

TECHNICAL UNIVERSITY OF LIBEREC

FACULTY OF TEXTILE ENGINEERING



# **DIPLOMA THESIS**

**2012**

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**TECHNICAL UNIVERSITY OF LIBEREC**

FACULTY OF TEXTILE ENGINEERING

DEPARTMENT OF TEXTILE CHEMISTRY

**WARNING CLOTHING - STUDY OF FLUORESCENCE FADING IN WASHING**

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## **Acknowledgements**

I first would love to pass my sincere gratitude towards Assoc. Prof. Michal Vik, and Ing. Martina Viková for their endless support and professional growth in compiling this research. Furthermore, would like to thank Ing. Pavlina Munzarova for her contribution as well as the whole Academic Staff at Technical University of Liberec, your profound input is highly appreciated.

I would further like to thank the KwaZulu Natal Department of Economic Development for affording me this opportunity; words could not express the gratitude. Last but not least, would like to thank my family for their constant support, without them I wouldn't have been able to persevere.

## Abstract

**High-visibility clothing**, is a type of personal protective equipment (PPE), is any clothing worn that has highly reflective properties or a color that is easily discernible from any background. Yellow waistcoats worn by emergency services are a common example.

Part of the surface of the garment may have retro reflective stripes. This way they become much more visible in the dark for observers near a light source, such as the driver of a car with its headlights on. The pattern of the retro reflecting parts also helps to distinguish between objects and people. Area reflective fabric has proven to be the most effective way of outlining the body, so that drivers can distinguish a human shape at night. For greater visibility during the daytime, very bright colors are used for the main body of the garment by means of fluorescent material. In general, people who wear high-visibility clothing are those who need to be seen during poor lighting or weather conditions, or when working in environments where there is a lot of moving machinery.

### **Types of high-visibility clothing:**

There are three different classifications for high-visibility clothing:

1. Class D – Outdoor daytime use only, with fluorescent or other non-retro reflective high-visibility material
2. Class N – Night-time use only, with retro reflective material on a ‘non-specified’ background
3. Class D/N – Day or night use, with a combination of fluorescent and retro reflective material.

Retro reflective material reflects light back. Non-retro reflective material does not. If retro reflective

Before purchasing a garment, a risk assessment should be conducted to determine when and where the clothing will be worn, and what work tasks are to be completed.

Environmental factors that may influence your choice of clothing include:

- Temperature
- Lighting and visibility (including during the day or night and different types of weather).

Primary concerned regarding these garments has been the fading due to the external environmental factors as well as constant washing. This report will simply focus on fading due to washing.

## Table of Contents

Chapter 1	Introduction.....	14
Chapter 2	Literature review .....	15
2.1	Color Perception.....	15
2.1.1.	The nature of color.....	16
2.1.2.	The physical basis of color .....	18
2.1.3.	Color perception .....	19
2.2	Color Description/Specification Systems .....	20
2.2.1.	The nature of measurement.....	20
2.2.2.	The CIE system of color specification.....	24
2.2.3.	Relationships between tristimulus values and color appearance .....	25
2.2.4.	Usefulness and limitations of the CIE system .....	27
2.3	Color Measurements .....	30
2.3.1.	Types of color measurement.....	30
2.3.2.	Regular reflectance .....	31
2.3.3.	Diffuse reflectance.....	32
2.3.4.	Regular transmittance .....	32
2.3.5.	Diffuse transmission .....	32
2.3.6.	Radiance factor and transmission factor.....	32
2.4	Geometries of measurement.....	33
2.4.1.	CIE Standard Geometries-Reflectance .....	34
2.5	Instrumental Color measurement .....	36
2.5.1.	Single-scale instruments .....	37
2.5.2.	Visual instruments .....	37
2.5.3.	Hand-held/portable instruments.....	38

2.5.4.	Multiangle instruments .....	39
2.5.5.	Bench top instruments .....	39
2.5.6.	Goniometric instruments.....	40
2.5.7.	Fluorimeter.....	41
2.5.8.	Spectrofluorometer .....	41
2.5.9.	Spectrophotometers .....	42
2.5.10.	Inter-instrument agreement and traceability .....	43
2.6	Fluorescent Colorants.....	44
2.6.1.	Absorbance .....	46
2.6.2.	Vibrational Relaxation and Internal Conversion .....	47
2.6.3.	Fluorescence .....	48
2.6.4.	Intersystem Crossing.....	49
2.6.5.	Dyes .....	49
2.7	High Visibility Warning Clothing.....	52
2.7.1.	Purpose.....	53
2.7.2.	Types, Levels, Classes and Colors.....	53
2.7.3.	Test methods - High Visibility Material Properties.....	56
2.7.4.	Color Fastness.....	58
Chapter 3	Experimental Materials and Procedures .....	60
3.1	Materials.....	60
3.2	Procedure.....	63
3.2.1.	Preparation of Washing Bath.....	63
3.2.2.	Washing Process .....	63
3.2.3.	Reflectance Measurements .....	64
3.3	Samples .....	65



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Chapter 4	Results and Discussion .....	66
4.1	Most Resistant samples from fading .....	66
4.2	Intermediate samples from fading .....	74
4.3	Non- resistant samples from fading .....	82
4.4	Comparison of Resistant and Non Resistant .....	90
Chapter 5	Conclusion .....	91
Chapter 6	References .....	94
Chapter 7	Appendix A .....	96
Chapter 8	Appendix B .....	99
Chapter 9	Appendix C .....	129

## List of Figures

Figure 1: Representation of Visible spectrum .....	17
Figure 2: The geometry of Specular reflection .....	19
Figure 3:Diagram representations of Munsell Color System .....	23
Figure 4: Chromaticity Diagram.....	26
Figure 5:Diagrams of Specular and Diffuse Reflection.....	31
Figure 6: Regular reflectance.....	31
Figure 7: Simplified diagrams of the four CIE recommended geometries for color measurement. ....	33
Figure 8: Visual representation of the working concept of a spectrophotometer .....	43
Figure 9: Representation of Jablonski Energy Diagrams .....	45
Figure 10: Chemical Structure of Xanthene .....	50
Figure 11: Chemical formation of Fluorescein Dye. ....	50
Figure 12: Absorption and emission spectra of fluorescein .....	51
Figure 13: Eosin Y and B respectively .....	51
Figure 14: Instrument for measuring the melting point of yarns from a fabric .....	60
Figure 15: outside and inside outlook of a Data Color Eco Washing Machine.....	63
Figure 16: Full view of the Data color Spectrophotometer .....	64
Figure 17: Picture of the samples before being subjected to washing and after washing ...	65
Figure 18: Green 4B Wavelength vs Reflectance.....	66
Figure 19: Green 4B Time vs .....	67
Figure 20: Green 4B Time vs $\Delta E$ .....	68
Figure 21: Green 4B Time against % of .....	69
Figure 22: Green 1 Wavelength vs Reflectance .....	69
Figure 23: : Green 1 Time vs Maximum Reflectance .....	70
Figure 24: Green 1 Time vs $\Delta E$ .....	71
Figure 25: Green 1 Time against % of.....	72
Figure 26: Green 4B Wavelength vs Reflectance.....	74
Figure 27: Green 4 Time vs Maximum Reflectance.....	75
Figure 28: Green 4 Time vs $\Delta E$ .....	76

Figure 29: Green 4 Time against % .....	77
Figure 30: Orange 4ZA Wavelength vs Reflectance .....	78
Figure 31: Orange 4ZA Time vs.....	79
Figure 32: Orange 4ZA Time vs $\Delta E$ .....	80
Figure 33: Orange 4ZA Time against % .....	81
Figure 34: Orange 8 Wavelength vs Reflectance .....	82
Figure 35: Orange 8 Time vs maximum reflectance .....	83
Figure 36: Orange 8 Time vs $\Delta E$ .....	84
Figure 37: Orange 8 Time against % of.....	85
Figure 38: Orange 6 Wavelength vs Reflectance .....	85
Figure 39: : Orange 6 Time vs maximum reflectance .....	86
Figure 40: Orange 6 Time vs $\Delta E$ .....	87
Figure 41: Orange 6 Time against % of.....	88
Figure 42: Comparison of Resistant and Non resistant substrates based on $\Delta E$ .....	90
Figure 43: Comparison of Resistant and Non-Resistant substrates based on % of colour..	90

## List of Tables

Table 1: Color requirements for background and area performance .....	56
Table 2: Basic Parameters of some of the samples utilized during experimentation .....	61
Table 3: Properties of Syntapon ABA .....	62
Table 4: Number of hours of washing against Maximum Reflectance .....	66
Table 5: Number of hours of washing against $\Delta E$ .....	67
Table 6: Number of hours of washing against the percentage of color remaining .....	68
Table 7: Number of hours of washing against Maximum Reflectance .....	70
Table 8: Number of hours of washing against $\Delta E$ .....	71
Table 9: Number of hours of washing against the percentage of color remaining.....	72
Table 10: Number of hours of washing against Maximum Reflectance .....	75
Table 11: Number of hours of washing against $\Delta E$ .....	76
Table 12: Number of hours of washing against % of color remaining.....	77
Table 13: Number of hours of washing against Maximum Reflectance .....	78
Table 14: Number of hours of washing against $\Delta E$ .....	79
Table 15: Number of hours of washing against % of color remaining.....	80
Table 16: Number of hours of washing against Maximum Reflectance .....	82
Table 17: Number of hours of washing against $\Delta E$ .....	83
Table 18: Number of hours of washing against % of color remaining.....	84
Table 19: Number of hours of washing against Maximum Reflectance .....	86
Table 20: Number of Hours of washing against $\Delta E$ .....	87
Table 21: Number of hours of washing against % of color remaining.....	88

## Definitions

- **Background Material:** Colored material intended to be used in High Visibility Clothing, but not intended to comply with the requirements of this standard for retro reflective material.
- **Coefficient of Luminous Intensity (RI):** is the ratio of the luminous intensity (I) of the reflector in the direction of the observer to the illuminance (E), expressed in candelas per lux ( $\text{cd.lx}^{-1}$ )
- **Area-performance material:** Either a retro reflective material that is also a fluorescent material or a retro reflective material covers part of background material.
- **Combined Performance Retro reflective Material:** Retro reflective Material which contains a colored reflective system or mix in with a colored background material, so that the material has both reflective function and color function.
- **Conspicuity:** The characteristics of an object influencing the probability that it will come to the attention of an observer at critical observation distance.
- **Fluorescent material:** Material that instantaneously emits optical radiation within the visible range at wavelengths longer than absorbed and for which emission ceases upon removal of the source of irradiation. These materials enhance daytime visibility, especially during dawn and dusk.
- **High Visibility Risk-Related Clothing:** Personal apparel containing retro reflective and/or colored background elements to be visible by vehicle drivers in critical detection distance and intended to be worn and covered a part of human body .
- **Illuminance (E):** the amount of light striking a surface measured in lux (lx).
- **Luminance:** light retro-reflected back to an observer, seen as —brightness
- **Luminous Intensity (I):** is the luminance measured in candelas per square meter ( $\text{cd.m}^{-2}$ )
- **PPE:** High visibility risk-related clothing is considered to be a Personal Protective Equipment (PPE).
- **Retro reflective Material:** Material that is a retro reflector and is intended to comply with the requirements of this standard for high visibility risk-related clothing.

## **Chapter 1 Introduction**

High Visibility Clothing is designed to prevent the danger whereas the majority of other safety clothing is designed to protect against danger. Wearing High Visibility Clothing is essential in such circumstances, enabling workers to be extremely visible, lighting up almost as beacons. This greatly helps increase operator awareness of nearby personnel, and has been shown to drastically reduce the chance of accidents or injuries within a working environment.

But where environment is concerned there are several aspects which also need to be considered, any of which could, over time, render the high visibility clothing much less effective. Placing too much faith in equipment which is old, worn, faded or damaged can be even more dangerous than not wearing the equipment at all in some cases. Although high visibility safety clothing is manufactured under strict and very high standards, there is always going to be an inevitable reduction in effectiveness over time, and this can be exacerbated as a result of particular conditions.

Wearing high visibility clothing outdoors can result in gradual decline in effectiveness. This could be due to UV damage over time through being in direct sunlight for prolonged periods of time or even cracking, fading or general deterioration due to wash the clothing more regularly if it is subject to working conditions causing it to become soiled. High visibility garments generally have two design criteria: background fabric and retro reflective tape. The garment is composed primarily of high quality fluorescent fabric in colors including fluorescent yellow/green, fluorescent orange/red and fluorescent red. The fluorescent fabric is used to make the wearer more visible in daylight hours, particularly in twilight conditions. The degradation of dyed polymer textiles due to light exposure and washing is of great importance in terms of prolonging the lifetime of clothing. The number of wash cycle, combined with the amount of light exposure that textiles can endure is essential. Fastness to washing is dependent on the substantivity as well as the polarity of a dye molecule. The greater the substantivity, the greater will be the force to prevent removal of the dye during washing.

## **Chapter 2 Literature review**

### **2.1 Color Perception**

Color exists only in the mind; it is a perceptual response to light that enters the eye either directly from self-luminous light sources or, indirectly, from light reflected by illuminated objects. Light that enters the eye is sampled by three classes of light-sensitive cells in the retina known as cones. In order to understand color, it is necessary to appreciate that the effective spectral sensitivities of these cones are not static; rather, they change with the illumination conditions and the responses of spatially neighboring cells, to name but two factors. Furthermore, the three classes of signals from the cones are processed by the neural pathways that lead from the retina to various areas of the cortex in the brain. Although our understanding of color processing in the human visual system is sufficient to allow us to predict when two spectrally dissimilar objects will be a visual match, it does not allow us to make reliable predictions of color appearance.

Color has always been important, but especially so in the modern world. We only have to look around us to see the variety of colors produced on textiles, painted surfaces, paper and plastics. In most cases the color is an important factor in the production of the material and is often vital to the commercial success of a product. Textiles often sell as much on color and design as on quality of materials. In our homes, colors of carpets, curtains and paints are carefully chosen to produce a pleasing effect. The same colors may be represented as color prints, for example in mail order catalogues, or on computer screens for design work or in e-commerce. In some cases, such as foods, we use the color to judge the quality of the material, while in other cases, such as packaging, the color is important in attracting customers.

In almost all applications it is difficult to produce exactly the color required and to ensure that successive batches are the same color as each other. Raw textile materials such as cotton and wool vary from batch to batch as do dyes and pigments, despite strenuous

efforts by producers to try to ensure good quality control. There are normally two main considerations for the producer of colored products (or computer images). Firstly, whether the color is reasonably close to that desired. Secondly, whether repeat samples or batches match each other. For example, successive batches of paint, or arrays of clothing items displayed together should match very closely. In this case, it is the differences in color between samples or within a sample that matter.

Two alternative methods are available to assess the correctness of the colors. For many years, only visual assessment was available. This worked fairly well, but there were problems. It is difficult to remember colors accurately and difficult to describe differences in color. Experienced colorists have a good idea as to the size of difference which might be tolerated, but there is no objective way to settle differences of opinion between say a dyer who considers that a match is close enough, and a customer of the opposite opinion.

### **2.1.1. The nature of color**

Light is a form of energy. Specifically, it is that part of the spectrum of electromagnetic radiation that our eyes are sensitive to. Radio waves and X-rays, as well as ultraviolet and infrared radiation, are all part of the spectrum of electromagnetic radiation but the human visual system is only capable of sensing a very narrow band of wavelengths in the approximate range 360–780 nm (a nanometer is  $10^{-9}$  meters). The light from any source can be usefully described in terms of the relative power emitted at each wavelength in the visible spectrum. Figure 1.2 shows the wavelengths of the visible spectrum and the colors with which we normally associate the wavelengths.



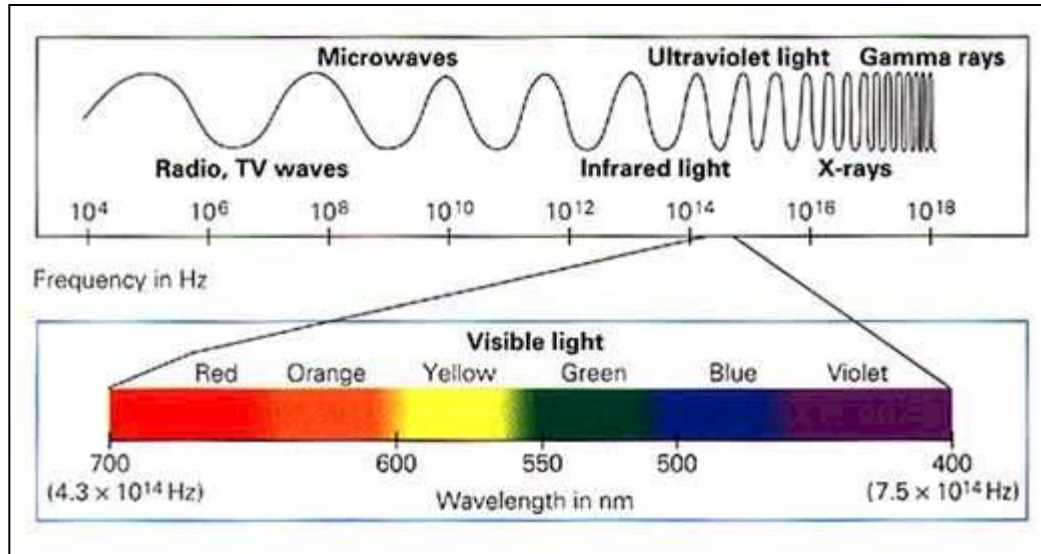


Figure 1: Representation of Visible spectrum

1. A **blackbody** is a hollow heated chamber with a small hole; as the blackbody is heated, the spectral power distribution of the light emitted from the hole varies.

However, Newton was famously aware that ‘the rays are not colored’. By this phrase Newton meant that light is not intrinsically colored; short-wave light, for example, has no intrinsic property by which it is blue but, rather, it may induce in us the sensation of blueness. Under some circumstances, however, short-wave light may appear black or some color other than blue. It is therefore clear that color cannot be understood without a study of the properties of the human visual system, since color exists only in the brain. The spectral power distribution of daylight varies with geographical position, atmospheric conditions, and with the time of day and year but the set of daylight power distributions is very similar to that emitted by a blackbody<sup>1</sup> heated at different temperatures (Judd et al., 1964).

For many light sources it is useful to refer to the temperature (usually expressed in Kelvin) of the blackbody whose radiation most closely resembles that of the light source. This temperature is called the correlated color temperature (Sinclair, 1997). The radiation of north sky daylight on a cloudy day has a correlated color temperature of about 6500 K,

whereas the light from a tungsten filament bulb has relatively more power at the long wavelengths which gives it a much lower correlated color temperature.

### 2.1.2. The physical basis of color

When light strikes an object, some light is always reflected from the surface, at the boundary between the object and air, because of the change in refractive index as the light passes from air to a denser medium. This surface reflectance has the same relative spectral power distribution as the illuminating source and may be diffuse or specular in nature. Diffuse reflectance, where the light is dispersed in many different directions, occurs when the surface is rough, whereas smooth glass-like surfaces give rise to specular surface reflectance where the angle of reflection is equal to (but with opposite sign) the angle of incidence of the illumination.

The light that is not reflected at the surface enters the body of the object, where further interactions take place. If the material is transparent, some light will pass through the material and emerge at the other side. The most common processes that reduce transparency are absorption and scattering. **Absorption** is a process whereby light is removed by an interaction with the molecules of the object at an electronic level. Most objects are colored because this absorption process is more efficient at certain wavelengths than at others, in a way that depends upon the properties of the molecules (Zollinger, 1999). **Scattering** is a kind of reflection that occurs when particles (or air bubbles) are present in the material. The amount and directional nature of the scattering depends upon the size of the particles and their refractive indices (relative to the medium in which they are contained). Many opaque (non-transparent) white materials are manufactured by adding particles of a white pigment such as titanium dioxide, which has a particularly high refractive index.

**Translucency** is a visual phenomenon that can give materials a milky or cloudy appearance and occurs when the material is partially transparent but exhibits scattering. The proportion of light reflected by a sample can be measured using a reflectance spectrophotometer and

represents the (physical) color fingerprint of the sample. A spectrophotometer typically measures the proportion (sometimes expressed as a percentage) of light reflected by the object at each of several equally spaced wavelength intervals. Commercially available instruments typically measure at 31 wavelength intervals centered at 400 nm, 410 nm, 420 nm, 690 nm, and 700 nm. Most reflectance spectra are smooth functions of wavelength so that it is reasonable to measure the reflectance at wavelength intervals of 5 nm or even 10 nm with little loss of information (Maloney, 1986). For non-fluorescent materials, the spectral reflectance factors are independent of the intensity or spectral distribution of the light source that is used by the spectrophotometer. That is to say, if a given object reflects 50% of the light at a given wavelength, this is independent of whether the incident illumination contains 100 or 1000 units of power at that wavelength. The spectral reflectance factor is obtained by comparing the intensity of the reflected light for an object at a given wavelength with the intensity of the light reflected by a perfect Lambertian diffuser.

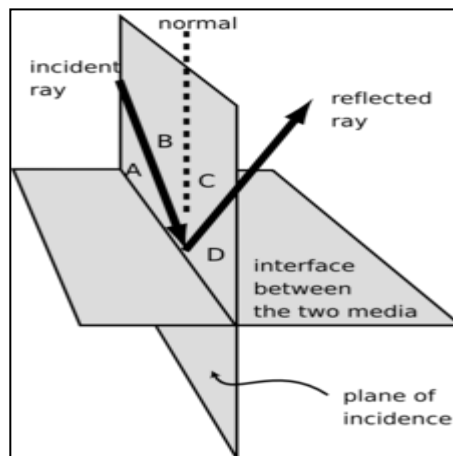


Figure 2: The geometry of Specular reflection

### 2.1.3. Color perception

Color perception for humans is three-dimensional, a fact that almost certainly stems from the existence in the retina of three different classes of light-receptive cells. Three terms, or numbers, are necessary and sufficient to define a color stimulus for the visual system under standard conditions (Westland and Ripamonti, 2004). For example, we might describe a

color by its hue, its colorfulness and its brightness or we might specify a stimulus by the XYZ tristimulus values of the CIE system. It is important to note, however, that color is only one aspect of total appearance for surfaces in the world and many other phenomena contribute to overall appearance, including gloss and texture. Furthermore, the complex nature of color perception means that it is impossible to predict even the approximate color appearance of a patch in a scene without specifying the surrounding colors and the state of adaptation of the eye.

## **2.2 Color Description/Specification Systems**

### **2.2.1. The nature of measurement**

In all branches of science and engineering, measurement plays an important part. In commerce materials are usually bought and sold by weight or volume. Without standardized systems for measuring mass, length and time, modern life would be very difficult. It is obvious that a standard system for measuring and specifying color is equally desirable. However, there are important differences between color and, for example, length. The color of an object depends on many factors, such as lighting, size of sample, and background and surrounding colors. Much more importantly, color is a subjective phenomenon and depends on the observer. The measurement of subjective phenomena, such as color, taste and smell, is obviously more difficult than that of objective phenomena such as mass, length and time.

Provided that good instruments are used carefully, we can be confident that, for objective measurements, the results will be correct. With color the situation is completely different. If a color does not look to be correct, it is not correct, no matter what any instrument indicates. The final arbiter is the human eye. One problem with regard to color measurement is that the human eye is readily available and particularly sensitive to color; millions of different colors can be distinguished. Any measurement that is less reliable than the unaided eye will be of limited value.

Another consideration is that, with color, we are often concerned with differences in color rather than with color itself. For many purposes the exact color is not as important as uniformity of color. When buying a blue shirt, the exact shade of blue is unlikely to matter,

but any appreciable difference between the collar, sleeves and other parts would not be acceptable. Small differences between different shirts on display at the same time would give an impression of carelessness on the part of the manufacturer. Similarly, when buying paint, a customer will often accept any color within reasonable range of the desired color, but would be much less tolerant of even a small difference between the paint from two different cans.

With color, we should never forget that the final objective is to produce something that is pleasing or satisfactory to the eye. If the color looks wrong, it is wrong. For the present we will simply examine how a system of color specification can be set up. We will return to the question of how far such a system fulfills our needs. In considering the appearance of an object, factors such as texture and gloss are important, as well as color. Almost all modern color measurement is based on the CIE system of color specification. The initials come from the French title of the international committee (Commission Internationale de l'Éclairage) who set up the system in 1931.

Although additions have been made since, the basic structure and principles are unchanged and the system is widely used. It should also be emphasized at this point that the system is empirical, i.e. it is based on experimental observations rather than on theories of color vision. When discussing color in general, we could be considering colored lights, colored solutions or colored surfaces such as painted surfaces, plastics and textiles. In most practical situations we are concerned with colored surfaces, although, as we shall see, the properties of colored lights are used in the specification of the color of surfaces.

It is important to realize that the color of an object depends on the light source used to illuminate its surface, the particular observer who views it, as well as the properties of the surface itself. The nature of the surface is the most important factor. A piece of white paper will look white under all normal light sources when viewed by any observer with normal color vision. (This statement is not completely true, for example small areas of 'white' paper viewed as part of a pattern formed by a variety of colors could look to be a different color. In trying to understand the principles involved in color it is probably best to ignore

such exceptions for the moment and adopt a simplified view of color. In practical applications, however, such factors must be considered whenever appropriate.)

Because our white paper does remain white, there is a tendency to think of color as a property of the surface. In considering the measurement of color, the light source and the observer cannot be ignored; we should think about surface, light source and observer. The CIE system basically attempts to tell us how a color might be reproduced (by a mixture of three primary light sources) rather than described. The amounts of the three primaries required to match a particular color provide a numerical specification of that color. A different color would require different amounts of the primaries and hence the specification would be different.

It turns out that, in many applications, this is all that is required. Some idea of the color seen can be deduced from CIE color specifications; furthermore, we would never attempt to reproduce a color by actually mixing the CIE primaries. It is well known that color is three-dimensional. This is apparent in various ways. Color atlases such as the Munsell atlas arrange colors using three scales (hue, value, and Chroma in the case of the Munsell system). We can match a wide range of colors using a mixture of three dyes, and the concentrations of three specific dyes required on a particular substrate to match a color could be used to specify that color.

We would need to specify the light source, under which the color was seen, but the three concentrations would give a numerical specification of the color; the specification would be different for different colors and it would be possible for someone else to reproduce the color. Unfortunately, dyes or pigments tend to be impure and the precise color depends on the method of manufacture. Even repeat batches from the same plant will not match exactly, and properties of mixtures are not completely predictable. Colored lights are much easier to define and reproduce. Imagine a red light obtained by isolating the wavelength 700 nm from the spectrum. All laboratories in the world capable of measuring wavelength accurately (an objective physical measurement) could produce the same red color. A green color corresponding to 546.1 nm could be produced even more easily.

A mercury lamp emits light at only four wavelengths in the visible region (404.7 nm, 435.8 nm, 546.1 nm and 577.8 nm). By filtering out the other three, the required green wavelength could be obtained. The wavelengths 404.7 nm and 435.8 nm could be obtained in a similar manner. Small variations in the operating conditions have no significant effect on the wavelengths emitted by a mercury lamp. Hence, three primary light sources could be defined simply as appropriate wavelengths and be easily reproduced. Mixtures of three colored lights can be produced in various ways, but the simplest is to imagine three spotlights shining on the same area on a white screen. The color produced would be a mixture of the three colors being mixed and it is possible to produce a wide range of colors by varying the amounts of the three primaries. The colors to be matched could include surface colors illuminated by a particular light source.

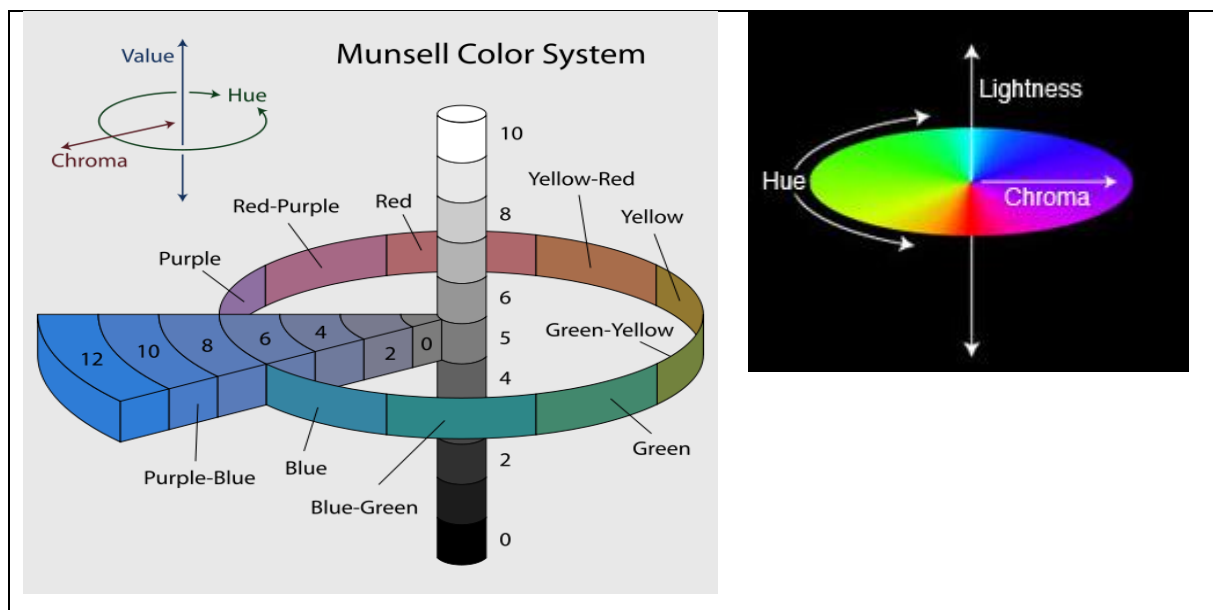


Figure 3:Diagram representations of Munsell Color System

### 2.2.2. The CIE system of color specification

If we were to select and define three particular primaries (R), (B) and (G), the amounts of these required to match any color could be used to specify the color and be called tristimulus values. Each different color would require different amounts, the tristimulus values would therefore define the color and with practice we could deduce the appearance of the color from the tristimulus values. However, different results would be obtained by anyone using a different set of primaries. It can be shown that sets of tristimulus values obtained using one set of primaries can be converted to the corresponding results that would have been obtained using a second set, provided that the amounts of one set of primaries required to match each primary of the second set of primaries in turn are known. Hence we could either insist that one set of primaries is always used, or allow the use of different sets, but insist that the results are converted to those which would have been obtained using a standard set.

Even using very pure colors for our set of primaries, there would still be some very pure colors that could not be matched. For example, a very pure cyan (blue–green) might be more saturated than the colors obtained by mixing the blue and green primaries. Adding the third primary (red) would produce even less saturated mixtures. A possible solution in this case would be to add some of the red primary to the pure cyan color, and then match the resultant color using the blue and green primaries. Experimentally, it has been found that, if this procedure is followed, all colors can be matched using one set of primaries, the only restriction in the choice of primaries being that it must not be possible to match any one of the primaries using a mixture of the other two. Negative values are undesirable.

By careful choice of primaries it is possible to reduce the incidence of negative tristimulus values. The best primaries are red, green and blue spectrum colors. Mixtures of these give the widest possible range of colors. However, there is no set of real primary colors that can be used to match all colors using positive amounts of the primaries, i.e. there is no set of real primaries that will eliminate negative tristimulus values entirely. Since it is possible to



calculate tristimulus values for one set of primaries from those obtained using a second set, there is no need to restrict ourselves to a set of real primary colors. Purely imaginary primaries can be used; it is only necessary that these have been defined in terms of the three real primaries being used to actually produce a match. This is not just a hypothetical possibility. Negative tristimulus values would be a nuisance in practice and, in the CIE system, imaginary primaries are indeed used so as to avoid negative values.

If we produced a visual match, the amounts of the primaries required could be noted, and the results converted to the equivalent values for a standard set of primaries. Such a procedure is perfectly possible, the main problem lying in the precision and accuracy achievable. The results would vary from one observer to another because of differences between eyes. It must be stressed that the CIE system incorporates the features described earlier, i.e. a color is to be specified by the amounts of the (X), (Y), and (Z) primaries required, in an additive mixture, to match it. The ‘standard observer’ data is added to the framework already described. It is possible to calculate tristimulus values (i.e. the amounts of three primaries which, if additively mixed, would match a color) of a sample specified. The CIE had to define standard primaries, standard light sources and a standard observer, together with standard observing and viewing conditions.

### **2.2.3. Relationships between tristimulus values and color appearance**

It is difficult to relate, in a simple way, the tristimulus values of a sample to the color appearance. One reason is that the color depends not only on the stimulus, but also on surrounding colors and the state of adaptation of the eye. Even ignoring such factors, the three-dimensional nature of color makes it difficult to determine relationships and it is usual to simplify any relationship involving color by considering only one or two dimensions at a time. It was indicated earlier that, in choosing primaries for the CIE system, the wide range of possibilities had been used to produce certain desirable features in the final system.

A consequence of ensuring that the  $y_\lambda$  curve corresponded to the  $V_\lambda$  curve was that the Y tristimulus value should roughly represent the lightness of a sample, i.e. the higher the Y value, the lighter the sample appears. The scale is far from uniform and caution should be exercised when comparing the lightness of quite different colors such as reds and greys.

Nonetheless, in general it will be found that, the higher the Y value, the lighter a sample will look. Thus if  $Y = 80$ , we can be sure that the sample will appear light, while if  $Y = 3$ , the sample will look dark.

### *Chromaticity diagrams*

To represent the other two dimensions of color, it was usual to first define ‘chromaticity coordinates’ (x, y and z) and then plot y against x:

$$x = X/(X + Y + Z)$$

$$y = Y/(X + Y + Z)$$

And

$$z = Z/(X + Y + Z) \quad [2.2.3]$$

From (2.2.3) it follows that  $x + y + z = 1$  for all colors; it is therefore only necessary to quote two of the chromaticity coordinates and these can be plotted on a normal two-dimensional graph. It can also be shown that X and Z can easily be calculated from x, y and Y; hence the latter set is an acceptable form of specification, and consideration of Y values and plots of y against x should cover all possible colors. A plot of y against x is called a *chromaticity diagram* and, at one time, was widely used.

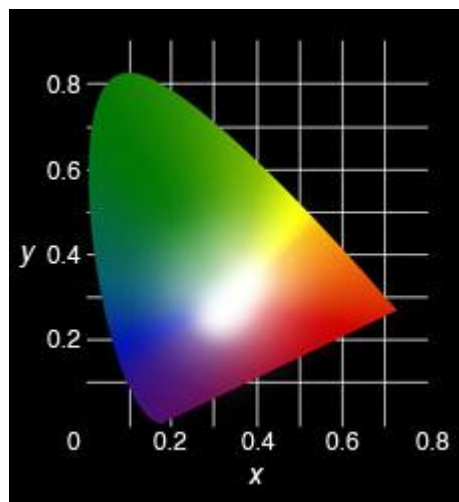


Figure 4: Chromaticity Diagram

It is described in detail in many textbooks on color. It was stated earlier that the Y scale is far from uniform. The same applies to the x y diagram; equal distances in the diagram do not correspond to equal visual differences. For a fixed difference in x and y, the difference seen would be much smaller for a pair of green samples than for pairs of blue or grey samples.

A further disadvantage of the x y diagram is that colors measured under different standard illuminants, e.g. Illuminant D65 and Illuminant A are represented by completely different points in the diagram. It has been emphasized that color is three-dimensional. Thus any two-dimensional plot cannot represent color completely. In the case of the chromaticity diagram, it is simplest to regard the missing factor as the Y tristimulus value. In general, any one point on any chromaticity diagram corresponds to a range of colors differing in lightness, and this should always be kept in mind when trying to visualize the colors corresponding to particular chromaticity coordinates.

#### **2.2.4. Usefulness and limitations of the CIE system**

In many ways the CIE system of color specification has been remarkably successful. Almost all important applications of color measurement use the CIE system. The basic system has survived unchanged for over 70 years. The additions made since 1931 have led to improvements in some respects, but have not changed the basic principles of the system in any way. It is unlikely that any major changes will be made in the foreseeable future.

On the other hand, we must consider the limitations of the system. These stem basically from the limited objectives of the system rather than from a failure to meet the objectives. The CIE tristimulus values for a sample are related to the color of the sample, but ignore other important features such as surface texture, gloss, sheen, etc. Thus a gloss paint sample and a matt paint sample might have the same tristimulus values, but obviously will not look the same. Whether the colors of the two samples will look the same depends critically on their geometrical arrangements for illuminating and viewing the samples. Only if the instrumental geometry of illumination and viewing conditions is close to that used visually will the colors seen be close. An instrument will always average out the light reflected from the area being measured (typically a 2 cm diameter circle). In judging a

color visually some sort of averaging takes place, but the observer is always conscious of any non-uniformity over the area viewed. Thus a matt paint surface, a woven textile surface and a pile fabric will always look different from one another, but their measured tristimulus values could be the same.

Ignoring all features other than color, the tristimulus values for a sample give only a limited amount of information. Basically, the tristimulus values tell us the amounts of three imaginary primaries, which if additively mixed will give the same color as a surface illuminated by a standard source and viewed by a standard observer using one of the standard geometries. It follows that the mixture of the CIE primaries would be unlikely to match the surface if the latter was illuminated by a different source or if the 'match' was viewed by an individual observer or if a different illuminating or viewing geometry was used. Control can be exercised (to some extent) over the source and the geometry. If these are important, we must try to ensure that the instrumental conditions correspond as closely as possible to those to be used when viewing the object visually.

The only choice as far as the standard observer is concerned is whether to use the 1931 ( $2^\circ$ ) observer or the 1964 ( $10^\circ$ ) observer. Neither is likely to correspond closely to any individual observer. However, the standard observers may well correspond reasonably closely with the average judgment of real observers, bearing in mind that, in many applications, the product is mass produced and will be seen by many different observers. A full specification of a color requires X, Y and Z values (or equivalent sets such as x, y and Y or  $L^*$ ,  $a^*$ , and  $b^*$ ) for several different illuminants. The results are still only valid for the standard observer and could be unsatisfactory for a real observer. This should not be a problem in practice since we usually require colors to be acceptable to a large number of potential customers; the standard observer is probably a better guide to the population in general than any one observer.

However, situations often do arise where one particular individual (e.g. a head dyer or a buyer for a chain store) inspects material and problems will occur when that individual's color vision is appreciably different from that of the standard observer. Problems will be much more severe for highly metameric pairs of samples. Strictly speaking, the tristimulus values tell us nothing about the color of a sample although, as discussed above, with

experience we can make a reasonable estimate of the color from either X, Y and Z or x, y and Y values. In such cases it is essential that the illuminant used for the measurements is known. Chromaticity coordinates of  $x = 0.314$  and  $y = 0.331$  correspond to a neutral color if derived from measurements under illuminant D65, but if derived from measurements under illuminant A will correspond to a blue color. In many applications the aim is to match a particular target, which might be defined by a set of tristimulus values. If we produce a sample and wish to test whether this matches the target, it is essential that sample and target measurements correspond to exactly the same conditions (illuminant, standard observer, illuminating and viewing geometries, and, in practice, the same instrument). If, for example, the sample is a really good match to the target, but the tristimulus values are to be measured using different standard observers for the sample and target, the resulting tristimulus values and chromaticity coordinates would be appreciably different. Again, the sample and target might have different surface structures, such as those of matt paints, gloss paints or pile carpets. In these cases the tristimulus values could be identical but the surfaces would look appreciably different. Whenever possible, sample and target should have the same surface structure.

It is usually important that the colors within one batch and between repeat batches of material match closely. In these cases the samples will be of the same material, and the same dyes or pigments will have been used. It would be natural to measure all the samples using the same instrument and (if a spectrophotometer was used) to calculate the tristimulus values for the same standard observer and standard illuminant. Under these conditions, if the tristimulus values for a sample are very close to those for the standard, the sample will be a close visual match to the standard for any normal observer viewing under a light source roughly equivalent to the standard illuminant used to calculate the tristimulus values.

(Exceptions can occur, for example, with metallic paints, where the appearance depends very much on the illuminating and viewing geometries.) If the variation of appearance with, say, viewing angle is different for the sample and for the standard, they may not match visually, although according to the instrumental results (obtained with a different viewing angle) they should be a good match. In many ways the chief limitation of the CIE

system is its non-uniformity. Equal changes in  $x$ ,  $y$  or  $Y$  do not correspond to the same perceived difference.

Many attempts have been made to provide a more uniform system. In each case the basic approach has been to start with the tristimulus values or chromaticity coordinates from the CIE system, and to transform these in some way to give a more uniform system. The end result is a color difference formula which, for a pair of samples, gives a number that is intended to be proportional to the difference seen.

