Paper — Determination of light scattering and absorption coefficients (using Kubelka-Munk theory)

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British Standards

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ISO 9416 was prepared by Technical Committee ISO/TC 6, *Paper, board and pulps*.

This second edition cancels and replaces the first edition (ISO 9416:1998), of which it constitutes a technical revision.

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Introduction

The opacity of a paper is dependent on its grammage, but it is also intrinsically dependent on the light-absorption and light-scattering coefficients of the material. These coefficients are calculated from the values of the reflectance factor over a black backing, the intrinsic reflectance factor and the grammage of the sheet.

The calculation of these coefficients requires luminance factor data obtained by measurement under specified conditions. Apart from the optical properties of the sample, the luminance factor depends on the conditions of measurement and particularly on the spectral and geometric characteristics of the instrument used for its determination. This International Standard should therefore be read in conjunction with ISO 2469 and ISO 2471.

NOTE This method is based on a theory developed by Kubelka and Munk. This theory describes scattering and absorption processes with certain approximations and simplifications and can therefore yield questionable results in extreme cases. However, the Kubelka-Munk theory offers a simple method for determining these coefficients with the instrument used for the determination of optical properties of paper and pulps. Moreover, the method based on this theory has been successfully used in practical applications.

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Paper — Determination of light scattering and absorption coefficients (using Kubelka-Munk theory)

1 Scope

This International Standard specifies a method for the calculation of light-scattering and light-absorption coefficients based upon diffuse reflectance measurements made under the conditions specified in ISO 2469 using the colour matching function $y(\lambda)$ and CIE illuminant C.

It is emphasized that the strict evaluation of the light-scattering and light-absorption coefficients requires conditions which cannot be achieved with the instrumentation specified here. The values obtained by application of this International Standard are dependent on the application of the Kubelka-Munk equations, not to full reflectance data but to reflectance factor data obtained using the specified d/0° geometry and a gloss trap.

The use of the method is restricted to white and near-white uncoated papers with an opacity less than about 95 %. Paper that has been treated with a fluorescent dyestuff or that exhibits significant fluorescence can only be dealt with if a filter with a cut-off wavelength of 420 nm is used to eliminate all the fluorescence effect in the UVex(420) mode.

NOTE 1 The residual UV-level in the instrument may depend on whether the instrument is adjusted to UV(C) or UV(D65) conditions prior to switching to the UVex(420) mode, but it is considered that this uncertainty in the residual level can be ignored in the application of this International Standard.

NOTE 2 Although this method is restricted to paper, it can be applied to pulp sheets, although this is not in accordance with this International Standard. In general, when pulps are tested, the light-absorption coefficient at 457 nm corresponding to the ISO brightness value or the spectral absorption coefficients are of greater interest than the weighted value standardized in this International Standard.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 186, *Paper and board — Sampling to determine average quality*

ISO 187, *Paper, board and pulps — Standard atmosphere for conditioning and testing and procedure for monitoring the atmosphere and conditioning of samples*

ISO 536, *Paper and board — Determination of grammage*

ISO 2469, *Paper, board and pulps — Measurement of diffuse radiance factor*

ISO 2471, *Paper and board — Determination of opacity (paper backing) — Diffuse reflectance method*

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3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
reflectance factor
R
ratio of the radiation reflected by a surface element of a body, in the direction delimited by a given cone with its apex at the surface element, to that reflected by the perfect reflecting diffuser under the same conditions of irradiation

NOTE The ratio is often expressed as a percentage.

3.2
luminance factor (C)
R_y
reflectance factor defined with reference to the visual efficiency function $V(\lambda)$ and the CIE illuminant C

NOTE 1 The visual efficiency function describes the sensitivity of the eye to light, so that the luminance factor corresponds to the attribute of visual perception of the reflecting surface.

NOTE 2 For computational purposes, the $V(\lambda)$ function is identical to the CIE 1931 colour matching function $\bar{y}(\lambda)$.

