THE EVALUATION OF CATHOLYTE TREATMENT ON THE COLOUR AND TENSILE PROPERTIES OF DYED COTTON, POLYESTER AND POLYAMIDE 6,6 FABRICS

Natasha Cronjé

Thesis submitted in accordance with the requirements for the degree

Philosophiae Doctor

in the
Faculty of Natural and Agricultural Sciences
Department of Consumer Science
at the
University of the Free State, Bloemfontein, South Africa

January 2015

Promoter: Professor H.J.H. Steyn

Few things are impossible to diligence and skill. Great works are performed, not by strength, but perseverance.

Samuel Johnson

ACKNOWLEDGEMENTS

Completing a project of any magnitude cannot be done without the assistance, prayers and support of certain individuals in one's life. I wish to acknowledge and thank those individuals who contributed to this project in their own way:

Praise and thanksgiving be unto God, my Father, who strengthened me and granted me perseverance to complete this task. I am eternally grateful.

I wish to thank Professor Steyn, my supervisor and mentor, for her valuable input, time and patience. Her love for research, textiles and students is truly an inspiration. I am very privileged to be under her guidance.

I wish to acknowledge Professor Schall for the statistical analysis and interpretation of the results obtained in this study.

Thanks are due to Mrs. Adine Gericke from the University of Stellenbosch, Textile Science. Her assistance with some of the tests is appreciated.

Thank you to every lecturer at the Department of Consumer Science for your support, encouraging attitude and wise words.

I especially want to thank Dr. Jana Vermaas who encouraged and supported me throughout this project.

I am thankful for my husband, Minnaar, who loves me unconditionally and supports me in whatever I endeavor to do. I love you with all my heart and appreciate you so much. Your encouragement, understanding and support is my fuel.

To my family: I am blessed with the most precious sisters, brothers, nieces and nephews. Your understanding and love carried me. Thank you for your support and encouragement. To both my Moms and my Dad, thank you for your endless love and grace! I appreciate it more than you will ever know.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 General Introduction

An increase in environmental awareness amongst consumers (Chen & Burns, 2006:248) and researchers alike stimulates the need for product development in the detergent industry (Oakes, Gratton & Dixon: 2004:277b). This is mainly because laundering textile materials plays a major role in the daily lives of almost every household in the world (Cameron, 2007:151).

According to life cycle assessments done on clothes, detergents and washing machines, the period of use by consumers is usually the most energy demanding, and it is also the most polluting. The area of the greatest concern is thus the environmental impact of these clothes during continuous domestic laundering (Laitala, Boks & Klepp, 2011:255).

One of the contributing factors towards this pollution is phosphate. Phosphate is one of the most important ingredients in conventional laundry detergents, because it is used as a builder and inactivates the mineral ions which causes the water to be hard, and are able to suspend the ions in the solution (Köhler, 2006:58). Phosphate is also associated with environmental issues such as eutrophication. Eutrophication occurs when great amounts of phosphate are present in fresh water, which stimulates algae growth. The exponential growth of the algae depletes the oxygen resources of the water and the aquatic life dependent on the oxygen, die. (Hui & Chao, 2006:401).

Through the years, there has been much debate about the impact of phosphate and the dangers it poses (Bajpai & Tyagi, 2007:328). As a result, legislation to ban phosphate-containing detergents or to limit the phosphorus content in the detergents in countries around the world was introduced. This restriction was followed by new developments in detergent formulations (Van Ginkel, 2011:394).

Among these recent developments, was the experimental use of electrochemically activated water (Catholyte) as a possible environmentally friendly laundry detergent (Cronjé, Steyn & Schall, 2013:4). Catholyte (which is an alkaline medium), as well as its acidic counterpart, Anolyte, is activated by passing a 5% sodium chloride water solution through the electrochemical cells, anode and cathode. Each of these solutions has a unique set of properties and characteristics (Aider *et al.*, 2012:4). Exposure of the water to electrochemical activation results in the altering of the molecular state of the water, thus the activity of electrons in the water, the electric conductivity and the pH will differ from the original water used for the activation (Thorn *et al.*, 2011:642).

The production process does require energy, but the apparatus is simple and concise, therefore, lower energy consumption is experienced when compared to the manufacturing of conventional laundry detergents. The production does not cause any effluent emissions and the Catholyte will return to "normal water" after 48 hours. However, even in its activated state, it is non-toxic to the environment (Thorn *et al.*, 2011:642).

Several studies were conducted to determine if Catholyte may be a suitable environmentally friendly alternative to conventional laundry detergents, all the studies indicating favourable results. Results indicated that soil was efficiently removed from polyamide 6,6, cotton, polyester and a polyester/cotton blend without detrimental effects on the mechanical properties of the textile materials (Van Zyl, 2012:126; Van Heerden, 2010:185). Thantsha and Cloete (2006:238) found that Catholyte may also provide an environmentally sensible alternative to chlorine and other solvents.

However, such studies are yet to be done with regards to the effect that Catholyte has on the colourfastness to laundering and staining of dyed textile materials. Because most fibres are naturally off-white, colour is thus one of the most significant factors in the appeal and marketability of textile products (Jackman, Dixon & Condra, 2003:123). Colourfastness of textile materials towards repeated washing has also become an increasingly important consideration for consumers (Alam *et al.*, 2008:58).

During daily use of the textile materials, they are exposed to a variety of treatments that can cause colour changes, of which laundering is the most important (Fu *et al.*,

2013:3101). Changes occur because the dye molecules decompose in the fabric, or are removed into an external medium. Bleeding, which is the transfer of colour to a secondary, accompanying textile material, can also occur. It generally is expressed as staining (Boardman & Jarvis, 2000:63).

Cotton is one of the most produced and used fibres in the world (Mowbray, 2011:23), but it is also associated with considerable environmental impact regarding the dyeing thereof (Chen & Burns, 2006:248). Therefore, it should be an advantageous opportunity to reduce the environmental impact during the consumer use stage if Catholyte is used to launder cotton textiles.

1.2 Research Problem & Objectives

Several studies have been done to determine the influence of Catholyte on the tensile and breaking strength as well as soil removal efficacy of Catholyte on cotton, polyester, cotton/polyester blend (Van Zyl, 2012:126), polyamide 6,6 and machine washable wool (Van Heerden, 2010:185). To date, there are no known studies conducted to evaluate the influence of Catholyte on the colourfastness and tensile strength properties of dyed textile materials.

It was the aim of this study to determine the influence of Catholyte on the wash fastness, staining, colourfastness to rubbing, dry and wet, and tensile properties of disperse red dyed polyester, acid red dyed polyamide 6,6 and reactive (black, red, blue, violet, green), direct (black, red), sulphur black and azoic (orange) dyed cotton.

1.2.1 Objectives

It was the aim of the researcher:

1. To compare the influence of Catholyte versus detergent on the wash fastness of sulphur, direct and reactive black dyed cotton.

2. To compare the influence of Catholyte versus detergent on the wash fastness of disperse red dyed polyester, acid red dyed polyamide 6,6, azoic orange, direct red and reactive red dyed cotton.
3. To compare the influence of Catholyte versus detergent on the wash fastness of reactive blue, violet and green dyed cotton.
4. To compare the influence of Catholyte versus detergent on the staining of sulphur, direct and reactive black dyed cotton.
5. To compare the influence of Catholyte versus detergent on the staining of disperse red dyed polyester, acid red dyed polyamide 6,6, azoic orange, direct red and reactive red dyed cotton.
6. To compare the influence of Catholyte versus detergent on the staining of reactive blue, violet and green dyed cotton.
7. To compare the influence of Catholyte versus detergent on the colourfastness to dry and wet rubbing of sulphur, direct and reactive black dyed cotton.
8. To compare the influence of Catholyte versus detergent on the colourfastness to dry and wet rubbing of disperse red dyed polyester, acid red dyed polyamide 6,6, azoic orange, direct red and reactive red dyed cotton.
9. To compare the influence of Catholyte versus detergent on the colourfastness to dry and wet rubbing of reactive blue, violet and green dyed cotton.
10. To compare the influence of Catholyte versus detergent on the tensile strength of sulphur, direct and reactive black dyed cotton.
11. To compare the influence of Catholyte versus detergent on the tensile strength of disperse red dyed polyester, acid red dyed polyamide 6,6, azoic orange, direct red and reactive red dyed cotton.
12. To compare the influence of Catholyte versus detergent on the tensile strength of reactive blue, violet and green dyed cotton.

1.3 Terminology

Anolyte: Acidic water in which hydroperoxide compounds and oxygen chlorine compounds are present as a result of electrochemical

exposure near the anode in an electrochemical activation system (Bakhir, 2005:3).

Catholyte: Alkaline water marked by the presence of HO2-, O2- and OH- ions as a result of electrochemical exposure near the cathode in an electrochemical activation system (Bakhir, 2005:3).

Colourfastness: It can be described as the resistance of a textile material to a change in any of its colour characteristics (Schindler & Hauser, 2004:144).

Detergent: "A chemical compound which is formulated to remove soil or other material from textiles" (Kadolph, 2010:442).

Dyestuff: Dyes are complex organic compounds. They are composed of a chromophore (the coloured portion of the dye molecule) and an auxochrome (which slightly alters the colour). The auxochrome makes the dye soluble and is a site for bonding to the fibre (Freeman & Mock, 2003:506).

Electrochemically Activated Aqueous Media: Low-mineralized water which is characterised by meta-stability and a change in physico-chemical parameters (Bakhir, 2005:3).

Electrochemical Activation: A technology used to produce meta-stable aqueous media by way of electrochemical exposure (Bakhir, 2005:3).

