Shade Passing : Applications in the Manufacturing of Multi-Component Apparel with Particular Reference to Colour Matching

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Dr. K.M. Sin, Mr. S.K. Ku and Prof. K.W. Yeung

by

Lam Siu Wing

Institute of Textiles and Clothing

The Hong Kong Polytechnic University

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submitted by Lam Siu Wing

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Abstract

In recent years, computer colour management systems have become increasingly important to the colour industry where techniques such as instrumental pass/fail analysis are widely used by manufacturers, buying offices etc. However, a matter of major concern remains the assessment of pass/fail on a single component. In the case of apparel comprising a multiple of components, the existing commercial instrumental pass/fail systems seems not suitable.

The Polytechnic University is supported to implement the Teaching Company Scheme (TCS). Under the TCS, research project directly related to the needs of client company, Triumph International Overseas Ltd.(Hong Kong Branch), was undertaken under the supervision of an academic staff member.

Referring to Triumph's practice, three equations chosen for study were CIELab 1976, CMC(2:1) and CIE94(2:1:1). Colour difference, ΔE, of 230 sample pairs with different textures was calculated using the above equations. Totally 33 experienced "shade passers", including Triumph's and external colour assessors, were

invited to assess these sample sets and gave comments on them. The comments given should be a pass match, fail match or marginal pass match. The data collected were then analyzed statistically. The percentages of acceptance were plotted against various ΔE calculated with respect to its equation. The results show that equation CMC(2:1) has a better correlation than the other two equations. The tolerance block so developed based on the CMC(2:1) equation was verified by applying the tolerance to one of the suppliers of Triumph. The precision and performance of the tolerance block developed is fairly good and acceptable. In addition, analyzed data show that better correlation could also be attained by increasing the number of observers.

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CHAPTER 1

INTRODUCTION

1.1 Background

In the textiles and clothing industry, one of the main interests in quality control is the colour of the final products. As far as the customer is concerned, the colour appearance of the product is a prime concern and usually determined by subjective assessment [1]. However visual measurements of colour are notorious for their variability between "shade passers": the decision makers on pass/fail of colour samples, and even for repeated assessment by the same shade passer. Theoretically the colour of a product should be controlled during manufacture by a large number of shade passers who would provide an average assessment of the colour in relation to the standard, or by means of a colour measurement instrument. To assess a colour visually is a very subjective matter and often leads to an unacceptably high level of rejects by the customer unless excessively tight tolerance is applied. Arguments then often arise. Even within the same garment, there may be different component materials sewn or linked together comprising different fibre type, yarn type or fabric structure. Matching the colour for each of these materials is extremely difficult - the problem still persists and remains unsolved [2]. Even in the case of garment dyeing, individual components may show apparent colour difference due to the difference in dye uptake, structural and textural effects.

On the other hand, components that appear to match well separately with the desired colour may give a completely different colour perception when assembled together. In order that a good match of colour may be obtained, controls in the coloration processes is vital and the product may be reprocessed, even several times, so as to match the colour standard. This inevitably leads to higher production costs and a longer lead time.

In recent years, quality assurance has become increasingly important to textile and clothing manufacturers [2]. They realise that a successful quality assurance programme can minimise their production costs and increase consumers' satisfaction. Increased competition from low cost offshore producers has made quality assurance programmes essential to textile and clothing manufacturers who wish to remain competitive. Because of its highly visible nature, colour is an important component in the quality assurance programmes. Unfortunately, colour is a manufacturing variable that is difficult to control because of the inability to control all colour related variables in production, manufacturers have developed methods to reduce the colour variability of fabric dyelots that are to be used together.

Much work has been carried out particularly in the coloration industry to tackle this problem and many colour difference equations (to be reviewed in Chapter 2) have been suggested to relate the magnitude of a colour difference. Colour difference can be expressed by a single number or a set of numbers. The objective of colour difference measurement is to decide whether the textile products dyed in process house in different batches are acceptable or not. The numbers given by the colour difference equation may not correspond to visually perceptible colour difference but these numbers may be useful in deciding the tolerance limit, i.e., acceptability. This can be determined either by coming to some mutual agreement or from a long term study of customer taste in colour. This tolerance limit can then be used to accept or reject the sample by looking at the numbers. It may be noted that once the tolerance limit is decided by mathematical numbers, it is valid only for the colour difference equation used for calculation. Further more, the acceptable limit of tolerance may vary with customer, type of shade and nature of the product. For colours of military uniforms, national flag, insignia and historical emblems, the tolerance limit may be very small. For others it may be large. In practice the tolerance limit is decided on the basis of acceptability rather than perceptibility. One may feel that there is no basic difference between perceptibility and acceptability except that the acceptable limit may be larger than the limit of perceptibility. The numbers given by the colour difference equations do not correspond to the magnitude of visually perceptible colour difference. Furthermore, the same magnitude of perceptibility may not result in the same rate of acceptability.

In textile processing, the coloration of similar fabrics using the same colorant formulation may result in a varying degree of colour differences. This may be attributed to the change in dyeing conditions and the quality of chemicals and colorants used by the processing house. It is desirable that a tolerance limit be first agreed upon by the supplier and customers. The tolerance limit so determined depends on the need of the customer and the production cost will be higher if the tolerance limit is small. The limit of tolerance is decided by either predicting the colour difference by human observation or measuring it by instruments. To precisely decide the tolerance range, it is desirable to prepare limit standards. It is a normal practice to prepare the limit standards in several dimensions of colour space. One of the most desirable procedures on the part of the supplier is to develop a tolerance chart from historical records of the instrumental measurements for every batch of a given colour shade. These data are plotted on, e.g. CIELAB, a colour space. The colour differences of each repeated batch are plotted with an indication of acceptance or rejection. By repeating the procedure with time, it becomes possible to draw a tolerance figure, which may be a circle or ellipse or a figure of any irregular shape. The target point may not be at the centre but this method provides a better understanding of the mind of the customer and a limit standard for visual judgement can also be selected from the batches near the boundary of the tolerance the figure. The preparation of the tolerance figure may take time. Standardisation of the techniques employed for measurement, in maintaining the stability of the instrument as well as that of the standard requires thorough caution. An alternative way to set up proper limit standards is to select a large number of samples from actual production which show all the possible variations that may be expected in the process. These samples may be separated into acceptable and non-acceptable ones by the group of qualified observers, i.e. shade passer, involved in final decisions. Measurement of these samples will provide the details to develop tolerance figure. As mentioned earlier, the total colour difference can be a single number ΔE^*, but it may be difficult to arrive at any decision from a single number. Therefore, it is always desirable to get three component limits for all colours in three dimension colour space, e.g., CIELAB L^*, a^*,b^* colour space.

All the measurements of samples are subjected to instrumental errors and care must be taken to ensure that the instruments used are in proper operating condition. It may be self-evident, but the sum of all these errors must not exceed any significant part of any tolerances. If these conditions are met, however, it will result in a great saving of time and effort when the measurement, whether visual or instrumental, automatically classifies the material without any further calculation.

The purpose of having a specification in colour is to provide a means of measure for the supplier that the product is satisfactory to the customers. If the specification is too strict , it is difficult to supply satisfactory product; if it is too loose, the end product may be unsatisfactory. Again, this is a case of agreement between the buyer and seller: the specification defines a material that the producer can provide and the customer can use, with satisfactory economic return. Not all aspects of colour are equally important in specification. e.g., hue is usually more important than strength.

There has been considerable argument as to which of the colour difference equations should be the best used to express the average-shade passer assessments of difference to be encountered. The recent improvements in colour measurement instruments have provided a means of obtaining reliable measured data for many types of coloured surface. The data used in these colour difference equations does not provide complete satisfaction in representing the assessment of shade passers on average.

1.2 The Use of Colour Measuring Systems in the Textiles Industries

Colour properties and measurements are critical processes and quality control parameters for textiles and polymers [3]. Colour measurement assists in identifying off-quality or out-of-process control products, both during and at the end of the manufacturing processes. The timely identification of off-quality products can lead to reduced production losses and reduced rework/culling expenses. Customer complaints can also be reduced due to the minimisation of the probability of off-quality material sent to customers and increased quality assurance. In addition, colour measurements provide versatile complementary data and information in the identification of the sources, e.g., manufacturing locations or textile manufacturing processes that were responsible for the off-quality conditions.

There are two types of instrument that can be used for measuring the amount of visible light reflected by opaque objects: reflectance spectrophotometers and trichromatic colorimeters. Such measurements have become increasingly important in all branches of the colour-using industries, predominant among these being dyeing, paint and printing ink making and the coloration of plastic articles. With the growth of mass production methods, the standardisation of the colour of parts and components made of different materials, possibly by different manufacturers, has become a continuing problem, as has the prediction of the recipes for achieving the desired colour in the first place. Whether the aim is to ensure the colour constancy of a production run or to devise colour formulations to match a new pattern, accurate and reproducible measurement of colour by instrumental methods have gradually been introduced to help the colourist in his task, by supplementing the traditional methods of experience plus trial and error. The basis of colour measurement was laid with the adoption of the CIE colour measuring system in 1931. Subsequent developments have concentrated on improving the instruments used for making measurements and on extending the system's ability to solve the problems encountered in practice.

In order to measure the colour of an opaque sample, e.g., textile materials, with a reflectance spectrophotometer it is necessary to measure only the reflectance/wavelength curve of the sample in the visible colour range from 400 to 700nm. Differences in the numerical specification of the colour to take account of the different appearance of the colour under different source and viewing conditions can be allowed for by using the appropriate standard tables of the characteristics of the source and observer.

For reflectance measurement on opaque samples, there is a much greater difference between the two paths, since the reference path contains a standard white while the sample path contains the coloured sample being measured. Problems arise because the colour of sample surfaces varies with the direction in which they are viewed. If the surface is very smooth there will be both a specular component and a diffuse component to the light coming from the surface. The specular component will not be wavelength dependent, but the diffuse component will depend on the absorption and scattering characteristics of the sample substrate (usually fabric or surface coating) and of the distribution and particle size of any colorants contains in the substrate. Generally both specular and diffuse components vary with the direction of illumination and viewing. Samples such as paint films, films of printing inks and the surfaces of plastic articles can range from smooth and glossy to semi-matt and matt. Textile samples show a much greater range depending on the nature of the fibre, natural or man-made, whether or not it is delustred, the yarn twist and the fabric construction, which the yarn is made. At one end if the range lie as continuous nylon filament in a sateen weave, and on the other, hand-knitted wool garments.

Those problems were not well recognised in the 1931 CIE system, where it was merely specified that for reflectance measurement the sample should be illuminated at 45° to the normal and viewed normally, i.e., at 90° to the surface. The so-called 45/0 condition looked fine in the form of a simple diagram showing light as single rays (Figure 1.2.1a) but led to a greater number of practical problems. Quite apart from the problems of glossy and matt surfaces, beams of light in instruments are not single rays but collections of rays in the form of converging or diverging beams. Instrument designers found it necessary to depart from the excessively restrictive 45/0 condition in order to get workable instruments. Illuminating beams were broadened and acceptance angles increased to allow measurable amounts of radiation to reach the detectors. The intensity is very low in designs similar to that in Figure 1.2.1a because of the attenuation attributable to absorption by the sample and also the small acceptance angle in the viewing direction. The greater part of the radiation emerging from the sample is lost due to diffusion in many directions, as shown in Figure 1.2.1b, which also shows a polar curve of light reflected from a semi-glossy surface.

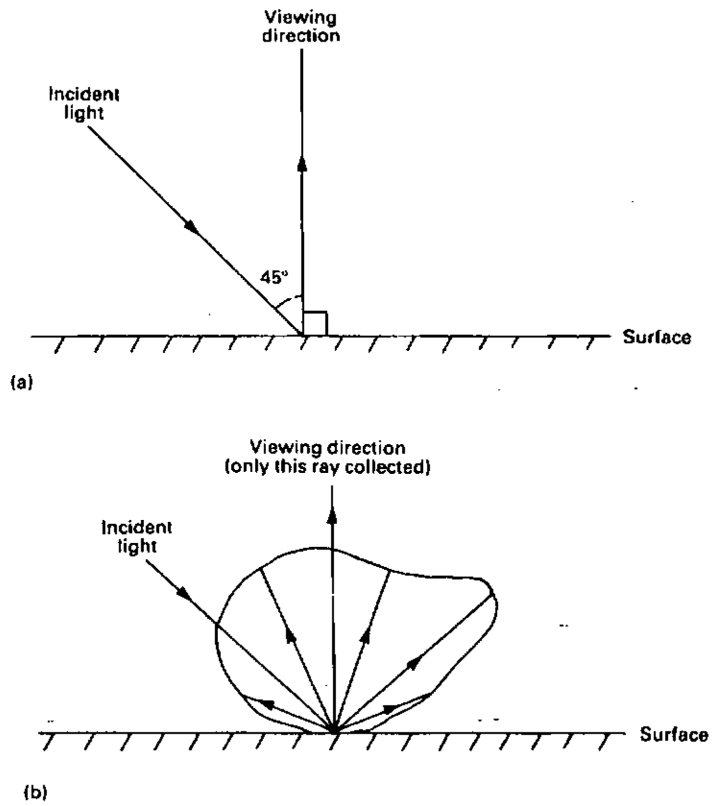


Figure 1.2.1: (a) Idealised viewing conditions in the 1931 CIE colour measurement system, (b) polar diagram of light reflected from a surface showing some specular reflection

This latter loss can be reduced by the use of an integrating sphere, which has its inner surface painted a matt white and the greater part of the radiation emerging from the sample can be collected and diffused from the inner surface by multiple paths, as illustrated in Figure 1.2.2 (c and d).

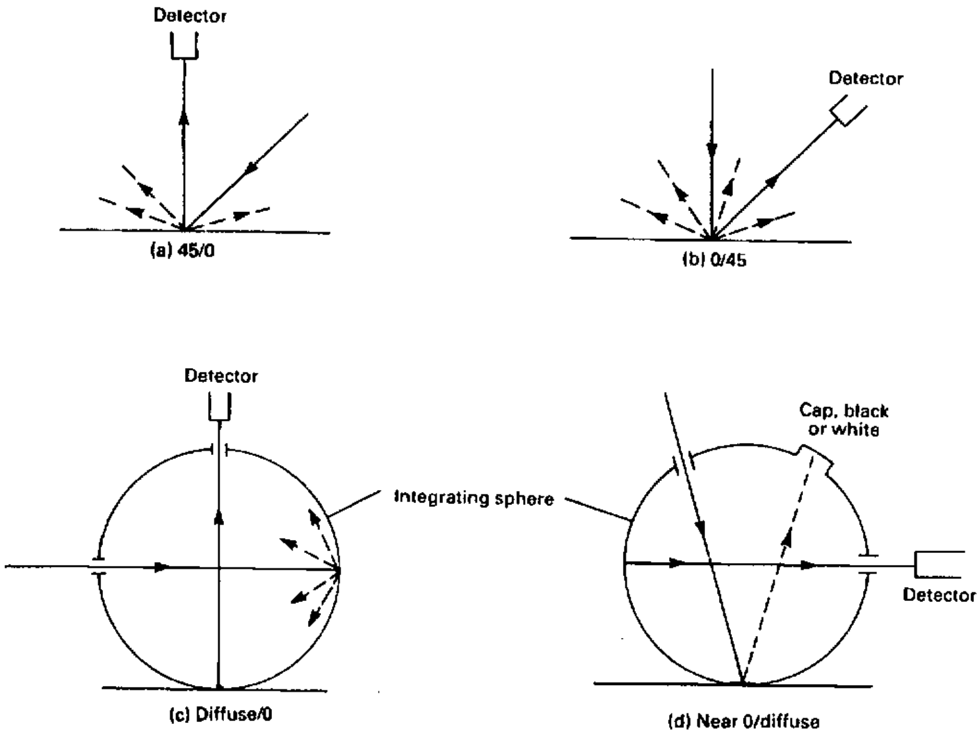


Figure 1.2.2 : CIE recommended illuminating and viewing conditions for reflectance measurements

Naturally only an averaged value can be obtained. The conditions for diffuse illumination of collection or radiation are two of the four viewing conditions recommended by the CIE since 1978, as shown in Figure 1.2.2. It has also been stipulated that in any beam the angle between the axis and any constituent ray should not exceed 5°. Widespread adoption of these recommendations will be of great help in eliminating the differences between measurements made by various instrument due to the unspecified departures from the required 45/0 geometry(Fig.1.2.2a) that designers allowed themselves to solve the intensity problems mentioned above. Many of the instruments used for reflectance measurements in the early 1950s were also unsatisfactory because they were originally designed as spectrophotometers for transmission measurements in the u.v. and visible regions, and then reflectance attachments were added as an after thought and as 'optional accessories'. As a result their photometric accuracy was not high enough for the purpose of colour measurement, and the disappointments arising from the use of such instruments contributed to the slow acceptance of colour measurement and recipe prediction methods in industry at that time. These design failings have now been recognised and eliminated, e.g., the spectrophotometers used for comparison in section 4.2.

The validity of a computed colour difference will be somewhat dependent on the accuracy but mainly on the precision of the instrument from which measurements were obtained. Instruments vary in optical geometry, mode of illumination of the specimen, bandpass of measured light, accuracy at low levels of reflectance and inherent precision of measurement. Data required for solving colour difference computations should be obtained from instruments capable of measuring and/or recording reflectance. The instrument frequently is interfaced to some type of computing device capable of converting reflectance data to CIE tristimulus values or to those units of any other colour space on which the colour difference equation used is based. Such a device might be a computer interfaced with the spectrophotometer.

The colour measurement spectrophotometers had performed satisfactorily and provided useful information for many years. However, they exhibited several deficiencies, primarily due to ageing, poor inter-instrument agreement (both in units and correlation between same and different systems) and limited software flexibility and capabilities. In addition, spectrophotometers require constant maintenance, which was hampered by the lack of readily available parts, poor field service and long term vendor-user logistical relationship.

Most spectrophotometers used today are not continuous - measuring spectrophotometers. They are the so-called abridged spectrophotometers. They are able to measure only the reflectance factors for certain wavelengths (usually 16 of 31) that are set by the instrument and not continuous for all wavelengths of the visible spectrum. Abridged spectrophotometers used today are not as big as the older ones. But they are still generally so large and heavy that a place for measurement has to be installed. The samples have to be taken to this place for measurement by the instrument. This means that the size of a sample is limited. To provide the ability for measuring larger samples, producers of spectrophotometers build instruments where the measuring head is a separate part connected by fibre optics and electrical wires to the main instrument. In such cases the measuring head can be put on the sample to be measured. Recently portable instruments have been introduced; they can be brought to the samples. The feasibilities for colour measurement are therefore increased. In certain spectrophotometer models, instruments are connected with a portable computer. Then both the instrument and the computer can be brought to the sample.

In the last few years, there have seen very great changes in the design of instruments for measuring colour, both in transparent and opaque samples, largely due to the introduction of computers. These have improved the accuracy and reproducibility of measurements and particularly in the measurement of the colours of opaque objects. The improvements have enabled the measurements to be transformed rapidly into a form that has an immediate practical application in industries where dyes and pigments are used to produce colour in textiles, plastics, inks and paints. These products are generally required to give close matches to previously agreed standards. With the accurate and readily available measurements now possible, colourists have valuable assistance to hand in making decisions on whether corrective measures need to be taken to reduce any mismatch to acceptable limits. It was also used in specifying numerically degrees of mismatch that are commercially acceptable.

Since much of the work in this project involved the use of spectrophotometers to measure different colours, a study of the performance of spectrophotometers was made [4].

1.3 Teaching Company Scheme

The Hong Kong Polytechnic University is the only tertiary institution supported by the Government's Industry Department to implement the Teaching Company Scheme (TCS). Under the TCS, research associates, registered for a research degree at the University undertake research projects directly related to the needs of client companies under the supervision of an academic staff member. The TCS covers areas such as improvements in efficiency of plant and manufacturing systems. Triumph International Overseas Ltd. (Hong Kong Branch), being one of the biggest garment manufacturers also faced with the problem in colour matching as stated in precious sections. A joint ventured project under the TCS was then developed to deal with this problem.

Traditionally colour assessment has been carried out visually by experienced colourist. However, converting a visual colour matching system to an instrumental one can offer several advantages including less subjective in evaluation and greater efficiency in shade passing and shade sorting processes. It was the intention of the project that a systematic approach of shade passing particularly to multi-component apparel is to be set up to identify the problem of mis-match and an objective measuring technique in colour matching is established. The tolerance block developed is then put into application in one of the Triumph's vendors. The precision is calculated referring to the selected colour difference equation, CMC (2:1) in 95% confidence level. The tolerance block is going to be applied to other suppliers of Triumph. In the future, it will be an objective measuring technique in colour measurement, which will be accepted by all parties in the textile and clothing industries.

1.4 Research Objectives

The aims of the research project are:

1. to compare different spectrophotometers of different illuminating, viewing geometry and of different brand name available commercially, in order to create a standardised environment to develop a more precise tolerance block,
2. to select a suitable colour difference formula for shade passing on multi-component apparel by comparing the correlation between visual assessment and the colour difference values calculated by various colour difference equations;
3. to establish a tolerance block with respect to the selected colour difference equation in colour matching that the tolerance is acceptable to all parties in the textile and clothing industries;
4. to verify the usefulness(precision) of the established tolerance block.

1.5 Experimental Design

Different integrating sphere based spectrophotometers with different illuminating, viewing geometry and brand names were compared, i.e., Datacolor SF600 (Schmidt & Co.,(H.K.) Ltd.) as reference, Macbeth Coloreye7000 (Libero Limited), Datacolor Elrepho 2000 (Hong Kong Polytechnic University) and Datacolor Texflash (Triumph International Overseas Ltd.(Hong Kong Branch)). The correlation of the spectrophotometers were calculated by measuring a set of samples. The spectrophotometer with the highest coefficient of correlation with reference to Datacolor SF600 was used for measuring the samples to generate a tolerance block.

A number of dyed samples of different substrates and textures (mainly Nylon) were collected from local and overseas subsidiaries of the Triumph International Overseas Ltd.(Hong Kong Branch). Totally there were 23 colours and for each colour 5 samples were obtained from different dyelots. Another set of colour sample, Yellowish Green, was prepared by using acid dye on different kind of nylon substrates to complete the gamut of colours.

The samples of each colour were paired and matched by experienced colourists including the colourists from the Hong Kong Polytechnic University, Q.C. of the Triumph International Overseas Ltd.(Hong Kong Branch) and their suppliers. The shade passers were tested by using the Davidson and Hemmendinger colour rule to ensure that they were of normal colour perceptibility. The assessments were done under the light source ADN (D65 + Natural) (Appendix 1) which is a light source exclusively used by Triumph. Three colour difference equations were selected for comparison, i.e., CIELAB, CMC(2:1) and CIE94(2:1:1). The colour difference equations CIELAB and CMC(2:1) were used because they were used by Triumph for quality control. The colour difference equation CIE94(2:1:1) was selected since it is a newly developed equation. The performance on pass/fail prediction was tried to be compared with the former equations. The precision of the developed tolerance block was checked by applying to one of the Triumph's suppliers.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

If two specimens have the same CIE tristimulus values **XYZ** [5], they will be a perfect match to the appropriate standard observer under the appropriate source and viewing geometry. The human eye is an efficient null detector and can determine if the colours of two specimens are matched [6]. Conversely if there is a perceptible difference between the standard and the sample, it is difficult for the eye and brain to assess the nature and magnitude of the difference. In visual assessment of colour difference, even having arrived at a common agreement about sources and team of observers, it is necessary to maintain tolerance charts prepared either by the use of instruments or from the history of the batches for production.

When the CIE tristimulus values of the standard and sample do not match, the overall difference is easily quantified by regarding the **XYZ** values as coordinates in a Euclidean colour space which is given by the application of the Pythagoras theorem to three dimensions [7](Eqn 2.1):

$$\Delta E = [(\Delta X)^2 + (\Delta Y)^2 + (\Delta Z)^2]^{1/2} \qquad \textbf{(2.1)}$$

where Δ signifies 'difference in' and **E** is the initial letter of the German word

Empfindung meaning sensation. However, Eqn 2.1 was not satisfactory as some colour differences that were perceptually equal in size gave different ΔE values for which were varying by a ratio of up to 30:1. Clearly **XYZ** space is markedly non-uniform as far as quantified differences are concerned. Therefore attempts were made to search for the best colour difference equation, which gave equal mathematical numbers for equal changes in perceptible colour difference.

Since the mid-1930s, more effort has been devoted to solving the problem of quantifying colour differences that were involved in the development of the 1931 CIE system of colour measurement, which started with Maxwell. Between 1936 and 1976 over 20 colour-difference equations or formulae were developed. Most of these formulae have involved the mathematical transformation of **XYZ** values into L, a and b values which defined a more uniform colour space Fig. 2.1.

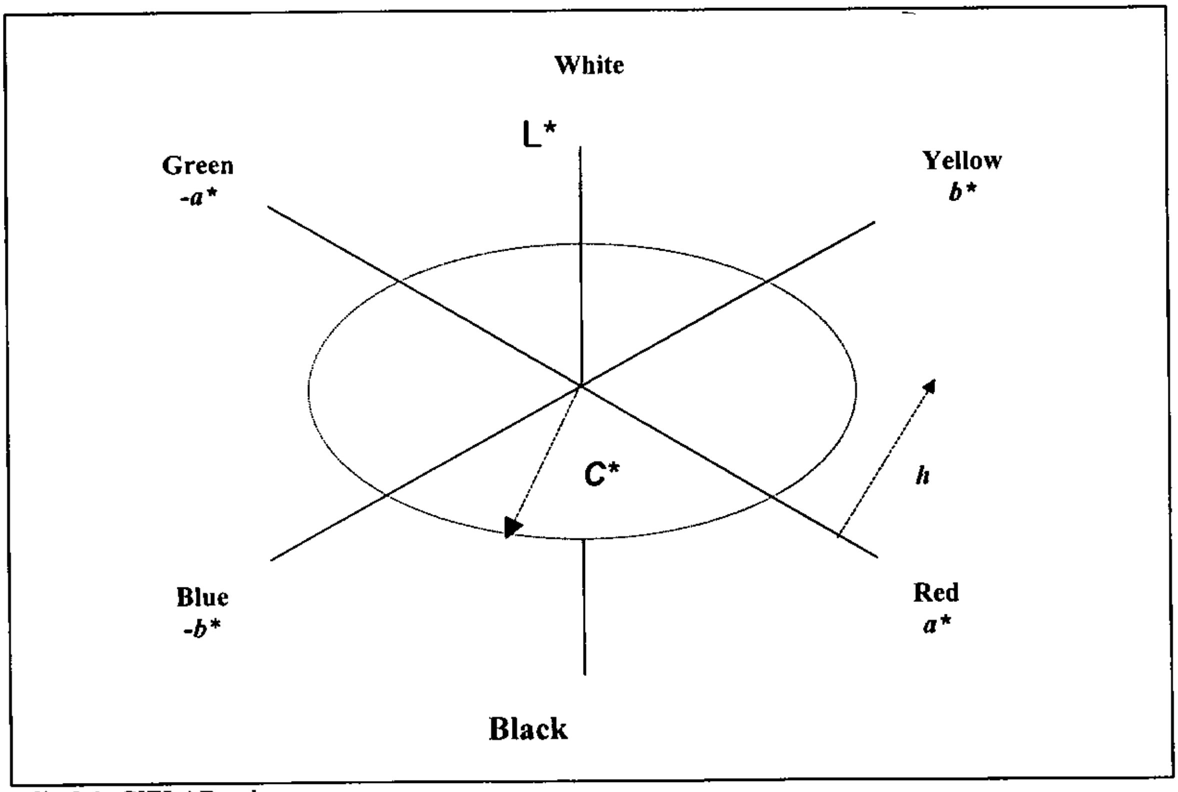


Fig 2.1: CIELAB colour space

MacAdam has made a large number of matches on series of test colour located at various points in the chromaticity diagram. The spread of this settings was used as a criterion of sensitivity of colour difference and plotted on CIE chromaticity diagram in the form of ellipse as shown in Figure 2.2. These are known as the famous MacAdam ellipses. If the lightness is taken into consideration, it results in corresponding ellipsoids. MacAdam ellipses are used to judge the performance of any colour difference equation. Each of the McAdam ellipses can be represented by Eqn 2.2 [8].

$$g_{11}(dx)^2 + 2g_{12}dxdy + g_{22}(dy)^2 = 1 \qquad (2.2)$$

where dx is the difference between the x coordinates of the ellipse centre and any point of the ellipse, dy is the corresponding difference in the y coordinates and g_{11}, g_{12}, g_{22} are metric coefficients.

