Colour measurement in practice

Contemporary wool dyeing and finishing

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Colour measurement in practice

Topics

1. Instrumental colour measurement
2. Classification of colours
3. Instrumental colour matching

1. Instrumental colour measurement

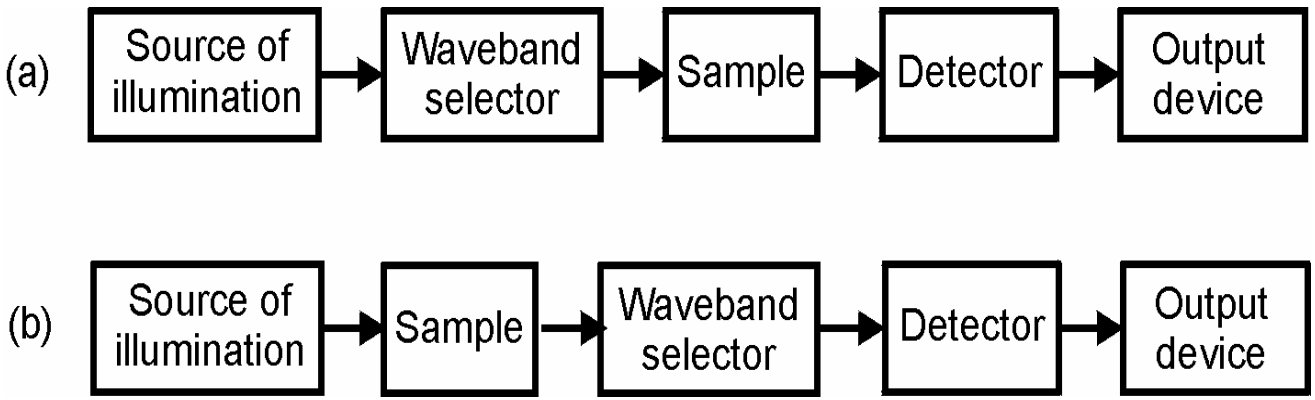
Instrumental measurement of colour

Why measure colour?

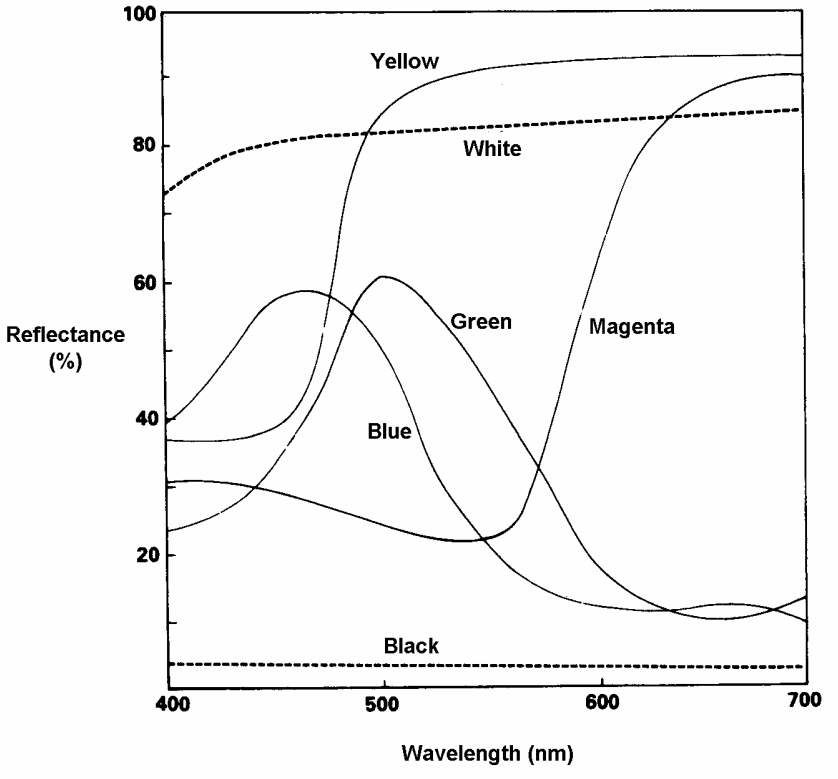
- To provide all aspects of the use of colour in everyday life with a scientific basis for:
  - colour communication
  - colour matching
  - colour difference.
- Instruments that measure colour are called spectrophotometers.

Spectrophotometers

There are two basic types of spectrophotometer. They can use:
(a) monochromatic illumination
or
(b) full spectrum illumination.



Relationship between reflectance and colour

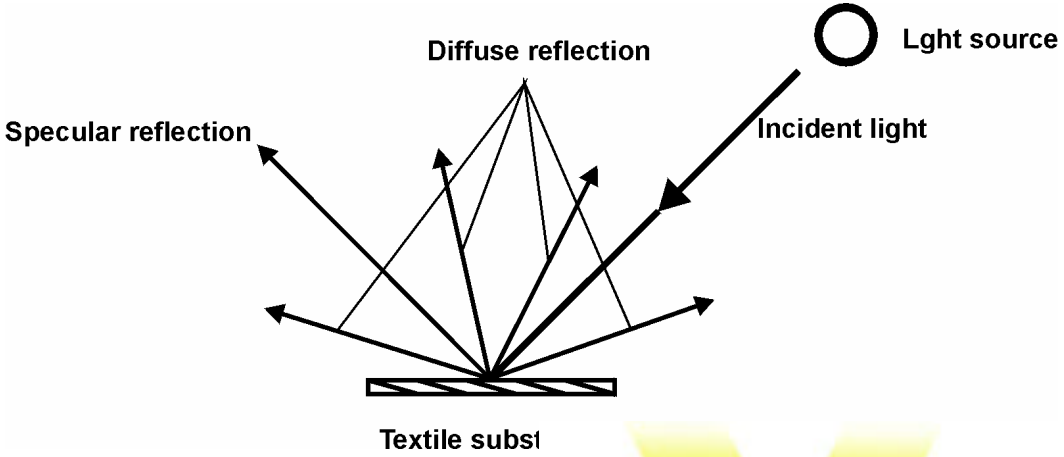


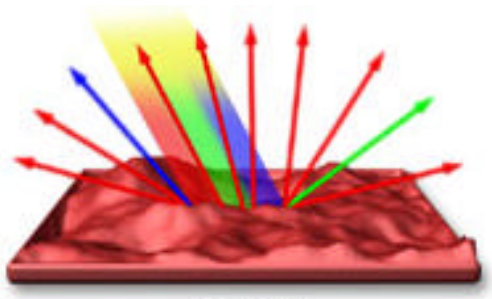
Typical reflectance spectra of different coloured samples.

The relationship between reflected colour and absorbed colour

Colour of reflected light from a substrate	Colour of light absorbed in the substrate
Magenta	Green, violet, some blue
Green	Red, blue, violet
Yellow	Violet-blue
Blue	Yellow-green, yellow, orange and some red

Scattering and absorption by a textile substrate





The specular and diffuse components of reflectance.

Interaction of a light beam with a single fibre

Fresnel's formula:

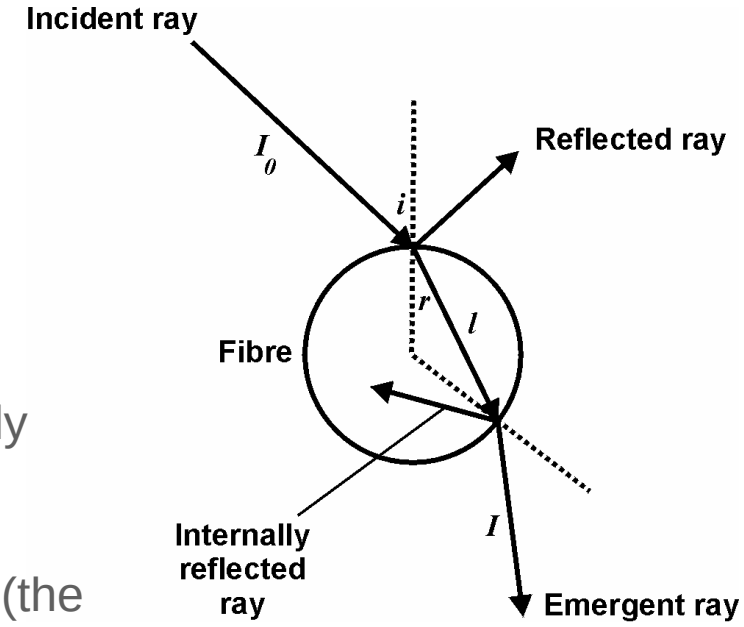
$$R = \frac{1}{2}\left[\frac{\sin^2(i-r)}{\sin^2(i+r)} + \frac{\tan^2(i-r)}{\tan^2(i+r)}\right]$$

where $$\frac{n_1}{n_2} = \frac{\sin r}{\sin i}$$

n_1 is the refractive index of air (nearly equal to unity)

n_2 is the refractive index of the fibre (the refractive index of wool is 1.3)

r is the angle to the normal of the refracted ray within the fibre.



Reflection and transmission of a light ray striking a fibre.

The Beer-Lambert law

Dyes inside fibres behave as though they are dissolved in the fibre and their absorption behaviour is similar to that of solutions.

The absorption of light in dyed fibres is described by the **Beer-Lambert law**:

$$I = I_0 \, 10^{-\varepsilon c l}$$

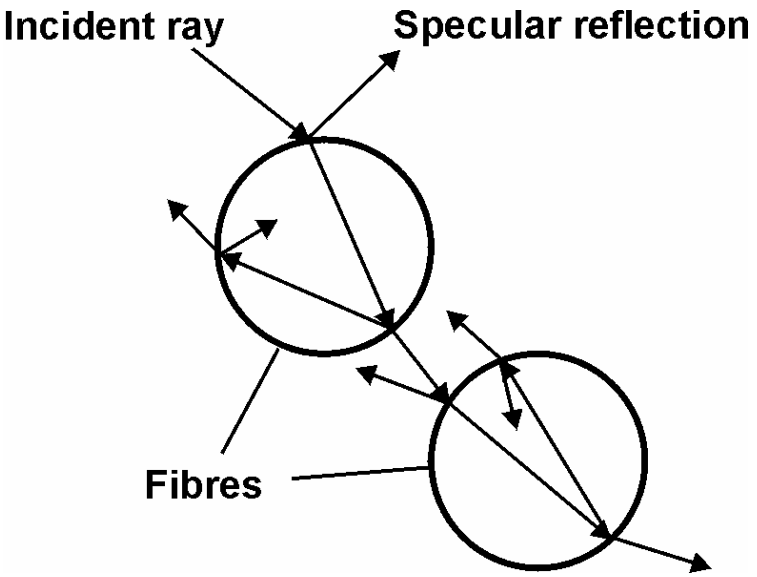
where I is the intensity of the transmitted radiation,
I_0 is the intensity of the incident radiation,
ε is the molar extinction coefficient (l mol^{-1} cm^{-1}),
c is the concentration of the absorbing substance (mol l^{-1})
l is the path length through which the radiation passes (cm).

When the percentage of incident light transmitted (T) is measured, the law can be written:

$$A = \log_{10} (100/T) = \varepsilon c l$$

where A is the absorbance.

Reflection from multiple fibres



Possible reflection, scattering and absorption processes within fibres.

The Kubelka-Munk function

$$K/S = \frac{(1 - R_\infty)^2}{2R_\infty}$$

and

$$R_\infty = (K/S + 1) - \sqrt{[(K/S + 1)^2 - 1]}$$

where

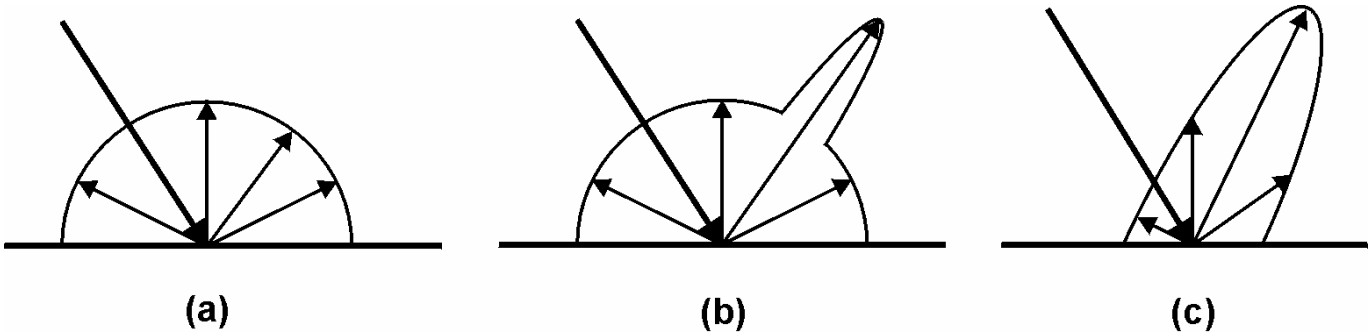
K is the absorption coefficient
S is the scattering coefficient
R_∞ is the reflectance of the surface having such a thickness that there is no further change in the reflectance by increasing the thickness.