Laundering: The process which removes soil and/or stains by washing with an aqueous detergent solution (Kadolph, 2007:245).

Staining: Staining, which is the transfer of colour to a secondary, accompanying textile material, can also occur (Schindler & Hauser, 2004:144).

Tensile Strength: The strength of a textile material under tension, measured through the resistance of a textile fabric to stretching in one specific

direction and the force required rupturing or breaking the fabric (Kadolph, 2007:156).

Textile: The general term used to refer to fibres, yarns and fabrics made from the fibres or yarns (Kadolph, 2010:461).

Van der Waal's forces: These forces are weak attractive forces between adjacent molecules that increase in strength as the molecules move closer together (Freeman & Mock, 2003:500).

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Increasing environmental awareness stimulates the need for environmentally responsible product development in the detergent industry (Nielsen & Munk, 2009:20), because laundering textile materials play a vital role in the daily lives of almost every household (Hollis, 2002:1). Life cycle assessments done on clothes, detergents and washing machines indicate that the period of use (laundering of the products) is usually the most energy demanding, and it can also be the most polluting (Laitala, Boks & Klepp, 2011:254). Hence, the area of greatest environmental impact is considered to be the period of use (Cotton Inc., 2011:3).

Phosphate, which is one of the most important ingredients in conventional laundry detergents, is associated with environmental issues such as eutrophication (Köhler, 2006:15). Eutrophication of natural water resources poses serious dangers, because water is one of the most critical elements for survival and needs to be protected (Bajpai & Tyagi, 2007:328). Legislation to ban phosphate-containing detergents, or to limit the phosphorus content in the detergents in countries around the world (Quayle *et al.*, 2010:3), was followed by new developments in detergent formulation (Chen & Burns, 2006:257).

Among these recent developments, studies were conducted to determine if electrochemically activated water may be a suitable environmentally friendly alternative to conventional laundry detergents. Results indicated that soil was effectively removed from polyamide 6,6 (Van Heerden, Steyn & Schall, 2012:689), cotton, polyester and a polyester/cotton blend (Van Zyl, 2012:126) without detrimental effects on the mechanical properties of the textile materials. Thantsha and Cloete (2006:237) found that electrochemically activated water may also provide an environmentally sensible alternative to chlorine and other solvents.

As most fibres are naturally an off-white colour (Wynne, 1997:2), colour is one of the most significant factors in the appeal and marketability of textile products (Kadolph, 2010:442). Colourfastness of textile materials towards repeated washing has also become increasingly important due to increased consumer and retailer demands (Burkinshaw, Son & Chevli, 2000:43). Whether electrochemically activated water influences the colourfastness of textile materials is, however, unknown and therefore needs to be investigated.

Cotton, polyester and polyamide 6,6 are the most prominent group of fibres used in the world (Mowbray, 2011:26), but they are also associated with considerable environmental impact regarding the dyeing thereof (Kadolph, 2010:468). Therefore, it should be an advantageous opportunity to counterbalance the environmentally negative dyeing profile by an improved laundry profile through the use of electrochemically activated water in the laundering process of these textiles.

2.2 Textile Dyeing

Almost all industrial dyeing uses synthetic dyes since they produce a greater colour range, improved colourfastness, better shade consistency, and more reliable resources. Natural dyes are used today mainly for craft and hobby items, although some such as indigo have some commercial value (Johnson & Cohen, 2010:154).

Dyeing textile materials with synthetic dyes is a chemical process (Chequer *et al.*, 2013:151) of imparting colour through an interaction with a dyestuff (Goodpaster & Liszewski, 2009:2010). It is a wet process that uses chemicals and large volumes of water, in addition to the dyes. The chemicals are introduced to the textile to obtain a uniform depth of colouration with colourfastness properties specifically suited for the end use (Ahmed & El-Shishtawy, 2010:1143).

A dye is a unique coloured substance that is able to absorb and reflect wavelengths in the visible spectrum of light, which exists between 400nm – 700nm (Goodpaster & Liszewski, 2009:2010). Dye molecules have at least one chromophore (which is a colour

bearing group); a conjugated system (a system in which the double and single bonds alternate); and it exhibits resonance (a stabilising force in organic compounds) (Freeman & Mock, 2003:552).

2.2.1 Mechanism of Dyeing

Before dyeing can take place, the textile fabric has to be cleaned to remove warp starches, oils and dirt. This procedure ensures better acceptance of dyes and chemical additives. It also prevents problems, such as colour spots or uneven colouration to arise (Johnson & Cohen, 2010:155).

The dyeing of textiles generally consists of four stages. Stage one involves the exhaustion of the dye bath. This implies that the individual dye molecules are transported from the dye bath to the fibre surface (Choudhury, 2006:383), because the dye reacts with the surface molecules first (Kadolph, 2010:448). It is important to note that inadequate stirring or circulation during this stage generally results in non-uniformity in dyeing (Choudhury, 2006:383).

During stage two, the dye molecules move from the fibre surface into the amorphous regions of the fibre, also known as the stage where diffusion takes place (Choudhury, 2006:383). Kadolph (2010:448) suggests that the stage, at which colour is applied, has no significant influence on the fastness, but rather dye penetration. The success of this stage is therefore of utmost importance.

Stage three entails the migration of the dye. The dye molecules then move from the regions of high concentration to regions of low concentration, thus the molecules become evenly distributed within the polymer matrix (Choudhury, 2006:383).

Stage four, commonly referred to as the fixation stage, involves the interaction of the dye molecules with the groups along the polymer chain of the fibre (Freeman & Mock, 2003:506-507). Moisture and heat swell the fibres, causing polymer chains to move farther apart so that sites in the fibres interior are exposed to react with the dye (Kadolph, 2010:448).

In the case of acid and basic dyes, fixation is caused by ionic bonding. Covalent bonding takes place when fibres are dyed with reactive dyes. Aggregation of dye molecules inside the textile fibres is needed when dyeing with direct dyes. Dye molecules are insolubilized in the case of azoic and sulphur dyes, whereas the molecules are solubilized inside the fibre when dyeing with disperse dyes in polyester (Choudhury, 2006:391). During cooling and drying the polymer chains move back together, trapping the dye in the fibre (Kadolph, 2010:448).

After the dyeing process, the textile material must be scoured with soaps or detergents and rinsed thoroughly to remove excess dye that has not reacted with the fibre. This is a very important step, as failure to remove the excess and untreated dye results in poor initial colourfastness and excessive rubbing off of colour (Johnson & Cohen, 2010:155).

2.2.2 Classification of Dyes

Dyes are complex organic compounds and are composed of a chromophore (the coloured portion of the dye molecule) and an auxochrome (which slightly alters the colour). The auxochrome makes the dye soluble and is a site for bonding to the fibre (Kadolph, 2010:447).

Fibre dyes are classified in a number of ways, which includes the method of application, chemical class or the type of fibre to which it is applied (Goodpaster & Liszewski, 2009:2010). The dyes, to follow, are classified according to the chemical class of the dye (Freeman & Mock, 2003:506).

2.2.2.1 Acid Dyes

Acid dyes are typically applied to textile fibres from dye bath containing acid, hence the name of this class (Goodpaster & Liszewski, 2009:2010). These dyes were originally employed for application on wool and silk, although many acid dyes exhibit considerable substantivity towards polyamide 6,6 fibres from neutral dye baths

(Burkinshaw, 1995:83). These dyes are noted for their superior colourfastness, excellent fixation, and a wide range of available shades (Elsasser, 2010:204).

Chemically, acid dyes are similar to direct dyes with a few minor differences (Choudhury, 2006:375). Acid dyes vary widely in their molecular structure, but generally, have one or two sodium sulfonate (-SO_3NA) groups, which are illustrated in Figure 2.1 (Freeman & Mock, 2003:507). These dyes may or may not be coplanar and some of them are of low molecular size and consequently have lower colourfastness (Choudhury, 2006:375).

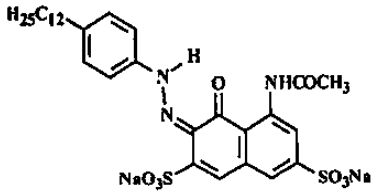
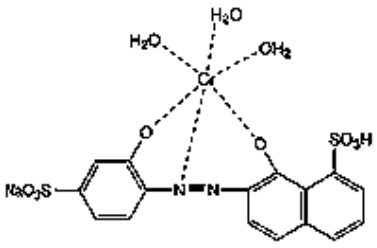
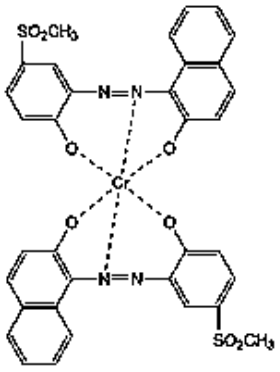


Fig. 2.1 Acid Red 138 (Freeman & Mock, 2003:507)

If these dyes have two hydroxyl groups, or one hydroxyl and a carboxylic group in O-O' position with respect to the azo group, the dye is capable of forming a complex with multivalent metal atoms like chromium, which improves colourfastness, illustrated in Figure 2.2. The metals, that are mostly used for these reactions, are cobalt, chromium and iron (Freeman & Mock, 2003:509).



(a)



(b)

Fig. 2.2 (a) 1:1 Metal complex C.I. Acid Blue 159; (b) 2:1 Metal complex C.I. Acid Violet 78 (Freeman & Mock, 2003:507)

The complex may be formed during dyeing or during dye manufacture. The latter, known as pre-metallised dyes, may be of two types – 1:1 or 1:2, each representing a complex having one or two dye molecules per metal atom respectively (Choudhury, 2006:375).