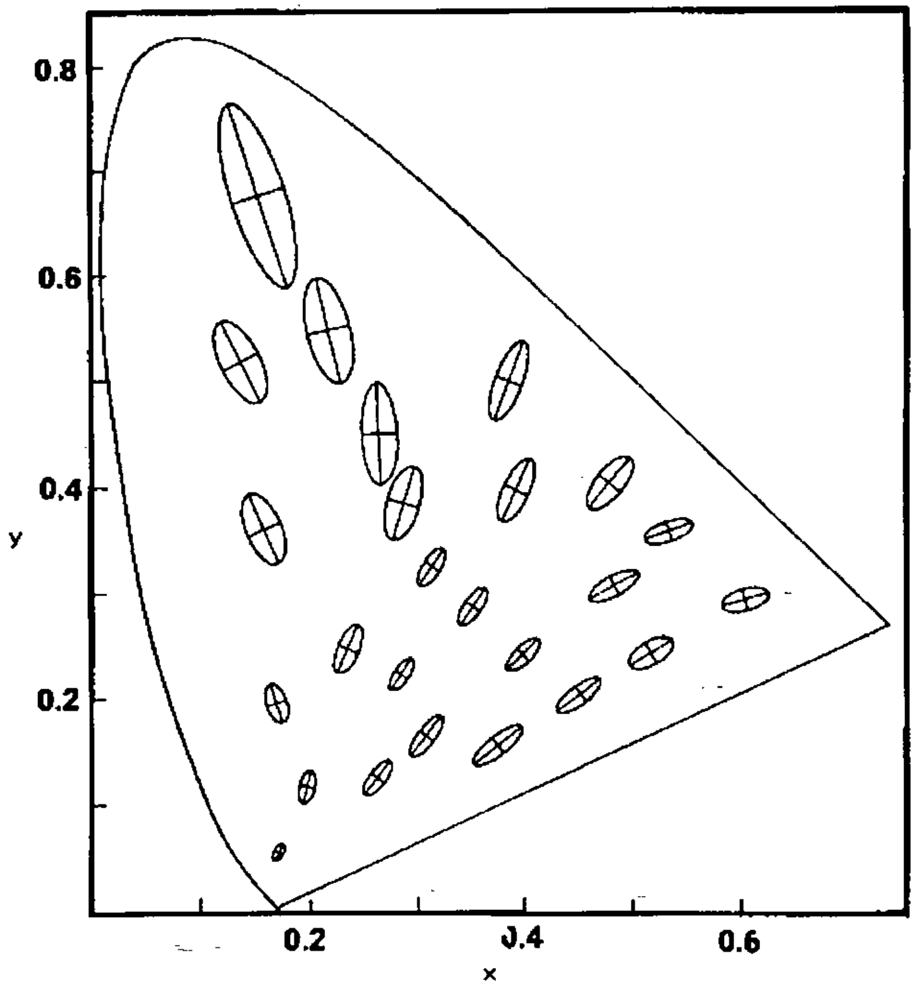


Fig 2.2: MacAdam ellipse plotted on a CIE 1931 chromaticity diagram representing standard deviation magnified by a factor of 10

2.2 Colour Difference Equations

Since 1931, CIE defined colour coordinates to assess the colour in numerals, attempts are made to express the colour by a single mathematical number [9]. This parameter is extremely useful in quality control of coloration. Therefore a number of colour difference equations were proposed in the literature. Most of these equations were developed so as to fit a set of visual assessment data well. To maintain the uniformity in practice, CIE recommended new colour difference equations from time to time.

The colour difference equations proposed prior to CIE 1976 recommendations could approximately classify into three groups :

1. Equations based on Munsell System
2. Equation based on the perceptible colour difference data
3. Equations based on the MacAdam ellipses

2.2.1 Equations based on Munsell System

The first group of equations is based on the Munsell scales hue, Munsell scales values and chroma. Eventhough the Munsell scales have uniformity in step size, the differences are much larger than the perceptible difference and those of industrial interest. The work on Munsell spacing has shown that the uniformity in step size can be retained down to 4-5 times of the just perceptible difference. The first colour difference equation known as Nickerson Index of fading was proposed by

Nickerson[10] Eqn 2.3, used for textiles.

$$\Delta E = C/5(2\Delta H) + 6\Delta V + 3\Delta C \tag{2.3}$$

The equation consists of the differences of Munsell parameters of sample and standard. They were added together by weighting so as to agree with visual assessment data. However, this Nickerson equation based on the visual observations on dyed cotton, wool and silk specimens were purely empirical. The Nickerson equation was successively tested using textile dyeing and also modified in several stages. Eqn 2.4 [11] was known as the Godlove index of fading where H, V and C are Munsell renotation hue, value and chroma respectively; $(H_1\text{-}H_2)$ is the hue difference expressed in the hue circuit; $3.6(H_1\text{-}H_2)$ expresses the same angle in degrees; and f_s is a surround factor.

$$\Delta E = f_s\{2C_1C_2[1\text{-}\cos 3.6(H_1\text{-}H_2)] + (C_1\text{-}C_2)^2 + 16(V_1\text{-}V_2)^2\}^{1/2} \tag{2.4}$$

In 1923, Adams developed a colour vision theory [12] in part based on the opponent-colours theory of Hering. However, differing from it that is postulated, the differencing mechanisms which produced the chromatic sensations were between the R(red sensitive) and G(green sensitive) cones to give the red-green response and between the B(blue sensitive) and G cones to give the yellow-blue response.

The green cone response in the XYZ system is defined by the $\bar{y}(\lambda)$ curve of the standard observer, but the relationship between the perceived uniform lightness scale and the CIE Y tristimulus value is non-linear. If the scale values of the Munsell

Value scale are plotted against their respective Y values, a smooth curve is obtained. Several non-linear transformations were developed to define the curve, the most important being the fifth degree polynomial devised by Judd for the Optical Society of America, Sub-committee on Spacing of Munsell Colours (Eqn 2.5):

$$Y' = 100Y/100 = 1.2219V_y - 0.23111V_y^2 + 0.2395V_y^3 - 0.021009V_y^4 + 0.0008404V_y^5 \quad (2.5)$$

where Y' is the luminous reflectance, expressed as a percentage relative to the perfect reflecting diffuser with Y = 100.

A similar equation was postulated for the relationship between the red cones and CIE X value, the blue cones and CIE Z value, for colour under illuminant C (Eqn.2.6):

$$X' = 100X/98.071 = 1.2219V_x - 0.23111V_x^2 + 0.2395V_x^3 - 0.021009V_x^4 + 0.0008404V_x^5$$

$$Z' = 100Z/118.225 = 1.2219V_z - 0.23111V_z^2 + 0.2395V_z^3 - 0.021009V_z^4 + 0.0008404V_z^5 \quad (2.6)$$

where 98.071 and 118.255 are the X and Z tristimulus values of the perfect reflecting diffuser under Illuminant C.

The subtractions (V_x-V_y) and (V_z-V_y) are the nerve connections in the retina postulated in his theory of colour vision. Under the Illuminant C, a neutral colour is defined as one where X'=Y'=Z'. Under these circumstances, V_x, V_y and V_z will lie at the origin and all chromatic colours will lie around this point at a distance that increases according to the saturation of the colour. Adams found that, by scaling the (V_x-V_y) values to 2.5 times that of the (V_z-V_y) values, near-circular contours were obtained when colours of the same saturation (Munsell Chroma) were plotted. Thus, the Value system became $L_{val} = V_y$, $a_{val} = V_x - V_y$, $b_{val} = 0.4(V_z - V_y)$. The scaling thus yields a uniform chromacticity scale diagram of constant lightness, which is more regular than the CIE chromacticity diagram. The lightness scale to combine with Adams chromaticity diagram was the Munsell value V_y, multiplied by a scale factor so that unit difference in V_y is the same perceptually as unit difference in (V_z-V_y). In 1944, Nickerson discovered that a difference of one unit in (V_z-V_y) was equal to 8.75 Chroma steps and that two Chroma steps were equal to one Value step. The appropriate scale factor was thus 2/8.72 = 0.23. In order to obtain numerical differences of reasonable size between pairs of samples which are perceptually different, a scaling factor[13] must be applied to the equations. The coordinates of the modified Adams Nickerson colour space with a scaling factor 42 therefore become Eqn 2.7:

$$\mathbf{L = 42(0.23V_y) = 9.66\,V_y}$$

$$\mathbf{a = 42(V_x - V_y)}$$

$$\mathbf{b = 42[0.4(V_y - V_z)] = 16.8(V_y - V_z)} \qquad \mathbf{(2.7)}$$

Nickerson promoted the use of Adam parameters and Adam-Nickerson colour difference equation came into existence. This formula is further modified by Miss Nickerson by changing Adam-Nickerson unit of colour difference that describes the L, a, b type opponent colour scales with the constant 40 applied to V_x-V_y [14]. This equation is now identified as ANLAB 40 colour difference equation. The colour difference in ANLAB space is defined as the distance between the standard and sample is Eqn 2.8:

$$\Delta E = (\Delta L^2 + \Delta a^2 + \Delta b^2)^{1/2} \quad \textbf{(2.8)}$$

where ΔL, Δa, Δb are the differences between the coordinates of the standard and sample.

Glasser and Reilly discovered that the cube root of tristimulus value of reflectance could be substituted for Munsell value function without significant changes in measured magnitude of colour difference.

2.2.2 Equation based on the perceptible colour difference data

The second group of equations is based on perceptible colour difference data[15]. In 1935, Judd derived a projective transformation of the types in the following:

$$x' = (c_{11}x + c_{12}y + c_{13})/(a_{31}x + a_{32}y + a_{33})$$

$$y' = (c_{21}x + c_{22}y + c_{23})/(c_{31}x + c_{32}y + c_{33})$$

which converts the CIE 1931 (x,y)-chromacticity diagram into a new (x',y')-chromacticity diagram. This new chromacticity diagram is called a uniform-chromacticity-scale (UCS) diagram. The colour difference data unit in this group is based on NBS (National Bureau of Standards) units [16]. This NBS units was proposed by Judd. It represented the average maximum colour difference acceptable in series of dye house during the commercial matches. The presently referred NBS unit is that modified by Hunter based it on the 'alpha-beta' chromacticity diagram. This equation is in the form Eqn. 2.9 defined the NBS unit of colour difference.

$$\Delta E_{NBS} = f_g\{221 Y_m^{1/4}((\Delta\alpha)^2+(\Delta\beta)^2)^{1/2}]^2 + [k\Delta Y^{1/2}]^2\}^{1/2} \quad (2.9)$$

where $Y_m=(Y_1+Y_2)/2$, $\Delta Y^{1/2}=Y_1^{1/2}-Y_2^{1/2}$

$\Delta\alpha=\alpha_1-\alpha_2$, $\Delta\beta=\beta_1-\beta_2$

when the first colour is given by α_1,β_1,Y_1 and the second colour by α_2,β_2,Y_2, $f_g=Y_m/(Y_m+2.5)$, which is a constant factor which takes account of the masking influence of a glossy surface on the detection of colour difference. Although ΔE_{NBS} is evaluated as the square root of the sum of squares, the Judd-Hunter equation does not conform to Euclidean space.

During 1948 to 1950 Hunter developed a direct reading tristimulus colorimeter. It worked by using Hunter opponent colour order system coordinates L, a and b. The instrument was able to assess direct colour difference using these coordinates.

The next year after Judd-Hunter's equation released, Scofield proposed a modification of the Judd-Hunter equation [17], in which Scofield used the square root of reflectance factor instead, for estimating the size of colour differences (Eqn 2.10).

$$\Delta E = [(L_1-L_2)^2 + (a_1-a_2)^2 + (b_1-b_2)^2]^{1/2} \qquad (2.10)$$

where $L_1 = 10Y_1^{1/2}$ $L_2 = 10Y_2^{1/2}$

$a_1 = 7L_1\alpha_1$ $a_2 = 7L_2\alpha_2$

$b_1 = 7L_1\beta_1$ $b_2 = 7L_2\beta_2$

The MacAdam transformation of the (x,y)-chromacticity diagram which became the 1960 CIE Uniform Colour Space diagram with coordinates:

$$u = 4x/(-2x+12y+3)$$

$$v = 6y/(-2x+12y+3)$$

and recommended an extension of the 1960 Uniform Colour Space diagram into three dimension in 1964 [18]. The recommended rectangular coordinates U*, V*, W* have elements of similarity to the Judd NBS unit scales and the Glasser cube roots scales. They were non-linearly related to the CIE tristimulus values. The distance between colour (U_1^*, V_1^*, W_1^*) and colour (U_2^*, V_2^*, W_2^*) is defined as Eqn 2.11:

$$\Delta E = [(U_1^*-U_2^*)^2 + (V_1^*-V_2^*)^2 + (W_1^*-W_2^*)^2]^{1/2} \qquad (2.11)$$

Colour difference can also be measured by the line elements approach [19]. Line elements are normally based on threshold measurements and on standard deviations of colour matching. All line elements proposed to data have been assumed to have the Riemannian form which defines the colour difference be a definite and positive quadratic equation for the just perceptible colour difference, i.e., a very small colour difference, dx. For two samples in the three-dimensional Riemannian colour space, the colour difference between them mathematically corresponds to integrating the equation along the so-called geodesic line. It started at the first point and ended at the second and dividing the result by the constant value, ds, representing the just perceptible difference. In ordinary space, the geodesic lines would be straight lines but in Reimannian space they are generally curved. In Euclidean space, the distance (colour difference), ds, between two points with rectangular coordinates U1, U2, U3 and U1+dU1, U2+dU2, U3+dU3 are given by Eqn 2.12:

$$(ds)^2 = (dU1)^2 + (dU2)^2 + (dU3)^2 \qquad (2.12)$$

While in Riemannian space the following quadratic form, Eqn 2.13, is generally assumed :

$$(ds)^2 = g_{11}(dU1)^2 + 2g_{12}(dU1dU2) + g_{22}(dU2)^2 + 2g_{23}(dU2dU3) + g_{33}(dU3)^2 + 2g_{31}(dU3dU1) \qquad (2.13)$$

where the coefficient g_{ik} may be any continuous function of the coordinates U1, U2, U3 which make the form positive and definite.

In addition, there are two approaches used to determine the metric coefficients of the quadratic equation 2.13:

1. The inductive method: based on the theoretical considerations of the visual mechanism.
2. The empirical method: based on the threshold measurements of large blocks of data, or of the closely related standard deviations of colour matching.

2.2.3 Equations based on the MacAdam ellipses

The third group of colour difference equations is based on standard deviation of visual colour matching . These equations incorporate MacAdam unit represented minimum perceptible colour difference determined in MacAdam's chromacticity-discrimination experiments(Eqn 2.2) [20]. The value of g_{ik} can be computed for the length of the major axis (a) and minor axis (b), and the angle of inclination θ to the x-axis:

$$g_{11} = 1/a^2\cos^2\theta + 1/b^2\sin^2\theta$$

$$g_{12} = (1/a^2 - 1/b^2)\sin\theta\cos\theta$$

$$g_{22} = 1/a^2\sin^2\theta + 1/b^2\cos^2\theta$$

The MacAdam colour difference for any points in colour space can then be computed with the metric coefficients read from the special CIE chromacticity charts.

The McAdam ellipse defines a just perceptible difference, i.e., in the equation, unit difference ds=1 which is approximately one-third part of a just perceptible difference, the MacAdam unit.

Brown and MacAdam supplemented the MacAdam chromaticity scales with lightness interval data[21]. The discrimination ellipsoids could be defined by the Eqn 2.14 :

$$(ds)^2 = g_{11}(dx)^2 + 2g_{12}(dxdy) + g_{22}(dy)^2 + 2g_{23}(dydl) + g_{33}(dl)^2 + 2g_{13}(dxdl) \qquad (2.14)$$

where l represents the lightness dimension and $l = 1/5\log_{10}Y$

The calculation of colour differences in MacAdam units, by Eqn 2.14, was quite time consuming. Davidson and Halon, Simon and Goodwin, and Foster[22] had devised sets of charts for different regions of the x-y diagram in which linear distances represented chromacticity differences in MacAdam units. Other charts were also devised for calculating the lightness difference. Such charts provided a means for rapid calculation of colour differences. Besides, there was a common feature of these early MacAdam measures of colour difference in that they did not identify the direction but only the magnitude.

Davidson and Friede showed that 2.5 MacAdam units of chromacticity difference made a good limit of commercial acceptability in textile dyeing. Later, Friele, MacAdam and Chickering collaborated to produce two colour difference equations known as FMC-1(Friele MacAdam Chickering formula) (Eqn 2.15) and FMC-2, formed by taking the first letter of each of the authors. The FMC-2 equation was most widely used in early colour instruments as the computer programme for this equation was readily available. Despite its wide use FMC equations were not considered in CIE 1976 recommendations.

$$\Delta E = [(\Delta L)^2 + (\Delta C_{r\text{-}g})^2 + (\Delta C_{y\text{-}b})^2]^{1/2} \quad (2.15)$$

where $\Delta L = K_2 l/a[(P\Delta P + Q\Delta Q)/(P^2+Q^2)^{1/2}]$

$\Delta C_{r\text{-}g} = K_1/a[(Q\Delta P\text{-}P\Delta Q)/(P^2+Q^2)^{1/2}]$

$\Delta C_{y\text{-}b} = K_1/b[S(P\Delta P+Q\Delta Q)/(P^2+Q^2)^{1/2} - \Delta S]$

$P = 0.724X + 0.382Y - 0.098Z$

$Q = -0.480X + 1.370Y + 0.1276Z$

$S = 0.686Z$

$a^2 = \alpha^2(P^2+Q^2)/[1+(NP^2Q^2/P^4+Q^4)]$

$b^2 = \beta^2[S^2+(pY)^2]$

$\alpha = 0.00416 \qquad \beta = 0.0176$

$p = 0.4489 \qquad l = 0.279$

$N = 2.73 \qquad K_1 = K_2 = 1$

The FMC-1 equation were extended into three dimensions (in terms of opponent-colours dimensions), which included two new parameters K_1 and K_2, both are functions of the luminance factor Y. This version, known as FMC-2, was recommended by the CIE in 1967 for further study along with CIE 1964 formula. Moreover, these three-dimensional measurements indicated both magnitude and direction of colour difference. The FMC-2 colour difference equation is the same as FMC-1 with the added constants.

CIE recommended CIELAB and CIELUV colour difference equations in 1976[23]. The interest in developing new improved equations continued even after these recommendations. The CIELAB equations are given in Eqn. 2.16:

$$
\begin{aligned}
\mathbf{L^* = 116(Y/Y_n)^{1/3} - 16} &\qquad \mathbf{Y/Y_n > 0.008856} \\
\mathbf{a^* = 500[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}]} &\qquad \mathbf{X/X_n > 0.008856} \\
\mathbf{b^* = 200[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]} &\qquad \mathbf{Z/Z_n > 0.008856}
\end{aligned}
\tag{2.16}
$$

In calculating L*, values of Y/Y_n less than 0.008856 may be included if the normal formula is used for values of Y/Y_n greater than 0.008856, and the following modified formula Eqn. 2.17 is used for values Y/Y_n equal to or less than 0.008856:

$$\mathbf{L^* = 903.3(Y/Y_n)} \qquad \mathbf{Y/Y_n \leq 0.008856} \tag{2.17}$$

In calculating a* and b*, values of X/X_n, Y/Y_n and Z/Z_n less than 0.008856 may be included if the normal formulae are replaced by the following modified versions Eqn 2.18:

$$
\begin{aligned}
\mathbf{a^* = 500[f(X/X_n) - f(Y/Y_n)]} \\
\mathbf{b^* = 200[f(Y/Y_n) - f(Z/Z_n)]}
\end{aligned}
\tag{2.18}
$$

where $f(X/X_n) = (X/X_n)^{1/3}$ $\quad X/X_n > 0.008856$

$f(X/X_n) = 7.787(X/X_n) + 16/116 \quad X/X_n \leq 0.008856$

$f(Y/Y_n) = (Y/Y_n)^{1/3} \quad Y/Y_n > 0.008856$

$f(Y/Y_n) = 7.787(Y/Y_n) + 16/116 \quad Y/Y_n \leq 0.008856$

$f(Z/Z_n) = (Z/Z_n)^{1/3} \quad Z/Z_n > 0.008856$

$f(Z/Z_n) = 7.787(Z/Z_n) + 16/116 \quad Z/Z_n \leq 0.008856$

where X, Y and Z are the tristimulus values of the perfect diffuser.

Colour differences in CIELAB units are then given by Eqn. 2.19:

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \tag{2.19}$$

When the Cartesian coordinates L*a*b* are further transformed into the cylindrical coordinates L*C*h* using Eqn. 2.20:

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

$$h = \arctan b^*/a^* \tag{2.20}$$

These values quantify the Munsell variables of hue, value and chroma. Value (lightness) is quantified by L* on a scale such that a perfect black has an L* value zero and a fluorescent orange may have a C* value of 150. The hue angle (in degrees) is termed h; the four psychological primaries, e.g., a red which is neither yellowish nor bluish, have the following approximate hue angles: red 27°, yellow 95°, green 162° and blue 260°. As Δh is an angular difference, it is not in CIELAB units and therefore the preferred component, represented by ΔH^*, is given by Eqn. 2.21:

$$\Delta H^* = [(\Delta E^*)^2 - (\Delta L^*)^2 - (\Delta C^*)^2]^{1/2} \qquad (2.21)$$

Since 1976, J and P Coats (U.K.) had developed equation for pass/fail decisions in their production [24]. This equation had underwent number of modifications during its continuous use by their Research and Development laboratory. This equation was then published as the JPC 79 colour difference equation and successfully used for industrial shade passing. In fact, the published version of the JPC79 equation Eqn 2.22 [25] is a modification of the ANLAB equation:

$$\Delta E_{JPC79} = [(\Delta L/sA_L)^2 + (\Delta C/sA_C)^2 + (\Delta H/sA_{H)}{}^2]^{1/2} \qquad (2.22)$$

where $sA_L = 0.08195L/(1+0.01765L)$

$sA_C = 0.0638C/(1+0.0131C) + 0.638$

$sA_H = t\, sA_C$

$t = 1$ if $C < 0.638$, otherwise

$t = 0.36 + |0.4\cos(h° + 35)|$

unless h° is between 164° and 345° when

$t = 0.56 + |0.2\cos(h° + 168)|$

L, C and h° were refering to the standard from a pair of samples and all values are calculated from ANLAB(43.909) L, A and B values.

JPC 79 equation was modified by increasing lightness weighting by a factor of two. The new formula had significantly improved performance in quantifying perceptibility and was known as CMC (l:c) equation [26] (Eqn 2.23):

$$\Delta E_{CMC} = [(\Delta L^*/lS_L)^2 + (\Delta C^*/cS_C)^2 + (\Delta H^*/S_H)^2]^{1/2} \qquad \textbf{(2.23)}$$

where $S_L = 0.040975L^*/(1+0.01765L_1^*)$

unless $L_1 < 16$ when $S_L = 0.511$

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

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

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

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

unless h_1 is between 164° and 345° when

$T = 0.56 + |0.2\cos(h_1+168)|$

The two variables *l* and *c*, which are fixed, quantified the tolerances for lightness differences and chroma differences respectively relative to the hue differences. L^*_1, C_1^* and h_1 refer to the standard of pairs of samples, these values and ΔL^*, ΔC^* and ΔH^* being calculated from the CIELAB formula. The constants in the equation were fixed so that when *l* and *c* are set at unity (CMC(1:1)), the equation developed is the most reliable so far for quantifying the perceptibility of small colour differences, up to ten CIELAB units. In judging the perceptibility of colour difference, equal importance is given to differences in lightness, chroma and hue. For maximum reliability for predicting the acceptability of a batch as a 'good commercial match'. In the textile industry, *l* should be 2 and *c* should be 1, making the equation more tolerant to variations in lightness. The CMC(*l*:*c*) formula has been evaluated against six sets of acceptability and four sets of perceptibility data using all the various methods which have been developed for assessing reliability. In November 1986 it was issued as a draft British Standard and issued as British Standard 6923 in 1988 [27].

This equation was further modified as BFD(l:c) equation [28-29]. The different forms of BFD(l:c) equations are suggested which can be used for perceptibility and acceptability data separately (Eqn 2.24):

$$\Delta E(BFD) = \{[\Delta L(BFD)/l]^2 + [\Delta C^*/(cD_C)]^2 + (\Delta H^*/D_H)^2 + R_T(\Delta C^*/D_C)(\Delta H^*/D_H)\}^{1/2} \quad (2.24)$$

where $D_C = 0.035\,\bar{C}^*/(1+0.00365\,\bar{C}^*) + 0.521$

$D_H = D_C(GT' + 1 - G)$

$G = \{(\bar{C}^*)^4/[(\bar{C}^*)^4 + 14000]\}^{1/2}$

$T' = 0.627 + 0.055\cos(\bar{h} - 254°) - 0.004\cos(2\bar{h} - 136°) + 0.070\cos(3\bar{h} - 32°) + 0.049\cos(4\bar{h} + 114°) - 0.015\cos(5\bar{h} - 103°)$

$R_T = R_H R_C$

$$R_H = -0.260\cos(\bar{h}-308°) - 0.379\cos(2\bar{h}-160°)$$

$$- 0.636\cos(3\bar{h}+254°) + 0.226\cos(4\bar{h}+140°)$$

$$- 0.194\cos(5\bar{h}+280°)$$

$$R_C = \{(\bar{C}^*)^6/[(\bar{C}^*)^6 + 7x10^7]\}^{1/2}$$

$$L(BFD) = 54.6\log(Y+1.5) - 9.6$$

The terms $\bar{C}^*$ and $\bar{h}$ refer to the mean of the C* and h values for the standard and sample, these values and ΔC* and ΔH* being calculated from the CIE L* a* b* formula. Care should be taken in calculating ΔC* and ΔH*. If ΔC* is equal to the C* value of sample B minus that of the sample A, then the ΔH* value is positive if sample A is clockwise relative to sample B on a plot of a* against b*. As in the CMC formula, different *l* and *c* values can be used for different applications.

In addition to the above equation, Taylor of Marks and Spencer discussed the 'optimised equation' approach to single-number shade passing with McDonald and his colleagues, began an independent attack on the problem in 1975 [30]. In collaboration with Smart of Instrumental Colour System, a colour-difference formula was developed that, unlike JPC79, lent itself to 'fine tuning' to eliminate any weakness with extensive industrial usage might reveal. This resulted in several modifications. Although in widespread use, the formula has not been published.

The CIE established its technical committee TC1-29 (industrial colour-difference equation) in 1989, with a remit to study existing metrics used in industry to evaluate colour differences between object colours in daylight illumination and to develop a recommendation on this subject. A new formula was published as a CIE technical report in 1995 [31]. The full title was the 'CIE 1994 (ΔL^* ΔC^*_{ab} ΔH^*_{ab}) colour-difference model' with the official abbreviation CIE94 and colour-difference symbol ΔE^*_{94}. The new formula was based in CIELAB colour space. TC1-29 rightly regarded as important both the wide acceptance in the coloration industries of the associated colour-difference formula and its incorporation of the perceptual correlates of lightness, chroma and hue differences. The formula replaces those previously recommended for the calculation of small to moderate colour differences between coloured materials. It does not replace CIELAB and CIELUV as approximately uniform colour spaces. The CIE94 formula includes a new term (ΔV), which is the visually perceived magnitude of a colour difference (Eqn.2.25).

$$\Delta V = k_E^{-1} \Delta E^*_{94} \tag{2.25}$$

where k_E is not to be used as a measure of commercial tolerance, but is an overall visual sensitivity factor, set to unity and therefore making $\Delta V = \Delta E^*_{94}$ under the conditions usually applying in industrial assessments. The CIE94 formula is Eqn 2.26:

$$\Delta E^*_{94} = [(\Delta L^*/k_L S_L)^2 + (\Delta C^*_{ab}/k_C S_C)^2 + (\Delta H^*_{ab}/k_H S_H)^2]^{1/2} \tag{2.26}$$

The purpose of the variables k_L, k_C and k_H is the same as that of l, c and h in the CMC(l:c) formula (which may be considered as having a relative tolerance h to hue differences in the divisor of the term in ΔH^*_{ab}, but since h = 1 (always) it is omitted). They are, however, called 'parametric factors', hence avoiding the confusion with acceptability tolerances caused by l and c being called 'relative tolerances'. Under reference conditions they are set to $k_L = k_C = k_H = 1$. Other values allow adjustment to be made independently to each colour-difference component to account for any deviations from the reference conditions that cause component-specific variations in visual tolerances. A reduction in lightness sensitivity is well established when assessments of textile pairs are made, it is reasonable to expect better correlation of CIE94 results with those from visual assessments of textile specimens when $k_L = 2$ and $k_C = k_H = 1$.

As is the case in the CMC(l:c) formula, the lengths of the ellipsoid semi-axes (S_L, S_C, S_H), termed 'weighting functions' CIE94, allow adjustment of their respective components according to the location of the standard in CIELAB colour space, but they are defined differently from their CMC(l:c) counterparts by linear equations Eqn 2.27:

$$\mathbf{S_L = 1}$$

$$\mathbf{S_C = 1+0.045C^*_{ab,X}}$$

$$\mathbf{S_H = 1+0.015C^*_{ab,X}} \qquad \mathbf{(2.27)}$$

where $C^*_{ab,X} = C^*_{ab,S}$ when the standard of a pair of specimens may be clearly distinguished from the batch, as is usually the case in industrial pass/fail decisions. The asymmetry of optimised formulae usually causes the colour difference between a pair of specimens, A and B, when calculated with A as standard to be different from that obtained when B is taken as standard. When neither specimen can logically be standard, $C_{ab,X}$ may be defined as the geometric mean of the CIELAB chromas of the pair as follow Eqn 2.28:

$$C^*_{ab,X} = (C^*_{ab,A}C^*_{ab,B})^{1/2} \qquad (2.28)$$

It should perhaps be noted that, whilst many members of TC1-29 wished to make CIE94 a recommendation, others did not. The technical report of TC1-29 is ambivalent; whilst its title does not include the word 'recommendation', its text clearly states that CIE94 replaces the CIELAB formula in colour-difference evaluation.

