CHAPTER 2

THEORETICAL CONSIDERATIONS AND LITERATURE REVIEW

Colour fastness is meant the resistance of the colour of textiles to the different agents to which these materials may be exposed during manufacture and their subsequent use (3). To investigate the acceptibility of the formulae relevant to visual assessment. There are some consideration for determination of colour fastness as follows (4).

- The colour fastness formula which is used for the calculation must be specified.
- The colour difference tolerance is dependent on the product being tested and observers.
- There is no colour fastness formula that is absolutely uniform.
- The light source for the visual assessment must as closely as possible with the standard illuminant used for the instrumental assessment.
- The observer always has a sensitivity that does not correspond with the sensitivity of the standard observer.

In order to evaluate colour fastness by instrumental method, it is necessary to study about colour order system.

2.1 Colour System

2.1.1 Munsell System

In 1905, artist Albert H. Munsell originated a colour ordering system. The Munsell system which is based on human perception assigns numerical values to the three properties of colour: hue, value and chroma, as shown in Figure 2-1 (5). Adjacent colour samples represent equal intervals of visual perception.

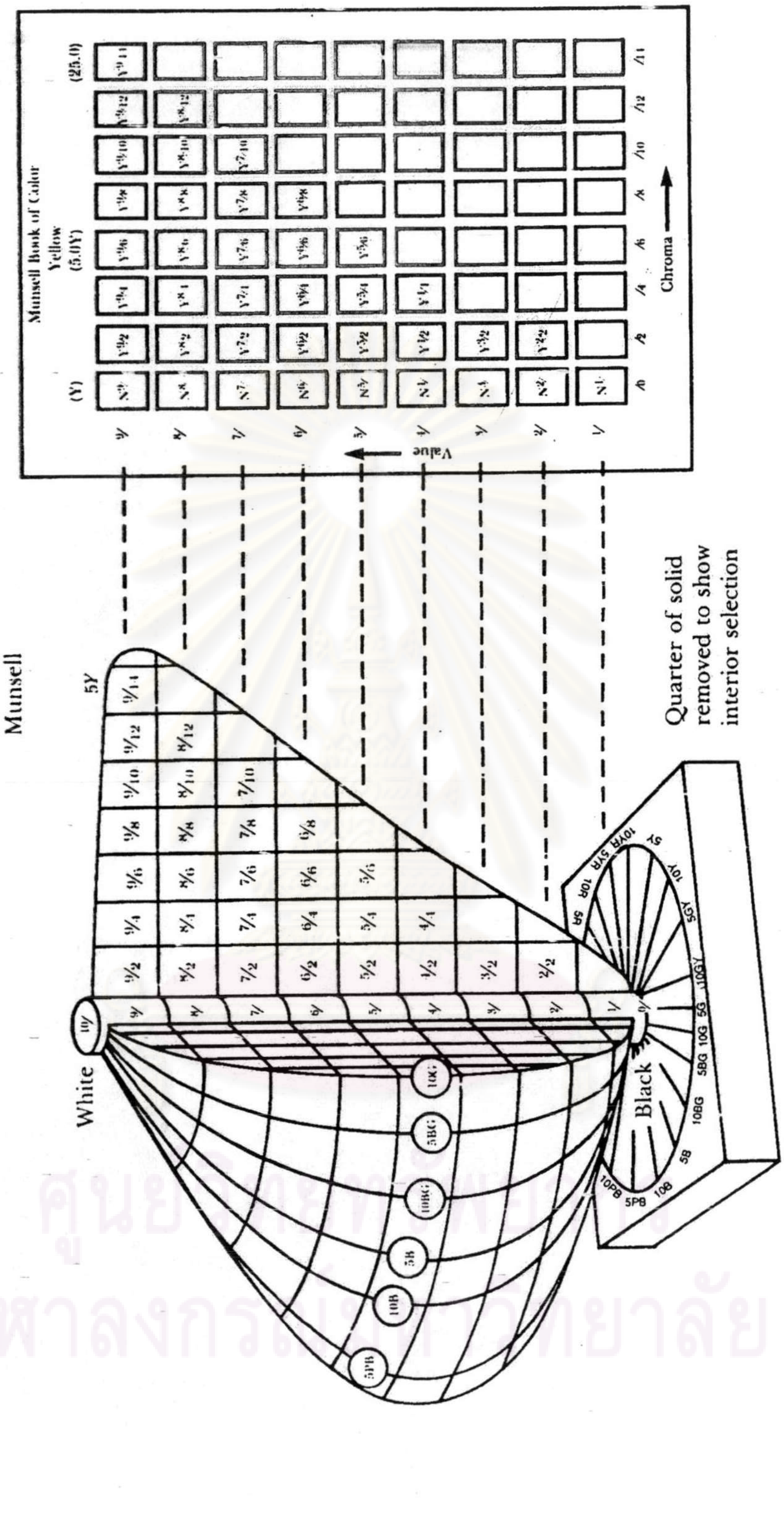

Figure 2-1 Munsell colour space

2.1.1.1 Munsell Hue

Hue is that quality of colour described by the words red, yellow, green, blue and so on. The spacing of the hue around the grey scale represent the uniform difference of perceived hue between neighboring hue pages. There are five principal hues, Red, Yellow, Green, Blue and Purple, and they are designated 5R, 5Y, 5G, 5B and 5P, respectively. The intermediate hues are designated 5YR, 5GY, 5GB, 5PB and 5RP. Finer divisions between way two major neighboring hues are represented by decimals, as shown in Figure 2-2 (5). There are ten major hues ranging in the hue circle. Each of the ten is divided into 10 hue steps. Thus, the Munsell system contains totally 100 hues.