It should be noted that the metallisation of dyes enhances the light fastness of the end fabric, reduces water solubility, but causes a bathochromic shift in colour and dulls the shade. Therefore, it is mostly used to dye leather (Akram *et al.*, 2012:33). If the metal-complex dyes can be formed inside textile fibres by treating suitably dyed fibres with a solution containing a metal ion, the dye dye is known as mordant dyes. The chemical structure of these mordant dyes is similar to Figure 2.3 (Choudhury, 2006:375).

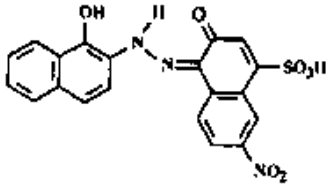


Fig. 2.3 Mordant Black 11 (Freeman & Mock, 2003:507)

Acid dyes are water soluble, capable of bonding with fibres having cationic sites (Freeman & Mock, 2003:507) and the acidic conditions in which the textiles are dyed, render the functional groups on the substrate protonated and positively charged. These groups form ionic bonds with the sulphonate groups on the dye molecule (Goodpaster & Liszewski, 2009:2010).

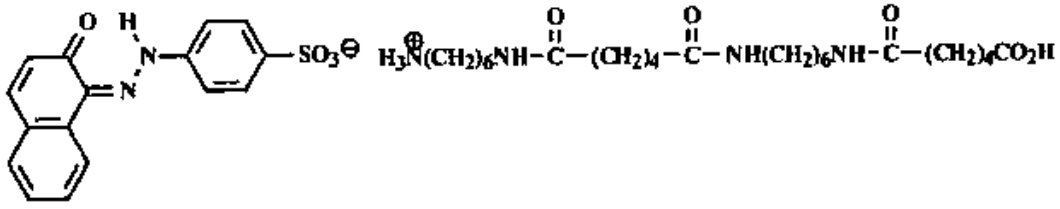


Fig. 2.4 Ionic bond formation between polyamide 6,6 and acid dye (C.I. Acid Orange 7) (Freeman & Mock, 2003:506).

The substantivity of acid dyes towards polyamide fibres arises primarily by virtue of ion-ion forces of interaction operating between the anionic (usually sulphonate) groups in the dye and the protonated terminal amino groups in the fibre. Other forces of interaction, such as hydrogen bonding, dispersion forces and polar van der Waals forces, can also be expected to contribute to dye-fibre substantivity (Burkinshaw, 1995:81).

Acid dyes are characterised by good migration and therefore produce level dyeings with time (Freeman & Mock, 2003:508). They have no substantivity for cellulosic fibres or fibres sensitive to alkalis (Choudhury, 2006:375).

Acid dyes produce bright colours, but most are not fast to laundering, although exhibiting good colourfastness to dry-cleaning (Johnson & Cohen, 2010:157). When good colourfastness to laundering is an important factor in relation to the end use of the textile material, the use of milling acid dyes or super milling acid dyes are a preferred selection. Milling acid dyes are generally applied from weakly acid dye baths whereas super milling acid dyes are mostly applied at a neutral pH, with the molecular size increasing as the acid strength decreases (Freeman & Mock, 2003:508). Acid dyes vary from poor to good fastness with regards to light and perspiration (Johnson & Cohen, 2010:157).

2.2.2.2 Azoic Dyes

Azoic dyes are mainly bright orange and red monoazo dyes (Freeman & Mock, 2003:509), which are often used on cellulosic fibres such as cotton (Johnson & Cohen, 2010:157). Dull violet and blue colours are also attainable. Azoic dyes are often referred to as azoic combinations instead of dyes because the dye does not exist as colourants until it is formed inside the cotton fibres (Freeman & Mock, 2003:509).

The generic structure of azoic dyes can be illustrated as follows:

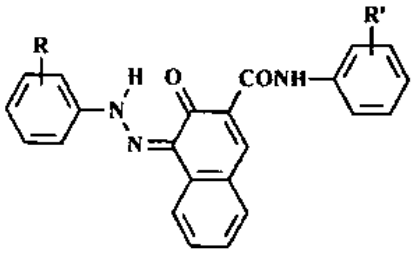


Fig 2.5 Generic structure for azoic dyes, where R and R' = alkyl, alkoxy, halo, and nitro groups (Freeman & Mock, 2003:511)

The formation of azoic dyes requires an azoic coupling component as well as an azoic diazo component (Goodpaster & Liszewski, 2009:2011). The azoic coupling components are beta-naphthol acid derivatives and the azoic diazo components are substituted anilines (Freeman & Mock, 2003:509). Consequently, azoic dyes are sometimes also referred to as naphthol dyes (Choudhury, 2006:600). During the conventional application of azoic dyes, the coupling component is applied followed by a subsequent development with the diazotized base. These two components are applied, as ions, generally at low temperature under alkaline conditions (Burkinshaw, 1995:69).

At first, the naphthols (solubilised aromatic hydroxyl compounds) are applied on textile materials by a process called naphtholation as they have some affinity for the cellulosic materials. Insoluble azo pigments are then formed inside the textile. Afterwards, the textile is treated with a soluble diazotized form of the base, during which intense colour is formed. The latter step is known as coupling or development. The solubilization of the base is carried out with sodium nitrate and hydrochloric acid at low temperature and the process is known as diazotization (Choudhury, 2006:600). These compounds are applied cold, and the fabric is then washed with detergent in hot water (Collier & Tortora, 2001:423).

Azoic dyes can be produced in batch or continuous processes. They are best known for their ability to provide economical wet fast orange and red shades on cotton (Freeman & Mock, 2003:509). Although azoic colourants have been applied to protein fibres, their

suitability is doubtful especially because of the high alkaline conditions which are maintained during dyeing (Choudhury, 2006:376).

This class of dye is especially important when printing on cotton, as it yields good light fastness in heavy depths. If good fastness to crocking is required, efficient soaping after the applications step is mandatory (Freeman & Mock, 2003:509), as these dyes have a tendency to crock/rub off onto other fabrics (Elsasser, 2010:204). Colourfastness to laundering and perspiration are good to excellent (Johnson & Cohen, 2010:157).

Most azoic combinations are fast to chlorine bleaching but frequently inadequately fast to hydrogen peroxide. The main weakness of azoic dyeing is their limited fastness to organic solvents used in dry cleaning and spotting (Choudhury, 2006:601).

2.2.2.3 Direct Dyes

Direct dyes form the largest and commercially most important group of dyes (Kadolph, 2010:449), because they are low in cost and relatively easy to apply (Burkinshaw & Gotsopoulos, 1999:179). They are anionic colourants which are best suited for cellulosic fibres (Goodpaster & Liszewski, 2009:2011). Direct dyes were the first class of dyes that could be used on cotton without the presence of a mordant, and are, therefore, also known as direct cotton dyes (Freeman & Mock, 2003:513).

Like acid dyes, direct dyes contain one or more sodium sulfonate (-SO_3Na) group. The dye molecules interact with the cellulose via secondary valency forces. Because of these weak forces and sulphonated structures, direct dyes have low intrinsic colourfastness to laundering. Direct dyes can by suitably substituted to be converted to metal complexes using copper(Freeman & Mock, 2003:513).

Chemically, direct dyes are the sodium salt of sulphonic acid derivatives or organic aromatic compounds and thus contain one or more azo groups(Choudhury, 2006:375). These structures are linear and will appear like the illustration in Figure 2.6 (Inglesby & Zeronian, 2002:19). The forces of interaction that operate between this class of dye and cellulosic fibres are predominantly van der Waal's forces. This is a result from the highly

conjugated, linear and coplanar structure of the dyes. Due to this structure, the dyes exhibit a marked aggregation tendency both in solution and within the fibre substrate (Burkinshaw, 1995:130). Direct dyes are dissolved in water, and a salt is added to control the rate of absorption into the fibres (Freeman & Mock, 2003:514).

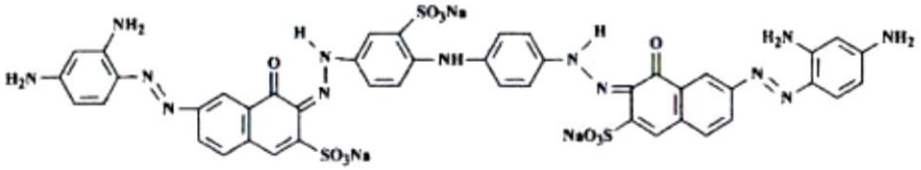


Fig. 2.6 Linear structure of Direct Black 22 (Freeman & Mock, 2003:512)

Colourfastness to laundering may be poor (Collier & Tortora, 2001:424), therefore cotton dyed with direct dyes is often treated with a chemical agent to improve the colourfastness, commonly referred to as an after-treatment process. The most widely used methods for these after-treatment processes involve cationic fixatives, copper sulphate, diazotization and coupling reactions. The cationic fixatives tie up the sodium sulphonate groups, which reduces the water solubility of the treated dye. The main purpose of the copper sulphate after-treatment is to enhance the light fastness. However, the reduction in water that accompanies the Cu-complex formation has a beneficial effect on the colourfastness to laundering of the fabric. Diazotization and coupling enlarge the size of the dye molecule, making desorption more difficult, and simultaneously making the dye less hydrophilic (Freeman & Mock, 2003:514).

Although direct dyes have a particularly good affinity for cellulose fibres (Inglesby & Zeronian, 2002:19), these dyes can also be applied on protein fibres, such as wool and silk, but are not commonly used because the rate of dye exhaustion is very slow (Choudhury, 2006:375).