NOTE 3 The luminance factor (C) is also known as the Y(C/2°)-value. In the previous edition of this International Standard, it was referred to as the luminous reflectance factor.

3.3
single-sheet luminance factor (C)
R_0
luminance factor (C) of a single sheet of paper with a black cavity as backing

3.4
intrinsic luminance factor (C)
R_∞
luminance factor (C) 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

3.5
opacity (paper backing)
ratio of the single-sheet luminance factor (C), R_0, to the intrinsic luminance factor (C), R_∞, of the same sample

NOTE The opacity is expressed as a percentage.

3.6
light-absorption coefficient
k
fraction of the spectral radiant flux diffusely incident on a differential layer within a material that is absorbed when the flux passes through the layer, divided by the thickness of the layer

NOTE The flux referred to is a radiant flux across the differential layer.

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3.7
light-scattering coefficient
s
fraction of the spectral radiant flux diffusely incident on a differential layer within a material that is reflected when the flux passes through the layer, divided by the thickness of the layer

NOTE 1 The flux referred to is a radiant flux across the differential layer.

NOTE 2 It is assumed that no reflection occurs at the boundaries of the material.

NOTE 3 In a two-flux system, the scattering coefficient is equal to the net transfer of flux from the stronger flux to the weaker flux in a differential layer within a material divided by the product of the thickness of the layer and the difference between the fluxes (Reference [1] in the Bibliography).

3.8
light-scattering coefficient by reflectance factor measurements (Kubelka-Munk method)
s_r
coefficient calculated by application of the Kubelka-Munk equations to luminance factor data weighted with respect to the CIE illuminant C, obtained in an instrument having a specified geometry and calibrated in a specified manner, on the basis of grammage

NOTE s_r is expressed in square metres per kilogram (m^2/kg).

3.9
light-absorption coefficient by reflectance factor measurements (Kubelka-Munk method)
k_r
coefficient calculated by application of the Kubelka-Munk equations to luminance factor data weighted with respect to the CIE illuminant C, obtained in an instrument having a specified geometry and calibrated in a specified manner, on the basis of grammage

NOTE 1 k_r is expressed in square metres per kilogram (m^2/kg).

NOTE 2 Definitions 3.6 and 3.7 are strictly applicable to monochromatic light but, for the purpose of this International Standard, they apply to broad-band radiation. In research work, s and k can and should be determined at the relevant wavelength for the study concerned. As general descriptions of a given paper, they are defined here in relation to the $V(\lambda)$ function and the CIE illuminant C.

4 Principle

The luminance factor of a single sheet of the paper over a black cavity and the intrinsic luminance factor of the paper are determined. The grammage is determined in accordance with ISO 536.

The light-absorption and light-scattering coefficients are then calculated from these data using the Kubelka-Munk theory.

5 Apparatus

5.1 Reflectometer, having the geometric, spectral and photometric characteristics described in ISO 2469, equipped for the measurement of luminance factor, and calibrated in accordance with the provisions of ISO 2469.

5.2 Filter-function. In the case of a filter reflectometer, a filter that, in conjunction with the optical characteristics of the basic instrument, gives an overall response equivalent to the CIE tristimulus value Y of the CIE 1931 standard colorimetric system of the test piece evaluated for the CIE illuminant C.

In the case of an abridged spectrophotometer, a function that permits calculation of the CIE tristimulus value Y of the CIE 1931 standard colorimetric system of the test piece evaluated for the CIE illuminant C using the weighting functions given in Annex A.

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5.3 UV-cut-off filter. To eliminate any fluorescence effect, the instrument shall be equipped with a sharp cut-off, UV-absorbing filter having a transmittance not exceeding 0,5 % at and below a wavelength of 410 nm and not exceeding 50 % at a wavelength of 420 nm.

5.4 Two working standards. Two plates of flat opal glass or ceramic or other suitable material, cleaned and calibrated as described in ISO 2469.