## **2.3 Color Measurements**

Color measurement instrumentation is very varied. It varies from large top of the range scanning spectrophotometers, maybe coupled with reflectance accessories through bench-top instruments, to hand-held small portable instruments. The instrumentation may be set up to make a variety of different color measurements or to only make measurements on one particular color scale. *Color measurements* are essentially measurements of visible light shining through an object or visible light reflected from an object. There are many optical configurations to achieve the measurement of transmitted and reflected color. There are standard or recommended geometries for making these measurements and nomenclature for describing them and the variations that are possible. The choice of measurement geometry usually depends on the properties of the artifact to be measured, but maybe due to historical use within a particular industry or product area.

### **2.3.1. Types of color measurement**

Color measurement divides into two areas, reflectance and transmittance. Each of these can be further divided into diffuse and regular. Regular means the light travels through undeviated or is reflected off the sample in a mirror-like way without change of frequency, and diffuse means that the light is scattered as it is reflected by, or transmitted through, a sample, again without change of frequency of the light. The total reflectance or transmittance is the sum of the regular and diffuse parts. The geometry of illumination and detection with respect to the sample is used to define the measurement geometry. Reflectance and transmittance are defined in terms of the ratio of the incident light to the

reflected or transmitted light. These are special cases of the more general definitions of radiance or luminance factor, which are defined in terms of measurements made for a specific illumination and detection geometry in comparison to the perfect reflecting diffuser identically illuminated.

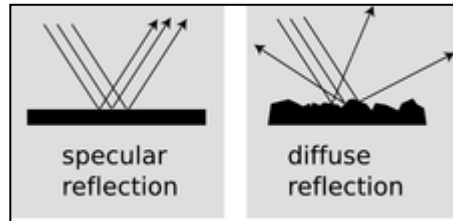


Figure 5: Diagrams of Specular and Diffuse Reflection

### 2.3.2. Regular reflectance

Regular reflectance is the regularly reflected or specular component of the illumination, i.e. light that is reflected in a mirror-like way off a surface at the same angle and in the same plane as the illumination beam. It usually has the same spectral profile as the illuminating source. When measuring color with an integrating sphere, this component is either included or excluded from the measurement. It is not usual when making color measurements to measure this component separately, as it has the same spectral profile as the illumination. Regular reflectance is usually only measured on its own when the sample has a very high regular reflectance, such as a mirror.

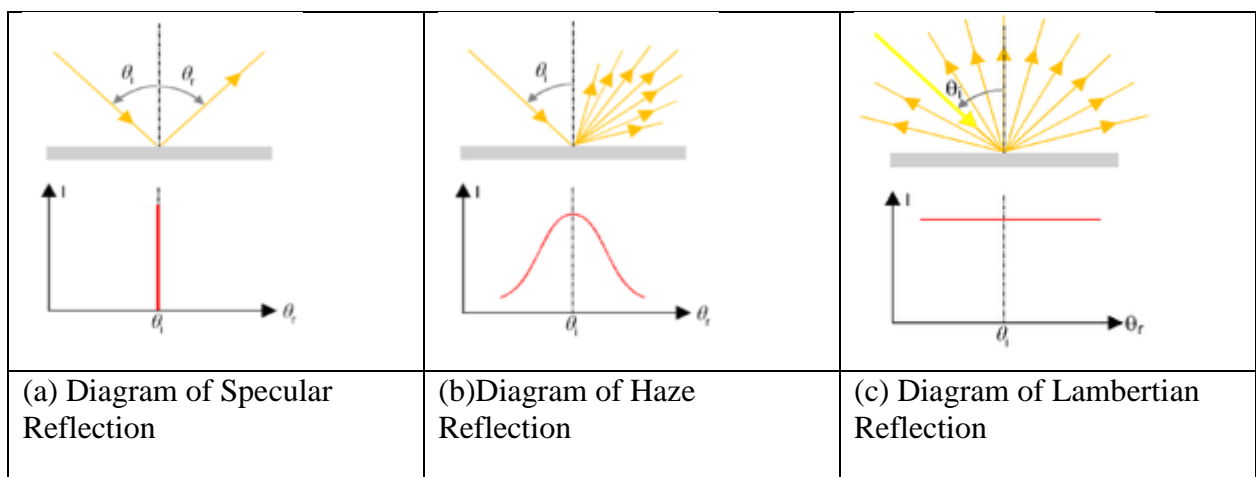


Figure 6: Regular reflectance

### **2.3.3. Diffuse reflectance**

Diffuse reflectance is probably the measurement that most people think of when referring to color measurement. This is measurement of light scattered from a surface and is most commonly measured using an instrument incorporating an integrating sphere. Quite often, the measurement referred to as diffuse reflectance by some users is not strictly the diffuse reflectance, but includes the regular component and is actually the total reflectance. The simplest measurement geometry is illumination at the sample normal or near normal and detection over the whole hemisphere, but excluding the regular or specular component.

The instrumentation could also be set up the other way, due to Helmholtz reciprocity and the reversibility of light paths, with diffuse illumination and detection at the normal or near normal. For reflectance measurements, the trade-off is between light level and the ratio of the sphere surface area to total port area. The more ports and/or the bigger the ports in a sphere, the larger the sphere needs to be. The CIE has recommended that the total area of ports in a sphere should be less than 10% of the total surface area.

### **2.3.4. Regular transmittance**

Regular transmittance is light that is undeviated as it passes through a sample. The sample may attenuate (absorb) the light but the direction is not changed. This is the normal type of light transmission such as looking through a clear pane of glass.

### **2.3.5. Diffuse transmission**

Light that does not pass through a sample in a regular way is diffuse transmission, i.e. the light direction has been changed. An example of this is the covers to lamps that spread the illumination over a larger area than would be possible without them.

### **2.3.6. Radiance factor and transmission factor**

Radiance factor and transmission factor are the fundamentals of the reflectance and transmittance measurement geometries, as the others can be made up from a series of radiance or transmittance factor measurements. At its simplest, the radiance factor refers to illumination of a sample in a specific direction, over a specific angular range, with detection at another specified direction and angular range. The most common color



measurement geometry of this type is illumination at the normal ( $0^\circ$ ) to a sample with detection at  $45^\circ$  to the sample normal (or vice versa).

## 2.4 Geometries of measurement

There are endless ways of arranging the optical system to make color measurements. The color of a sample varies, depending on the way it is measured. A sample may reflect differently depending on the illumination angle, whether the sample is translucent, the state of polarization of the illumination, the detection angular range, the way the detector measures the reflected light, etc. For example, illuminating a sample from a particular direction may not give the same result as illuminating it from all directions equally (diffusely).

For measurements made on the same sample on different instruments to be comparable they have to be made in a consistent way with regard to geometry, and also with respect to other parameters such as traceability, orientation, polarization, etc. To this end the CIE1 recommends the use of three reflectance measurement geometries: specular included, specular excluded and  $0^\circ/45^\circ$  and their reciprocal geometries. They have recommended geometric arrangements for directional, conic and integrating sphere illumination or influx angles, and detection or efflux angles. The beam cone sizes and their tolerances are defined along with descriptive nomenclature for the measurement geometry. Use of these geometries is not mandatory but it makes sharing and comparing measurements with others a possibility.

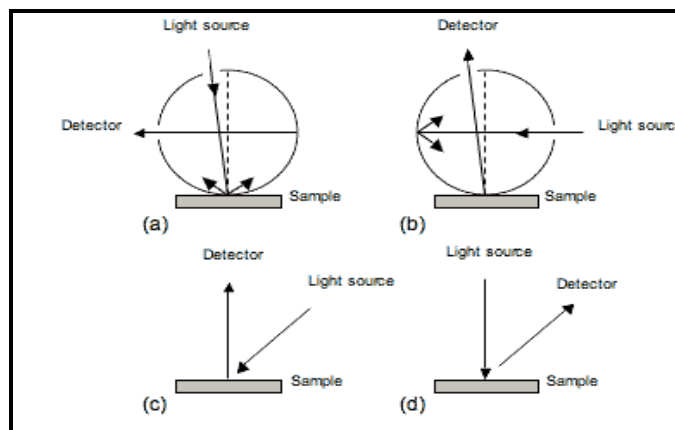


Figure 7: Simplified diagrams of the four CIE recommended geometries for color measurement.

### 2.4.1. CIE Standard Geometries-Reflectance

Recommended geometry for reflection measurements

- *Diffuse: eight-degree geometry, specular component included (di:8°)*

For di:8° geometry, it is recommended that the sample be irradiated by an integrating sphere, that the measured area be overfilled, that the area of the sampling aperture be uniformly irradiated, that it be irradiated uniformly from all directions within the hemisphere bounded by its plane, that the responsivity of the receiver be uniform over the area of the sampling aperture, that the axis of the reflected (efflux) beam be 8° off the normal to the centre of the sample, and that radiation reflected at the sampling aperture be evaluated uniformly at all directions within 5° of the axis of the collection (efflux) beam. The size of the sampling aperture, area and angular uniformity of irradiation, angular displacement of the collected (efflux) beam from the normal, and area and angular uniformity of responsivity of the receiver can affect measured values and may be standardized in the future.

- *Diffuse: eight-degree geometry, specular component excluded (de:8°)*

It is recommended that the specifications for di:8° be met, except that there be no radiation reflected in the direction of the receiver by a plane first-surface mirror at the sampling aperture and that there be no rays specularly reflected within 1° of such rays, as an allowance for instrumental scattering of stray light or misalignment. The amount of stray light specularly reflected in the direction of the receiver may affect measured values and may be standardized in the future.

- *Eight degree: diffuse geometry, specular component included (8°:di)*

It is recommended that the conditions for di:8° be met, but with the light path reversed, so the sampling aperture is irradiated under 8° and flux reflected at the sampling aperture is collected at all angles in the hemisphere bounded by the reference plane. The sampling aperture should be underfilled with radiation.

- *Eight degree: diffuse geometry, specular component excluded (8°:de)*

It is recommended that the geometric conditions for de:8° be met, but with the light path reversed. The sampling aperture should be underfilled with radiation.

- *Diffuse / diffuse geometry (d:d)*

It is recommended that for irradiation the specifications for di:8° be met, and flux reflected at the sampling aperture is collected at all angles in the hemisphere bounded by the reference plane. In this geometry the sampling aperture can be neither under filled nor overfilled.

- *Alternative diffuse geometry (d:0°)*

An alternative diffuse geometry is the strict specular excluded geometry defined when the efflux direction is along the specimen normal.

- *Forty-five degree annular / normal geometry (45°a:0°)*

It is recommended that the sampling aperture be irradiated uniformly from all directions between two right circular cones with their axes on the normal to the sampling aperture and apices at the centre of the sampling aperture, the smaller cone having a half angle of 40° and the larger of 50°. It is recommended that the receiver uniformly collects and evaluates all radiation reflected within a cone with its axis on the normal to the sampling aperture, apex at the centre of the sampling aperture, and a half angle of 5°. These angular specifications and the surface and angular uniformity of irradiation and sensing may affect measured values and may be standardized in the future.

- *Normal / forty-five degree annular geometry (0°:45°a)*

It is recommended that the angular and spatial conditions for 45°a:0° be met, with the light path reversed, so the sampling aperture is irradiated normally and reflected radiation is collected within an annulus centred at 45° to the normal.

- *Forty-five degree directional / normal geometry (45°x:0°)*

It is recommended that the angular and spatial conditions for 45°a:0° be met with the exception that irradiation is only at one azimuth angle, this excludes the specular component, but emphasizes texture and directionality.

## 2.5 Instrumental Color measurement

There are many reasons for wanting to measure color, but it is important to have a color measuring instrument that will measure what is required with the necessary accuracy. Firstly, the user needs to determine what the instrument specification is for the task. This may mean defining the spectral range, the data interval, the bandwidth, the colorimetric data required, the measurement geometry, the measurement area, the accuracy, the precision, the traceability, reference artifacts, software, export of data options, etc.

There may be a specification to meet in terms of measurement geometry, measurement area/instrument port size. Usually, the type of samples that are being measured will define the most suitable measurement geometry, but standards and common usage within certain industries will also have an influence. The CIE recommend measurement geometries and parameters for port sizes and other geometric considerations. ASTM also recommends geometries for color measurement, especially for single color scales. Special effect/appearance materials will need careful consideration as to the choice of a suitable measurement instrument. There are a number of technologies that can determine a stimulus' tristimulus values or CIELAB coordinates.

However, they all can be categorized by their number of signals from the minimum of three (one for each tristimulus value) to a maximum of 471 (one for every nanometer wavelength between 360 nm and 830 nm, the full range of each set of color-matching functions.) A key consideration is whether spectral properties are directly measured, estimated, or integrated. As the number of signals increases, an instrument changes from *colorimeter* to a *spectrometer*. When measuring materials the spectrometer is termed a *spectrophotometer*, and when measuring sources the term *spectroradiometer* is used.

Colorimeters directly measure colorimetric quantities whereas spectrometers calculate colorimetric quantities from spectral data. Various mathematical techniques are used to estimate either colorimetric or continuous spectral values. Important consideration must be given to measurements geometries of the instruments used.

**Precision** is a measure of how well an instrument repeats a measurement. **Accuracy** is a measure of how well the instrument will make measurements compared to particular standard reference materials, which should be traceable to a national standards laboratory. The instrument may come with a calibration artifact traceable to a particular national measurement institute. There may be differences in scales between national measurement institutes so the users need to be aware of the traceability route of their instruments and any with which they are comparing measurements.

### **2.5.1. Single-scale instruments**

These are instruments that are primarily for measuring a specific color measurement scale, in order to ascertain where the sample lies on the scale. These types of instruments are used in medicine, chemistry, manufacturing control, food processing, etc. These types of instruments are usually associated with measurements of a specific product such as petroleum, honey, beer, oil and chlorophyll. These are designed to assess the quality of a particular product by linking color to purity, refinement level, impurity indicator, desirability, etc. Many of these instruments measure the color of a liquid or require the product, e.g. waxes, to be measured in a liquid form. The most common instruments for this type of measurement are those from Tintometer Ltd such as the Comparator 2000/3000, PFX195, PFX880 and PFX995. Many of these instruments incorporate calibrated color standards or come with calibrated reference materials for the particular scale of interest, and can be operated as a stand-alone instrument or as a computer-controlled instrument.

### **2.5.2. Visual instruments**

Visual instruments are usually of a comparative nature. They allow a sample to be viewed under the same conditions as a reference artifact or artifacts and the user determines if they are a match. The most common of these would be a simple light box, which usually has neutral grey walls, and a choice of light sources designed to simulate recommended sources. The reference and the test samples can be viewed side by side. This is how the textile industry used to do much of its color matching. Alternative instruments are those

such as The Tintometer model F, for visual assessment of transmitting samples using the Lovibond RYBN scale.

A light source and white diffuser provide the illumination, with the viewing being done through an eyepiece. A bipartite field is presented to the user. The test sample is placed in one side of the field and the user moves neutral, red, blue and yellow glass filters into the other half of the field to match the color. The filters used will indicate the color in terms of Lovibond units. Other instruments act as comparators and glass discs of values of the single color scales mentioned above can be rotated into place to match the sample.

### **2.5.3. Hand-held/portable instruments**

Hand-held instruments come in a variety of types, from small spectrophotometers to much simpler colorimeters. Generally, these are small instruments, measuring a small area. They have the advantage that they can be Instrumental color measurement taken to the object to be measured instead of bringing the sample to the instrument. This means that finished products such as cars, vehicle interiors, large objects and interior decoration can be measured in situ without the need to remove samples for testing. The disadvantage of these types of instruments is that there are compromises in measurement performance in order to achieve portability. Sphere-based instruments will generally have a smaller size sphere than the bench top equivalent, functions available may be more limited, and data resolution is likely to be lower. If the user has a held-hand colorimeter, it may be limited to certain illuminants and observer combinations for colorimetric data. However, many have the capability to store a large number of measurements, for downloading later to a computer. The measurement uncertainty from one of these instruments is almost certainly higher than a larger bench top instrument because of these factors. In some cases the measurement geometry available is not truly one of the recommended CIE geometries, but a compromise between these and realizing a practical result. So long as the user is aware of the limitation, this type of instrument is more than adequate for a lot of color measurements.

Example instruments are Minolta spectrophotometers and colorimeters; some of these can be used to obtain displays as well as other measurements. Tintometer and X-Rite have a

range of portable  $0^\circ/45^\circ$  and integrating sphere instruments. Aventes produces the Ava-mouse, which plugs into a computer and has a similar shape and size to a computer mouse, but gives  $45^\circ/0^\circ$  data.

#### **2.5.4. Multiangle instruments**

Multiangle instruments have a lot of the features of other instrumentation, but offer several fixed angle geometries, rather than just  $0^\circ/45^\circ$  or a sphere based geometry. They are an attempt to measure appearance or special effect samples. By looking at their properties at several angles, the user can pick out the best angles for meaningful results on the sample types being investigated. These are a cheap alternative to goniometric measurements. One popular instrument of this type is the X-Rite MA68, measuring at five detection angles, and variants which have found favor with the automotive industry as they can provide useful results on metallic paints.

#### **2.5.5. Bench top instruments**

Most of the colors measuring instrument manufacturers sell more instruments of this type than any other. For reflectance measurements, these instruments generally incorporate diode array detectors in their optical systems. The light source is generally a xenon flash tube. Because of these features, measurements can be made very rapidly. Some are quite sophisticated in that they have double gratings and arrays in them, one viewing the sphere wall or reference and the other the sample, enabling them to compensate for the light source.

Others achieve this by using one array with moveable optics and two xenon flashes, one for viewing the sample and the other for viewing the sphere wall or reference. The geometry of these instruments is usually in the alternative configuration from scanning instruments. Bench-top instruments usually have diffuse or directional illumination with detection at the normal or near normal, e.g.  $d/8^\circ$  geometry. Bench-top instruments are mainly set up to perform comparisons of one sample against a reference, for example, in a dye house for matching a production sample to the required reference color. The software allows for easy comparison of samples and references. Tolerances on the closeness of color match can be

set to the user's requirements. For reflectance instruments the data resolution may vary from 5 nm at the top end through 10 nm to 20 nm. The spectral range available is also variable. All spectral instruments will include the range 400 nm to 700 nm, but the better instruments will offer wavelengths outside this range, down to 360 nm and up to 780 nm.

For transmittance instruments measurements in the range 200 nm to 800 nm plus will generally be available with at least 1 nm resolution. Spectral range and resolution are important for the type of samples to be measured. Those with sharp or rapidly changing features will require more point measurements to avoid features being smoothed out or missed. Bench-top reflectance instruments are usually supplied with a white reference standard. The user needs to be aware as to where it is traceable to. The instrument should also come with a good black reference that approximates to zero – a black trap for integrating sphere geometries and a black glass for 0°/45° geometry. Typical manufacturers are Data color, Gretag Macbeth, X-Rite, Tintometer and Analytic.

#### **2.5.6. Goniometric instruments**

Goniometric instruments are the most exciting instruments and more will become available in the future. These instruments allow light to be put onto a sample at a wide variety of angles, and then detected at a wide variety of angles, quite often over the hemisphere. This makes this type of instrument very useful when measuring special effect samples, as the best parameters in terms of illumination and detection can be chosen by the user. These instruments are very versatile, but also require a lot of specialist knowledge to operate them.

Some of this type of instrument are self-built and operated by national standards laboratories. Such instruments included the STARR at NIST and the reference reflectometer at the National Physical Laboratory (NPL). The operation of these instruments can be quite time consuming. Faster commercial instruments are available from Murakami in Japan, and Tintometer have developed a gonio apparent spectrophotometer (GASP), the first one being for NPL, UK.



### 2.5.7. Fluorimeter

This instrument is specifically designed to get round the problems of measurements on fluorescent samples without using standard illumination sources. True fluorimeters are able to illuminate and detect independently, by using two monochromatic systems, or filters in such a way that the fluorescent component can be separated from the normal reflectance or transmittance component. The overall color for any observer and illuminant combination can then be calculated.

### 2.5.8. Spectrofluorometer

The *spectrofluorometer* is an instrument which takes advantage of fluorescent properties of some compounds in order to provide information regarding their concentration and chemical environment in a sample. A certain excitation wavelength is selected, and the emission is observed either at a single wavelength or a scan is performed to record the intensity versus wavelength also called an emission spectra.

Generally spectrofluorometers use high intensity light sources to bombard a sample with as many photons as possible. This allows for the maximum number of molecules to be in the excited state at any one point in time. The light is either passed through a filter, selecting a fixed wavelength, or monochromator, which allows you to select a wavelength of interest to use as the exciting light. The emission is collected at 90 degrees to the exciting light. The emission is either passed through a filter or a monochromator before being detected by a PMT photodiode, or CCD detector. The signal can either be processed as a digital or analog output. Systems vary greatly and a few things must be considered when choosing. First is signal to noise, there are many ways to look at the signal to noise of a given system but the accepted standard is by using water Raman. Sensitivity or detection limit is another spec to look at that is how little light they can measure. The standard for this would be fluorescein in NaOH; typical values for a high end instrument are in the femtomolar range. Stray light is another big issue in these instruments. Stray light is basically how monochromatic the light is. This matters when you have a highly scattering sample,

however one can always use an excitation wavelength further away from the emission band to negate this issue or use a laser or interference filter.

### **2.5.9. Spectrophotometers**

*Spectrophotometers* are instruments that measure the reflectance from, or the transmittance through, materials as a function of wavelength. The main components of all spectrophotometers for color measurement are a source of optical radiation, an optical system for defining the geometric conditions of measurement, some means of dispersing light and a detector and signal processing system that converts light into signals suitable for analysis. Physical properties of the specimens to be measured ultimately determine instrument design. In particular, many materials are fluorescent, using fluorescent colorants or fluorescent whitening agents; this affects the design of the illumination system. The absorption and scattering characteristics of colorants lead to slowly varying reflectance's and transmittances as a function of wavelength in the visible spectrum; this affects the design of the dispersing and detector and signal processing systems.

Reflectance and transmittance are both ratios in comparison to incident light. Accordingly, any light source with sufficient power over the visible spectrum can be used for spectrophotometry. However, when a specimen is fluorescent, the spectral properties of the light source affect the final measured value. Therefore, the light source in a spectrophotometer ideally should be identical to the light of the viewing environment.

Because this ideal is impractical, most instruments use sources that attempt to match the spectral characteristics of D65 between 300 and 780 nm (ASTM E 991). Because D65 cannot practically be realized in any light booth, this practice has led to poor correlation between instrumental and visual measurements of fluorescent materials. The ultraviolet region is important to match because this is the region of excitation for fluorescent whitening agents. Common sources include incandescent (tungsten halogen) and pulsed xenon. Glass filters are used to adjust their spectral properties to simulate those of D65.

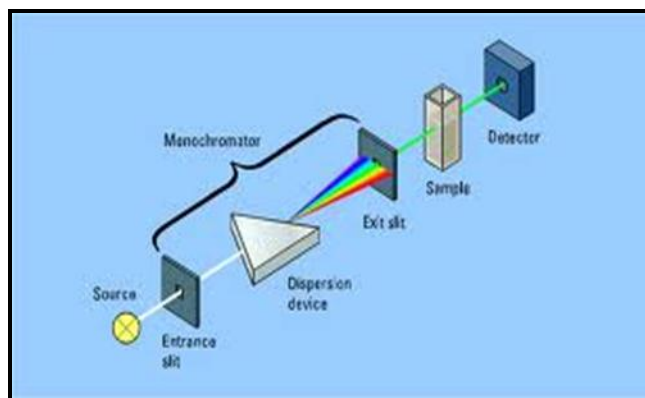


Figure 8: Visual representation of the working concept of a spectrophotometer

### 2.5.10. Inter-instrument agreement and traceability

Agreement and traceability are important issues for the user who has several color measuring instruments or who wishes to share or compare measurements with another user's instrument. If the user has several identical instruments from the same manufacturer purchased at the same time, they should agree with each other. If they are different models or have been purchased over a longer time period, the probability of good agreement is much less.

The instruments to be compared should have the same geometric specification for there to be a chance of agreement. Then the two instruments need to be traceable to the same measurement scale. *Traceability* refers to showing an unbroken link from a scale disseminated by a national measurement institute, such as NPL in the UK, NIST in the USA, BAM in Germany, etc., to the scale the instrument is using, with an appropriate uncertainty statement. The scales disseminated by the national measurement institutes are the most accurate, with the lowest uncertainties. As the scale is disseminated downwards, each level adds a further degree of uncertainty.

For two instruments from the same manufacturer, the scale to which they are traceable is likely to be the same. Most manufacturers have a master instrument to which all the instruments they produce are compared, and this instrument in turn is traceable to a national measurement institute. However, there are, at the time of writing, differences between national measurement institute scales of reflectance, and scales from national measurement institutes can change with time. National measurement institutes compare

their scales with each other, work to understand the causes of differences and then try to minimize these differences in their scales.

The best way to check that instruments are traceable to the same scale is to use an independent check, rather than relying on the scale the manufacturer has used. The easiest way to do this is to purchase some calibrated color transfer standards from a national measurement institute or from an ISO 17025 accredited laboratory. Suitable accredited laboratories are those that are UKAS or equivalently accredited. The standards can then be measured using your own instruments and the results compared to the calibration values for the standards. If they do not agree within the combination of the uncertainty of the measurement and the uncertainty of the calibration of the standard, appropriate corrections can be calculated to correct the measurements on your instruments.

Another issue that raises itself here is the different way in which each manufacturer's instrument communicates the measurement results. This is usually in some proprietary way that is incompatible with anyone else's way. The NPL, The Society of Dyers and Colorists and The University of Leeds with others, mainly in the UK, are working with instrument manufacturers and users to define a format for the exchange of colorimetric data. This format is HTML based. This means that the data files produced are totally text based. The format has been defined and is currently being proposed as an ISO standard. The aim is for instrument manufacturers and software writers to incorporate the format into instruments and into their control software in order to make it easy to import and export measurement results so that measurements can be compared. This, along with suitable traceability, makes it possible for a particular color to be specified numerically for matching, without needing to send a sample of the color for measurement, and without being restricted to one manufacturer in the choice of instrument for measuring the samples.

## **2.6 Fluorescent Colorants**

While perceived colors of all objects depend on the nature of the light, the object, and the observer, there are some special colorants whose presence makes these interactions more complicated than most. These are the fluorescent colorants, both white and chromatic, the flake pigments such as aluminum and zinc, and pearlescent and interference pigments such as titanium dioxide coated mica.

Fluorescent colorants include fluorescent whitening agents (FWAs) and chromatic fluorescent dyes and pigments. All these materials absorb light at one wavelength and emit some of it at longer wavelengths. The fluorescent whiteners absorb ultraviolet radiation (at less than 380 nm) and emit it in the visible region. For this reason the amount of light at the wavelength of emission can exceed 100% of the incident light of that wavelength. It is the conversion of invisible radiation to visible light that gives FWAs the ability to make materials look “whiter than white” (Siegrist 1987). What happens is that such a material radiates more visible light than is incident on it, making it look brighter than a non-fluorescent material that, at best, can only reflect all the visible light that falls on it.

To obtain this effect, the light source must contain energy at the appropriate wavelengths in the ultraviolet range to excite the emission in the visible. Lacking the proper spectral power distribution, we cannot obtain fluorescent emission. It is evident that no more radiation comes off the sample that has fallen on it. Chromatic fluorescent colorants are used for safety and signal purposes as well as for advertising and decoration. Fabrics colored using fluorescent dyes are quite popular and considerably extend color gamut in comparison to traditional dyes. Chromatic fluorescent colorants differ from FWAs in that their wavelengths of both excitation and emission are in the visible region. This concept is best described by Jablonsky's diagram below:

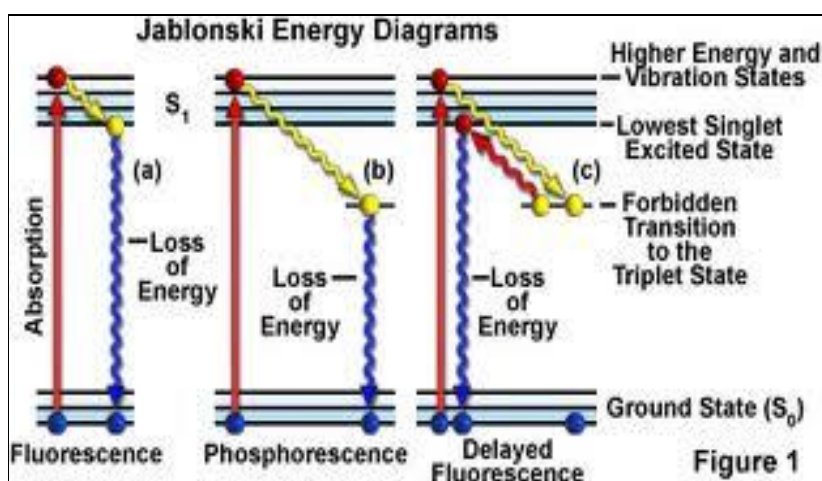


Figure 9: Representation of Jablonski Energy Diagrams

A Jablonski diagram is basically an energy diagram, arranged with energy on a vertical axis. The energy levels can be quantitatively denoted, but most of these diagrams use energy levels schematically. The rest of the diagram is arranged into columns. Every column usually represents a specific spin multiplicity for a particular species. However, some diagrams divide energy levels within the same spin multiplicity into different columns. Within each column, horizontal lines represent Eigen states for that particular molecule.

Bold horizontal lines are representations of the limits of electronic energy states. Within each electronic energy state are multiple vibronic energy states that may be coupled with the electronic state. Usually only a portion of these vibrational Eigen states are represented due to the massive number of possible vibrations in a molecule. Each of these vibrational energy states can be subdivided even further into rotational energy levels; however, typical Jablonski diagrams omit such intense levels of detail. As electronic energy states increase, the difference in energy becomes continually less, eventually becoming a continuum that can be approached with classical mechanics. Additionally, as the electronic energy levels get closer together, the overlap of vibronic energy levels increases.

Through the use of straight and curved lines, these figures show transitions between Eigen states that occur from the exposure of a molecule to a particular wavelength of light. Straight lines show the conversion between a photon of light and the energy of an electron. Curved lines show transitions of electrons without any interaction with light. Within a Jablonski diagram several different pathways show how an electron may accept and then dissipate the energy from a photon of a particular wavelength. Thus, most diagrams start with arrows going from the ground electronic state and finish with arrows going to the ground electronic state.

### **2.6.1. Absorbance**

The first transition in most Jablonski diagrams is the absorbance of a photon of a particular energy by the molecule of interest. This is indicated by a straight arrow pointing up. Absorbance is the method by which an electron is excited from a lower energy level to a higher energy level. The energy of the photon is transferred to the particular electron.

Those electron then transitions to a different Eigen state corresponding to the amount of energy transferred. Only certain wavelengths of light are possible for absorbance, that is, wavelengths that have energies that correspond to the energy difference between two different Eigen states of the particular molecule. Absorbance is a very fast transition, on the order of 10-15seconds. Most Jablonski diagrams, however, do not indicate a time scale for the phenomenon being indicated. This transition will usually occur from the lowest (ground) electronic state due to the statistical mechanical issue of most electrons occupying a low lying state at reasonable temperatures. There is a Boltzmann distribution of electrons within these low lying levels, based on the energy available to the molecules. This energy available is a function of the Boltzmann's constant and the temperature of the system. These low lying electrons will transition to an excited electronic state as well as some excited vibrational state.

### **2.6.2. Vibrational Relaxation and Internal Conversion**

Once an electron is excited, there is a multitude of ways that energy may be dissipated. The first is through vibrational relaxation, a non-radioactive process. This is indicated on the Jablonski diagram as a curved arrow between vibrational levels. Vibrational relaxation is where the energy deposited by the photon into the electron is given away to other vibrational modes as kinetic energy. This kinetic energy may stay within the same molecule, or it may be transferred to other molecules around the excited molecule, largely depending on the phase of the probed sample. This process is also very fast, between  $10^{-14}$  and  $10^{-11}$  seconds. Since this is a very fast transition, it is extremely likely to occur immediately following absorbance. This relaxation occurs between vibrational levels, so generally electrons will not change from one electronic level to another through this method.

However, if vibrational energy levels strongly overlap electronic energy levels, a possibility exists that the excited electron can transition from a vibration level in one electronic state to another vibration level in a lower electronic state. This process is called internal conversion and mechanistically is identical to vibrational relaxation. It is also indicated as a curved line on a Jablonski diagram, between two vibrational levels in different electronic states. Internal Conversion occurs because of the overlap of vibrational

and electronic energy states. As energies increase, the manifold of vibrational and electronic Eigen states becomes ever closer distributed.

At energy levels greater than the first excited state, the manifold of vibrational energy levels strongly overlaps with the electronic levels. This overlap gives a higher degree of probability that the electron can transition between vibrational levels that will lower the electronic state. Internal conversion occurs in the same time frame as vibrational relaxation, therefore, is a very likely way for molecules to dissipate energy from light perturbation. However, due to a lack of vibrational and electronic energy state overlap and a large energy difference between the ground state and first excited state, internal conversion is very slow for an electron to return to the ground state. This slow return to the ground state lets other transitive processes compete with internal conversion at the first electronically excited state. Both vibrational relaxation and internal conversion occur in most perturbations, yet are seldom the final transition.

### **2.6.3. Fluorescence**

Another pathway for molecules to deal with energy received from photons is to emit a photon. This is termed fluorescence. It is indicated on a Jablonski diagram as a straight line going down on the energy axis between electronic states. Fluorescence is a slow process on the order of  $10^{-9}$  to  $10^{-7}$  seconds; therefore, it is not a very likely path for an electron to dissipate energy especially at electronic energy states higher than the first excited state. While this transition is slow, it is an allowed transition with the electron staying in the same multiplicity manifold. Fluorescence is most often observed between the first excited electron state and the ground state for any particular molecule because at higher energies it is more likely that energy will be dissipated through internal conversion and vibrational relaxation.

At the first excited state, fluorescence can compete in regard to timescales with other non-radioactive processes. The energy of the photon emitted in fluorescence is the same energy as the difference between the Eigen states of the transition; however, the energy of fluorescent photons is always less than that of the exciting photons. This difference is because energy is lost in internal conversion and vibrational relaxation, where it is transferred away from the electron. Due to the large number of vibrational levels that can



be coupled into the transition between electronic states, measured emission is usually distributed over a range of wavelengths.

#### **2.6.4. Intersystem Crossing**

Yet another path a molecule may take in the dissipation of energy is called intersystem crossing. This is where the electron changes spin multiplicity from an excited singlet state to an excited triplet state. It is indicated by a horizontal, curved arrow from one column to another. This is the slowest process in the Jablonski diagram, several orders of magnitude slower than fluorescence. This slow transition is a forbidden transition, that is, a transition that based strictly on electronic selection rules should not happen. However, by coupling vibrational factors into the selection rules, the transition becomes weakly allowed and able to compete with the time scale of fluorescence. Intersystem crossing leads to several interesting routes back to the ground electronic state. One direct transition is phosphorescence, where a radioactive transition from an excited triplet state to a singlet ground state occurs. This is also a very slow, forbidden transition. Another possibility is delayed fluorescence, the transition back to the first excited singlet level, leading to the emitting transition to the ground electronic state. Other non-emitting transitions from excited state to ground state exist and account for the majority of molecules not exhibiting fluorescence or phosphorescent behavior. One process is the energy transfer between molecules through molecular collisions. Another path is through quenching, energy transfer between molecules through overlap in absorption and fluorescence spectrums. These are non-emitting processes that will compete with fluorescence as the molecule relaxes back down to the ground electronic state. In a Jablonski diagram, each of these processes is indicated with a curved line going down to on the energy scale.

#### **2.6.5. Dyes**

**Xanthene dyes** can be identified by a common structural feature shown below. They are obtained by condensing phenols with phthalic anhydride in the presence of zinc chloride, sulphuric acid, or anhydrous oxalic acid. Examples of this class are fluorescein, eosin, and rhodamine B.

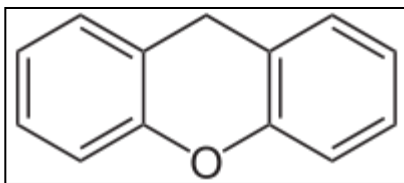


Figure 10: Chemical Structure of Xanthene

**Fluorescein:** It is prepared by heating resorcinol (2 molecules) and phthalic anhydride (1 molecule) with zinc chloride at 190°C.

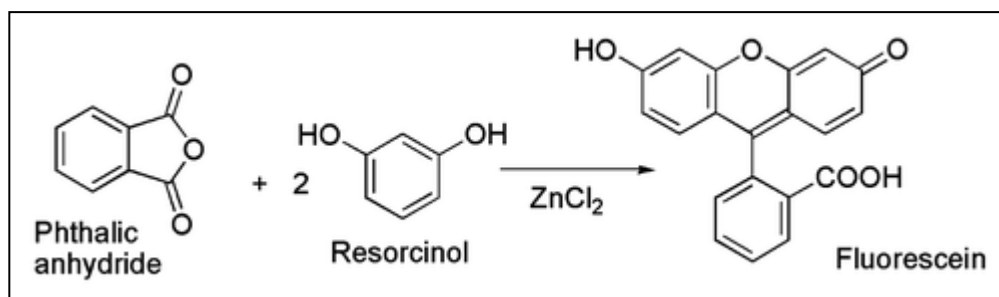


Figure 11: Chemical formation of Fluorescein Dye.

Fluorescein is of no value as a dye. It is red powder, which is insoluble in water. A dilute solution of fluorescein in sodium hydroxide gives a strong yellow-green fluorescence when exposed to light. It is used to trace pollution of water supplies by sewerage, since if a small quantity of it is put in at the suspected source of pollution, the color will be detectable at some distance from the source, even after extensive dilution. Fluorescein is also used as a mild purgative.

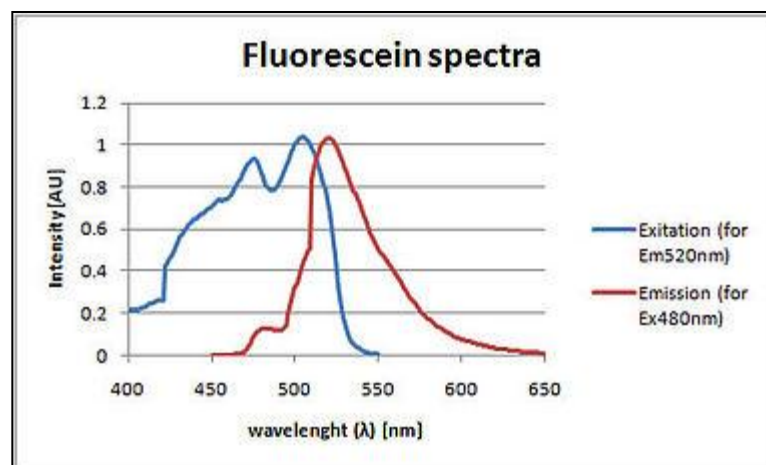


Figure 12: Absorption and emission spectra of fluorescein

**Eosin:** It is the sodium salt of tetrabromofluorescein. Eosin is obtained by brominating fluorescein in glacial acetic acid to give tetrabromofluorescein. Treatment of this with sodium hydroxide yields the dye.

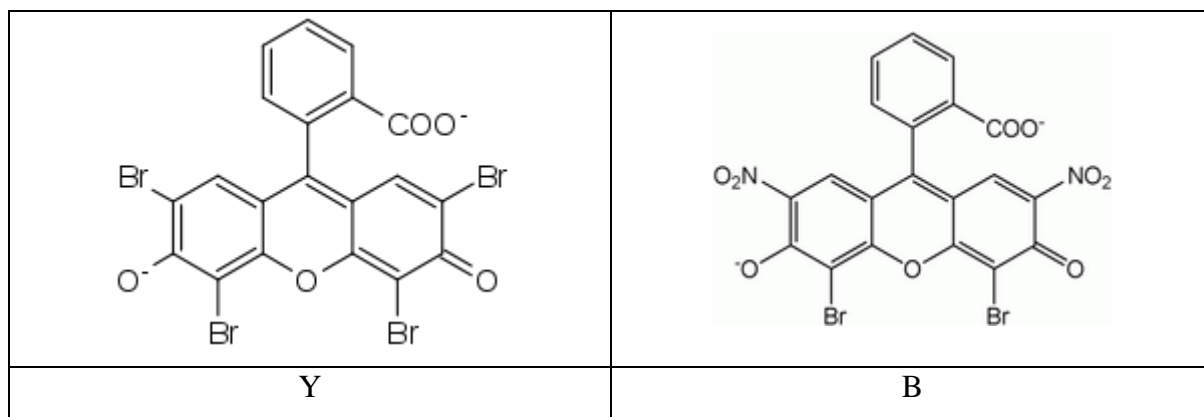


Figure 13: Eosin Y and B respectively

Eosin is a red solid, which is soluble in water. Alkaline solutions of eosin show a yellow-green fluorescence. Eosin is used for dyeing wool, silk, and paper; for making red ink and as the coloring matter in lipsticks and nail polishes. There are actually two very closely related compounds commonly referred to as eosin. Most often used is eosin Y (also known as eosin Y, eosin yellowish, Acid Red 87, C.I. 45380, bromoeosine, bromofluoresceic acid, D&C Red No. 22); it has a very slightly yellowish cast. The other eosin compound is eosin B (eosin bluish, Acid Red 91, C.I. 45400, Saffrosine, Eosin Scarlet, or imperial red); it has

a very faint bluish cast. The two dyes are interchangeable, and the use of one or the other is a matter of preference and tradition. Eosin Y is a tetrabromo derivate of fluorescein. Eosin B is a dibromo dinitro derivate of fluorescein.