Fastness to light varies, but some are excellent and used in drapery and upholstery. Fastness to perspiration and dry-cleaning are good to excellent (Johnson & Cohen, 2010:157).

2.2.2.4 Disperse Dyes

According to Burkinshaw (1995:3), disperse dyes can be defined as a "substantially water-insoluble dye having substantivity for one or more hydrophobic fibres and usually applied from fine aqueous dispersion". Disperse dyes were initially invented to dye the first hydrophobic fibre developed, namely cellulose acetate. These dyes are now suitable for a variety of hydrophobic fibres including acetate, triacetate, polyester, nylon, acrylic and polyolefin fibres (Freeman & Mock, 2003:517). The molecular structure can be illustrated as follows:

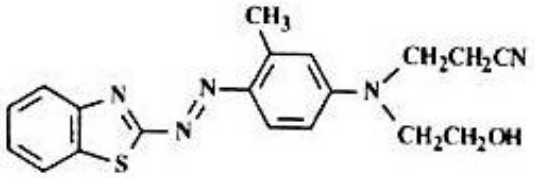


Fig. 2.7 Molecular structure of Disperse Red 156 (Freeman & Mock, 2003:518)

Disperse dyes have low molecular weight and are crystalline substances with a high melting point (Choudhury, 2006:703). Although the dyes do not contain ionic groups they possess polar groups which contribute to its relatively small molecular size, and minor, although highly important, aqueous solubility (Burkinshaw, 1995:3). Hence, disperse dyes are used in conjunction with dispersing agents to achieve stable aqueous dispersions at high temperatures (Fitè, 1995:361). Due to the absence of ionisable groups, disperse dyes have the tendency to vapourise without decomposing (Choudhury, 2006:703).

A small amount of the disperse dye forms an aqueous solution with the greater proportion of the dye in dispersion in the dye bath. Monomolecular dye is absorbed onto the surface of the fibre from the aqueous dye solution situated at the fibre surface. As dye molecules diffuse, monomolecularly, from the surface to the interior of the substrate, dye particles from the bulk dispersion dissolve in the depleted aqueous dye solution. This solution can consequently be replenished with monomolecular dye that can be further adsorbed onto the fibre surface. This process continues until either the dye bath is exhausted of dye or the fibre is saturated with dye (Burkinshaw, 1995:10).

The dye binds to the fabric substrate through weak van der Waal's forces and some hydrogen bonding (Goodpaster & Liszewski, 2009:2011).

The distinct behaviour of disperse dyes lies in the fact that at room temperature only a small fraction of the dye in the bath is available in its soluble form, the remainder still being insoluble. Only the soluble form can penetrate the fibres, therefore when dyeing, the concentration of the water soluble disperse dye in the bath should be taken into consideration and not the total concentration (Ferus-Comelo, 2009:353). Due to the insolubility of disperse dyes, some particles of dye may precipitate on the surface of the fibres at the end of the dyeing process. These precipitations can cause a decrease in brightness and a decline in fastness to laundering and rubbing (Gharanjig *et al.*, 2010:37).

Colourfastness of disperse dyes to laundering varies with regards to the fibre it is applied to. It is excellent on polyester (Johnson & Cohen, 2010:157), although colour loss and colour change can be caused by atmospheric fumes, in particular gaseous oxides of nitrogen (Collier & Tortora, 2001:425). The fastness to perspiration, crocking and dry-cleaning varies from good to excellent whereas light fastness is fair to good (Johnson & Cohen, 2010:157).

2.2.2.5 Reactive Dyes

Reactive dyes are mainly used for cellulosic fibres like cotton (Freeman & Mock, 2003:519), but special reactive dyes for wool, polyamide (Choudhury, 2006:376), linen and silk are also available (Broughton, 2001:9). As a class, fibre reactive dyes, are some of the least efficient dyes in terms of the water, salt, and alkali required, as well as the unfixed (hydrolyzed) colour waste produced (Farrell *et al.*, 2011:44). However, it remains one of the most important and widely used colourants (Jung & Sun, 3391). These dyes produce bright colours with excellent colourfastness to laundering (Elsasser, 2010:204).

Reactive dyes differ fundamentally from other dye-classes, in the fact that they chemically react with the textile fibre (Taylor, Pasha & Phillips, 2001:145). These dyes contain reactive groups, which react with hydroxyl or amino groups of textile fibres forming covalent bonds. These bonds form between a carbon atom of the dye ion and oxygen, nitrogen, sulphur atom of a hydroxyl or an amino group of the substrate (Choudhury, 2006:515).

The different structural components of reactive dyes can be categorized as (1) a chromogen responsible for the colour; (2) solubilising groups responsible for the solubility of the dye; (3) a reactive group, which forms a covalent bond with the substrate; and (4) an optional bridging link between the reactive group and the chromophoric system (Choudhury, 2006:517). These basic parts are illustrated in Figure 2.8 and can be listed as follow (Freeman & Mock, 2003:519):

SG-C-B-RG-LG

Where: SG = Water solubilizing group (-SO3Na)

C = Chromogen (Azo, anthraquinone)

B = Bridging or linking group (-NH-)

RG = Reactive group (Chlorotriazine, vinyl sulfone)

LG = Leaving group (-Cl, -F, -SO4H)

Fig. 2.8 Structure illustrating the basic parts of a fibre-reactive dye (Freeman & Mock, 2003:519)

The presence of one or more $-SO_3Na$ groups in reactive dyes, renders it water soluble. Therefore, it needs to undergo fixation to polymer chains via covalent bond formation (Freeman & Mock, 2003:519). The reactive dye is held by the fibre as long as the covalent bond is intact. The bonds are generally stable under domestic and industrial wet treatments, and are fast to repeated laundering. For conventional dyes, the molecular size of the dye plays an important role in determining fastness properties – bigger molecular sizes are preferred for better fastness to laundering (Choudhury, 2006:516). Reactive dye structures can be relatively small, much smaller than, for example, the structures of direct dyes. Due to the smaller structures, reactive dyes have significantly lower inherent affinity for cotton (Freeman & Mock, 2003:519). Therefore, the fastness of reactive dyes largely depends on the strength of the covalent bonds formed, allowing flexibility of the molecular size (Choudhury, 2006:516).

The most generally used reactive systems involve the halotriazine and sulfatoethylsulfone (vinyl sulfone) groups, although halogenated pyrimidines, phthalazines and quinoxalines are also available for use. For all these systems, alkali is used to facilitate dye-fibre fixation. The fixation occurs through nucleophilic substitution or addition (Freeman & Mock, 2003:520).

Because alkali is required, hydrolysis of the reactive groups can occur before dye-fibre fixation. This is undesirable as the hydrolysed dye cannot react with the fibre, and leads to wasted dye and the need to treat the residual colour in the wastewater prior to dye house discharges (Freeman & Mock, 2003:520).

Reactive dyes have very high fastness to laundering (Collier & Tortora, 2001), hence it is often used for leisure wear and applications requiring stability to repeated laundering. In addition, reactive dyes generally yield bright shades. This is due to the fact that reactive dyes are mostly acid dye structures linked to reactive groups (Freeman & Mock, 2003:519). A drawback is their susceptibility to damage from chlorine. Colourfastness to dry cleaning, fume fading, crocking, and perspiration can vary from good to excellent (Johnson & Cohen, 2010:157).

2.2.2.6 Sulphur Dyes

Sulphur dyes are complex organic compounds containing sulphur linkages within the molecules. This class of dyes are the most economic dye class (Choudhury, 2006:586) and are generally applied to cotton. Sulphur dyes predominantly yields dull shades of navy, black and brown (Johnson & Cohen, 2010:157).

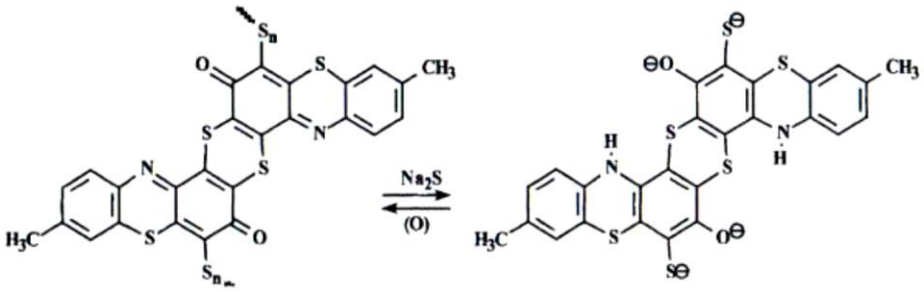


Fig. 2.9 The steps involved in the application of sulphur dyes to cotton (Freeman & Mock, 2003:524)

A characteristic feature of sulphur dyes is the presence of sulphide (-S-) bonds (Figure 2.9). This is also the feature that makes dye application from an aqueous medium possible. The reaction of the sulphur dyes with sodium sulphide (Na_2S) at a pH >10, affects the reduction of the sulphide bonds, giving their water-soluble (leuco) forms. These reduced forms behave like direct dyes in the sense that they exhaust onto cotton in the presence of salt. Once the dyes are applied, the reduced dyes are reoxidized to their water-insoluble form, which imparts good fastness to laundering properties. Oxygenic air can be used for the oxidation step, but an agent like hydrogen peroxide is generally used because it works faster (Ahmed & El-Shishtawy, 2010:1145; Freeman & Mock, 2003:524).