NOTE In some instruments, the function of the primary working standard can be taken over by a built-in internal standard.

5.5 Black cavity, having a reflectance factor which does not differ from its nominal value by more than 0,2 % at all wavelengths. The black cavity should be stored upside down in a dust-free environment or with a protective cover.

NOTE 1 The condition of the black cavity can be checked by reference to the instrument maker.

NOTE 2 The nominal value is given by the manufacturer.

6 Sampling and conditioning

If the tests are being made to evaluate a lot of paper or board, the sample should be selected in accordance with ISO 186. If the tests are made on another type of sample, make sure that the test pieces taken are representative of the sample received.

Conditioning according to ISO 187 is recommended but not required, but preconditioning with elevated temperatures should not be applied since it might change the optical properties.

7 Preparation of test pieces

Avoiding watermarks, dirt and obvious defects, cut rectangular test pieces approximately 75 mm × 150 mm. Assemble at least 10 of the test pieces in a pad with their top sides uppermost; the number of test pieces should be such that doubling the number does not alter the reflectance factor. Protect the pad by placing an additional sheet on both the top and bottom of the pad; avoid contamination and unnecessary exposure to light or heat.

Mark the top test piece in one corner to identify the sample and its top side.

If the top side can be distinguished from the wire side, it shall be uppermost; if not, as may be the case for papers manufactured on twin-wire machines, ensure that the same side of the sheet is uppermost.

8 Procedure

8.1 If the sample contains or may contain a fluorescent whitening agent, check that the 420 nm UV-cut-off filter is in the UVex(420) position.

8.2 Remove the protecting sheets from the test-piece pad. Without touching the test area, use the procedure appropriate to the instrument, and the working standard, to measure the intrinsic luminance factor R_∞ of the top side of the test-piece pad. Read and record the value to the nearest 0,01 % of the reflectance factor.

8.3 Remove the top test piece from the pad and, with the black cavity backing the test piece, measure the luminance factor, R_0, for the same area of the test piece. Read and record the value to the nearest 0,01 % of the luminance factor.

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Subclauses 8.2 and 8.3 describe the two independent measurements required to calculate the light absorption and scattering coefficients using the Kubelka-Munk theory in Clause 9. This text is not intended to imply that the two measurements shall necessarily be made in this order.

8.4 Move the measured test piece to the bottom of the pad. Repeat the measurements of R_∞ and R_0, moving the top test piece to the bottom of the pad after each pair of measurements, until five pairs of measurements have been made.

This clause implies that measurements of R_∞ and R_0 shall be made alternately, but this is not an essential requirement of this International Standard. The five measurements of R_0 may be made before or after the five measurements of R_∞ if such a procedure is preferred, or the measurements may be made alternately.

8.5 Turn the pad upside down and repeat procedures 8.2 to 8.4 for the other side.

8.6 Determine the grammage of the material according to ISO 536 after conditioning in accordance with ISO 187.

NOTE For greater accuracy, the grammage of each individual test piece should be determined.

9 Calculation of results

Calculate the means of R_∞ and R_0 for each side of the sample and use these values to calculate the Kubelka-Munk coefficients as in Equations (1) and (2).

If R_∞ and R_0 are expressed as percentages, convert the percentage values to decimal fractions, and calculate the light-scattering coefficient s_r and the light-absorption coefficient k_r using the equations:

$$s_r = \frac{1000}{w} \times \frac{R_\infty}{\left(1 - R_\infty^2\right)} \times \ln \frac{R_\infty \left(1 - R_0 R_\infty\right)}{R_\infty - R_0} \tag{1}$$

$$k_r = \frac{s_r \left(1 - R_\infty\right)^2}{2 R_\infty} \tag{2}$$

where w is the grammage, in grams per square metre (g/m^2).

NOTE For greater accuracy, if the grammage of each individual test piece is known, calculate s_r and k_r for each pair of measurements and then calculate the mean values.