For dark shades, R_∞ is replaced by a corrected value: $R_\infty = R - R_0$

$$K/S = \frac{[1 - (R - R_0)]^2}{2(R - R_0)}$$

where R is the measured value of reflectance at a particular wavelength
R_0 is the minimum value of reflectance obtained with the deepest possible dyeing at the wavelength of maximum absorption.

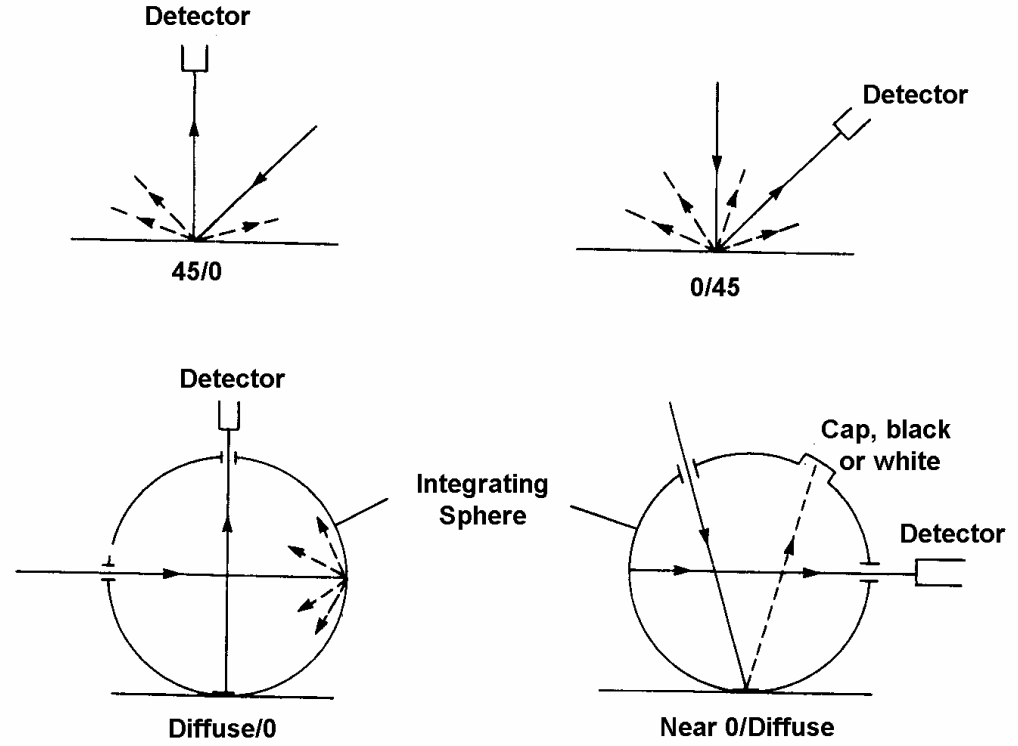
Standard conditions for illumination, viewing and measurement



Different surface scattering characteristics:

(a) matte surface - most light is diffusely reflected
(b) eggshell finish - some light is specularly reflected
(c) glossy finish - most light is specularly reflected.

Four sets of measurement conditions are recommended



Schematic diagrams of common illuminating and viewing conditions in spectrophotometry of textiles.

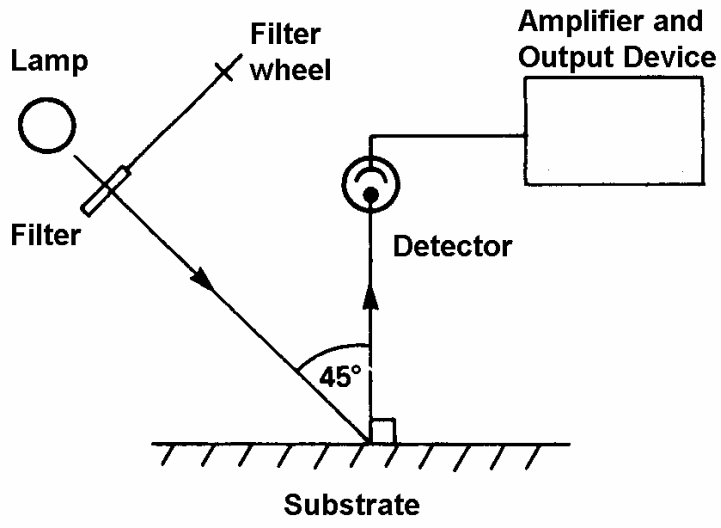
Measurement of the reflectance of fluorescent materials

- A fluorescent sample absorbs radiation in the ultraviolet wavelength region of the spectrum and re-emits some of the absorbed energy at a longer wavelength in the blue region.
  - Fluorescent samples illuminated with illuminant D65 will fluoresce because of the ultraviolet component in the illuminating radiation.
  - Under Illuminant A, a sample will not fluoresce because of the absence of ultraviolet radiation.
- This can be the basis of the measurement of fluorescent materials.

- For precise measurement of fluorescence, a special double monochromator instrument is required.
  - Samples are illuminated with monochromatic radiation and the spectrum of the scattered radiation is obtained then using stepwise changes in the wavelength of the incident radiation.

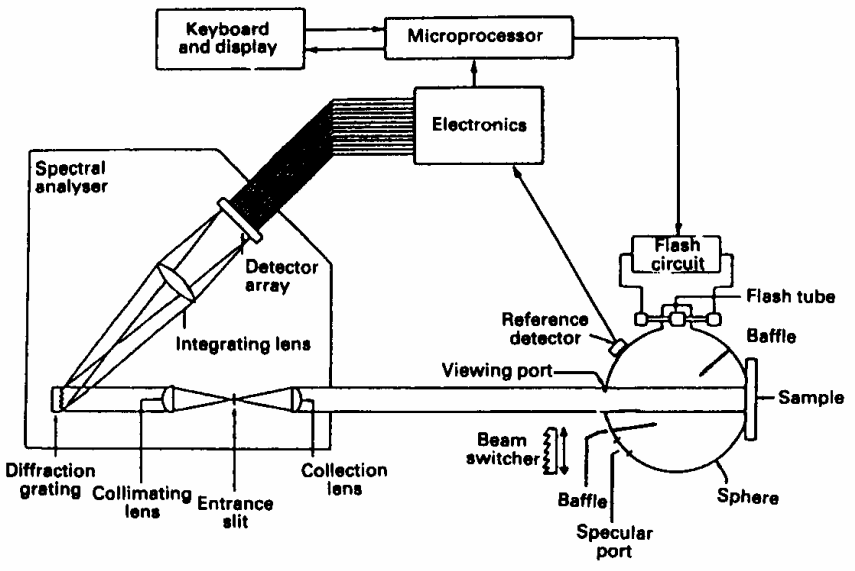
Trichromatic colorimeters

- The transmission characteristics of the filters match the eye sensitivity functions for the 2º or 10º CIE standard observers.
- The filters in the light path can be changed in succession and data automatically processed by simple electronic circuitry.
- Tristimulus values can be obtained after calibration of the instrument with an appropriate white standard.
- CIELAB data and colour differences between samples can be calculated.



Reflectance spectrophotometers

- The sample is diffusely illuminated with filtered light from a high-pressure xenon arc flash tube that emulates illuminant D65.
- Radiation reflected from the sample at 8^{o} to the normal is refracted by a diffraction grating and the spectrum passes to an array of 18 solid state detectors covering the range 380-700 nm.
- A reference signal is obtained from a detector that measures the intensity of the illuminating radiation
- The specular component of reflectance can be excluded by replacing the ‘specular port’ on the integrating sphere (at 8^{o} to the normal and at a complementary angle to the measurement port) with a black trap.



Macbeth MS2020 spectrophotometer.

Reflectance spectrophometer

datacolor

Because Color Matters

Sample preparation

Wool samples should be conditioned at 20ºC and 65% relative humidity before measurement, because colour may vary with regain.

A conditioned room is best but a conditioning oven can be used.

Datacolor conditioner.

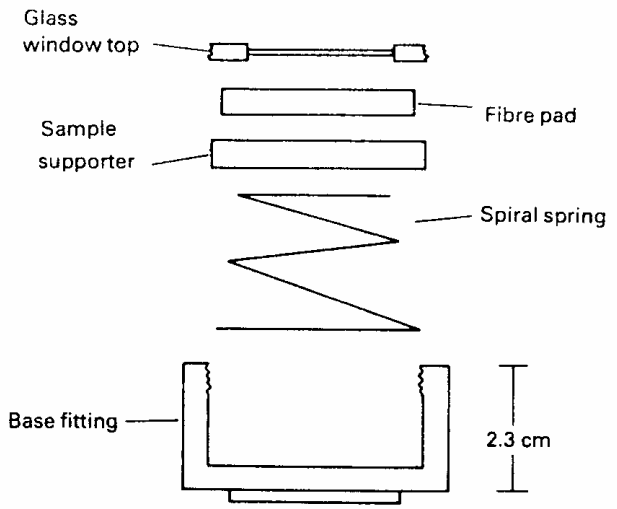
Sample presentation

Samples must satisfy the thickness requirement for reflectance measurement of K/S (i.e. $R = R_8$).

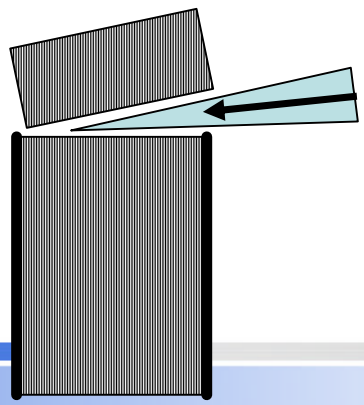
- Fabric is normally folded at least twice.
- Yarn is usually wound on a card to form a thick, even, wad but it may be drawn onto a tube and viewed end-on.
- Loose fibre can be felted into a pad placed in a cell with a transparent window, or drawn onto a tube and viewed end-on.

Sample presentation for loose fibre

A cell for measurement of the colour of loose fibres made into a pad.



Alternatively, yarn and loose fibre may be measured with the fibres end-on by drawing the fibre or yarn into a tube of suitable diameter to form a dense plug and the end of the plug is then trimmed flat using a sharp blade.



Reflectance standards

- Formerly magnesium oxide and barium sulphate were used as reference standards but they were often fragile and prone to yellowing.
- Recently, standards made from opaline glass have become available. They are very white, stable and relatively robust and are the standards of choice.

Tristimulus values of a perfect reflecting diffuser for the 10^{o} observer

Illuminant	X_n	Y_n	Z_n
A	111.1	100.0	35.2
C	97.3	100.0	116.1
D65	94.8	100.0	107.3

2. Classification of colours

Colour Atlases

- Three common features are described to classify colours:
  - **hue**
  - **purity or saturation**
  - **lightness or darkness.**

- **Hue** gives rise to colour names, such as red, yellow, orange, green, blue, purple and so on. Most of these colours can be represented by a single wavelength of visible light.

- **Purity** or saturation describes the visual sensation related to the strength of the colour. It is independent of hue and can be represented on a scale varying from white to pure colour.

- **Lightness or darkness** is the visual sensation related to the brightness of a colour. It can be rated on a scale varying from white to black. It is independent of hue and saturation.

Well-known colour atlases

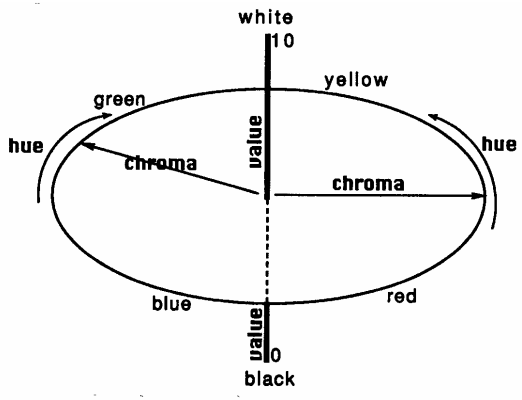
- The Dictionary of Colour (A. Maerz and M. R Paul, McGraw Hill, New York, 1930).
- The Colour Harmony Manual (Oswald).
- The ICI Colour Atlas (ICI).
- Pantone Colour System (Colour marketing Group, USA).
- DIN Colour Chart (M Richter, Farbe 1 (1953a) 85).
- Munsell System (Munsell Colour Co.).
- Normacolour Spatial System (M-canorma).