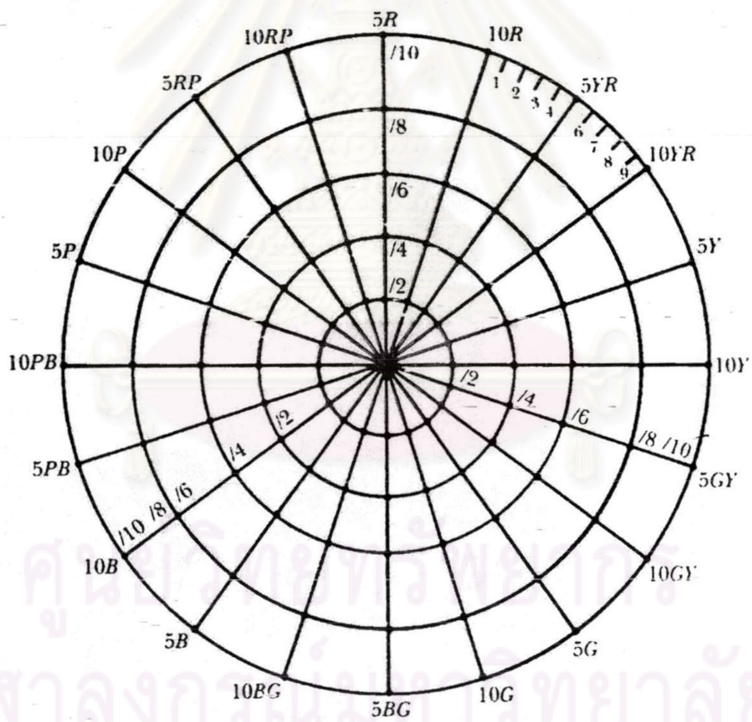

Figure 2-2 Munsell hue spacing (circumferentially) and chroma (radially)

2.1.1.2 Munsell Value

Munsell value, representing the lightness scale, is arranged in the vertical direction or the backbone of the Munsell system. Value is that quality by which a colour can be classified as equivalent in lightness to some member of the series of qrey samples ranging from white to black. It is denoted 10/ when white and 0/ when black. From decimal, there are 9 grey concentrations uniformly locating in between black and white and designating the values, as shown in Figure 2-1. For example, a value of 7.5 is perceptually midway in lightness between sample having value of 7 and 8.

2.1.1.3 Munsell Chroma

Chroma is the quality that describes the degree of difference between a colour and a grey of the same value or lightness. The distances of the samples from value axis are intended to represent uniform differences in perceived chroma and are given numbers. Typically, number 4 or less represents weak colour, and number 10 or more stands for strong colour. The scale of chroma increase in step of 2 from /0, /2, /4, so on until it reaches /10, /12, /14 and more, as shown in Figure 2-1.

2.1.2 CIELAB System

In the CIELAB system, as shown in Figure 2-3 (6), the total colour difference (ΔE^*) combines the difference of three independent variables. The colour difference can be expressed in two ways:

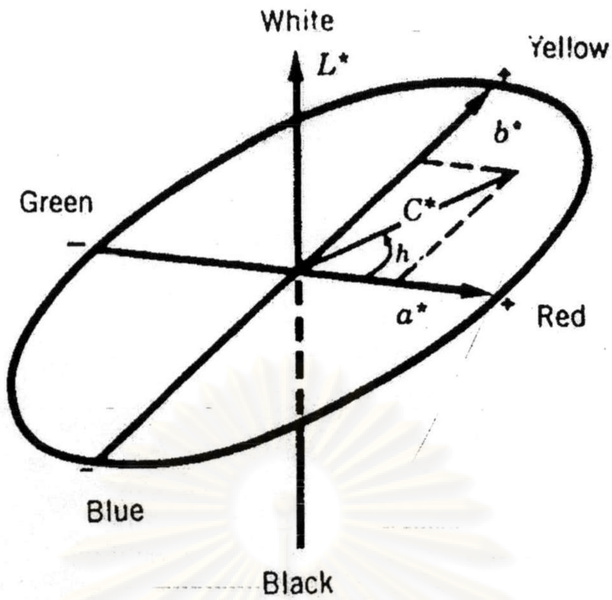

Figure 2-3 CIELAB colour space

2.1.2.1 Rectangular Coordinates.

The method of expressing The colour difference in rectangular coordinates, L*, a* and b*, uses the basic concept of the opponent colours of vision as shown in Figure 2-4 (6).

- red - green variation , with projection of the difference onto the a* axis,
- yellow - blue variation, with projection of the difference onto the b* axis.