## **2.7 High Visibility Warning Clothing**

Regulations for the design and use of High-visibility warning clothing vary among countries. The performance of the conspicuous materials to be used in “High visibility clothing” is specified together with minimum areas and placement of the materials. Conspicuity is enhanced by high contrast between the clothing and the ambient background against which it is seen; and by larger areas of conspicuous materials specified. Three areas of background and combined performance material colors are defined in an appropriate manner or clothing material, all of which will confer conspicuity against most backgrounds found in urban and rural situations in daylight. However, users should consider the prevailing ambient background in which protection is required and select the color that provides the preferred contrast.

Two classes of separate performance retro reflective materials are included. Higher levels of retro reflective provide greater contrast and visibility of warning clothing when seen in headlights during darkness. When greater conspicuity is required the higher class of retro reflecting material should be used. Three classes of warning clothing are specified in terms of minimum areas of the materials to be incorporated. Whilst the area comprising clothing is obviously dictated by the type of clothing and also the size of the wearer, it should be noted that class 3 clothing offers greater conspicuity against most urban and rural backgrounds than class 2 garments which in turn are significantly superior to class 1 clothing.

Standards specifies requirements for clothing capable of signaling the user’s presence visually, intended to provide conspicuity of the user in hazardous situations under any light conditions by day and under illumination by vehicle headlights in the dark. Performance requirements are included for color and retro reflection as well as for the minimum areas and for the disposition of materials. Test methods ensure minimum level of protection is

maintained when the garments are subjected to care procedures. This standard gives requirements for very high visibility clothing during risk-related situations for safety purposes.

### **2.7.1. Purpose**

The high visibility risk-related clothing is for enhancing the visibility and safety of pedestrians, cyclists, and workers at the applicable location/situation. Performance Level guidelines are identified with corresponding recommendations for selection based on risk hazards, such as complex backgrounds, type of vehicular traffic, and speeds encountered.

## **Compliance**

Manufacturers of high visibility risk-related clothing, apparel, and headwear shall verify that the clothing and the material used in manufacturing the clothing comply with this standard. All certificates and test reports that verify the performance of materials used in manufacturing the finished item shall be retained by the manufacturer and be made available to ensure that all items labeled as meeting this standard have completed all of the testing and certification required by the standard. Manufacturers of the finished items shall certify or self-certify compliance that all garment design requirements are achieved to meet requirements of Section 7 in their entirety.

### **2.7.2. Types, Levels, Classes and Colors**

#### **2.7.2.1 Garment Types**

High visibility risk-related clothing includes, but is not limited to ponchos, vests, waistcoats, harness, jackets, trousers, coveralls, and headgears, etc.

#### **2.7.2.2 Visibility Performance Levels**

Three Levels of performance in each garment are defined based on different minimum areas of retro reflective, fluorescent and/or area performance and/or other color background materials. This involves with consideration of the factors which may affect an observer's ability to detect that a person is present. Each of these performance Classes and Levels will provide the observer the needs both to perceive and to recognize the wearer early and then

needs to be able to take appropriate avoidance action. Users should select the required Level of Performance based on location/situation of the risk environment where the protection afforded by clothing to this standard is required.

- **Performance Level 1** is for pedestrians or pedestrian workers used in but not limited to urban street, airport, or parking lots where predominant vehicles are passenger cars, pickups, vans, and small trucks.
- **Performance Level 2** is for cyclists traveling or professionals working on rural roadways, where the traffic includes passenger cars, pickups, vans, small trucks, full size trucks, and buses. Photometric performance of Level 2 must also meet all requirements of Level 1.
- **Performance Level 3** is for motor vehicle operators traveling on or professional working on highways with all kinds of vehicles. Photometric performance of Level 3 must also meet all requirements of Level 2.

### **2.7.2.3 Visibility Performance Classes**

Four Classes of performance are defined based on different use of the high visibility risk-related clothing. This will involve consideration of the activity which may affect an observer's ability to detect that the user is present. Each Class will provide the observer the ability to perceive and recognize the wearer early, that the observer is able to take appropriate avoidance action. Users should select the Class of Application based on the activity the user is partaking in, so that the protection offered by the clothing provides sufficient protection.

An activity analysis for the application is suggested to determine the appropriate Performance Class. Each type of high visibility risk-related clothing is classified based on the Level of conspicuity and the Class of application described here below:

Trousers or pants with reflective panels are assumed to be worn in combination with other tops. The reflective and background areas could be counted in front, side, and rear views. The reflective area on reflective headgears is considered to have the same visibility effect as the shoulder area.

- **Performance Class 1** is for pedestrians or pedestrian workers who are normally standing in upright position, alert to incoming vehicles, and need to be visible by vehicles from the front and back directions.
- **Performance Class 2** is for pedestrians or pedestrian workers, who are not always alert to incoming vehicles, who need to bend down facing incoming traffic, and need to be visible by vehicles from the front, back, and top directions.
- **Performance Class 3** is for pedestrians or pedestrian workers who need to be visible in 360° horizontally and 180° vertically, who need to be visible by incoming traffic all the times, and seldom bend over. When these users bend over, they will be alert to incoming traffic and bend facing towards the traffic so that they are visible from the top of their shoulders. The garment should be made up of high-visibility material visible on all sides, as it is difficult to foresee from which direction the user will be approached by traffic.
- **Performance Class 4** is for cyclists or professionals working, who need to bend down frequently, requiring to be visible by oncoming traffic at all times from 360° horizontally and 360° vertically. The garment should be made up of high-visibility material visible from all viewing direction, as it is difficult to foresee from which direction the user will be approached by traffic in all directions.

#### **2.7.2.4 Color Selection**

The color of the background material shall stand out from the urban environment where the high visibility warning clothing is applicable. For the clothing fluorescent color is selected, the chromaticity shall lie within one of the chromaticity coordinates defined in Table 1 and also the luminance factor and the background material area shall exceed the corresponding minimum in Table 1.

Table 1: Color requirements for background and area performance

Color	Chromaticity coordinates		Mini-mum Luminance Factor $\beta_{min}$	Mini-mum Area $cm^2/(in^2)$
	X	y		
Fluorescent lime-yellow	0.358	0.638	0.70	5,000 / (775)
	0.329	0.528		
	0.398	0.452		
	0.460	0.540		
Fluorescent orange-red	0.483	0.384	0.25	5,000 / (775)
	0.593	0.408		
	0.690	0.310		
	0.535	0.319		

### 2.7.3. Test methods - High Visibility Material Properties

#### 2.7.3.1 Sampling and conditioning

- a) *Specimens*: Samples for testing shall be taken from original garment or from material or materials as used in the finished garment
- b) *Specimens preparation*: Specimens must be washed the number of cycles according to the care label.
- c) *Number of tests*: Unless otherwise specified, one specimen of each material must be tested and must comply with the minimum requirements.
- d) *Conditioning of specimens*: The specimens shall be conditioned for at least 24 h at  $(20 \pm 2) ^\circ C$  and  $(65 \pm 5) \%$  relative humidity. If the test is carried out in other conditions, the test shall begin within 5 min after withdrawal from the conditioning atmosphere. For tropical or subtropical countries, the specimens shall be conditioned for at least 24 h and tested at  $(27 \pm 2) ^\circ C$  and  $(65 \pm 5) \%$  relative humidity.



### **2.7.3.2 Determination of Color**

The color shall be measured in accordance with the procedures defined in CIE 15, using an instrument with polychromatic illumination (D85 simulator). The instrument shall have (45°a:0°) or (0°:45°a) illuminating and viewing geometry as defined in CIE 15. The quality of irradiating instrument light source should be more than category BC (CIELAB) estimated by ISO 23603/CIE S012 method. The color coordinates shall be determined using CIE standard illuminant D65 and 2° standard observer. The specimen shall be measured with a single layer including any backing or lining used in its constructions and backing by a black underlay with a reflectance of less than 0.04. At least eight (8) measurements shall be carried out at 45° incremental steps about the measurement axis and the mean value shall be given as test result. Note: If the instrument is known to be either of the annular or circumferential type then only a single measurement may be required.

### **2.7.3.3 Color Fastness to light of background material and all non-fluorescent material layers after test exposure**

The color after exposure shall be within the areas defined by the coordinates in Table 1 for background materials and area performance materials and its luminance factor shall exceed the minimum value for the luminance factor of the color that is obtained on exposure to xenon light e. g. a fluorescent red is acceptable if after exposure to xenon light its color-coordinates are within the tolerated area for orange-red and if its luminance factor is higher than 0, 4. The exposure of the test sample shall be performed according to ISO 105-B02:1994, method 3.

Exposure shall continue until the blue scale control standard number 5 has changed to step 3 for red and orange-red materials and for yellow materials the blue scale control standard number 4 has changed to step 4 of the grey scale. If the color can change from one color box to another, this shall be mentioned in the instructions for use. The color fastness (dry) when determined in accordance with ISO 105-A02 shall be at least step 4 of the grey scale. The test shall be conducted in accordance with ISO 105-X12.

### **2.7.3.4 Color Fastness to Perspiration**

The color fastness when determined in accordance with ISO 105-A02 shall be at least step 4 of the grey scale for the color change of the specimen; and when determined in

accordance with ISO 105-A03 at least step 3 with respect to staining. The test shall be conducted in accordance with ISO 105-E04.

### **2.7.3.5 Washing According to Care Label**

When the care label in the garment indicates that it is suitable for washing, the retro reflective material shall meet the minimum performance requirements after a minimum of five washing cycles. The test samples shall be washed in accordance with ISO 6330:2000, Textiles – Domestic washing and drying procedures for textile testing, Method 2A. The specified wash cycle shall be applied to the test sample for the number of times stated in the label. After the last wash cycle the samples shall be flat dried, stress free, at  $50 \pm 5^{\circ}\text{C}$  ( $122 \pm 5^{\circ}\text{F}$ ), according to ISO 2330 C.

### **2.7.4. Color Fastness**

Preparation of the specimen material shall be done in accordance with ASTM D1776 –90, Standard Practice for Conditioning Textiles for Testing, according to the care recommendation of the garment. The enclosed carbon arc apparatus is also described in JIS L 0842 ASTM G 1155 and AATCC Test Method 16-2001, Textiles - Colorfastness to Light (Test Option 3) - Xenon Arc Lamp, Continuous Light. Expose the materials to 40 AATCC Fading Units. The light fastness of the test sample shall be determined in accordance with AATCC 16-1998, Textiles – Colorfastness to Light (Test Option 3) – Xenon Arc Lamp, Continuous Light. Expose the materials to 40 AATCC Fading Units ( $170 \text{ KJ/m}^2@420\text{nm}$ ).

#### **2.7.4.1 Colorfastness to Perspiration**

The color fastness to perspiration shall be at least grade 4.0 by the Gray Scale for Color Change and at least a grade 3.0 by the Gray Scale for Staining in accordance with AATCC 15-2002, Textiles - Tests for colorfastness - colorfastness to Perspiration. The color fastness when determined in accordance with ISO 105-A02 shall be at least step 4 of the grey scale for the color change of the specimen; and when determined in accordance with ISO 105-A03 at least step 3 with respect to staining. The test shall be conducted in

accordance with ISO 105-E04. Requirement to change in color shade applies only to fluorescent colors

#### **2.7.4.2 Colorfastness — When Laundered, Dry-cleaned, Hypochlorite Bleached and Hot Pressed**

When the care label requirements are as specified in Table 6.3.1 and Table 6.3.2 the colorfastness shall be determined in accordance with the performance requirements and test methods stated in Table 6.5.1. Specimens shall be line dried at a temperature not exceeding 60° C (140° F) with parts in contact only at the lines of stitching. Hot-pressing: Samples shall be pressed in the dry condition only. The hot-pressing shall be tested in accordance with the ironing instructions on the garment care label, where

(.) Is a temperature of  $110 \pm 2^{\circ}$  C ( $230 \pm 2^{\circ}$  F)

(..) Is  $150 \pm 2^{\circ}$  C ( $302 \pm 2^{\circ}$  F) and

(...) is  $200 \pm 2^{\circ}$  C ( $392 \pm 2^{\circ}$  F)

The colorfastness shall be determined in accordance with ISO 105-A02 for change in color and with ISO 105-A03 for staining with the performance requirements.

#### **2.7.4.3 Wash fastness:**

Washing, Domestic and Laundering, Commercial: Accelerated (AATCC 61-1975) (ANSI L 14.81-1973): These accelerated laundering tests are designed for evaluating the wash fastness of textiles. One 45 min test approximates the color loss and/or abrasive action of five average hand, commercial, or home launderings.

## Chapter 3 Experimental Materials and Procedures

### 3.1 Materials

27 *High Visibility (fluorescent dyed) samples* were utilized as part of our experiment. They were yellow/green and red/orange in color. The fiber composition of the samples was determined by the use of Microscope, using warp/weft incision. This exercise was useful for the identification of cellulosic and animal fibers in which case only one sample was identified as having cellulosic fibers.

The next exercise was to use the melting points of fibers as means of identifying the fibers and it was found that all of the samples were polyesters with the melting point range of 220-260°C and some of these polyester fibers were blended with cotton and others had elastic fibers. Basic parameters for these samples will be depicted in a *Table 2*.



Figure 14: Instrument for measuring the melting point of yarns from a fabric

Table 2: Basic Parameters of some of the samples utilized during experimentation

	<b>Green 4A (Knitted)</b>	<b>Green 1 (Knitted)</b>	<b>Green 4B (Knitted)</b>	<b>Orange 4ZA (Knitted)</b>	<b>Orange 6 (Knitted)</b>	<b>Orange 8 (Knitted)</b>
Mass (g)	0.228	0.825	0.734	0.623	1.007	0.954
Warp Density (loops/1cm)	13	21	31	29	26	24
Weft Density (lines/1cm)	23	34	30	39	52	48
Width (mm)	30	25	31	24	56	58
Length (mm)	55	78	95	66	92	92
Thickness (mm)	0.21	0.35	0.86	0.65	0.58	0.57
Area Density (kg. m <sup>-2</sup> )	0.138	0.423	0.249	0.393	0.195	0.179
Volume Density(kg.m <sup>-3</sup> )	657.1	1208.6	289.5	604.6	336.2	313.7
Composition	PES	PES	PES	PES	PES/EL	PES/EL

*Syntapon ABA* is an efficient ecological washing, boiling and soaping agent with high surfactant and dispersing efficiency while cold or boiling. It is easily biodegradable and meets the strict requirements of reach. It fits for use with all types of fibers and their mixtures thus can also be used in industrial and civic laundries. Syntapon ABA is a blend of anionic surfactants in water. It is liquid 10 ° C and foaming agent.

Table 3: Properties of Syntapon ABA

Property	Syntapon ABA
Character	Anionic
Appearance, at 20° C	Brown Viscous Liquid
Density at 20°C, gcm <sup>-3</sup> , approx.	1.04
Color, grades	14
pH	7-9

The reason why a surfactant like Syntapon ABA wash chosen as a washing agent is that most typical laundry washing powders contain Florescent Whitening Agents (FWAs?) which will impact negatively on the results and while Syntapon ABA does not contain such agents.

**Glassware:** 1000 ml of Glass beaker was used to prepare the washing bath as well as 100 ml of Measuring Cylinder. This glass ware was vigorously cleaned prior to being used.

**Data color Eco Washing Machine and Washing Cylinders** were also used with specific desired settings.

**Dryer set at 105°C** was used to dry the samples after washing.

**Data Color Spectrophotometer** was used for the measurements of reflectance after each and every cycle of washing. The Spectrophotometer was designed for superior transmittance and haze measurements, yet it is capable of handling measurements in the reflectance mode as well. The unit delivers transmission measurements for all sample types, including regular transmittance of transparent solid and liquid samples; total and diffuse transmittance of translucent samples (i.e., those samples that are neither completely transparent nor totally opaque); and haze measurements for those slightly cloudy samples that scatter little light. The unit also handles the sequential reflectance and total-transmittance measurements required by some color-matching applications.

## 3.2 Procedure

### 3.2.1. Preparation of Washing Bath

Washing cylinders were washed thoroughly to remove any impurities that might be embedded on the cylinders. 2 g of Syntapon ABA was measured using a weighing scale and was mixed with 1000 ml of distilled water in a 1000 ml Beaker. 100 ml measuring cylinder was subsequently used to measure the amount of the bath that will be poured into washing cylinders. Samples were then inserted into the washing cylinders. It is imperative that all the glass ware is thoroughly cleaned so as to avoid tainting the results.

### 3.2.2. Washing Process

The washing cylinders with washing bath and samples were further assembled inside a Data Color Eco washing machine which was initially set with the following parameters:

- Temperature: 60° C
- Grade: 4° C/ m
- Speed: 25 rpm

One washing cycle was **1 hour** and thereafter the samples were rinsed and dried in a dryer set for 105 ° C.



Figure 15: outside and inside outlook of a Data Color Eco Washing Machine

### 3.2.3. Reflectance Measurements

After the samples were effectively dried, the reflectance was measured using a data color Spectrophotometer. Four measurements were taken for each sample and were then stored as data which would later be exported to Microsoft Excel for analysis. Basically the instrument measures the wavelengths in a visible region of spectrum i.e. (400 nm-700nm) in intervals of 10nm. That data is utilized for plotting the graphs. Also obtained were the CIE color scale values, L\* a\* b\* where maximum L would be 100 representing white and minimum L would be 0 representing black. Positive a\* is red and negative a\* is green; positive b\* is yellow and negative b\* is blue. These values will ultimately be used in calculate  $\Delta E$ , the color difference.

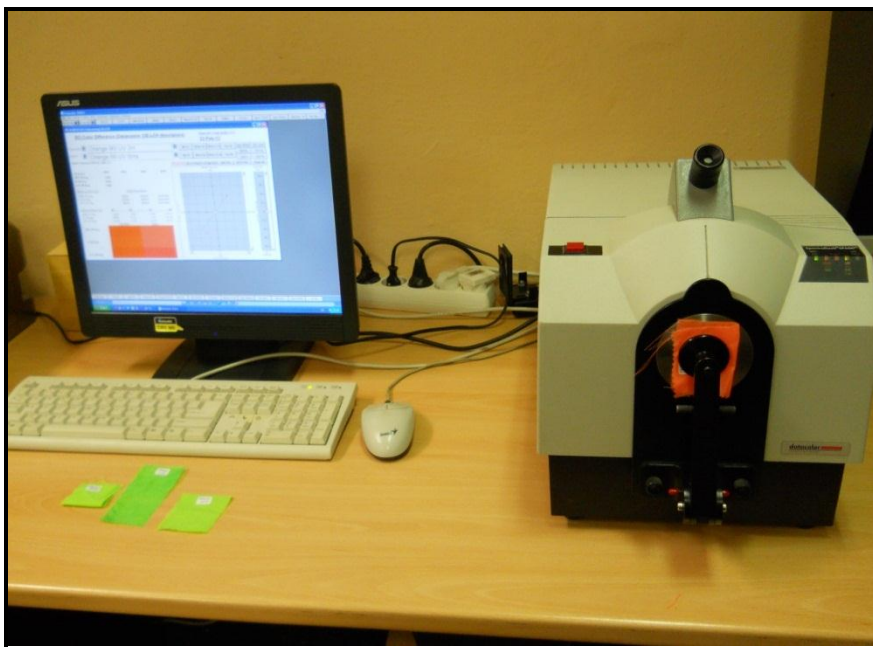


Figure 16: Full view of the Data color Spectrophotometer

*N: B The whole procedure was repeated for quite a number of hours so as to attain fading of samples effectively.*



### 3.3 Samples



Figure 17: Picture of the samples before being subjected to washing and after washing

## Chapter 4 Results and Discussion

### 4.1 Most Resistant samples from fading

#### a) Green 4B Sample

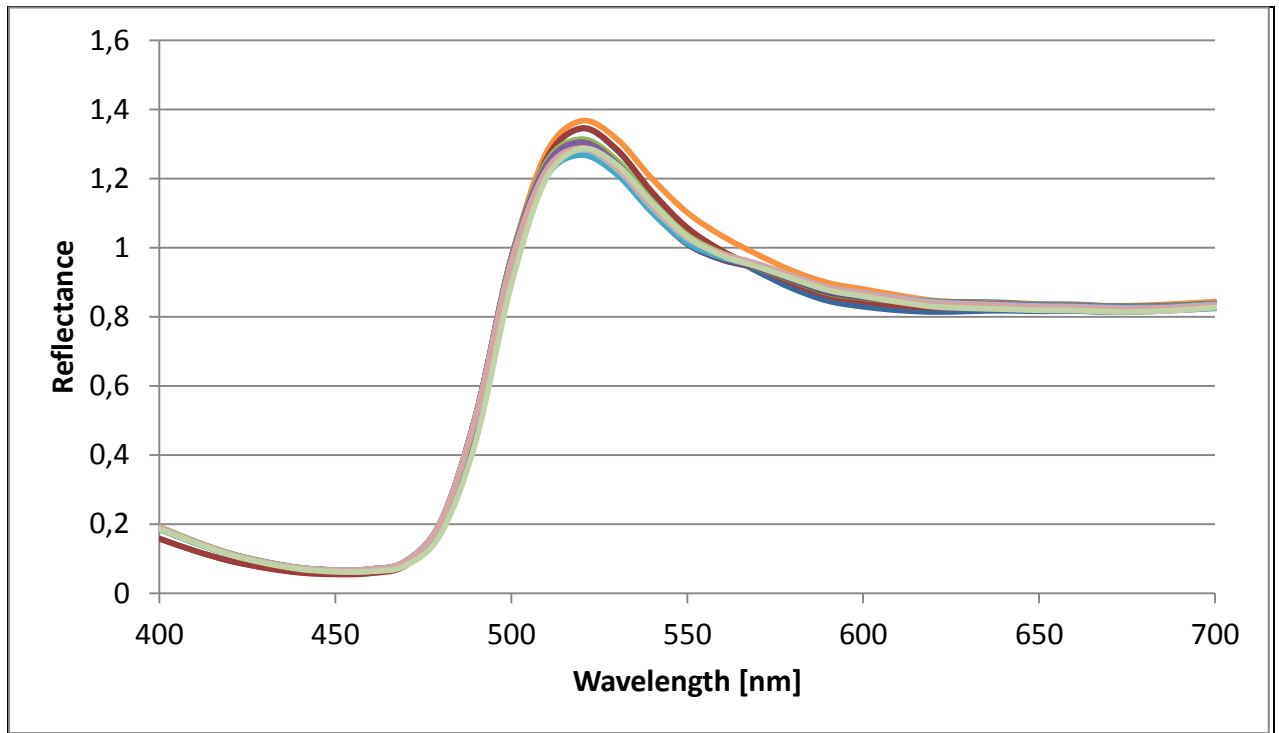


Figure 18: Green 4B Wavelength vs Reflectance

Table 4: Number of hours of washing against Maximum Reflectance

Number of Hours	Maximum Reflectance 520 nm
0	1.3668716
1	1.34448826
2	1.34559309
3	1.29178476
4	1.28705311
5	1.2958672
6	1.29584992
7	1.30351603
8	1.29857945
9	1.31391978
10	1.30514646
11	1.26779783
12	1.28410339
13	1.28825164
14	1.28581417

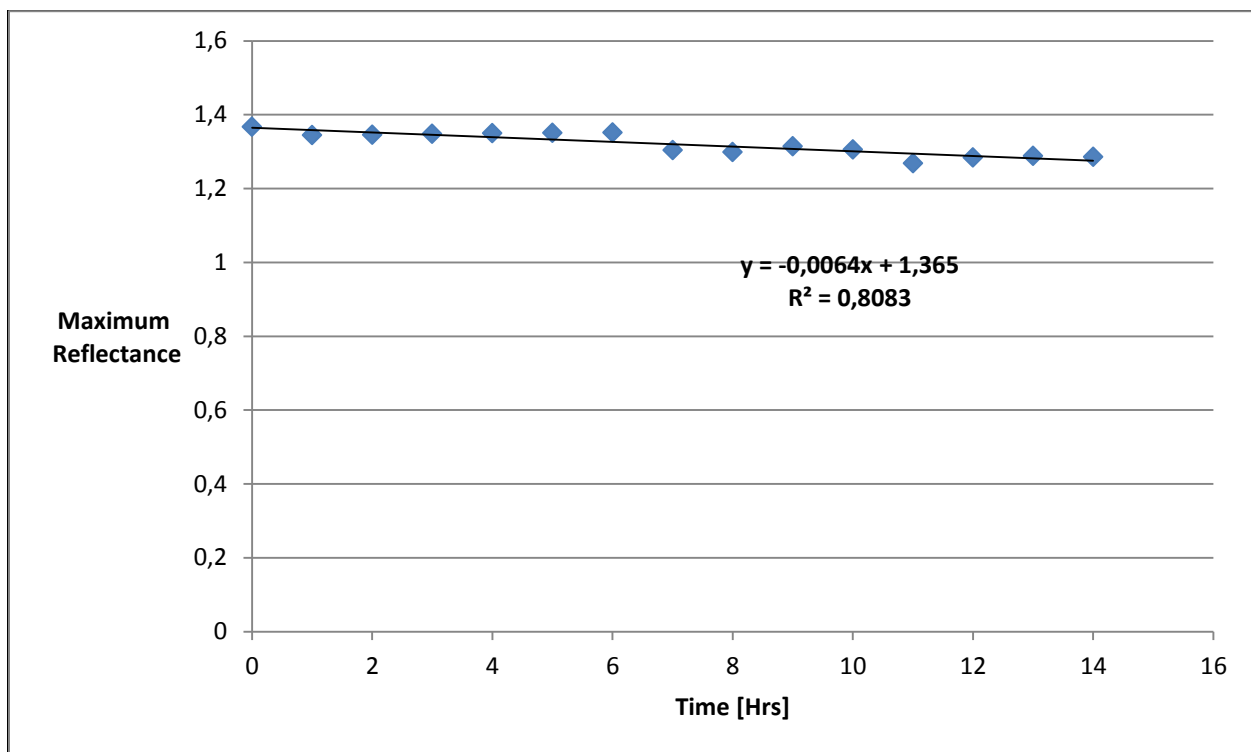


Figure 19: Green 4B Time vs

Table 5: Number of hours of washing against  $\Delta E$ 

Number of Hours	$\Delta E$
0	
1	1.82413
2	1.93245
3	2.04571
4	2.34247
5	2.83254
6	3.05547
7	3.14782
8	3.24785
9	3.18524
10	3.42996
11	3.72015
12	3.84103
13	3.95689
14	4.02156

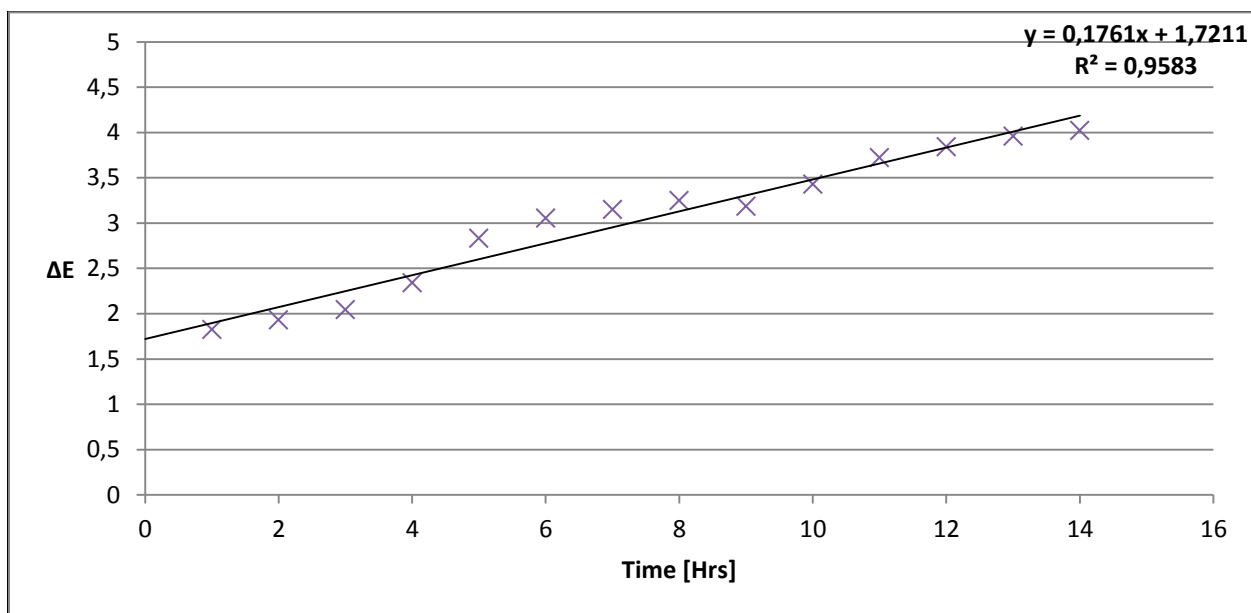


Figure 20: Green 4B Time vs ΔE

Table 6: Number of hours of washing against the percentage of color remaining

Number of Hours	% of color remaining
0	100
1	99.6073
2	97.45753
3	95.36396
4	94.99542
5	94.61411
6	91.05248
7	89.61182
8	85.91199
9	67.36895
10	57.76813
11	48.32559
12	40.62394
13	38.59724

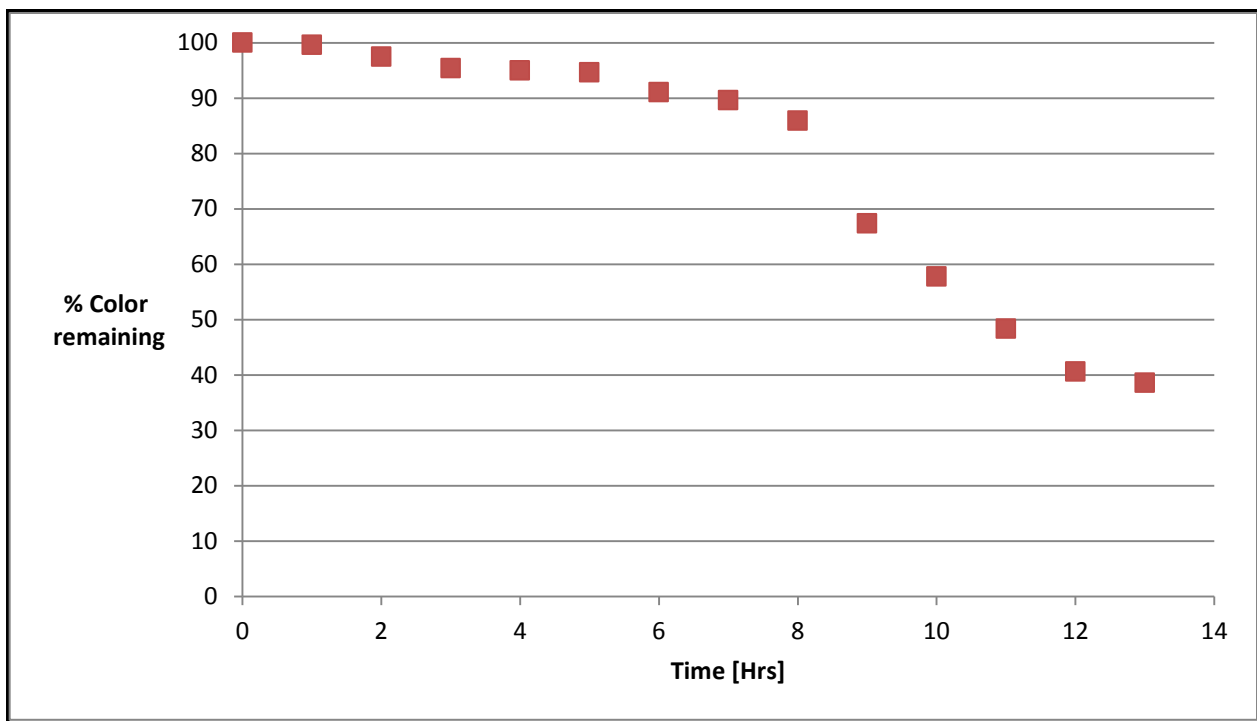


Figure 21: Green 4B Time against % of

**Green 1 Sample**

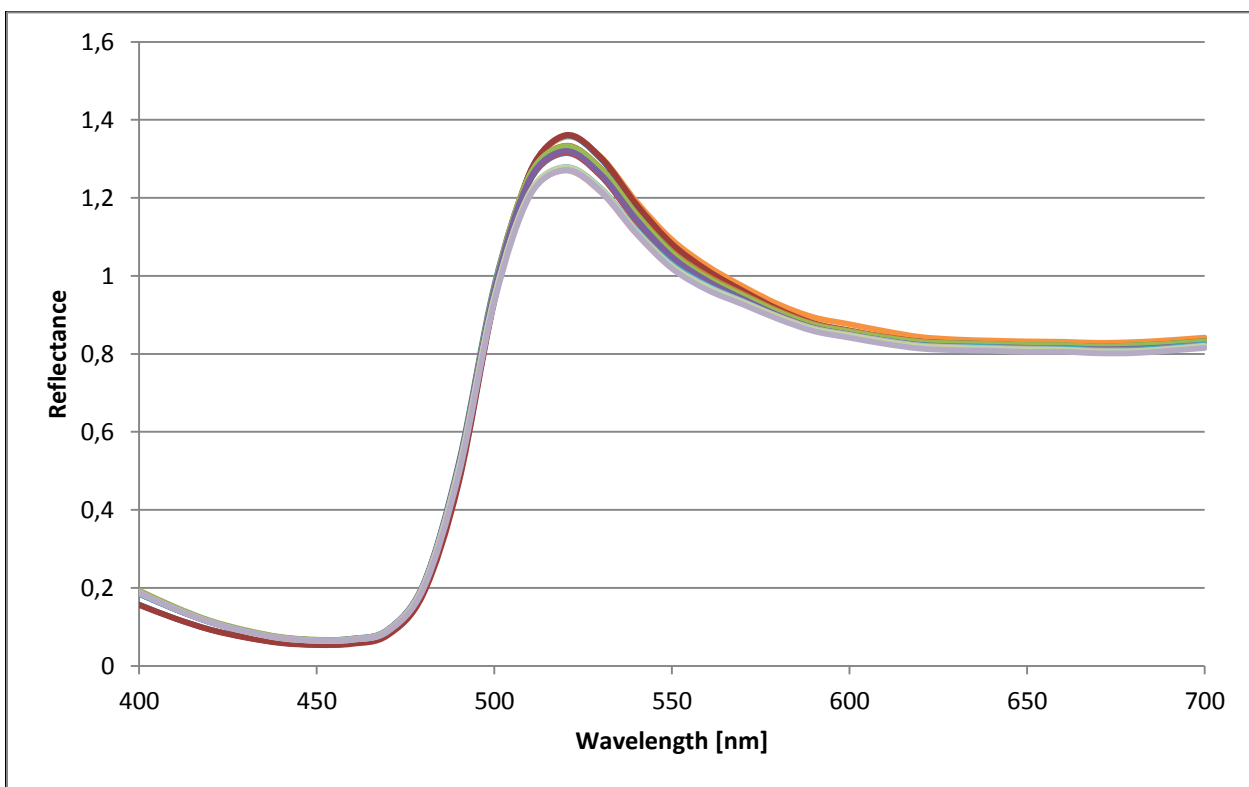


Figure 22: Green 1 Wavelength vs Reflectance

Table 7: Number of hours of washing against Maximum Reflectance

Number of Hours	Maximum Reflectance 520 nm
0	1.35639238
1	1.35918736
2	1.36095846
3	1.33362794
4	1.32121229
5	1.32615995
6	1.33310604
7	1.31458378
8	1.31612074
9	1.33241582
10	1.32016933
11	1.27887619
12	1.27672029
13	1.26995158
14	1.27870917
15	1.27156067

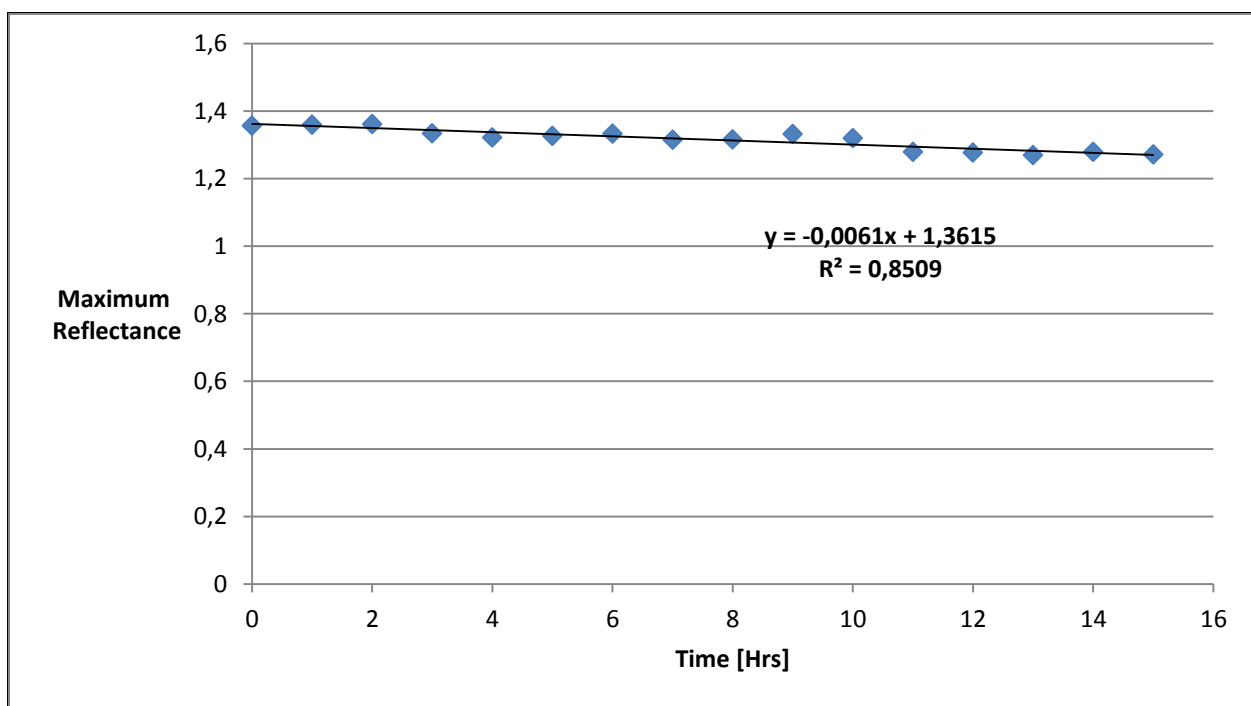


Figure 23: : Green 1 Time vs Maximum Reflectance

Table 8: Number of hours of washing against  $\Delta E$ 

Number of Hours	$\Delta E$
0	
1	1.556082
2	1.692524
3	1.786643
4	2.227641
5	2.209992
6	2.201403
7	2.231095
8	2.277386
9	2.980154
10	3.270045
11	3.578513
12	3.834994
13	4.049142
14	3.971023
15	3.809028

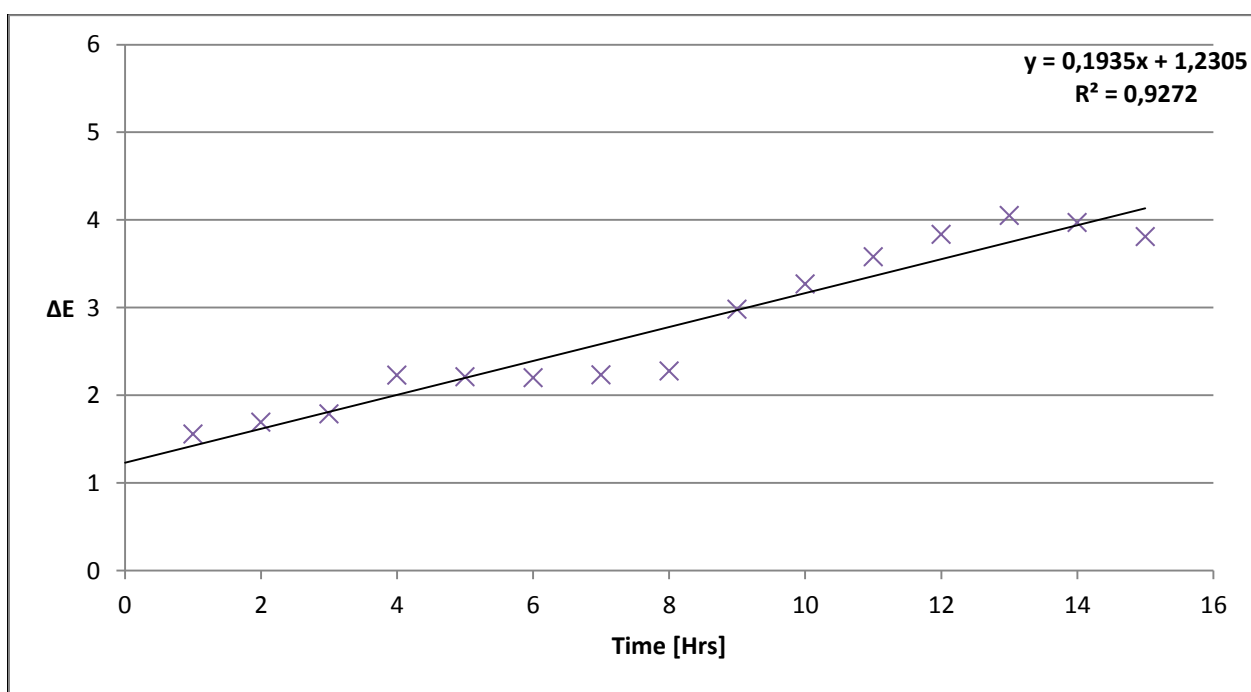
Figure 24: Green 1 Time vs  $\Delta E$

Table 9: Number of hours of washing against the percentage of color remaining.