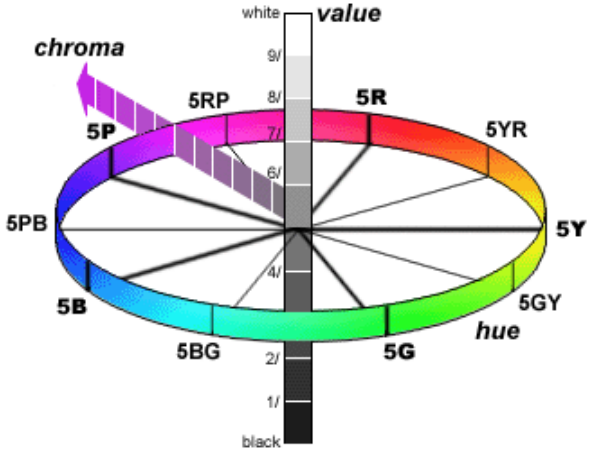
Munsell colour system

Hue is the colour name chosen from violet, violet-blue, blue, blue-green, green, green-yellow, yellow, yellow-red, and red-violet. Each of the 10 hues is further divided into 10 subdivisions.

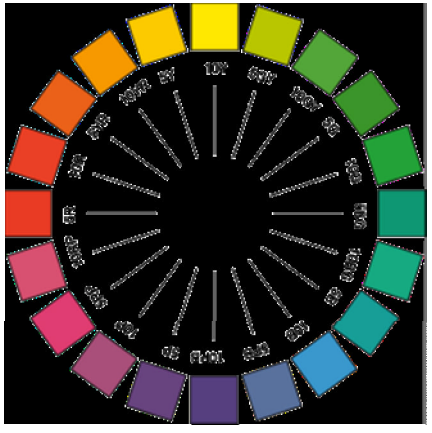
Value expresses the **lightness or darkness** of a colour on a scale of 0 to 10.
A perfect white is given the value 10 and a perfect black 0. Colours fall in the range 1 to 9.

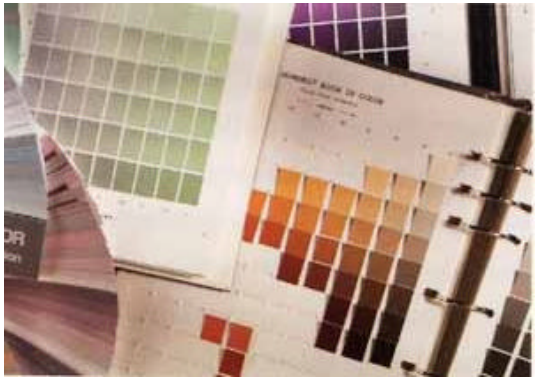
Chroma indicates the **saturation of the colour** or the amount of colour (hue) in a sample compared to a grey colour with the same value. This is expressed by numbers of I to 12 (originally 1 to 10) where a higher number corresponds to a colour with a higher saturation.
Black, greys and white have zero chroma.

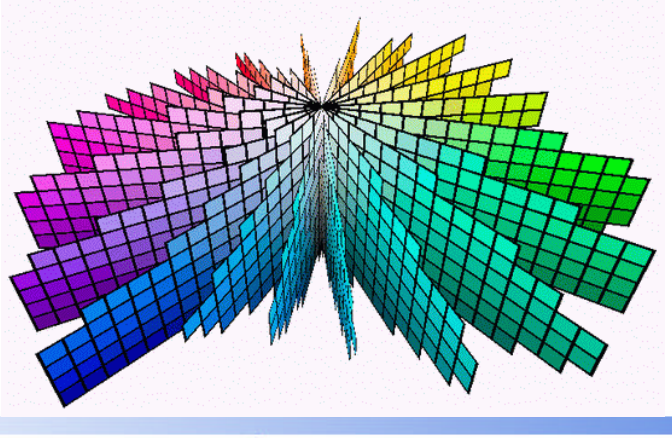


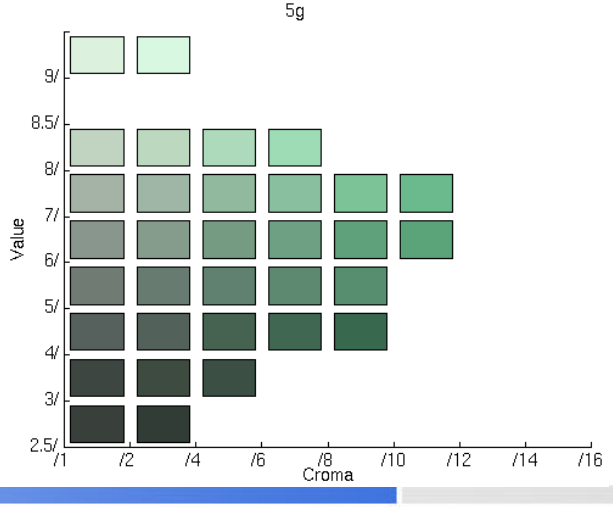


The Munsell colour system







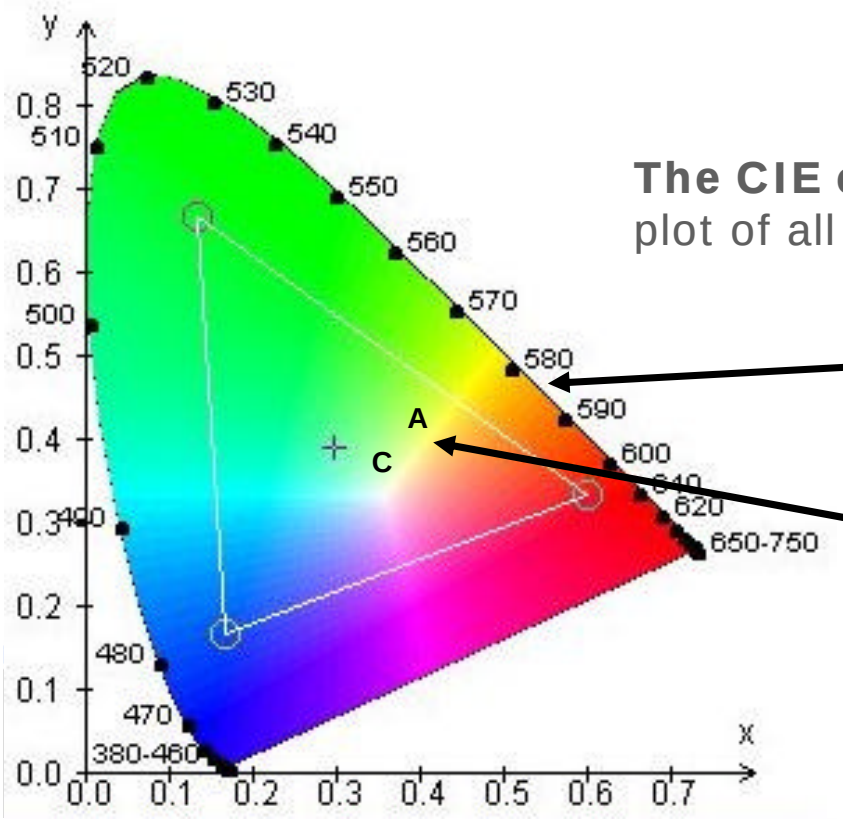


Chromaticity colour coordinates

These are defined as follows:

$$x = \frac{X}{X+Y+Z} \quad , \quad y = \frac{Y}{X+Y+Z} \quad , \quad z = \frac{Z}{X+Y+Z}$$

where $x + y + z = 1$



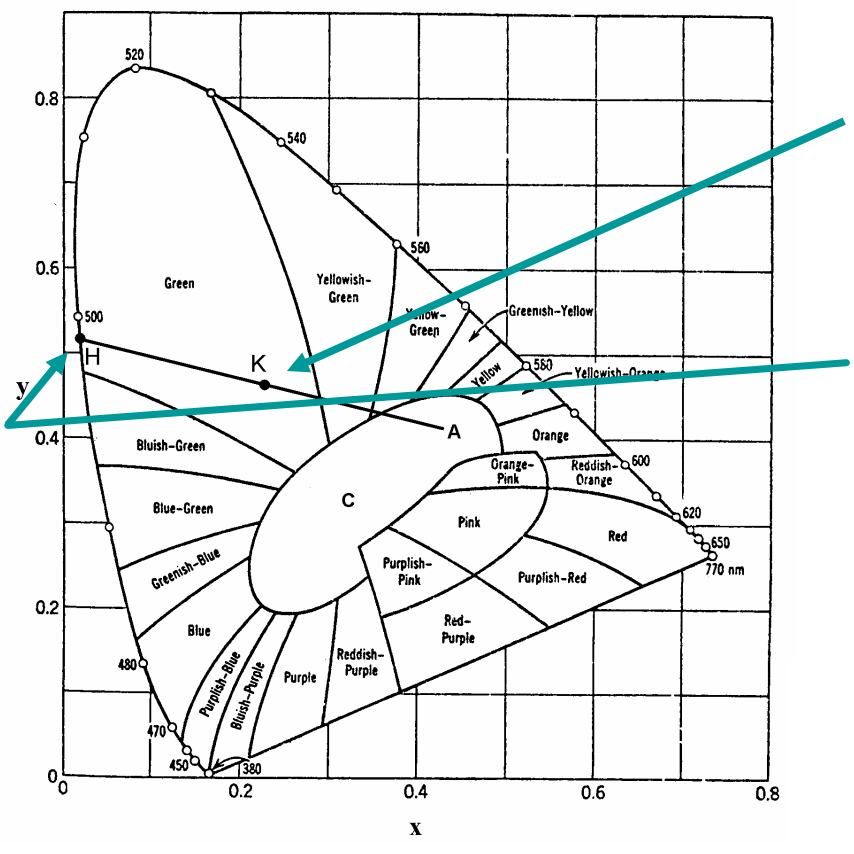
The CIE chromaticity diagram shows a plot of all possible values of x and y.

The spectral locus showing the equivalent single wavelengths.

The positions of illuminants A and C on the diagram.

Colourimetric purity

This is the percentage distance of the point representing the chromaticity coordinates of the sample colour from the point representing the chromaticity coordinates of the illuminant, relative to the distance of the point on the spectrum locus representing the dominant wavelength of the colour from the point representing the chromaticity coordinates of the illuminant.



A green colour is represented at K and has x = 0.230 and y = 0.465.

When observed under illuminant A, this colour has a dominant wavelength of 499 nm (H).

The **colourimetric purity** of this colour is 50% and is given by 100(AK)/(AH).

Specification of colour and colour differences

Measurement of colour differences

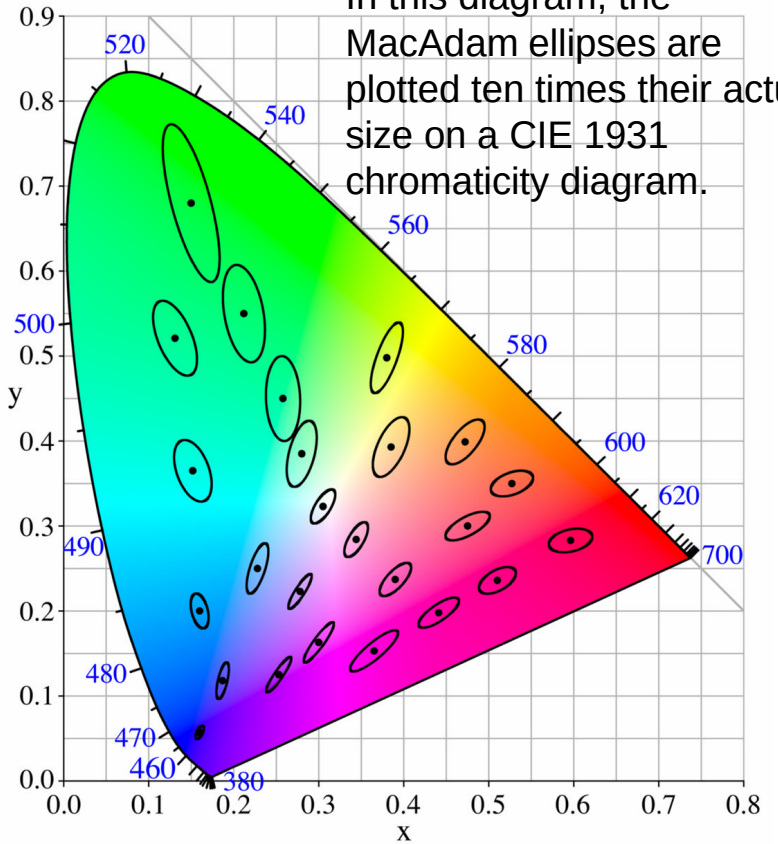
Why measure colour differences?