The wet fastness of sulphur dyes are good when laundering with soap, but are less resistant to laundering with synthetic detergents and perborate, particularly above 50°C. The fastness to rubbing is very much dependent on the fabric itself, its preparation and the dyeing process, especially the efficiency of rinsing before oxidation (Choudhury, 2006:589). Sulphur dyes display excellent fastness to light and perspiration, but poor fastness to chlorine. Some sulphur dyes are known to cause weakening of the fabric

when the fabric is stored for great lengths of time (Johnson & Cohen, 2010:157). Weakening or disintegration of the fabric may also be caused if the dye is not properly applied (Kadolph, 2010:449).

2.2.3 Environmental Impact of Textile Dyestuffs

Wastewater from dyeing and finishing plants of the textile industry has been a serious problem for quite some years (Can *et al.*, 2006:181), because of its significant impact on the environment. The impact is not only with regards to the use of the dyestuffs, but also the production of dyes and pigments; water and other chemical use; discharge of dyes, pigments and other chemicals into water systems; air pollution; and energy consumption (Kadolph, 2010:468).

Textile processing requires an enormous amount of water, several thousands of cubic metres per day in fact, for a typical dyeing plant (Fung, Ng & Tsui, 2011:41). In most cases, water acts as a medium for transporting dyes inside textile fibres. Therefore, the solubility of dyes in water is very important for the applicability on textile materials (Choudhury, 2006:358). Water is also used to prepare textiles for dyeing, to mix up the dye bath, and to rinse textiles after dyeing (Kadolph, 2010:450). During the dyeing process, it has been estimated that the losses of colourants to the environment can reach 10–50%. It is noteworthy that some dyes are highly toxic and mutagenic, and also decrease light penetration and photosynthetic activity, causing oxygen deficiency and limiting downstream beneficial uses such as recreation, drinking water and irrigation (Chequer *et al.*, 2013:152).

As a result of these processes the water from dye houses contains oils and waxes from natural fibres, sizes used for weaving, oils used in knitting, bleaches, acids and alkalis (Patterson, 2011:50). In addition to these substances present in the wastewater, the effects caused by other pollutants in textile wastewater, and the presence of very small amounts of dyes (<1 mg/L for some dyes) in the water, seriously affects the aesthetic quality and transparency of water bodies such as lakes, rivers and others, leading to

damage to the aquatic environment (Chequer *et al.*, 2013:152). The wastewater may also be hot and contain carcinogens or highly toxic residues (Patterson, 2011:50).

The wastewater must be treated to remove contaminants (including colour) before it is returned to the natural or municipal water systems (Kadolph, 2010:450). This is an environmental, as well as an economical problem as more strict regulations on chemicals present in dye house discharge, are being instated (Van der Kraan *et al.*, 2007:470). In addition to this, the treatment of wastewater is not easy because dyeing is not a single homogenous process. It is a sequence of different chemical procedures that operate at different temperatures and pH levels. This complicates the development of multiple treatment processes for multiple waste streams. However, if done well, it works in protecting the environment from the chemicals used in the dyeing industry (Patterson, 2011:51).

Indicators used for assessing water quality problems include colour, salt, acids, and heavy metals. Some materials create serious challenges during treatment because of high biological oxygen demand (BOD); others have high chemical oxygen demand (COD). High BOD and COD materials create environments that are hostile to aquatic plants and animals and gradually create problems with future use of the water. Colour in water creates problems with photosynthesis of aquatic plant life (Kadolph, 2010:468).

These substances present in the effluent are toxic and therefore needs to be removed to a certain level. The textile industry has been working on the development of chemical, physical and biological processes, although the net environmental effect is still a concern (Chen & Burns, 2006:249). Chemical and physical treatment processes for the water are effective in removing the colour, but chemical waste is also generated from these processes. It further uses more energy and chemicals than biological treatment processes. (Sirianuntapiboon & Srisornsak, 2007:1057).

Biological methods aren't always a solution (Can *et al.*, 2006:181), because dyestuffs are a type of refractory organic matter. Thus, microorganisms find it difficult to use dyestuffs as either a carbon or an energy source (Sirianuntapiboon & Srisornsak, 2007:1057). Furthermore, the chemicals present in most textile wastewaters are too toxic for the organism used in the processes. Chemical coagulation is not an effective

method to remove the dissolved reactive dyestuffs. Activated carbon adsorption has the associated cost and difficulty of the regeneration process and a high waste disposal cost and processes such as ozonation, UV and ozone/UV combined oxidation, photo catalysis, Fenton reactive and ultrasonic oxidation are not economically feasible (Can *et al.*, 2006:181). However, researchers are still interested in biological treatment to process wastewater as the cost is low and no chemical waste is produced (Sirianuntapiboon & Srisornsak, 2007:1057).

2.3 Textile Fibres

2.3.1 Cotton

2.3.1.1 Production

Cotton is a seed fibre that is attached to the seed of the cotton plant (Johnson & Cohen, 2010:36) of the botanical family *Gossypium* (Choudhury, 2006:9). Three species are commercially important, namely: *Gossyoiumhirsutum*, *Gossypium barbadense* and *Gossypium arboretum* (Kadolph, 2010:62).

It grows on bushes of about 1.4 to 1.6 metres in height. After the blossom drops off, the seedpod begins to grow. Seven to eight seeds with thousands of cotton fibres are present in each pod. Each cotton seed may have as many as 20 000 fibres growing from its surface (Kadolph, 2010:61). The development of the fibre begins on the day when the plant starts blooming, right on through to its full maturity (Asif, 2010:5). When the seedpod is ripe, and more or less the size of a walnut, the white fibres expand and as they grow, it eventually causes the pod to split open (Kadolph, 2010:61).

Once split open, the fibres can become spoiled by the weather rather quick, therefore, the cotton must be picked or harvested very soon (Mather & Wardman, 2011:23). It also should be mentioned that all cotton bolls do not open at the same time, which presents a problem with industrialised harvesting (Hatch, 1993:170).

The main producing countries of cotton are India, China, the United States of America, Pakistan and Brazil (Mather & Wardman, 2011:23), although commercially produced in more than 80 countries around the world (Asif, 2010:1). The highest quality cotton fibres are grown in the Sea Island and Egypt regions (Mather & Wardman, 2011:23).

2.3.1.2 Structure

The unusual way in which the cotton seeds are grown is one of the contributing factors towards its unusual morphological features (Mather & Wardman, 2011:23).

The length of cotton fibres is one of the most important aspects of the quality of cotton fibres, and is also directly related to yarn fineness, strength, and spinning efficiency (Asif, 2010:8). The length generally varies from 1.25cm – 5cm depending on the genetic variety and can be classified as a staple fibre (Freeman & Mock, 2003:503). It should be noted that fibre length vary significantly even on a single seed, because longer fibres occur at the lower end of the seed, and shorter fibres are found at the pointed end (Asif, 2010:10).

Cotton is one of the textile fibres with the smallest diameters (Hatch, 1993:163), ranging between 16 to 21 microns (Kadolph, 2010:62; Freeman & Mock, 2003:503). As the fibre becomes longer, it also becomes narrower and is characterised by a length-to-breadth ratio in the range of 6000:1 to 350:1 (Hatch, 1993:163).

Cotton is a single cell fibre (Asif, 2010:4), which forms a convoluted tube with a high degree of twist in the length of the fibre (Freeman & Mock, 2003:503). One end of the fibre tapers to a point, whilst the other end, is open where it has been removed from the seed by the ginning process (Choudhury, 2006:10). Generally it is more than a thousand times as long as what it is thick (Kadoloph, 2010:61), and seen under a microscope, cotton looks like a flat twisted tube (Johnson & Cohen, 2010:36).

The fibre is a complex series of reversing spiral fibrils and grows to almost full length as a hollow tube before a secondary wall begins to form (Kadolph, 2010:62). Immature cotton fibres tend to be U-shaped with thin cell walls, whereas mature fibres are nearly

circular with thick cell walls (Kadolph, 2010:62).The cross-section is kidney-shaped or similar to a collapsed tube (Choudhury, 2006:10). This happens as a result of the seed hairs drying out and shrinking.

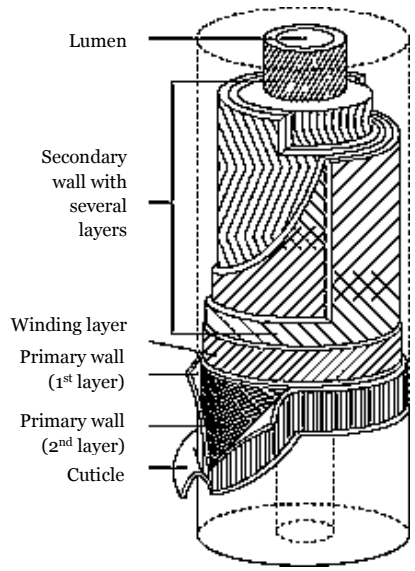


Fig. 2.10 Schematic representation of a cotton fibre (Mather & Wardman, 2011:25)

Cotton fibres consist of four main parts (Figure 2.10), namely: the cuticle, the primary wall, the secondary wall and the lumen (Mather & Wardman, 2011:23). Hatch (1993:164), however defines a fifth region in the fibre called the winding layer.

The cuticle is a thin, waxy film covering (Kadolph, 2010:62) that serves a protecting role. It is, however, necessary to remove this layer before cotton can be dyed, otherwise the dyes cannot diffuse into the fibre (Mather & Wardman, 2011:24).

Situated underneath the cuticle is the primary wall which is made up of fibrils of cellulose, arranged in a spiralling network along the fibre (Mather & Wardman, 2011:24).