2.3 Colour Tolerance Block

It has long been generally accepted that if perceived colour difference between a standard and batch 1, say, is judged to be equal in size to that between the same standard and batch 2. The chances of both being accepted or both being rejected as 'good commercial matches' will not necessarily be equal. This is especially true if the colour difference between batch 1 and standard is mainly one of hue and that between batch 2 and standard is mainly one of depth and/brightness. In industrial acceptability matching there is usually a greater tolerance towards depth and/or brightness variation than towards hue variation. A tolerance block is then a tolerance limit in three dimensions. For example, the shape of this tolerance block will be an ellipsoid with the Lightness, Chroma and Hue be the three axes for the CMC (*l;c*) equation.

CHAPTER 3

METHODOLOGY

3.1 Experiment 1: Preparation of Samples

Samples (majority were Nylon) for this research project were obtained from:

1. Triumph International Overseas Ltd.(Hong Kong Branch) and the local or overseas subsidiaries. (131 samples for spectrophotometers comparison, 110 samples for developing tolerance block and 163 samples for tolerance verification).
2. Prepared in the Textile Chemistry Laboratory of The Hong Kong Polytechnic University. One set of Nylon samples were dyed with acid dyes in order to cover a wider range of colour. The colour distribution of the samples were measured under the Illuminant ADN (Appendix 1).

3.1.1 Apparatus and Materials

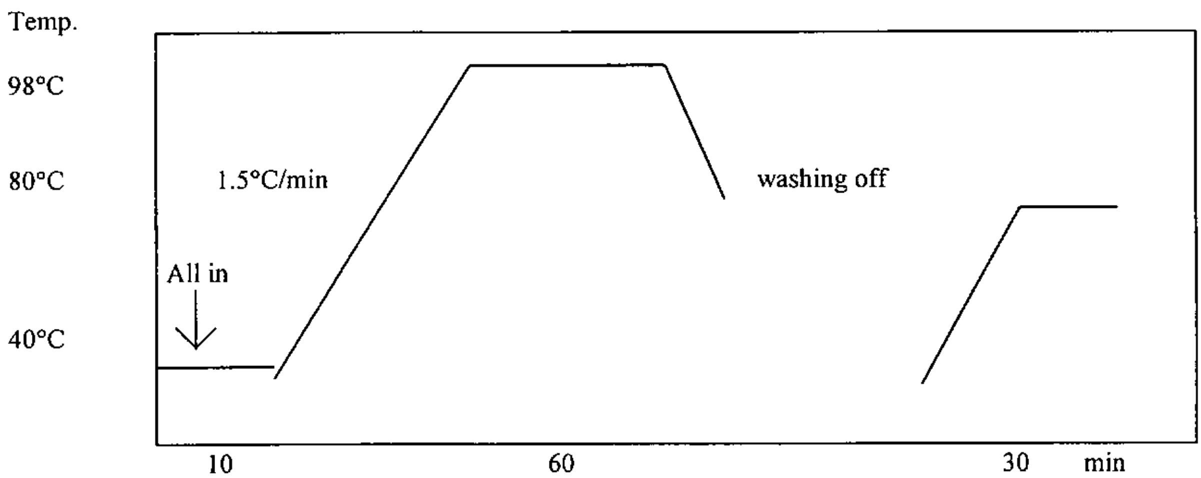
1. 20g Nylon fabric for each of six different substrates (different in constructions, textures and degree of elasticity) about 20cm x 20cm in dimension.

2. Dyestuffs: Erionyl Yellow 3Gs 100% and Solophenyl Turquoise BRL 400%
3. Auxiliaries: Albegol (leveling Agent)
4. Chemicals: Acetic acid
5. Dyeing machinery: Lauder-Ometer (Fig. 3.1)
6. Spectrophotometer: Datacolor Elrepho 2000 (Fig. 3.2)

3.1.2 Procedure

3.1.2.1 Preparation of the dyeing recipe

1. A database for the selected acid dyes, Erionyl Yellow 3Gs 00% and Solophenyl BRL 400%, from Ciba Geigy were prepared according to the dyeing profile given.



- Liquor ratio = 20 : 1
- Levelling agent : 1% Albegol (Ciba Geigy)
- Dyeing at pH 5, adjusted by acetic acid
- Washing off by 1% non-ionic detergent at 80°C for 30 minutes, rinsed in cold water and dried

2. Calibration samples were dyed with eight different depth for each substrate. i.e., 0.05%, 0.1%, 0.5%, 1.0%, 1.5%, 2%, 3%, 4%.
3. The reflectance values of the yellowish green standard were measured using the spectrophotometer.
4. Recipes for the yellowish green was predicted by the colour recipe calculation programme of the spectrophotometer from the database prepared and the standard database existed in the spectrophotometer.
5. The recipes predicted were further modified. It was intended to prepare samples with minor colour difference.

3.2 Experiment 2 : Instrumental Measurement of the Coloured Samples

3.2.1 Aim

To obtain the spectral reflectance and colour coordinates values of the sample pairs instrumentally.

3.2.2 Apparatus and materials

1. Dyed samples.
2. Spectrophotometers: Elrepho2000.
3. Computer terminal with supporting computer programme Osiris manual version 2.3 plus.
4. Visual display unit.(Fig3.3)
5. Data output either print out directly or saved in the floppy disk.

3.2.3 Procedures

1. The spectrophotometer calibrated by using barium sulphate tile for white standard and black trap for black standard.
2. A diaphragm of 18mm in diameter was chosen to perform the measurement.
3. The option "Without gloss mask" was chosen for measurement, i.e., specular component included
4. " Normal range " was chosen for the measurement, i.e., 400-700nm for 20nm interval. i.e. 16 points data.
5. 100%of UV transmission was selected.

In fact, the settings and configurations were recommended to Triumph by the spectrophotometer supplier.

3.2.3.1 Measurement of the spectral reflectance distribution of the samples

1. Basically the instrumental measuring method from the Technical manual of the American Association of Textile Chemists and Colourists 1988, AATCC Test Method 153-1985, was followed.
2. Samples used for testing the correlation for different spectrophotometers were in single layer and mounted on a white paper board. Totally 131 samples were used.
3. Samples for visual assessment were folded in four layers.
4. The option for multiple measurement was selected for measuring the sample. i.e. Every sample was measured four times for every 90° rotation.

3.3 Experiment 3: Comparison of different Spectrophotometers

3.3.1 Aim

To determine the performance of the existing spectrophotometers involved in this project.(For details of spectrophotometers being compared please refer to table 4.2.1)

3.3.2 Apparatus and materials

1. Dyed nylon samples, totally 131 samples, mounted on a white paper board.
2. Datacolor Elrepho 2000 reflectance spectrophotometer with the supporting computer programme Osiris manual version 2.3 plus, display unit and output device. e.g., floppy disk and floppy disk drive.
3. Datacolor Texflash (Fig. 3.4) reflectance spectrophotometer with the supporting computer programme Osiris manual version 2.3 plus, display unit and output device. e.g., floppy disk and floppy disk drive, printer.
4. Datacolor Spectraflash 600 (Fig.3.5) reflectance spectrophotometer with the supporting computer programme Datamaster 3.1 in Window, display unit and output device. e.g., floppy disk and floppy disk drive.
5. Macbeth Coloreye 7000 (Fig.3.6) reflectance spectrophotometer with the supporting computer programme Optimatch in Window, display unit and output device. e.g., floppy disk and floppy disk drive, printer.

3.3.3 Procedures

1. For Datacolor Texflash and Spectraflash 600, the procedure was same as Datacolor Elrepho 2000 in 3.2.3. except at the prompt "Gloss mask:", "Small" was chosen. i.e., the specular component excluded.
2. For Macbeth Coloreye 7000, specular component excluded and 100% UV transmission was selected.
3. The data from Coloreye 7000 was exported in database format with the extension .DBF from the directory "c:\opti\".

3.4 Experiment 4: Visual Assessment of the Samples under the Light Source ADN (D65 + N)

3.4.1 Aim

To assess the acceptability, in merit pass rate, of sample pairs by different shade passers including Triumph's Q.C., suppliers and experienced colourists from The Hong Kong Polytechnic University(Appendix II).

3.4.2 Apparatus and materials

1. Veri-vide Multi-light Viewing Cabinet (Fig.3.7)
2. Davidson and Hemmendinger Colour Rule (D&H Test) (Fig. 3.8)
3. Samples
4. Data sheets

3.4.3 Procedure

1. Data sheets were distributed to the shade passers.
2. D&H Test [32] was applied to each shade passer under their viewing cabinet to test whether each of the shade passers were having a normal colour vision and the performance of the multi-light Viewing Cabinet.
3. The shade passers were requested to provide information such as age, experience of related field, comment on the project..etc.
4. The viewing cabinet was switched on with the light sources D65 and Natural together.

5. The sample pairs were then assessed by the shade passers at a viewing and illuminating geometry about 0°/45°.
6. The results i.e., pass (P), fail(F) of marginal pass(M) was marked on a data sheet by the shade passers provided.
7. Shade passers were allowed to rest for minutes if they felt tired during the assessment.

3.5 Data Analysis

3.5.1 Aim

To determine the correlation of different spectrophotometers involved in this project and develop objective tolerance blocks from subjective shade passing assessments with respected to different colour difference equations.

3.5.2 Apparatus and materials

1. Personal computer with the software Datacolor Osiris manual version 2.3 plus, Datamaster 3.1 and software Macbeth Optimatch[33].
2. Microsoft Excel 5.0 [33].
3. Visual display unit.
4. Printer.

3.5.3 Procedure

3.5.3.1 Determine the correlation coefficient from different sets of data measured by the spectrophotometers.

1. The colour coordinates calculated from the spectral reflectance values by the Osiris manual version 2.3 plus was exported through printer.
2. The colour coordinates were then plotted in different graphs.
3. Using the colour coordinates measured by the Spectraflash 600 as reference, graphs of L^* Vs L^*, a^* Vs a^*, b^* Vs b^*, ΔL^* Vs L^*, Δa^* Vs a^*, Δb^* Vs b^* of the other three spectrophotometers were plotted and the coefficients of

correlation were calculated by Microsoft Excel 5.0.

4. Since the reflectance values from the Macbeth Coloreye 7000 were in different format, therefore the data from Coloreye 7000 was first exported in a floppy disk. The data file was then retrieved by the software Excel 5.0 to eliminate unnecessary data. i.e. To selected data that is in 20nm interval. The modified data was then exported by Microsoft Excel 5.0 in ASCII format. It was further edited by using the programme "Editor" to rearrange the data format into .LSP format, ASCII format [33], before it could be read by the Osiris manual version 2.3 plus.
5. Data could be input through the programme Datacolor Osiris manual version 2.3 plus from another spectrophotometer.

3.5.3.2 Developing the tolerance block

1. "Smart Tolerancing" was selected for calculating the tolerance block from the Macbeth Optimatch software [33]. In fact it is simply a database which recorded down all the conditions that a sample will be passed or failed numerically.
2. Colour difference equation was selected and the desire colour difference equation was input. e.g., CIELAB, CMC(2:1) and CIE94(2:1:1).
3. Light source ADN was selected. It was abridged by inputting the spectral power distribution of the ADN light source, which could be obtained from the software Datamaster 3.1 [33].

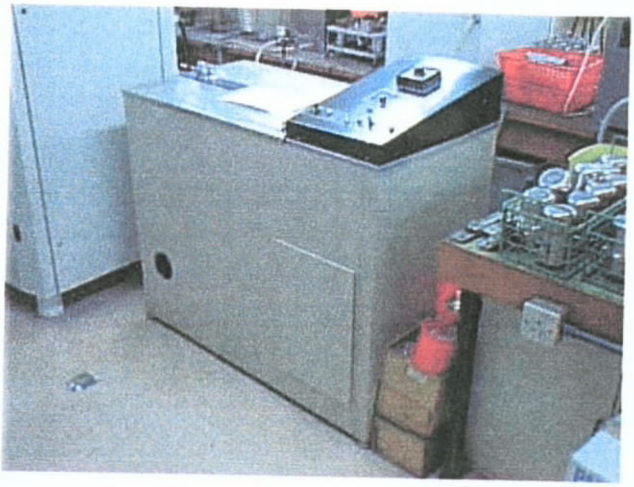


Fig. 3.1: Atlas Launder-Ometer

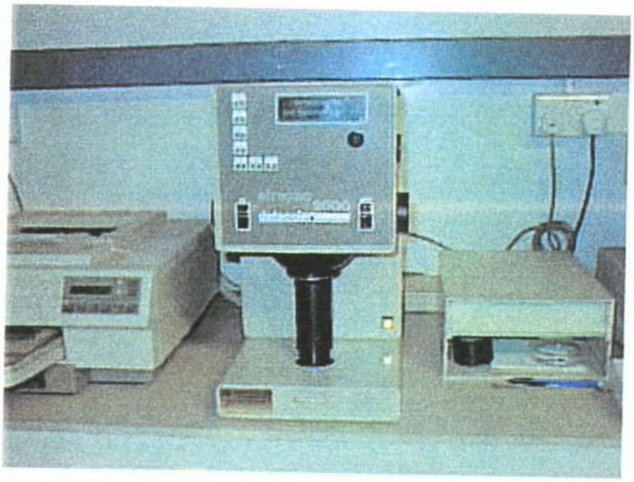


Fig. 3.2: Datacolor Elrepho 2000

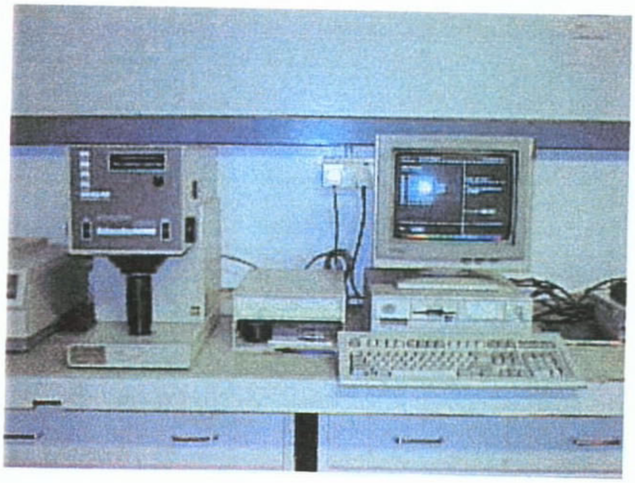


Fig. 3.3: Elrepho 2000 and visual displaying unit

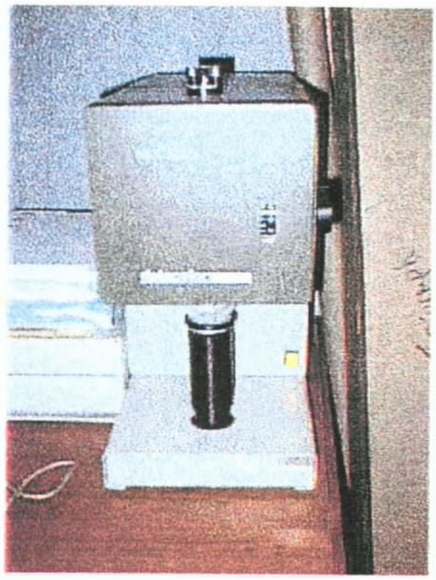


Fig. 3.4: Datacolor Texflash

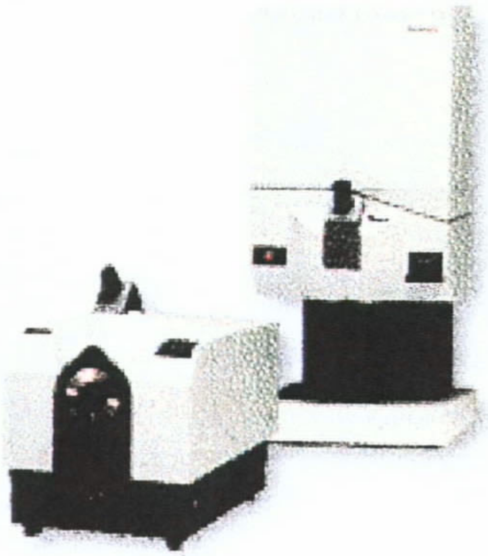


Fig. 3.5: Datacolor Spectraflash 600 (Left : Horizontal type, Right : Vertical Type)

Fig. 3.6: Macbeth Coloreye 7000

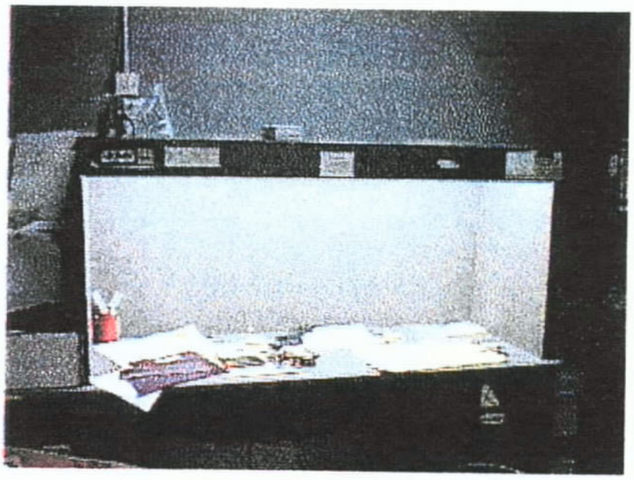


Fig. 3.7: Veri-vide Multi-light Viewing Cabinet

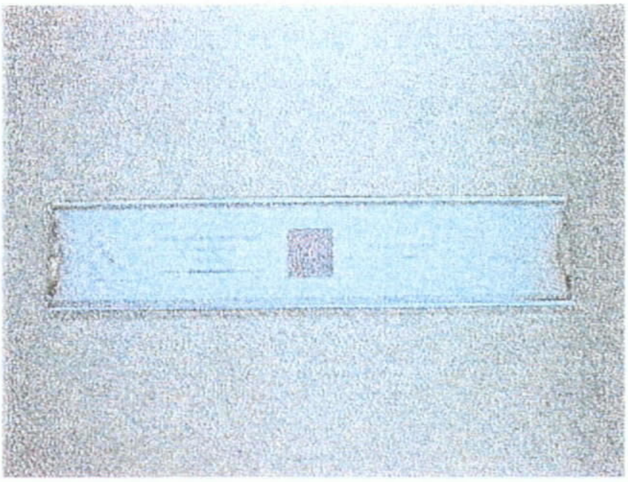


Fig. 3.8: Davidson and Hemmendinger Colour Rule

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

Colour difference equations are intended to give a single number [34], ΔE that is proportional to the difference seen between paired samples. For colour differences between pairs of samples in dissimilar directions for the same colour, all differences seen to be the same should have the same ΔE value. Although a colour difference equation should, ideally, be based on colour appearance model, most equations in common use are empirically based. Of the many proposed, none are completely satisfactory, but advances have been made in recent years,-which were discussed in Chapter 2. Traditionally, colour assessment has been carried out visually by experienced colourists [35], however, converting a visual colour matching system to an instrumental one can offer several advantages including less subjectivity in evaluations and greater efficiency in shade passing and shade sorting [36] processes.

The failure to set tolerances on the colour requirement in a purchase order is one of the causes of reject. On small amounts of goods it does not pay. Large corporations and government agencies, however, often make large single purchases on the open market and demand in their big requests to know in advance exactly that they are buying, including exactly how closely the colour requirement will be met. Whether a colour tolerance should be set also depends on the economic situation. In a seller's market the buyer is glad to get the goods even if badly off-colour; he will not complain and a colour tolerance is not necessary. But in a buyer's market the insertion of a tolerance on the colour requirement is a protection to the supplier against arbitrary rejection to the goods as off-colour by an unscrupulous buyer who has found another supplier offering the goods at a lower price. In normal times, it is a protection to both buyer and seller. A colour tolerance, like other tolerances in a purchase order, represents a compromise between what the purchaser really would like to get and what the manufacturer can supply at a reasonable price.

The actual decision as to what colour range is written into the contract as acceptable is not easy. There is a great temptation to make a guess as to the correct colour, tell the supplier what the colour has to do with the intended use of the article or material and trust to his competence to deliver goods suited to purpose. If the operation involves mass production, it is dangerous to yield to this temptation. The colour serves some purpose. It must coordinate with some other colour to some degree. If the colour tolerance is large, money can be saved by adopting simple inspection procedures; if it is small, the most careful selection of colour tolerances coupled with most reliable colour measurement and control possible will pay higher dividends.

Colour tolerances can be stated in terms of special colour standards made up for one or long term orders. They may be stated in terms of a collection of colour chips possessed both by purchaser and by supplier may be based upon measurements, either by direct colourimetry or by spectrophotometry and calculation.

4.2 Methodology for Comparing the Spectrophotometers

Four abridged spectrophotometers were involved in this evaluation from Triumph International Overseas Ltd.(Hong Kong Branch), its vendors and The Hong Kong Polytechnic University . These four systems are:

1. Datacolor Texflash [Triumph International Overseas Ltd.(Hong Kong Branch)].
2. Datacolor Elrepho 2000 [Hong Kong Polytechnic University].
3. Datacolor Spectraflash 600 [Schmidt Co. Ltd.].
4. Macbeth Coloreye 7000 [Libero Ltd.].

The main features and operating conditions of the spectrophotometers was shown in table 4.2.1:

Instruments	Datacolor Texflash	Datacolor Elrepho 2000	Datacolor [a] Spectraflash 600	Macbeth [a] Coloreye 7000
Measuring Geometry	Cone D/0°	Sphere [b] D/8°	Sphere D/8°	Sphere D/8°
Wavelength range (nm)	400 - 700	400 - 700	360 - 750	360 - 750
Measuring Diaphragm (mm)	18	18	18	[c] 25
Measuring area Diameter (mm)	16	16	16	[c] 22
Measuring Interval (nm)	20	20	10	10
Specular component	Excluded	[b] Included	Excluded	Excluded
Stand alone Retractable cutoff filter	No	Yes	Yes	Yes
Gloss Trap	Yes	No	Yes	Yes
Illumination	1 Xenon Flash Lamp	2 Xenon Flash Lamps	2 Xenon Flash Lamps	2 Xenon Flash Lamps
Monochromator	Holographic Gratings	Holographic Gratings	Holographic Gratings	Holographic Gratings
Min. Spectral band width (nm)	20	20	3	10
Detector Types	Si Diode Arrays	Si Diode Arrays	Si Diode Arrays	Si Diode Arrays

Table 4.2.1 Remarks: [a] Although the range is measured at 360 - 750 nm and with 10nm interval, the data were further adjusted to in the range 400 - 700nm and 10nm interval for comparison.

[b] The instrument settings were fixed and could not be changed.

[c] The closest and available diaphragm compared to other system.

In addition, the spectrophotometers were compared under the light source ADN (D65 + N) in the CIELAB colour space and CIE 1964 10° Standard Observer (Appendix I).

In the process of comparison, 131 colour standards were selected from Triumph for which they are the most frequently used colours. The colours cover all four quadrants of the CIELAB colour space (Fig. 4.2.1).

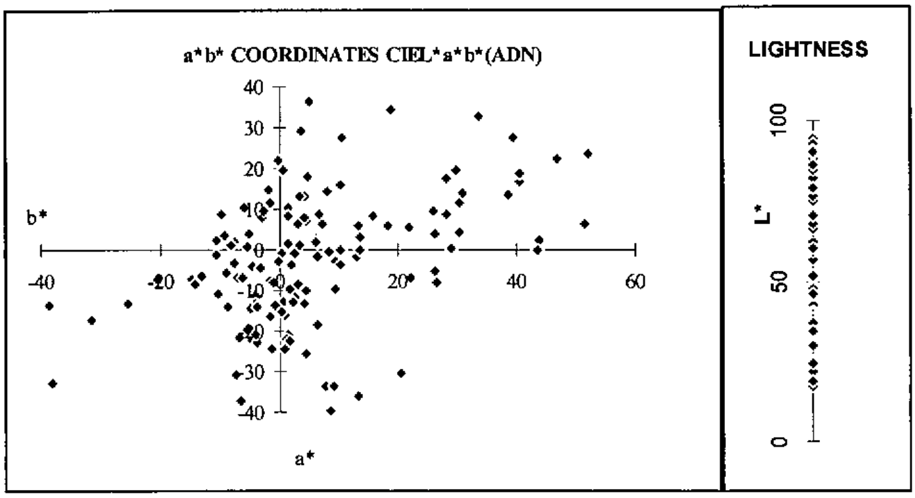


Fig. 4.2.1: The Colour coordinates of the 131 selected colour standards in the CIELAB colour space.

All the colour standards were measured by the four spectrophotometers based on the AATCC Test Method 153-1985, Colour Measurement of Textiles: Instrumental. The samples were measured in the same measuring condition, e.g., wavelength range and measuring interval. However, some of the configurations of the spectrophotometers were fixed, e.g., only specular component included could be selected for Datacolor Elrepho 2000, different diaphragm size of Macbeth Coloreye 7000 from other Datacolor spectrophotometers involved in this project. All the L*, a* and b* values were calculated by the Datacolor's software Datamaster version 3.1. The L*, a* and b* values obtained were analysed by plotting different graphs to evaluate the correlation between spectrophotometers using the values measured by Datacolor Spectraflash 600 as reference. The Spectraflash 600 from Datacolor was calibrated by the supplier that it was in the best condition before starting the experiment, therefore it was believed that the spectrophotometer was in a condition of high precision. In the other words, if spectrophotometers having a good correlation with Spectraflash 600, then it should have a good precision too, i.e., comparison of L* a* and b*, the ΔL* Vs L*, Δa* Vs a* and Δb* Vs b* of different spectrophotometers. The coefficient of correlation R [37] was used to determine the extent of interinstrument correlation and could reflect the instrument precision indirectly.