- Measurement is of colour differences is crucial to effective quality control in the colour industry.
- The need to agree on colour tolerances in production is becoming increasingly important to ensure commercial profitability.

How can colour differences be measured?

- Represent all available colours in space in a diagram.
- Measure linear distances between points representing individual colours in the colour space diagram.
- This task is greatly facilitated by construction of uniform representations of colour space.

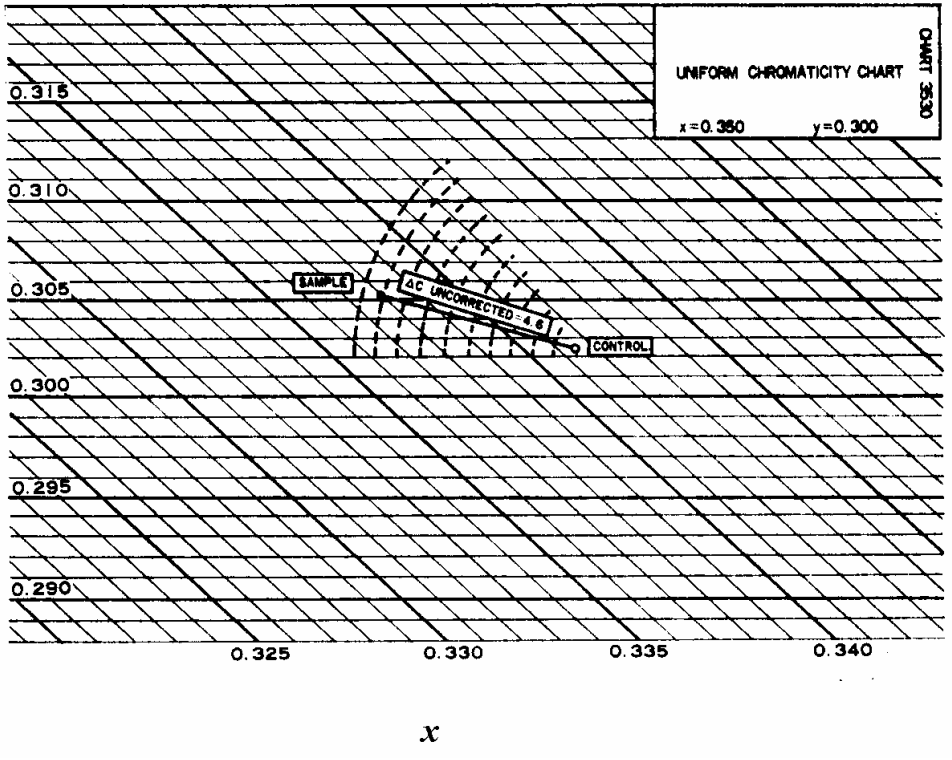
MacAdam ellipses (1942)



- In the MacAdam experiment, a ‘test’ colour was fixed and an observer was asked to adjust another colour until it matched the test colour.
- It was found that all of the matches fell into an ellipse on the CIE chromaticity diagram.
- The sizes of the ellipses on the diagram varied depending on the test colour.
- These ellipses embody a method of measuring distance in colour space. Each of the ellipses are, by definition, circles of equal colour perception, and the only reason that they appear to be ellipses of different sizes is because CIE xy space is non linear with respect to the human perception of colour space.

Simon-Goodwin charts

Simon-Goodwin charts are used for obtaining chromaticity differences from measurements of chromaticity coordinates. The charts were drawn by angling and scaling the x and y axes over small areas of the CIE chromaticity diagram, to make the MacAdam ellipses into circles.



Thus, over small areas of the chromaticity diagram, chromaticity differences could be represented as straight lines and the length of the line represented the magnitude of the chromaticity difference.

CIELAB colour space

In 1976, the CIE introduced this now widely used three-dimensional **uniform colour space** using the coordinates L*, a* and b* calculated from tristimulus measurements.

$$L^* = 116\,(Y/Yn)^{1/3} - 16$$
$$a^* = 500\,[(X/Xn)^{1/3} - (Y/Yn)^{1/3}]$$
$$b^* = 200\,[(Y/Yn)^{1/3} - (Z/Zn)^{1/3}]$$

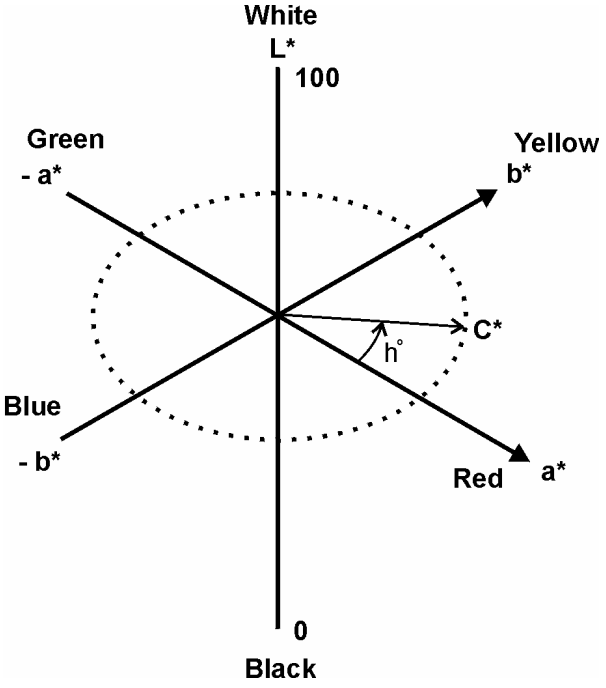
where Xn, Yn, and Zn are the tristimulus values for the relevant standard illuminant and observer.

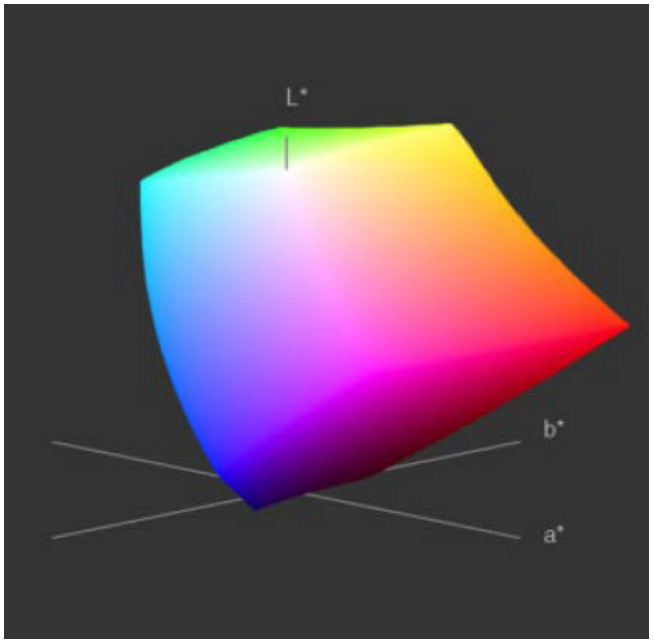
These equations only apply when X/Xn, Y/Yn and Z/Zn > 0.008856.

When X/Xn, Y/Yn and Z/Zn < 0.008856, that is, for very dark colours:

$$L^* = 903.3\,(Y/Yn)$$
$$a^* = 3893.5\,[(X/Xn) - (Y/Yn)]$$
$$b^* = 1557.4\,[(Y/Yn) - (Z/Zn)]$$

CIELAB colour space





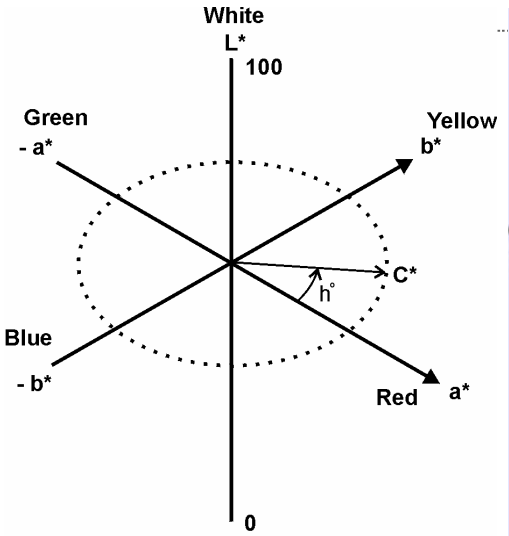
All visible colours.

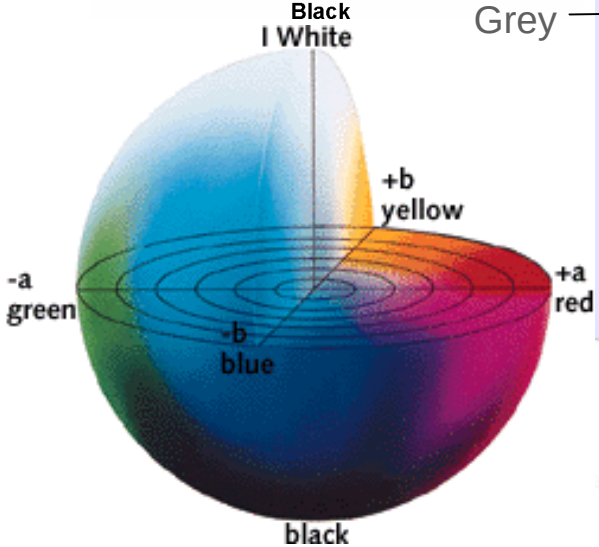
CIELAB values can also be expressed in cylindrical coordinates:

$$C^* = [(a^*)^2 + (b^*)^2]^{1/2}$$

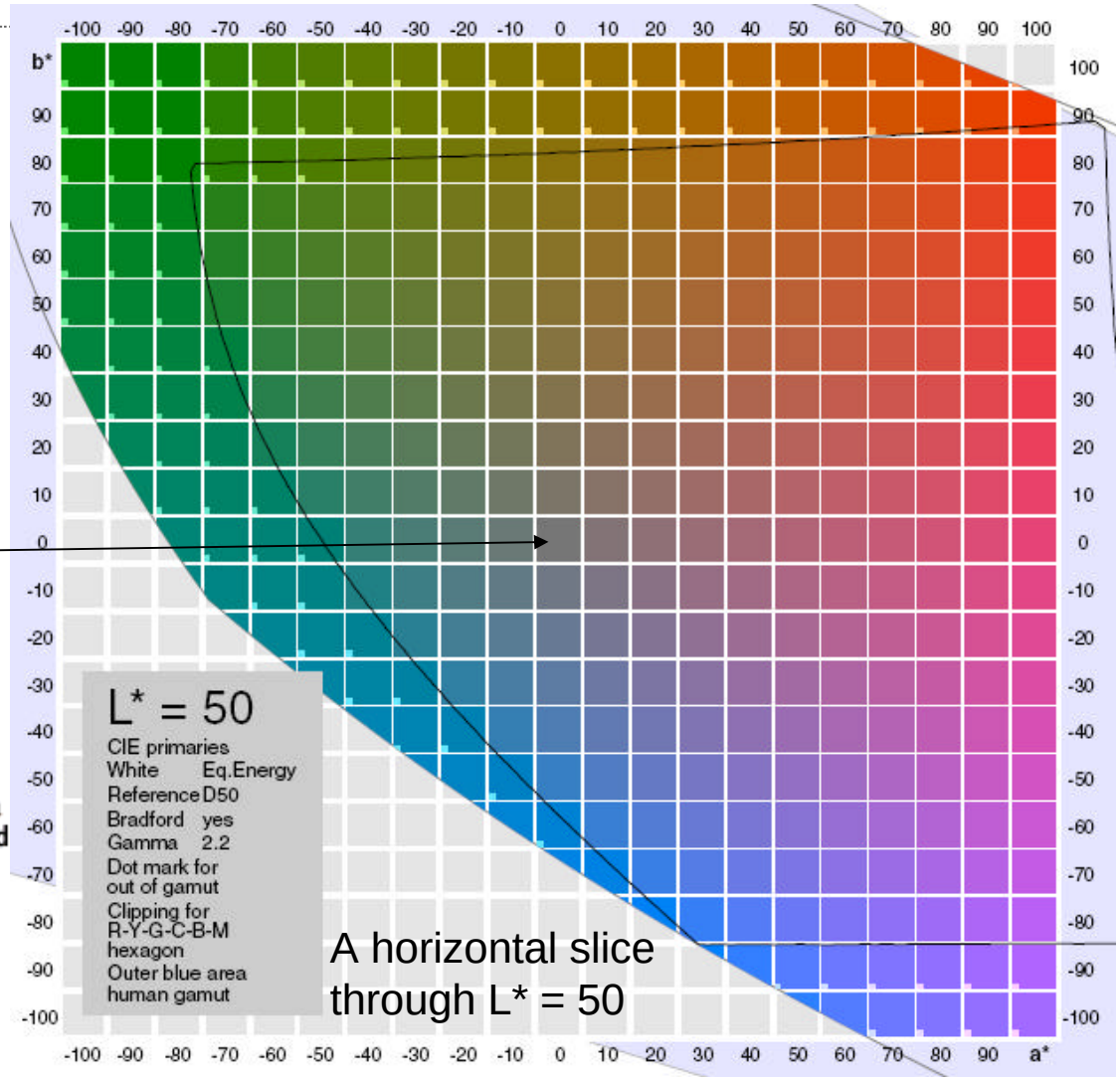
$$h = \arctan(b^*/a^*).$$

CIELAB colour space





Grey



A horizontal slice through L* = 50

The CIELAB colour difference (DE*)

The **colour difference** between two samples (1 and 2)

with CIE coodinates L^*_1, a^*_1, b^*_1 and L^*_2, a^*_2, b^*_2,

is the linear distance between the coordinates and is given by:

$$\Delta E^* = [(L^*_1 - L^*_2)^2 + (a^*_1 - a^*_2)^2 + (b^*_1 - b^*_2)^2]^{1/2}$$

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

The **chromaticity difference** Δc is also sometimes used as a measure of the variation in hue not due to changes in lightness.