The secondary wall, found underneath the primary wall, is made up of several layers of cellulose (Kadolph, 2010:62). The secondary wall forms the majority of the cotton fibre. The fibrils in the layers of cellulose found in the part of the fibre show a reversal of twist from an S to Z direction. Cotton's inherent high strength can be ascribed to this spiralling of the fibrils along the axis (Mather & Wardman, 2011:24), however, where the fibrils change in direction regarding their spirals, a weak area exists in the wall. It is

at these weak areas that the fibre alters the direction of twist (Hatch, 1993:165). These reverse spirals also contribute to the development of the convolutions that affect the fibre's elastic recovery and elongation (Kadolph, 2010:62).

The layers of the secondary wall that was deposited during the night differs in density from the layers deposited during the day. This causes growth rings which are visible in the cross-section (Kadolph, 2010:62). The first layer of cellulose, that is deposited, differs entirely from the rest of the secondary wall and is referred to as the winding layer (Hatch, 1993:165). The cellulose is deposited daily for twenty to thirty days, until the fibre is mature (Kadolph, 2010:62). These twists form a natural texture that enables the fibres to cling to one another (Asif, 2010:4).

The lumen is the central canal running through the fibre (Mather & Wardman, 2011:24). Nourishment travels through the lumen during fibre development. The dried nutrients in the lumen may result in dark areas that are visible under the microscope in mature fibres. When the fibre is mature, the central canal or lumen collapses. The reverse spirals in the secondary wall cause the fibres to twist (Asif, 2010:4).

2.3.1.3 Chemical Composition

The composition of cotton fibres is mainly cellulose (Freeman & Mock, 2003:305). When these fibres are picked, it is almost 94% cellulose and in finished fabrics more or less 99% cellulose (Kadolph, 2010:64).

Cellulose is a long-chain polymer of anhydro-glucose units (Figure 2.11) connected by ether linkages (Freeman & Mock, 2003:503). These polymers can have up to 10 000 – 16 000 ß-anhydro-glucose units (Choudhury, 2006:9). Hydroxyl groups are the most important chemical group on the cellulose polymer (Hatch, 1993:165). Throughout the length of the polymer chain, these primary and secondary alcohol groups are uniformly distributed. The high water absorption of cotton is attributed to these hydroxyl groups (Freeman & Mock 2003:503). It can also act as reactive sites along the polymer chain (Kadolph, 2010:64).The hydroxyl groups react with a variety of chemicals, thus it is

possible to modify cotton fibres by creating reactions of chemical finishing resins within it (Hatch, 1993:165).

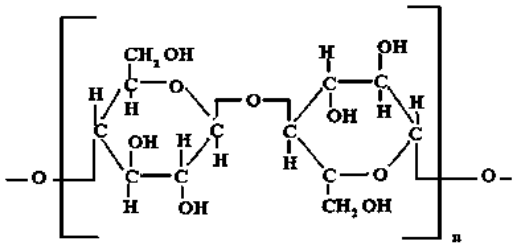


Fig. 2.11 Chemical structure of repeating unit cellulose in cotton fibres (Kadolph, 2010:59)

The monomers are connected in long linear chains and are arranged in a spiral form within the fibre. The length of the chain is a contributing factor towards the strength of the fibre (Kadolph, 2010:64). Due to the complex fibre morphology, it is not surprising that the packing of the cellulose molecules within the fibres is very inconsistent (Mather & Wardman, 2011:23).

The hydrogen bonds (hydrogen atoms of the hydroxyl groups are hydrogen-bonded) hold several adjacent cellulose chains in close alignment to form crystalline areas called microfibrils (Choudhury, 2006:10). It is estimated that 65% - 70% of the cotton fibre is crystalline (Hatch, 1993:165). The crystalline regions provide strength and rigidity, and are inaccessible for dyes (Choudhury, 2006:492).

Between the crystalline regions, disordered amorphous regions are found. Penetration of dyes and chemicals occur more readily in these amorphous regions. The amorphous regions are associated with flexibility, sorption and reactivity of the fibre. The dyes and chemicals are first adsorbed on the fibre surface and then they diffuse within the disordered or accessible region of the fibre (Choudhury, 2006:10).The relative proportion and distribution of the crystalline and amorphous regions determine the dyeing behaviour of the fibre (Choudhury, 2006:492).

2.3.1.4 Chemical Properties

Effect of Alkali

Due to the cuticle that provides resistance to the fibre (Mather & Wardman 2011:24), cotton is not greatly harmed by alkalis (Kadolph, 2010:66; Johnson & Cohen, 2010:37). Hence, cotton apparel cannot be harmed by detergents, especially non-phosphate detergents, which is the most alkaline (Hatch, 1993:168).

Effect of Acids

In acidic conditions, the glucoside oxygen atom (which is the link between the glucose units forming the polymer) is hydrolysed. Hot, dilute acids cause the fibre to disintegrate whilst cold, dilute acids cause gradual fibre degradation. The degradation process is slow and air pollutants, which are usually acidic, is one of the many causes for gradual fibre degradation. Combined with prolonged exposure to sunlight and the presence of vat and sulphur dyes, the degradation process can be speeded up considerably. Inorganic acids are stronger than organic acids and will hydrolyse (degrade) the cotton polymer more rapidly (Hatch, 1993:168).

Effect of Bleaches

Chlorine, as well as oxygen bleaches, can be used on cotton fabrics. However, prolonged or extensive use of bleaches can cause degradation of the fibres. If bleaches are used correctly, the biggest part of the polymer system stays intact (Hatch, 1993:168).

Effect of Solvents

Most of the organic solvents which are used during normal care and stain removal do not harm cotton. It should be noted that cotton becomes soluble in cuprammonium hydroxide and cupriethylene diamine. However, these chemicals are rarely encountered and do not form part of everyday living (Hatch, 1993:168).

2.3.1.5 Physical Properties

Cotton fibre quality is defined by the physical properties that relate to its ability to be spun into yarn, which contributes to textile performance and quality (Asif, Mirza & Zafar, 2008:1209).

Aesthetics

The convoluted fibre surface reflects light in a scattered pattern, resulting in a low lustre (Hatch, 1993:168) and a matt appearance. Long staple cotton fibres contribute to the lustre of fabrics (Kadolph, 2010:64).

Dimensional Stability & Appearance Retention

Cotton has poor dimensional stability due to very poor elastic recovery and resiliency (Humphries, 2009:22). The recovery is only 75% at a 2% extension and at a 5% extension; it recovers less than 50%. During elongation, the hydrogen bonds are broken and reforms as the polymers slide by, and stays in the new locations after the stress is removed, thus explaining the poor recovery (Hatch, 1993:166).

Overall appearance retention is moderate as cotton has low resiliency. The hydrogen bonds holding the molecular chains together are weak. All cotton fabrics shrink unless the fabric has been treated with a durable press or shrinkage resistant finish. Elastic recovery is moderate. Cotton recovers 75% from a 2-5% stretch (Kadolph, 2010:65).

Durability

The fibre strength is related to the average length of the cellulose molecules deposited inside the cotton fibre, therefore, the longer the cellulose chains, the stronger the fibre (Asif, 2010:10). The initial modulus, as well as the tenacity of cotton, is medium (Hatch, 1993:165), consequently cotton is classified as a medium strength fibre (Kadolph, 2010:64).

When a force acts on cotton, the spiralling polymers around the primary and secondary walls are pulled in alignment with the fibre axis. Thus, although elongation of the fibre occurs, it is low. The low elongation can also be ascribed to the effectiveness of the

hydrogen bonded system. In highly crystalline fibres, the cotton fibre will break instead of elongate, because the strength of the covalent bonds along the polymer chain is lower than the strength of the hydrogen bonds (Hatch, 1993:165).

It has good abrasion resistance (Kadolph, 2010:64), although excessive abrasive action can tear fibre cell walls, crack fibres or break fibre tips which results in damaged appearance and thinning fabrics (Hatch, 1993:166).

Comfort and Conductivity

Cotton is extremely comfortable due to its high absorbency (Kadolph, 2010:65). The more water cotton absorbs, the less rigid it becomes. Wet cotton fabrics are often deemed as uncomfortable due to increased contact with the skin and the slow drying time. However, under drier conditions cotton is very comfortable to wear. The fibres absorb water vapour readily; hence the skin does not become wet (Hatch, 1993:167). Cotton has a soft hand and good heat and electrical conductivity. Static build-up is not a problem generally associated with cotton (Kadolph, 2010:65).

Absorbency and Moisture Regain

Cotton is a hydrophilic fibre (Hatch, 1993:166) and absorbs water easily. It can absorb up to 20% water vapour without feeling wet, and up to 65% of its weight without dripping (Elsasser, 2010:49). High count woven fabrics can even be water repellent (Kadolph, 2010:650).

Soiling and Launderability

Due to cotton's inherent hydrophilic nature, it is subject to water-borne soiling. Oil can be absorbed which fills the lumen, and solid dirt particles become wedged between the twists of the fibre. However, the oily dirt and particulate soil is readily released by the cotton fibre (Hatch, 1993:167).

Cotton is 30% stronger when wet (Kadolph, 2010:167), and is one of the few fibres to gain tenacity when it is wet. Hatch (1993:167) suggests that this might be due to a temporary improvement in polymer alignment in the amorphous regions of the polymer, as a result of the fibre swelling when wet. The fibre also becomes untwisted

due to the increased water uptake in the lumen, which increases tenacity (Hatch, 1993:168).

Cotton can be laundered with strong detergents and it requires no special care during laundering and drying (Kadolph, 2010:65), however, elongation might increase after repeated washing (Munshi *et al.*, 1992:177). White cottons can be laundered in hot water and it is better to launder coloured cottons in warm (not hot) water. The use of chlorine bleach is appropriate for spot removal, although it may have a bleaching effect on the fabric (Kadolph, 2010:65).