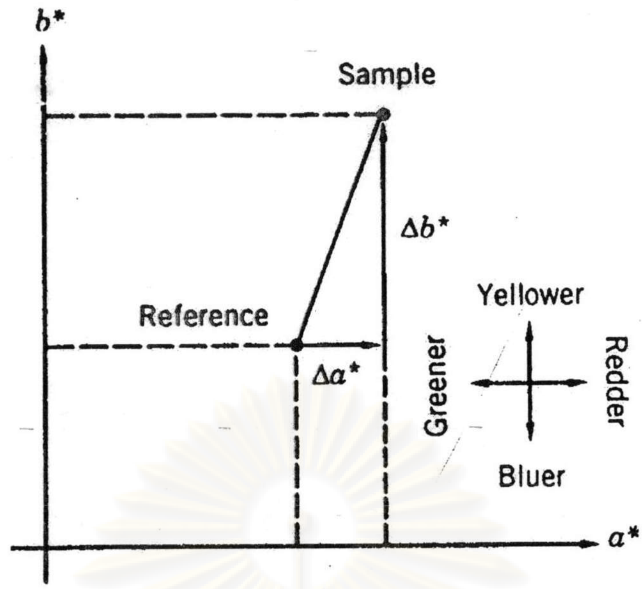

Figure 2-4 Resolution of the chromaticity difference into Δa* and Δb* in the CIELAB system

In ΔL*, expressing The lightness difference, the sign of the difference indicates the direction of the variation in relation to psychosensorial perception.

- a negative value means a shift to darker (black),
- a positive value means a shift to lighter (white)

In the same way, the projections onto the other components, a* and b*, specifying the colour plane, will express:

- Δa*, the red-green colour difference,
- Δb*, the yellow-blue colour difference.

The sign of the difference indicates the direction of the variation:

- Δa* positive means more red,
- Δa* negative means more green,

- Δb^* positive means more yellow,
- Δb^* negative means more blue.

The L* a* b* method of expressing colour differences is very practical and is frequently used by companies.

2.1.2.2 Cylindrical Coordinates

The L* C* h values of referencing in cylindrical co-ordinates in the CIELAB space are used to express colour and colour differences as we perceive them visually. They enable us to separate the hue difference (ΔH^*) from the lightness difference (ΔL^*) and the saturation difference (ΔC^*) in the total colour difference (ΔE^*) as shown in Figure 2-5 (6).

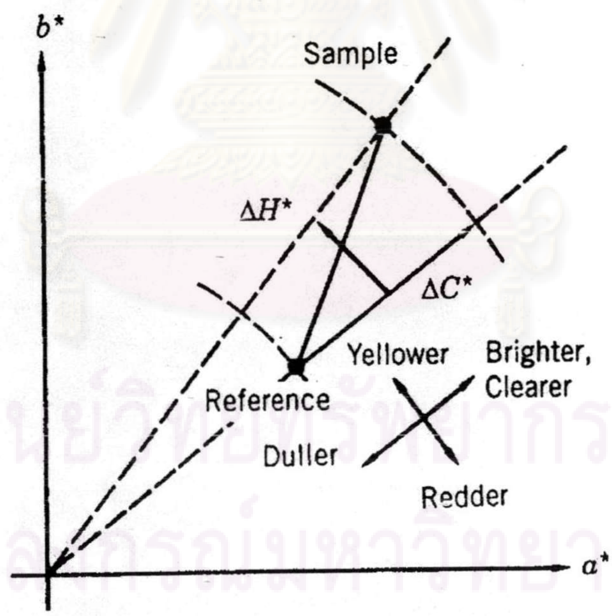

Figure 2-5 Resolution of the chromaticity difference into ΔC and ΔH in the CIELAB system

The total colour difference (ΔE^*) is broken down into its main components.

- The lightness difference (ΔL^*), whose value and interpretation is the same as in the L* a* b* system,
- The chroma difference (ΔC^*), which represents the difference of the distances between each colour point and the lightness axis.

The hue angle difference, (Δh), represents the angular difference (in degrees) between the directions of the vectors representing the two hues to be compared. This value transformed into a distance difference in order to be homogeneous with the other difference terms, becomes the metric hue difference, ΔH^*, forming part of the total colour difference, ΔE^*.

Composition of the total colour difference, ΔE^*, in ΔL^*, ΔC^* and ΔH^*, brings the expression of colour differences down to visual evaluation in the natural classification of colours. This is simple and practical and is the method used most frequently.

2.1.3 CMC Conformity System

In principle, the method begin with the basic formula for calculating colour differences in the CIELAB system. Expressed as ΔL^*, ΔC^*,ΔH^*, but we weight the lightness, chroma and hue differences with corrective terms, which themselves are related to the lightness, the chroma and the hue.

The corrective terms (S_L–S_C-S_H), have been evaluated empirically, and are give by formulae which allow them to be calculated in advance. In addition, two extra factors l and c, can modify the results according to the particular nature of the problem set, especially the acceptability of a difference.

The l and c parameters, which can be adjusted by the user, can both be taken as equal to 1, and this is the most frequent case when judging the perceptibility of colour differences. It is possible to change and increase l and c to judge acceptability (e.g. in the textile industry, l = 2 and c = 1).

The lightness difference (ΔL^*) is modified only by the lightness. It is smaller for low lightness and larger for high lightness. The chroma differences (ΔC^*) are modified by chroma only. These are generally smaller than in CIELAB, except for the smaller values of chroma (less than 6). Finally the hue differences (ΔH^*) are modified by the hue angle and by the chroma. It can be seen in particular that for the oranges, the hue differences are increased in relation to the green hues. We can conclude that the hue difference effect is significantly smaller than in CIELAB when the colours are quite saturated.