4.3 Data Analysis for the Comparison of Different Spectrophotometers

After the L* a* and b* values were obtained, they were plotted in the following graphs:

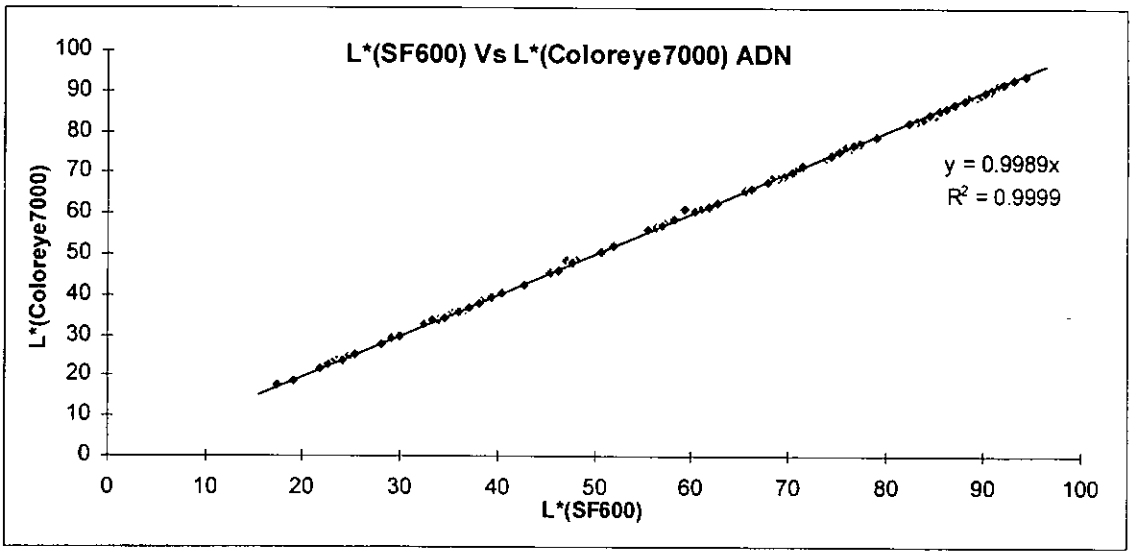


Fig. 4.3.1: L*(SF600) Vs L*(Coloreye 7000) under light source ADN

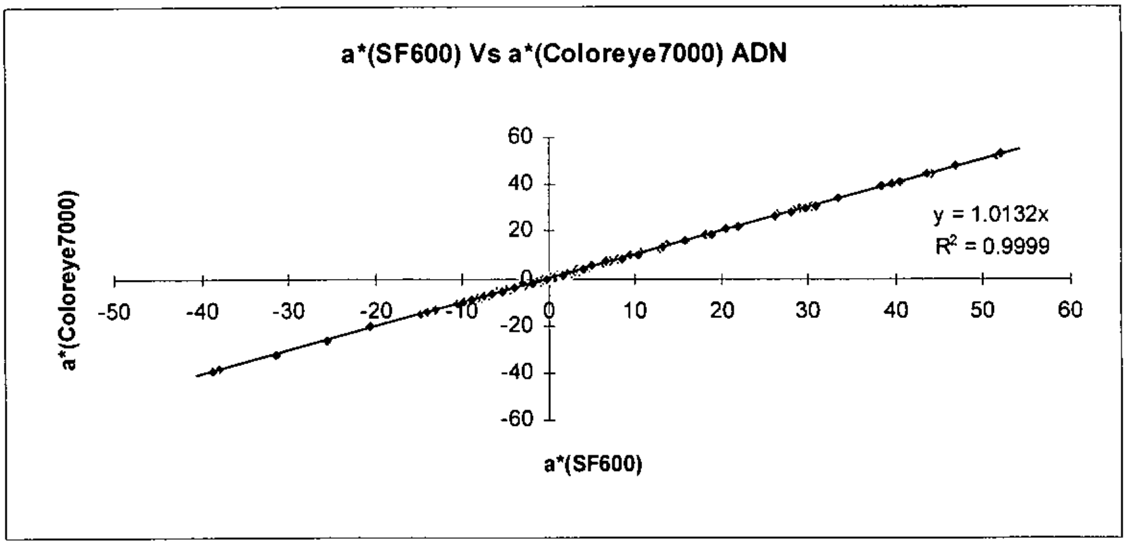


Fig. 4.3.2: a*(SF600) Vs a*(Coloreye 7000) under light source ADN

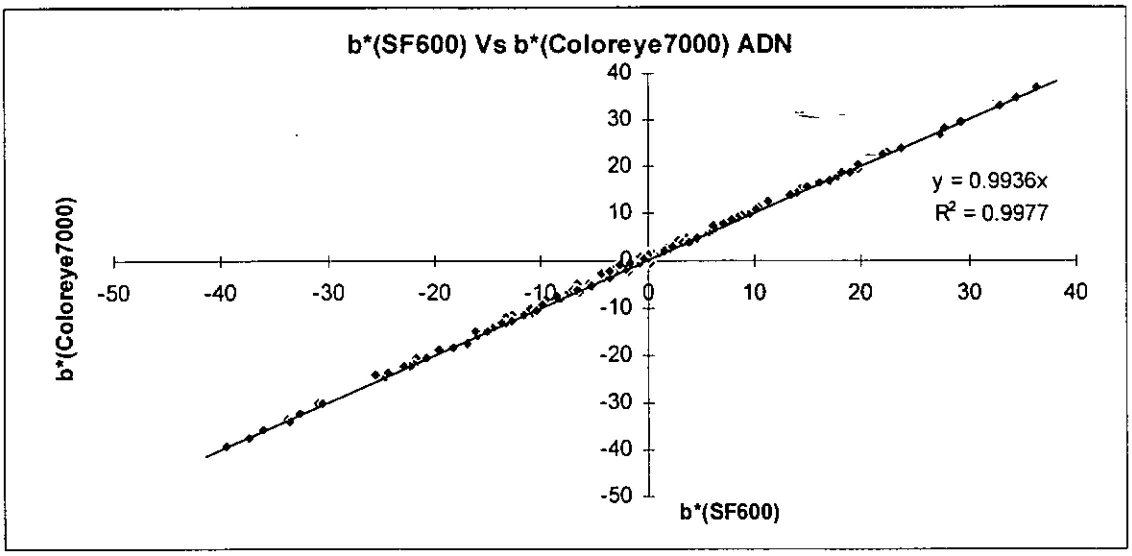


Fig. 4.3.3: b*(SF600) Vs b*(Coloreye 7000) under light source ADN

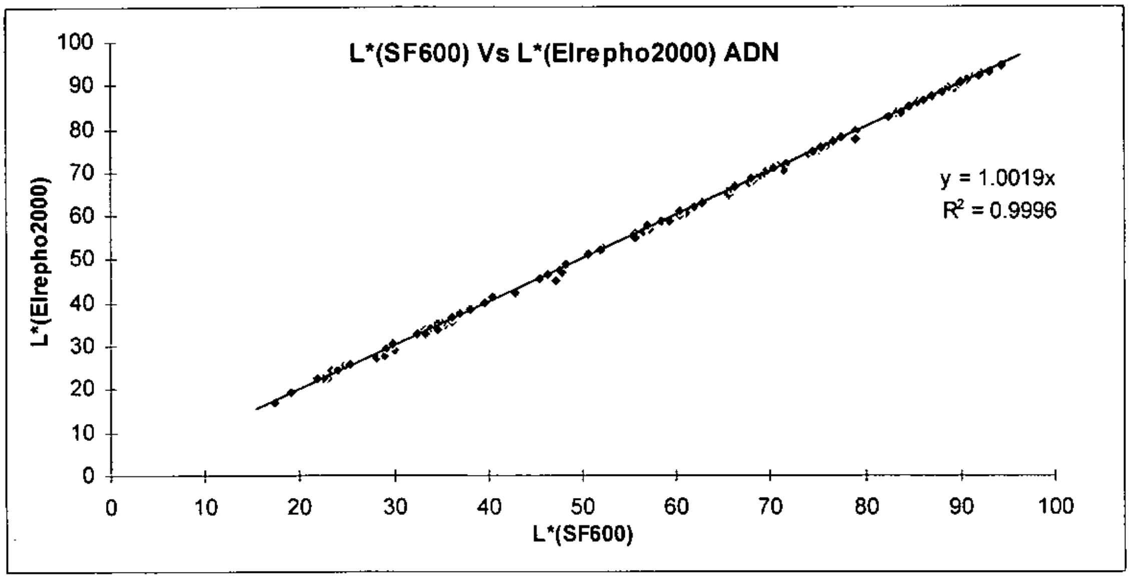


Fig. 4.3.4: L*(SF600) Vs L*(Elrepho 2000) under light source ADN

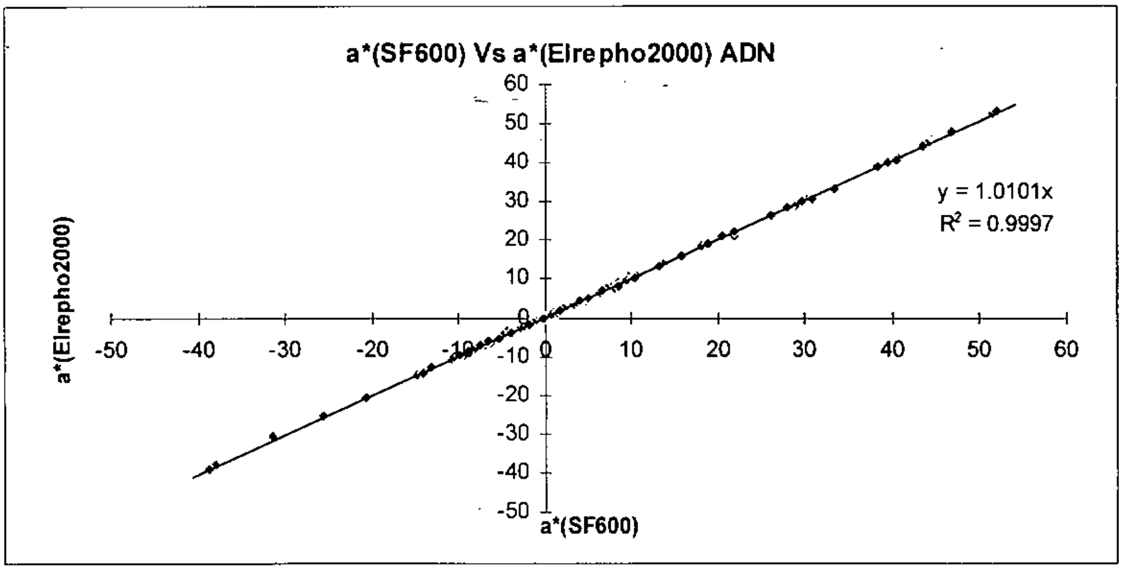


Fig. 4.3.5: a*(SF600) Vs a*(Elrepho 2000) under light source ADN

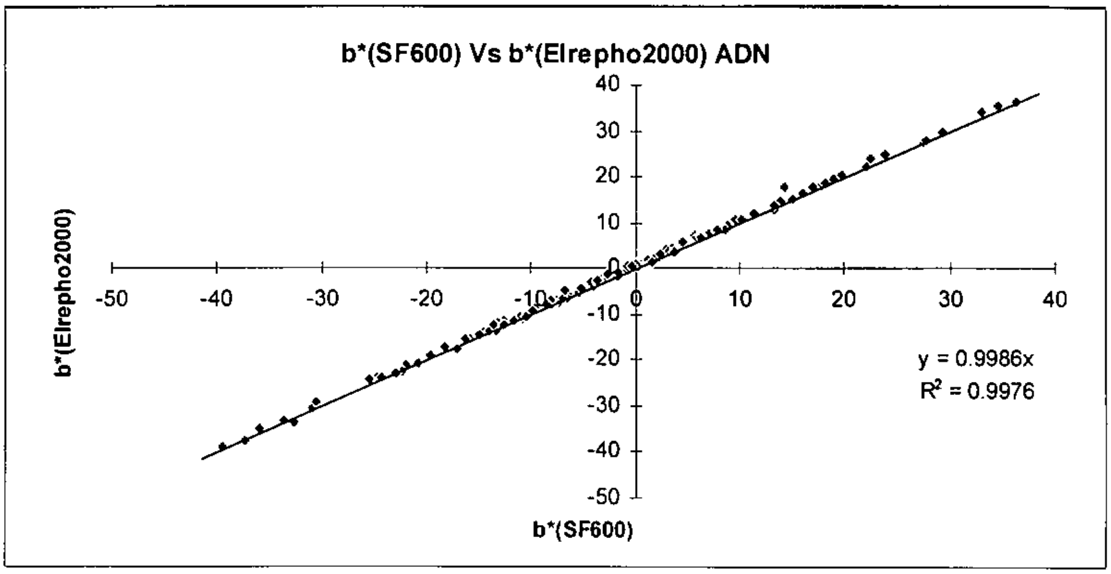


Fig. 4.3.6: b*(SF600) Vs b*(Elrepho 2000) under light source ADN

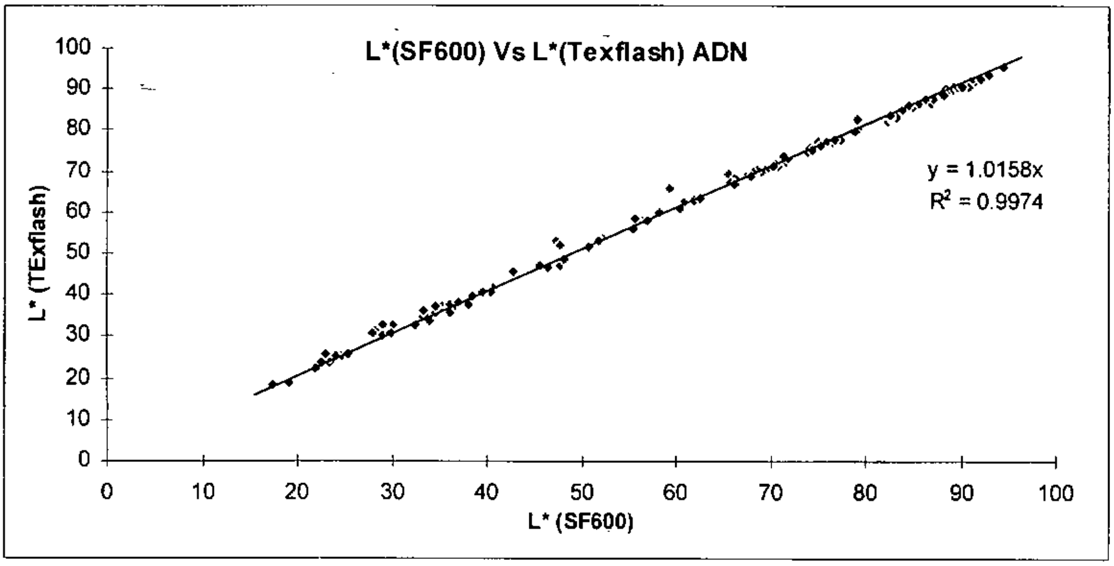


Fig. 4.3.7: L*(SF600) Vs L*(Texflash) under light source ADN

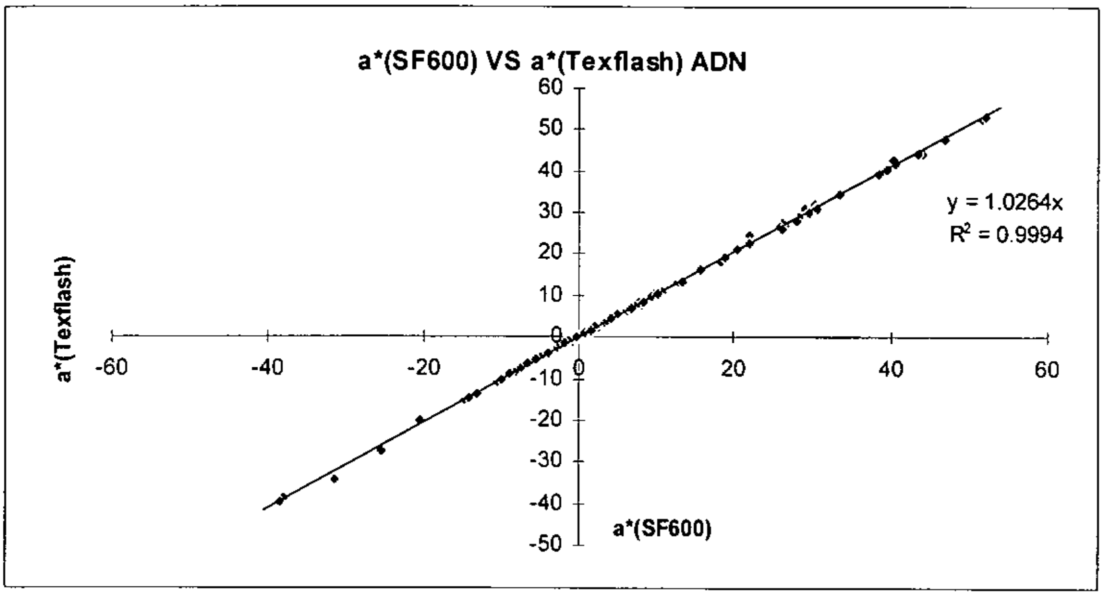


Fig. 4.3.8: a*(SF600) Vs a*(Texflash) under light source ADN

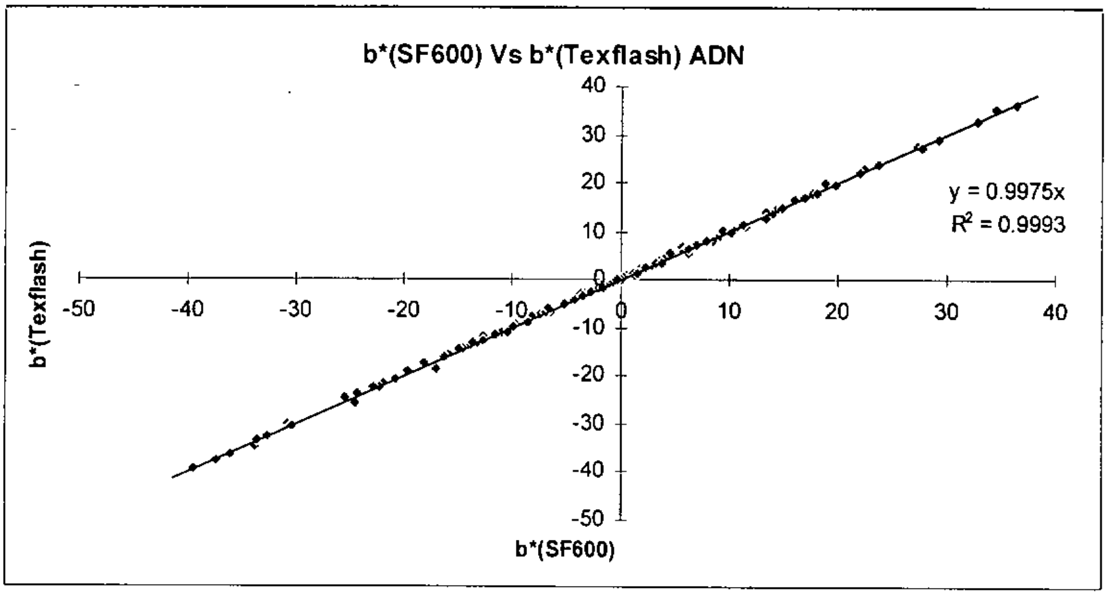


Fig. 4.3.9: b*(SF600) Vs b*(Texflash) under light source ADN

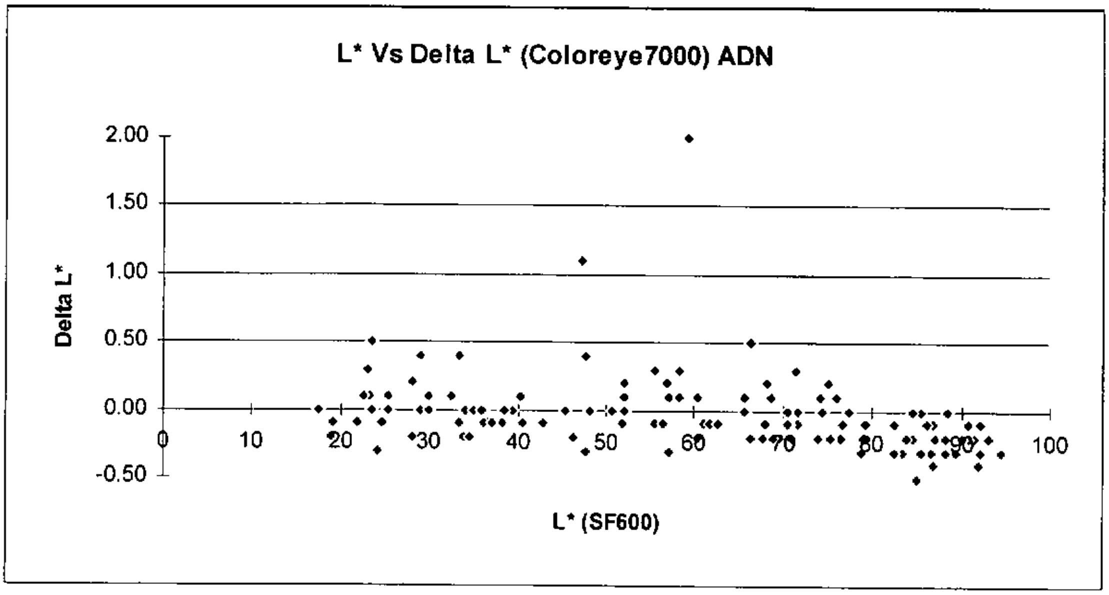


Fig. 4.3.10:L*Vs Delta L*(Coloreye 7000 c.f. SF600) under light source ADN

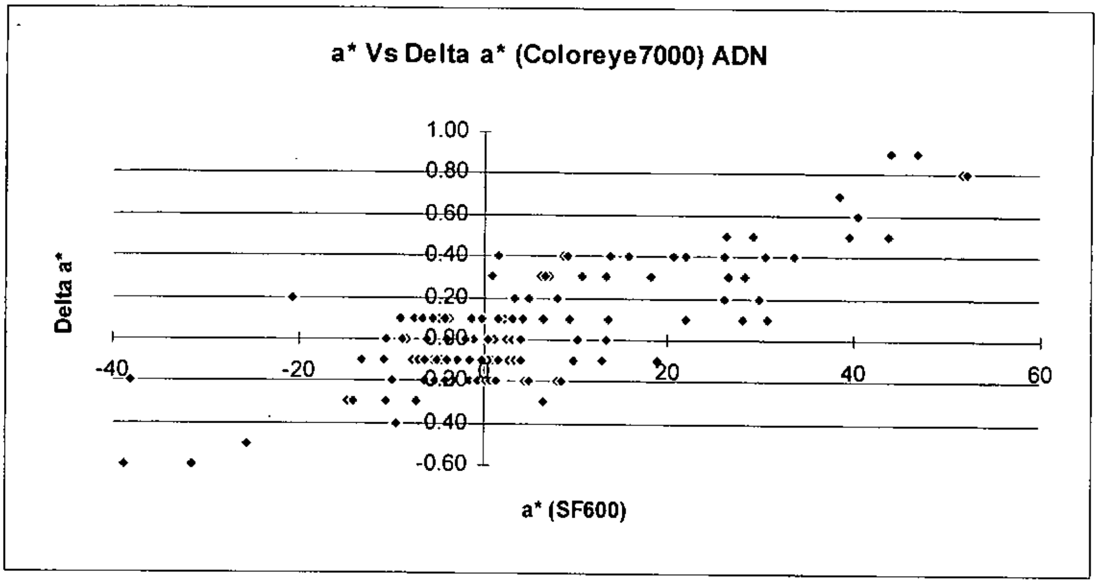


Fig. 4.3.11: a* Vs Delta a*(Coloreye 7000 c.f. SF600) under light source ADN

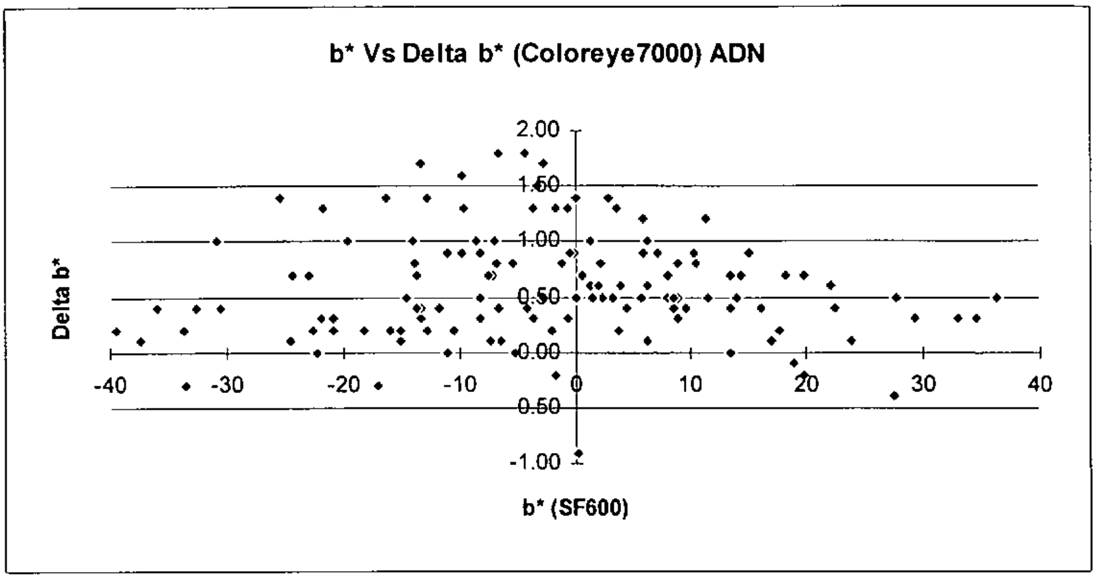


Fig. 4.3.12: b*Vs Delta b*(Coloreye 7000 c.f. SF600) under light source ADN

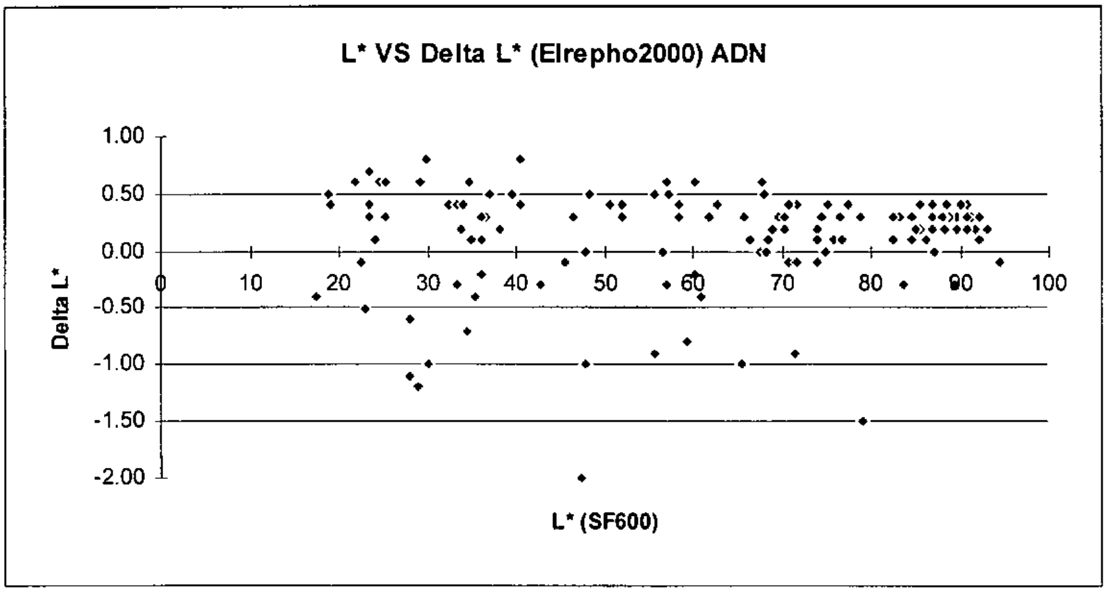


Fig. 4.3.13: L* Vs Delta L*(Elrepho 2000 c.f. SF600) under light source ADN

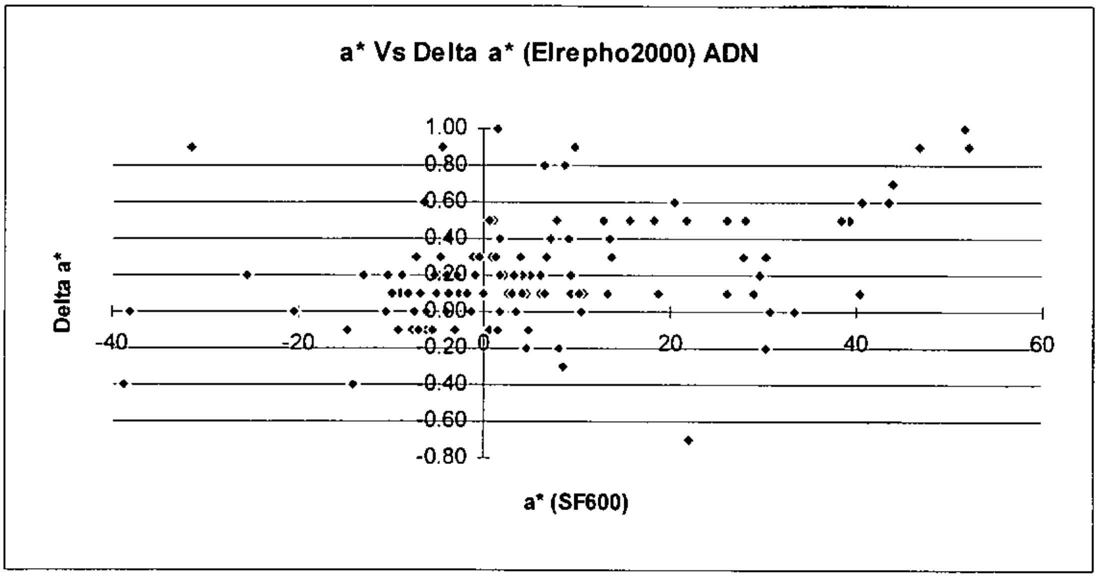


Fig. 4.3.14: a* Vs Delta a*(Elrepho 2000 c.f. SF600) under light source ADN

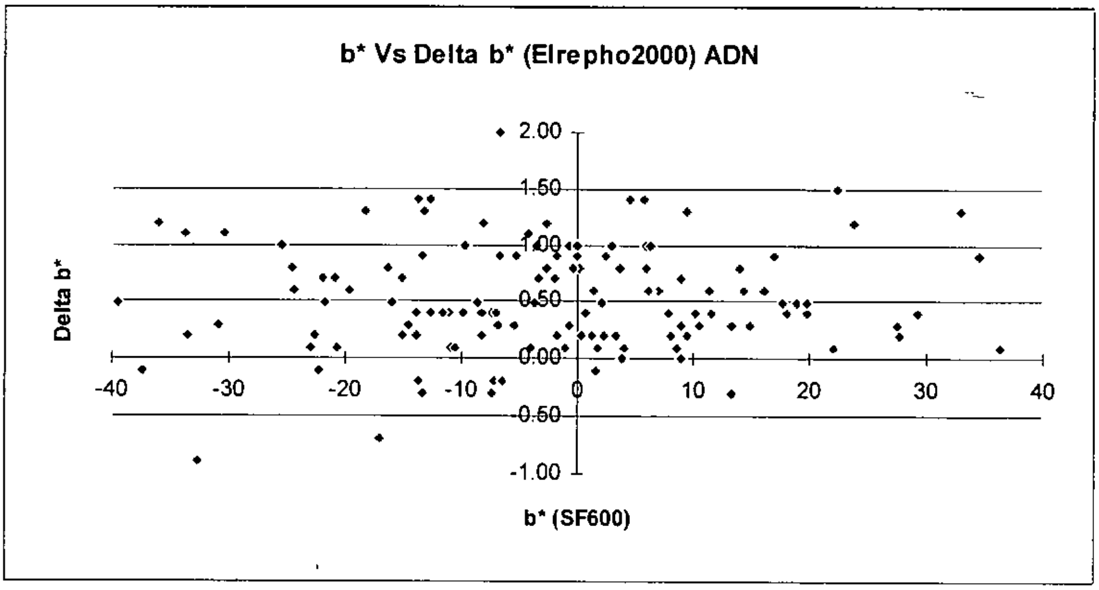


Fig. 4.3.15: b* Vs Delta b*(Elrepho 2000 c.f. SF600) under light source ADN

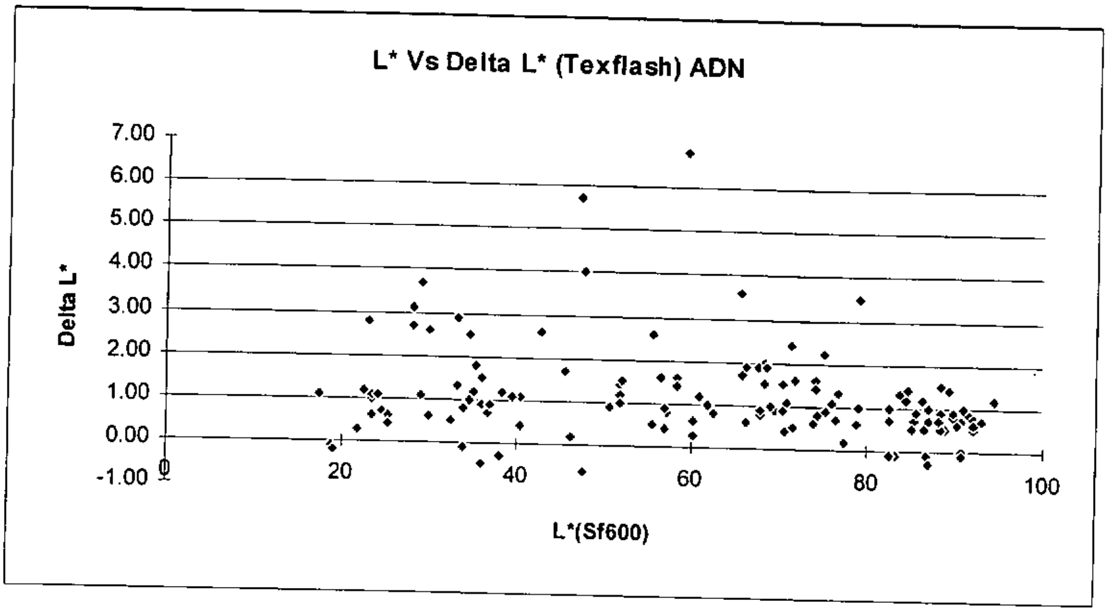


Fig. 4.3.16: L* Vs Delta L*(Texflash c.f. SF600) under light source ADN

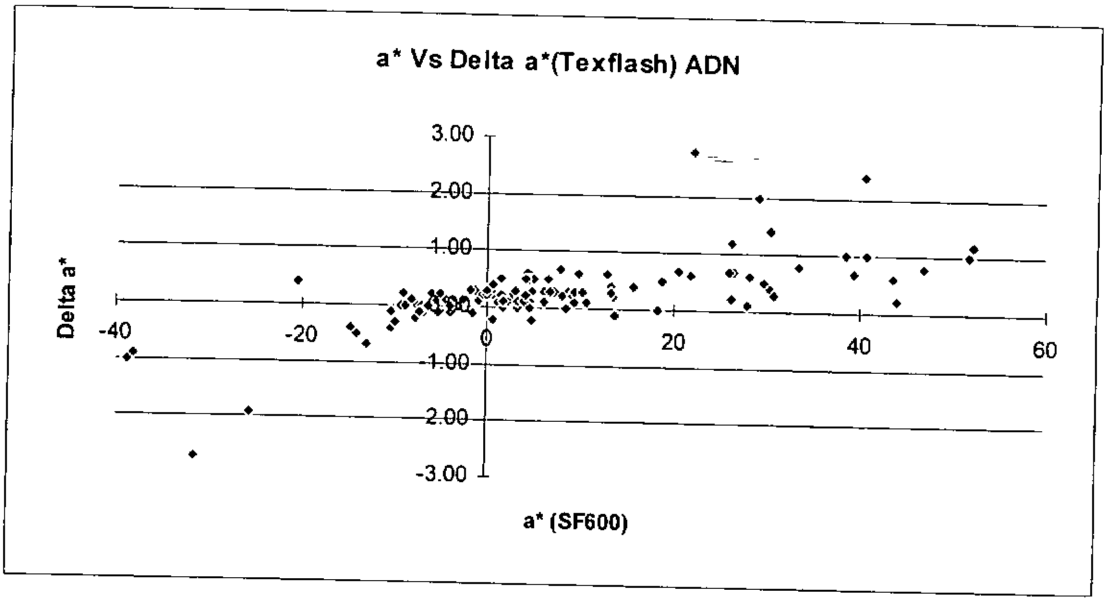


Fig. 4.3.17: a* Vs Delta a*(Texflash c.f. SF600) under light source ADN

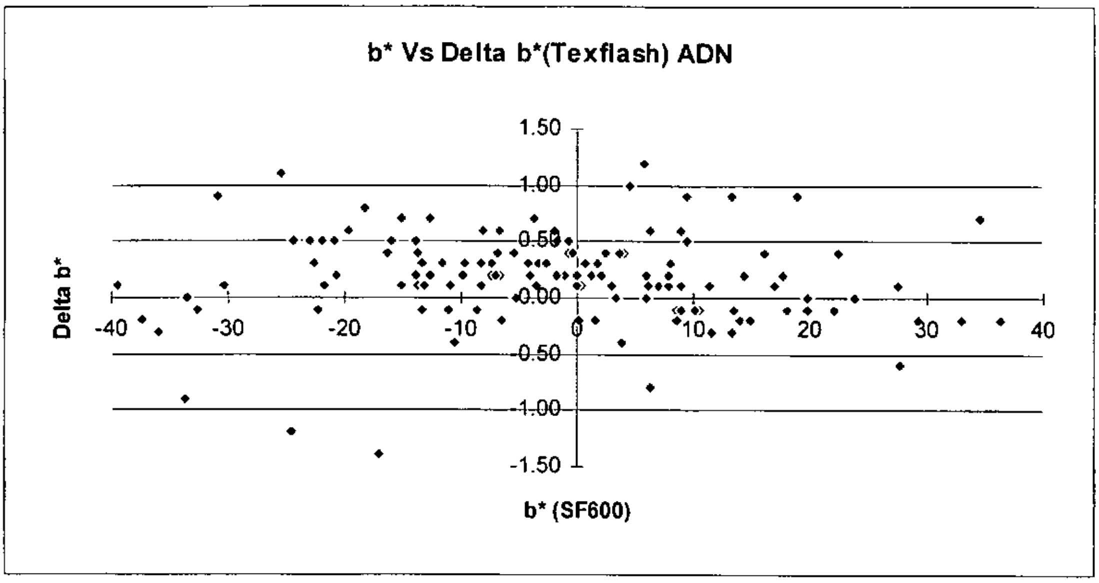


Fig. 4.3.18: b* Vs Delta b*(Texflash c.f. SF600) under light source ADN

Combination (X Vs Y)	R (L*)	R (a*)	R (b*)
SF600 Vs CE7000	0.9999	0.9999	0.9988
SF600 Vs Elrepho 2000	0.9998	0.9998	0.9988
SF600 Vs Texflash	0.9987	0.9997	0.9996

Table 4.3.1: Correlation of L*, a* and b* between spectrophotometers

It can be seen from Table 4.3.1 that the spectrophotometer Coloreye 7000 were processed the highest correlation with the Spectraflash 600. The R value for two spectrophotometers of L*, a* and b* were 0.9999, 0.9999 and 0.9988 (Fig. 4.3.1, Fig. 4.3.2 and Fig. 4.3.3). For Elrepho 2000 and Spectraflash 600 were 0.9998, 0.9998 and 0.9988 (Fig. 4.3.4, Fig. 4.3.5 and Fig. 4.3.6). While for Texflash and Spectraflash 600 were 0.9987, 0.9997 and 0.9996 respectively (Fig. 4.3.7, Fig. 4.3.8 and Fig. 4.3.9). Although the correlation of the b* component measured by Texflash is the highest compared with the b* component of the three spectrophotometers to Spectraflash 600, the correlation in L* is the lowest. Fig. 4.3.7 also shows a wider dispersion. For Elrepho 2000, its data showed an overall acceptable performance.

In the studies of the relation between ΔL* and L*, Δa* and a*, Δb* and b* of the samples measured with reference to the L*, a* and b* values obtained from the Spectraflash 600, three phenomena were observed:

1. No significant change of ΔL* if the L* value of a sample increased (Fig. 4.3.10, Fig. 4.3.13 and Fig. 4.3.16).
2. There was a trend that if the a* value increased, the Δa* value of two spectrophotometers increased. It was especially obvious in the positive region of a*, i.e., if a sample measured is redder, the difference of a* measured between the two spectrophotometers will be increased (Fig. 4.3.11, Fig. 4.3.14 and Fig. 4.3.17).
3. For the relation between b* and Δb*, it was same as L* and ΔL*. Increase or decrease of the b* value will not affect the Δb* value between spectrophotometers.

In addition, the precision of the Coloreye 7000 was higher than Elrepho 2000 and Texflash. In Fig. 4.3.10 (Coloreye 7000), ΔL* of the samples lay between +0.5 and -0.5, while for Elrepho 2000 and Texflash (Fig. 4.3.13 and Fig. 4.3.16) were between +0.8 and -1.2, +4.0 and -0.5 respectively. For Δb* value (Fig. 4.3.12, Fig. 4.3.15 and Fig. 4.3.18) the range that the b* lay were almost the same between 1.5 and -0.5, i.e., the performance in measuring b* was similar. Moreover, with reference to Spectraflash 600, the b* values of samples measured by the three spectrophotometers were more positive, i.e., the samples looked yellower.

4.4 Discussions on Comparison of Spectrophotometers

The accuracy of colorimetric data will be dependent on the specimen presented to the instrument for measurement. The specimen should be uniform, evenly dyed and clean. Any fabric irregularities or spots visible to the eye should be avoided in the measurement. This particularly applies to instruments having small areas of specimen viewing. To minimise the effect of small variations in shade with a specimen on the colorimetric data, replicate measurements should be taken and their averages used. Sample should be of an adequate size to cover completely the sample port of the instrument. When presented to an instrument, a specimen should be of sufficient thickness to be opaque, otherwise, light will pass through the specimen and reflect off the backing material or holder. A higher or lower reading in reflectance factor occurs when a specimen of insufficient thickness is backed by a lighter or darker material, respectively. The required thickness for any given specimen can be determined by measuring it with increasing layers until no further change in the reflectance data is observed. If the amount of the material available is insufficient to form the required number of layers to absorb the total light, all measurements should be made with the same backing in place. Proper tension should be applied to the specimen when presenting it to the specimen port of an instrument. If the mounting is too slack, shadows are apt to appear by the attendant wrinkling and incorrect measurements were obtained. If mounted under excessive tension, the fabric will become distorted, especially in knitted fabrics, which accentuate any directional differences.

Choosing the Datacolor Spectraflash 600 as reference, the Macbeth Coloreye

7000 showed a fairly good correlation in L*, a* and b*. However, the performance of Datacolor Texflash was rather poor especially for the L* component while the Datacolor Elrepho 2000 showed an overall acceptable performance. For Spectraflash 600 and Coloreye 7000 they were completely new, therefore it was assumed that those two systems should be in good correlation. In the case of Elrepho 2000, the system had been used for over ten years and with the fixed specular component included. However, the correlation of the system to the reference is rather high which were resulted by good maintenance. The Texflash had been used for five years since the first installation. The configurations were similar to the reference system except the light dispersing unit which is a conical type and different from the others, i.e., integrating sphere. The correlation of Texflash to the reference was the worst especially the Lightness component L*. The problem may be due to difference in the geometry of the light dispersing unit or ageing of the specific components of the instrument, e.g., filters, lens, integrating sphere etc. Follow up action was taken to recalibrate the system. Although the significance of the differences in the coefficients correlation were not extreme, another problem for Texflash was that the manufacturer stop manufacturing of this model. The reason as stated from the manufacturer was that the conical integrating device was not as good as spherical. Also spare parts were therefore not readily available for Texflash.

