus matches the stimulus from the sample (cf. CIE publ. 17.4, 845-03-44).

*Note 1* – Not all stimuli have a corresponding dominant wavelength, e.g. stimuli with a purplish appearance.

A.19 *Complementary wavelength*,  $\lambda_C$  – Wavelength of the monochromatic stimulus which can be additively mixed with the stimulus from the sample so that the mixed stimulus matches a chosen achromatic stimulus.

*Note 1* – Not all stimuli have a corresponding complementary wavelength, e.g. stimuli with  $\lambda_D \approx 520$  nm.

A.20 *Excitation purity*,  $p_e$  – Ratio of the distance from the point representing the achromatic stimulus ( $x_n, y_n$ ) to the colour stimulus considered ( $x_s, y_s$ ) to the distance from the point representing the achromatic stimulus ( $x_n, y_n$ ) to the point on the spectrum locus representing the dominant wavelength ( $x_D, y_D$ ) (cf. CIE publ. 17.4, 845-03-48).

A.21 *Diffuse blue reflectance factor (ISO brightness)*,  $R_{457}$  – Intrinsic radiance factor measured with a reflectometer having the characteristics described in ISO 2469, equipped with a filter or corresponding function having an effective wavelength of 457 nm and a width at half height of 44 nm, and adjusted so that the UV-content of the illumination incident upon the test piece corresponds to that of the CIE illuminant C (ISO 2470:1999).

*Note 1* – The symbol  $R_B$  may be used instead of  $R_{457}$ .

A.22 *D65 diffuse blue reflectance factor (D65-brightness)*  $R_{457, D65}$  – Diffuse blue radiance factor measured when the UV-content of the irradiation has been adjusted as specified in ISO 11475 to correspond to the CIE standard illuminant D65.

A.23 *Light-scattering coefficient*,  $s$  – The fraction of the diffuse light flux that is reflected on its passage through an infinitesimally thin layer of material. This may be related to a finite layer using the Kubelka-Munk theory which takes into account the grammage of the material, so that  $s$  has the units  $m^2/kg$  (ISO 9416).

*Note 1* – When  $s$  is determined as a spectral quantity, it is denoted  $s(\lambda)$ .

*Note 2* – When it is determined according to ISO 9416 as a weighted average for the C-illuminant and the photopic visual efficiency function, it is denoted  $s_v$ . If the information in the suffix can unambiguously be deduced from the context, the suffix may be omitted.

A.24 *Light-absorption coefficient*,  $k$  – The fraction of the diffuse light flux that is absorbed on its passage through an infinitesimally thin layer of material. This may be related to a finite layer using the Kubelka-Munk

theory which takes into account the grammage of the material, so that  $k$  has the units  $\text{m}^2/\text{kg}$  (ISO 9416).

*Note 1* – When  $k$  is determined as a spectral quantity, it is denoted  $k(\lambda)$ .

*Note 2* – When it is determined according to ISO 9416 as a weighted average for the C-illuminant and the photopic visual efficiency function, it is denoted  $k_v$ . If the information in the suffix can unambiguously be deduced from the context, the suffix may be omitted.

A.25 *CIELAB colour (C/2°), ( $L^*, a^*, b^*$ )* –  $L^*$ ,  $a^*$  and  $b^*$  values of the sample according to the CIELAB 1976 system, evaluated according to the CIE 1931 Standard Observer and the CIE illuminant C.

A.26 *CIELAB colour (D65/10°), ( $L^*, a^*, b^*$ )* –  $L^*$ ,  $a^*$  and  $b^*$  values of the sample according to the CIELAB 1976 system, evaluated according to the CIE 1964 Supplementary Standard Observer and the CIE standard illuminant D65.

A.27 *CIELAB colour difference,  $\Delta E^*_{ab}$*  – Distance in the CIELAB colour space between two colour stimuli.

A.28 *CIE-whiteness,  $W$*  – Measure of whiteness derived from the CIE tristimulus values determined under specified conditions, and expressed as whiteness units (ISO 11475, ISO 11476).

*Note 1* – If it cannot be unambiguously deduced from the context, the observer and illuminant shall be specified as a suffix, e.g.  $W_{D65/10}$ .

*Note 2* – If the sample is fluorescent, the UV content in the radiation falling on the sample shall correspond to UV(D65) or UV(C) conditions respectively to meet the requirements of ISO 11475 or ISO 11476.

*Note 3* – For paper and board and for outdoor daylight conditions,  $W_{D65/10}$  is used, and for indoor illumination conditions,  $W_{C/2}$ , i.e. C/2°, is used.

A.29 *Green/red tint, CIE tint,  $T_w$*  – Measure of deviation from whiteness towards the green or red region, and expressed as tint units (ISO 11475, ISO 11476).

*Note 1* – If it cannot be unambiguously deduced from the context, the observer and illuminant should be specified as a suffix, e.g.  $T_{w,D65/10}$ .

A.30 *Fluorescence component (of CIE-whiteness),  $W_F$*  – Measure of the extent to which the whiteness of the material is affected by excitation of the added fluorescent whitening agent (FWA) under the conditions specified in the relevant International Standard (ISO 11475, ISO 11476).