2.1.4 Dyer's Colour System

In the dye-stuff industry, colour is specified by two terms: shade and depth, shade being a two dimensional quantity comprising hue and dyer's brightness. Colour differences are estimated as pale and deep (referring to depth); red, yellow. green, blue (referring to hue); and vivid and dull (referring to dyer's brightness). Figure 2-6 show the loci of constant dyer's brightnes (solid lines) on a plot of lightness against chroma of the corresponding colour perceptions (7). Dotted lines show schematically the loci of constant strength. When dyes are absorbed by a textile material, the colour simultaneously reduces lightness and increases chroma from the undyed substrate. Subsequently the chroma reaches its maximum and starts to decrease. Using such a dyer's colour system, it is easy to evaluate the dye absorption in terms of colour depth increase only, without change in dyer's brightness (cf. Simultaneous change in lightness and chroma in colour spaces such as Munsell and CIELAB).

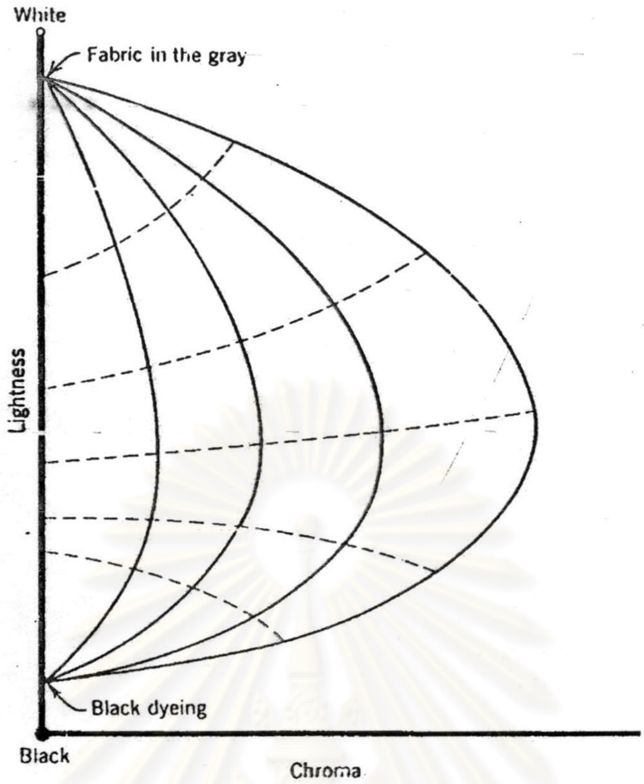

Figure 2-6 Constant loci of colour depth and dyer's brightness on a plot of lightness against chroma

2.2 Simple Linear Regression

Regression analysis (8) is a statistical technique for modeling and investigation the relationship between two or more variables. In general, suppose that there is a single dependent variable or response y that is related to k independent of regression variables, $x_1, x_2, \ldots, x_k$ The response variable y is so called a random variable, while the regression variables $x_1, x_2, \ldots, x_k$ are measured with negligible error. The regression model is fitted to a set of data. In some instances, the experimenter will know the exact form of the true functional relationship between y and $x_1, x_2, \ldots, x_k$ However, in most cases, the true functional relationship is unknown, the appropriate function to approximate the true function is carefully created. The simple model is the linear regression model, which is shown in Equation 2.1.

$$Y = \beta_0+\beta_1 x \qquad \text{Equation 2.1}$$

Where, β_0 = the intercept

β_1 = the slope

2.3 Correlation Coefficient

The correlation coefficient (9), which is denoted by *p*, is a dimensionless quantity that measures the linear association between two random variables. The estimator of *p* is the sample correlation coefficient, r, which is shown in Equation 2.2.

$$r = \sum_{i=1}^{n} y_i(x_i - \bar{x}) / [\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2]^{1/2} \qquad \text{Equation 2.2}$$

The sample correlation coefficient, r, measures the linear association between y and x, while β_1 measure the predicted change in the mean of y for a unit change in x. The meaning of r is following.

- The value of r will be on the interval [-1, +1].
- If r = 0 then y and x are not correlated.
- If the values of r are minus, the values of x are increase while the values of y are decrease and when the values of x are decrease, the values of y are increase.
- Conversely, if the values of r are plus, the values of x are increase, the values of y are increase and when the values of x are decrease, the values of y are also decrease.
- If the values of r near 1, x and y have high correlation in same direction.

- If the values of r near –1, x and y have high correlation but opposite direction.
- If the values of r near 0, the correlation between x and y are low.

2.4 Formulae for Assessing Colour Fastness

2.4.1 Formulae for Assessing Change in Colour

2.4.1.1 CIELAB Colour Difference Formula

CIELAB colour difference formula was recommended in 1976 by the CIE (Commission International de l'Eclairage). It is the result of a mathematical transformation of the CIE 1931 system. In ISO 105-A02 (grey scale for assessing change in colour), nine grades (from 1 to 5 together with the half-step fastness values) are specified in terms of CIELAB ΔE values. The formula is given in Equation 2.3.

$$\Delta E^* = [(\Delta L^*)^2+(\Delta a^*)^2+(\Delta b^*)^2]^{1/2} \qquad \text{Equation 2.3}$$

L*	=	lightness
a*	=	red–green colour component
b*	=	yellow-blue colour component

The grade was obtained using a linear interpolation method between the ΔE and grade value given in Table 2-1 (10).