Spectrophotometers from Datacolor and Macbeth are the two systems, which are more popular in Hong Kong. That's why those system were selected for comparison. Since the system Datacolor Spectraflash 600 and Macbeth Coloreye 7000 were borrowed from the suppliers as references and the correlation condition of Texflash was not good for this project. Therefore the Datacolor Elrepho 2000 was probably the choice. In addition, the repeatability of the Elrepho 2000 was further tested by measuring the samples again after three months from the date that the samples were first measured. The colour differences were measured under the CIELab colour space and the Illuminant ADN. The maximum colour difference for repeatability were $\Delta E^*_{Max} = 0.3$, $\Delta L^*_{Max} = 0.2$, $\Delta a^* = 0.1$ and $\Delta b^* = 0.2$. These results may be used as reference for assessing the acceptability of data importing from other systems into the Elrepho 2000.

4.5 Methodology for the Selection of Colour Difference Equation to Develop a Tolerance Block for Multi-Component Fabrics

In this study, all the samples were of different materials and surface textures, e.g., nylon, cotton, polyester..etc., were provided by Triumph International Overseas Ltd.(Hong Kong Branch). Twenty three groups, each with five, totally hundred and fifteen coloured samples were used in the research (Appendix III). The samples of each group were subjected to a pass/fail assessment [38-41] by 33 shade passers in 10 combinations, i.e., there was 10 combinations for 5 samples, ${}_5C_2 = 10$. Therefore, totally 230 sets of sample pairs were obtained for assessment. A total of 7590 assessments were made on these samples. The shade passers performed the assessment under the ADN light source, which was used by Triumph exclusively. Actually it was a multiple light source of D65 (6500K) and N (4000K) where a 10 degree observer was used for calculation.

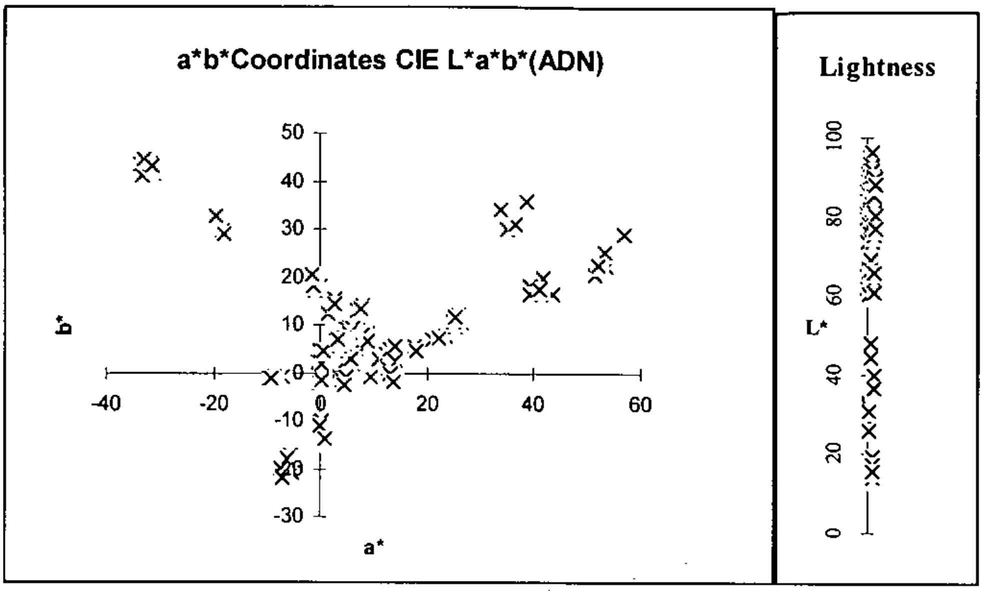


Fig. 4.5.1: The Colour coordinates of the 23 groups of colour samples in the CIELAB colour space.

The samples were measured using a spectrophotometer and the colour differences were calculated using the CIELab, CMC(2:1) and CIE94(2:1:1) colour difference equations. The ΔE values of these equations were plotted against the percentage of acceptance %A (Appendix IV). The percentage of acceptance was calculated by means of a point system. The shade passers were asked to comment on sample pairs as follows: pass, fail or marginal pass. For each 'pass' and 'marginal pass', 2 points and 1 point were given respectively. The sum of the points was then used to calculate the %A [41]. The correlations of the equations with the data were indicated by the coefficient of correlation R which represented a perfect correlation when R=1, and a perfect inverse correlation when R= -1 [42]. R is known as the Pearson product moment correlation coefficient, which is the oldest and most widely used measure of correlation (4.2.1).

$$R = [n\sum xy - (\sum x)(\sum y)] / \{[n\sum x^2 - (\sum x)^2]\,[n\sum y^2 - (\sum y)^2]\}^{1/2} \qquad (4.2.1)$$

where x, y represent the data in two sets and n is the number of pairs of values.

4.6 The Results and Data Analysis of the Selection of the Colour Difference Equation and Development of the Tolerance Block with Respect to the Selected Equation

Three scattered graphs were obtained from the data of 33 shade passers. Three kinds of regression line, linear, logarithmic and 2nd degree polynomial, were inserted for each graph (Figures 4.6.1, 4.6.2 and 4.6.3).

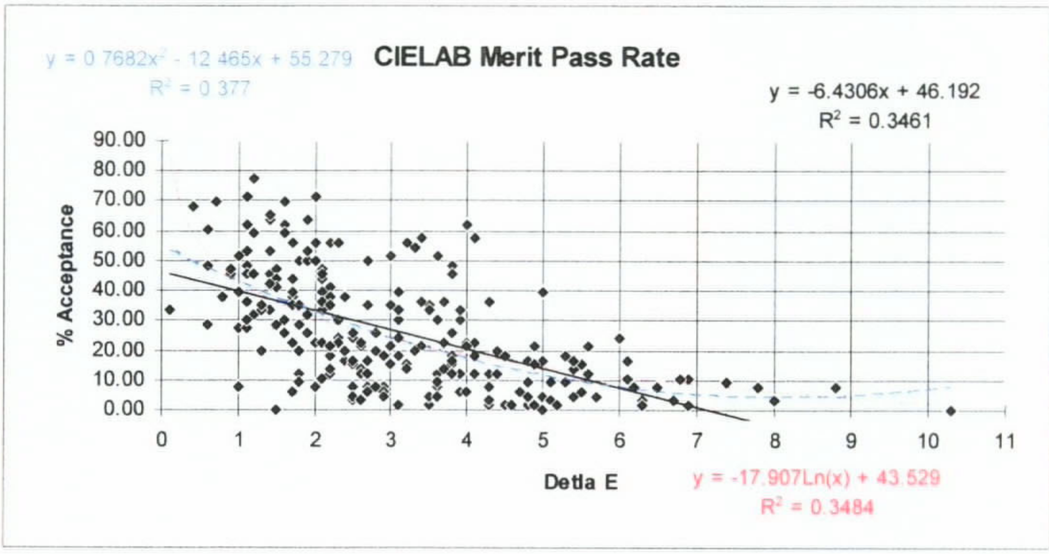


Figure 4.6.1: CIELAB Merit Pass Rate

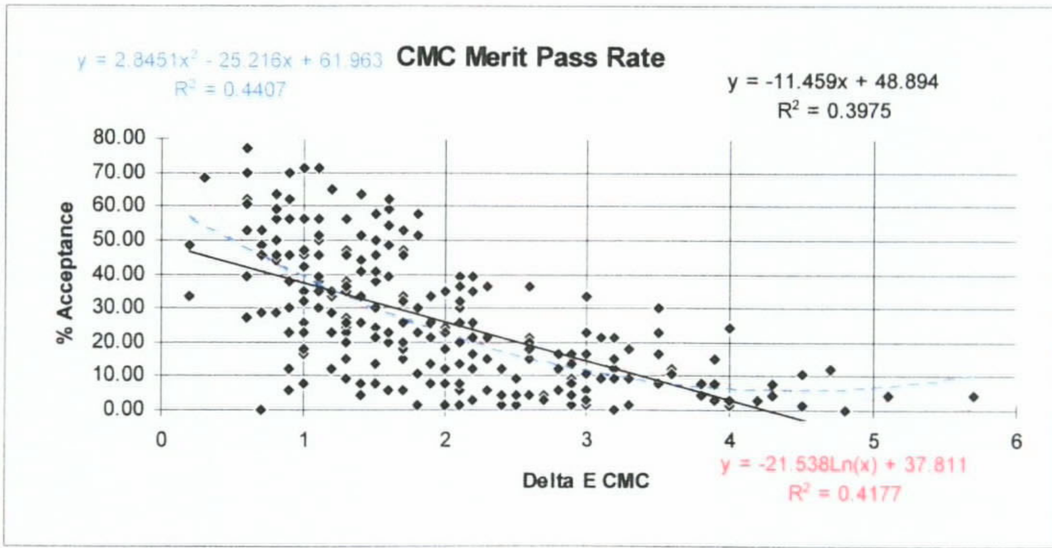


Figure 4.6.2: CMC (2:1) Merit Pass Rate

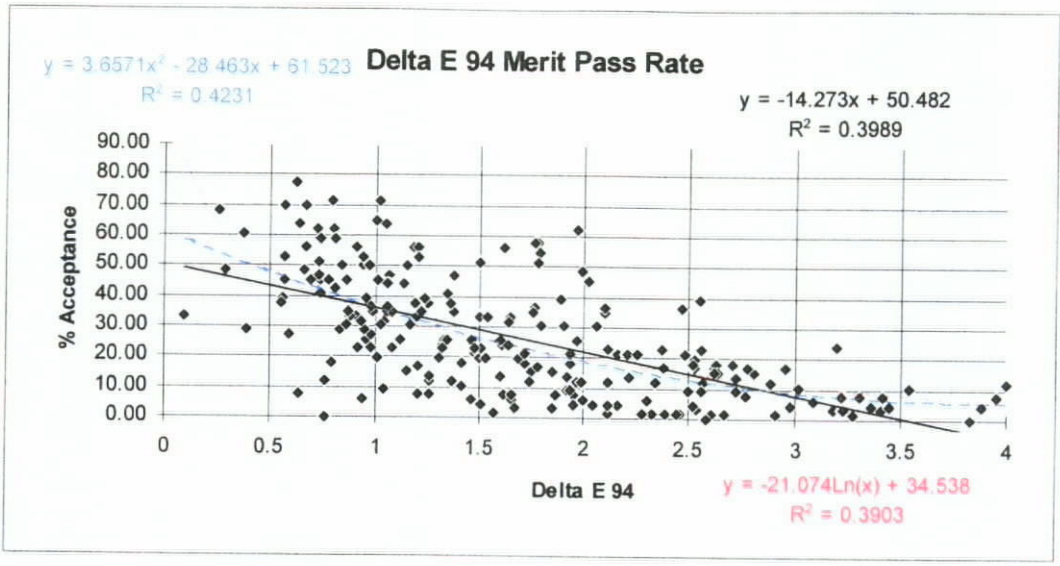


Figure 4.6.3: CIE94 (2:1:1) Merit Pass Rate

Colour Difference Equation	Coefficient of Correlation R_L (Linear)	Coefficient of Correlation R_{2P} (2nd degree polynomial)	Coefficient of Correlation R_{ln} (Logarithmic)
CIELAB	-0.588	-0.614	-0.590
CMC (2:1)	-0.630	-0.664	-0.646
CIE94 (2:1:1)	-0.632	-0.650	-0.625

Table 4.6.1: R value obtained from 33 shade passers

From the scattered graphs, coefficients of correlation were tabled as shown in Table 4.6.1. It can be seen that R_{2P} is the highest while the R_L is the lowest for the 3 colour difference equations, i.e., the data set is more probably 2nd degree polynomial correlated than linear. When comparing these equations with reference to the R_{2P}, CMC(2:1) equation and CIE94(2:1:1) equation showed the smallest difference in R_{2P}. For traditionally used linear regression, CIE94(2:1:1) equation seemed to have a better correlation to the data than CIELAB equation but with similar performance as CMC(2:1) equation. In the case of 2nd degree polynomial and logarithmic regression, the CMC(2:1) equation exhibited a better performance than the others although it was close to CIE94(2:1:1) equation. The suitability of the colour difference equations was further examined by means of practical verification.

The tolerance blocks created with respect to each of the equations are shown in Table 4.6.2.

Colour Difference Equation	Tolerance in ΔL^*	Tolerance in $\Delta a^*/\Delta C^*$	Tolerance in $\Delta b^*/\Delta H^*$	Tolerance in ΔE
CIELAB	$-2.17 \leq \Delta L^* \leq 1.73$	$-0.54 \leq \Delta a^* \leq 1.74$	$-0.71 \leq \Delta b^* \leq 0.39$	$\Delta E^* \leq 4.02$
CMC (2:1)	$-0.79 \leq \Delta L^* \leq 0.72$	$-0.48 \leq \Delta C^* \leq 0.88$	$-0.48 \leq \Delta H^* \leq 0.4$	$\Delta E_{CMC} \leq 1.75$
CIE94 (2:1:1)	$-1.09 \leq \Delta L^* \leq 0.87$	$-0.42 \leq \Delta C^* \leq 0.75$	$-0.39 \leq \Delta H^* \leq 0.28$	$\Delta E^*_{94} \leq 2.07$

Table 4.6.2: Tolerance block based on the data from 33 shade passers

Two groups of shade passers were further divided from 33 shade passers, i.e., shade passers from Triumph and External Shade passers. The R values and tolerance blocks were created in tables 4.6.3, 4.6.4, 4.6.5 and 4.6.6 respectively.

Colour Difference Equation	Coefficient of Correlation R_L (Linear)	Coefficient of Correlation R_{2P} (2nd degree polynomial)	Coefficient of Correlation R_{ln} (Logarithmic)
CIELAB	-0.501	-0.545	-0.527
CMC (2:1)	-0.575	-0.611	-0.594
CIE94 (2:1:1)	-0.564	-0.592	-0.571

Table 4.6.3: R value obtained from 14 shade passers form Triumph

Colour Difference Equation	Coefficient of Correlation R_L (Linear)	Coefficient of Correlation R_{2P} (2nd degree polynomial)	Coefficient of Correlation R_{ln} (Logarithmic)
CIELAB	-0.593	-0.608	-0.579
CMC (2:1)	-0.611	-0.640	-0.623
CIE94 (2:1:1)	-0.620	-0.633	-0.604

Table 4.6.4: R value obtained from 19 external shade passers

Colour Difference Equation	Tolerance in ΔL*	Tolerance in Δa*/ΔC*	Tolerance in Δb*/ΔH*	Tolerance in ΔE
CIELAB	-2.17 ≤ ΔL* ≤ 2.06	-0.98 ≤ Δa* ≤ 1.85	-0.82 ≤ Δb* ≤ 0.42	ΔE* ≤ 4.02
CMC (2:1)	-0.79 ≤ ΔL* ≤ 0.78	-0.57 ≤ ΔC* ≤ 0.99	-0.96 ≤ ΔH* ≤ 0.51	ΔE_{CMC} ≤ 1.75
CIE94 (2:1:1)	-1.09 ≤ ΔL* ≤ 1.03	-0.42 ≤ ΔC* ≤ 0.75	-0.71 ≤ ΔH* ≤ 0.37	ΔE^*_{94} ≤ 2.07

Table 4.6.5: Tolerance block based on data from 14 Triumph shade passers

Colour Difference Equation	Tolerance in ΔL*	Tolerance in Δa*/ΔC*	Tolerance in Δb*/ΔH*	Tolerance in ΔE
CIELAB	-1.45 ≤ ΔL* ≤ 1.73	-0.54 ≤ Δa* ≤ 1.53	-0.65 ≤ Δb* ≤ 0.45	ΔE* ≤ 3.99
CMC (2:1)	-0.62 ≤ ΔL* ≤ 0.78	-0.43 ≤ ΔC* ≤ 0.96	-0.81 ≤ ΔH* ≤ 0.51	ΔE_{CMC} ≤ 2.11
CIE94 (2:1:1)	-0.72 ≤ ΔL* ≤ 0.87	-0.36 ≤ ΔC* ≤ 0.75	-0.55 ≤ ΔH* ≤ 0.37	ΔE^*_{94} ≤ 2.21

Table 4.6.6: Tolerance block based on data from 19 external shade passers

It was found that the correlation behaviour was better for the 19 external shade passers than 14 Triumph's shade passers reflected by the values of coefficient of correlation. The values of coefficient of correlation were always higher for the 19 external shade passers than the 14 Triumph's shade passers with respect to different equations and regressions (Table 4.6.3 and 4.6.4). Apparently, the tolerance developed from the 19 external shade passers was stricter than the one developed from the 14 Triumph's shade passers in terms of ΔL*, ΔC*, and ΔH* or ΔL*, Δa*, and Δb*(Table 4.6.5 and 4.6.6).

4.7 Verification of the Developed Tolerance Block

The tolerance block developed was put into implementation. One of the suppliers of Triumph, Penn Philippine, was chosen for the verification of the tolerance blocks. The precision of the tolerance blocks was tested by applying it to all coloured samples (excluding white) submitted to Triumph within two months. Totally 163 coloured samples were collected and were measured by the spectrophotometer for 3 times. The precision of the tolerance blocks was measured in terms of P% with a 95% confidence level, i.e., how the visual assessment agree with the instrumental assessment based on the tolerance blocks. For the ease of application, the tolerance blocks were rounded up to one decimal place as in Table 4.7.1.