*Note 1* – The UV-radiation from the source of light is excluded by a UV-absorbing filter having a cut-off wavelength of 420 nm.

A.31 *Fluorescence component of diffuse blue reflectance factor (fluorescence component of ISO brightness),  $R_{457,F}$*  – Difference between the ISO brightness measured using a source of light having a UV-content corresponding to the C-illuminant and the ISO brightness measured with a source without radiation in the excitation band (cf. A.30).

*Note 1* –  $R_{457,F}$  is used as a measure of the extent to which the ISO brightness of the material is affected by emission from added fluorescent whitening agent (FWA) when the light source emits UV radiation.

*Note 2* – The of UV-radiation from the source of light is excluded by a UV-absorbing filter having a cut-off wavelength of 420 nm.

*Note 3* – The symbol  $R_{B,F}$  may be used instead of  $R_{457,F}$ .

A.32 *Yellowness index,  $J$*  – A measure of the extent to which a nearly achromatic stimulus deviates in yellowness from an achromatic stimulus having the same  $Y$ -value.

A.33 *Metamerism* – Phenomenon that object colours appear the same although the stimuli are spectrally different (cf. CIE publ. 17.4, 845-03-05).

*Note 1* – Two such stimuli are called a *metameric pair* or *metamers*.

A.34 *Metamerism index,  $M_{II/I}$*  – Colour difference  $\Delta E^*_{ab}$  between two samples, which are metamers under a reference illuminant/observer condition, determined under a different set of illuminant/observer conditions.

## Annex B – UV conditions for whiteness and brightness

### B.1 Illuminant and observer conditions for whiteness

Illuminants used in the paper industry are:

- CIE illuminant C
- CIE standard illuminant D65.

If a colorimetric value is reported as having been calculated according to a certain illuminant, this does not automatically mean that the spectrum of the actual light source used in the measurement resembles the spectrum of the illuminant. In many cases, the spectrum of the light source used is unimportant.

CIE has defined two standard observers:

- CIE 1931 standard observer – the 2° observer
- CIE 1964 standard observer – the 10° observer.

The paper industry uses the following combinations of illuminant and observer function for whiteness:

- C/2° indoor whiteness (ISO 11476:2000)
- D65/10° outdoor whiteness (ISO 11475:1999).

### B.2 Brightness calculations

The diffuse blue reflectance factor (ISO brightness),  $R_{457}$ , is calculated from radiance factor data using the weighting function  $F(\lambda)$  according to clause 6 on page 5. The C-illuminant is specified, but it is only important in the case of fluorescent samples (ISO 2470:1999).

### B.3 UV conditions of the instrument

All modern spectrophotometers use one or more xenon flash lamps as light source. Two UV-absorption filters with cut-off wavelengths of 395 nm and 420 nm adjust the UV-content of the lamp. If either of the filters is fully inserted in the light beam before the light enters the integrating sphere, we have the UV-excluded conditions:

- UVex (395)
- UVex(420).

In most instruments, the 395 nm filter can be partly inserted into the beam making it possible to adjust the UV content of the source. The filter is sometimes called the UV trim filter or the UV adjustment filter. Different positions of the UV trim filter give the following UV conditions:

- UV(full) – The filter is not in the beam. The UV content is the maximum UV content of the instrument and is not defined. It is recommended that this setting should never be used except when it is known that there is no fluorescence present.

- UV(D65) – The UV content corresponds to the UV content of illuminant D65. Note however that the light source in the instrument is not spectrally identical to illuminant D65.
- UV(C) – The UV content corresponds to the UV content of illuminant C. Note however that the light source in the instrument is not spectrally identical to illuminant C.

If both filters are used at the same time, the UV condition is strictly the product of the two, e.g. UV(C) × UVex(420), but this is usually considered to be UVex(420).

The UV conditions may also be obtained by a combination of separate measurements under e.g. the UV(full), UVex(395) and UVex(420) conditions.

### B.4 Samples containing optical brighteners

When measurements are made on papers containing optical brightening agents (OBA, FWA), the UV condition must match the measured quantities according to the following table.

Weighting function	UV(C)	UV(D65)	UVex(420)
D65/10°	–	Outdoor whiteness, $W_{D65/10}$	Whiteness without fluorescence, $W_{D65/10,0}$
C/2°	Indoor whiteness, $W_{C/2}$	–	Whiteness without fluorescence, $W_{C/2,0}$
$F(\lambda)$	ISO brightness, $R_{457}$	D65 brightness, $R_{457,D65}$	Brightness without fluorescence, $R_{457,0}$

The fluorescent components of the quantities  $W_{D65/10}$ ,  $W_{C/2}$  and  $R_{457}$  are calculated as

$$\begin{aligned}
 W_{D65/10,F} &= W_{D65/10} - W_{D65/10,0} \\
 W_{C/2,F} &= W_{C/2} - W_{C/2,0} \\
 R_{457,F} &= R_{457} - R_{457,0}
 \end{aligned}
 \tag{B.1}$$

There is no ISO standard for D65 brightness.

In the measurement of non-fluorescent samples, the UV condition is not important except that UVex(420) is not acceptable. If the sample is sensitive to UV radiation, UVex(395) may be recommended.