Table 2-1 CIELAB ΔE values and colour fastness grades for the ISO 105-A02 grey scale for assessing change in colour

ΔE^*	Grade
$\Delta E^* < 0.40$	5
$0.40 \leq \Delta E^* < 1.25$	4-5
$1.25 \leq \Delta E^* < 2.10$	4
$2.10 \leq \Delta E^* < 2.95$	3-4
$2.95 \leq \Delta E^* < 4.10$	3
$4.10 \leq \Delta E^* < 5.80$	2-3
$5.80 \leq \Delta E^* < 8.20$	2
$8.20 \leq \Delta E^* < 11.60$	1-2
$11.60 \leq \Delta E^*$	1

2.4.1.2 CMC (l:c) Formula

The industries in which colour difference formulae are used a great deal, either to evaluate tolerances or to automate conformity testing (in the textile industry in particular), and which traditionally use the CIELAB space, have reached the conclusion that the CIELAB differences sometime lead to errors.

In Great Britain, where research has gone on continuously since 1970, a modification of the CIELAB formula has been developed progressively. This has been tested by tens of thousands of visual judgements and has finally been standardized by the British Standards Institute.

This method, which was proposed by Technical Committee (TC)38, Subcommittee 1(SC1) of ISO, is now called CMC (Color Measurement Committee of the Society of Dyers and Colorists). The formula is given in Equation 2.4(11).

$$\Delta E_{CMC} = [(\Delta L^*/lS_L)^2+(\Delta C^*/cS_c)^2+(\Delta H^*/S_H)^2]^{1/2} \qquad \text{Equation 2.4}$$

where $l = 1$ or 2

$c = 1$

$S_L = 0.040975L_o^*/(1+0.01765L_o^*)$ if $L_o^* \geq 16$

or $S_L = 0.511$ if $L_o^* < 16$

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

$S_H = S_C(fT+1-f)$

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

$T = 0.36+|0.4\cos(h_o+35)|$ if $h_o \geq 345°$ or $h_o \leq 164°$

or $T = 0.56+|0.2\cos(h_o+168)|$ if $164° < h_o < 345°$

where L^*_o : CIELAB L* of untreated specimen

C^*_o : CIELAB C* of untreated specimen

h_o : CIELAB h of untreated specimen

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

where $p = 1$ if $m \geq 0$

or $p = -1$ if $m < 0$

and $q = 1$ if $|m| \leq 180$

or $q = -1$ if $|m| > 180$

where $m = h_t - h_o$

As for the CIELAB formula, the colour fastness grade is then linearly interpolated between the ΔE_{cmc} values and grades from the standard grey scale as shown in Table 2-2.

Table 2-2 ΔE_{cmc} values and colour fastness grades

ΔE_{CMC}	Grade
$\Delta E_{CMC} < 0.20$	5
$0.20 \le \Delta E_{CMC} < 1.26$	4-5
$1.26 \le \Delta E_{CMC} < 2.15$	4
$2.15 \le \Delta E_{CMC} < 3.05$	3-4
$3.05 \le \Delta E_{CMC} < 4.20$	3
$4.20 \le \Delta E_{CMC} < 5.95$	2-3
$5.95 \le \Delta E_{CMC} < 8.40$	2
$8.40 \le \Delta E_{CMC} < 11.85$	1-2
$11.85 \le \Delta E_{CMC}$	1

2.4.1.3 ISO Formula

As for the CMC (l:c) formula, ISO standard formula was modified from the CIELAB colour difference formula to fit a number of visual judgements. It was proposed by Technical Committee (TC) 38, Subcommittee 1 (SC1) of ISO. The formula is given in Equation 2.5 (12).

$$\Delta E_F = [(\Delta L^*)^2+(\Delta C_F)^2+(\Delta H_F)^2]^{1/2} \qquad \text{Equation 2.5}$$

where

$$\Delta H_F = \Delta H_K/[1+(10C_M/1000)^2]$$

$$\Delta C_F = \Delta C_K/[1+(20C_M/1000)^2]$$

$$\Delta H_K = \Delta H^* - D$$

$$\Delta C_K = \Delta C^* - D$$

$$D = [\Delta C^* C_M \exp(-x)]/100$$

$$C_M = (C^*_t - C^*_0)/2$$

$$x = [(h_M-280)/30]^2 \quad \text{if } |h_M-280| \le 180$$

$$x = [(360-|h_M-280|)/30]^2 \qquad \text{if } |h_M-280|>180$$

$$h_M = (h_t+h_o)/2 \qquad \text{if } |h_t-h_o| \leq 180$$

$$h_M = (h_t+h_o)/2+180 \qquad \text{if } |h_t-h_o|>180 \text{ and } |h_t+h_o|<360$$

$$h_M = (h_t+h_o)/2-180 \qquad \text{if } |h_t-h_o|>180 \text{ and } |h_t+h_o| \geq 360$$

$$\Delta L^* = L^*_t - L^*_o$$

$$\Delta C^* = C^*_t - C^*_o$$

L^*_t, C^*_t, h_t ; lightness, chroma and hue of treated specimen

L^*_o, C^*_o, h_o ; lightness, chroma and hue of untreated specimen

As for the two previous formulae, the colour fastness grade is calculated via interpolation between the ΔE_F values and grades from the standard grey scale as shown in Table 2-3.