Colour Difference Equation	**Tolerance in ΔL***	**Tolerance in ΔC***	**Tolerance in ΔH***
CMC (2:1)	$-0.8 \le \Delta L^* \le 0.7$	$-0.5 \le \Delta C^* \le 0.9$	$-0.5 \le \Delta H^* \le 0.4$
CIE94 (2:1:1)	$-1.1 \le \Delta L^* \le 0.9$	$-0.4 \le \Delta C^* \le 0.8$	$-0.4 \le \Delta H^* \le 0.3$

Table 4.7.1: Modified tolerance blocks from Table 4.6.2

Equation of Tolerance Block based on	**P%**	**PP%**	**FF%**
CMC (2:1)	61.55 ± 1.73%	91.86 ± 0.60%	48.40 ± 0.98%
CIE94 (2:1:1)	54.40 ± 2.29%	86.69 ± 1.56%	43.77 ± 1.28%

Table 4.7.2: Verification results of the precision of tolerance blocks

The results (table 4.7.2) showed that the P% of CMC(2:1) and CIE94(2:1:1) was 61.55 ± 1.73% and 54.40 ± 2.29% respectively. It also showed that CMC(2:1) equation gave a better performance than CIE94(2:1:1) equation for the samples. The results obtained was the same as predicted.

The P% of CMC(2:1)equation, 61.55 ± 1.73%, was further elaborated into 2 parts, i.e., PP% and FF% where PP% was the precision to predict passed samples while FF% was the precision to predict failed samples. The PP% calculated was 91.86 ± 0.60% which means that there was 91.86 ± 0.60% of instrumentally passed samples agreed with the visually passed assessment. For which the precision was especially good for assessing colour CS (Light Flesh), 04 (Black) and 26 (Deep Flesh). The precision was more than 95%. The FF% calculated was 48.40 ± 0.98% which means that the precision of agreement was just 48.40 ± 0.98%, i.e., about 50% of samples rejected by the tolerance block were re-accepted by visual assessment.

4.8 Discussion of the Developed Tolerance Block

Logically, when ΔE=0, the percentage of acceptance, %A, should be equal to 100% for all shade passers with normal vision. However, the linear and 2nd degree polynomial regression lines exhibit intersections with the y-axis (%A). For the logarithmic regression lines, %A tends to infinity when x (ΔE) tends to zero and %A=100% when ΔE^*_{LAB}=0.043, ΔE_{CMC}=0.056 and ΔE^*_{94}=0.045. Actually it can be treated as zero colour difference. Since normal human vision could perceive a colour difference, ΔE_{CMC} or ΔE^*_{LAB}, not less than 0.5 [43] or for extremely sensitive vision less than 0.3 [44], it is therefore believed that the regression line changes its shape for different regions of ΔE [45], i.e., is not linearly correlated and the %A will be equal to 100% when ΔE lies between 0 ~ 0.5. From the data and human vision behaviour, the regression line seems to follow the logarithmic behaviour when ΔE is less than 0.5 and with a 2nd degree polynomial behaviour when ΔE > 0.5. In fact, when using polynomial regression lines, the coefficient of correlation, R, increases with the degrees of the polynomial regression lines as shown in Table 4.8.1. However it reflected, irrespective of the degree of the polynomial regression lines, the same result as the 2nd degree polynomial regression line, i.e., the CMC(2:1) equation describes the data sets better than the other two equations. Although regression lines with degree higher than 2nd degree polynomial could achieve a better correlation coefficient, the freedom of the regression lines increased at the same time which allowed the regression lines to change their shapes in order to fit the data sets better. In such circumstances, %A for smaller ΔE may be less than a greater ΔE. Therefore a 2nd degree polynomial regression line, rather than higher degree, were used since it allowed a single direction of the regression, i.e., %A always increases when ΔE decreases.

Colour Difference Equation	R of 3rd Degree Polynomial Regression line	R of 4th Degree Polynomial Regression line	R of 5th Degree Polynomial Regression line	R of 6th Degree Polynomial Regression line
CIELAB	-0.615	-0.615	-0.616	-0.621
CMC (2:1)	-0.664	-0.667	-0.668	-0.669
CIE94(2:1:1)	-0.651	-0.651	-0.655	-0.657

Table 4.8.1: Change of R values with different degree of polynomials and respective colour difference equations

In addition, it was realised that the coefficient of correlation increases with the number of shade passers (Table 4.8.2, 4.8.3 and 4.8.4), i.e., it is believed that the optimum number of shade passers, 33, had been reached since the coefficients of correlation remained quite steady.

No. of Shade passers CIELAB	10	14	19	25	27	29	33
Coefficient of Correlation R_L (Linear)	-0.484	-0.501	-0.593	-0.601	-0.595	-0.595	-0.588
Coefficient of Correlation R_{2P} (2nd degree polynomial)	-0.533	-0.545	-0.608	-0.629	-0.621	-0.620	-0.614
Coefficient of Correlation R_{ln} (Logarithmic)	-0.524	-0.527	-0.579	-0.607	-0.601	-0.599	-0.590

Table 4.8.2: Change of R with the no. of shade passers based on the CIELAB equation

No. of Shade passers CMC (2:1)	10	14	19	25	27	29	33
Coefficient of Correlation R_L (Linear)	-0.557	-0.575	-0.611	-0.634	-0.634	-0.633	-0.630
Coefficient of Correlation R_{2P} (2nd degree polynomial)	-0.590	-0.611	-0.640	-0.668	-0.668	-0.666	-0.664
Coefficient of Correlation R_{ln} (Logarithmic)	-0.578	-0.594	-0.623	-0.643	-0.652	-0.649	-0.646

Table 4.8.3: Change of R with the no. of shade passers based on the CMC(2:1) equation

No. of Shade passers CIE94 (2:1:1)	10	14	19	25	27	29	33
Coefficient of Correlation R_L (Linear)	-0.551	-0.564	-0.620	-0.643	-0.639	-0.637	-0.632
Coefficient of Correlation R_{2P} (2nd degree polynomial)	-0.583	-0.592	-0.633	-0.664	-0.660	-0.657	-0.650
Coefficient of Correlation R_{ln} (Logarithmic)	-0.569	-0.571	-0.604	-0.634	-0.636	-0.633	-0.625

Table 4.8.4: Change of R with the no. of shade passers based on the CIE94(2:1:1) equation

Equation of Tolerance block based on	Average % Wrong Decisions	Average % Wrong Rejections	Average % Wrong Acceptances
CMC (2:1)	38.4%	35.9%	2.5%
CIE94 (2:1:1)	45.6%	42.3%	3.3%

Table 4.8.5: Average % of wrong decisions

From the verification results, the percentage of wrong decision was tabled in Table 4.8.5. The percentage of wrong decision based on CMC(2:1) equation was 38.4%. The figure is higher than the result of 17% that was obtained by McDonald [45]. The reason for this percentage of wrong decision is mainly due to samples that were rejected by the tolerance block were re-accepted during visual assessment. As may be seen from table 4.8.5 and table 4.8.6, it was found that the tolerance for the Triumph's shade passers were less stringent than the 19 external shade passers. The reason was that a single decision maker was used for Triumph [45], causing a higher percentage in wrong decision due to re-accepted samples. In fact, the tolerance block could be developed just from the data obtained by the Triumph's shade passers.. However, it is too subjective and the number of shade passers are not optimum as mentioned in the last paragraph. Therefore, the tolerance block developed from 33 shade passers should be used. Another possible reason for explaining the worse wrong decision than that of McDonald's study is that multi-component material is more difficult to assess than that of uniform material.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Recent developments of spectrophotometers have ensured that spectrophotometers are stable, reproducible and accurate. The availability of reflectance data, measured by spectrophotometers, can increase the response of it with ability to transmit non-physical standards by fax, e-mail, etc. The use of non-physical standards, together with numerical pass/fail using the tolerance developed based on the CMC(2:1) equation, could eliminate the problems associated with human observers, variation in illuminants and soiling of standards. The effectiveness was checked by applying the tolerance to one the Triumph's supplier, Penn Philippine, a satisfactory result that the tolerance block was running in a good precision was obtained.

The samples selected for the comparison of spectrophotometers were not coloured on the same kind of substrate, the result obtained were assumed not to be uniform since some of the substrates had a directional problem, i.e., reflectance changed when the measurement direction changed. However, the results obtained were rather linear. The reason was due to the method of measurement, which averaged the reflectance of a sample from four directions.

The coefficient of correlation also showed that the correlation of spectrophotometer was not related to the brand name, i.e., systems under same brand name could have poor data correlation but systems under different brand could have good data correlation. In addition, maintenance of spectrophotometers is a must for a spectrophotometer to perform well.

In the comparison of different colour difference equations achieved using the coefficient of correlation R, the CIE94(2:1:1) equation gave a better performance than CIELAB equation but similar to CMC(2:1) equation as reflected from R_L by using the traditional linear regression line. However, when the equations were compared with reference to R_{2P} and R_{ln}, the and logarithmic regression line showed a much better correlation to the data, especially the 2nd degree polynomial. Moreover, based on the logical thinking of $\Delta E = 0$, then %A = 100% and normal human eyes cannot perceive a colour difference, $\Delta E < 0.5$. It is better to use a non-linear regression line, i.e., 2nd degree polynomial, to compare the performance of different colour difference equations. Although the correlation improves with the degree of the polynomials, it gives the same result. For the data set of multi-component samples, the CMC(2:1) equation exhibited a better performance. But there were a similar performance compared to the CIE94(2:1:1) equation as reflected from R_{2P} and R_{ln}.

Through the verification process, it was shown that the CMC(2:1) colour difference equation could describe the colour space of a fabric with multi-component nature better than CIE94(2:1:1) colour difference equation. The result obtained was the same as predicted from comparing the coefficient of correlation. The tolerance block developed based on the CMC(2:1) colour difference equation provide a very high precision, 91.86 ± 0.6%, to predict a pass sample and which especially good for colour CS (Light Flesh), 04 (Black) and 26 (Deep Flesh), i.e., if the colour differences of the samples were within the tolerance block, there is a probability of 91.86 ± 0.6% that the visual assessment will give it a pass. For the colour differences of the samples that exceeded the tolerance block there was only a precision of 48.4 ± 0.98%. The average percentage of wrong decision was 38.4%, which was caused by re-acceptances of rejected samples in visual assessment. In fact, the shade passers from Triumph was less stringent than the shade passers in the other sector of the textile industry.

5.2 Recommendations

It is recommended that there is no need to perform re-assessment visually for the samples, which are passed/failed by the tolerance block, but only for the samples that the colour differences of which exceeded the tolerance block. The tolerance block could replace at least 30%, based on the samples from Penn Philippine, to 100% of the assessment work, which depends on the quality of the samples submitted. Moreover, the shade passers from the Triumph were more lenient than other shade passers for the textile industry to incoming samples. It is recommended that the shade passers of Triumph should assess samples with a higher degree of stringency in order to reduce problems in mis-match of multi-component apparels. Moreover time for sorting could then be reduced.

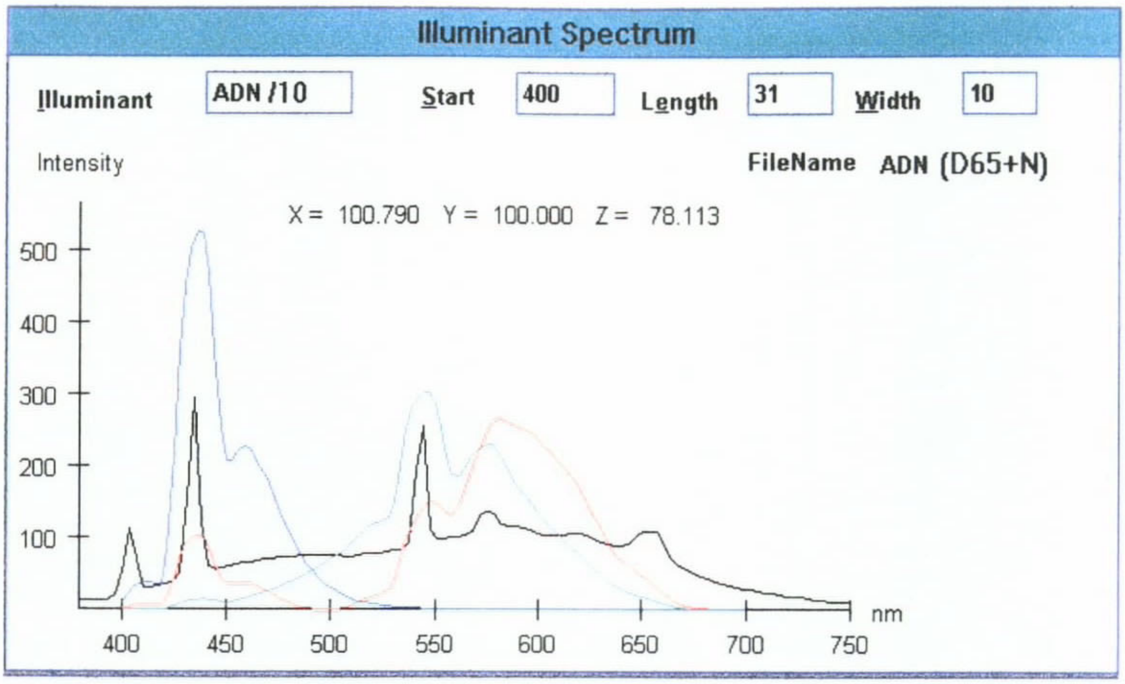
Referring to the result from Penn Philippine, the objective assessment system, i.e., use of the developed tolerance block to perform pass/fail assessment, gave a acceptable result for shade passing. It is recommended to apply this system to other suppliers of Triumph with the required equipment, i.e., spectrophotometers.

In addition, in the case of change of light source, it is not necessary to measure the sample sets for assessment again. The reason is that the colour difference under different light sources of a set of colour could be calculated by the respective set of reflectance data (Chapter 3). The procedure that is necessary to be performed is to re-assess the sample sets and give comments of the sample sets (Chapter 4) under the required light source. The data is necessary to re-select a suitable colour difference equation and with the data could calculate the tolerance under the respective light source. Verification is also necessary according to the procedure performed in Chapter 4.

Moreover, the regression line used for selecting the colour difference equation could be more precise by using a more complicated function. e.g., $Y = aX^n + bx^{n-1} + \ldots + c_n + f(x)$ where $f(x)$ could be an exponential function or other type of functions. The fitness to the data should further be tested.

Appendix I

Spectral Power Distribution of Light Source ADN



Note :

1. The black line representing the spectral power distribution of light source ADN.
2. The red, green and blue lines are representing the colour matching function of a CIE 1964 10° observer.
3. The data was measured by Datacolor International.

Spectral Power Distribution of Light Source ADN (D65+ N)

Wavelength (nm)	E_λ	Wavelength (nm)	E_λ
380	13.2	570	107.6
385	12.9	575	135.8
390	13.8	580	134.1
395	15.4	585	115.6
400	42.9	590	116.8
405	116.2	595	112.9
410	32.9	600	107.6
415	30.2	605	103.4
420	34.6	610	102.8
425	39.3	615	102.8
430	71.6	620	106.3
435	298.5	625	103.5
440	80.7	630	97.8
445	56.1	635	91.6
450	59.6	640	89.2
455	63	645	90.1
460	65.5	650	102.5
465	67.5	655	108.8
470	69.8	660	109.5
475	71.9	665	80.5
480	73.1	670	61.1
485	74	675	54
490	75.8	680	47.3
495	75.3	685	42
500	75.3	690	37.8
505	74.9	695	34
510	72.9	700	30
515	75.1	705	27.6
520	78.2	710	24.7
525	79.6	715	22.6
530	82.7	720	21
535	83.7	725	18.5
540	103.6	730	17.4
545	272.2	735	14.7
550	103.8	740	12.9
555	98.1	745	11.7
560	100	750	10.8
565	101.5		

Appendix II

Information of the experienced Shade Passers

Occupation	Age	Sex	Experience in related field (years)
Colour Technician	26	M	3
Dyeing Supervisor	35	M	4
Assistant Printing Supervisor	24	M	2
Laboratory Manager	26	M	4
Garment Accessories Co-ordinator	25	F	2
Dyeing Technical Support	27	M	5
Laboratory Technician	26	F	3
Research Assistant	27	F	3
Colour Application Enginner	30	M	6
Garment Factory Manager	35	F	10
Director of Garment Trading Company	32	M	6
Teaching Assistant	28	M	5
Technical Manager	35	M	14
Research Student	25	M	1
Research Student	25	F	2
Quality Controller	23	F	2
Technical Support	28	F	6
Laboratory Technician	29	M	6
Research Assistant	28	F	8
Assistant Quality Assurance Manager	32	M	4
Purchasing Manager	34	M	15
Purchasing Co-ordinator	33	M	3
Purchasing Co-ordinator	32	M	5
Quality Controller	35	F	2
Quality Controller	34	F	5
Quality Controller	30	F	1
Assistant Quality Assurance Manager	29	M	3
Quality Controller	35	F	3
Quality Controller	33	F	5
Quality Controller	24	F	2
Quality Controller	28	F	6
Quality Controller	32	F	7
Material Quality Assurance Manager	36	M	14

The Matching Point Obtained in the D&H Test by the Shade Passers

Shade Passer Number	*Matching Point*	
Number 01	J	8
Number 02	H - I	9 - 10
Number 03	I - J	9
Number 04	I	9
Number 05	I	8
Number 06	F - G	10 - 11
Number 07	H - I	7 - 8
Number 08	I	8 - 9
Number 09	I	9
Number 10	J	10
Number 11	I	8
Number 12	I	7 - 8
Number 13	H	8
Number 14	I	8 - 9
Number 15	G - H	6 - 7
Number 16	I	8 - 9
Number 17	H - I	7
Number 18	K	9
Number 19	G	8
Number 20	K	10
Number 21	I	8
Number 22	H - I	6 - 7
Number 23	G	7 - 8
Number 24	G - H	7 - 8
Number 25	H - I	9 - 10
Number 26	H	7
Number 27	I - J	9 - 10
Number 28	I	8
Number 29	I	9
Number 30	J	9
Number 31	K	11
Number 32	G	9
Number 33	H	8
Average Matching Point	***I***	***8 - 9***

Appendix III

Reflectance Data of Samples

Reflectance Data of Samples for Visual Assessment in Percentage

Wavelength (nm)	400	420	440	460	480	500	520	540	560	580	600	620	640	660	680	700
LT01 LT	47.34	58.95	60.86	66.49	72.96	75.61	72.23	68.35	63.03	59.78	56.94	55.09	54.66	56.74	61.27	67.93
LT02 LT	60.48	63.56	65.77	69.99	75.52	78.31	75.91	71.91	66.22	63.53	58.83	60.97	58.72	59.75	77.83	85.99
LT03 LT	55.66	64.91	66.79	70.64	75.70	78.42	76.10	72.52	67.57	65.48	61.50	63.80	61.76	63.36	80.26	89.25
LT04 LT	52.40	61.24	58.83	60.26	72.81	73.33	69.71	65.26	60.04	56.58	54.79	54.81	54.54	62.41	77.32	85.75
LT05 LT	58.29	59.70	61.62	67.21	72.17	73.86	72.06	69.00	64.49	61.21	57.76	55.38	53.98	53.38	53.91	56.47
PC01 PC	75.12	77.69	76.75	74.88	73.84	68.93	62.47	58.15	52.87	51.28	48.41	47.58	48.37	47.06	46.92	55.18
PC02 PC	69.78	74.07	75.27	74.43	72.08	66.21	58.64	52.42	47.23	43.84	42.33	44.11	41.21	52.95	76.07	89.25
PC03 PC	60.95	66.57	68.13	69.17	69.08	64.57	57.34	51.24	46.10	42.90	41.32	43.02	40.53	51.30	73.87	86.97
PC04 PC	48.05	66.05	73.16	75.92	72.11	66.33	59.22	53.61	47.78	44.39	42.25	41.74	41.57	45.40	54.66	67.40
PC05 PC	52.50	72.54	72.16	68.45	65.61	61.38	54.10	49.24	42.47	40.89	37.18	36.97	37.42	37.81	37.98	48.29
PL01 PL	28.78	28.40	28.57	31.06	33.81	32.26	28.27	27.05	28.49	32.14	32.33	31.76	31.59	35.50	45.64	61.84
PL02 PL	31.23	30.94	31.51	35.39	40.43	39.74	33.95	31.17	30.04	32.36	36.92	38.17	37.93	41.71	51.40	65.26
PL03 PL	27.60	29.20	28.59	28.45	29.18	29.80	29.01	28.04	26.92	27.83	29.66	29.80	30.16	44.64	66.16	82.36
PL04 PL	50.15	40.68	35.64	33.86	41.74	39.44	34.71	34.69	32.94	35.85	38.32	38.18	36.82	45.84	66.82	84.07
PL05 PL	33.08	35.75	36.50	36.80	37.36	37.80	36.15	35.27	33.58	35.72	38.44	38.63	37.50	52.07	72.87	86.43
UK01 UK	63.26	67.47	68.87	69.31	68.89	65.09	61.14	55.32	54.75	51.60	54.33	60.11	58.06	59.14	76.83	84.52
UK02 UK	75.99	80.09	80.19	78.85	76.49	73.88	69.37	65.86	63.12	62.39	63.12	65.19	69.21	74.75	79.54	84.51
UK03 UK	48.94	72.99	77.98	77.49	74.26	69.96	62.67	58.92	52.64	54.64	51.46	60.88	69.22	71.33	72.12	79.13
UK04 UK	53.46	78.52	82.60	82.38	80.11	76.55	71.27	66.64	63.03	62.39	61.11	68.75	71.52	76.42	83.69	88.72
UK05 UK	72.85	80.73	82.28	80.40	77.28	73.32	66.57	63.22	57.63	59.46	56.37	64.20	70.64	71.45	72.13	78.95
AQ01 AQ	5.43	5.33	4.89	4.01	3.49	3.17	3.00	3.20	3.97	6.02	8.26	9.64	10.90	14.58	25.08	42.71
AQ02 AQ	7.15	6.01	5.34	4.97	4.73	4.34	3.82	3.85	4.01	6.00	9.52	11.35	12.43	17.68	29.44	46.94
AQ03 AQ	5.58	5.77	5.45	5.00	4.74	4.27	3.80	3.74	4.21	6.46	11.39	14.13	14.49	19.02	30.95	49.85
AQ04 AQ	5.34	4.67	4.59	4.61	4.54	4.24	3.82	3.71	3.93	4.77	7.41	12.87	21.55	33.59	46.25	58.84
AQ05 AQ	8.34	7.26	5.98	5.09	4.91	4.75	4.61	4.71	5.17	6.32	9.48	14.99	21.15	30.81	45.34	61.52
CR01 CR	4.09	4.56	4.50	4.00	3.68	3.29	2.77	2.82	2.86	5.63	12.39	14.64	15.13	24.87	40.74	58.00
CR02 CR	4.67	5.39	5.25	4.66	4.32	3.93	3.17	3.30	3.41	7.11	13.62	14.62	14.84	27.11	47.84	67.10
CR03 CR	3.45	3.42	3.51	3.67	3.50	3.00	2.62	2.60	3.11	4.80	8.13	12.73	18.20	25.20	35.79	51.07
CR04 CR	4.11	4.72	4.46	3.88	3.49	3.11	2.88	2.86	3.69	6.84	12.18	12.23	16.05	32.22	56.01	75.91
CR05 CR	3.09	3.45	3.13	2.55	2.28	2.06	1.93	1.96	2.44	4.55	8.79	9.13	11.86	26.59	51.80	71.96
HW01 HW	49.08	65.19	66.68	66.28	64.56	63.06	58.13	61.70	62.42	76.78	84.75	84.67	83.97	85.47	86.09	88.59
HW02 HW	65.24	68.52	68.32	67.58	65.42	62.67	60.65	61.37	65.89	75.98	82.93	83.95	84.00	85.48	88.73	91.10
HW03 HW	65.69	68.30	68.94	69.71	68.78	67.20	64.51	64.79	65.32	75.10	88.93	93.75	94.41	94.56	94.69	95.13

Reflectance Data of Samples for Visual Assessment in Percentage

Wavelength (nm)	400	420	440	460	480	500	520	540	560	580	600	620	640	660	680	700
HW04 HW	70.80	75.55	75.70	71.33	66.78	63.69	63.47	66.84	75.56	85.72	92.01	93.49	94.07	94.58	94.85	95.14
HW05 HW	64.67	68.33	68.43	67.31	65.90	64.85	60.28	63.79	64.60	79.68	91.15	93.62	92.91	92.47	92.30	92.09
IR01 IR	16.67	18.24	17.36	14.46	12.29	11.82	13.64	19.98	27.12	41.49	65.26	79.41	83.03	84.57	85.77	86.43
IR02 IR	29.87	22.90	18.42	15.74	15.13	15.29	16.51	19.14	27.79	41.50	59.41	72.97	77.68	78.72	78.71	79.77
IR03 IR	19.39	17.55	16.73	16.65	16.86	17.19	17.54	19.44	23.37	37.33	62.34	77.73	81.82	84.32	86.29	87.45
IR04 IR	32.32	25.06	18.93	14.68	13.41	13.24	14.70	19.07	32.13	49.14	68.68	81.39	86.07	87.85	88.65	89.10
IR05 IR	22.40	21.75	17.95	14.70	12.64	11.16	11.84	13.59	33.10	53.87	61.34	62.91	63.00	66.36	74.64	83.43
VB01 VB	8.14	8.87	9.00	6.72	5.03	4.08	3.50	3.65	4.40	7.57	26.37	59.59	73.83	78.59	81.27	83.08
VB02 VB	8.15	8.72	8.50	6.63	4.79	3.52	2.79	2.78	3.63	11.21	33.03	57.88	67.50	73.19	79.69	84.49
VB03 VB	9.14	10.14	9.90	7.28	5.03	3.62	2.85	2.84	3.71	11.41	33.08	54.00	60.14	65.51	73.18	79.99
VB04 VB	7.30	8.30	8.55	6.37	4.74	3.73	3.04	3.13	3.26	10.62	36.33	66.78	79.77	84.08	85.89	87.00
VB05 VB	5.76	7.07	8.04	6.93	5.11	3.61	2.52	2.56	2.56	9.13	33.00	52.17	57.87	68.50	79.51	84.87
WT01 WT	66.27	69.09	67.97	65.40	62.90	61.34	56.88	59.68	60.51	73.52	84.18	87.50	87.09	86.74	86.80	86.57
WT02 WT	51.59	69.34	68.64	65.29	61.55	59.25	54.42	57.74	58.63	72.30	79.83	80.38	79.59	82.27	85.94	87.45
WT03 WT	67.65	76.08	76.97	74.67	70.54	66.09	62.84	62.72	67.26	78.63	87.63	90.08	90.70	90.80	90.63	91.94
WT04 WT	70.46	72.06	69.67	66.24	64.00	61.30	59.22	59.39	63.19	68.93	74.42	78.45	78.51	79.03	85.21	86.81
WT05 WT	80.90	81.13	76.98	72.28	68.70	65.11	60.88	62.48	63.29	73.08	84.25	90.93	91.73	91.18	90.74	90.38
EC01 EC	42.09	49.88	53.10	59.35	67.32	73.88	77.24	78.78	80.37	82.01	83.09	84.25	85.29	86.36	87.42	87.98
EC02 EC	46.18	53.78	56.21	61.89	69.59	76.01	79.54	80.98	82.14	82.89	83.62	84.58	85.32	86.37	87.87	88.79
EC03 EC	49.28	58.66	59.07	63.32	71.29	79.29	83.66	85.03	85.80	85.91	87.42	87.06	88.27	91.48	92.55	92.91
EC04 EC	55.50	57.31	59.60	65.54	74.67	82.90	86.72	87.99	89.57	90.46	91.07	91.48	91.52	91.60	91.93	91.98
EC05 EC	55.42	54.35	54.13	59.86	67.90	75.45	82.85	86.51	87.84	87.34	86.77	86.33	86.30	88.36	91.29	93.04
GK01 GK	63.58	60.67	59.18	60.50	64.06	70.09	72.81	73.13	74.14	77.42	80.52	81.11	81.18	82.24	84.72	87.54
GK02 GK	47.35	54.40	56.45	61.99	69.66	75.08	74.68	76.74	76.95	83.33	86.85	86.98	87.76	90.71	91.51	91.65
GK03 GK	44.20	52.78	55.04	60.00	66.35	70.46	69.14	71.23	70.93	77.22	78.83	77.60	76.85	77.03	77.57	81.71
GK04 GK	51.06	56.97	58.70	63.61	70.86	75.85	76.82	77.14	79.43	82.81	86.67	88.69	89.39	90.02	90.65	91.87
GK05 GK	53.72	54.82	56.23	60.44	66.47	70.62	72.11	73.38	76.51	79.65	81.83	84.44	84.61	85.20	90.07	91.35
DL01 DL	48.55	50.68	51.10	51.09	50.53	50.29	51.93	55.85	62.74	65.37	66.04	65.52	68.38	75.84	82.24	86.33
DL02 DL	36.19	43.66	45.01	47.43	50.54	52.54	50.57	53.74	54.53	64.18	67.66	67.60	67.15	68.64	71.60	77.86
DL03 DL	42.76	45.62	46.32	49.83	55.19	56.77	53.31	52.33	53.20	59.30	66.38	68.42	68.71	71.57	77.38	83.85
DL04 DL	43.18	46.47	47.40	49.72	52.55	54.00	51.91	55.13	55.97	65.78	69.19	69.05	68.23	69.67	71.73	78.50
DL05 DL	43.41	49.41	50.02	51.65	54.24	55.44	54.29	56.17	56.76	62.63	63.59	70.28	73.28	75.93	85.12	87.71
GT01 GT	80.03	83.50	84.12	84.66	85.83	87.34	87.94	88.15	88.36	88.49	88.59	88.66	88.73	88.79	88.91	89.04