Number of Hours	% of color remaining
0	100
1	97.12549
2	94.82398
3	93.91782
4	67.80034
5	55.66674
6	51.83977
7	47.47239
8	43.39014
9	39.23809
10	35.63812
11	29.6824
12	26.83482
13	19.2545
14	19.10255

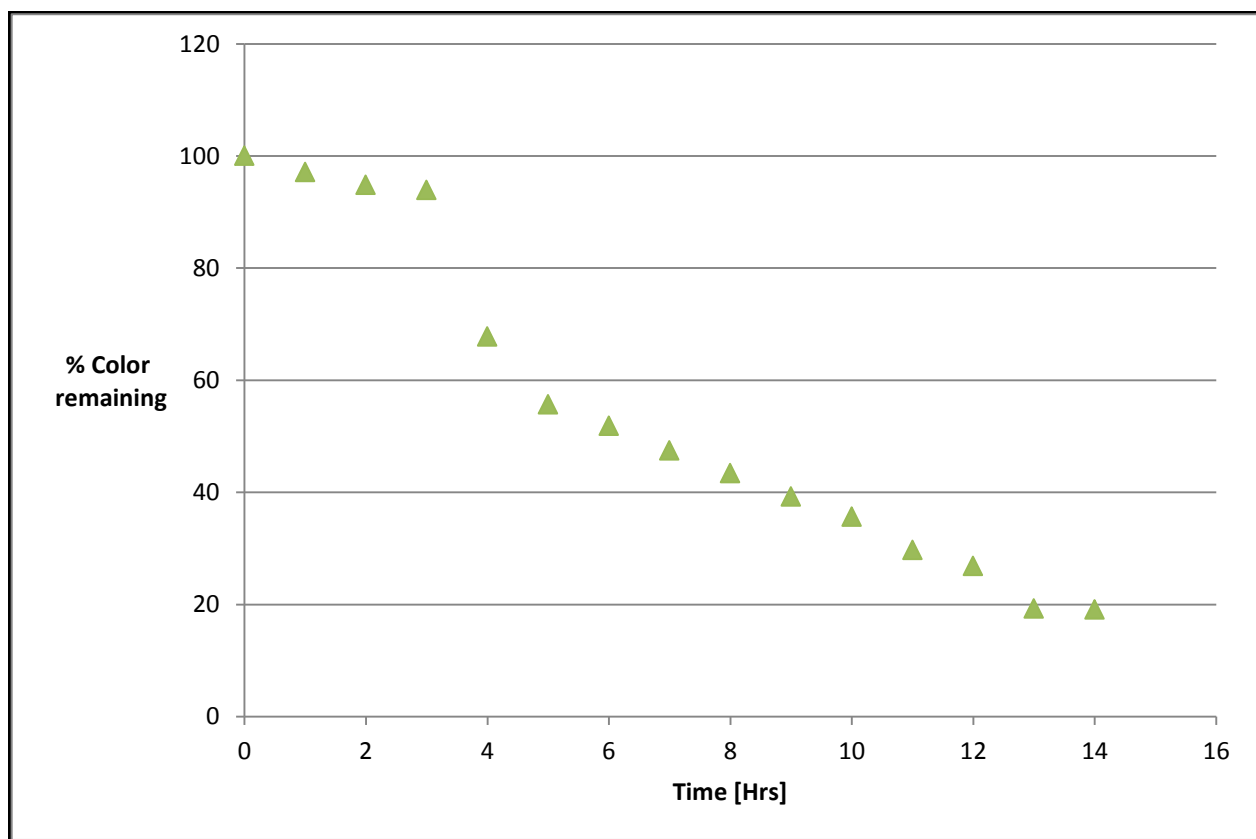


Figure 25: Green 1 Time against % of



From the two samples that have been represented by the graphs above, it is pretty much clear that these two samples are very much resistant to fading having been exposed to washing for 15 hours. Having established that these two samples are polyesters, possible reasons for such resistance could be that the time of exposure was not long enough to ultimately remove the dyeing stuff or it could be that the dyeing stuff used has formed strong covalent bonds with the fabric in such a way that degradation or fading by washing inevitably becomes difficult no matter how long the exposure maybe. This is typical of reactive dyes with cellulose; it becomes difficult to remove the dye especially with washing. In explaining this concept *order of reaction* best describes the change or the non-visible change. Order of reaction refers to the number of atoms or molecules whose concentration seems clearly, on the basis of empirical evidence, to determine the velocity of the process. The rate of change in the concentration of a substance at any given moment in time can be expressed mathematically in general way as:

$$dC/ dt = kC^n \quad (4.1.1)$$

This equation states that the change in concentration of a substrate,  $dC$ , over a very small interval of time,  $dt$  that is, the instantaneous rate of change; is proportional to its concentration at that time,  $C$ , raised to some power,  $n$ . The factor or constant relating one side of the equation to the other is  $k$ . When  $n$  is zero, one or two, the reaction is said to be zero, first order or second order. These are the most commonly encountered modes of chemical change.

When looking at results from graph 3 and 6 one would be tempted to think that the trend in terms of the order of reaction is zero order where a decrease in concentration of dye stuff proceeds at a constant rate. The change in concentration with time is constant and is expressed as follows:

$$dC/ dt = k \quad (4.1.2)$$

However, this is not the case, the reactions above follows *the first order kinetic reaction* expressed as follows:

$$dC/ dt = Kc \quad (4.1.3)$$

The straight line trend could be an indication of induction time or rapid initial stage being present and hence causing confusion as to which order does the substrate follow. In looking at the % color graph, the trend seems to deviate from the expected which is a negative slope linear graph, there seems to be a breaking point where it initially is stable and non-fading and after some time it starts to fade.

There could be a plethora of reasons for such behavior, it could be instrumental errors, it could be the fabric has been coated with some cationic dye fixing agent and hence the stable state merely represents the removal of that fixing agent or it could be when the sample was initially dyed, the particles of dye remained on the surface of the fabric. All these reasons are just mere speculations, leaving an opportunity for further research in looking at the rate of fading of fluorescence fabric containing fixing agent and the one without.

## 4.2 Intermediate samples from fading

### a) Green4B

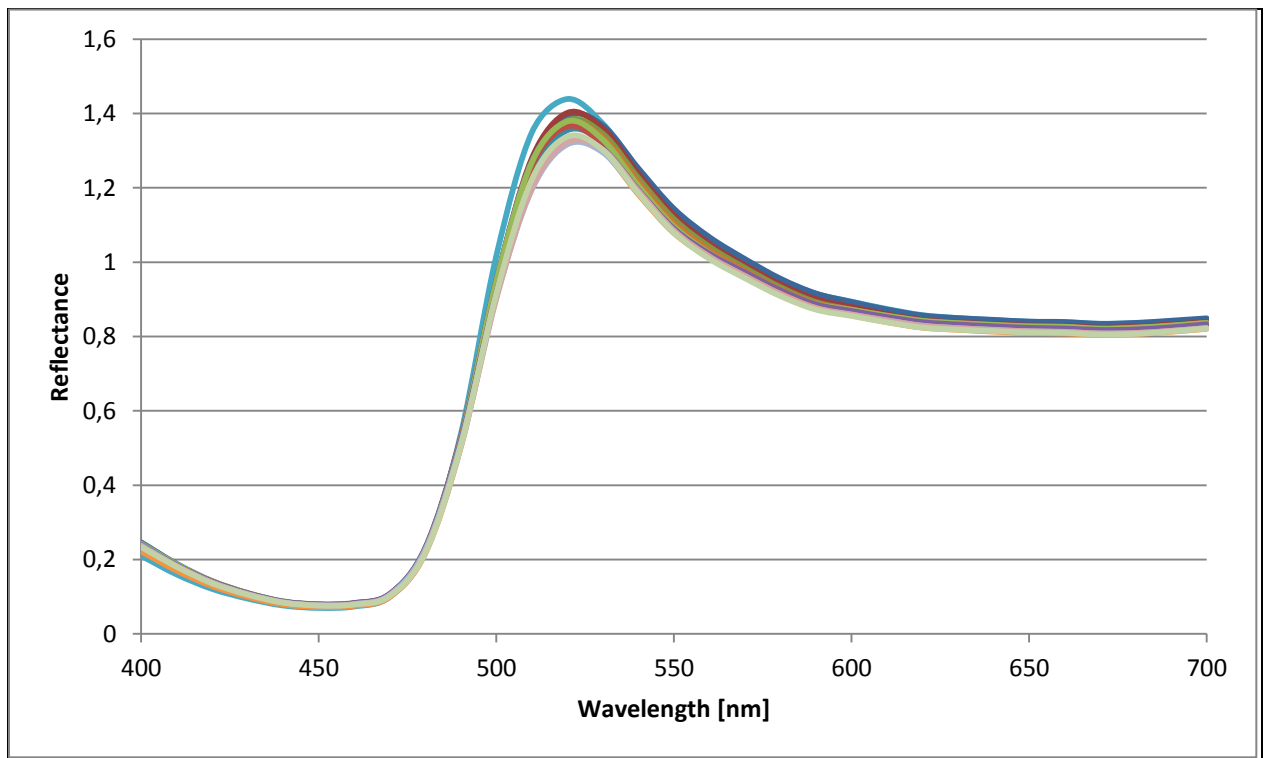


Figure 26: Green 4B Wavelength vs Reflectance

Table 10: Number of hours of washing against Maximum Reflectance

Number of Hours	Maximum Reflectance 520 nm
0	1.43874669
1	1.39378881
2	1.40150547
3	1.38105404
4	1.36042297
5	1.35493505
6	1.37563062
7	1.37743831
8	1.36548793
9	1.37850153
10	1.32690597
11	1.33426392
12	1.31678057
13	1.3228687
14	1.3376354

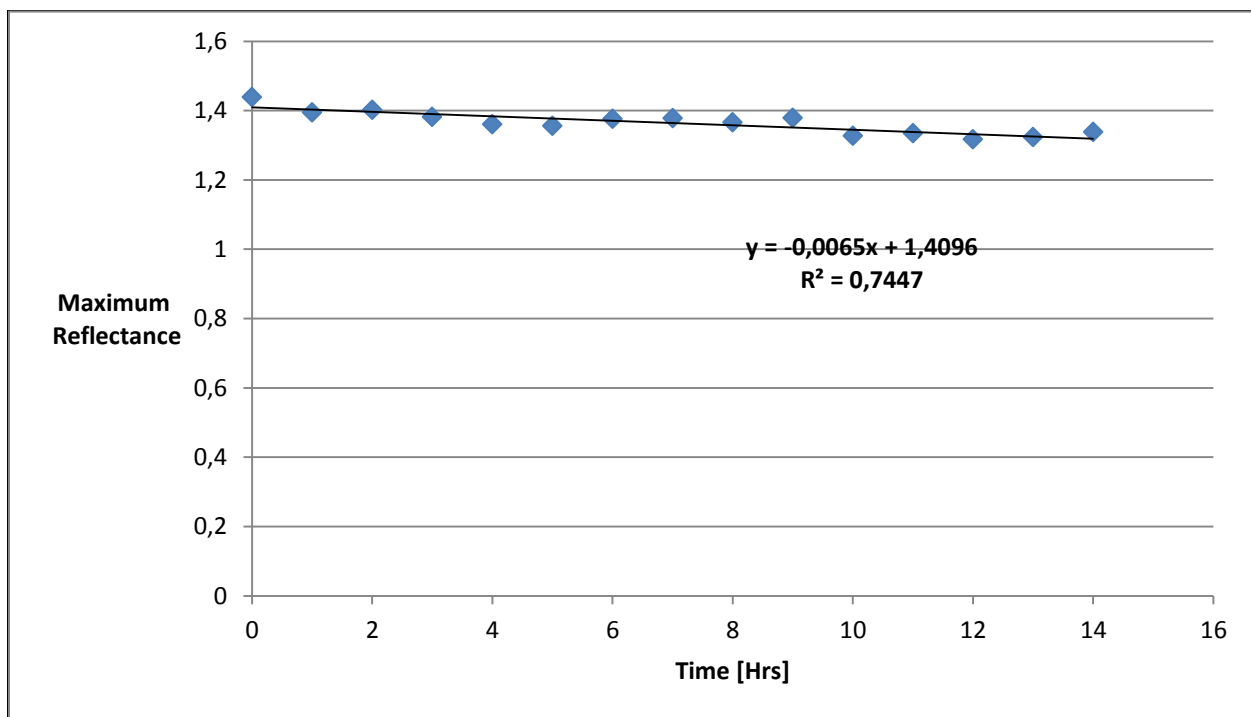


Figure 27: Green 4 Time vs Maximum Reflectance

Table 11: Number of hours of washing against  $\Delta E$ 

Number of Hours	$\Delta E$
0	
1	2.940024
2	3.124713
3	3.481601
4	4.090073
5	4.966266
6	4.294552
7	4.636631
8	5.280397
9	4.697516
10	6.070315
11	4.695151
12	6.066894
13	5.687113
14	5.352692

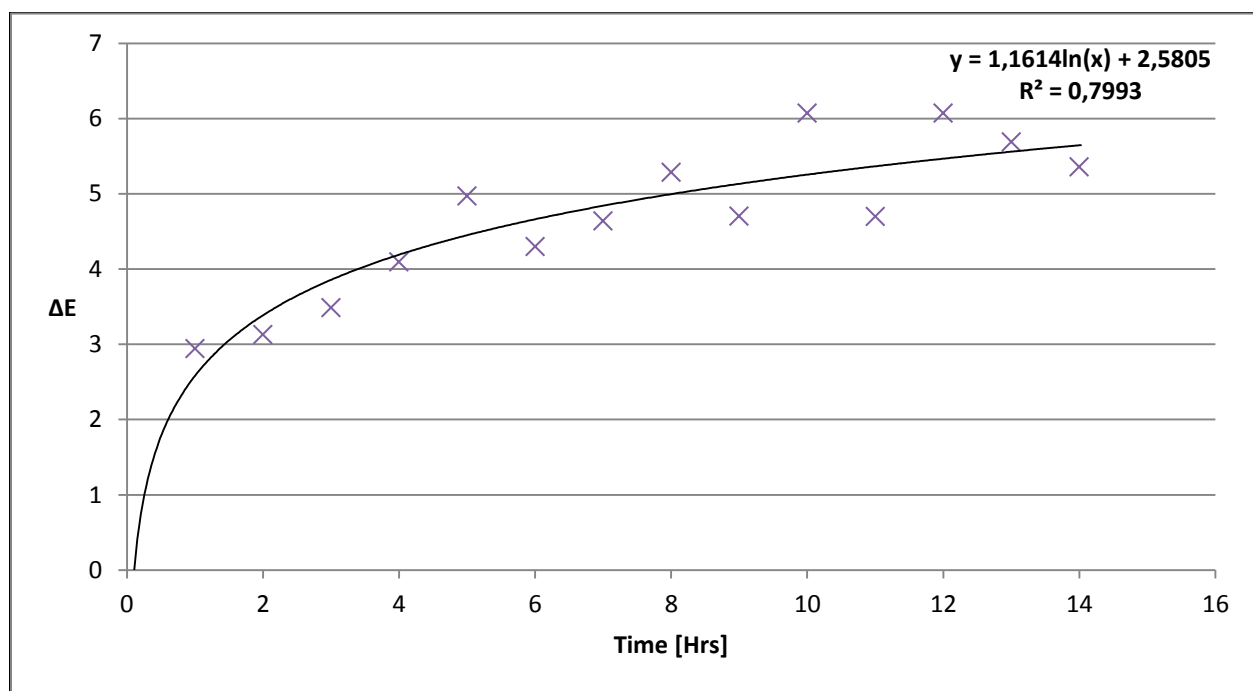
Figure 28: Green 4 Time vs  $\Delta E$

Table 12: Number of hours of washing against % of color remaining.

Number of Hours	% of color remaining
0	100
1	84.89168
2	78.19128
3	76.5436
4	59.27041
5	44.13533
6	44.48547
7	44.91424
8	46.23854
9	43.82546
10	43.04157
11	42.26537
12	35.67855
13	32.93594

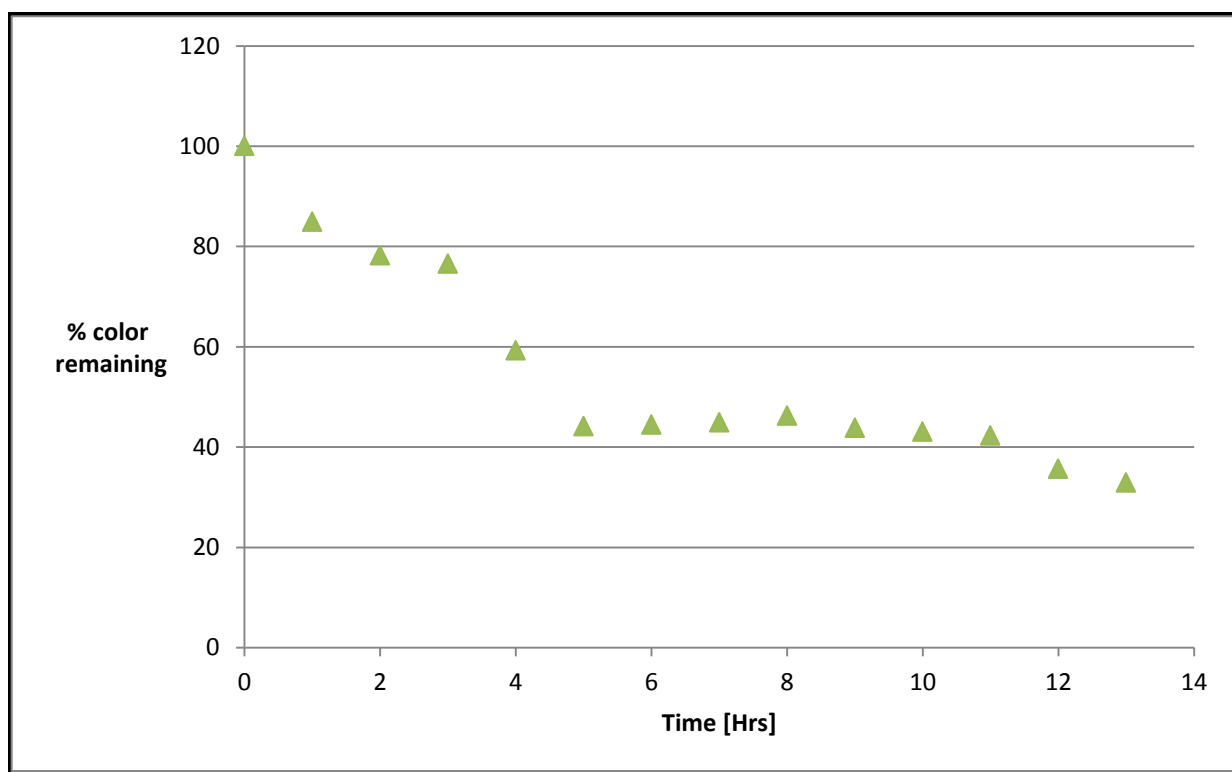


Figure 29: Green 4 Time against %

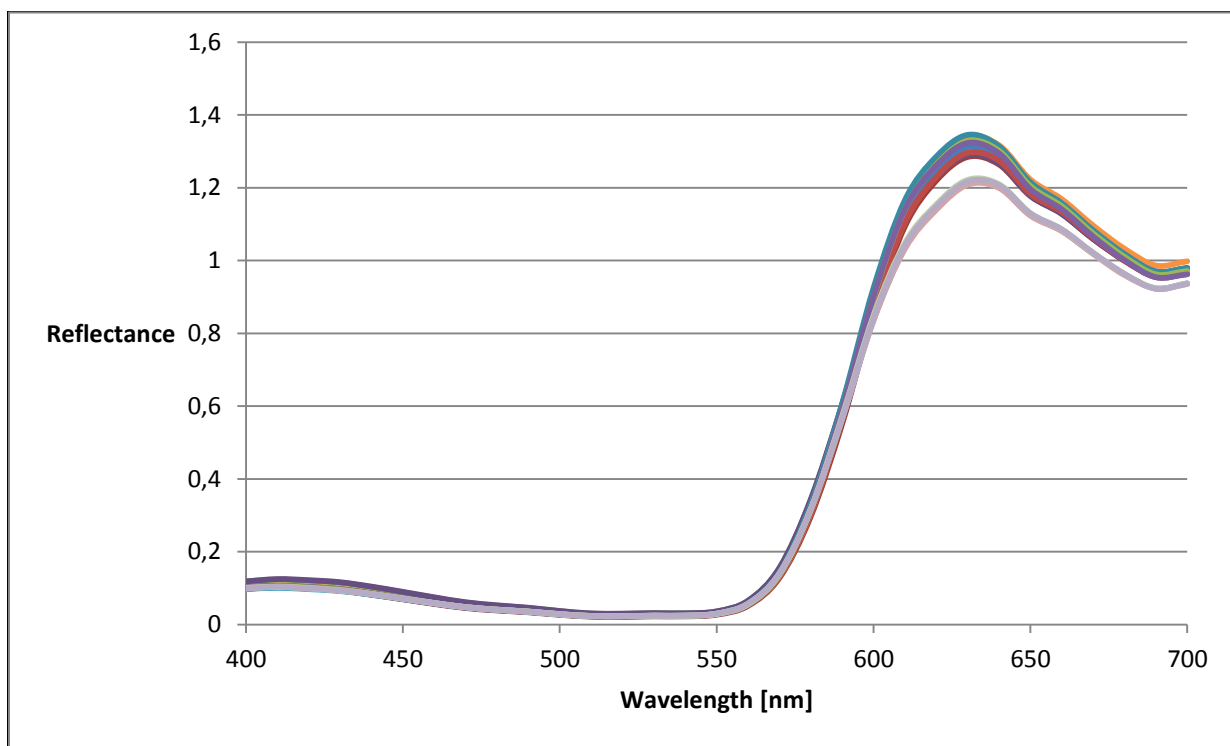
**b) Orange 4ZA**

Figure 30: Orange 4ZA Wavelength vs Reflectance

Table 13: Number of hours of washing against Maximum Reflectance

Number of hours	Maximum Reflectance 630 nm
0	1.34060359
1	1.30856907
2	1.28450847
3	1.29135799
4	1.29018462
5	1.29145783
6	1.29851389
7	1.29021458
8	1.29544294
9	1.28456321
10	1.28124573
11	1.28452172
12	1.25781204
13	1.20819914
14	1.22170997
15	1.21724725

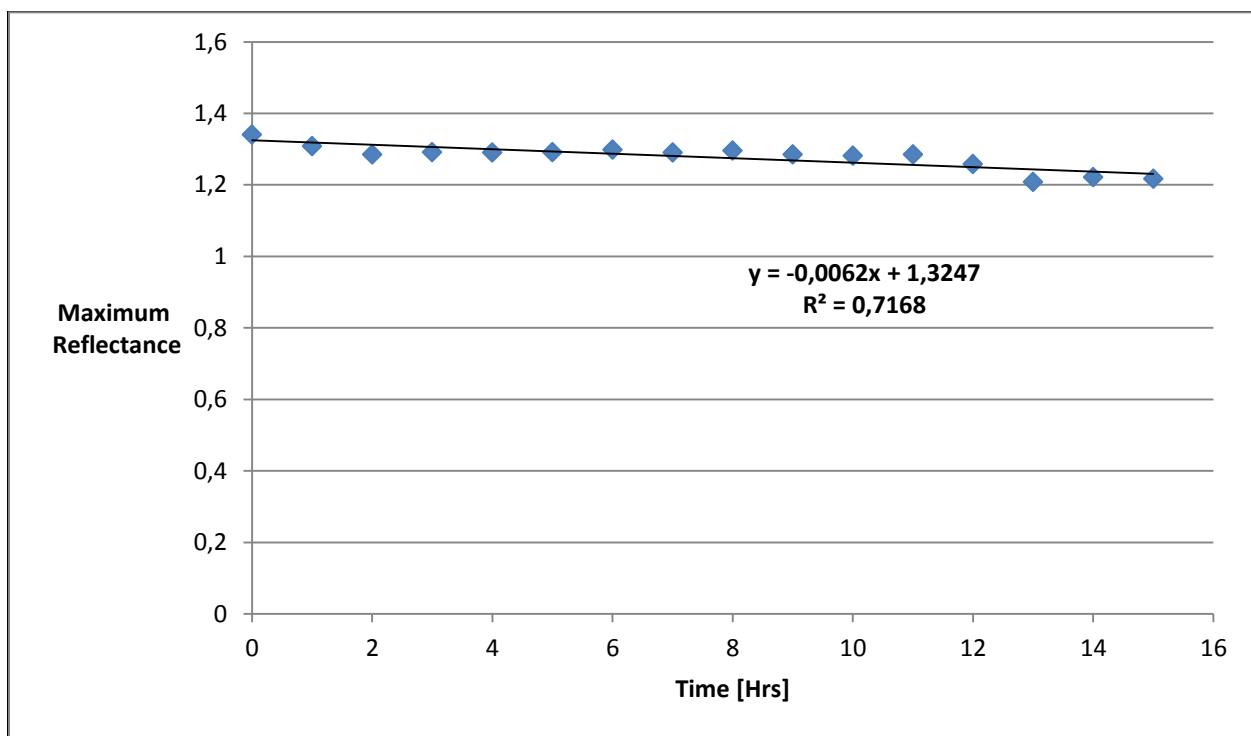


Figure 31: Orange 4ZA Time vs

Table 14: Number of hours of washing against  $\Delta E$ 

Number of Hours	$\Delta E$
0	
1	0.818546
2	1.417156
3	1.532456
4	1.832489
5	2.052923
6	2.156323
7	2.387956
8	2.654234
9	2.901248
10	3.189742
11	3.495123
12	3.752395
13	3.818644
14	3.912459
15	4.002548

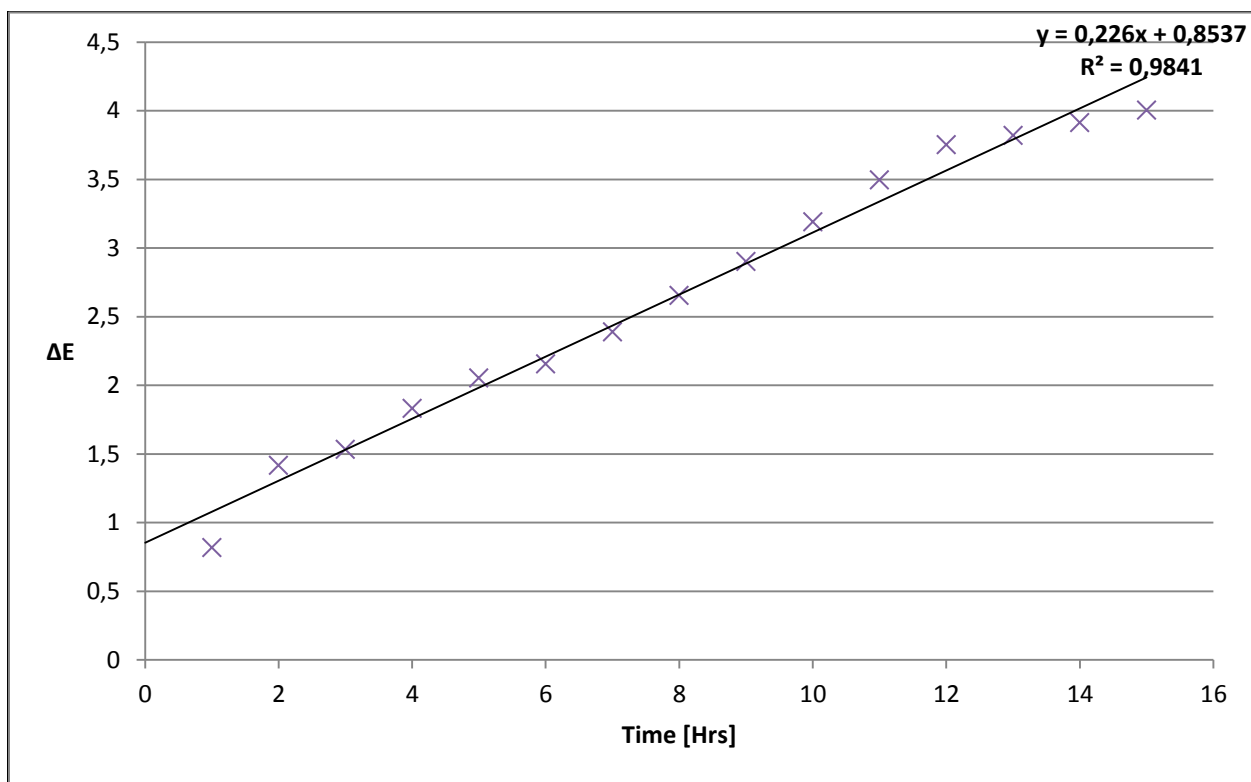
Figure 32: Orange 4ZA Time vs  $\Delta E$ 

Table 15: Number of hours of washing against % of color remaining

Number of Hours	% of color remaining
0	100
1	96.38225
2	74.90855
3	67.11576
4	45.46331
5	48.11902
6	45.42967
7	36.60991
8	40.84833
9	34.12042
10	39.84048
11	40.87262
12	39.92142
13	37.36745
14	25.96909



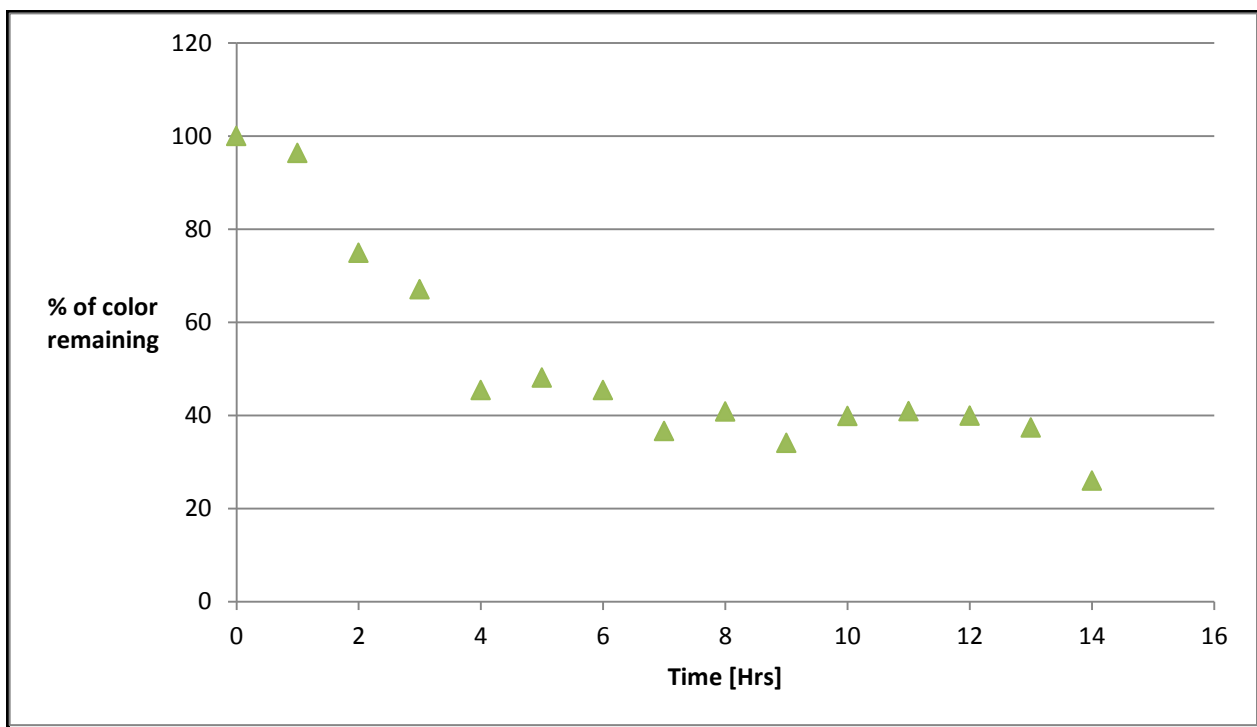


Figure 33: Orange 4ZA Time against %

Looking at the intermediate samples shown above, the graphs depicts that they are not so resistant to fading and yet not so easily susceptible to fading either. The  $\Delta E$  has slightly increased showing a possibility of fading but after a long exposure time. One could also reiterate the contribution of the bond formed between a polyester sample with the dyeing stuff used, it's not easily broken even anionic surfactants like Syntapon ABA cannot contribute towards breaking that bond. However; long hours of washing might eventually cause fading because the trend from the graphs shows some kind of fading effect that was beginning to take place.

Also the percentage color graph is showing an unfamiliar trend where initially the color fades and at a certain time it begins to stop and follow a constant trend. This phenomenon is quite perplexing leaving such a desire to research the course and ambiguity of these results. Perhaps a further analysis of the dyestuff used to dye the samples could give a clear perspective on this predicament.

### 4.3 Non-resistant samples from fading

#### a) Orange 8

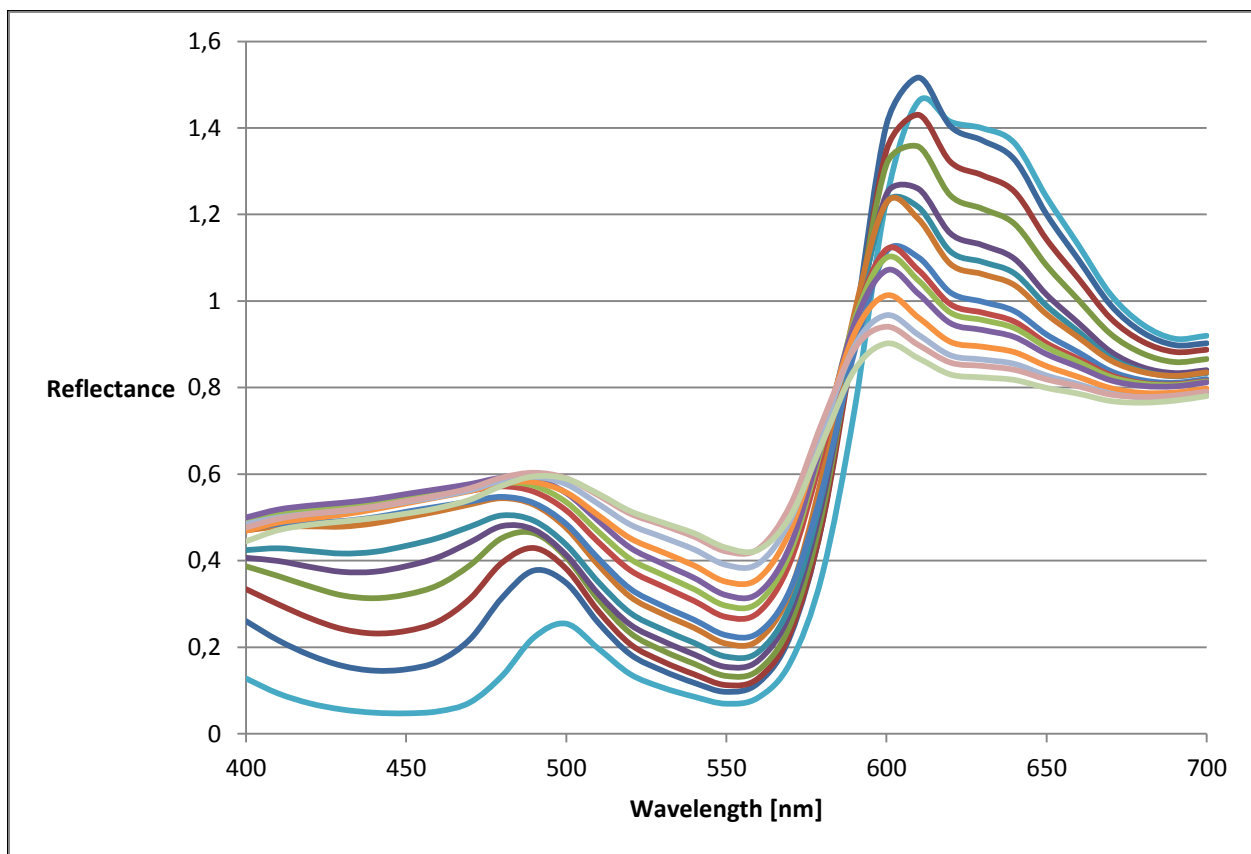


Figure 34: Orange 8 Wavelength vs Reflectance

Table 16: Number of hours of washing against Maximum Reflectance

Number of Hours	Maximum Reflectance 610 nm
0	1.64129993
1	1.51642686
2	1.43036747
3	1.35688615
4	1.25924623
5	1.21688795
6	1.18933856
7	1.10086226
8	1.07148314
9	1.04745066
10	1.01677608
11	0.96186709
12	0.92207915
13	0.89839381
14	0.86776513

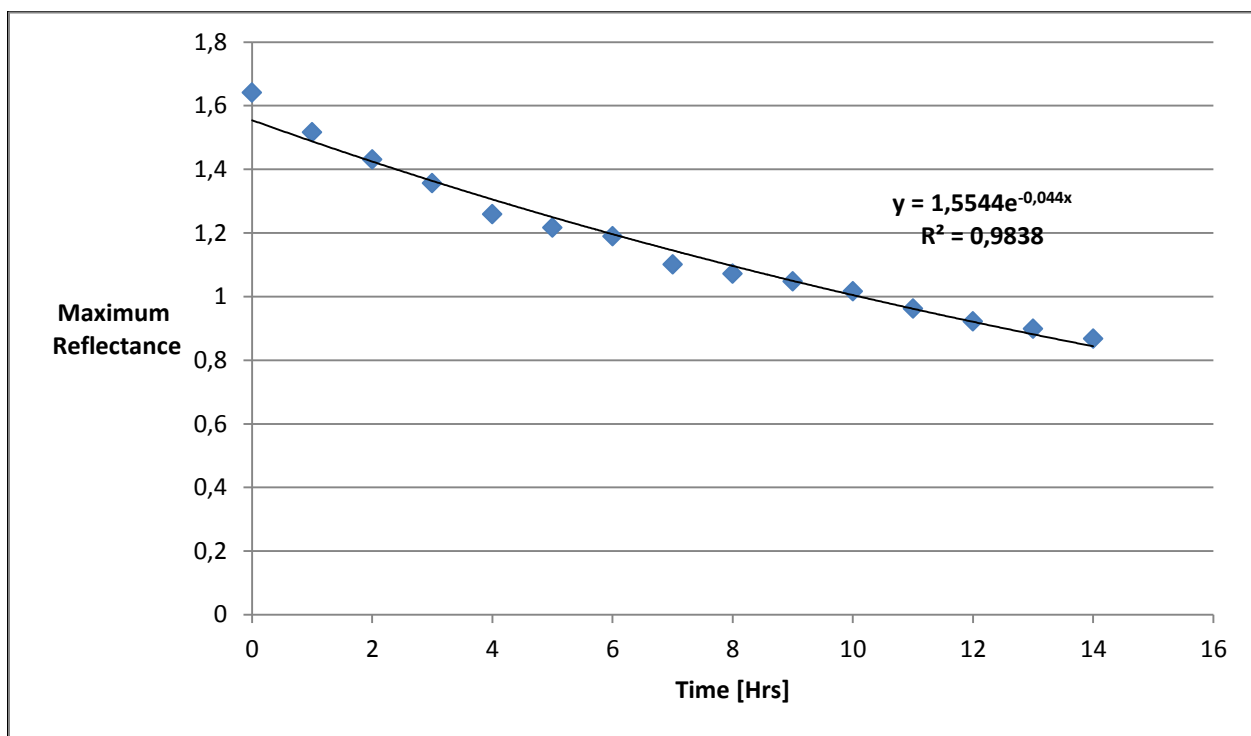


Figure 35: Orange 8 Time vs maximum reflectance

Table 17: Number of hours of washing against  $\Delta E$ 

Number of Hours	$\Delta E$
0	
1	33.63549
2	42.25842
3	48.25793
4	55.22553
5	59.19532
6	63.63789
7	67.15794
8	68.03496
9	68.80638
10	70.2759
11	70.364
12	72.33755
13	73.36914
14	73.80708