Aftercare

Cotton is not thermoplastic, thus it can be ironed safely at high temperatures (Kadolph, 2010:168). This might be due to the extremely long fibre polymers and hydrogen bonds. The polymers are prevented from occupying new positions (Hatch, 1993:168). Cotton can withstand temperatures of up to 150°C; above this temperature the tensile strength decreases (Mather & Wardman, 2011:36). It should be noted that cotton burns readily (Kadolph, 2010:168).

Cotton should be stored in a cool dry place. Mildew will form in damp and humid conditions. Mildew digests cellulose, so holes may form if enough time elapses (Kadolph, 2010:65).

2.3.1.6 Dyeability

Due to the hydrophilic nature of cotton and the presence of hydroxyl groups, a variety of chemicals such as dyes can be used successfully on cotton thereby enhancing its appearance (Mather & Wardman, 2011:38). This is especially important because colour plays a vital role in the use of cotton fibres (Parvinzadeh, 2007:219). Cotton has a remarkable affinity for various dye-classes. It is dyed with a very large number of dyes using various machines and methods, depending on the availability, fastness requirements and cost permitted (Choudhury, 2006:491).

Cotton is predominantly dyed with direct and reactive dyes (Cai, Pailthorpe & David, 1999:440), because it yields bright shades, wide colour ranges, flexible application procedures and good colourfastness (Lewis & Vo, 2007:306). However, these dyes have only moderate affinity for cotton fibres. This is usually overcome by adding high levels of electrolytes to the exhaust dyeings. Dye fixation is also low. Due to this, the dyeing process of cotton is highly water and energy intensive and results in a significant amount of chemicals and colour in the dye house effluent (Karahan *et al.*, 2008:106).

Chemically cellulose behaves as a polyhydric alcohol and most commercial reactive dyes can only react with it under alkaline conditions. Under neutral conditions, reactive dyes adsorb and diffuse inside the fibre, but do not react with it as the concentration of cellulosate ion is extremely low (Slater, 2003:81). Reactive dyes, react with the hydroxyl (-OH) groups to form a stable covalent bond with the fibre. The wash fastness of reactive dyed cottons is especially good, so it is ideal for products which are often dyed to heavy depths of shade and are likely to be frequently washed (Mather & Wardman, 2011:38). Reactive dyes are also easily applied to cotton (Ahmed & El-Shishtawy, 2010:1149).

For reactive dyes to have a reaction with cotton, the process relies on an elevated pH and large amounts of electrolyte to achieve satisfactory results (Lewis & Vo, 2007:306). A significant portion of these dyes is however not fixed on the fibre at the end of the dyeing process. A portion of the unfixed dye may be hydrolysed and thus be unavailable for recovery or reuse. Despite this, the application of reactive dyes to cotton, continues to be costly for the dye house in terms of dye wasted, electrolyte and alkali used and in addition, present a large pollution problem (Burkinshaw *et al.*, 2000:259).

Dyeing cotton with direct dyes is a very energy- and water-intensive process. Cotton builds up negative surface charges in water and these charges act to repel anionic dyes and retard exhaustion. This lack in affinity is bridged by adding high concentrations of electrolytes in the dye bath. These electrolytes overcome the build-up of negative charges on the cotton fibre and reduces the solubility of the dye. Rinses and washes after dyeing are employed to remove unfixed dyes. Resultant of these processes is large volumes of wastewater, containing significant amounts of dyes and chemicals and are discharged from the typical cotton dye houses (Hauser & Tabba, 2001:282).

Direct dyes are water-soluble and have varying fastness to washing, light, perspiration and other wet fastness properties. These dyes are also unstable to hypochlorites. The dye should withstand prolonged multi-machine washing in the presence of activated oxygen bleach-containing detergents (Choudhury, 2006:515).

Sulphur dyes are widely used to dye cotton (Parvinzadeh, 2007:219). It is assumed that single sulphur bonds (-S-) between benzene rings also exist which provide substantivity to cellulose and survive a reduction with sodium sulphide. A sulphur dye may be defined as a water-insoluble dye, containing sulphur both as integral part of chromophore and in attached polysulphide chains, normally applied in alkaline reduced liquor and subsequently oxidized to the insoluble form on the fibre. However, sulphur dyes dissolve in a solution of alkaline reducing agents such as sodium sulphide and become substantive to cellulose. Once inside the textile materials, they are converted back to original pigment form by oxidation (Choudhury, 2006:588).

Azoic dyeing exhibits exceptionally good wet fastness on cellulosic fibres. All naphthol combinations withstand washing temperatures up to boiling point (Choudhury, 2006:601). Acid dyes have low substantivity for cotton fibres and, therefore, these dyes are not normally used for the dyeing of cotton (Karahan *et al.*, 2008:106).

In an effort to improve cotton dyeing, covalently bound cationic dye sites into the cotton fibres were introduced, improving the fibres affinity for the dyes. The rinsing and after-washing processes can be therefore eliminated, thus reducing environmental pollution (Chen & Burns, 2006:250).

Cotton oxidises in sunlight. Some dyes are especially sensitive to sunlight, and when used in window treatment fabrics the dyed areas disintegrate (Kadolph, 2010:66).

'Dead cotton' is a term used to describe fibres that did not reach maturity due to attack by pests and disease. They are characterised by having virtually no secondary wall structure. 'Neps' are thin ribbon form and entangles easily into knots. These 'neps' are very difficult to remove from mature fibres and tend to reflect as white spots on dyed cotton fabric (Hatch, 1993:166).

2.3.1.7 Environmental Impact and Sustainability

Cotton is biodegradable (Hatch, 1993:169), comes from a renewable resource and is a natural cellulosic fibre. Due to these attributes many consumers tend to believe that it is an environmentally responsible product (Chen & Burns, 2006:249). However, it cannot be produced without some environmental impact (Kadolph, 2010:66). Cotton uses approximately 3% of world's farmland, but 25% of the world's pesticides (Chen & Burns, 2006:249). There is still a great deal to do to improve the environmental profile of cotton (Mowbray, 2011:24).

Cotton is a water intensive crop. When rainfall is low or irregular, irrigation is used. Excessive irrigation can upset the water table or the water level in the soil (Kadolph, 2010:67). About 8 million tonnes of cotton are grown in China, which already has a significant water stressed population and more land ear-marked for food crops, expansion of cotton crops here are limited (Mowbray, 2011:24).

Agricultural chemicals are used to fertilise the soil, fight insects and diseases, control plant growth and strip the leaves for harvest. Excess rain can create problems with runoff contaminated with these chemicals. Many of these chemicals are toxic to other plants, insects, animals and people (Kadolph, 2010:66). The biggest impact cotton has on agriculture is because of the nitrogen (fertiliser production), ginning (energy) and irrigation (Eco Textile, 2011:32).

Cotton, that is harvested by machine, is often treated with defoliant chemicals to remove the leaves. Machine-picked cotton usually also includes impurities such as seeds, dirt and plant residues which requires more effort in cleaning. Handpicked cotton does not include these components, but children are sometimes used as slave labour to pick the cotton (Kadolph, 2010:67).

Tilling the soil contributes to soil erosion by water and the wind. Cotton also uses large quantities of water, energy and chemical compounds to clean the fibre and to finish and dye the fabrics. In order to add colour in dyeing, cotton is bleached in a chemical and water solution and rinsed. Dyes and finishing chemicals add to the consumer appeal of

cotton product, but all these steps make extensive use of water, other chemicals and heat (Kadolph, 2010:67).

Organic cotton is a term used to refer to cotton that is produced without the use of synthetic fertiliser, herbicides, and pesticides. This cotton is grown by using manure as natural fertilisers and replacing pesticides with beneficial insects to prey on insects harmful to the plants. Certified organic cotton is stored without rodenticides or fungicides (Chen & Burns, 2006:250).

Green Cotton refers to cotton that has been washed with mild natural-bases soap, and the fabric is not treated with any chemicals or bleach, although natural dyes might have been used (Chen & Burns, 2006:250).

Despite the introduction of these environmentally responsible cottons, conventional cotton remains to dominate the majority of the products (Chen & Burns, 2006:250). A Life Cycle Assessment conducted by Cotton Incorporated revealed that the area of greatest environmental impact is the consumer use phase, due to the laundering habits for the care of cotton products over their life span (Cotton Inc, 2011:3).

2.3.2 Polyamide 6,6

2.3.2.1 Production

Polymers are materials of very high molecular weight which are obtained through chemical reactions of monomers. Monomers are very small molecular compounds. Condensation polymers are formed from bi- or polyfunctional monomers (Kumar & Gupta, 1998:11).

Different types of polyamides are manufactured, for example, polyamide 6, polyamide 6,6, polyamide 11 and polyamide 6,10 (Gupta, 2003:454). The notation at the end of polyamide terms is an indicator of the number of carbon atoms in the starting material. This implies that there are two monomers present in polyamide 6,6 and each contains six carbon atoms (Craver & Carraher, 2000:50).

Polyamide 6,6 is formed by the polymerisation of diamine (hexamethylene diamine) and dicarboxylic acid (adipic acid) (Collier & Tortora, 2001:166) and is a truly synthetic fibre and no naturally occurring polymer is used in the production thereof (Gupta, 2003:455).