Table 2-3 ΔE_F values and colour fastness grades

ΔE_F	Grade
$\Delta E_F < 0.40$	5
$0.40 \leq \Delta E_F < 1.25$	4.5
$1.25 \leq \Delta E_F < 2.10$	4
$2.10 \leq \Delta E_F < 2.95$	3.5
$2.95 \leq \Delta E_F < 4.10$	3
$1.40 \leq \Delta E_F < 5.80$	2.5
$5.80 \leq \Delta E_F < 8.20$	2
$8.20 \leq \Delta E_F < 11.60$	1.5
$\Delta E_F \leq 11.60$	1

2.4.1.4 $N_c^{\#}$ Formula

Teraji and co-workers developed a dyer's colour system based on hue, colour depth and dyer's brightness scales, which was originated by Godlove and Judd (7). Three attributes: hue, colour depth and dyer's brightness derived from munsell coordinated. $N_c^{\#}$ formula is capable of directly calculating the fastness grade without an additional interpolating procedure as used in CIELAB, CMC and ISO formulae. The formula is given in Equation 2.6(1).

$$N_c^{\#} = 5.5-\ln\{\varepsilon(\Delta E^{**}/D_{x,o})/0.015+1\}/\ln(2) \qquad \text{Equation 2.6}$$

Where $\varepsilon = \{p((\Delta E^{**}/D^*_o))\}^h$

$p = 1.1 - 0.65\cos(3.6^{\circ} x \Delta H_{5Y})$

$h = 0.3$

$\Delta E^{**} = [f_1 x 2 C_o C_t (1-\cos(3.6^{\circ} x \Delta H)+f_2(\Delta D^*)^2+f_3(\Delta B^*(10-V_t)V_t/25)^2]^{1/2}$

$f_1 = 0.5$

$f_2 = 1$

$f_3 = 1$

$B^* = 10xC/\{V(10-V)\}$

D^* : colour depth

ΔH : Munsell hue step difference, $|H_t - H_o|$

V : Munsell value

C : Munsell chroma

ΔH_{5P} : Munsell hue step difference from 5P, $0 \le \Delta H_{5P} \le 50$, $|H_t - H_{5P}|$

B^* : dyer's brightness

ΔE^{**} : total colour difference

2.4.1.5 F_C Formula

F_C formula is based on dyer's colour system as for the $N_C^{\#}$ formula but the three attributes: hue, colour depth and dyer's brightness derived from CIELAB coordinates. F_C formula is capable of directly predicting the grade of the colour fastness. The formula is given in Equation 2.7 (1).

$$F_C = 5-5\,\{k_1(\Delta E_{DBH}/D_o)\}^{k2} \qquad \text{Equation 2.7}$$

$$\Delta E_{DBH} = [(\Delta D)^2+\{\Delta B_D(100-L^*_t)L^*_t/2000\}^2+2C'_oC'_t\{1-\cos(\Delta h)\}]^{1/2}$$

$$k_1 = 2+0.0005\,(1+0.00005\Delta h_{290,0}\,C'_o)D_o^{\,2}$$

$$k_2 = 0.6+0.00004\Delta h_{290,0}C'_o$$

$$D = 100-L^* +(0.1+\Delta h_{290}/360)(1-\Delta h_{290}/360)C^*$$

$$B_D = 2000(1-\Delta h_{290}/360)C^*/(L^*(100-L^*))$$

$$C' = (1-\Delta h_{290}/360)C^*$$

where, L^* : lightness

C^* : chroma

C' : improved metric chroma

D : color depth

B_D : dyer's brightness

ΔD : depth difference between treated specimen and untreated specimen, $\Delta D = D_t - D_o$

ΔB_D : brightness difference between treated specimen and untreated specimen , $\Delta B_D = B_{Dt} - B_{DO}$

Δh : metric hue angle difference between treated specimen and untreated specimen, $\Delta h = | h_t - h_o |$

Δh_{290} : metric hue angle difference from h = 290

2.4.2 Formulae for Assessing Staining

2.4.2.1 CIELAB Colour Difference Formula

The CIELAB formula is test as both change in colour and staining formula in this study. In the ISO 105: A03 (grey scale for assessing staining), nine grades (from 1 to 5 together with the half step fastness) are specified in terms of CIELAB ΔE values as given in Equation 2.3. The grade is obtained using the conversion table between the ΔE^* and grade values in Table 1-4 (13).

Table 2-4 CIELAB colour difference value for each staining fastness grade

ΔE^*	Grade
$\Delta E^* < 1.10$	5
$1.10 \leq \Delta E^* < 3.25$	4-5
$3.25 \leq \Delta E^* < 5.15$	4
$5.15 \leq \Delta E^* < 7.25$	3-4
$7.25 \leq \Delta E^* < 10.25$	3
$10.25 \leq \Delta E^* < 14.45$	2-3
$14.45 \leq \Delta E^* < 20.45$	2
$20.45 \leq \Delta E^* < 29.05$	1-2
$29.05 \leq \Delta E^*$	1

2.4.2.2 SSR (UK) Formula

The SSR(UK) formula was developed by the members in the CMC, UK. This formula is given as Equation 2.8 (2).

$$SSR(UK) = 7.05 - 1.43 \ln(\Delta E^* + 4.4) \qquad \text{Equation 2.8}$$

The grade is obtained using the conversion table between the $\Delta E_{SSR(UK)}$ and grade values in Table 2-5 (14).