Reflectance Data of Samples for Visual Assessment in Percentage

Wavelength (nm)	400	420	440	460	480	500	520	540	560	580	600	620	640	660	680	700
GT04 GT	73.44	78.02	79.63	80.75	81.64	82.49	82.91	83.06	83.14	83.17	83.14	83.11	83.05	82.96	82.92	82.87
GT05 GT	60.38	76.99	78.42	79.20	79.62	80.13	80.38	80.52	80.66	80.89	81.09	81.50	81.91	82.30	82.61	82.84
GT07 GT	79.79	82.87	83.70	84.99	86.71	89.24	90.83	91.40	91.85	92.05	92.20	92.36	92.39	92.49	92.61	92.73
GT08 GT	50.02	72.90	75.69	78.03	80.01	81.19	81.56	81.88	82.67	83.12	84.23	84.57	85.67	88.01	89.10	89.76
DM01 DM	48.28	60.55	61.85	64.10	66.00	66.44	62.82	65.84	66.53	78.11	84.70	85.26	85.46	87.78	88.31	88.31
DM02 DM	68.19	68.80	67.76	67.32	67.82	67.56	67.43	68.93	73.62	78.86	84.38	88.05	89.55	90.12	90.35	90.46
DM03 DM	65.38	67.42	67.88	69.33	71.36	71.08	69.64	69.82	73.39	78.93	85.62	89.57	90.36	90.62	91.13	91.24
DM08 DM	48.98	62.91	63.85	64.16	64.67	65.18	64.37	67.62	69.52	77.94	82.66	83.94	85.03	86.22	87.21	87.71
DM09 DM	57.18	69.49	69.46	69.63	69.79	69.83	67.75	71.03	72.06	83.17	89.02	89.79	89.85	88.62	83.69	90.16
WM01 WM	42.98	60.66	64.39	66.06	66.15	65.62	63.07	64.03	64.12	69.60	75.23	79.47	81.33	82.57	83.79	84.60
WM03 WM	51.30	73.36	75.39	75.42	74.65	74.27	72.26	74.14	74.50	80.49	83.16	83.93	84.30	85.00	85.65	86.24
WM08 WM	79.83	80.18	80.05	80.32	79.87	78.65	77.03	77.00	79.24	84.65	90.93	93.35	93.76	93.91	94.00	94.07
WM09 WM	57.38	74.28	75.66	75.31	74.23	73.53	71.46	72.78	73.30	79.12	83.67	86.04	86.80	87.37	87.74	88.02
WM10 WM	58.36	75.77	76.77	76.76	75.84	75.38	73.20	75.43	75.94	83.22	86.87	87.77	87.94	88.45	88.96	89.35
T0401 04	1.97	1.83	1.79	1.78	1.82	1.82	1.72	1.64	1.60	1.61	1.67	1.64	1.69	1.90	3.21	7.59
T0402 04	3.90	3.41	3.19	3.05	3.03	3.02	2.95	2.86	2.73	2.69	2.72	2.71	2.78	3.04	4.13	7.56
T0404 04	2.12	1.96	1.90	1.89	1.95	1.97	1.84	1.71	1.64	1.64	1.74	1.75	1.80	2.13	4.10	10.52
T0405 04	3.91	2.83	2.54	2.42	2.51	2.47	2.43	2.36	2.26	2.26	2.35	2.30	2.32	2.48	4.19	12.21
T0410 04	2.66	2.32	2.24	2.16	2.18	2.20	2.13	2.04	1.97	1.97	2.03	2.01	2.05	2.36	3.95	9.12
T2601 26	35.68	37.83	36.52	36.53	38.49	41.51	44.58	45.87	46.80	49.46	53.85	57.44	60.32	68.40	76.62	82.07
T2604 26	29.32	32.78	33.17	34.58	36.85	38.38	38.57	41.67	44.48	50.59	52.33	55.10	55.69	58.92	68.49	74.63
T2608 26	37.44	38.05	37.12	37.54	39.27	41.03	43.19	46.46	49.80	53.89	55.38	59.89	62.19	66.89	79.90	86.15
T2609 26	33.92	34.29	35.32	37.84	41.18	42.40	42.34	43.56	47.51	51.82	54.01	58.95	57.74	59.28	77.44	86.50
T2610 26	32.17	34.47	35.47	37.70	40.45	41.85	41.31	44.18	46.41	53.37	55.77	57.84	58.16	60.97	68.82	76.99
AI02 AI	5.11	5.40	5.60	4.92	4.13	3.41	2.67	2.74	2.73	7.76	22.86	29.40	35.69	55.92	73.47	80.25
AI03 AI	4.53	4.85	5.03	4.24	3.47	2.85	2.30	2.34	2.33	6.23	20.20	29.04	30.24	34.35	46.27	62.41
AI07 AI	8.64	7.56	5.60	4.06	3.51	3.04	2.75	2.81	3.62	6.80	15.80	27.78	36.68	45.91	58.39	72.04
AI09 AI	5.41	6.31	7.19	6.54	5.09	3.64	2.50	2.55	2.56	8.63	26.48	34.59	36.27	50.75	70.17	83.04
AI10 AI	5.41	5.93	5.65	4.79	3.62	2.81	2.45	2.47	3.33	7.55	16.68	27.16	39.55	54.62	68.40	79.00
CS01 CS	49.13	61.60	63.52	66.99	70.39	71.85	69.38	71.77	72.16	80.42	84.41	84.61	85.00	87.22	87.67	87.74
CS04 CS	68.33	61.48	57.99	59.76	69.06	68.66	65.39	67.20	67.64	74.92	80.92	81.85	81.21	83.96	88.43	90.00
CS05 CS	56.83	58.46	59.46	61.39	63.94	65.19	65.33	66.65	70.49	74.40	77.04	80.29	80.53	81.53	87.88	89.55
CS08 CS	69.66	63.94	60.41	61.76	71.31	71.00	67.58	69.34	69.79	77.71	84.82	85.88	85.19	87.28	90.72	91.68

Reflectance Data of Samples for Visual Assessment in Percentage

Wavelength (nm)	400	420	440	460	480	500	520	540	560	580	600	620	640	660	680	700
CS09 CS	57.98	59.00	59.58	61.35	63.67	64.42	64.35	65.59	69.39	73.47	76.22	79.79	79.92	80.87	88.10	89.94
YGN03 YGN	23.12	25.67	28.04	35.36	46.68	63.16	76.11	76.19	68.59	61.84	53.81	48.89	48.10	44.23	39.08	59.82
YGN06 YGN	27.68	27.72	30.37	38.43	50.26	66.95	79.72	79.91	72.00	65.55	57.21	51.80	50.72	46.21	40.57	62.70
YGN12 YGN	20.09	20.29	22.78	30.16	41.44	58.48	73.01	72.72	63.83	56.83	49.42	45.27	44.55	40.50	35.39	55.74
YGN14 YGN	5.10	5.28	6.29	10.14	17.94	33.39	52.23	50.41	37.08	28.98	21.84	18.45	18.36	16.07	12.86	27.97
YGN15 YGN	5.31	5.11	6.05	9.56	16.92	32.84	53.56	52.06	37.78	29.36	22.02	18.44	18.10	15.71	12.66	27.90
YGN18 YGN	6.21	5.88	6.75	10.26	17.84	34.87	56.87	55.14	39.71	30.47	22.54	18.72	18.30	15.76	12.74	28.77
YGN22 YGN	3.91	3.79	4.62	8.04	15.11	29.05	47.02	44.78	31.55	23.95	17.40	14.22	14.10	12.24	9.59	23.34
YGN24 YGN	3.98	3.88	4.66	7.69	14.38	28.83	47.78	45.89	32.89	25.34	18.94	16.00	15.79	13.34	10.50	25.24
YGN38 YGN	4.89	5.08	6.05	9.61	17.12	32.26	51.49	50.17	36.75	28.64	21.57	18.10	17.93	15.67	12.58	27.54
YGN39 YGN	5.08	4.98	5.94	9.43	16.78	32.58	52.90	51.36	37.36	29.02	21.74	18.20	17.90	15.54	12.60	27.91
YGN42 YGN	5.89	5.68	6.49	9.80	17.15	33.83	56.01	54.95	39.83	30.69	22.73	18.81	18.30	15.60	12.58	28.75
YGN48 YGN	3.98	3.77	4.60	7.59	14.08	28.25	46.92	45.22	32.63	25.09	18.68	15.69	15.40	12.93	10.19	24.85
FI01 FI	40.87	44.42	44.37	44.36	45.65	47.29	48.20	48.71	49.92	53.29	56.25	56.99	56.90	60.37	68.26	78.34
FI02 FI	51.13	50.62	48.84	48.56	49.87	51.77	53.40	54.58	55.14	57.19	60.61	61.68	61.67	65.23	72.20	80.06
FI03 FI	43.66	43.42	43.47	47.31	53.27	54.58	50.47	48.47	48.19	51.38	57.53	59.79	60.04	63.24	70.44	79.28
FI04 FI	44.67	46.44	48.11	51.73	55.87	56.62	53.94	54.13	54.68	59.64	60.43	64.10	61.94	63.09	80.63	88.25
FI05 FI	32.95	41.23	42.84	46.41	50.11	50.61	48.16	48.48	49.21	53.94	54.55	57.88	56.16	59.48	78.00	86.58
IA01 IA	74.73	77.70	77.40	76.86	76.55	74.78	72.26	71.46	71.96	74.67	76.70	80.38	83.49	86.82	89.85	90.57
IA02 IA	73.81	77.72	78.34	77.28	74.96	72.02	69.47	69.17	71.70	76.22	77.29	77.33	77.27	79.25	83.20	86.90
IA03 IA	59.67	75.70	76.36	75.41	74.15	72.86	69.78	70.05	68.60	73.22	73.09	80.36	85.07	86.20	87.52	87.77
IA04 IA	60.36	78.08	78.21	76.59	74.86	73.51	69.84	71.87	71.66	78.63	81.25	79.51	78.95	80.15	80.05	84.21
IA05 IA	71.30	75.07	76.43	76.53	75.03	72.21	68.97	68.16	69.27	73.78	76.68	78.16	77.78	77.20	82.99	86.92

Appendix IV

Colour Differences and Merit Pass Rate of Sample Sets

Colour Difference and the Merit Pass Rate of the Sample sets

Total no. of Shade Passers : 14 Triumph's Shade Passers

Reference	sample	dE CIELab	dECMC (2:1)	dE94 (2:1:1)	No. of Pass	No. of Marginal Pass	Merit Pass Rate%
LT01	LT02	2.1	1.2	1.2	1	4	21.43
LT01	LT03	3.5	2.2	2.1	1	5	25.00
LT01	LT04	1.6	1	0.96	0	3	10.71
LT01	LT05	0.4	0.3	0.26	4	8	57.14
LT02	LT03	1.7	1.5	1.25	1	6	28.57
LT02	LT04	3.1	1.3	1.61	2	3	25.00
LT02	LT05	1.7	1	0.99	1	4	21.43
LT03	LT04	4	1.8	2.12	1	4	21.43
LT03	LT05	3.1	2.1	1.89	2	5	32.14
LT04	LT05	1.7	0.9	0.92	0	3	10.71
PC01	PC02	4.8	2.8	2.62	0	2	7.14
PC01	PC03	3.9	1.6	1.98	0	0	0.00
PC01	PC04	4.3	2.4	2.28	0	0	0.00
PC01	PC05	7.8	3.9	3.95	1	0	7.14
PC02	PC03	3.5	2.4	2.12	0	0	0.00
PC02	PC04	2.5	2.2	1.85	0	0	0.00
PC02	PC05	3.6	1.9	1.95	0	1	3.57
PC03	PC04	2.5	1.5	1.32	0	3	10.71
PC03	PC05	4.8	2.9	2.5	0	2	7.14
PC04	PC05	3.8	1.9	1.97	0	4	14.29
PL01	PL02	3.2	1.7	1.75	1	1	10.71
PL01	PL03	1.5	0.7	0.76	0	0	0.00
PL01	PL04	4.8	2.5	2.61	0	0	0.00
PL01	PL05	4.9	2.1	2.46	0	0	0.00
PL02	PL03	4.5	2	2.33	0	1	3.57
PL02	PL04	1.7	0.9	0.94	0	0	0.00
PL02	PL05	2	1.4	1.21	0	0	0.00
PL03	PL04	6.2	2.9	3.22	1	3	17.86
PL03	PL05	6.3	2.7	3.18	0	1	3.57
PL04	PL05	1	1.3	0.98	1	4	21.43
UK01	UK02	4.9	1.9	2.48	0	3	10.71
UK01	UK03	4.3	3.5	2.77	0	0	0.00
UK01	UK04	5.4	2.1	2.72	0	1	3.57
UK01	UK05	4.9	3.3	2.91	0	0	0.00
UK02	UK03	5.7	3.8	3.36	0	2	7.14
UK02	UK04	1.1	0.9	0.72	4	5	46.43
UK02	UK05	4.1	3.2	2.57	0	1	3.57
UK03	UK04	5.5	3	3.09	0	1	3.57
UK03	UK05	2.3	0.9	1.17	1	4	21.43
UK04	UK05	3.5	2.5	2.16	0	2	7.14
AQ01	AQ02	2.1	1.6	1.24	4	3	39.29
AQ01	AQ03	5	3.2	2.58	0	0	0.00
AQ01	AQ04	6.7	4.2	3.41	0	1	3.57
AQ01	AQ05	6.9	4.5	3.54	0	2	7.14
AQ02	AQ03	4.3	3	2.39	0	0	0.00
AQ02	AQ04	6.5	4.3	3.42	0	0	0.00
AQ02	AQ05	6	4	3.2	0	6	21.43
AQ03	AQ04	2.9	1.7	1.42	1	4	21.43
AQ03	AQ05	2	1.2	0.98	0	7	25.00
AQ04	AQ05	3	1.8	1.5	1	7	32.14

Colour Difference and the Merit Pass Rate of the Sample sets

Reference	sample	dE CIELab	dECMC (2:1)	dE94 (2:1:1)	No. of Pass	No. of Marginal Pass	Merit Pass Rate
CR01	CR02	2.2	1.3	1.06	1	5	25.00
CR01	CR03	2.5	1.5	1.26	0	0	0.00
CR01	CR04	2.1	1.8	1.42	0	0	0.00
CR01	CR05	4.6	3	2.44	0	0	0.00
CR02	CR03	3.9	2.4	2	0	0	0.00
CR02	CR04	2.7	2	1.62	0	0	0.00
CR02	CR05	6.3	4	3.28	0	1	3.57
CR03	CR04	3.4	2.3	1.77	1	6	28.57
CR03	CR05	2.5	1.7	1.33	2	4	28.57
CR04	CR05	5.1	3.1	2.56	0	3	10.71
HW01	HW02	1.4	1.4	1.05	5	4	50.00
HW01	HW03	1.7	0.8	0.91	4	6	50.00
HW01	HW04	3.8	1.6	1.99	4	3	39.29
HW01	HW05	3	2	1.76	2	6	35.71
HW02	HW03	2.2	1.5	1.35	2	4	28.57
HW02	HW04	4.3	2.6	2.47	1	2	14.29
HW02	HW05	4.1	3.3	2.63	1	1	10.71
HW03	HW04	2.2	1.1	1.18	2	6	35.71
HW03	HW05	2.1	1.7	1.38	4	4	42.86
HW04	HW05	2.2	1.1	1.2	2	4	28.57
IR01	IR02	6.9	2.9	2.28	0	1	3.57
IR01	IR03	5.3	2.5	1.92	0	0	0.00
IR01	IR04	2.4	1	1.21	0	3	10.71
IR01	IR05	5.3	2.6	1.94	1	2	14.29
IR02	IR03	2	0.9	0.67	2	8	42.86
IR02	IR04	7.4	3.3	2.72	1	1	10.71
IR02	IR05	4	3.2	2.16	0	3	10.71
IR03	IR04	6.1	3	2.52	0	5	17.86
IR03	IR05	4.1	3.5	2.37	0	3	10.71
IR04	IR05	5.6	2.6	2.2	1	2	14.29
VB01	VB02	3.1	1.8	1.57	0	1	3.57
VB01	VB03	2.7	1.1	0.84	4	4	42.86
VB01	VB04	8	3.9	3.22	0	2	7.14
VB01	VB05	1.8	0.9	0.76	0	1	3.57
VB02	VB03	5	2.6	2.12	0	0	0.00
VB02	VB04	5.5	2.3	1.85	1	4	21.43
VB02	VB05	3.5	1.7	1.5	2	8	42.86
VB03	VB04	10.3	4.8	3.83	0	0	0.00
VB03	VB05	2.5	1.3	1.15	0	2	7.14
VB04	VB05	8.8	3.8	3.31	1	3	17.86
WT01	WT02	2.5	2.2	1.78	1	4	21.43
WT01	WT03	3.8	3.3	2.71	1	0	7.14
WT01	WT04	5.6	4.7	4	0	1	3.57
WT01	WT05	4.8	5.1	3.88	0	0	0.00
WT02	WT03	3.8	1.7	2.02	3	5	39.29
WT02	WT04	3.7	3	2.56	1	1	10.71
WT02	WT05	3.8	3.2	2.64	0	2	7.14
WT03	WT04	5	2.9	2.96	0	4	14.29
WT03	WT05	2.3	2	1.64	1	1	10.71
WT04	WT05	5.1	4	3.23	0	0	0.00
EC01	EC02	1.8	1.3	1.08	0	7	25.00

Colour Difference and the Merit Pass Rate of the Sample sets

Reference	sample	dE CIELab	dECMC (2:1)	dE94 (2:1:1)	No. of Pass	No. of Marginal Pass	Merit Pass Rate
EC01	EC03	2.6	1.5	1.48	0	4	14.29
EC01	EC04	3.9	1.8	2.06	1	1	10.71
EC01	EC05	3.6	2.4	2.05	0	0	0.00
EC02	EC03	1.6	0.6	0.8	5	6	57.14
EC02	EC04	3.4	1.5	1.78	3	8	50.00
EC02	EC05	4.3	2.8	2.34	0	1	3.57
EC03	EC04	2	1	1.02	6	5	60.71
EC03	EC05	3.6	2.4	1.97	0	3	10.71
EC04	EC05	2.8	1.6	1.5	0	2	7.14
GK01	GK02	4.3	3	2.54	0	0	0.00
GK01	GK03	1.4	1.5	1.01	3	6	42.86
GK01	GK04	3.7	2.3	2.1	3	5	39.29
GK01	GK05	2.6	1.9	1.6	0	3	10.71
GK02	GK03	4.4	2.6	2.53	1	0	7.14
GK02	GK04	1.1	0.7	0.66	4	4	42.86
GK02	GK05	1.9	1	1.04	1	4	21.43
GK03	GK04	4	2.2	2.21	2	4	28.57
GK03	GK05	2.7	2.1	1.66	0	1	3.57
GK04	GK05	1.8	0.8	0.94	1	4	21.43
DL01	DL02	2.9	2.9	1.87	0	1	3.57
DL01	DL03	1.5	0.8	0.83	3	3	32.14
DL01	DL04	1.6	1.5	1.03	1	5	25.00
DL01	DL05	1.1	1	0.73	2	5	32.14
DL02	DL03	3.4	3.1	2.26	2	5	32.14
DL02	DL04	1.4	1.4	0.91	0	2	7.14
DL02	DL05	3.8	3.5	2.53	1	2	14.29
DL03	DL04	2.5	2.1	1.6	1	3	17.86
DL03	DL05	1.1	0.6	0.59	2	5	32.14
DL04	DL05	2.6	2.4	1.74	0	1	3.57
GT01	GT04	2.3	1	1.21	5	7	60.71
GT01	GT05	3.3	1.6	1.79	2	6	35.71
GT01	GT07	2.5	2.7	1.95	0	0	0.00
GT01	GT08	3.2	2.9	2.22	0	1	3.57
GT04	GT05	1.1	0.9	0.74	2	4	28.57
GT04	GT07	4.4	3.6	2.89	0	3	10.71
GT04	GT08	2.7	3.5	2.38	1	2	14.29
GT05	GT07	5.4	4.3	3.45	0	1	3.57
GT05	GT08	3	3.9	2.62	0	2	7.14
GT07	GT08	3.7	1.5	1.92	0	2	7.14
DM01	DM02	2.3	2	1.51	0	4	14.29
DM01	DM03	3.1	2.1	1.91	2	4	28.57
DM01	DM08	1.1	1.1	0.79	5	8	64.29
DM01	DM09	2.8	2.1	1.66	0	1	3.57
DM02	DM03	0.9	0.7	0.57	5	3	46.43
DM02	DM08	1.9	2.2	1.35	0	3	10.71
DM02	DM09	1	0.6	0.56	1	4	21.43
DM03	DM08	2.4	2.1	1.53	0	4	14.29
DM03	DM09	1.3	1.2	0.88	1	3	17.86
DM08	DM09	2.6	2.7	1.67	0	0	0.00
WM01	WM03	4.9	2.6	2.81	0	2	7.14
WM01	WM08	6.8	3	3.54	1	1	10.71

Colour Difference and the Merit Pass Rate of the Sample sets

Reference	sample	dE CIELab	dECMC (2:1)	dE94 (2:1:1)	No. of Pass	No. of Marginal Pass	Merit Pass Rate
WM01	WM09	4.5	2.6	2.52	0	1	3.57
WM01	WM10	5.4	2.2	2.78	0	2	7.14
WM03	WM08	3	2.3	1.94	0	5	17.86
WM03	WM09	1.4	1.7	1.21	3	8	50.00
WM03	WM10	1.5	1.3	1.07	2	9	46.43
WM08	WM09	2.7	1.1	1.38	0	8	28.57
WM08	WM10	1.7	1.4	1.14	1	4	21.43
WM09	WM10	1.5	1.4	1.07	5	6	57.14
T0401	T0402	5.7	5.7	2.98	0	1	3.57
T0401	T0404	0.6	0.7	0.39	2	3	25.00
T0401	T0405	3.6	3.5	1.8	0	4	14.29
T0401	T0410	2.1	2.1	1.06	2	4	28.57
T0402	T0404	5.2	4.5	2.67	0	0	0.00
T0402	T0405	2.2	2	1.26	0	1	3.57
T0402	T0410	3.6	3.2	1.94	0	1	3.57
T0404	T0405	3.1	3	1.54	0	3	10.71
T0404	T0410	1.6	1.6	0.81	5	5	53.57
T0405	T0410	1.5	1.4	0.74	1	4	21.43
T2601	T2604	2.2	1.5	1.26	1	4	21.43
T2601	T2608	1.8	1.3	1.04	0	2	7.14
T2601	T2609	0.1	0.2	0.09	2	4	28.57
T2601	T2610	1	1	0.64	0	3	10.71
T2604	T2608	2.6	1	1.32	0	6	21.43
T2604	T2609	2.2	1.3	1.22	0	8	28.57
T2604	T2610	1.9	0.8	0.97	1	4	21.43
T2608	T2609	1.7	1.1	0.96	2	7	39.29
T2608	T2610	1.1	0.6	0.57	6	5	60.71
T2609	T2610	0.8	0.9	0.55	4	7	53.57
AI02	AI03	3.9	1.9	1.65	0	4	14.29
AI02	AI07	4.7	2.3	2	0	1	3.57
AI02	AI09	4	2.8	2.3	0	0	0.00
AI02	AI10	2.9	1.7	1.46	0	2	7.14
AI03	AI07	1.8	1.2	0.95	0	8	28.57
AI03	AI09	6.1	3.6	3.02	0	1	3.57
AI03	AI10	2.1	1.3	1.08	1	5	25.00
AI07	AI09	5.7	2.9	2.52	0	1	3.57
AI07	AI10	2.2	1	0.79	0	3	10.71
AI09	AI10	4.1	2.2	1.99	0	2	7.14
CS01	CS04	2.1	0.8	1.06	2	5	32.14
CS01	CS05	2.4	0.9	1.19	1	3	17.86
CS01	CS08	1.3	1.2	0.87	0	4	14.29
CS01	CS09	2.8	1.4	1.46	2	1	17.86
CS04	CS05	0.6	0.6	0.37	2	11	53.57
CS04	CS08	1.4	1	0.81	4	5	46.43
CS04	CS09	1.2	1.1	0.78	2	6	35.71
CS05	CS08	2	1.5	1.15	6	6	64.29
CS05	CS09	0.9	1.3	0.69	3	6	42.86
CS08	CS09	2.4	1.3	1.36	3	3	32.14
YGN03	YGN06	1.9	0.7	0.94	4	6	50.00
YGN03	YGN12	4.1	1.8	1.77	4	8	57.14
YGN14	YGN39	1.9	0.8	0.64	6	6	64.29

Colour Difference and the Merit Pass Rate of the Sample sets

Total no. of Shade Passers : 19 External Shade Passers

Reference	sample	dE CIELab	dECMC (2:1)	dE94 (2:1:1)	No. of Pass	No. of Marginal Pass	Merit Pass Rate%
LT01	LT02	2.1	1.2	1.2	3	10	42.11
LT01	LT03	3.5	2.2	2.1	5	6	42.11
LT01	LT04	1.6	1	0.96	5	4	36.84
LT01	LT05	0.4	0.3	0.26	11	7	76.32
LT02	LT03	1.7	1.5	1.25	4	9	44.74
LT02	LT04	3.1	1.3	1.61	1	7	23.68
LT02	LT05	1.7	1	0.99	5	7	44.74
LT03	LT04	4	1.8	2.12	3	3	23.68
LT03	LT05	3.1	2.1	1.89	6	5	44.74
LT04	LT05	1.7	0.9	0.92	3	6	31.58
PC01	PC02	4.8	2.8	2.62	2	5	23.68
PC01	PC03	3.9	1.6	1.98	1	2	10.53
PC01	PC04	4.3	2.4	2.28	0	1	2.63
PC01	PC05	7.8	3.9	3.95	0	3	7.89
PC02	PC03	3.5	2.4	2.12	0	1	2.63
PC02	PC04	2.5	2.2	1.85	0	2	5.26
PC02	PC05	3.6	1.9	1.95	0	4	10.53
PC03	PC04	2.5	1.5	1.32	4	5	34.21
PC03	PC05	4.8	2.9	2.5	0	4	10.53
PC04	PC05	3.8	1.9	1.97	4	5	34.21
PL01	PL02	3.2	1.7	1.75	1	5	18.42
PL01	PL03	1.5	0.7	0.76	0	0	0.00
PL01	PL04	4.8	2.5	2.61	0	1	2.63
PL01	PL05	4.9	2.1	2.46	0	1	2.63
PL02	PL03	4.5	2	2.33	0	0	0.00
PL02	PL04	1.7	0.9	0.94	0	4	10.53
PL02	PL05	2	1.4	1.21	1	3	13.16
PL03	PL04	6.2	2.9	3.22	0	0	0.00
PL03	PL05	6.3	2.7	3.18	0	1	2.63
PL04	PL05	1	1.3	0.98	3	6	31.58
UK01	UK02	4.9	1.9	2.48	2	7	28.95
UK01	UK03	4.3	3.5	2.77	1	3	13.16
UK01	UK04	5.4	2.1	2.72	1	6	21.05
UK01	UK05	4.9	3.3	2.91	0	1	2.63
UK02	UK03	5.7	3.8	3.36	0	1	2.63
UK02	UK04	1.1	0.9	0.72	11	6	73.68
UK02	UK05	4.1	3.2	2.57	1	5	18.42
UK03	UK04	5.5	3	3.09	0	3	7.89
UK03	UK05	2.3	0.9	1.17	1	12	36.84
UK04	UK05	3.5	2.5	2.16	0	1	2.63
AQ01	AQ02	2.1	1.6	1.24	1	13	39.47
AQ01	AQ03	5	3.2	2.58	0	0	0.00
AQ01	AQ04	6.7	4.2	3.41	0	1	2.63
AQ01	AQ05	6.9	4.5	3.54	0	5	13.16
AQ02	AQ03	4.3	3	2.39	0	1	2.63
AQ02	AQ04	6.5	4.3	3.42	1	3	13.16
AQ02	AQ05	6	4	3.2	2	6	26.32
AQ03	AQ04	2.9	1.7	1.42	0	6	15.79
AQ03	AQ05	2	1.2	0.98	2	4	21.05
AQ04	AQ05	3	1.8	1.5	8	9	65.79