Calculate these values to the nearest 0,1 m^2/kg for each set of measurements. Report the light-scattering coefficient to the nearest whole number. If the light-scattering coefficients for the two sides of the sample do not differ by more than 1,0 m^2/kg, report the overall average. If the two sides differ by more than 1,0 m^2/kg, report the average value for each side separately. Similarly, report the light-absorption coefficient to the nearest 0,1 m^2/kg.

10 Precision

In “Round Robin” tests involving 12 laboratories, the standard deviation within laboratories was about 0,7 m^2/kg for the light-scattering coefficient and about 0,05 m^2/kg for the light-absorption coefficient.

The standard deviation between the different laboratories was about 2,0 m^2/kg for the light-scattering coefficient and 0,2 m^2/kg for the light-absorption coefficient.

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11 Test report

The test report shall include the following information:

a) a reference to this International Standard;

b) precise identification of the sample;

c) date and place of testing;

d) the light-scattering coefficient and light-absorption coefficient;

e) the type of instrument used, and whether or not the instrument was adjusted to UVex(420) conditions;

f) the atmosphere used for conditioning;

g) any departure from this International Standard or any circumstances or influences that may have affected the results.

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Annex A
(informative)

Spectral characteristics of reflectometers for measuring luminance factor

A.1 For filter colorimeters

The required spectral characteristics of the reflectometer are arrived at by a combination of lamps, integrating spheres, glass optics, filters and photoelectric detectors. The filters should be such that they, together with the optical characteristics of the instrument, give a response equivalent to the CIE tristimulus *Y*-value for the CIE 1931 (2°) standard observer of the test piece established for the CIE illuminant C.

A.2 For abridged spectrophotometers

The desired reflectance factors are obtained by summing the products of the spectral reflectance factors and the weighting functions in Table A.1, given in ASTM E308-06 [1)] for the CIE 1931 (2°) observer and the CIE illuminant C.

The instructions given in A.3 should be followed.

A.3 Data available only for wavelength ranges shorter than 360 nm to 780 nm

When data for $R(\lambda)$ are not available for the full wavelength range, add the weights at the wavelengths for which data are not available to the weights at the shortest and longest wavelength for which spectral data are available. That is: add the weights for wavelengths of 360 nm..., up to the last wavelength for which measured data are not available, to the next higher weight, for which such data are available; add the weights for wavelengths of 780 nm..., down to the last wavelength for which measured data are not available, to the next lower weight, for which such data are available.

1) Reprinted, with permission, from E308-06, *Standard Practice for Computing the Colors of Objects by Using the CIE System*, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428, USA. A copy of the complete standard may be obtained from ASTM (http://www.astm.org).

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Table A.1 — ASTM E308-06 weighting functions for instruments measuring at 10 nm and 20 nm intervals, respectively

Wavelength nm	**Y-weights** 10 nm	**Y-weights** 20 nm
360	0,000	0,000
370	0,000	
380	0,000	0,000
390	0,000	
400	0,002	0,001
410	0,007	
420	0,032	0,044
430	0,118	
440	0,259	0,491
450	0,437	
460	0,684	1,308
470	1,042	
480	1,600	3,062
490	2,332	
500	3,375	6,596
510	4,823	
520	6,468	12,925
530	7,951	
540	9,193	18,650
550	9,889	
560	9,898	20,143
570	9,186	
580	8,008	16,095
590	6,621	
600	5,302	10,537
610	4,168	
620	3,147	6,211
630	2,174	
640	1,427	2,743
650	0,873	
660	0,492	0,911
670	0,250	
680	0,129	0,218
690	0,059	
700	0,028	0,049
710	0,014	
720	0,006	0,011
730	0,003	
740	0,001	0,002
750	0,001	
760	0,000	0,001
770	0,000	
780	0,000	0,000
Check sum	**99,999**	**99,998**
White point	**100,000**	**100,000**

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[1] CIE Publication No. 38:1977, *Radiometric and photometric characteristics of materials and their measurement*

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