Table 2-5 $\Delta E_{SSR(UK)}$ values and colour fastness grades

ΔE_{SSR}	Grade
$\Delta E_{SSR} \geq 4.75$	5
$4.75 > \Delta E_{SSR} \geq 4.25$	4-5
$4.25 > \Delta E_{SSR} \geq 3.75$	4
$3.75 > \Delta E_{SSR} \geq 3.25$	3-4
$3.25 > \Delta E_{SSR} \geq 2.75$	3
$2.75 > \Delta E_{SSR} \geq 2.25$	2-3
$2.25 > \Delta E_{SSR} \geq 1.75$	2
$1.75 > \Delta E_{SSR} \geq 1.25$	1-2
$29.05 > \Delta E_{SSR}$	1

2.4.2.3 SSR (ISO) Formula

This formula was proposed by the German national committee and has been adopted as the ISO (ISO 105:A04) since 1987. The formula is given in Equations 2.9 and 2.10 (14). The SSR(ISO) formula consists of two equations for grade values greater and less than 4, respectively. The ΔE_{GS} converts the colour difference to the lightness difference to the lightness difference on the standard grey scale. The grade is obtained using the conversion table between the $\Delta E_{SSR(ISO)}$ and grade values in Table 2-5.

rating 1-4: SSR $= 6.1 - 1.45 \ln(\Delta E_{GS})$ Equation 2.9

rating > 4: SSR $= 5 - 0.23\,\Delta E_{GS}$ Equation 2.10

where: $\Delta E_{GS} = \Delta E^* - 0.4\,[\,(\Delta E^{*2} - \Delta L^{*2})^{1/2}]$

2.4.2.4 N_S Formula

Teraji and co-workers developed N_S formula based on their colour depth and brightness scales. N_S formula is capable of directly calculating the fastness grade without an additional interpolating procedure. The formula is given in Equation 2.11 (2).

$$N_S = 5.5 - \ln((\Delta D^* / 0.18415 + 1) / \ln(2) \quad \text{Equation 2.11}$$

where $D^* = 10^n,\ n = 0.150515 \times (10\text{-}V) + C \times (5 + \Delta H_{5P}) \times 10^{-3}$

2.4.2.5 F_S Formula

This formula is similar to the F_C formula for assessing change in colour. F_C formula is capable of directly predicting the grade of the colour fastness. This formula is given in Equation 2.12 (2).

$$F_S = 5 - 5\,[k_1\{\Delta E_{DBH}/(100-D_o)\}]^{k2} \quad \text{Equation 2.12}$$

where $k_1 = 2.2 + 0.0001\,(\Delta h_{290,t} - 180)\,B_{Dt}$

$k_2 = 0.62 + 0.00004\,\Delta h_{290,t}\,B_{Dt}$

2.5 Literature Review

It is impossible to avoid the individual difference in the visual evaluation of colour fastness. Therefore, the colorimetric evaluations have been investigated.

Nakamura et al. (15) led N_c formula based on the ratio of the colour depth value ($\Delta C^* / C_o^*$). The grey scale for assessing change in colour is used for evaluation of the colour fastness of the cloths having various colour depth. The grey scale is based on the Adams Nickerson's colour difference value. But it seems to be difficult that its colour difference value is applied to the colour fastness of all coloured cloths. The formula was shown in Equation 2.13.

$$N_c = 5.5 \log (\Delta C^* / 0.015 C_o^* + 1) / \log 2 \qquad \text{Equation 2.13}$$

As far as we examined the many specimens, The values led by N_c coincided more closely with the visual evaluations at the various colour depth level than the usual colour difference values.

Nakamura et al. (16) inquired of five colour specialists and twenty university students to compare visual evaluation with the calculated one (N_c). This N_c values led from the grey scale for assessing change in colour coincided closely with the mean values of visual evaluations for the medium of achromatic colour, but we couldn't avoid the individual variance of visual evaluations. The only one third of visual evaluations coincided with N_c values and the others were different. The level of evaluations were different between colour specialists and student, and the latter varied the evaluations by the instruction of grey scale. Therefore it is impossible that the visual evaluations give the correct value. It seems reasonable that N_c can be used as the calculated evaluations of colour fastness in the discussion of hue and colour change.

Nakamura et al. (17) introduced the diminutive coefficient, as shown in Equation 2.14, to diminish the ratio of colour depth ($\Delta E^{**} / C_o^*$) in the evaluations by N_c formula.

$$\varepsilon = p\,(\Delta E^{**} / C_o^{*})^h \qquad \text{Equation 2.14}$$

As the values of p and h necessary to evaluate ε were not cleared, they introduced the theoretical colour scale and led next formula experimentally as shown in Equation 2.15.

$$h = 0.43\text{(constant)},\; p = a - b \cos (3.60\text{x}\, \Delta H_{5y}) \qquad \text{Equation 2.15}$$

Where a = 1.1, b = 65.