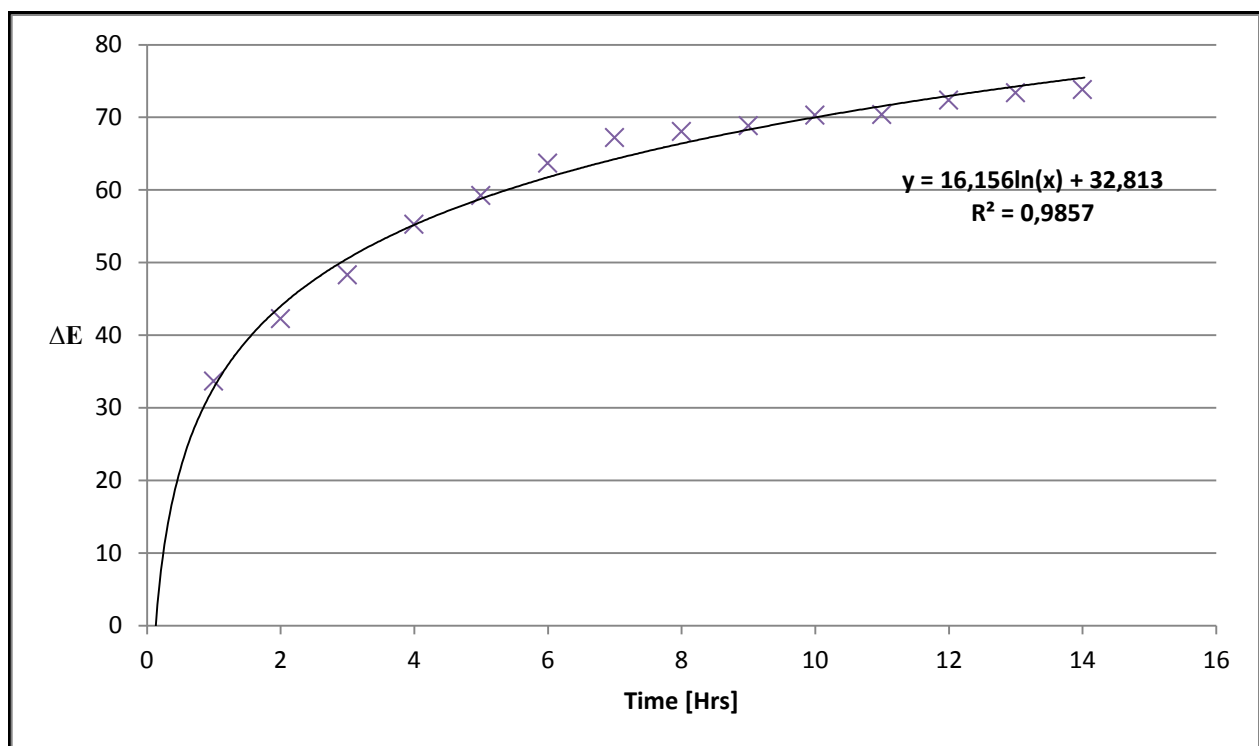
Figure 36: Orange 8 Time vs  $\Delta E$ 

Table 18: Number of hours of washing against % of color remaining

Number of hours	% of color remaining
0	100
1	96.04042621
2	92.9784643
3	87.83481187
4	80.73636044
5	76.77085285
6	73.66401384
7	69.865979
8	58.42805747
9	54.86656405
10	49.39062662
11	36.7680628
12	27.26864236
13	16.14317867

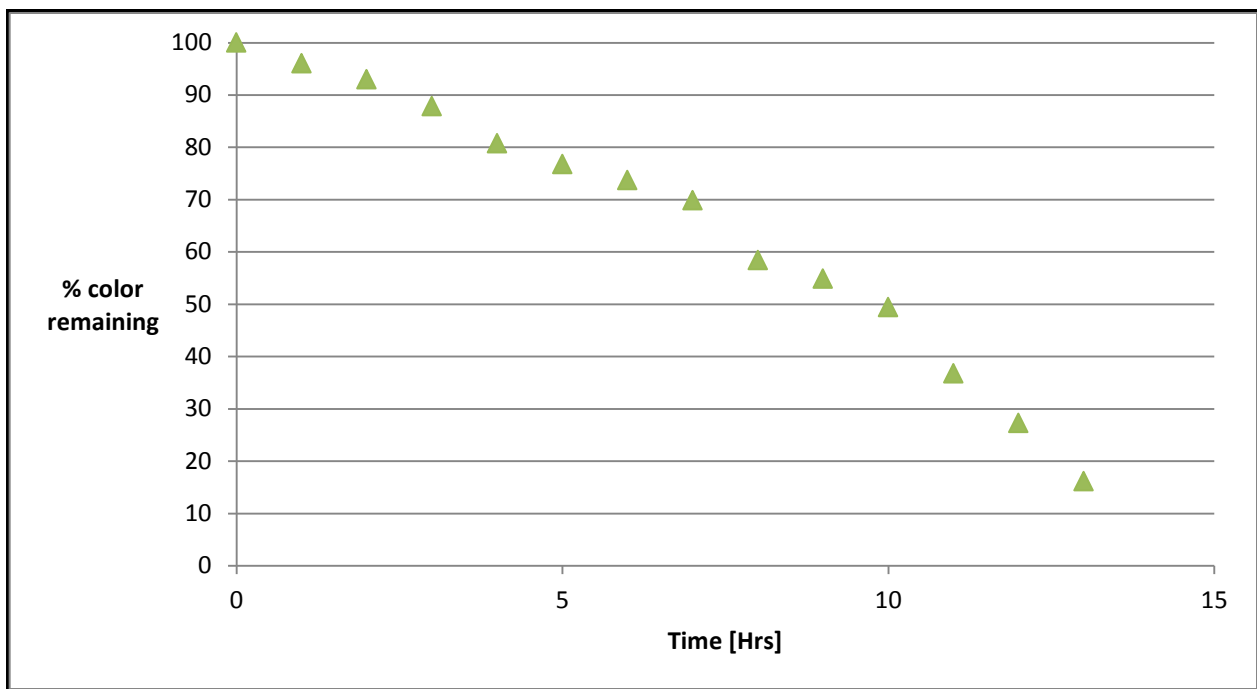


Figure 37: Orange 8 Time against % of

**b) Orange 6**

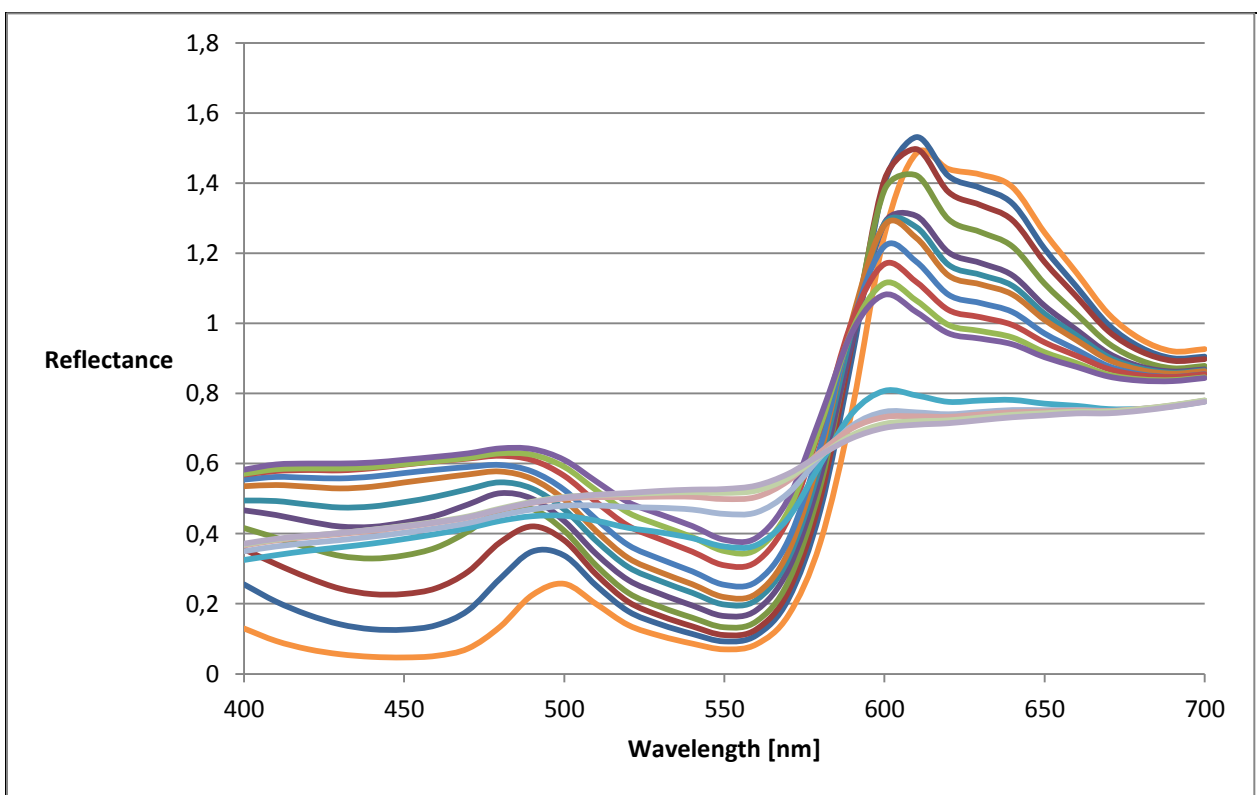


Figure 38: Orange 6 Wavelength vs Reflectance

Table 19: Number of hours of washing against Maximum Reflectance

Number of Hours	Maximum Reflectance 610 nm
0	1.48499012
1	1.53113127
2	1.49680054
3	1.42183542
4	1.30600202
5	1.27406371
6	1.24315691
7	1.17535341
8	1.11761844
9	1.06468105
10	1.03194296
11	0.79427606
12	0.74584037
13	0.73467982
14	0.72049022
15	0.71065623

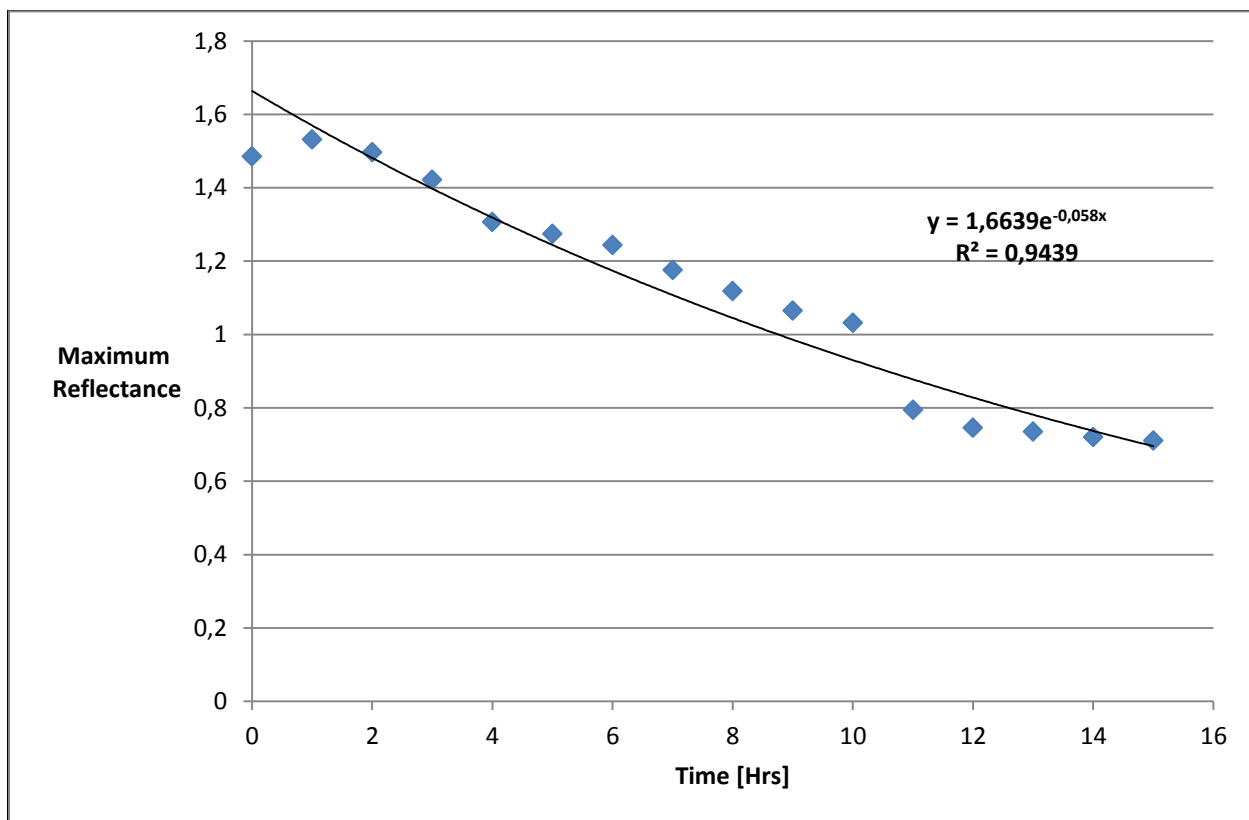


Figure 39: : Orange 6 Time vs maximum reflectance

Table 20: Number of Hours of washing against  $\Delta E$ 

Number of Hours	$\Delta E$
0	
1	30.12548
2	44.85479
3	49.06173
4	58.41937
5	62.29008
6	66.06978
7	68.72787
8	70.70893
9	72.32381
10	73.84759
11	67.47896
12	71.95135
13	74.14801
14	75.33077
15	75.77765

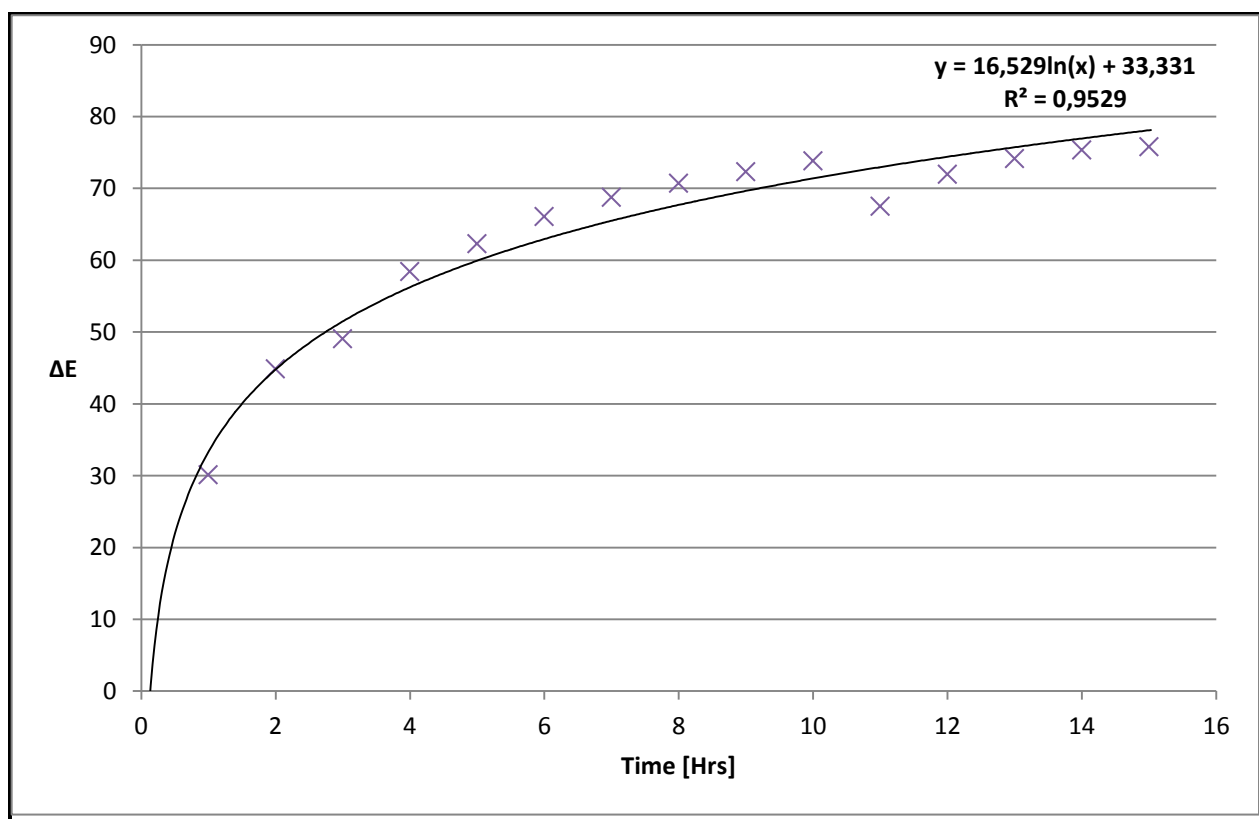
Figure 40: Orange 6 Time vs  $\Delta E$

Table 21: Number of hours of washing against % of color remaining

Number of Hours	% of color remaining
0	100
1	98.80685
2	97.08523
3	95.73112
4	89.85444
5	61.01842
6	57.04632
7	50.62345
8	43.61849
9	35.39192
10	31.64201
11	27.76695
12	13.71293
13	4.617447
14	3.648671

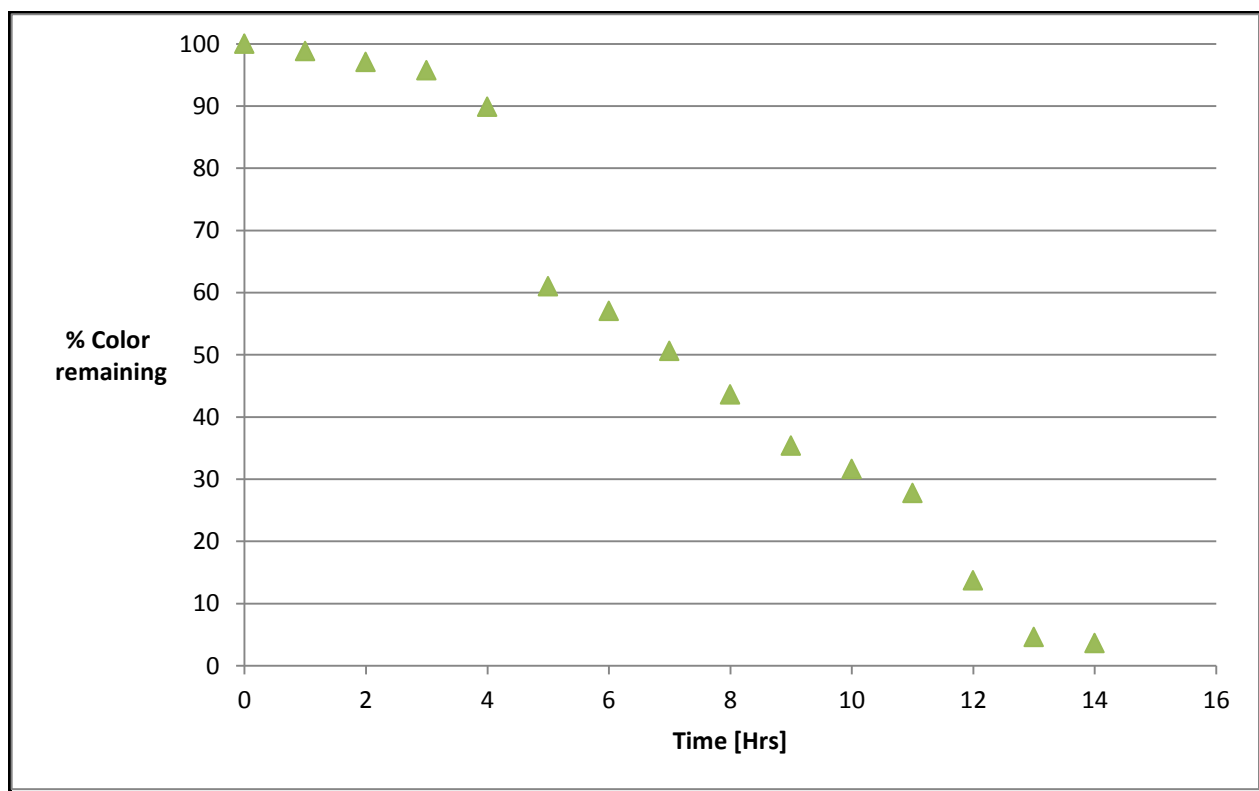


Figure 41: Orange 6 Time against % of



The two samples depicted by the graphs above are a clear indication of fading of a High Visible samples. As the sample fades the maximum reflectance of the sample decreases as it can be seen from Graph 18 and 22. The reason for this phenomenon is that as the dye gets removed from the substrate or sample, the visible light from the spectrophotometer gets transmitted or absorbed and not reflected. Furthermore, when looking at the Graphs 19 and 23, they relatively show high color difference giving high  $\Delta E$  values. The fading could be associated with the weak bonds between the substrate and the dye stuff and hence propels rapid fading. Meaning an anionic surfactant like Syntapon ABA was able to facilitate the breaking of bonds causing the fabric to lose its color and become yellowish.

In terms of the order of reaction, *first order reaction* is evident where the disappearance of color with time is clearly related to its concentration at any given time. This rate of degradation obeys the equation:

$$dC/ dt = Kc \quad (8.3.1)$$

This equation tells that, at any given moment, a certain fraction ( $k$ ) of the concentration of colorant that is present,  $C$  is being lost;  $k$  is called the *specific order reaction constant*.

The integrated form of equation 7.3.1 is:

$$2.303 \log C = 2.303 \log C_0 - Kt \quad (8.3.2)$$

The factor 2.303 converts to the natural logarithm (to the base  $e$ ) to the logarithm to the base 10.

Furthermore; from the results one can insinuate that the fading of the substrate happened in stages referred to as initiation, propagation and termination reactions. And at any particular stage the principal reaction can be evaluated in terms of zero, first or second order kinetics. These samples faded to an extent where they were becoming yellowish, showing that almost all the dye stuff had been removed from the fabric and a state of saturation was beginning to set in.

### 4.4 Comparison of Resistant and Non Resistant

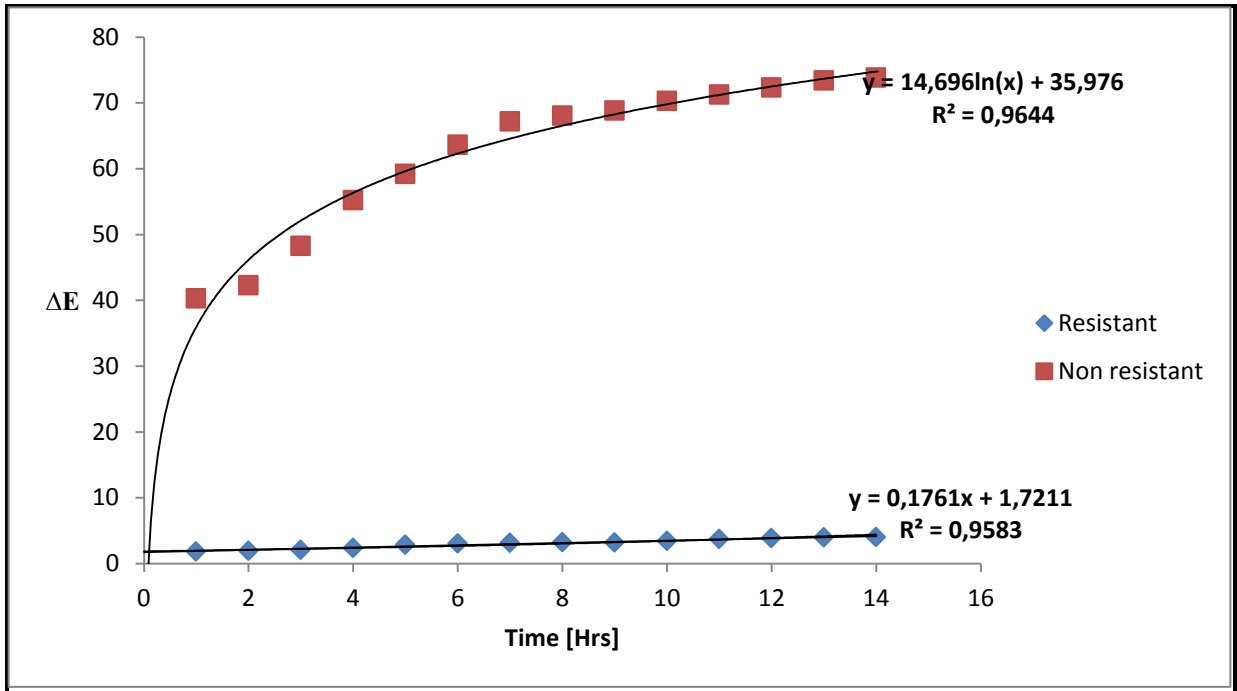


Figure 42: Comparison of Resistant and Non resistant substrates based on ΔE

A huge difference between these two graphs is noticeable **resistant dye** follows a *linear* pattern whereas **non-resistant dye** follows a *logarithm trend* or pattern.

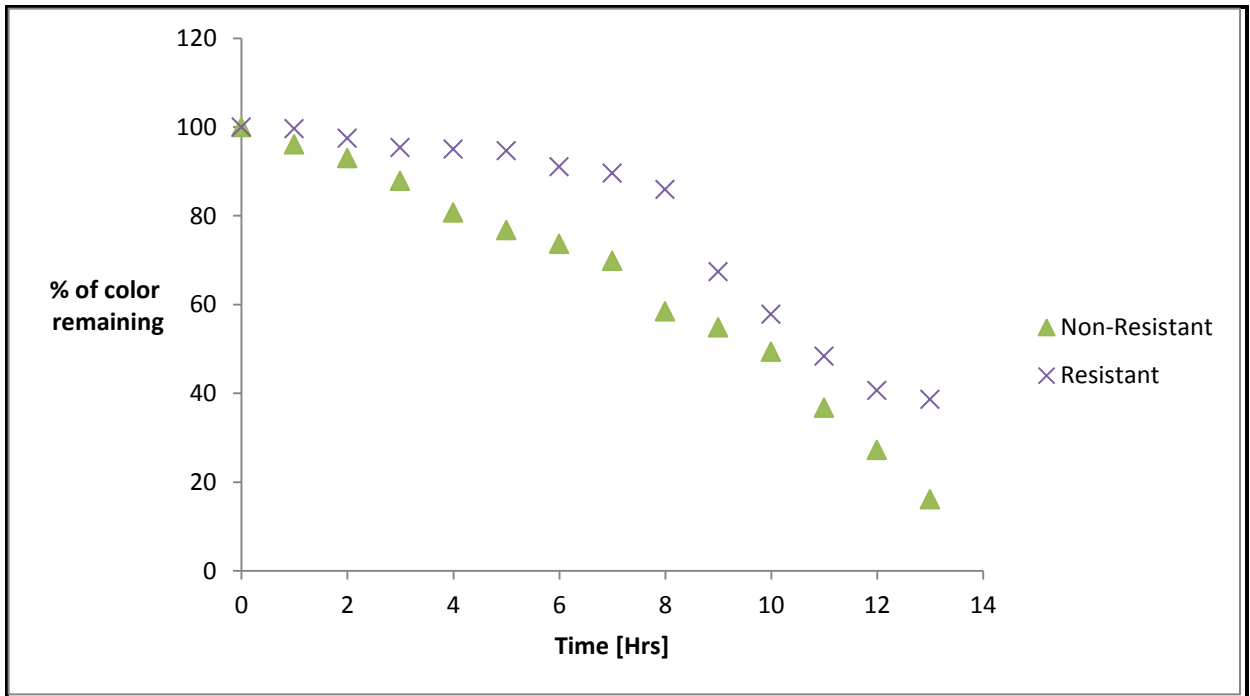


Figure 43: Comparison of Resistant and Non-Resistant substrates based on % of colour

## Chapter 5 Conclusion

High Visibility clothing play a very vital role in preventing danger and enhancing the visibility of workers whether it in daylight or night time. It becomes imperative that when manufacturing such garments, strict and high standards are adhered to in trying to prolong their lifetime and effectiveness even under harsh environmental conditions. In looking at the results from the experiments, it's evident that washing does contribute greatly towards the deterioration and fading of the high visibility clothing.

When looking at the applications of high visible clothing, it is inevitable that they will get soiled and will require washing. What is interesting also about these garments is prior to requiring washing, they gets exposed to sunlight which contributes greatly into their deterioration and fading. So essentially they experience a double dose of fading. It has been proven that Fastness to washing is dependent on the substantivity as well as the polarity of a dye molecule. It is said the greater the substantively, the greater will be the forces to prevent the removal of the dye during washing. *Substantivity* is referring to the high attraction between the fiber polymer and the dye molecule which makes it easy for a fiber to be dyed.

The results also indicated that there were certain samples that were resistant to fading, in other words it will take a whole number of cycles of washing to fade them and there were others who showed rapid fading within a short time. Having established that most of the samples were polyester blends and some were polyester/ lycra blends which were the ones that faded most rapidly. Spandex, also known as elastane, and often sold under the brand name of Lycra®, is elastomeric polyurethane. Even in very small proportions, it enables fabrics containing it to stretch.

Fabrics that contain spandex can be easily damaged by heat. Typical washing instructions for spandex call for avoiding all temperatures about 105°F. Far higher temperatures, up to 140°F (60°C), are used in industrial dyeing of spandex, but are not recommended for home use.

Spandex, also known as elastene, and often sold under the brand name of Lycra, is an elastomeric polyurethane. Even in very small proportions, it enables fabrics containing it to stretch. Fabrics containing spandex can be easily damaged by heat. Typical washing instructions for spandex call for avoiding all temperatures about 105°F. Far higher temperatures, up to 140°F (60°C), are used in industrial dyeing of spandex, but are not recommended for home use. Spandex must not be subjected to high heat, and is thus not appropriate for use with disperse dye. Most lycra garments contain a high percentage of cotton, which can be dyed with cool water fiber-reactive dye; often, the undyed lycra does not even show on the outside of the garment.

I'm inclined to believe that the reason for such contradicting behavior between polyester and spandex based upon the technology of dyeing, the fluorescent colorant certainly does not disseminate properly into the fibers or fabric, they will tend to get removed easily from the substrate on subjecting the substrate to washing. It would seem Spandex is not an appropriate fabric to be used for High Visibility Clothing for its poor fastness to washing, however it is regarded as sun protecting clothing and hence it plays a pivotal role in protecting workers against the sun rays.

In recommending a solution towards this predicament, one will be tempted to suggest a classical way of preventing dyes from running from a fabric, which is the use of vinegar, however, this seems like a cumbersome exercise and it doesn't always work. So the question still arises, what can be done. Essentially we are looking at increasing fastness to washing of High visible clothing and clearly we need to be asking ourselves these following questions:

- What is the chemical composition of the textile i.e. does it have high acid content? Are the chemicals used in its production might contribute to how it reacts to water or washing chemicals?
- What are the characteristics of the fibers? For example Cotton and Linen. Being the plant fibers, are both stronger in wet and dry, so may be able to withstand a more mechanical stress than something like silk.
- What colorants have been used and how will they react to washing?

- Considering the kind of environment in which these high visibility clothing are utilized, the choice of fibers or material used will play a pivotal role for comfort purposes.

In rendering answers to these questions, a prospective way of at least reducing the rate of fading of High Visibility Warning Clothing can be subsequently reached or formulated. A suggestion could be to increase the molecular size of dye, but this method is said to cause reduction in the permeability and substantivity of the dye. So further research still needs to be done.

## Chapter 6 References

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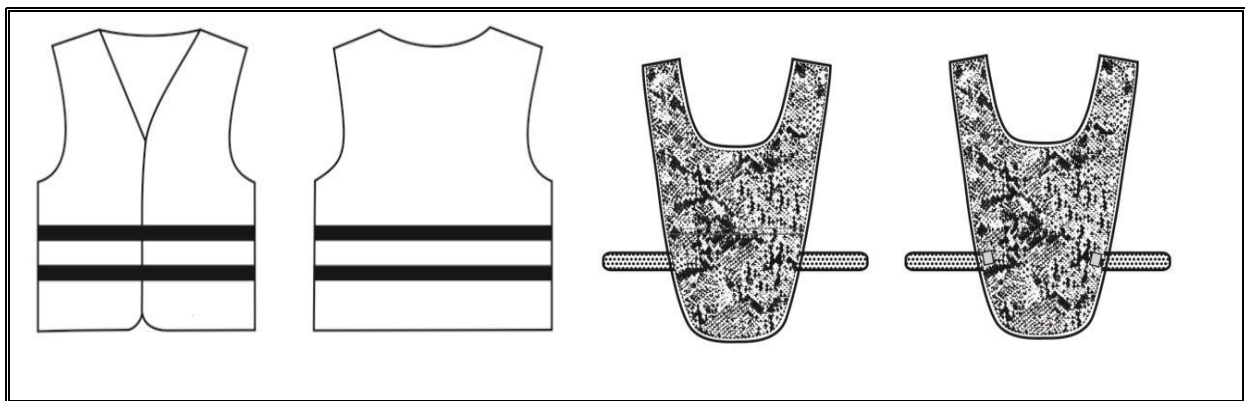
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## Chapter 7 Appendix A

### Examples of Garment Design

(Appendix A is not part of IHVCA High Visibility Risk-Related Clothing Standard but is included for information only).