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

Output from a colour measurement program

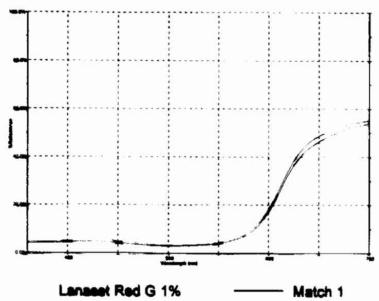
CIE L*a*b* Color Difference

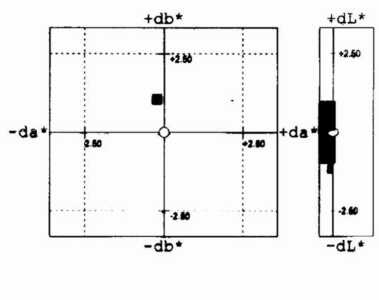
Report Date: 25-Jul-01
Time: 14:10
Std Meas Geometry: %R LAV SCI UV Inc
Batch Meas Geometry: %R LAV SCI UV Inc

Illuminant/Observer Conditions
1) D65 10 Deg
2) A 10 Deg
3) F2 10 Deg

	Ill/Obs	L*	a*	b*	C*	h
Standard Name:						
Lanaset Red G 1%	1	37.21	42.30	19.66	46.65	24.93
	2	43.49	43.46	31.26	53.53	35.72
	3	37.53	30.48	19.42	36.14	32.50
Batch Name:						
Match 1	1	36.03	42.07	20.72	46.90	26.23
Date Batch Measured: 25-Jul-01	2	42.31	43.24	32.24	53.94	36.71
Time Batch Measured: 14:08:42	3	36.33	30.37	20.53	36.66	34.07

Ill/Obs	DL*	Da*	Db*	DC*	DH*	DE*
D65 10 Deg	-1.18	-0.23	1.06	0.25	1.06	1.61
A 10 Deg	-1.17	-0.22	0.98	0.40	0.92	1.55
F2 10 Deg	-1.19	-0.11	1.12	0.52	0.99	1.64





Spreadsheet calculation of L*,a*, b* values

Under Illuminant A

$B10*C10 $B10*E10 $B10*G10

λ (nm)	R_λ (as fraction)	$E_\lambda . \bar{x}_\lambda$	$E_\lambda . \bar{x}_\lambda . R_\lambda$	$E_\lambda . \bar{y}_\lambda$	$E_\lambda . \bar{y}_\lambda . R_\lambda$	$E_\lambda . \bar{z}_\lambda$	$E_\lambda . \bar{z}_\lambda . R_\lambda$
400	0.821	0.034	0.028	0.003	0.002	0.139	0.114
420	0.887	0.792	0.703	0.081	0.072	3.780	3.352
440	0.907	1.896	1.719	0.305	0.277	9.735	8.828
460	0.872	1.978	1.725	0.859	0.749	11.523	10.045
480	0.799	0.718	0.573	2.135	1.705	6.770	5.407
500	0.690	0.037	0.025	4.886	3.369	2.299	1.585
520	0.551	1.523	0.840	9.653	5.323	0.747	0.412
540	0.401	5.674	2.274	14.464	5.797	0.201	0.080
560	0.292	12.437	3.637	17.484	5.112	0.005	0.001
580	0.199	20.546	4.095	17.580	3.504	-0.002	0.000
600	0.205	25.372	5.209	14.906	3.060	0.000	0.000
620	0.192	21.593	4.144	10.081	1.935	0.000	0.000
640	0.275	12.159	3.345	5.062	1.393	0.000	0.000
660	0.613	4.635	2.843	1.819	1.116	0.000	0.000
680	0.876	1.394	1.221	0.540	0.473	0.000	0.000
700	0.949	0.376	0.356	0.143	0.135	0.000	0.000
Sums		111.162	32.735	100.000	34.021	35.195	29.826

$$X = k \int_{\text{Min}\,\lambda}^{\text{Max}\,\lambda} E_\lambda \, \bar{x}_\lambda \, R_\lambda \, d\lambda$$

$$Y = k \int_{\text{Min}\,\lambda}^{\text{Max}\,\lambda} E_\lambda \, \bar{y}_\lambda \, R_\lambda \, d\lambda$$

$$Z = k \int_{\text{Min}\,\lambda}^{\text{Max}\,\lambda} E_\lambda \, \bar{z}_\lambda \, R_\lambda \, d\lambda$$

here $k = 1$

$$x = \frac{X}{X+Y+Z} \quad , \quad y = \frac{Y}{X+Y+Z} \quad , \quad z = \frac{Z}{X+Y+Z}$$

$L^* = 116\,(Y/Y_n)^{1/3} - 16$

$a^* = 500\,[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}]$

$b^* = 200\,[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]$

X_n Y_n Z_n SUM(H10:H25)

Tristimulus Values		Chromaticity Coordinates		CIE Lab Values	
X =	32.74	x =	0.3389	L* =	64.98
Y =	34.02	y =	0.3522	a* =	-16.39
Z =	29.83	z =	0.3088	b* =	-49.64

=116*POWER(D32/E26,1/3)-16

=500*(POWER((D31/C26),1/3)-(POWER((D32/E26),1/3)))

=200*(POWER((D32/E26),1/3)-(POWER((D33/G26),1/3)))

=D31/($D31+$D32+$D33)

=D32/($D31+$D32+$D33)

=D33/($D31+$D32+$D33)

Excel spreadsheet

Spreadsheet colour difference calculation

Excel spreadsheet

CIE Colour Difference Calculation

	L*	a*	b*	ΔL*	Δa*	Δb*	ΔC*
Reference	64.98	-16.39	-49.64				
Sample	63.77	-15.95	-49.32	1.21	-0.44	-0.32	1.3

=B6-B8

=C6-C8

=D6-D8

=POWER((POWER(E8,2)+POWER(F8,2)+POWER(G8,2)),1/2)

CIELUV colour space

CIELAB colour space is not quite visually uniform.

CIELUV colour space is more uniform but it has not proved as popular as the simpler CIELAB formulae.

$$L^* = 116\left(Y/Y_n\right)^{1/3} - 16$$

$$u^* = 13L^*\left(u' - u'_n\right)$$

$$v^* = 13L^*\left(v' - v'_n\right)$$

where $u' = 4X / (X + 15Y + 3Z)$ and $v' = 9Y / (X + 15Y + 3Z)$

and u'_n and v'_n are the u' and v' values calculated using X_n, Y_n and Z_n respectively.

Colour differences in **CIELUV colour space** are given by:

$$\Delta E = \left[(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2\right]^{1/2}$$

The CMC conformity system

The CMC (l:c) equation:

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

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

$S_L = 0.040975L_1^*/(1+0.01765L_1^*)$ unless $L_1^* < 16$ then $S_L = 0.511$

$S_C = 0.0638C_1^*/(1+0.0131C_1^*) + 0.638$

$S_H = S_C(Tf + 1 + f)$

$f = \{(C_1^*)^4/[(C_1^*)^4 + 1900]\}^{1/2}$

$T = 0.36 + |0.4\cos(h_1 + 35)|$

unless $164^o < h_1 < 345^o$, then $T = 0.56 + |0.2\cos(h_1 + 168)|$

and L_1^*, C_1^* and h_1 refer to the standard.

- The various constants are chosen so that l and c are set equal to unity and in this case the equation is referred to as the CMC (1:1) formula.
- This formula is the most reliable yet developed for relating perceived colour differences to instrumental measurements for colour differences of up to 10 CIELAB units.
- This formula is under consideration for adoption by the CIE to supersede the simpler CIELAB and CIELUV formulae.

The CIE 1994 acceptability formula

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

where:

S_L = 1, SC = 1 + 0.45 C*
S_H = 1 + 0.0015 C* are weighting factors
k_L, k_C and k_H are correction factors.

- In the textile industry, k_L = 2 and k_C = k_H = 1.
- When correction factors other than k_L = k_C = k_H = 1 are used, the factors should be specified.
- Thus for textiles, the appropriate terminology is ΔE*94 (2:1:1) or CIE 94 (2:1:1).

The practical use of colour difference formulae

Appropriate pass/fail criteria are selected along the following lines:

a. accept

- if $\Delta E <$ pass/fail value

b. marginal

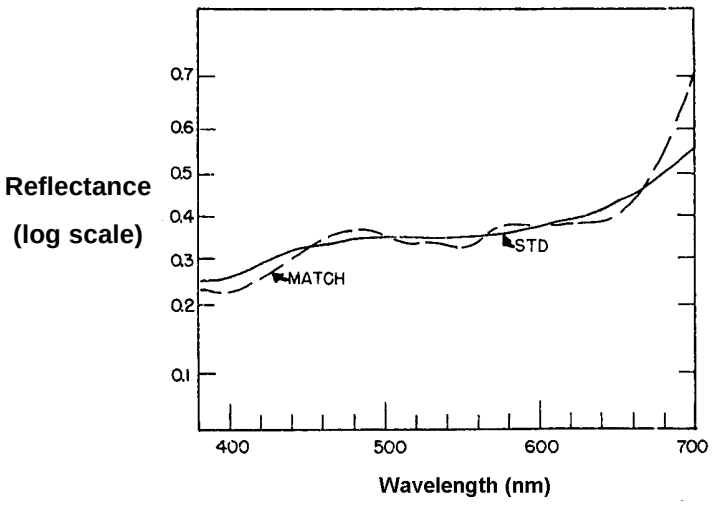
- if pass/fail value $< \Delta E <$ borderline tolerance value

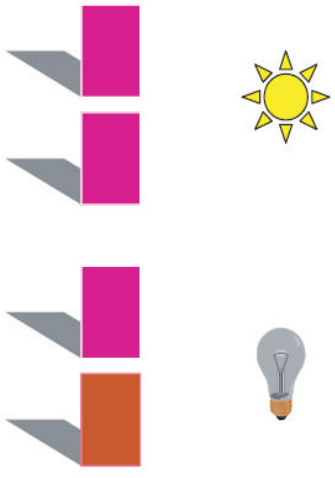
c. reject

- if $\Delta E >$ borderline tolerance value.

Metamerism

Metamerism occurs when two colours match under one set of illumination and viewing conditions, but fail to match under a second set of conditions.





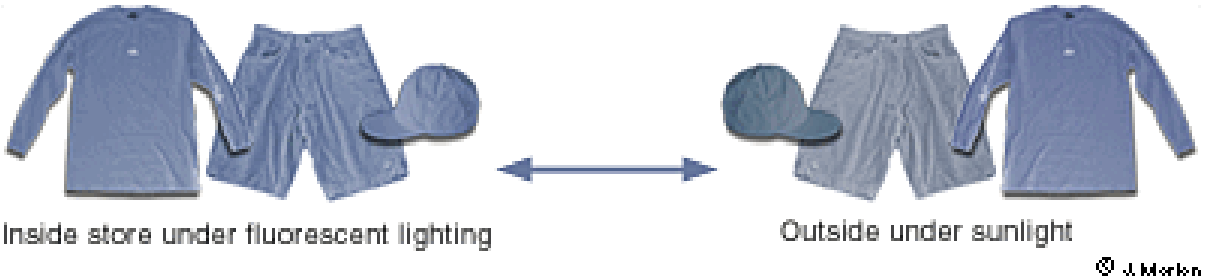
The reflectance curves of a metameric pair of samples cross **at least** at **three** wavelengths.