Colour Difference and the Merit Pass Rate of the Sample sets

Reference	sample	dE CIELab	dECMC (2:1)	dE94 (2:1:1)	No. of Pass	No. of Marginal Pass	Merit Pass Rate
CR01	CR02	2.2	1.3	1.06	2	12	42.11
CR01	CR03	2.5	1.5	1.26	2	1	13.16
CR01	CR04	2.1	1.8	1.42	1	5	18.42
CR01	CR05	4.6	3	2.44	0	1	2.63
CR02	CR03	3.9	2.4	2	2	4	21.05
CR02	CR04	2.7	2	1.62	0	5	13.16
CR02	CR05	6.3	4	3.28	0	0	0.00
CR03	CR04	3.4	2.3	1.77	5	6	42.11
CR03	CR05	2.5	1.7	1.33	1	7	23.68
CR04	CR05	5.1	3.1	2.56	1	1	7.89
HW01	HW02	1.4	1.4	1.05	11	6	73.68
HW01	HW03	1.7	0.8	0.91	7	9	60.53
HW01	HW04	3.8	1.6	1.99	6	9	55.26
HW01	HW05	3	2	1.76	3	7	34.21
HW02	HW03	2.2	1.5	1.35	5	9	50.00
HW02	HW04	4.3	2.6	2.47	8	4	52.63
HW02	HW05	4.1	3.3	2.63	0	9	23.68
HW03	HW04	2.2	1.1	1.18	11	5	71.05
HW03	HW05	2.1	1.7	1.38	5	9	50.00
HW04	HW05	2.2	1.1	1.2	5	7	44.74
IR01	IR02	6.9	2.9	2.28	0	0	0.00
IR01	IR03	5.3	2.5	1.92	0	6	15.79
IR01	IR04	2.4	1	1.21	1	6	21.05
IR01	IR05	5.3	2.6	1.94	1	6	21.05
IR02	IR03	2	0.9	0.67	10	5	65.79
IR02	IR04	7.4	3.3	2.72	0	3	7.89
IR02	IR05	4	3.2	2.16	3	5	28.95
IR03	IR04	6.1	3	2.52	1	4	15.79
IR03	IR05	4.1	3.5	2.37	4	4	31.58
IR04	IR05	5.6	2.6	2.2	2	6	26.32
VB01	VB02	3.1	1.8	1.57	0	0	0.00
VB01	VB03	2.7	1.1	0.84	5	11	55.26
VB01	VB04	8	3.9	3.22	0	0	0.00
VB01	VB05	1.8	0.9	0.76	0	7	18.42
VB02	VB03	5	2.6	2.12	0	3	7.89
VB02	VB04	5.5	2.3	1.85	0	4	10.53
VB02	VB05	3.5	1.7	1.5	0	10	26.32
VB03	VB04	10.3	4.8	3.83	0	0	0.00
VB03	VB05	2.5	1.3	1.15	0	8	21.05
VB04	VB05	8.8	3.8	3.31	0	0	0.00
WT01	WT02	2.5	2.2	1.78	1	3	13.16
WT01	WT03	3.8	3.3	2.71	3	4	26.32
WT01	WT04	5.6	4.7	4	1	5	18.42
WT01	WT05	4.8	5.1	3.88	0	3	7.89
WT02	WT03	3.8	1.7	2.02	5	9	50.00
WT02	WT04	3.7	3	2.56	1	10	31.58
WT02	WT05	3.8	3.2	2.64	2	4	21.05
WT03	WT04	5	2.9	2.96	1	5	18.42
WT03	WT05	2.3	2	1.64	4	5	34.21
WT04	WT05	5.1	4	3.23	0	2	5.26
EC01	EC02	1.8	1.3	1.08	3	10	42.11

Colour Difference and the Merit Pass Rate of the Sample sets

Reference	sample	dE CIELab	dECMC (2:1)	dE94 (2:1:1)	No. of Pass	No. of Marginal Pass	Merit Pass Rate
EC01	EC03	2.6	1.5	1.48	2	6	26.32
EC01	EC04	3.9	1.8	2.06	5	7	44.74
EC01	EC05	3.6	2.4	2.05	1	1	7.89
EC02	EC03	1.6	0.6	0.8	9	7	65.79
EC02	EC04	3.4	1.5	1.78	9	6	63.16
EC02	EC05	4.3	2.8	2.34	2	3	18.42
EC03	EC04	2	1	1.02	12	6	78.95
EC03	EC05	3.6	2.4	1.97	1	3	13.16
EC04	EC05	2.8	1.6	1.5	3	5	28.95
GK01	GK02	4.3	3	2.54	0	2	5.26
GK01	GK03	1.4	1.5	1.01	6	6	47.37
GK01	GK04	3.7	2.3	2.1	2	9	34.21
GK01	GK05	2.6	1.9	1.6	1	4	15.79
GK02	GK03	4.4	2.6	2.53	4	3	28.95
GK02	GK04	1.1	0.7	0.66	7	6	52.63
GK02	GK05	1.9	1	1.04	3	9	39.47
GK03	GK04	4	2.2	2.21	0	6	15.79
GK03	GK05	2.7	2.1	1.66	1	1	7.89
GK04	GK05	1.8	0.8	0.94	10	7	71.05
DL01	DL02	2.9	2.9	1.87	1	2	10.53
DL01	DL03	1.5	0.8	0.83	2	6	26.32
DL01	DL04	1.6	1.5	1.03	3	7	34.21
DL01	DL05	1.1	1	0.73	8	5	55.26
DL02	DL03	3.4	3.1	2.26	0	5	13.16
DL02	DL04	1.4	1.4	0.91	6	8	52.63
DL02	DL05	3.8	3.5	2.53	1	5	18.42
DL03	DL04	2.5	2.1	1.6	1	10	31.58
DL03	DL05	1.1	0.6	0.59	2	5	23.68
DL04	DL05	2.6	2.4	1.74	2	3	18.42
GT01	GT04	2.3	1	1.21	6	8	52.63
GT01	GT05	3.3	1.6	1.79	9	8	68.42
GT01	GT07	2.5	2.7	1.95	0	3	7.89
GT01	GT08	3.2	2.9	2.22	2	4	21.05
GT04	GT05	1.1	0.9	0.74	7	8	57.89
GT04	GT07	4.4	3.6	2.89	0	5	13.16
GT04	GT08	2.7	3.5	2.38	2	3	18.42
GT05	GT07	5.4	4.3	3.45	1	0	5.26
GT05	GT08	3	3.9	2.62	0	8	21.05
GT07	GT08	3.7	1.5	1.92	2	3	18.42
DM01	DM02	2.3	2	1.51	2	7	28.95
DM01	DM03	3.1	2.1	1.91	2	8	31.58
DM01	DM08	1.1	1.1	0.79	11	7	76.32
DM01	DM09	2.8	2.1	1.66	0	4	10.53
DM02	DM03	0.9	0.7	0.57	5	7	44.74
DM02	DM08	1.9	2.2	1.35	3	8	36.84
DM02	DM09	1	0.6	0.56	6	8	52.63
DM03	DM08	2.4	2.1	1.53	1	7	23.68
DM03	DM09	1.3	1.2	0.88	2	13	44.74
DM08	DM09	2.6	2.7	1.67	0	2	5.26
WM01	WM03	4.9	2.6	2.81	2	4	21.05
WM01	WM08	6.8	3	3.54	0	4	10.53

Colour Difference and the Merit Pass Rate of the Sample sets

Reference	sample	dE CIELab	dECMC (2:1)	dE94 (2:1:1)	No. of Pass	No. of Marginal Pass	Merit Pass Rate
WM01	WM09	4.5	2.6	2.52	2	7	28.95
WM01	WM10	5.4	2.2	2.78	1	7	23.68
WM03	WM08	3	2.3	1.94	3	3	23.68
WM03	WM09	1.4	1.7	1.21	8	5	55.26
WM03	WM10	1.5	1.3	1.07	5	8	47.37
WM08	WM09	2.7	1.1	1.38	4	7	39.47
WM08	WM10	1.7	1.4	1.14	8	7	60.53
WM09	WM10	1.5	1.4	1.07	5	3	34.21
T0401	T0402	5.7	5.7	2.98	1	0	5.26
T0401	T0404	0.6	0.7	0.39	1	10	31.58
T0401	T0405	3.6	3.5	1.8	3	10	42.11
T0401	T0410	2.1	2.1	1.06	4	8	42.11
T0402	T0404	5.2	4.5	2.67	0	1	2.63
T0402	T0405	2.2	2	1.26	2	3	18.42
T0402	T0410	3.6	3.2	1.94	1	3	13.16
T0404	T0405	3.1	3	1.54	6	7	50.00
T0404	T0410	1.6	1.6	0.81	7	10	63.16
T0405	T0410	1.5	1.4	0.74	8	5	55.26
T2601	T2604	2.2	1.5	1.26	0	3	7.89
T2601	T2608	1.8	1.3	1.04	0	4	10.53
T2601	T2609	0.1	0.2	0.09	3	8	36.84
T2601	T2610	1	1	0.64	0	2	5.26
T2604	T2608	2.6	1	1.32	3	3	23.68
T2604	T2609	2.2	1.3	1.22	3	9	39.47
T2604	T2610	1.9	0.8	0.97	11	5	71.05
T2608	T2609	1.7	1.1	0.96	5	5	39.47
T2608	T2610	1.1	0.6	0.57	5	8	47.37
T2609	T2610	0.8	0.9	0.55	2	6	26.32
AI02	AI03	3.9	1.9	1.65	4	10	47.37
AI02	AI07	4.7	2.3	2	1	1	7.89
AI02	AI09	4	2.8	2.3	1	2	10.53
AI02	AI10	2.9	1.7	1.46	0	2	5.26
AI03	AI07	1.8	1.2	0.95	2	7	28.95
AI03	AI09	6.1	3.6	3.02	2	2	15.79
AI03	AI10	2.1	1.3	1.08	1	6	21.05
AI07	AI09	5.7	2.9	2.52	1	0	5.26
AI07	AI10	2.2	1	0.79	0	9	23.68
AI09	AI10	4.1	2.2	1.99	0	6	15.79
CS01	CS04	2.1	0.8	1.06	6	8	52.63
CS01	CS05	2.4	0.9	1.19	7	6	52.63
CS01	CS08	1.3	1.2	0.87	6	7	50.00
CS01	CS09	2.8	1.4	1.46	2	8	31.58
CS04	CS05	0.6	0.6	0.37	9	7	65.79
CS04	CS08	1.4	1	0.81	6	3	39.47
CS04	CS09	1.2	1.1	0.78	5	10	52.63
CS05	CS08	2	1.5	1.15	4	7	39.47
CS05	CS09	0.9	1.3	0.69	5	8	47.37
CS08	CS09	2.4	1.3	1.36	2	12	42.11
YGN03	YGN06	1.9	0.7	0.94	6	9	55.26
YGN03	YGN12	4.1	1.8	1.77	8	6	57.89
YGN14	YGN39	1.9	0.8	0.64	8	8	63.16

Colour Difference and the Merit Pass Rate of the Sample sets

Reference	sample	dE CIELab	dECMC (2:1)	dE94 (2:1:1)	No. of Pass	No. of Marginal Pass	Merit Pass Rate
YGN15	YGN24	3.6	1.4	1.78	4	9	44.74
YGN15	YGN38	1.6	0.6	0.57	11	6	73.68
YGN15	YGN48	4	1.6	1.97	10	6	68.42
YGN18	YGN42	1.2	0.6	0.62	13	5	81.58
YGN22	YGN39	5	2.2	2.55	3	8	36.84
YGN24	YGN39	3.2	1.3	1.62	8	5	55.26
YGN39	YGN42	2.1	0.8	0.86	7	4	47.37
FI01	FI02	2.9	1.4	1.51	0	2	5.26
FI01	FI03	1.8	1.6	1.31	1	9	28.95
FI01	FI04	3.8	2.4	2.12	1	2	10.53
FI01	FI05	1.2	1.7	0.93	3	10	42.11
FI02	FI03	2.6	1.6	1.48	0	8	21.05
FI02	FI04	1	1.1	0.73	7	7	55.26
FI02	FI05	2.7	1.2	1.37	0	5	13.16
FI03	FI04	3.1	2	1.72	0	2	5.26
FI03	FI05	1.3	1.7	1.01	2	5	23.68
FI04	FI05	3.3	1.3	1.69	2	5	23.68
IA01	IA02	1.1	1.1	0.86	3	6	31.58
IA01	IA03	1.2	0.8	0.74	10	7	71.05
IA01	IA04	1.1	1.3	0.98	4	7	39.47
IA01	IA05	1.4	1.2	1	10	7	71.05
IA02	IA03	0.9	1	0.73	4	11	50.00
IA02	IA04	1.9	2.1	1.64	6	5	44.74
IA02	IA05	0.6	0.2	0.29	6	10	57.89
IA03	IA04	1.6	1.3	1.12	6	3	39.47
IA03	IA05	0.7	0.9	0.67	9	8	68.42
IA04	IA05	2.2	2.2	1.72	2	6	26.32

Colour Difference and the Merit Pass Rate of the Sample sets

Total no. of Shade Passers : 33 Triumph and External Shade Passers

Reference	sample	dE CIELab	dECMC (2:1)	dE94 (2:1:1)	No. of Pass	No. of Marginal Pass	Merit Pass Rate%
LT01	LT02	2.1	1.2	1.2	4	14	33.33
LT01	LT03	3.5	2.2	2.1	6	11	34.85
LT01	LT04	1.6	1	0.96	5	7	25.76
LT01	LT05	0.4	0.3	0.26	15	15	68.18
LT02	LT03	1.7	1.5	1.25	5	15	37.88
LT02	LT04	3.1	1.3	1.61	3	10	24.24
LT02	LT05	1.7	1	0.99	6	11	34.85
LT03	LT04	4	1.8	2.12	4	7	22.73
LT03	LT05	3.1	2.1	1.89	8	10	39.39
LT04	LT05	1.7	0.9	0.92	3	9	22.73
PC01	PC02	4.8	2.8	2.62	2	7	16.67
PC01	PC03	3.9	1.6	1.98	1	2	6.06
PC01	PC04	4.3	2.4	2.28	0	1	1.52
PC01	PC05	7.8	3.9	3.95	1	3	7.58
PC02	PC03	3.5	2.4	2.12	0	1	1.52
PC02	PC04	2.5	2.2	1.85	0	2	3.03
PC02	PC05	3.6	1.9	1.95	0	5	7.58
PC03	PC04	2.5	1.5	1.32	4	8	24.24
PC03	PC05	4.8	2.9	2.5	0	6	9.09
PC04	PC05	3.8	1.9	1.97	4	9	25.76
PL01	PL02	3.2	1.7	1.75	2	6	15.15
PL01	PL03	1.5	0.7	0.76	0	0	0.00
PL01	PL04	4.8	2.5	2.61	0	1	1.52
PL01	PL05	4.9	2.1	2.46	0	1	1.52
PL02	PL03	4.5	2	2.33	0	1	1.52
PL02	PL04	1.7	0.9	0.94	0	4	6.06
PL02	PL05	2	1.4	1.21	1	3	7.58
PL03	PL04	6.2	2.9	3.22	1	3	7.58
PL03	PL05	6.3	2.7	3.18	0	2	3.03
PL04	PL05	1	1.3	0.98	4	10	27.27
UK01	UK02	4.9	1.9	2.48	2	10	21.21
UK01	UK03	4.3	3.5	2.77	1	3	7.58
UK01	UK04	5.4	2.1	2.72	1	7	13.64
UK01	UK05	4.9	3.3	2.91	0	1	1.52
UK02	UK03	5.7	3.8	3.36	0	3	4.55
UK02	UK04	1.1	0.9	0.72	15	11	62.12
UK02	UK05	4.1	3.2	2.57	1	6	12.12
UK03	UK04	5.5	3	3.09	0	4	6.06
UK03	UK05	2.3	0.9	1.17	2	16	30.30
UK04	UK05	3.5	2.5	2.16	0	3	4.55
AQ01	AQ02	2.1	1.6	1.24	5	16	39.39
AQ01	AQ03	5	3.2	2.58	0	0	0.00
AQ01	AQ04	6.7	4.2	3.41	0	2	3.03
AQ01	AQ05	6.9	4.5	3.54	0	7	10.61
AQ02	AQ03	4.3	3	2.39	0	1	1.52
AQ02	AQ04	6.5	4.3	3.42	1	3	7.58
AQ02	AQ05	6	4	3.2	2	12	24.24
AQ03	AQ04	2.9	1.7	1.42	1	10	18.18
AQ03	AQ05	2	1.2	0.98	2	11	22.73
AQ04	AQ05	3	1.8	1.5	9	16	51.52

Colour Difference and the Merit Pass Rate of the Sample sets

Reference	sample	dE CIELab	dECMC (2:1)	dE94 (2:1:1)	No. of Pass	No. of Marginal Pass	Merit Pass Rate
CR01	CR02	2.2	1.3	1.06	3	17	34.85
CR01	CR03	2.5	1.5	1.26	2	1	7.58
CR01	CR04	2.1	1.8	1.42	1	5	10.61
CR01	CR05	4.6	3	2.44	0	1	1.52
CR02	CR03	3.9	2.4	2	2	4	12.12
CR02	CR04	2.7	2	1.62	0	5	7.58
CR02	CR05	6.3	4	3.28	0	1	1.52
CR03	CR04	3.4	2.3	1.77	6	12	36.36
CR03	CR05	2.5	1.7	1.33	3	11	25.76
CR04	CR05	5.1	3.1	2.56	1	4	9.09
HW01	HW02	1.4	1.4	1.05	16	10	63.64
HW01	HW03	1.7	0.8	0.91	11	15	56.06
HW01	HW04	3.8	1.6	1.99	10	12	48.48
HW01	HW05	3	2	1.76	5	13	34.85
HW02	HW03	2.2	1.5	1.35	7	13	40.91
HW02	HW04	4.3	2.6	2.47	9	6	36.36
HW02	HW05	4.1	3.3	2.63	1	10	18.18
HW03	HW04	2.2	1.1	1.18	13	11	56.06
HW03	HW05	2.1	1.7	1.38	9	13	46.97
HW04	HW05	2.2	1.1	1.2	7	11	37.88
IR01	IR02	6.9	2.9	2.28	0	1	1.52
IR01	IR03	5.3	2.5	1.92	0	6	9.09
IR01	IR04	2.4	1	1.21	1	9	16.67
IR01	IR05	5.3	2.6	1.94	2	8	18.18
IR02	IR03	2	0.9	0.67	12	13	56.06
IR02	IR04	7.4	3.3	2.72	1	4	9.09
IR02	IR05	4	3.2	2.16	3	8	21.21
IR03	IR04	6.1	3	2.52	1	9	16.67
IR03	IR05	4.1	3.5	2.37	4	7	22.73
IR04	IR05	5.6	2.6	2.2	3	8	21.21
VB01	VB02	3.1	1.8	1.57	0	1	1.52
VB01	VB03	2.7	1.1	0.84	9	15	50.00
VB01	VB04	8	3.9	3.22	0	2	3.03
VB01	VB05	1.8	0.9	0.76	0	8	12.12
VB02	VB03	5	2.6	2.12	0	3	4.55
VB02	VB04	5.5	2.3	1.85	1	8	15.15
VB02	VB05	3.5	1.7	1.5	2	18	33.33
VB03	VB04	10.3	4.8	3.83	0	0	0.00
VB03	VB05	2.5	1.3	1.15	0	10	15.15
VB04	VB05	8.8	3.8	3.31	1	3	7.58
WT01	WT02	2.5	2.2	1.78	2	7	16.67
WT01	WT03	3.8	3.3	2.71	4	4	18.18
WT01	WT04	5.6	4.7	4	1	6	12.12
WT01	WT05	4.8	5.1	3.88	0	3	4.55
WT02	WT03	3.8	1.7	2.02	8	14	45.45
WT02	WT04	3.7	3	2.56	2	11	22.73
WT02	WT05	3.8	3.2	2.64	2	6	15.15
WT03	WT04	5	2.9	2.96	1	9	16.67
WT03	WT05	2.3	2	1.64	5	6	24.24
WT04	WT05	5.1	4	3.23	0	2	3.03
EC01	EC02	1.8	1.3	1.08	3	17	34.85

Colour Difference and the Merit Pass Rate of the Sample sets

Reference	sample	dE CIELab	dECMC (2:1)	dE94 (2:1:1)	No. of Pass	No. of Marginal Pass	Merit Pass Rate
EC01	EC03	2.6	1.5	1.48	2	10	21.21
EC01	EC04	3.9	1.8	2.06	6	8	30.30
EC01	EC05	3.6	2.4	2.05	1	1	4.55
EC02	EC03	1.6	0.6	0.8	14	13	62.12
EC02	EC04	3.4	1.5	1.78	12	14	57.58
EC02	EC05	4.3	2.8	2.34	2	4	12.12
EC03	EC04	2	1	1.02	18	11	71.21
EC03	EC05	3.6	2.4	1.97	1	6	12.12
EC04	EC05	2.8	1.6	1.5	3	7	19.70
GK01	GK02	4.3	3	2.54	0	2	3.03
GK01	GK03	1.4	1.5	1.01	9	12	45.45
GK01	GK04	3.7	2.3	2.1	5	14	36.36
GK01	GK05	2.6	1.9	1.6	1	7	13.64
GK02	GK03	4.4	2.6	2.53	5	3	19.70
GK02	GK04	1.1	0.7	0.66	11	10	48.48
GK02	GK05	1.9	1	1.04	4	13	31.82
GK03	GK04	4	2.2	2.21	2	10	21.21
GK03	GK05	2.7	2.1	1.66	1	2	6.06
GK04	GK05	1.8	0.8	0.94	11	11	50.00
DL01	DL02	2.9	2.9	1.87	1	3	7.58
DL01	DL03	1.5	0.8	0.83	5	9	28.79
DL01	DL04	1.6	1.5	1.03	4	12	30.30
DL01	DL05	1.1	1	0.73	10	10	45.45
DL02	DL03	3.4	3.1	2.26	2	10	21.21
DL02	DL04	1.4	1.4	0.91	6	10	33.33
DL02	DL05	3.8	3.5	2.53	2	7	16.67
DL03	DL04	2.5	2.1	1.6	2	13	25.76
DL03	DL05	1.1	0.6	0.59	4	10	27.27
DL04	DL05	2.6	2.4	1.74	2	4	12.12
GT01	GT04	2.3	1	1.21	11	15	56.06
GT01	GT05	3.3	1.6	1.79	11	14	54.55
GT01	GT07	2.5	2.7	1.95	0	3	4.55
GT01	GT08	3.2	2.9	2.22	2	5	13.64
GT04	GT05	1.1	0.9	0.74	9	12	45.45
GT04	GT07	4.4	3.6	2.89	0	8	12.12
GT04	GT08	2.7	3.5	2.38	3	5	16.67
GT05	GT07	5.4	4.3	3.45	1	1	4.55
GT05	GT08	3	3.9	2.62	0	10	15.15
GT07	GT08	3.7	1.5	1.92	2	5	13.64
DM01	DM02	2.3	2	1.51	2	11	22.73
DM01	DM03	3.1	2.1	1.91	4	12	30.30
DM01	DM08	1.1	1.1	0.79	16	15	71.21
DM01	DM09	2.8	2.1	1.66	0	5	7.58
DM02	DM03	0.9	0.7	0.57	10	10	45.45
DM02	DM08	1.9	2.2	1.35	3	11	25.76
DM02	DM09	1	0.6	0.56	7	12	39.39
DM03	DM08	2.4	2.1	1.53	1	11	19.70
DM03	DM09	1.3	1.2	0.88	3	16	33.33
DM08	DM09	2.6	2.7	1.67	0	2	3.03
WM01	WM03	4.9	2.6	2.81	2	6	15.15
WM01	WM08	6.8	3	3.54	1	5	10.61

Colour Difference and the Merit Pass Rate of the Sample sets

Reference	sample	dE CIELab	dECMC (2:1)	dE94 (2:1:1)	No. of Pass	No. of Marginal Pass	Merit Pass Rate
WM01	WM09	4.5	2.6	2.52	2	8	18.18
WM01	WM10	5.4	2.2	2.78	1	9	16.67
WM03	WM08	3	2.3	1.94	3	8	21.21
WM03	WM09	1.4	1.7	1.21	11	13	53.03
WM03	WM10	1.5	1.3	1.07	7	17	46.97
WM08	WM09	2.7	1.1	1.38	4	15	34.85
WM08	WM10	1.7	1.4	1.14	9	11	43.94
WM09	WM10	1.5	1.4	1.07	10	9	43.94
T0401	T0402	5.7	5.7	2.98	1	1	4.55
T0401	T0404	0.6	0.7	0.39	3	13	28.79
T0401	T0405	3.6	3.5	1.8	3	14	30.30
T0401	T0410	2.1	2.1	1.06	6	12	36.36
T0402	T0404	5.2	4.5	2.67	0	1	1.52
T0402	T0405	2.2	2	1.26	2	4	12.12
T0402	T0410	3.6	3.2	1.94	1	4	9.09
T0404	T0405	3.1	3	1.54	6	10	33.33
T0404	T0410	1.6	1.6	0.81	12	15	59.09
T0405	T0410	1.5	1.4	0.74	9	9	40.91
T2601	T2604	2.2	1.5	1.26	1	7	13.64
T2601	T2608	1.8	1.3	1.04	0	6	9.09
T2601	T2609	0.1	0.2	0.09	5	12	33.33
T2601	T2610	1	1	0.64	0	5	7.58
T2604	T2608	2.6	1	1.32	3	9	22.73
T2604	T2609	2.2	1.3	1.22	3	17	34.85
T2604	T2610	1.9	0.8	0.97	12	9	50.00
T2608	T2609	1.7	1.1	0.96	7	12	39.39
T2608	T2610	1.1	0.6	0.57	11	13	53.03
T2609	T2610	0.8	0.9	0.55	6	13	37.88
AI02	AI03	3.9	1.9	1.65	4	14	33.33
AI02	AI07	4.7	2.3	2	1	2	6.06
AI02	AI09	4	2.8	2.3	1	2	6.06
AI02	AI10	2.9	1.7	1.46	0	4	6.06
AI03	AI07	1.8	1.2	0.95	2	15	28.79
AI03	AI09	6.1	3.6	3.02	2	3	10.61
AI03	AI10	2.1	1.3	1.08	2	11	22.73
AI07	AI09	5.7	2.9	2.52	1	1	4.55
AI07	AI10	2.2	1	0.79	0	12	18.18
AI09	AI10	4.1	2.2	1.99	0	8	12.12
CS01	CS04	2.1	0.8	1.06	8	13	43.94
CS01	CS05	2.4	0.9	1.19	8	9	37.88
CS01	CS08	1.3	1.2	0.87	6	11	34.85
CS01	CS09	2.8	1.4	1.46	4	9	25.76
CS04	CS05	0.6	0.6	0.37	11	18	60.61
CS04	CS08	1.4	1	0.81	10	8	42.42
CS04	CS09	1.2	1.1	0.78	7	16	45.45
CS05	CS08	2	1.5	1.15	10	13	50.00
CS05	CS09	0.9	1.3	0.69	8	14	45.45
CS08	CS09	2.4	1.3	1.36	5	15	37.88
YGN03	YGN06	1.9	0.7	0.94	10	15	53.03
YGN03	YGN12	4.1	1.8	1.77	12	14	57.58
YGN14	YGN39	1.9	0.8	0.64	14	14	63.64

Reference	sample	dE CIELab	dECMC (2:1)	dE94 (2:1:1)	No. of Pass	No. of Marginal Pass	Merit Pass Rate
YGN15	YGN24	3.6	1.4	1.78	10	14	51.52
YGN15	YGN38	1.6	0.6	0.57	18	10	69.70
YGN15	YGN48	4	1.6	1.97	15	11	62.12
YGN18	YGN42	1.2	0.6	0.62	20	11	77.27
YGN22	YGN39	5	2.2	2.55	6	14	39.39
YGN24	YGN39	3.2	1.3	1.62	13	11	56.06
YGN39	YGN42	2.1	0.8	0.86	10	10	45.45
FI01	FI02	2.9	1.4	1.51	0	3	4.55
FI01	FI03	1.8	1.6	1.31	1	11	19.70
FI01	FI04	3.8	2.4	2.12	1	6	12.12
FI01	FI05	1.2	1.7	0.93	4	13	31.82
FI02	FI03	2.6	1.6	1.48	1	13	22.73
FI02	FI04	1	1.1	0.73	9	16	51.52
FI02	FI05	2.7	1.2	1.37	1	6	12.12
FI03	FI04	3.1	2	1.72	3	6	18.18
FI03	FI05	1.3	1.7	1.01	2	9	19.70
FI04	FI05	3.3	1.3	1.69	3	7	19.70
IA01	IA02	1.1	1.1	0.86	3	14	30.30
IA01	IA03	1.2	0.8	0.74	13	13	59.09
IA01	IA04	1.1	1.3	0.98	6	12	36.36
IA01	IA05	1.4	1.2	1	15	13	65.15
IA02	IA03	0.9	1	0.73	6	19	46.97
IA02	IA04	1.9	2.1	1.64	7	7	31.82
IA02	IA05	0.6	0.2	0.29	9	14	48.48
IA03	IA04	1.6	1.3	1.12	7	3	25.76
IA03	IA05	0.7	0.9	0.67	17	12	69.70
IA04	IA05	2.2	2.2	1.72	2	10	21.21

Appendix V

Publications

Publications

1. Lam, S.W., Sin, K.M., Ku, S.K. and Yeung, K.W., "Shade passing in the manufacturing of Multi-component apparels with reference to different colour difference equations", 4th Asian Textile Conference held at Taipei, Taiwan, 24 - 26 June 1997, pp.779 - 786 (1997)

2. Lam, S.W., Sin, K.M., Ku, S.K. and Yeung, K.W., "A comparative study of colour measurement instrumentation: Correlation and compatibility between spectrophotometers", 4th Asian Textile Conference held at Taipei, Taiwan, 24 - 26 June 1997, pp.928 - 941 (1997).

3. Lam, S.W., Sin, K.M., Ku, S.K. and Yeung, K.W., "Selection of Colour Difference Equation for Colour Matching of Multi-Component Apparels", J.S.D.C. (Accepted, to be published in 1998).

4. Lam, S.W., Sin, K.M., Ku, S.K. and Yeung, K.W., "Verification of the Tolerance Blocks based on the Selected Colour Difference Equations for Colour Matching of Multi - Component Apparels".