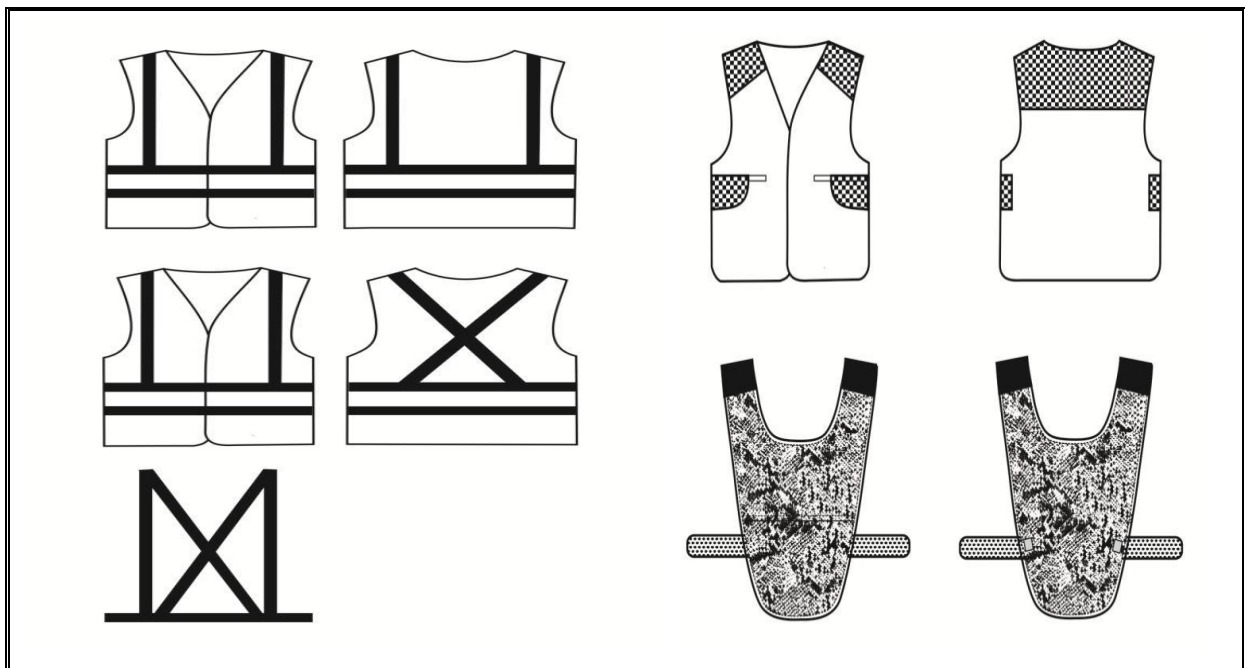
**Figure 1. Performance Class 1:**



**Solid Performance**

**Area Performance**

**Figure 2. Performance Class 2:**

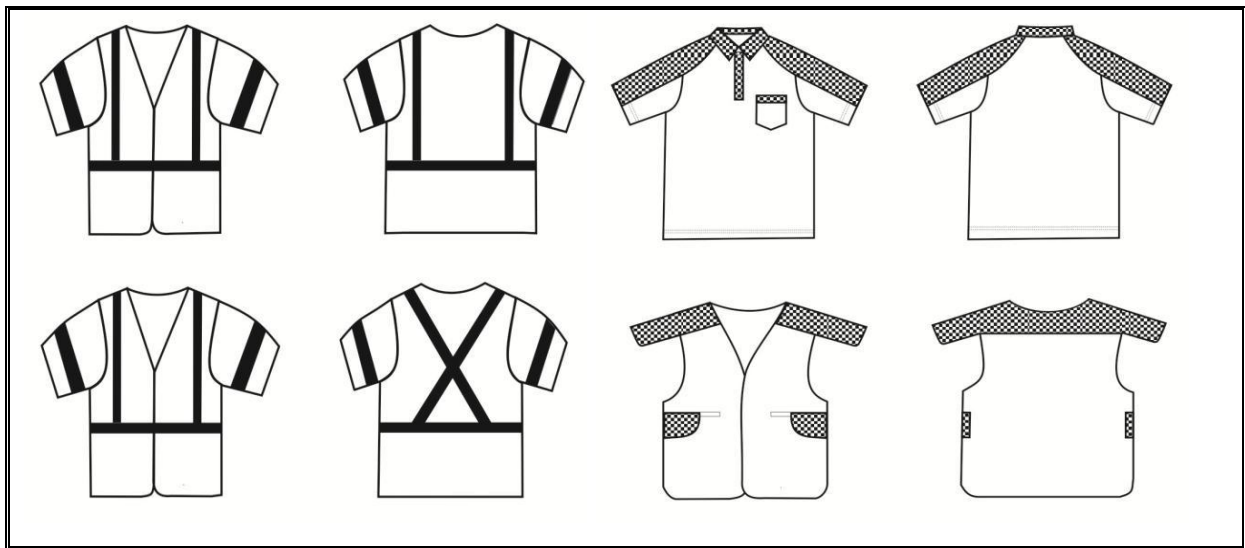


**Solid Performance**

**Area Performance**



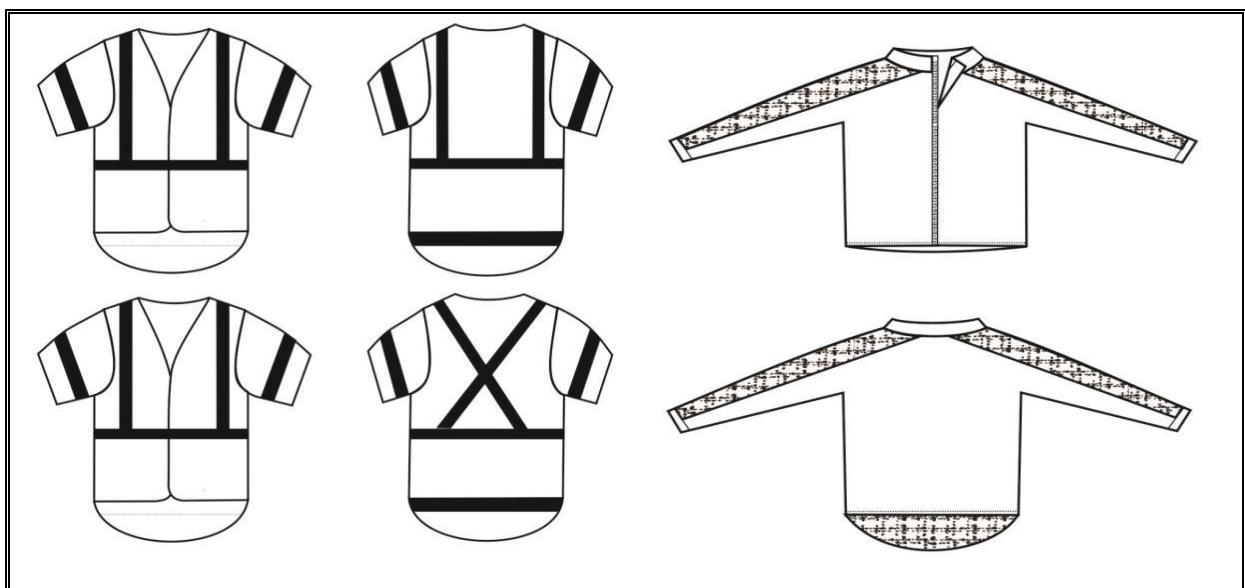
**Figure 3. Performance Class 3**



**Solid Performance**

**Area Performance**

**Figure 4. Performance Class 4**

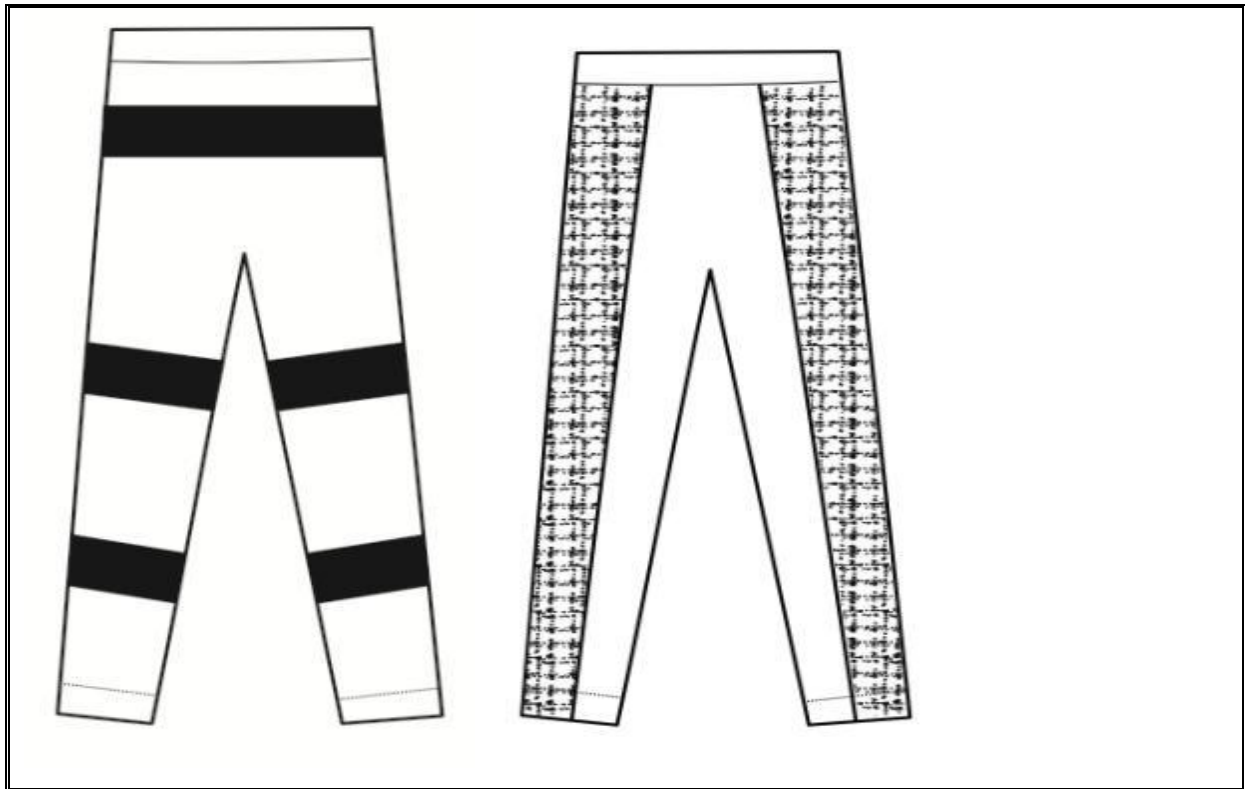


**Solid Performance**

**Area**

**Performance**

**Figure 5. Trousers or Pants**

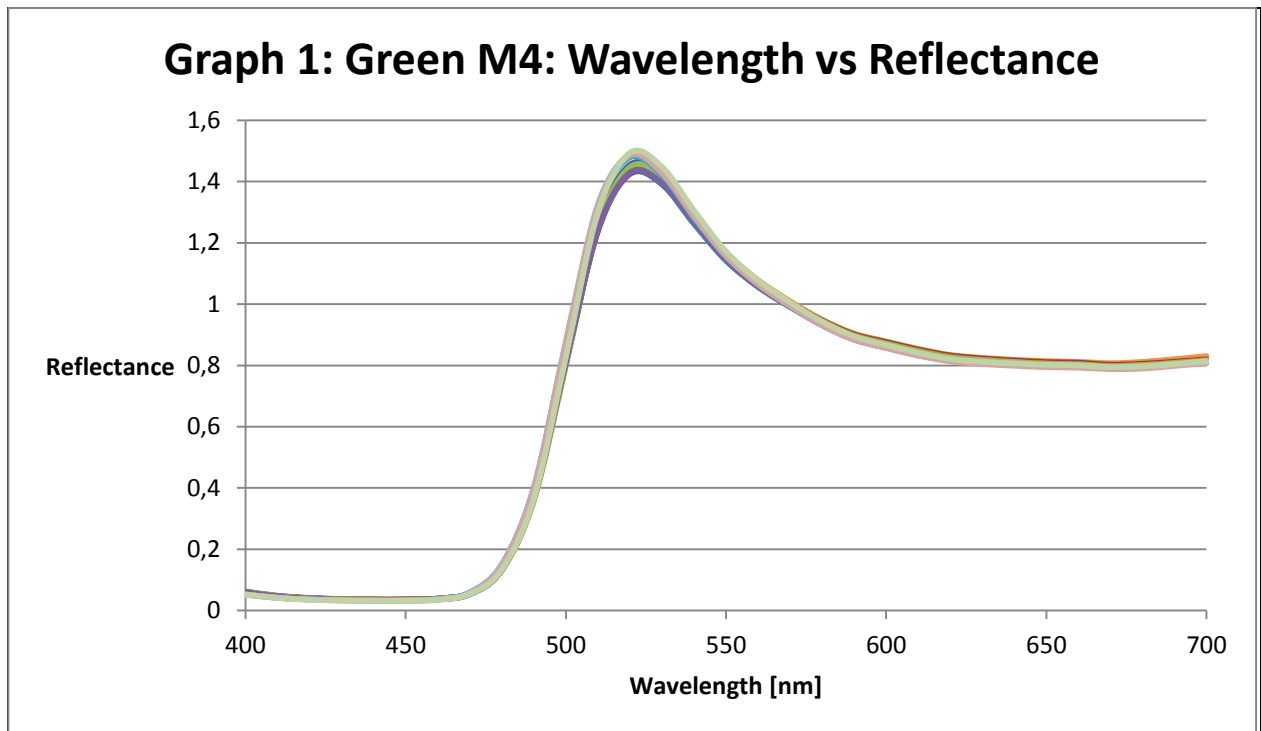


**Solid Performance**

**Area Performance**

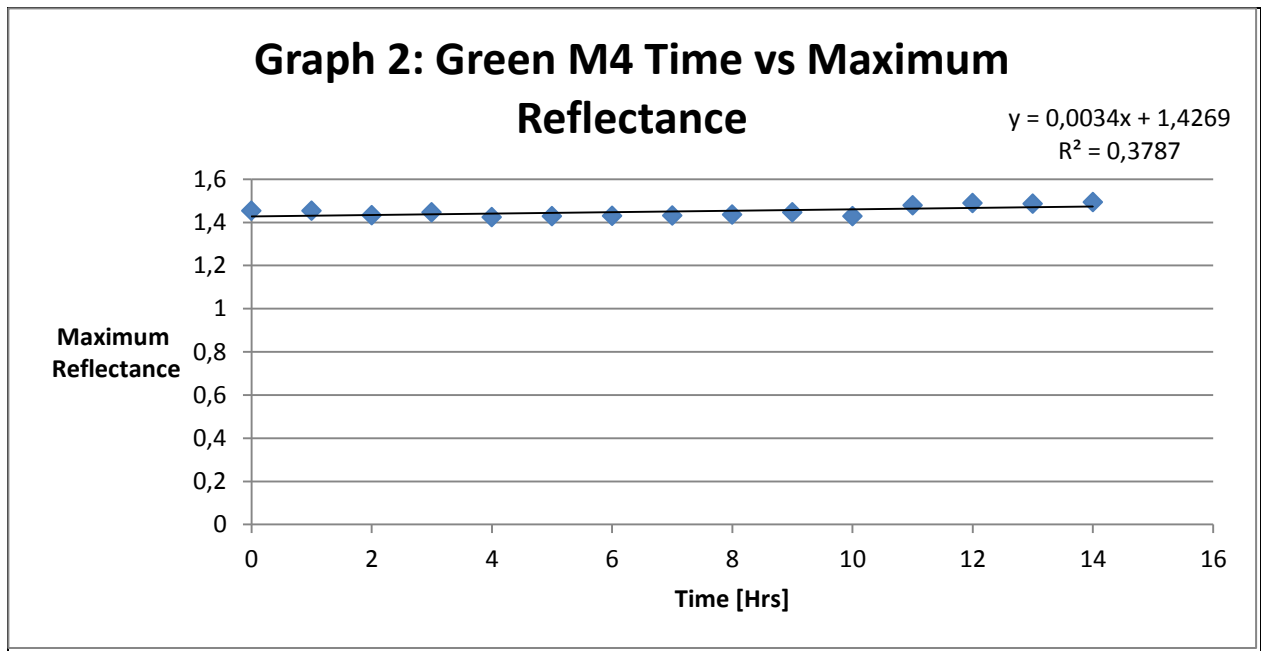
Note: Care recommendations according to ISO 3758

## Chapter 8 Appendix B



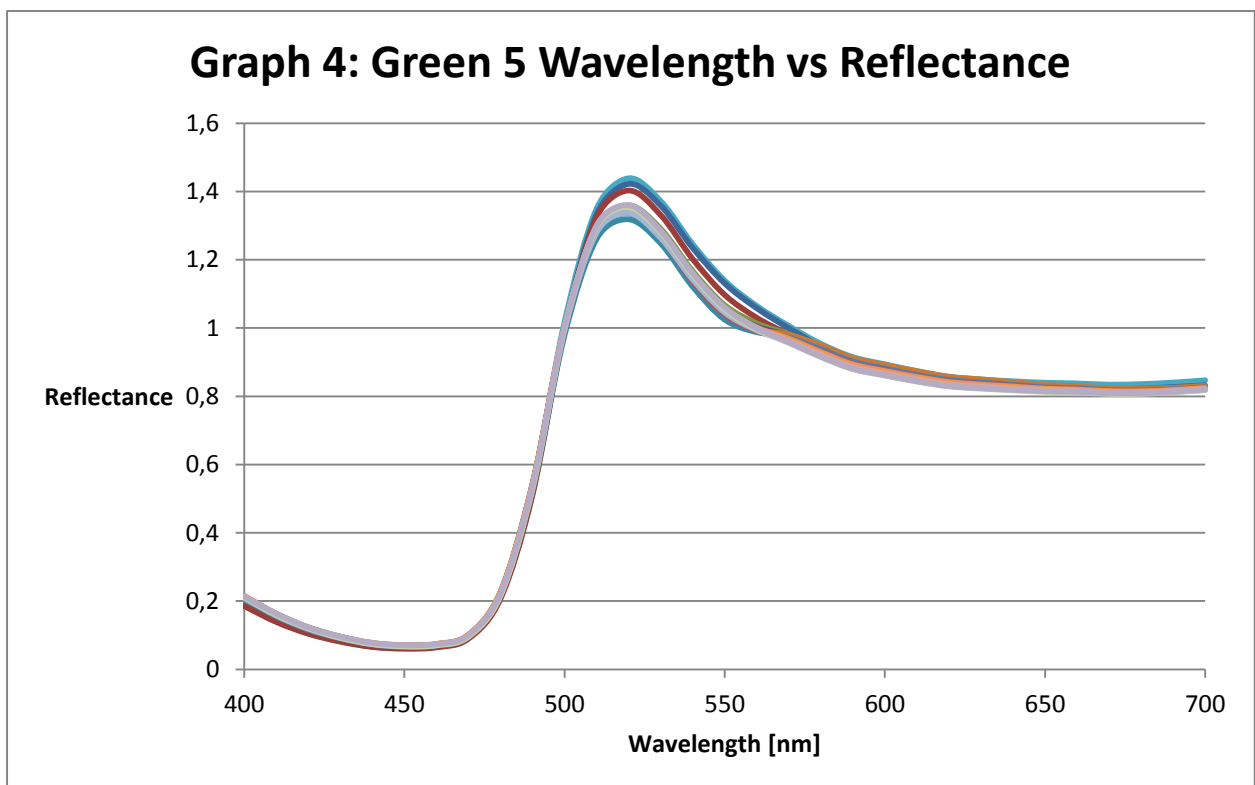
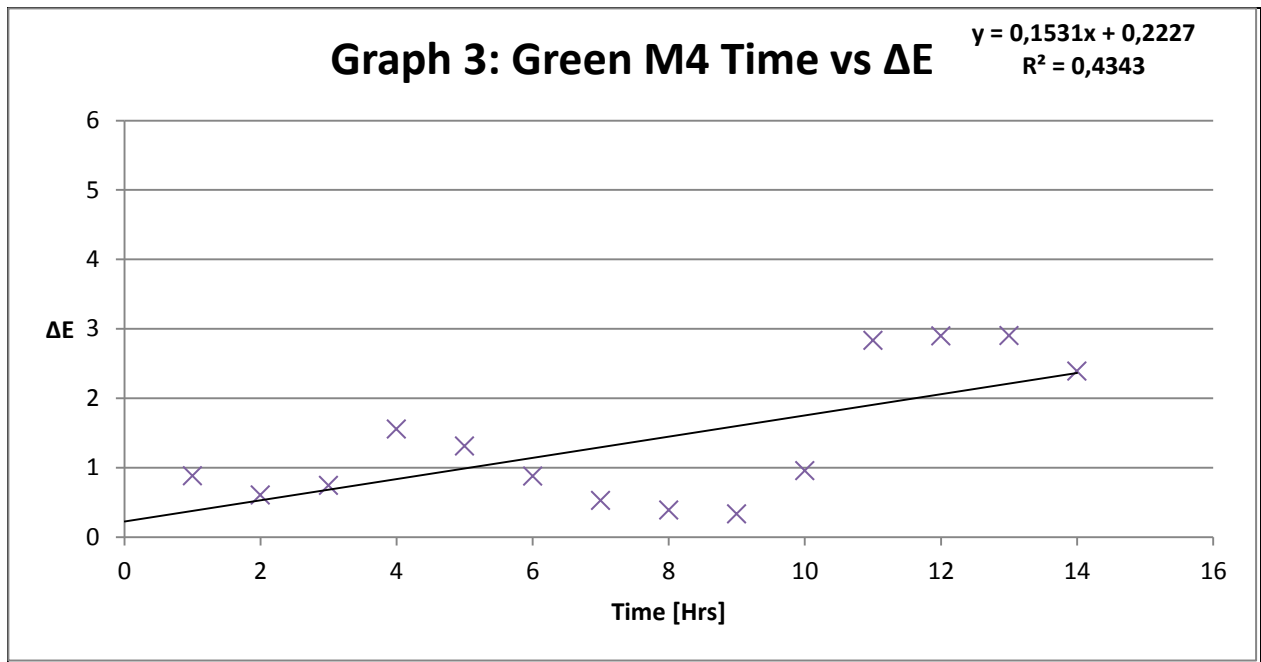
**Table 1:** Number of hours of washing against Maximum Reflectance

Number of Hours	Maximum Reflectance 520 nm
0	1.45285308
1	1.4541713
2	1.43282628
3	1.44554281
4	1.42430842
5	1.42878926
6	1.43032384
7	1.4311378
8	1.43536091
9	1.44641697
10	1.42888021
11	1.47860277
12	1.48896062
13	1.4860692
14	1.49370575



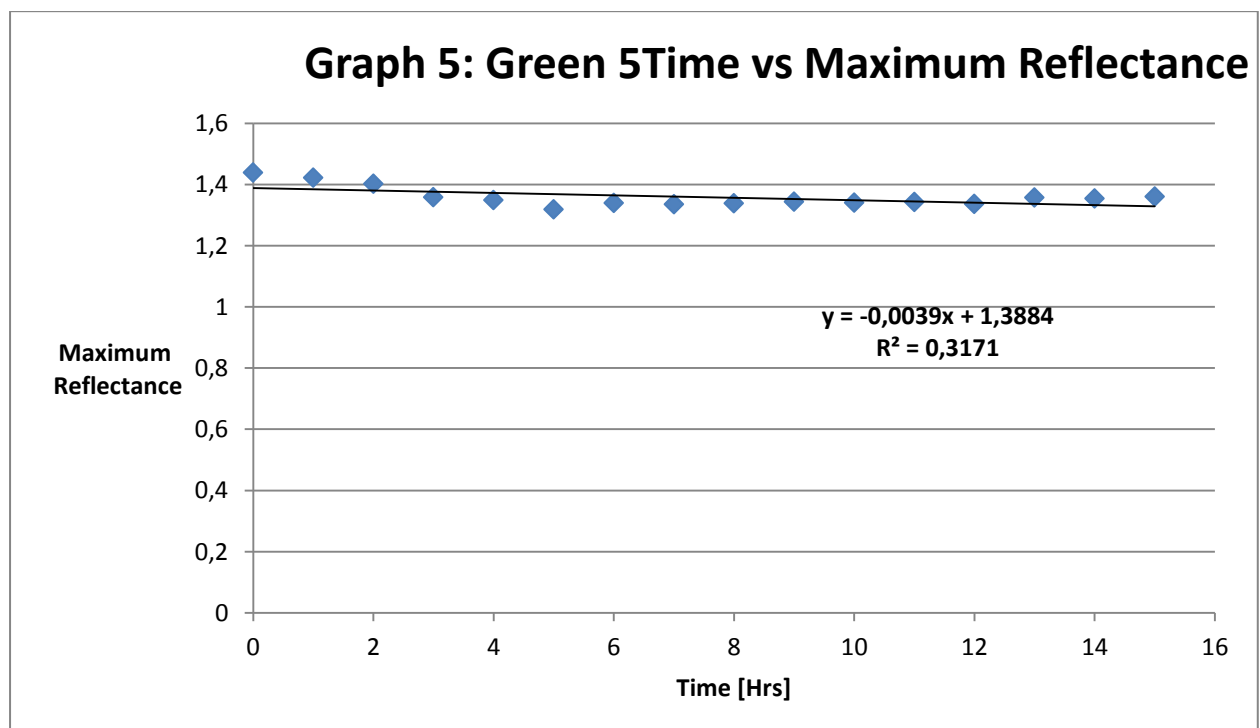
**Table 2:** Number of hours of washing against  $\Delta E$

Number of Hours	$\Delta E$
0	
1	0.882462
2	0.606477
3	0.741826
4	1.553263
5	1.310326
6	0.875013
7	0.525703
8	0.388106
9	0.33467
10	0.954731
11	2.833857
12	2.89686
13	2.902673
14	2.389466



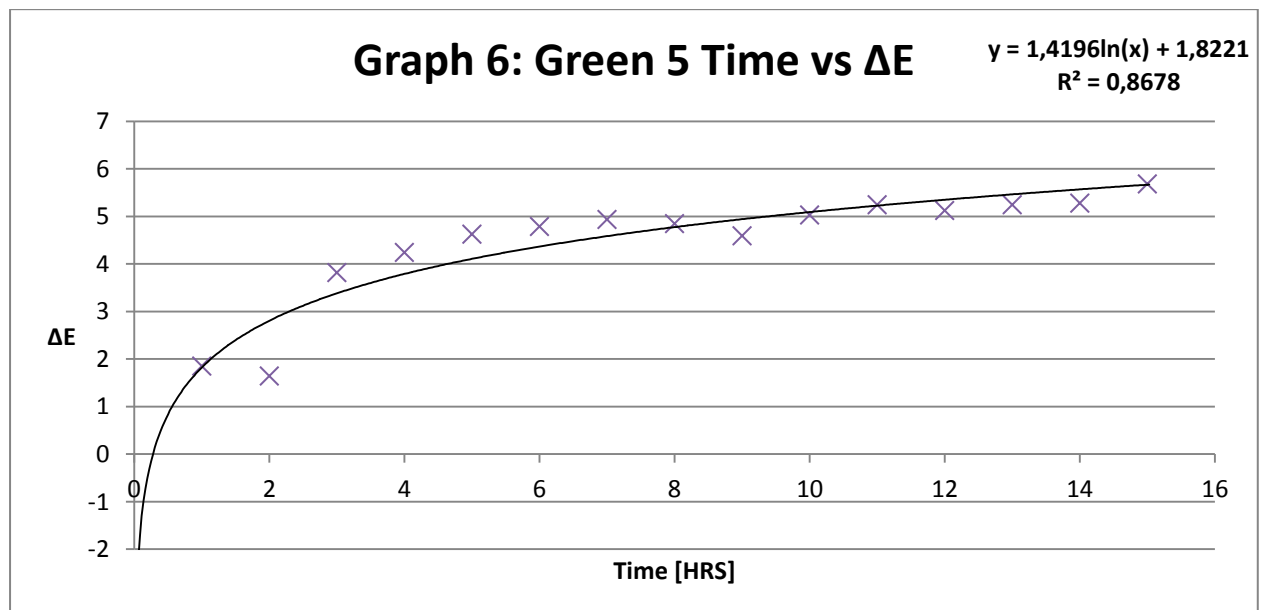
**Table 3:** Number of hours of washing against Maximum Reflectance

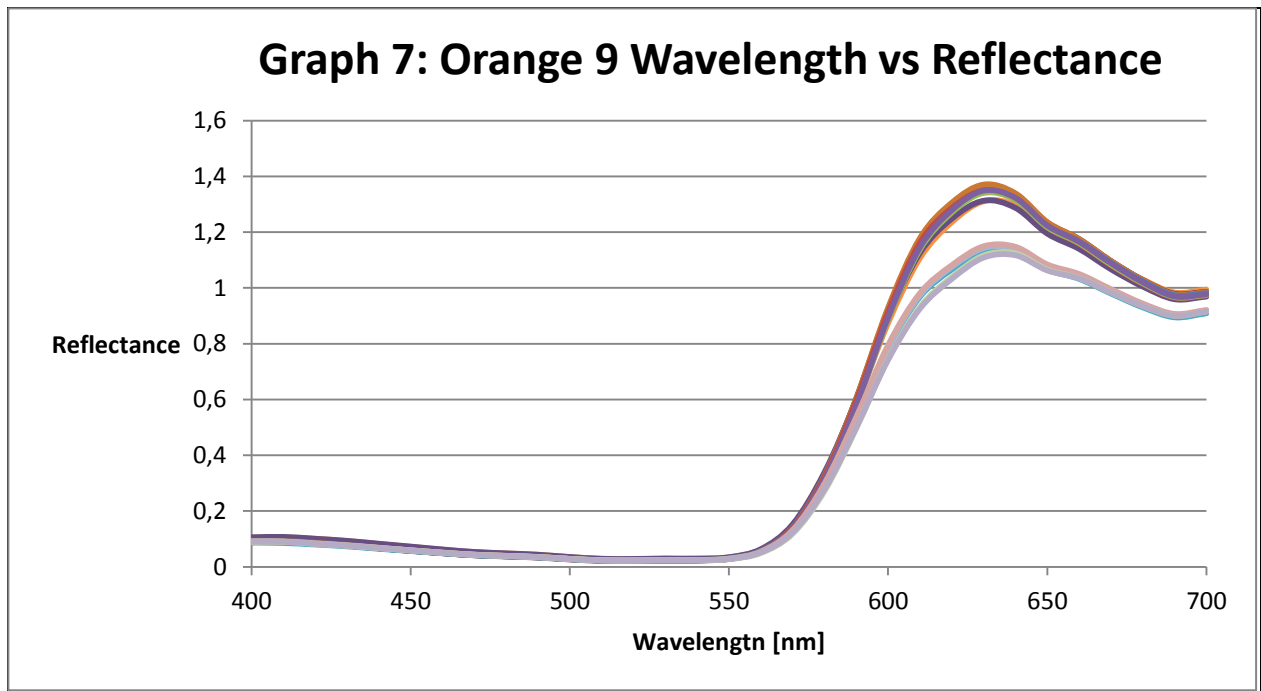
Number of Hours	Maximum Reflectance 520 nm
0	1.43874669
1	1.42228544
2	1.4028337
3	1.35877466
4	1.34956098
5	1.31842184
6	1.33945751
7	1.33565593
8	1.33852005
9	1.34425354
10	1.34023142
11	1.34297419
12	1.33698237
13	1.35742664
14	1.3537991
15	1.36017406



**Table 4:** Number of hours of washing against  $\Delta E$ 

Number of Hours	$\Delta E$
0	
1	1.850662
2	1.645212
3	3.816152
4	4.242187
5	4.625475
6	4.785214
7	4.935941
8	4.844615
9	4.589294
10	5.025842
11	5.245712
12	5.125646
13	5.245872
14	5.274589
15	5.684752

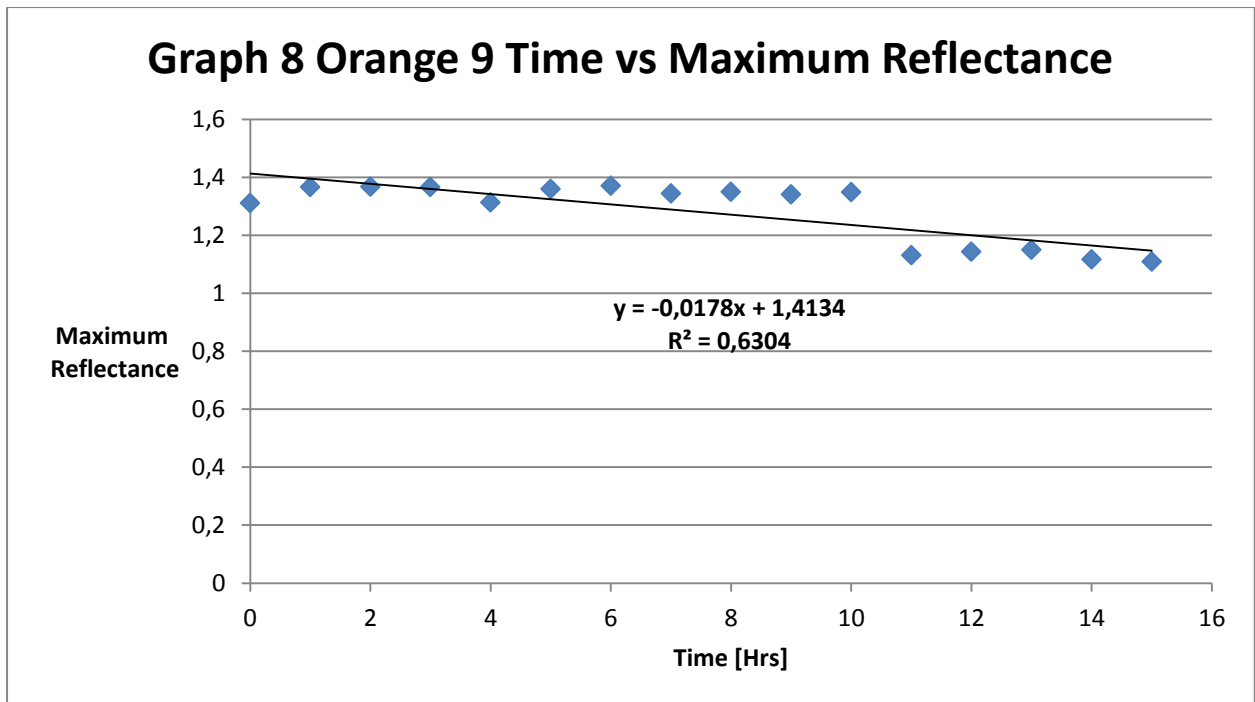




**Table 5: Number of hours of washing against Maximum Reflectance**

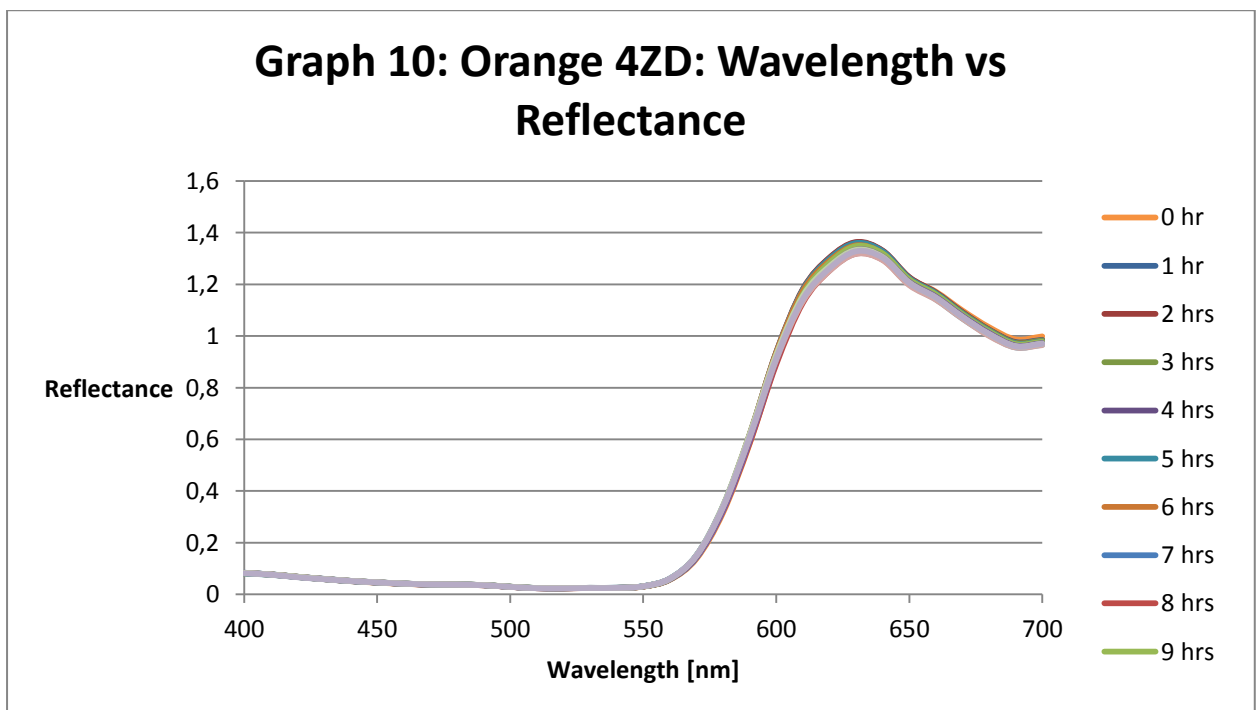
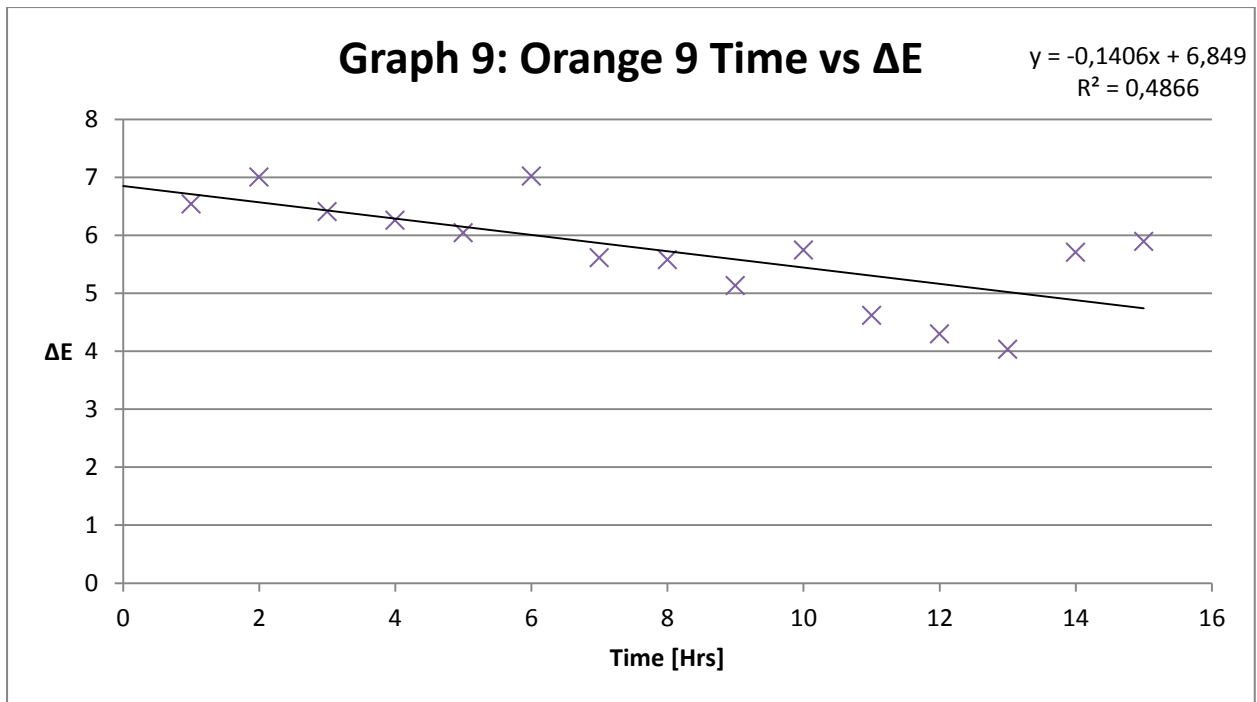
Number of Hours	Maximum Reflectance
0	1.31076038
1	1.36579931
2	1.36713862
3	1.36563921
4	1.31268835
5	1.35945392
6	1.37057948
7	1.34399199
8	1.34900165
9	1.34056592
10	1.34888721
11	1.13100696
12	1.14255297
13	1.14939833
14	1.11657619
15	1.10877609





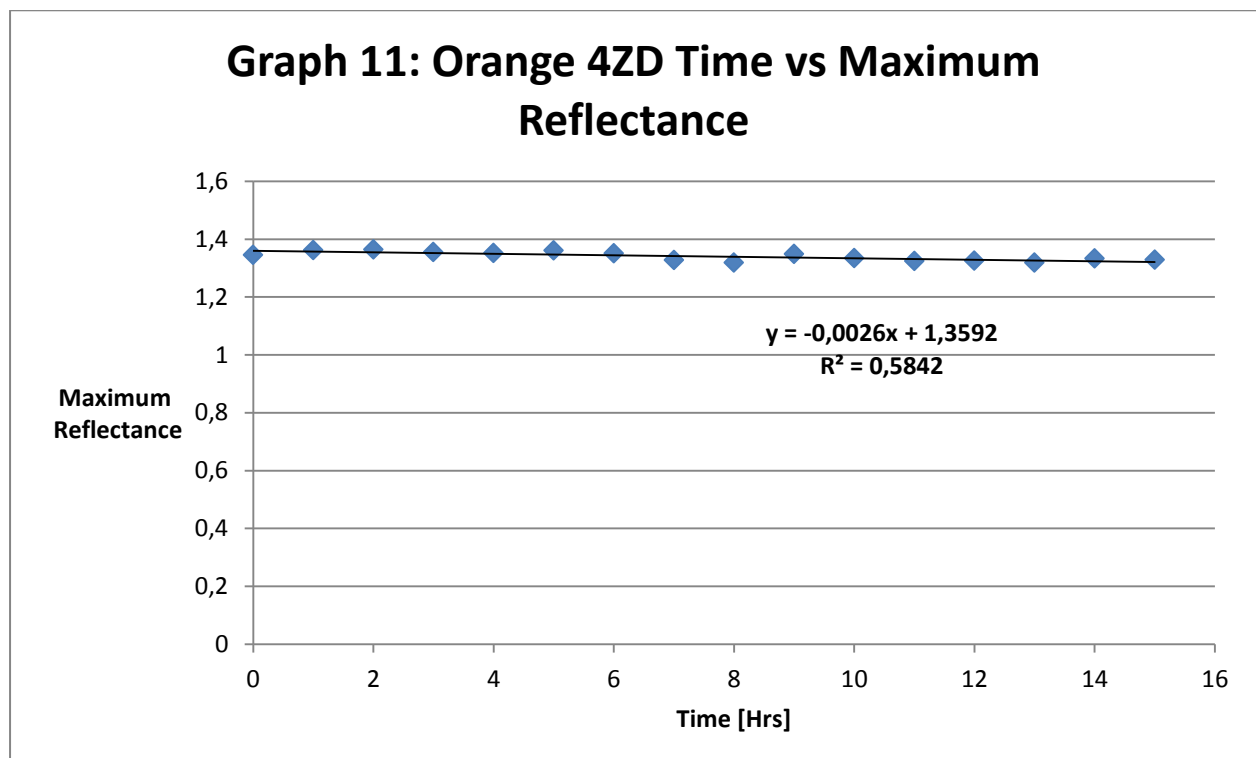
**Table 6: Number of hours of washing against  $\Delta E$**

Number of Hours	$\Delta E$
0	
1	6.538196
2	7.001804
3	6.407734
4	6.258742
5	6.040934
6	7.018074
7	5.609123
8	5.579197
9	5.131661
10	5.744748
11	4.616102
12	4.294901
13	4.03 409
14	5.704697
15	5.889119



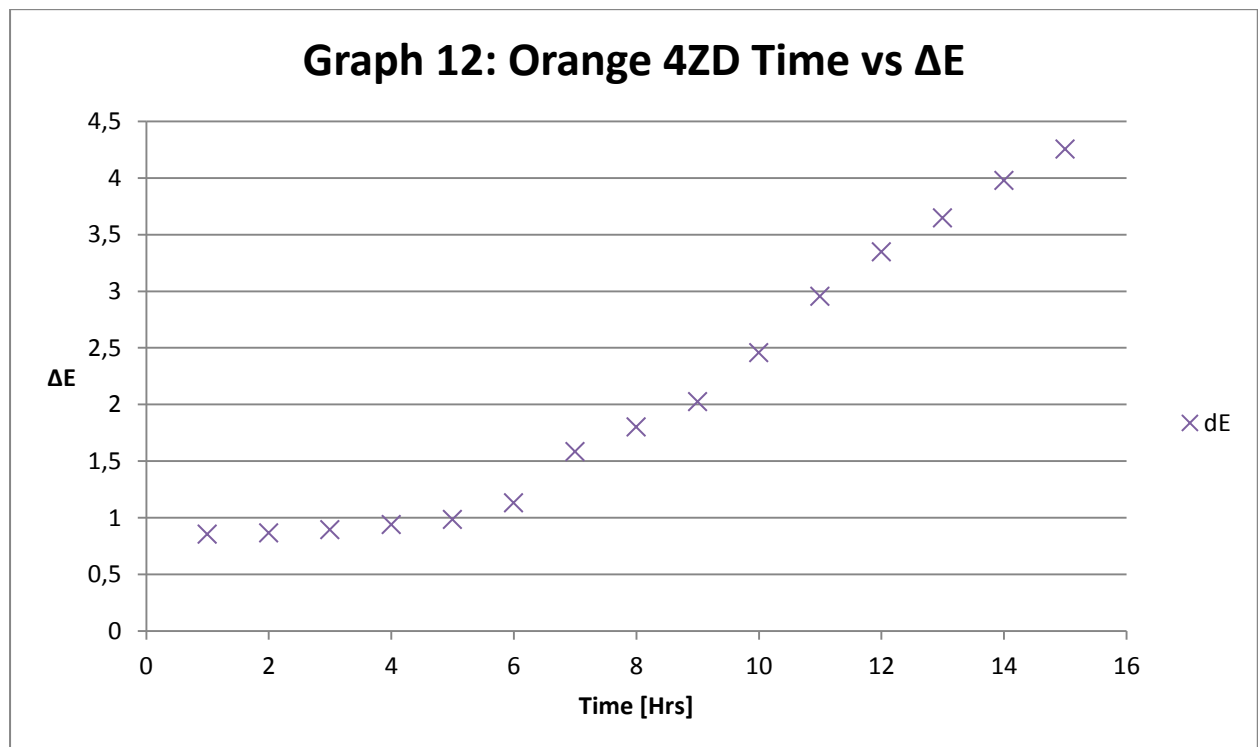
**Table 7: Number of hours of washing against Maximum Reflectance**