Four types of metamerism are recognised

- **Illuminant metamerism** is the most common type. A pair of samples match when viewed under one illuminant (say illuminant D65) but appear different when viewed under another illuminant (say illuminant C).
- **Observer metamerism** is exhibited when a metameric pair matches for one person, but fails to match for a second person. In this case, the wavelength sensitivities of the two people are different.
- **Field size metamerism** occurs when the field viewing angle changes with a single observer; for example from 2o to 10o.
- **Geometric metamerism** occurs when the viewing geometry changes.

Metamerism index

Someone who buys a coordinated outfit expects the jacket and slacks to match in daylight as well as under the fluorescent lights of the department store.



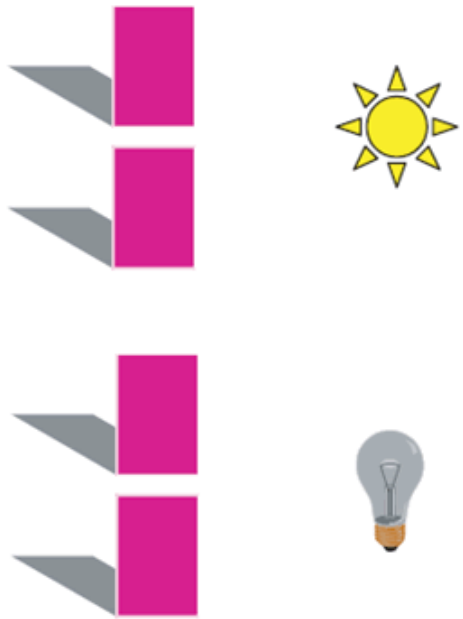
Metamerism index (MI) is a single-number index which indicates how well two materials that match under one illuminant will match under another illuminant.

$$MI = \sqrt{(\Delta L_{n1} - \Delta L_{n2})^2 + (\Delta a_{n1} - \Delta a_{n2})^2 - (\Delta b_{n1} - \Delta b_{n2})^2}$$

where n_1 is the first illuminant, n_2 is the second illuminant, and ? = $Value_{sample}$ - $Value_{standard}$.

Colour constancy

Colour constancy is a property of a single sample and it appears to be more or less the same colour when viewed under different light sources.



Measurement of whiteness

- CIE whiteness index, W:

$$W = Y + 800(x_n - x) + 1700(y_n - y)$$

where x, y and Y are the appropriate chromaticity and tristimulus values under illuminant D65,

and x_n and y_n are the chromaticity coordinates of the light source under which the sample is viewed.

- A perfectly white material will have a W value of 100.
- Samples treated with fluorescent whitening agents can give values as high as 150.

Measurement of yellowness

The yellowness index (YI) of a sample is defined as:

$$YI = 100(X-Y)/Y$$

A more suitable **yellowness index** formula has been defined by the American Society for Testing Materials (ASTM) in their Test Method D1925 as:

$$YI = \frac{128X - 106Z}{Y}$$

The whiter the substrate, the lower the yellowness index.

Visual assessment of samples

Requirements for a good quality colour matching cabinet:

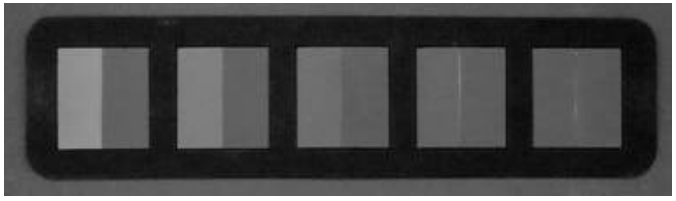
- **working space** should be at least about 700 cm in width and 40 cm in depth
- cabinet at a **comfortable height** so samples can be viewed under approximate d/0 conditions by holding the samples at about 45 degrees at a comfortable reading distance
- **even, diffuse illumination** which is no brighter than light entering a south-facing skylight window (southern hemisphere) in summer
- **switch-selectable light sources** to simulate illuminants A, C or D65, and a fluorescent lamp such as TL84 and a UV Blacklight (to reveal the presence of fluorescent dyes and optical brightening agents)
- **neutral grey walls**.

A colour matching cabinet

Grey scales

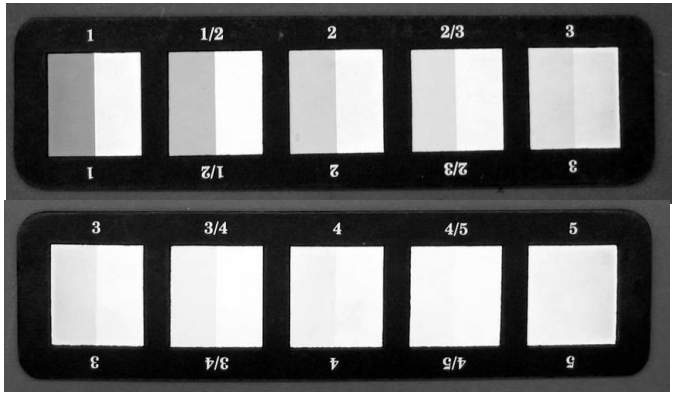
CIELAB colour differences corresponding to **colour changes and staining on the standard grey scales**, according to ISO recommendations.

Grade	Effect scale ISO 105-A02	Staining scale ISO 105-A03
5	0	0
4-5	0.8	2.2
4	1.7	4.3
3-4	2.5	6.0
3	3.4	8.5
2-3	4.8	12.0
2	6.8	16.9
1-2	9.6	24.0
1	13.6	34.1



1 2 3 4 5

Colour change.



Staining.

Reference viewing conditions

The reference viewing conditions for colour matching are:

- illumination by a source simulating **illuminant D65**
- lighting level of about **1000 lux**
- the **surroundings should be a uniform, neutral grey colour** with lightness L* = 50
- the dimensions of the sample and the observation distance should be arranged so that the **field of vision is greater than a solid angle of four degrees**
- the **samples should be placed side by side**, so that any lines of separation will be as imperceptible as possible
- the structure, texture and colour should be as **uniform as possible**
- for wool, the **samples should be at standard regain**.

3. Instrumental colour matching

The effect of dyestuff concentration on reflectance

When reflectance spectra are converted to K/S spectra, the plots obtained are similar to absorption spectra.
The height of a peak in the K/S spectrum is proportional to the concentration of dye in the substrate:

$$K/S = \frac{(1-R)^2}{2R} = kc + a$$

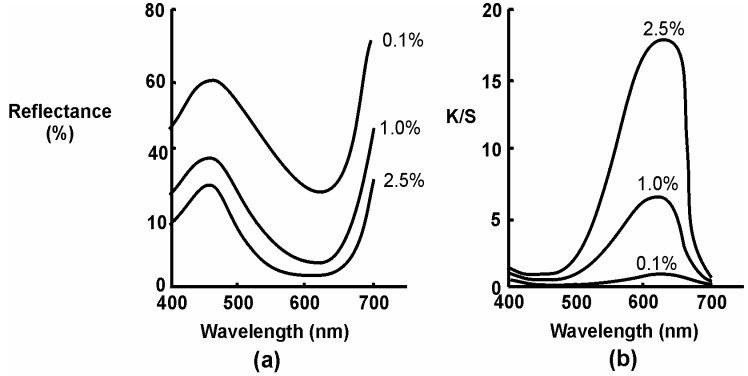
where: k is a constant equal to the gradient of the plot of K/S versus concentration,
a is a small positive intercept on the K/S axis
c is the concentration of dyestuff.

The value of a is actually the K/S value of the substrate, which can be written $(K/S)_S$
So:

$$K/S = kc + (K/S)_S$$

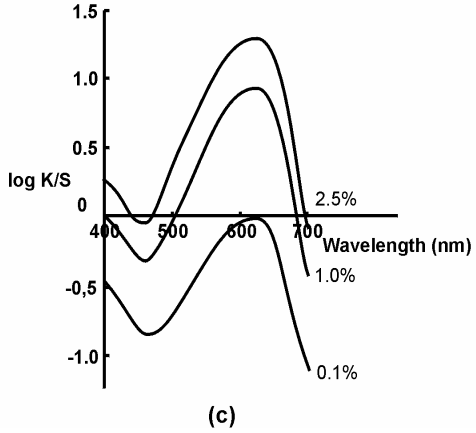
Variation in reflectance, K/S and log (K/S) with wavelength at different concentrations of dye

When the logarithm of the K/S values is plotted against wavelength, the resulting curves are found to be parallel.



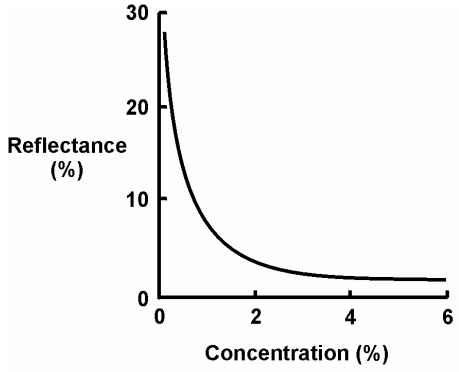
The graphs show different ways of plotting the same spectral data obtained from dyeings of Lanasyn Brilliant Blue FBL on wool at concentrations by weight of 0.1%, 1.0% and 2.5%.

(a) Reflectance vs wavelength.
(b) K/S vs wavelength.
(c) log(K/S) vs wavelength.

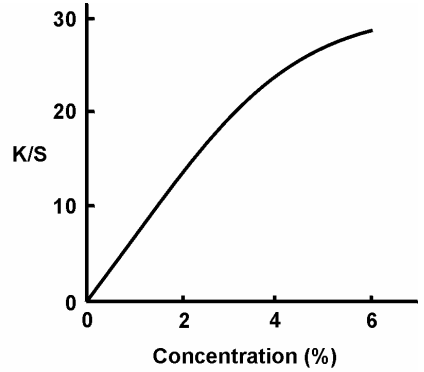


The effect of concentration on reflectance, K/S and log (K/S)

When K/S versus concentration data are plotted on log/log scales, a strait line is obtained over the usual concentration range for dyes on textiles.

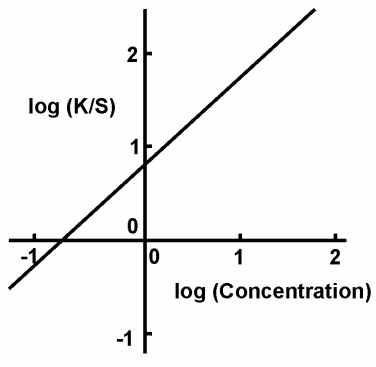


(d)



(e)

The graphs show the variation in concentration with measurements at 620 nm of dyeings with Lanasyn Brilliant Blue FBL on wool, (d) reflectance values, (e) K/S values, and (f) log (K/S) vs log (concentration).



(f)

Requirements for successful recipe prediction

The samples should fulfill the requirements of Kubelka-Munk theory:

- the fibres should be evenly dyed
- the dyestuff concentration inside the fibres must be accurately known
- the dyeings should have come to equilibrium
- the fibres should be free from ring dyeing.

Recipe prediction method

At any wavelength, when a substrate is dyed with a mixture of dyes:

$$(K/S)_{total} = k_1 c_1 + k_2 c_2 + k_3 c_3 + \ldots + (K/S)_S$$

where: the numerical subscripts denote the component dyes in the mixture.

k is sometimes called a 'normalised (K/S) value' or an 'absorption coefficient'.

$(K/S)_S$ is the K/S value of the substrate at that wavelength.

The term $(K/S)_S$ takes into account the fact that the substrate behaves as though it is a colourant of constant concentration.

Colour match prediction procedure

- The **spectrum** of the standard (i.e. sample to be matched) must be measured to obtain the $(K/S)_{total}$ values at a minimum of **16 wavelengths.**
- The **tristimulus values** X_{std}, Y_{std}, Z_{std} are then **computed**.
- A set of optimised concentrations of selected dyes, c_1, c_2, c_3 … etc. (for dyes 1, 2, 3 … etc.) are computed by solving the **16 simultaneous equations** relating K/S values at the 16 wavelengths to the dye concentrations, using predetermined k values for the dyes (absorption coefficient data).