The calculated evaluations which were revised by the ε value from formula 2.5 were coincided with the visual evaluations satisfactorily.

Nakamura et al. (18) prepared the specimens by selecting various colour samples from the colour tree in Munsell colour system and tried to verify the $N_c^{\#}$ values used in the previous paper. The results show that $N_c^{\#}$ values differed from the colour fastness grade obtained with visual evaluation for pale specimens, but they coincided closely with the grade for the other specimens except the pale areas. In the pale specimens, it seemed difficult to evaluate the change of hue independent of the change of colour depth using the grey scale which were classified by change of value alone based on medium shade. If was considered that the fact above mentioned caused the difference between $N_c^{\#}$ value and the visual evaluations.

Nakamura et al. (19) reverificated of $N_c^{\#}$ values for various specimens in Munsell colour tree was carried out. $N_c^{\#}$ values were calculated by the equation used in the previous paper, however the numerical value of h in this equation was revised to 0.30. More than 80% of the $N_c^{\#}$ values thus calculated were within the allowable range of visual evaluations with regard to various V/C as well as hue, and consequently it was found that this $N_c^{\#}$ value well coincided with the visual evaluations. These visual evaluations show the mean values of the grade given by judges. There are considerable variations in the individual evaluations. For this reason, there is a danger of a lack of accuracy when we depend on the visual evaluation alone for the determination of the grade. On the other hand, $N_c^{\#}$ value seemed to be well suited for the determination of the grade of colour fastness for colour shade.

Nakamura et al. (20) compared between $N_c^{\#}$ value from the previous report and CMC (2:1). The results were as follows:

- Comparing $N_c^{\#}$ with CMC(2:1), though the colorimetric system differed, there was a correlation between colour difference ΔE_{CMC} and ε (ΔE^{**} /C_o^*), both of which led the grade, in the case of the same level of of colour shade.
- However, if the colour shade differed, the difference in the ratio of evaluation between the above two was observed.
- On the whole, CMC(2:1) method was looser in grade determination than $N_c^{\#}$. This tendency becomes more pronunced as the colour shade becomes lighter from medium to pale. When both methods compare with visual evaluation, they did not differ significantly from this evaluation.
- However , with regard to the deviations in colour shades, the CMC (2:1) was more variable than that by $N_c^{\#}$ for each colour shade, and the CMC (2:1) seemed to show a tendency to give looser grade values except in very dense area.

Sato et al. (21) studied about the instrumental evaluation method to assess the change in colour on the CIELAB colour system. In the study, by using the gray scale and colour scales for assessing change in colour, the authors tried to obtained the instrumental method for the determination of colour fastness grade in assessment of change in colour. The empirical formula (F_c) to calculate the colour fastness was shown in Equation 2.7.

Sato et al. (1) evaluated the performance of colour fastness formulae for change in colour i.e. CIELAB, CMC (1:1), CMC(2:1), ISO standard, $N_c^{\#}$ and F_C using one particular set of Japanese data. The correlation coefficient and root mean square of the differences between the grades predicted by the formulae and the mean visual grades for each sample pair were also used to indicate the degree of agreement between prediction and visual results. The result indicted that the ISO and F_C formulae performed marginally the best. CMC (2:1) performed worse than CMC(1:1). This indicates that the grey scale assessment produces perceptibility results.

Sato et al. (22) tested the performance of the colour fastness formulae: CMC, ISO, $N_c^{\#}$, F_C and CIELAB using the constant grade contour. The difference between a particular formula and experimental results can be identified by the patterns of sizes, shapes and orientations of contours (ellipses). The results show that the CMC and ISO formulae agree better with the visual results than the other formulae. The F_C formula derived by one of the authors will be modified to fit this data set in the following areas:

- To follow the general trend in chroma direction, i.e. a larger size of contour in higher chroma areas than those in low chroma.
- To derive a new function of hue, which should be arranged to give a tighter tolerance in yellow and blue areas than the others.

Nakamura et al. (23) investigated for staining using colour depth value difference ΔC^* and colour difference ΔE (Adams-Nickerson, Hunter, CIE-L*u*v*) compared with the visual evaluation by 25 observers. In these results, it was found that the N_S value led by ΔC^* was closer to the visual evaluation than the ΔE by colour difference. The formula was shown in Equation 2.16.

$$N_S = 5.5 - \log(\Delta C^*/0.125+1)/\log 2 \qquad \text{Equation 2.16}$$

N_S value coincided closely with the mean value of visual evaluations for achromatic colour, but the variance in visual evaluations was not avoidable in the same way as colour change. Though the only one third of visual evaluations coincided with N_S value, the others were different from this evaluations. The evaluations were severer for the chromatic colour than for the achromatic colour, but the mode of distribution coincided with N_S value.

Sato et al. (24) used the grey scale and colour scales for assessment of staining, They tried to obtained the instrumental method for the determination of colour fastness grade in assessment of staining. They obtained the equation for calculating colour fastness as shown in Equation 1.10.

Sato et al. (2) tested the performance of various staining formulae i.e. CIELAB, SSR(UK), SSR(ISO), N_S and F_S using a set of experimental results.The results indicate that all formulae performed reasonably well. The F_S formula performed marginally the best. In general, all formulae performed better than the CIELAB formula.