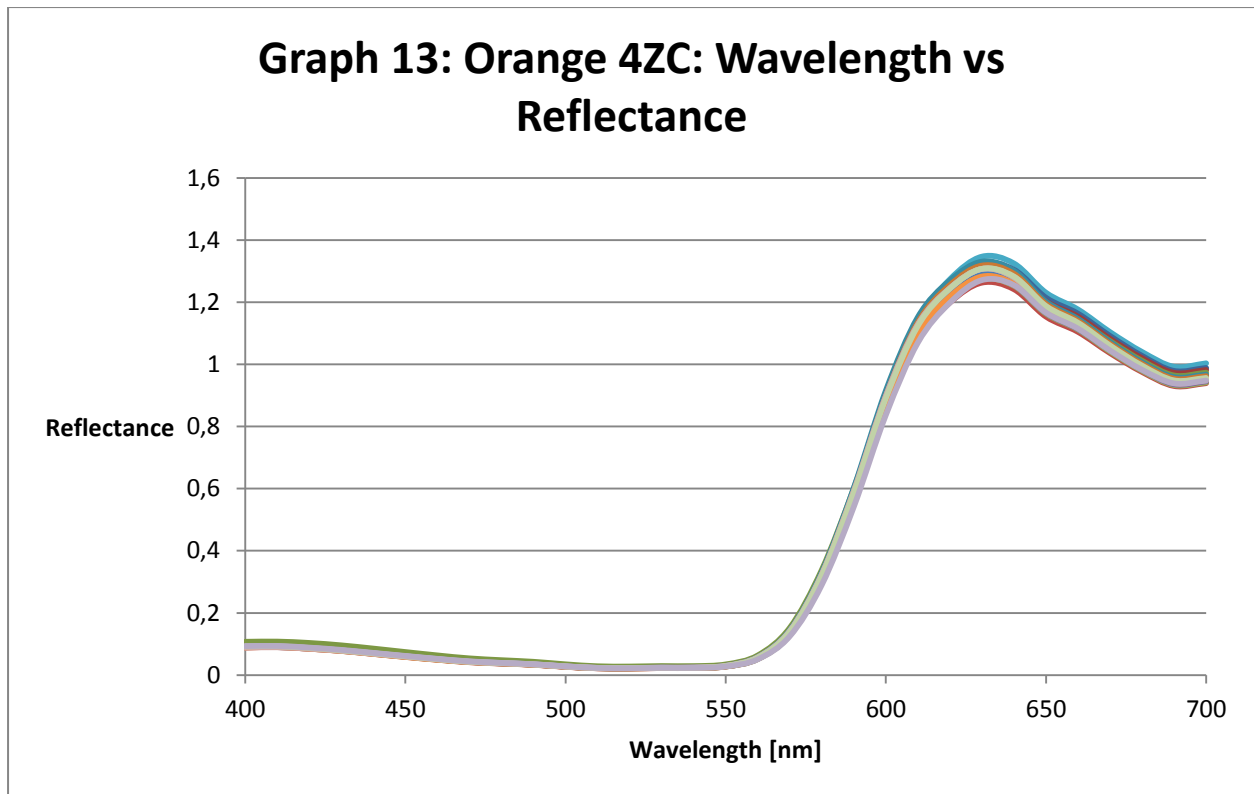
Number of Hours	Maximum Reflectance 630 nm
0	1.34491074
1	1.36163998
2	1.36344564
3	1.35424387
4	1.35113633
5	1.35972524
6	1.35078466
7	1.32724452
8	1.31854832
9	1.34775472
10	1.33382833
11	1.32318127
12	1.32517838
13	1.31782949
14	1.33310652
15	1.32775819



**Table 8: Number of hours of washing against  $\Delta E$** 

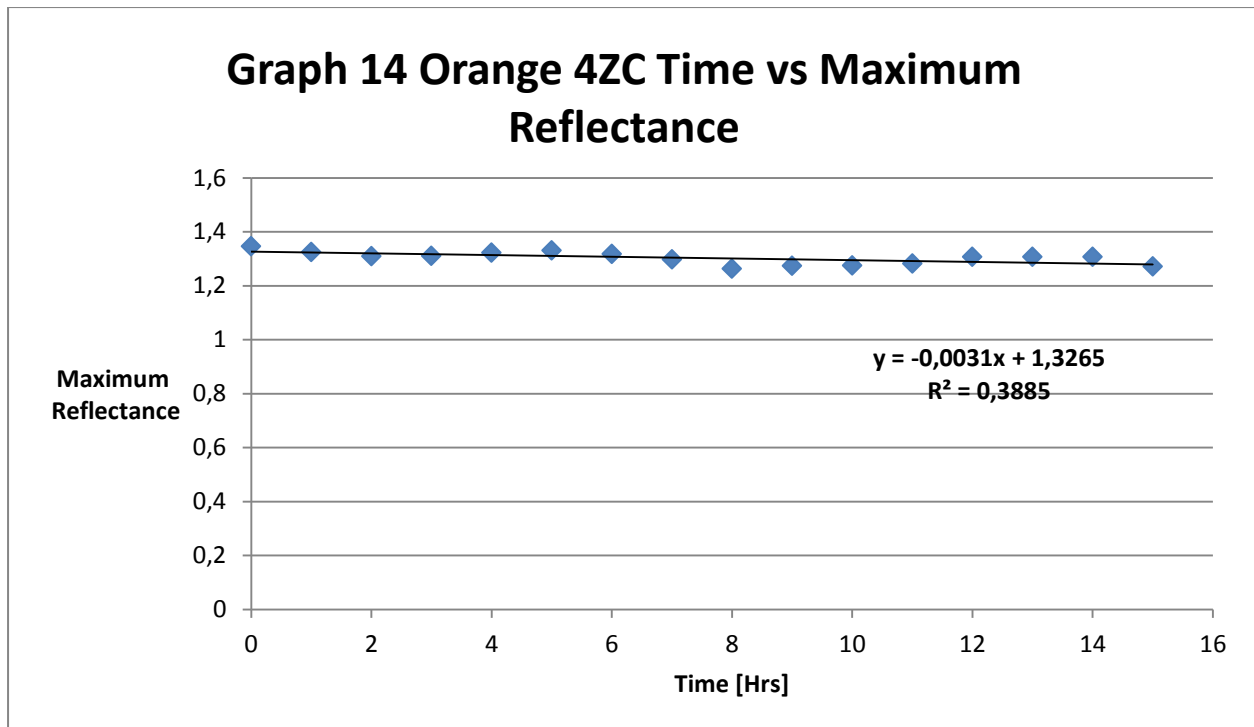
Number of Hours	$\Delta E$
0	
1	0.854521
2	0.865874
3	0.895412
4	0.940021
5	0.985471
6	1.132134
7	1.584578
8	1.801479
9	2.024587
10	2.45871
11	2.956215
12	3.347854
13	3.645871
14	3.7845
15	4.254873





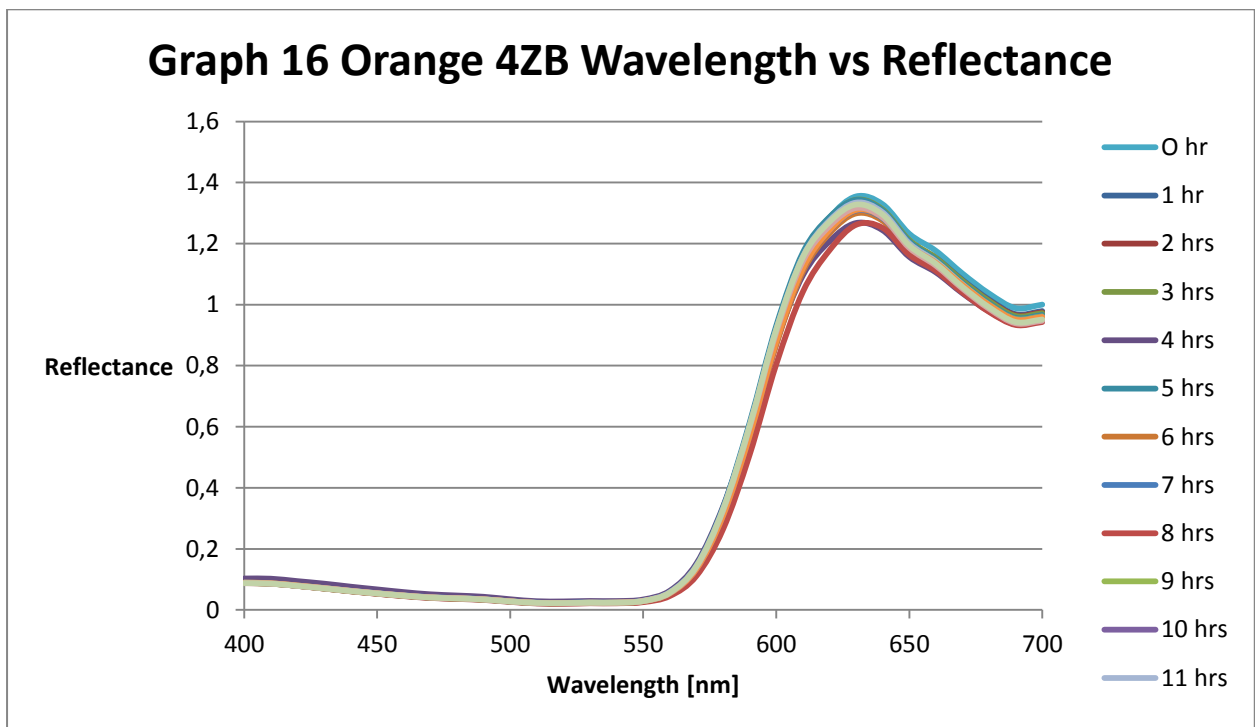
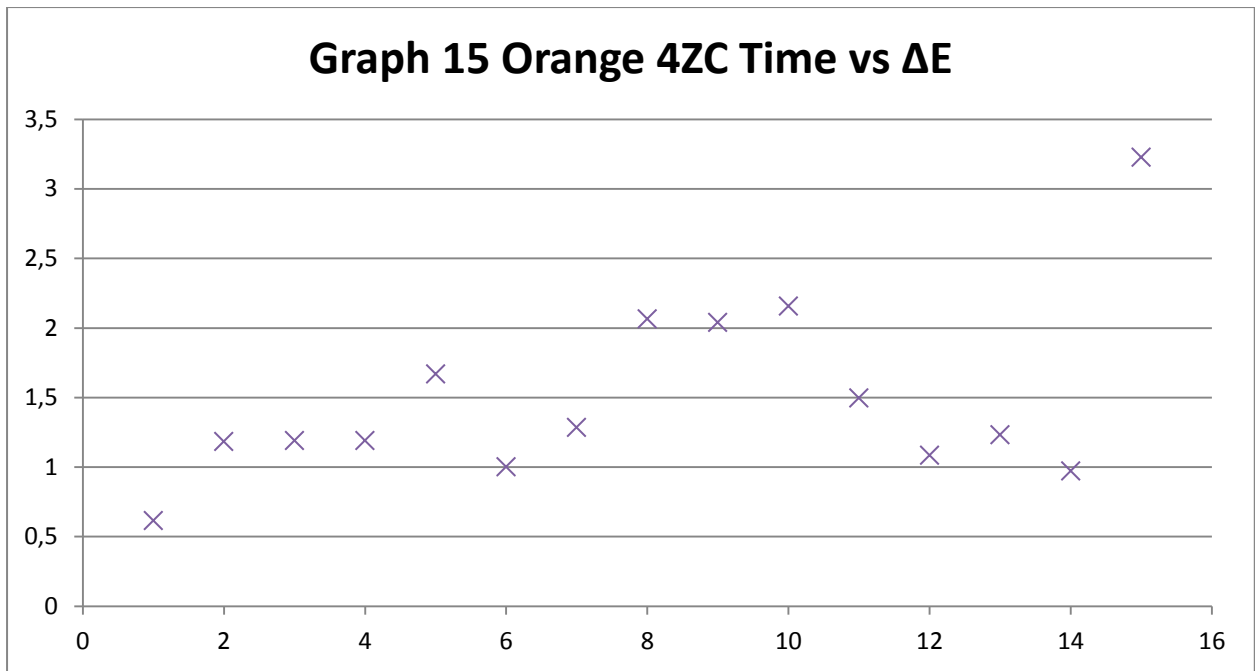
**Table 9: Number of hours of washing against Maximum Reflectance**

Number of Hours	Maximum Reflectance
0	1.34674168
1	1.32470524
2	1.30900896
3	1.31091928
4	1.32222652
5	1.33056712
6	1.31799388
7	1.29784536
8	1.26303554
9	1.2735759
10	1.27468395
11	1.28264499
12	1.30705118
13	1.30731893
14	1.30758977
15	1.27128339



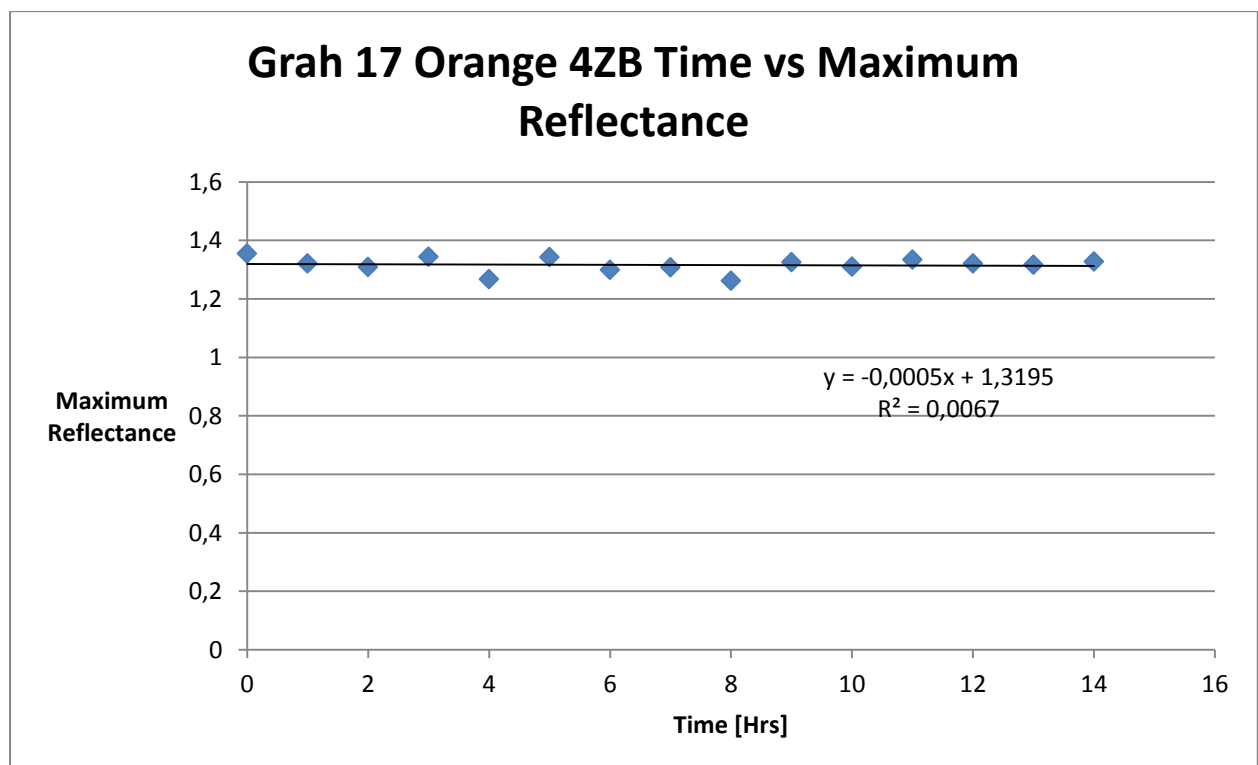
**Table 10: Number of hours of washing against  $\Delta E$**

Number of Hours	$\Delta E$
0	
1	0.613675
2	1.183702
3	1.188978
4	1.190363
5	1.668837
6	1.000801
7	1.284618
8	2.06442
9	2.03876
10	2.156741
11	1.496861
12	1.084689
13	1.231151
14	0.71646
15	3.227261



**Table 11: Number of hours of washing against Maximum Reflectance**

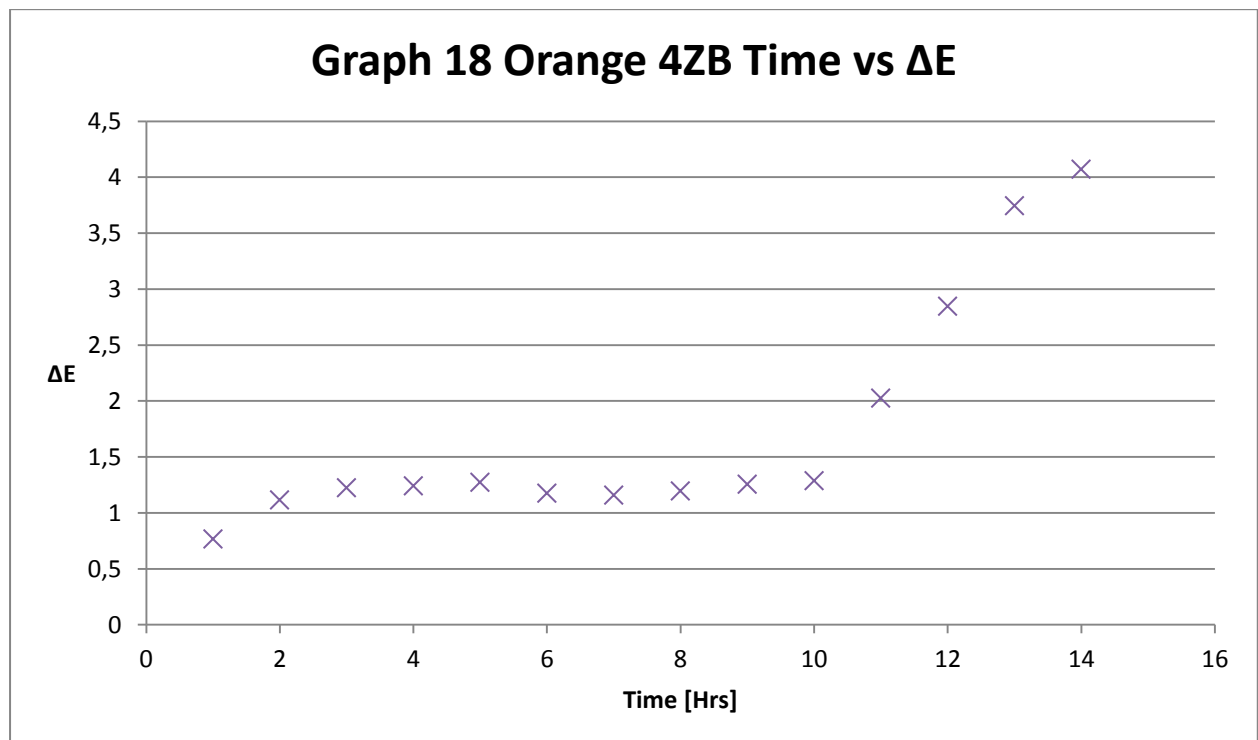
Number of Hours	Maximum Reflectance
0	1.35453463
1	1.32140124
2	1.30865467
3	1.34370089
4	1.26741934
5	1.34275854
6	1.29886317
7	1.30834198
8	1.2615546
9	1.32574403
10	1.3101207
11	1.33425069
12	1.32145274
13	1.31665456
14	1.32778335

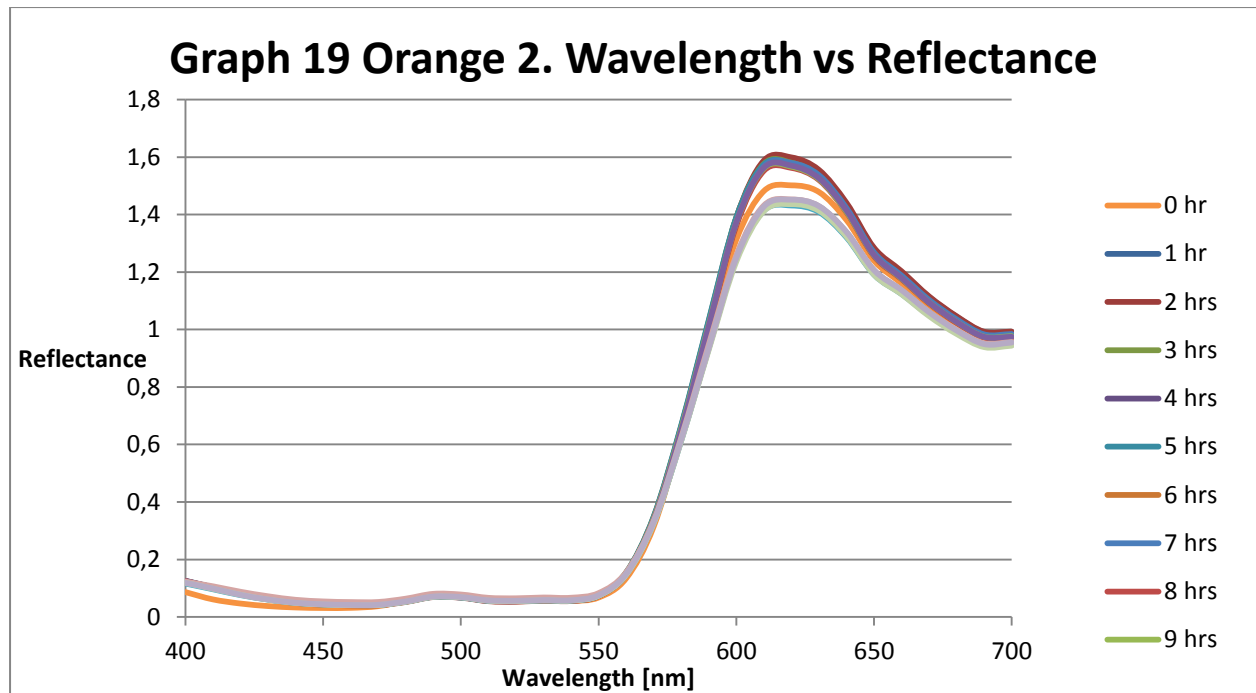




**Table 12: Number of hours of washing against  $\Delta E$** 

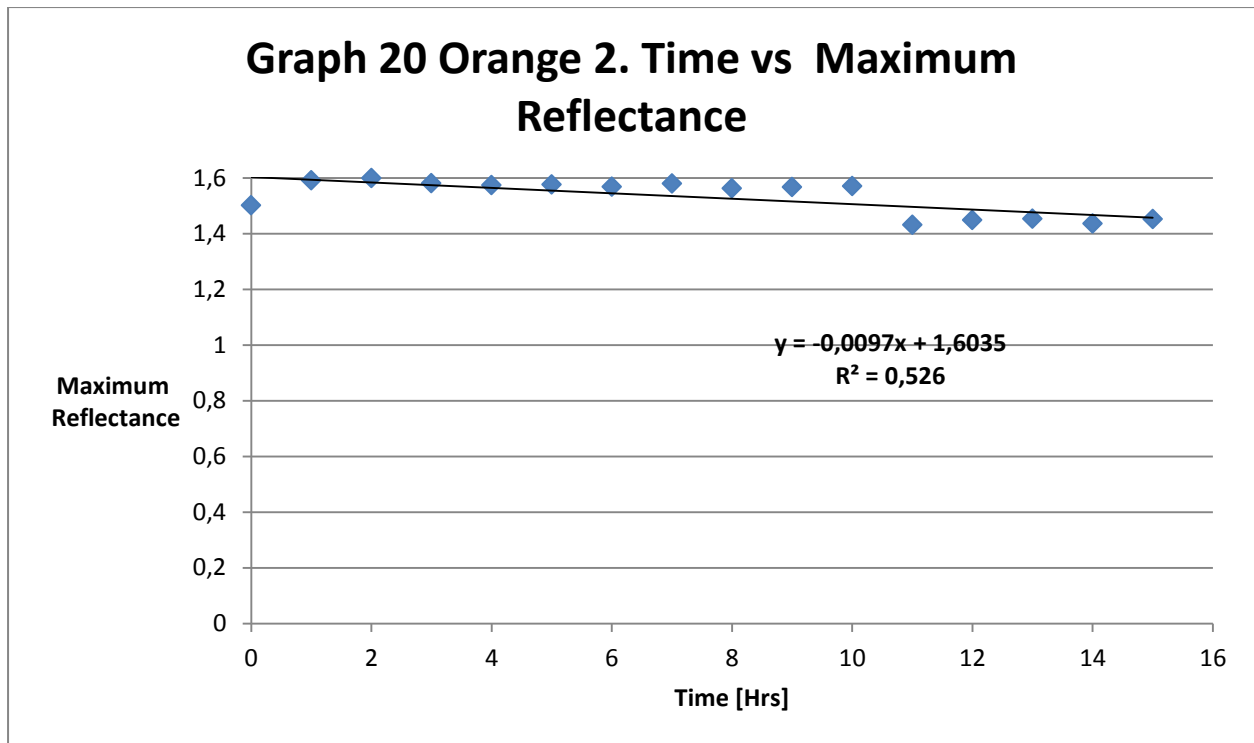
Number of Hours	$\Delta E$
0	
1	0.76577
2	1.114709
3	1.223543
4	1.242501
5	1.272693
6	1.17584
7	1.159423
8	1.194578
9	1.254741
10	1.287089
11	2.024785
12	2.84571
13	3.745871
14	4.07158





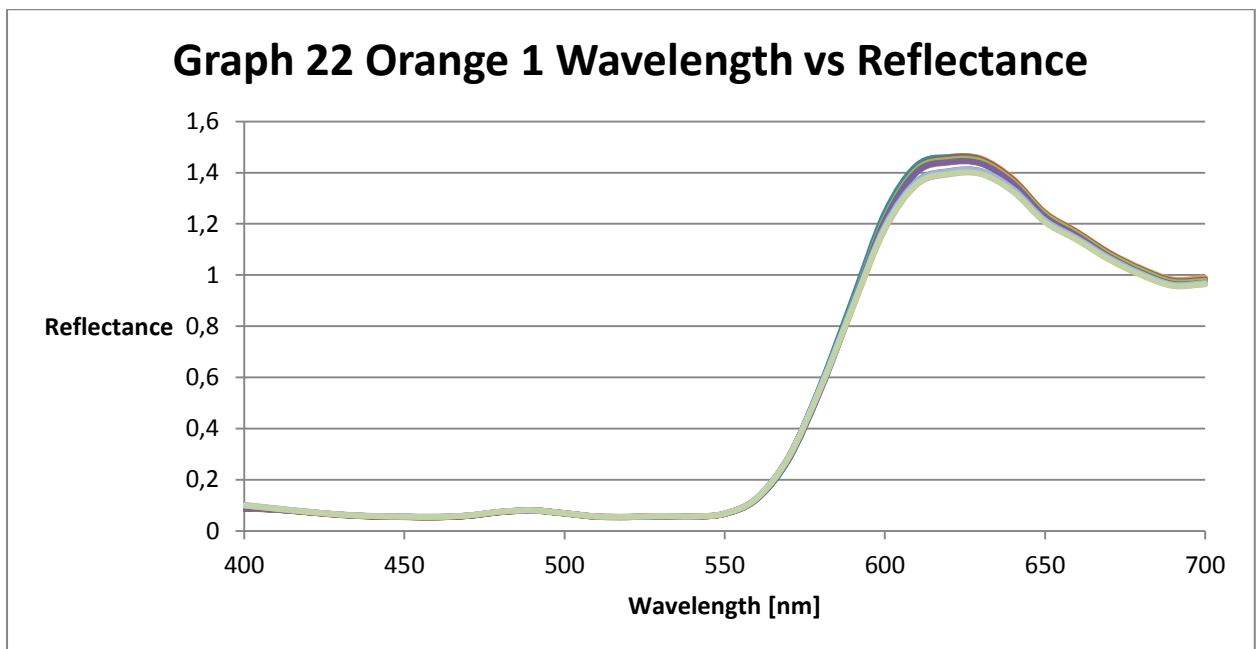
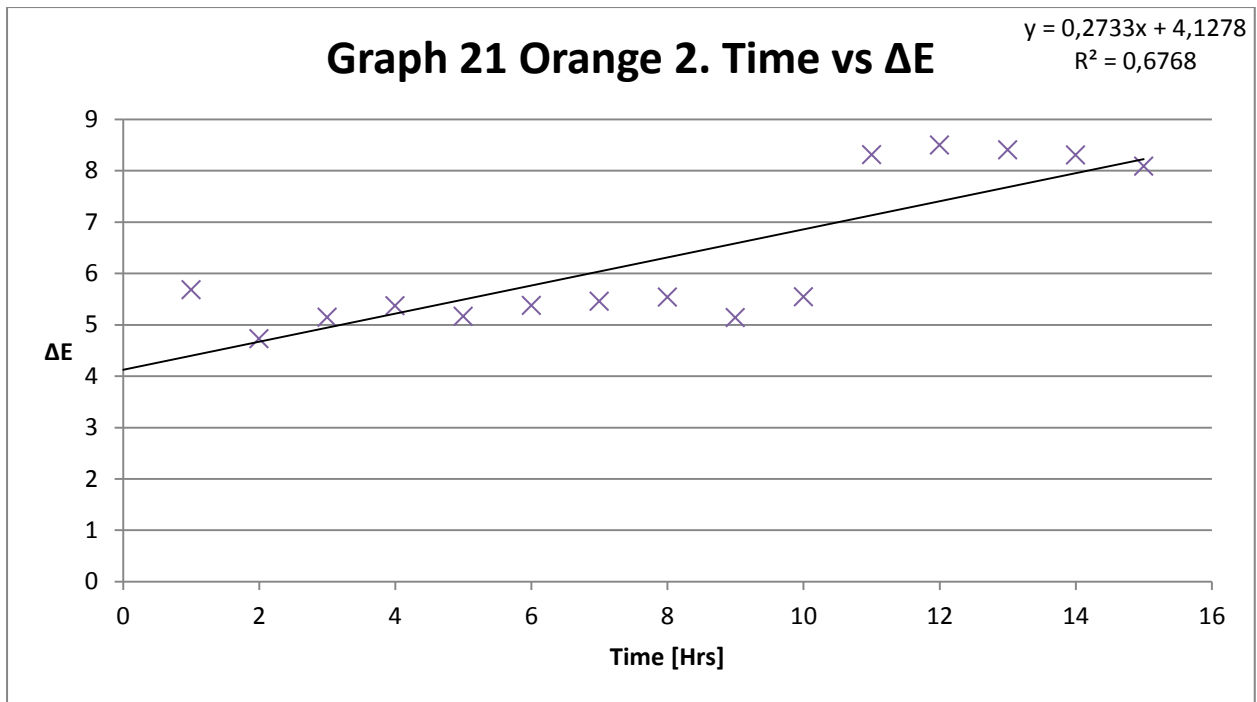
**Table 13: Number of hours of washing against Maximum Reflectance**

Number of Hours	Maximum Reflectance 620 nm
0	1.50170135
1	1.59123683
2	1.59890985
3	1.58056223
4	1.57336414
5	1.5766232
6	1.56759083
7	1.5795635
8	1.56246448
9	1.56675029
10	1.57018328
11	1.43162572
12	1.44844782
13	1.45264149
14	1.43624651
15	1.45168853



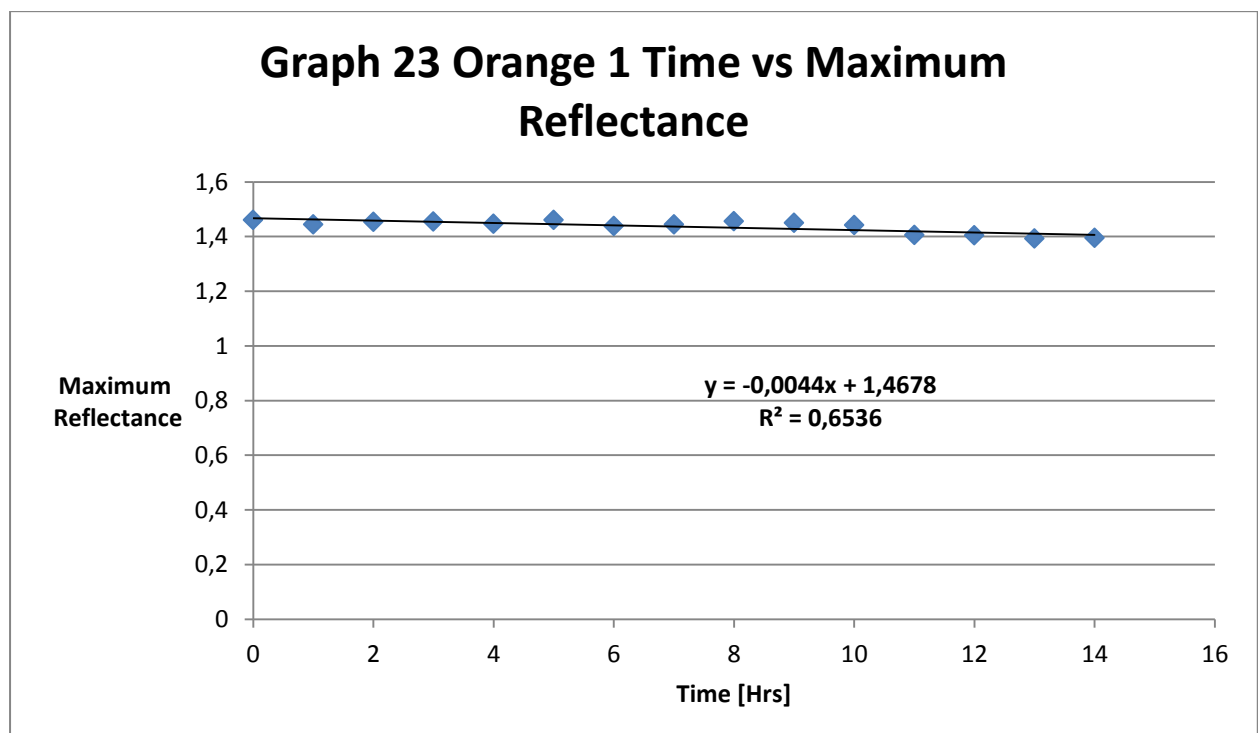
**Table 14: Number of hours of washing against  $\Delta E$**

Number of Hours	$\Delta E$
0	
1	5.679962
2	4.725637
3	5.14406
4	5.368446
5	5.162865
6	5.372667
7	5.456528
8	5.536628
9	5.134362
10	5.542734
11	8.310337
12	8.495011
13	11.72263
14	8 301136
15	8.082797



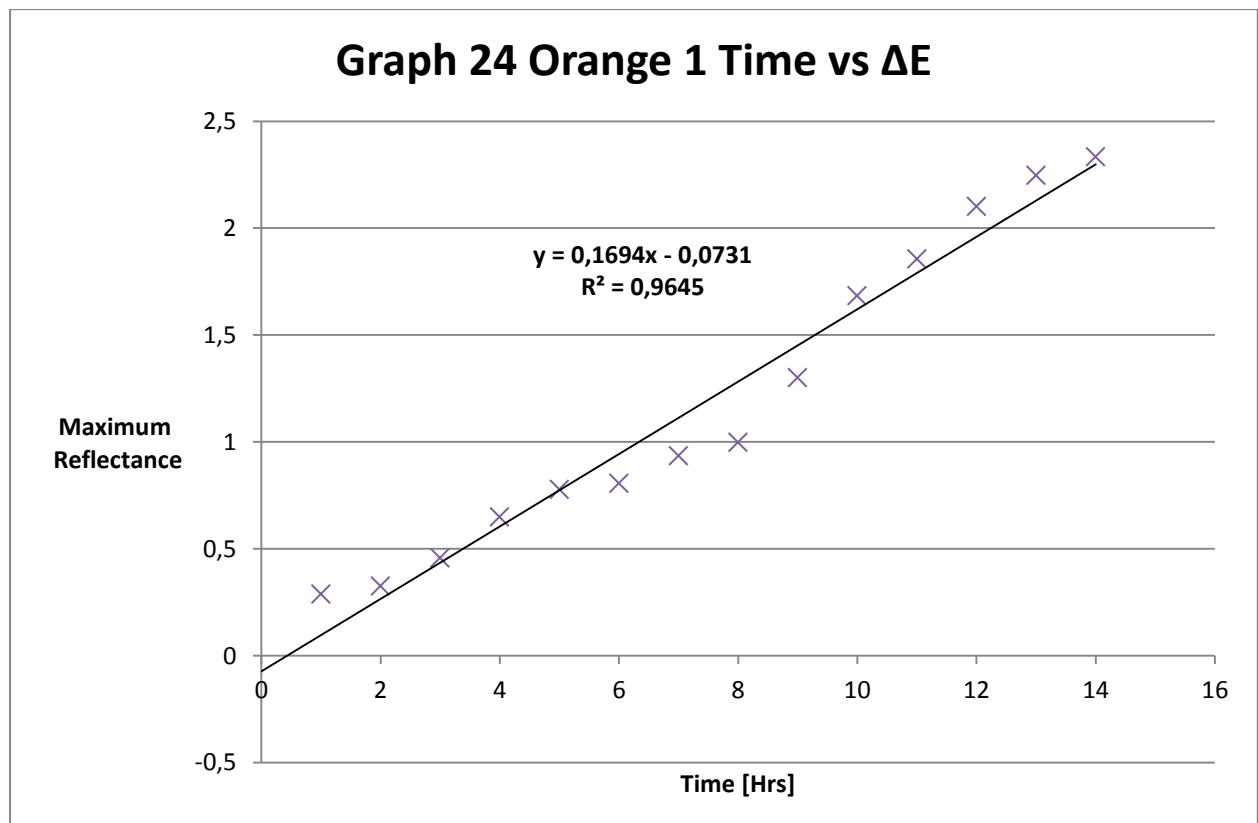
**Table 15: Number of hours of washing against Maximum Reflectance**

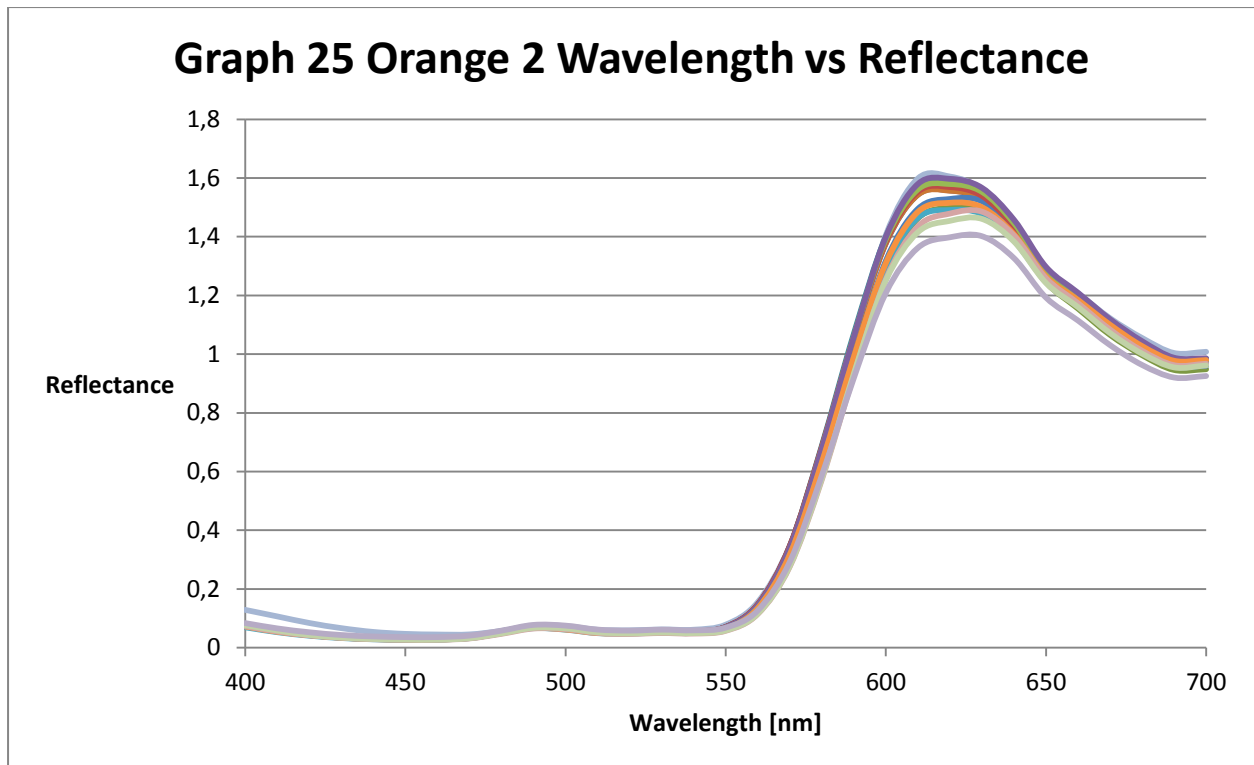
Number of Hours	Maximum Reflectance 620 nm
0	1.46084535
1	1.44431317
2	1.45373869
3	1.45556593
4	1.44710445
5	1.46146154
6	1.43904185
7	1.4448514
8	1.45612478
9	1.45084453
10	1.44186544
11	1.40643024
12	1.40508318
13	1.39288127
14	1.39477086