First predicted matching

- From the values of c_1, c_2, c_3 etc., the predicted values of $(K/S)_{pred}$ at each wavelength and the corresponding tristimulus values X_{pred}, Y_{pred}, Z_{pred} are calculated.
- The differences between the tristimulus values of the standard and the first prediction are then:

$$\Delta X = X_{std} - X_{pred}$$
$$\Delta Y = Y_{std} - Y_{pred}$$
$$\Delta Z = Z_{std} - Z_{pred}$$

- If the values of ΔX, ΔY and ΔZ are all less than a predetermined maximum tolerance value found by trial and error (say 1% of X_{std}, Y_{std}, Z_{std} respectively), then the colour difference between the standard and predicted match is calculated for illuminant C to give $(\Delta C)_C$.
- If $(\Delta C)_C$ is less than a predetermined maximum tolerance value (say 0.5 CIE units), the degree of metamerism is calculated (say $(\Delta C)D65 < 2$ CIE units) and the match accepted.
- Otherwise correction factors are calculated for the dye concentrations in an attempt to improve the match.

Colour correction

The aim of colour correction calculations is to calculate additions (or subtractions) to a starting dye recipe in an attempt to obtain an improved match using tristimulus functions.

- By changing c_1, c_2, c_3 etc., each in turn, by 1%, the corresponding changes in X_{pred}, Y_{pred} and Z_{pred} are calculated.
- $(c_1)_{corr}$, $(c_2)_{corr}$, $(c_3)_{corr}$ etc. are then used to calculate a set of new predicted K/S values at the 16 wavelengths and thence obtain new tristimulus values of X_{pred}, Y_{pred} and Z_{pred}.
- Then the colour difference between the standard and new predicted match is calculated for illuminant C $[(\Delta C)_C]$, as before, and the tolerances evaluated.
- The procedure is repeated till the colour difference falls under the tolerance limit, or the limit set for the number of iterations to be carried out is exceeded.
- If a match cannot be found, an alternative combination of dyes is selected and the procedure is repeated for all possible specified combinations of dyes.

Colour correction calculations

This table shows the dye concentrations and corresponding tristimulus values for colour correction calculations

Sample	Dye concentrations			Tristimulus values		
Standard				X_{std}	Y_{std}	Z_{std}
Predicted	c_1	c_2	c_3	X_{pred}	Y_{pred}	Z_{pred}
Predicted	$c_1 + c_1/100$	c_2	c_3	X_1	Y_1	Z_1
Predicted	c_1	$c_2 + c_2/100$	c_3	X_2	Y_2	Z_2
Predicted	c_1	c_2	$c_3 + c_3/100$	X_3	Y_3	Z_3

A matrix is formed:

$$\begin{bmatrix} \frac{dX_1}{dc_1} & \frac{dX_2}{dc_2} & \frac{dX_3}{dc_3} \\ \frac{dY_1}{dc_1} & \frac{dY_2}{dc_2} & \frac{dY_3}{dc_3} \\ \frac{dZ_1}{dc_1} & \frac{dZ_2}{dc_2} & \frac{dZ_3}{dc_3} \end{bmatrix}$$

where $dX_1 = X_1 - X_{pred}$,
$dY_1 = Y_1 - Y_{pred}$,
$dZ_1 = Z_1 - Z_{pred}$
$dc_1 = c_1/100$
etc.

The inverse of this matrix is:

$$\begin{bmatrix} \frac{\partial c_1}{\partial X_1} & \frac{\partial c_1}{\partial Y_1} & \frac{\partial c_1}{\partial Z_1} \\ \frac{\partial c_2}{\partial X_2} & \frac{\partial c_2}{\partial Y_2} & \frac{\partial c_2}{\partial Z_2} \\ \frac{\partial c_3}{\partial X_3} & \frac{\partial c_3}{\partial Y_3} & \frac{\partial c_3}{\partial Z_3} \end{bmatrix}$$

Corrections Δc_1, Δc_2, Δc_3 to c_1, c_2, c_3 respectively, are obtained by solving this equation using matrix algebra:

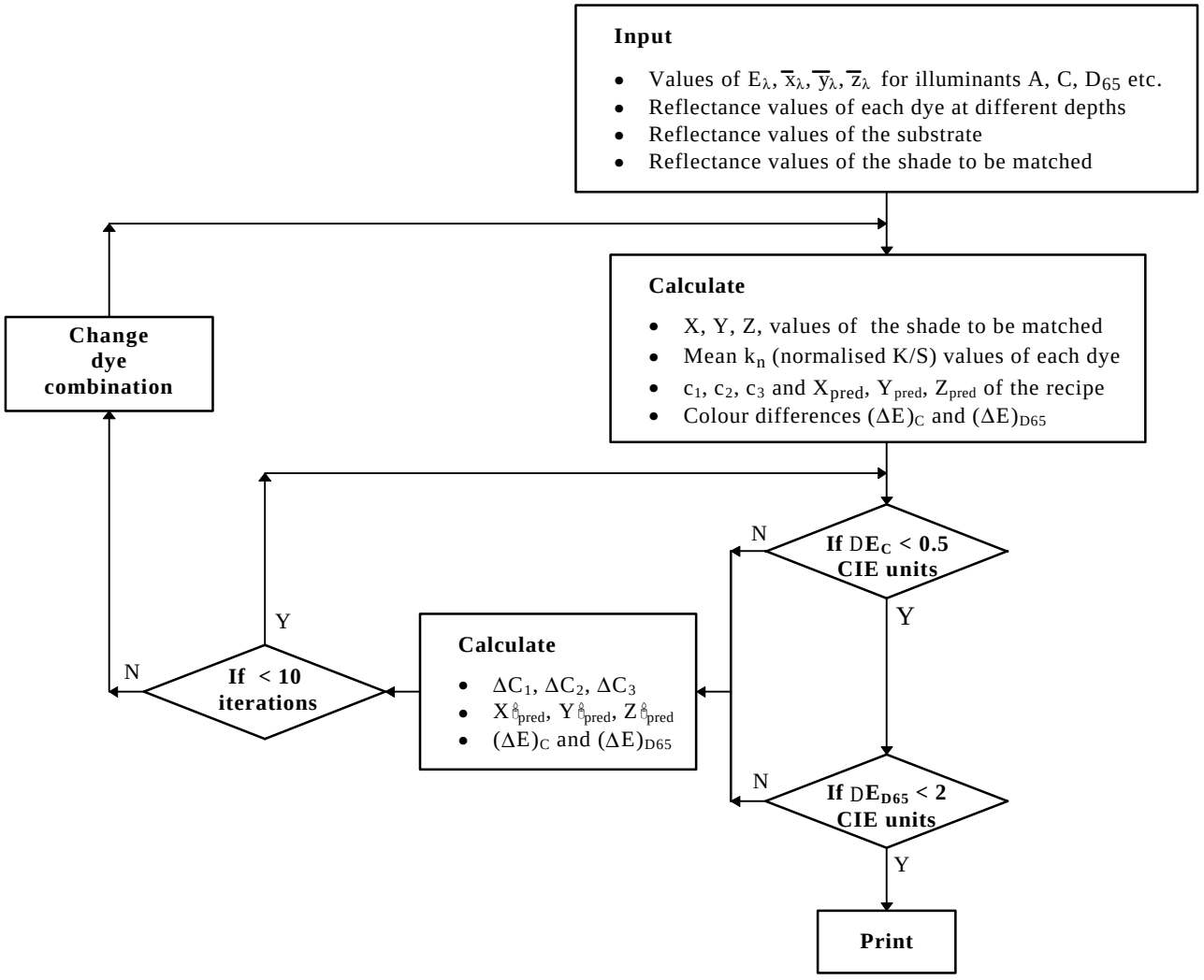
$$\begin{bmatrix} \Delta c_1 \\ \Delta c_2 \\ \Delta c_3 \end{bmatrix} = \begin{bmatrix} \frac{\partial c_1}{\partial X_1} & \frac{\partial c_1}{\partial Y_1} & \frac{\partial c_1}{\partial Z_1} \\ \frac{\partial c_2}{\partial X_2} & \frac{\partial c_2}{\partial Y_2} & \frac{\partial c_2}{\partial Z_2} \\ \frac{\partial c_3}{\partial X_3} & \frac{\partial c_3}{\partial Y_3} & \frac{\partial c_3}{\partial Z_3} \end{bmatrix} \times \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix}$$

$$\Delta c_1 = \frac{\partial c_1}{\partial X_1}\Delta X + \frac{\partial c_1}{\partial Y_1}\Delta Y + \frac{\partial c_1}{\partial Z_1}\Delta Z$$

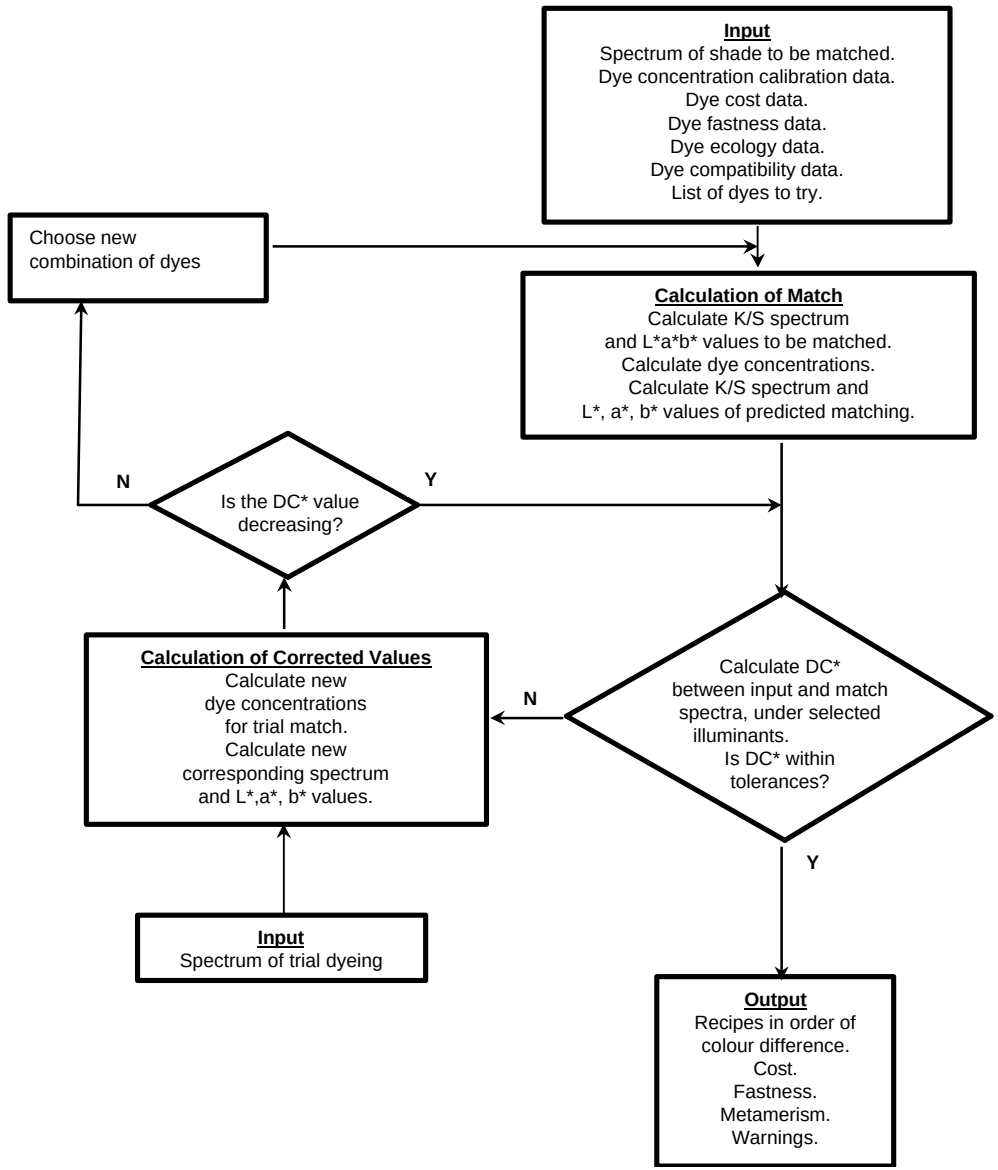
Therefore the corrected value of c_1 is: $(c_1)_{corr} = c_1 + \Delta c_1$

And corrected values of c_2 and c_3 are obtained in a similar way.