**Table 16: Number of hours of washing against  $\Delta E$** 

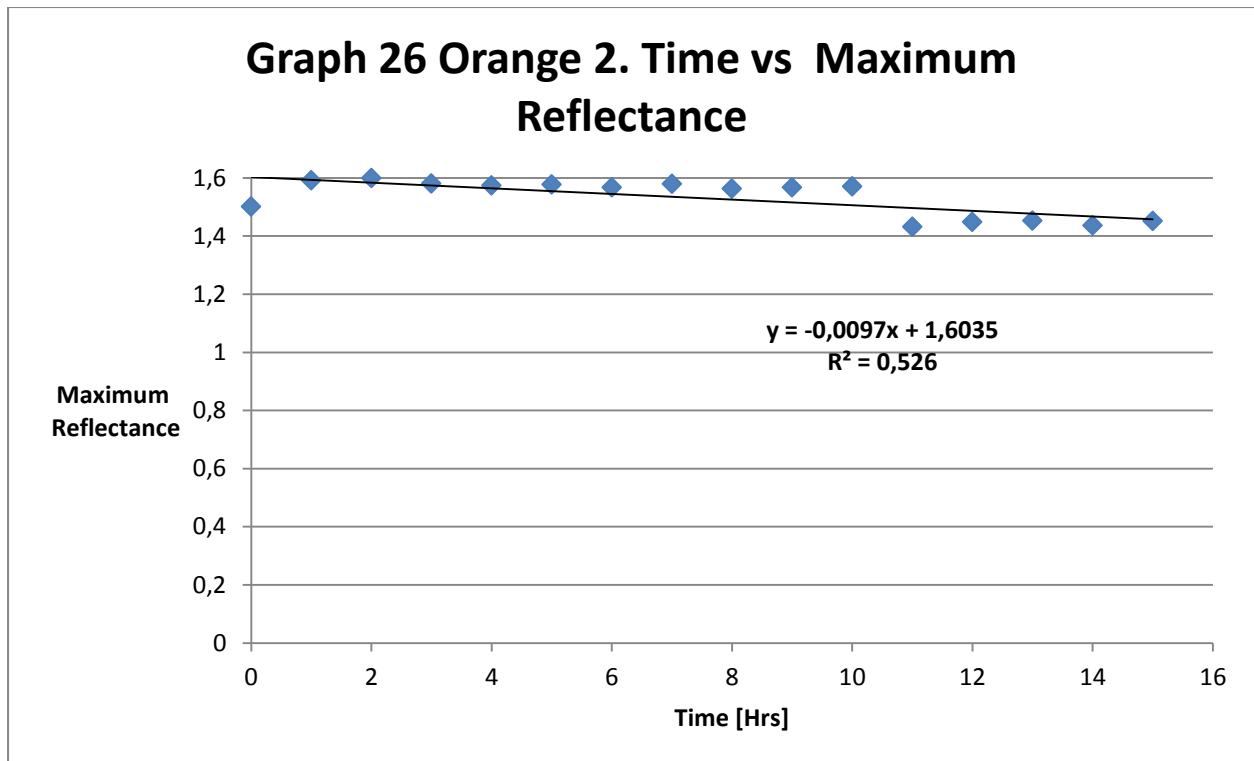
Number of Hours	$\Delta E$
0	
1	0.886192
2	0.362347
3	0.153347
4	0.317829
5	0.778237
6	0.651569
7	0.88934
8	0.457285
9	0.384158
10	0.620163
11	1.856791
12	2.102007
13	2.45989
14	2.333959





**Table 17: Number of hours of washing against Maximum Reflectance**

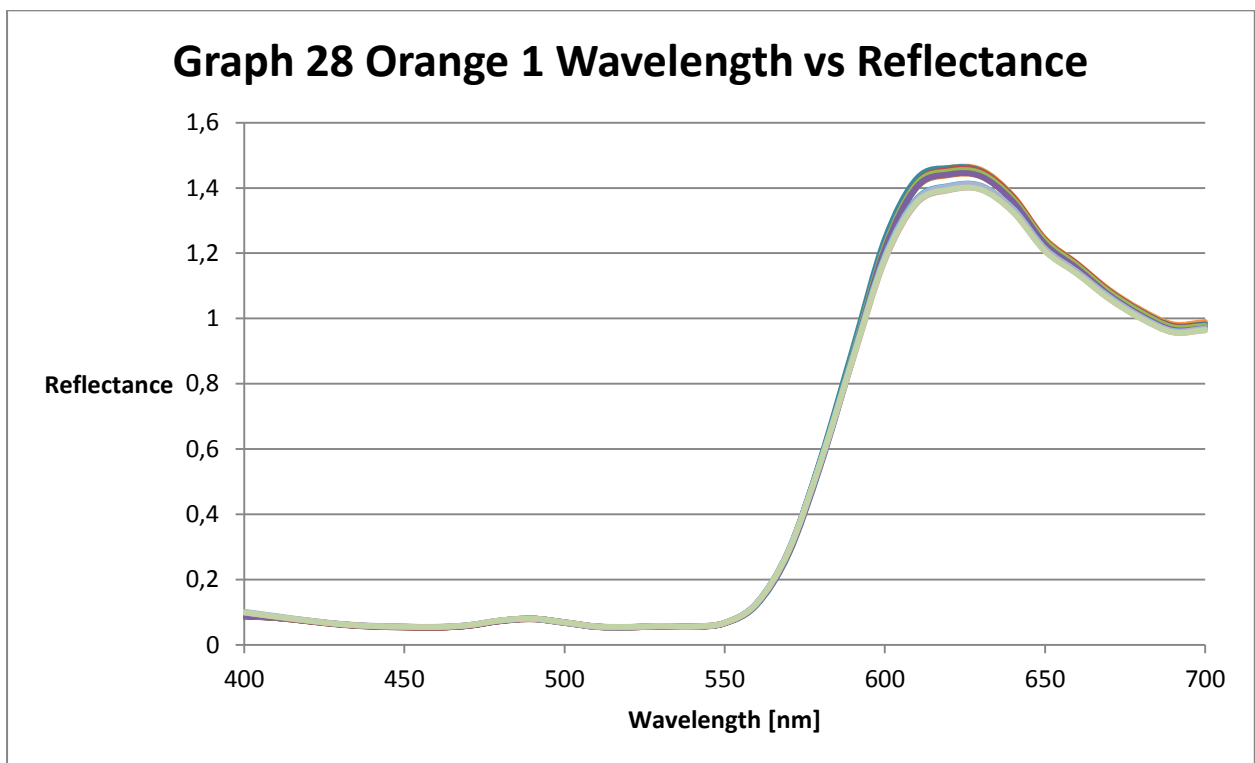
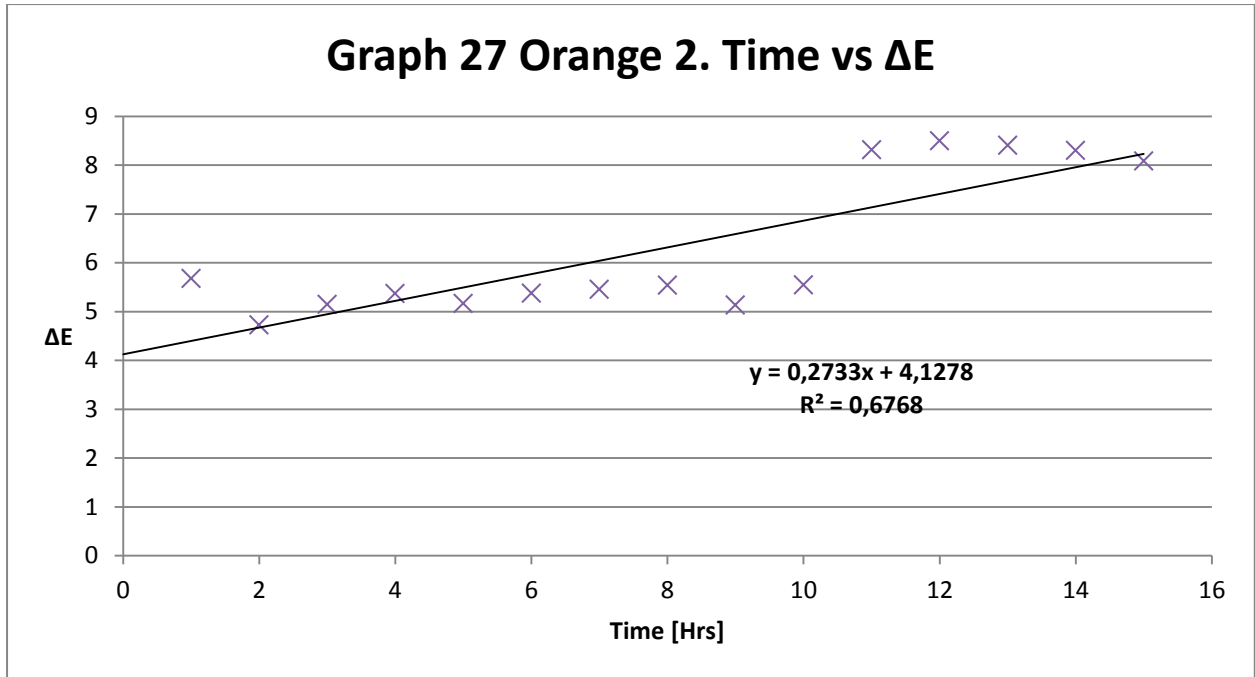
Number of Hours	Maximum Reflectance 620 nm
0	1.50170135
1	1.59123683
2	1.59890985
3	1.58056223
4	1.57336414
5	1.5766232
6	1.56759083
7	1.5795635
8	1.56246448
9	1.56675029
10	1.57018328
11	1.43162572
12	1.44844782
13	1.45264149
14	1.43624651
15	1.45168853



**Table 18: Number of hours of washing against  $\Delta E$**

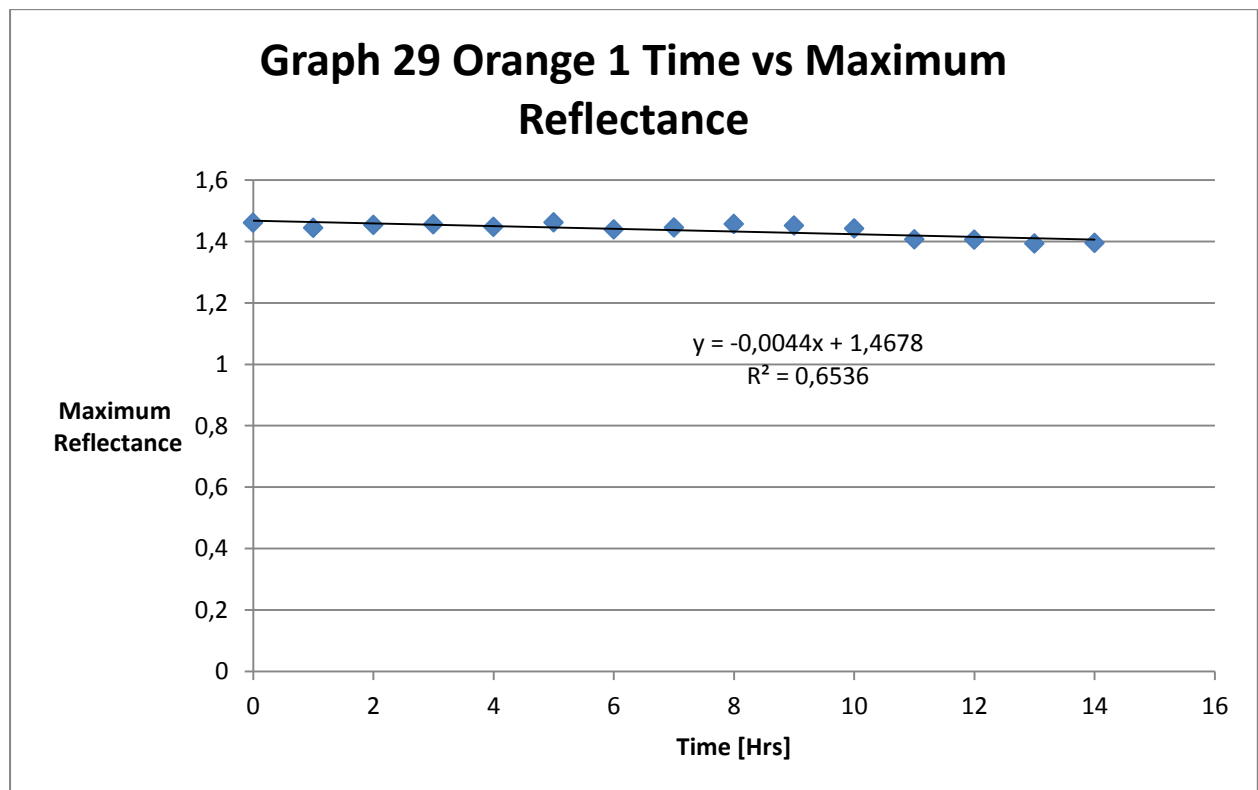
Number of Hours	$\Delta E$
0	
1	5.679962
2	4.725637
3	5.14406
4	5.368446
5	5.162865
6	5.372667
7	5.456528
8	5.536628
9	5.134362
10	5.542734
11	8.310337
12	8.495011
13	8.402547
14	.301136
15	8.082797





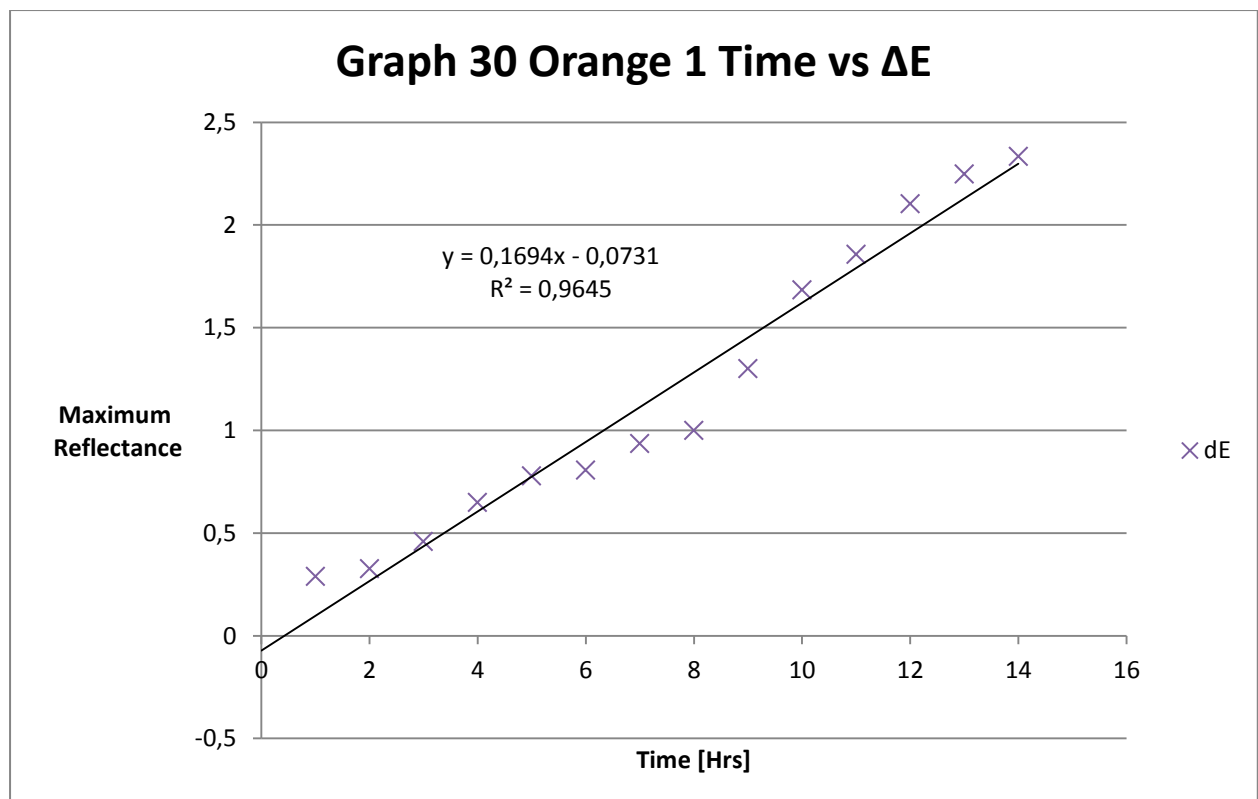
**Table 19: Number of hours of washing against Maximum Reflectance**

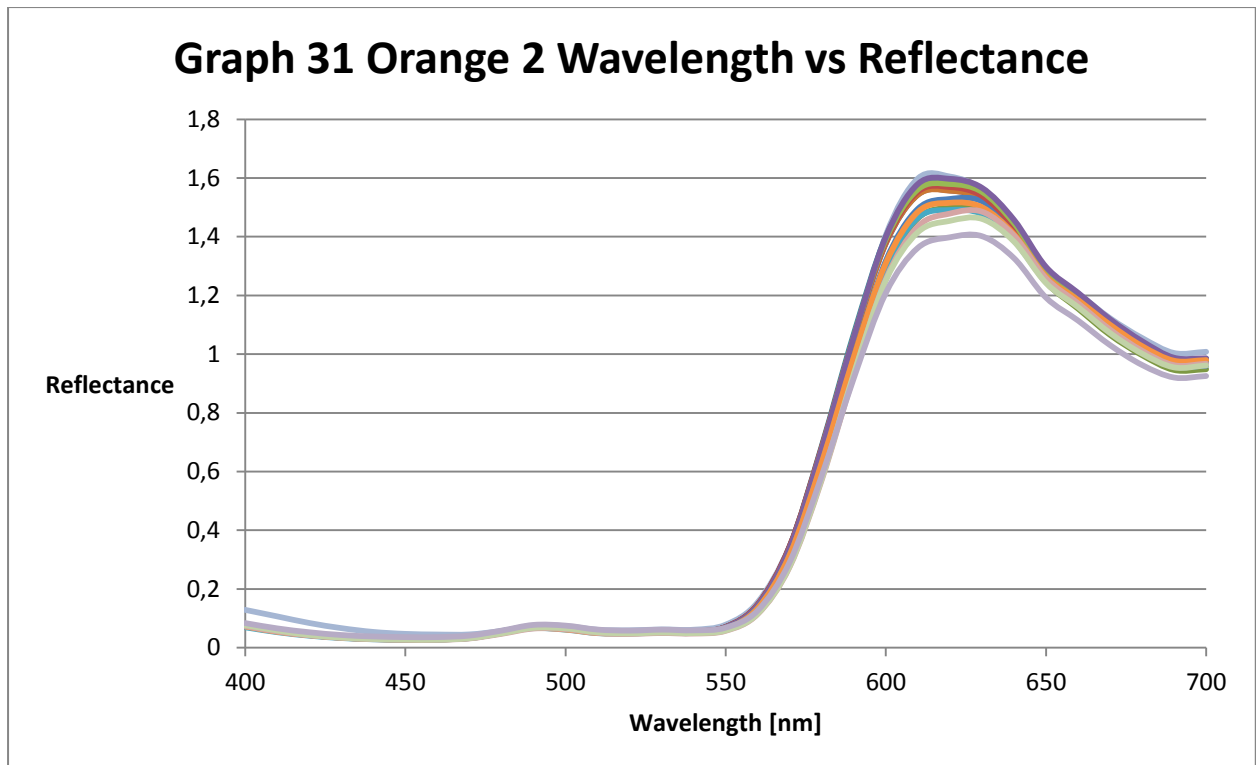
Number of Hours	Maximum Reflectance
0	1.46084535
1	1.44431317
2	1.45373869
3	1.45556593
4	1.44710445
5	1.46146154
6	1.43904185
7	1.4448514
8	1.45612478
9	1.45084453
10	1.44186544
11	1.40643024
12	1.40508318
13	1.39288127
14	1.39477086



**Table 20: Number of hours of washing against  $\Delta E$** 

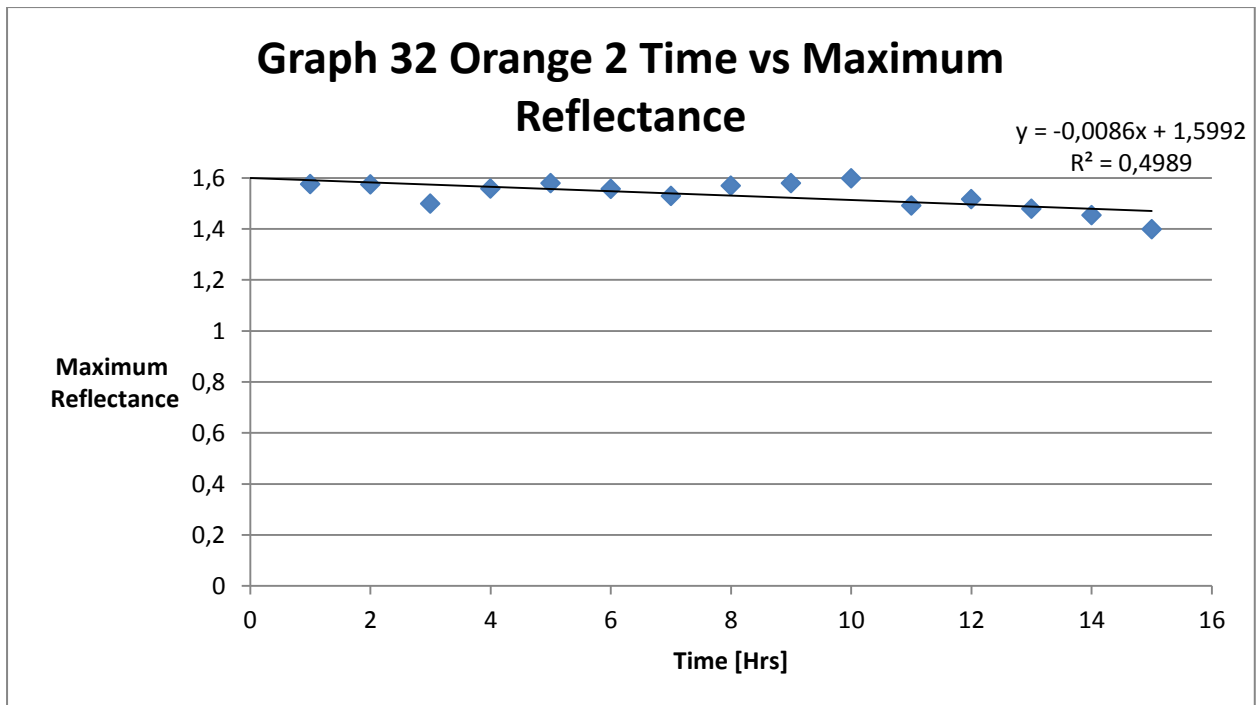
Number of Hours	$\Delta E$
0	
1	0.28795
2	0.325487
3	0.45782
4	0.64852
5	0.778237
6	0.805875
7	0.935481
8	0.998722
9	1.300525
10	1.684216
11	1.856791
12	2.102007
13	2.247591
14	2.333959





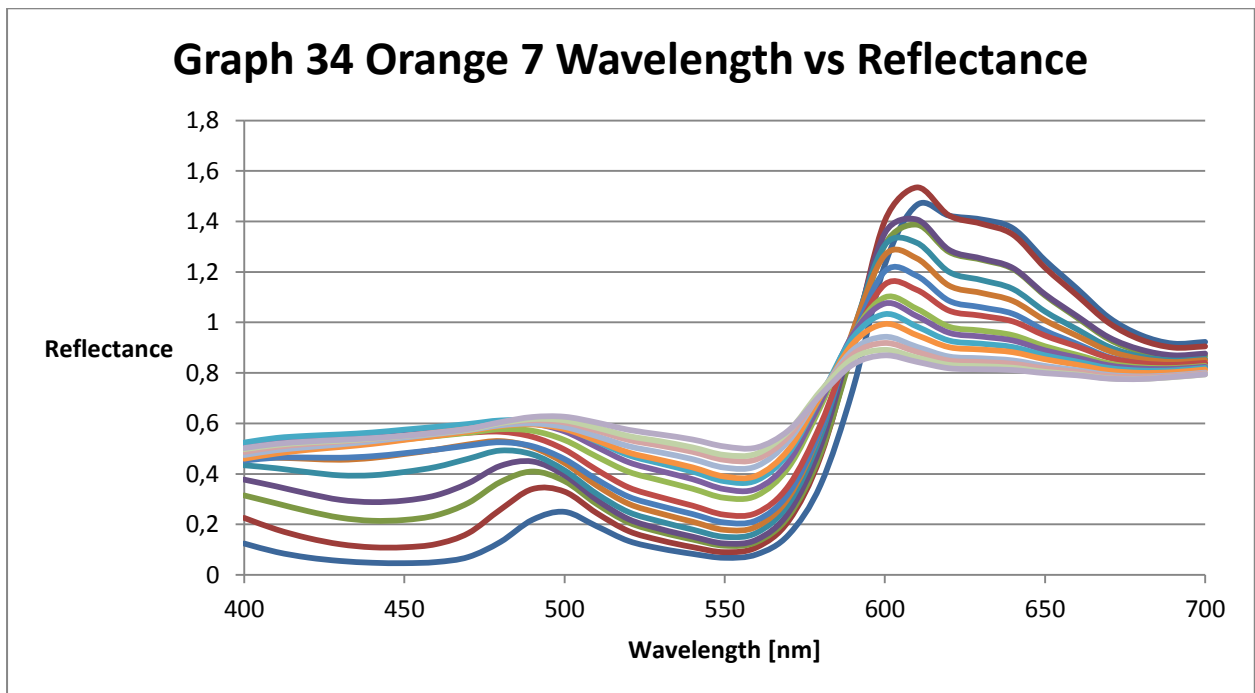
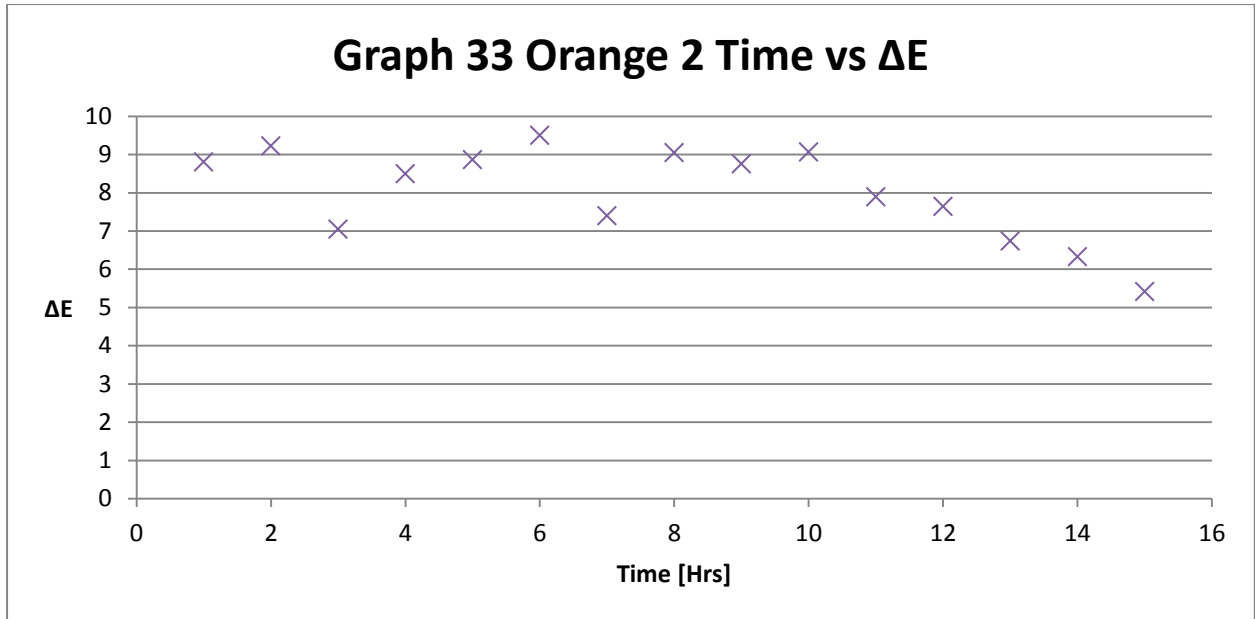
**Table 21: Number of hours of washing against Maximum Reflectance**

Number of Hours	Maximum Reflectance
0	1.60504246
1	1.57486296
2	1.57376361
3	1.49840117
4	1.55770946
5	1.5796237
6	1.55675435
7	1.52865183
8	1.56935537
9	1.57947719
10	1.59725082
11	1.49104357
12	1.51563644
13	1.47887743
14	1.4540745
15	1.39813924



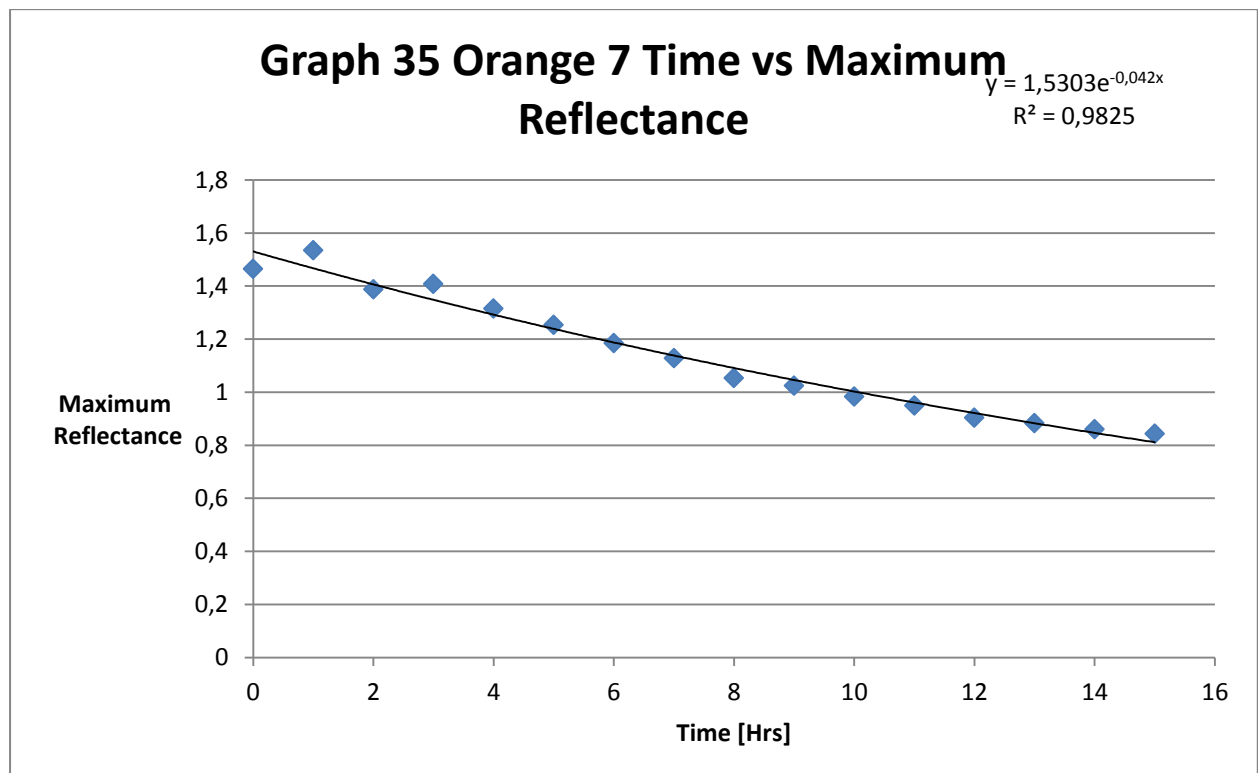
**Table 22: Number of hours of washing against ΔE**

Number of Hours	ΔE
0	
1	8.801147
2	9.219465
3	7.041737
4	8.493202
5	8.865494
6	9.499386
7	7.399414
8	9.049105
9	8.755987
10	9.065387
11	7.887889
12	7.642918
13	6.734514
14	.324642
15	5.412548



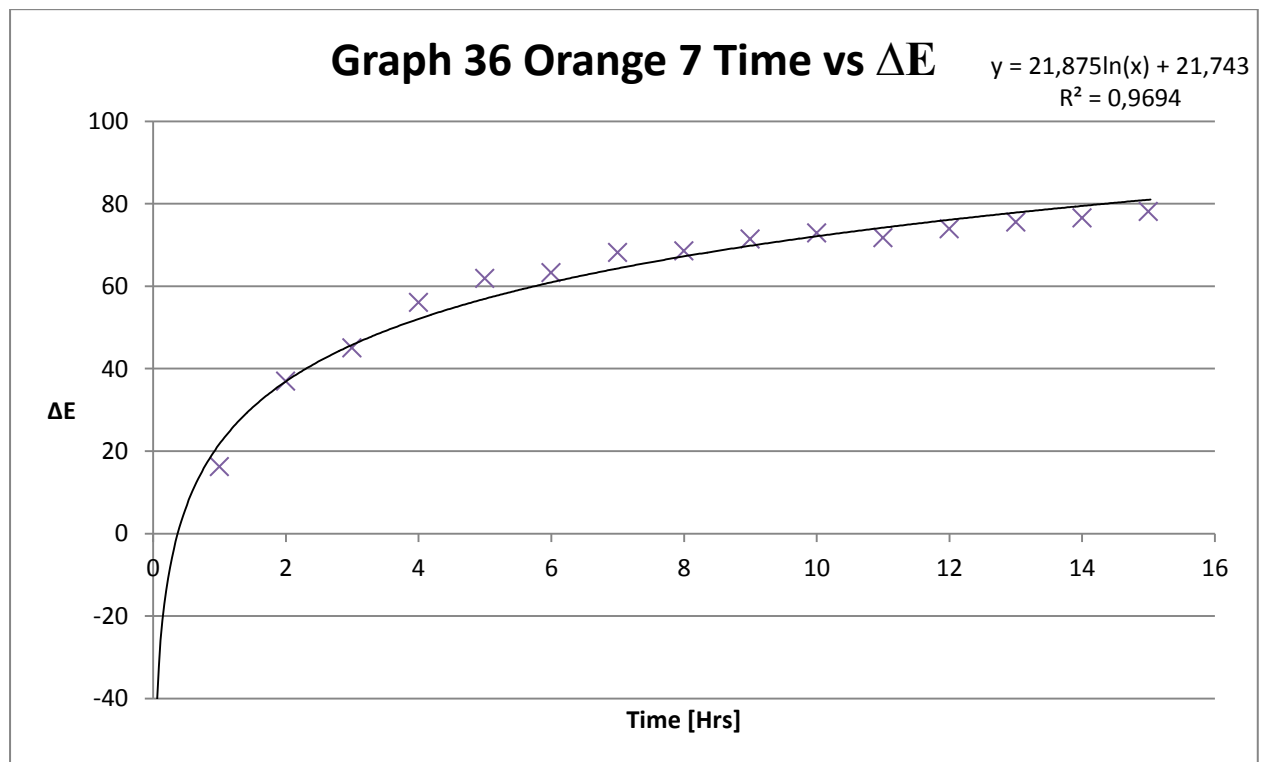
**Table 23: Number of hours of washing against Maximum Reflectance**

Number of Hours	Maximum Reflectance
0	1.46510577
1	1.53494084
2	1.38732219
3	1.40768015
4	1.31529188
5	1.25353336
6	1.18450892
7	1.12885082
8	1.0539
9	1.02487707
10	0.98384249
11	0.94951171
12	0.90337062
13	0.88302636
14	0.86043203
15	0.84384543



**Table 24: Number of hours of washing against  $\Delta E$** 

Number of Hours	$\Delta E$
0	
1	16.26861
2	36.92853
3	45.01553
4	56.03561
5	61.90207
6	63.24646
7	68.21383
8	68.55447
9	71.45815
10	72.94493
11	71.73836
12	73.89569
13	75.52815
14	6.59752
15	78.12083





## Chapter 9 Appendix C

### ASTM

*American Society for Testing and Materials (ASTM)* develops and delivers voluntary consensus standards to improve product quality, enhance safety, facilitate market access and trade, and build consumer confidence. ASTM's standards development is driven by the contributions of its members: more than 30,000 of the world's top technical experts and business professionals representing 135 countries. ASTM members deliver the test methods, specifications, guides, and practices that support industries and governments worldwide. Contact: ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 19428-2959 USA

1. **ASTM D1424** Standard Test Method for Tearing Strength of Fabrics by Falling-Pendulum Type (Elmendorf) Apparatus, 1996
2. **ASTM D3787** Standard Test Method for Bursting Strength of Knitted Goods - Constant-Rate-of- Traverse (CRT) Ball Burst Test, 2001
3. **ASTM D5034** Standard Test Method for Breaking Strength and Elongation of Textile Fabrics (Grab Test), 1995
4. **ASTM D5489** Standard Guide for Care Symbols for Care Instructions on Textile Products, 2001 a
5. **ASTM D1776** Standard Practice for Conditioning Textiles for Testing, 1990
6. **ASTM E96** Textiles - Standard Test Methods for Water Vapor Transmission of Materials, 2000
7. **ASTM E284** Standard Terminology of Appearance, 1996
8. **ASTM E808** Standard Practice for Describing Retro reflection, 2001
9. **ASTM E809**, Standard Practice for Measuring Photometric Characteristics of Retro reflectors, 2008
10. **ASTM E1164** Colorimetry - Standard Practice for Obtaining Spectrophotometric Data for Object-Color Evaluation, 1994 2002

11. **ASTM E1501** Standard Specification for Nighttime Photometric Performance of Retro reflective Pedestrian Markings for Visibility Enhancement, 1999
12. **ASTM F923** Standard Guide to Properties of High Visibility Materials Used to Improve Individual Safety, 2002The following European Norm (EN) and International Organization of Standards (ISO) references are available from the American National Standards Institute

## **AATCC**

*The American Association of Textile Chemists and Colorists (AATCC)* is a nonprofit organization that serves textile professionals since 1921. AATCC has individual and corporate members in more than 60 countries. The Association is internationally recognized for its standard methods of testing dyed and chemically treated fibers and fabrics to measure and evaluate such performance characteristics as colorfastness to light and washing, smoothness appearance, soil release, shrinkage, water resistance, and the many other conditions to which textiles may be subjected. AATCC is headquartered in Research Triangle Park, NC, USA.

1. **AATCC - EP1 Textiles** - Test Procedure for color change - Gray Scale for Color Change
2. **AATCC - EP2 Textiles** - Test Procedure for staining - Gray Scale for Staining
3. **AATCC 8 Textiles** - Tests for colorfastness - Colorfastness to Crocking, 2001
4. **AATCC 15 Textiles** -Tests for colorfastness - Colorfastness to Perspiration, 2002
5. **AATCC 16 Textiles** - Colorfastness to Light (Test Option 3) - Xenon Arc Lamp, Continuous Light, 1998
6. **AATCC 22 Textiles** - Tests for water resistance - Water Repellency: Spray Test, 2001
7. **AATCC 35 Textiles** - Tests for water resistance - Water Resistance: Rain Test, 2000
8. **AATCC 61 Textiles** - Tests for color fastness - Colorfastness to Laundering, Home and Commercial: Accelerated, 2001
9. **AATCC 96 Textiles** - Tests for dimensional changes - Dimensional Changes in Commercial Laundering of Woven and Knitted Fabrics except Wool, 1999

10. *AATCC 107 Textiles* - Tests for colorfastness - Colorfastness to Water, 2002
11. *AATCC 127-1999 Textiles* - Tests for water resistance - Water Resistance: Hydrostatic Pressure Test , 1998
12. *AATCC 132 Textiles* - Tests for colorfastness - Colorfastness to Dry-cleaning, 1998
13. *AATCC 133 Textiles* - Tests for colorfastness - Colorfastness to Heat: Hot Pressing, 1999
14. *AATCC 135 Textiles* - Test for dimensional changes - Dimensional Changes in Automatic Home Laundering of Woven and Knit Fabrics, 2000
15. *AATCC 158 Textiles* - Test for dimensional changes - Dimensional Changes on Dry-cleaning in Perchloroethylene: Machine Method, 1995

## **CIE**

*The International Commission on Illumination* (usually known as the CIE for its French-language name Commission Internationale de l'Eclairage) is the international authority on light, illumination, color, and color spaces. CIE provided recommendations about the precise way in which the basic principles of light and color measurement should be applied. The CIE has its headquarters in Vienna, Austria.

1. *CIE 15:2004*, Colorimetry
2. *CIE 17.4:1987*, International lighting vocabulary

## **ISO**

*The International Organization for Standardization known as ISO*, is an international-standard-setting body composed of representatives from various national standards organizations. Founded on February 23, 1947, the organization promulgates worldwide proprietary industrial and commercial standards. ISO defines itself as a non-governmental organization. In practice, ISO acts as a consortium with strong links to establish government rules and regulations. ISO has its headquarters in Geneva, Switzerland.

1. **ISO 105-A02, Textiles** - Tests for color fastness - Part A02: Grey Scale for assessing change in color
2. **ISO 105-A03, Textiles** - Tests for color fastness - Part A03: Grey Scale for assessing staining
3. **ISO 105-B02:1994, Textiles** - Tests for color fastness - Part B02: Color fastness to artificial light: Xenon Arc fading lamp test
4. **ISO 105-C06, Textiles** - Tests for color fastness — Part C06: Color fastness to domestic and commercial laundering
5. **ISO 105-D01, Textiles** - Tests for color fastness — Part D01: Color fastness to dry cleaning
6. **ISO 105-E04, Textiles** - Tests for color fastness — Part E04: Color fastness to perspiration
7. **ISO 3175-2:1998 Textiles** - Determination of dimensional change on dry cleaning in perchlorethylene - Machine method
8. **ISO 4675:1990** Rubber or plastic coated fabric - Low-temperature bend test
9. **ISO 5081 Textiles** - Woven Fabrics - Determination of breaking strength and elongation (Strip method)
10. **ISO 6330:2000 Textiles** - Domestic washing and drying procedures for textile testing
11. **ISO 7854:1997** Rubber- or plastics-coated fabrics - Determination of resistance to damage by flexing (dynamic method)