A flow chart for colour recipe prediction

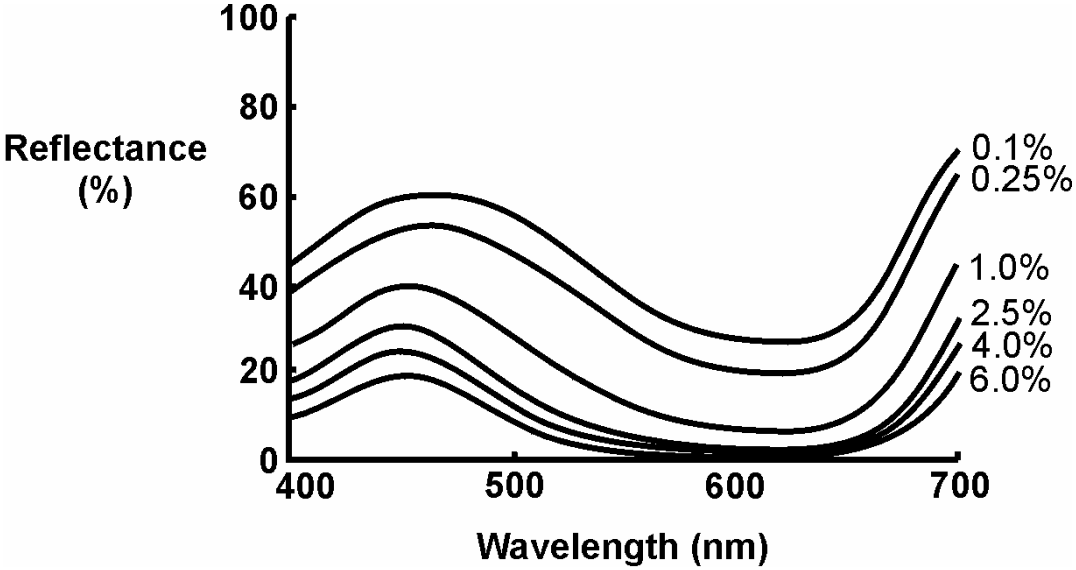


Practical Recipe Prediction Program



Practical reference data for instrumental colour matching

Typically, a series of dyeings on each particular substrate must be carried out at a range of at least six concentrations varying from say 0.1% to 5%:



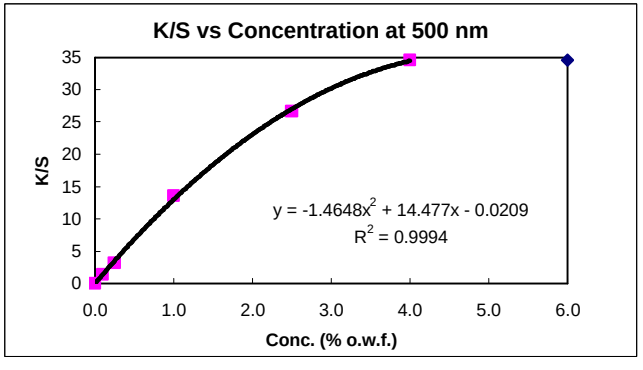
Calibration data for Lanasyn Brilliant Blue FBL on wool top.

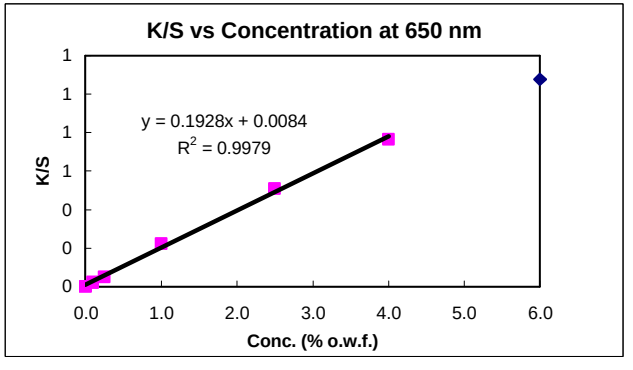
Typical reference data for instrumental colour matching

REFLECTANCE DATA

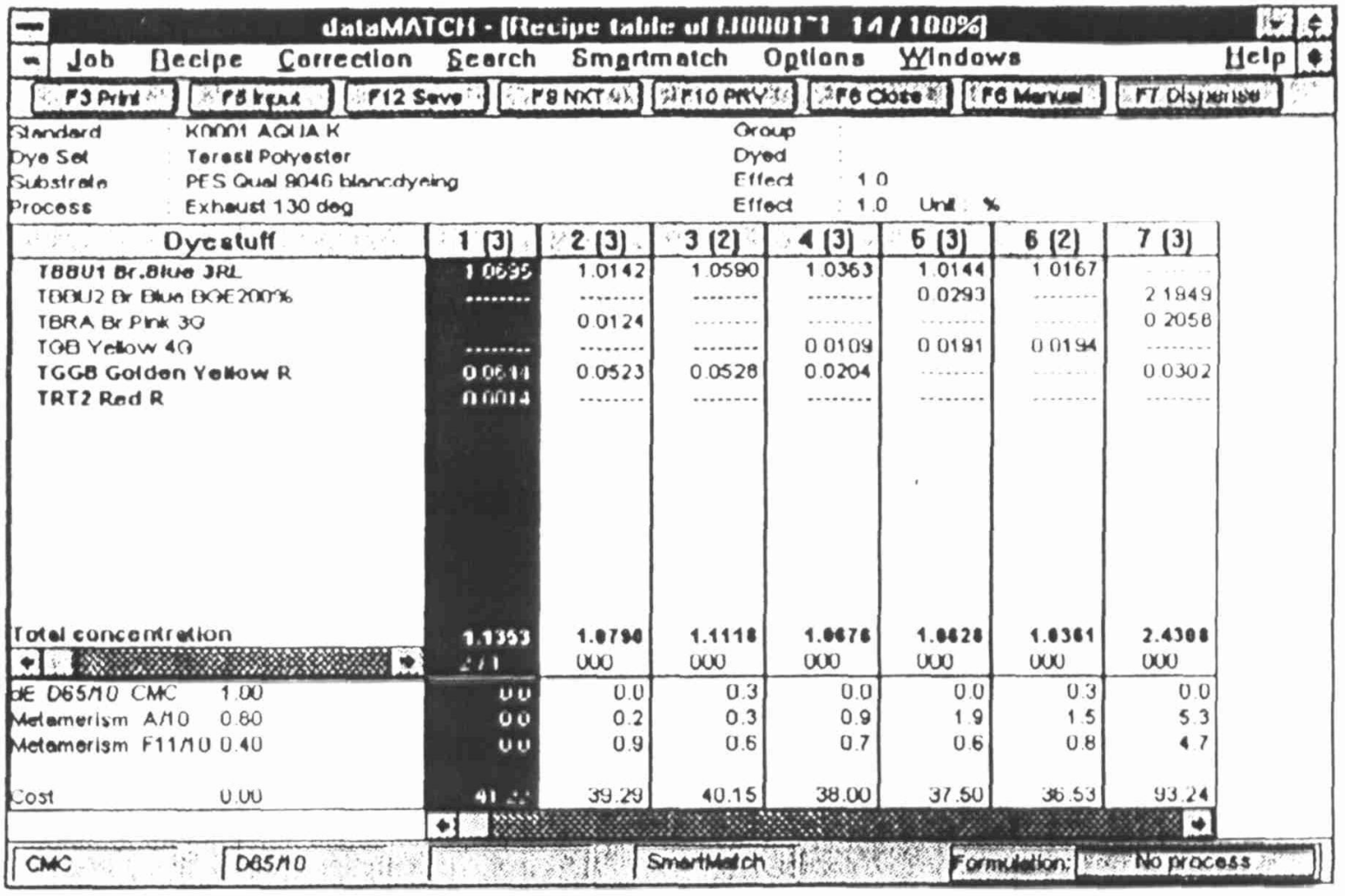
Lanaset Red G

Wavelength	500 nm				650 nm			
	Reflectance (%)	K/S	log (K/S)	(K/S)corr	Reflectance (%)	K/S	log (K/S)	(K/S)corr
Wool	57.8	0.15	-0.81		71.6	0.06	-1.25	
Dye Concentration (%o.w.f.)								
0	57.8	0.15	-0.81	0.00	71.6	0.06	-1.25	0.00
0.10	20.6	1.53	0.18	1.38	67.6	0.08	-1.11	0.02
0.25	11.6	3.37	0.53	3.21	63.4	0.11	-0.98	0.05
1.00	3.4	13.72	1.14	13.57	48.2	0.28	-0.56	0.22
2.50	1.8	26.79	1.43	26.63	36.2	0.56	-0.25	0.51
4.00	1.4	34.72	1.54	34.57	29.9	0.82	-0.09	0.77
6.00	1.4	34.72	1.54	34.57	24.9	1.13	0.05	1.08





Output from a recipe prediction program



dataMATCH - [Recipe table of K0001~1 14 / 100%]

Job Recipe Correction Search Smartmatch Options Windows Help

F3 Print F5 Input F12 Save F9 NXT 0% F10 PRV 0% F6 Close F6 Manual F7 Dispense

Standard	K0001 AQUA K	Group	
Dye Set	Terasil Polyester	Dyed	
Substrate	PES Qual 9046 blancdyeing	Effect	1.0
Process	Exhaust 130 deg	Effect	1.0 Unit: %

Dyestuff	1 (3)	2 (3)	3 (2)	4 (3)	5 (3)	6 (2)	7 (3)
TBBU1 Br.Blue 3RL	1.0635	1.0142	1.0590	1.0363	1.0144	1.0167	.....
TBBU2 Br Blue BGE200%	.....	.....	.....	.....	0.0293	.....	2.1949
TBRA Br Pink 3G		0.0124	.....	.....	.....	.....	0.2058
TGB Yellow 4G	.....	.....	.....	0.0109	0.0191	0.0194	.....
TGGB Golden Yellow R	0.0644	0.0523	0.0528	0.0204	.....	.....	0.0302
TRT2 Red R	0.0014	.....	.....	.....	.....	.....	.....
Total concentration	1.1353	1.0790	1.1118	1.0676	1.0628	1.0361	2.4308
	2 / 1	000	000	000	000	000	000
dE D65/10 CMC 1.00	0.0	0.0	0.3	0.0	0.0	0.3	0.0
Metamerism A/10 0.80	0.0	0.2	0.3	0.9	1.9	1.5	5.3
Metamerism F11/10 0.40	0.0	0.9	0.6	0.7	0.6	0.8	4.7
Cost 0.00	41.22	39.29	40.15	38.00	37.50	36.53	93.24

CMC | D65/10 | SmartMatch | Formulation: No process

Colour matching on blends

- It is assumed that the total light absorbance of the blended fibres is the sum of the component light absorbance values.

$$f(R) = a.f(R_1) + b.f(R_2) + c.f(R_3)$$

where a, b and c are the proportions of the different types of fibres present, $(a + b + c = 1)$,

R is the reflectance of the blend sample and

R_1, R_2, R_3 are the reflectance values of the three individual component fibres.

Also for each fibre type:

$$f(R) = \exp [- S(1 - R)2/2R]$$

where S is an experimentally optimised scattering factor (eg. for viscose $S = 0.28$).

- There are restrictions on the colours that can be combined if solid shade effects are to be obtained.
- Acceptable ranges of colours have been determined by trial and error.
- About 20 basic colours of dyed stock have been found necessary to produce a good gamut of blended-fibre colours.

Why use an instrumental colour matching system?

- Inventory of dyes can be reduced.
- Substitution of cheaper for expensive dyes becomes very easy.
- The number of shading additions in plant dyeings can be reduced by use of computed corrections for off-shade dyeings. “Right first time” dyeing becomes possible.
- Fewer trial laboratory dyeings are required to match new shades.
- Matches can be selected on fastness criteria, dye exhaustion and potential effluent load.

Why instrumental colour matching?

- **Inventory of dyes can be reduced**.
  - Assuming a total 15% saving of dyestuff cost on an annual dye bill of $250,000, a colour matching system costing $80,000 could be paid for in about two years.
- **Substitution of cheaper for expensive dyes becomes very easy**.
  - Computer match prediction can reduce the cost of preparing dye recipes by 10-30%.
- **Number of shading additions in plant dyeings can be reduced by use of computed corrections. 'Right first time' dyeing becomes possible.**
  - Some dyehouses report up to 96-97% of plant dyeings are 'right first time'. Each addition increases the cost of a dyeing by at least 30%, not necessarily in dye cost, but in wasted machinery and operator time and in lost production. These savings may prove to be larger than economies made on dye selection and inventory and may average around a 20% reduction in total dyeing cost.
- **Fewer trial laboratory dyeings are required** to match new shades.
  - If dyeings can be reduced from 6 to 1.3. Based on an equipment cost of say $80,000, the outlay can be justified if a laboratory is required to match more than 50 shades per week.

Optimal setup for instrumental colour matching

- Control of regain of wool to be dyed.
- Accurate weighing of goods.
- Automatic dispensing of dyes and chemicals in lab and mill.
- Computer-controlled laboratory and plant machines linked through a central computer.
- Lab results must be accurately duplicated in the mill.