The synthesis of this fibre is started by hydrogenating benzene to cyclohexane. The cyclohexane may also be obtained by the fractionation of petroleum. The cyclohexane is then oxidised to a cyclohexanol-cyclohexanone mixture using air. In turn, this mixture is oxidized by nitric acid to adipic acid. The adipic acid obtained through this process is both a reactant for the production of the polyamide and the raw material source for hexamethylene diamine, which is the other reactant (Gupta, 2003:455).

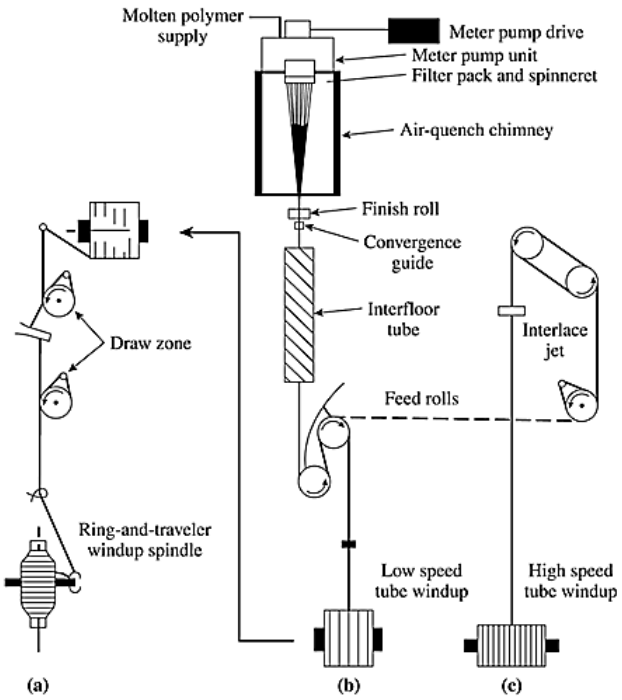


Fig. 2.12 Melt spin-draw processes for nylon yarn (a) draw-twist process, (b) conventional spinning process, and (c) coupled process (CPMA, 2013:2)

To synthesise the hexamethylene diamine, the adipic acid is first converted to adiponitrile by a reaction with ammonia and then to hexamethylene diamine by hydrogenation (Gupta, 2003:455).

Hexamethylenediamine and adipic acid are mixed in a solution to form hexamethylenediammoniumadipate, which is commonly known as nylon salt (Gupta, 2003:455). The salt is a compound and not a polymer (Collier & Tortora, 2001:167).

The salt is then purified and polymerised in an autoclave to obtain a material of the desired weight. The polymerised product is an extremely insoluble material and must be melt-spun. If it is necessary to add a delusterent or if a precoloured fabric is desired, the titanium oxide or coloured pigment is added to the polymerization batch prior to solidification (Gupta, 2003:455). The batch of nylon polymer is then extruded in a ribbon form and cut into smaller pieces, called chips (Collier & Tortora, 2001:167). Sometimes the liquid polymer is pumped directly to the fibre melt spinning operation instead of extruding it (Gupta, 2003:455).

After the ribbon is extruded and has been cut, the chips are heated on a grid. Once the freshly cut chips are melted, the chips are passed through a filter which removes any impurities (Burkinshaw, 1995:78). After the filtering, the molten polymer chips are then extruded through the small capillaries of spinnerets into cool air where the polyamide filament will be formed (Gupta, 2003:456). The cooling rates and cooling times have a major effect on the crystalline structure of the finished product and are monitored closely (Albano *et al.*, 2001:851).

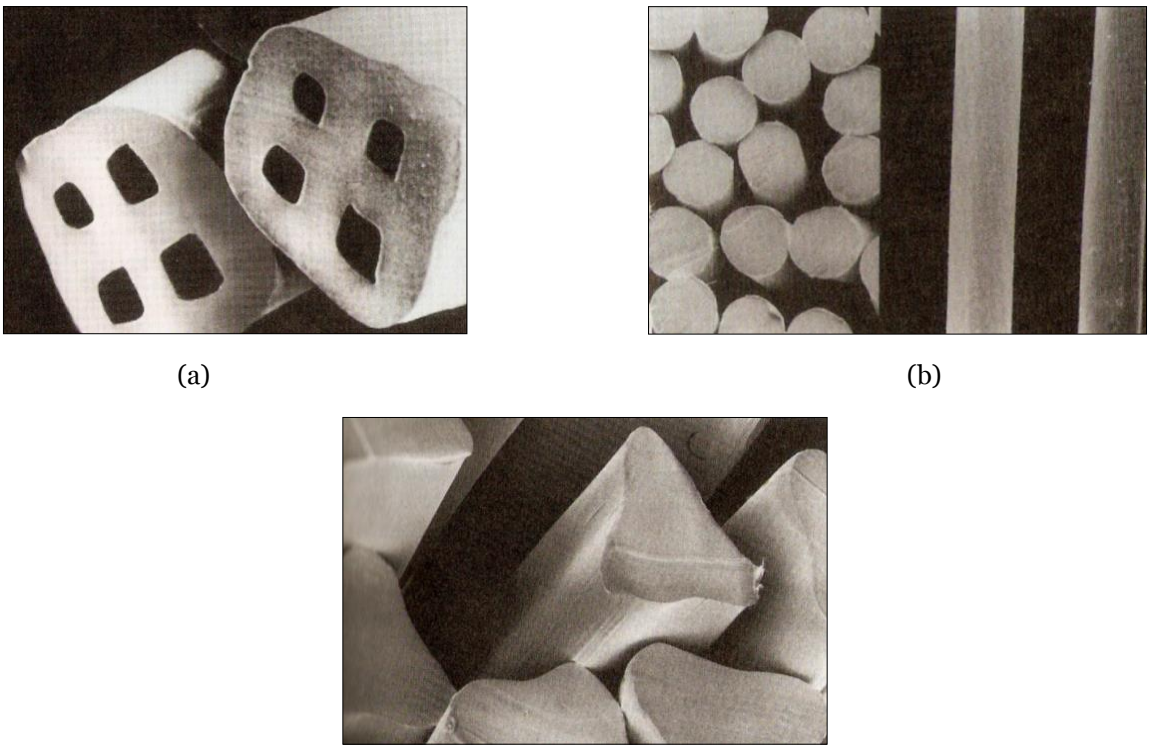
After the filaments have cooled, they are stretched or cold-drawn so that the molecules can be oriented and fibre strength and fineness can be developed. In many cases, the drawing can be combined with the spinning in a single operation (Gupta, 2003:457). During the drawing process, the fibres are stretched between four hundred and six hundred percent of their original length. It is the stretching that orientates the molecules in a more crystalline manner, thereby increasing the lustre and tensile strength (Collier & Tortora, 2001:168). Only filament fibres are cold drawn and not staple fibres. Therefore, staple fibres have lower degrees of crystallinity than filament fibres (Kadolph, 2010:160).

High-tenacity fibres are stronger than regular tenacity polyamide fibres because they are drawn to a greater degree than the regular fibres. The first mentioned fibres are, therefore, more crystalline and oriented (Kadolph, 2010:160).

2.3.2.2 Structure

Polyamide is available in a variety of lengths, which is usually determined by the manufacturer (Kadolph, 2010:159). It can be manufactured as staple fibre or continuous filament (Gruszka *et al*, 2005:133).The diameter of polyamide varies between 10 to 50 microns (Freeman & Mock, 2003:505) and is available in a variety of forms. It can be multifilament, monofilament, staple or tow. Polyamide can be manufactured in a wide range of deniers and shapes and can be partially drawn or completely finished filaments (Kadolph, 2010:159). It can also be round, tri-lobal or square (Ruchser, 2004:61; Freeman & Mock, 2003:505).

The uniform shape of polyamide produces fabrics with a very unattractive feel, hence the reason for polyamide being produced in various shapes. The fibre retains the shape of the spinneret hole (Kadolph, 2010:159).



(a) (b)

(c)

Fig. 2.13 Cross-section of square voided polyamide fibres (a), cross-section (left) and lengthwise (right) view of round polyamide fibres (b) and cross-section of tri-lobal polyamide fibres (c) (Kadolph, 2010:160)

Varying degrees of polymerisation and strengths are produced. Seen under the microscope, the fibres look like very fine glass rods. They are generally transparent, unless they were delustered or solution-dyed (Kadolph, 2010:159). Titanium dioxide is used to control the lustre of the fibres (Gupta, 2003:457). The fibres can vary from high lustre to ultra-dull fibres. Metallic look fibres were introduced to the industry early in the 21st century (Ruchser, 2004:61).

2.3.2.3 Chemical Composition

The Federal Trade Commission defines polyamide as "a manufactured fibre in which the fibre-forming substance is any long-chain, synthetic polyamide in which less than 85 percent of the amide linkages are attached directly to two aromatic rings" (Kadolph, 2010:160; Collier & Tortora. 2001:165).

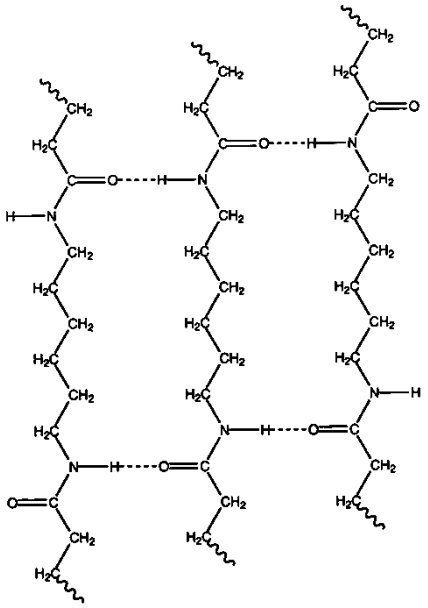


Fig. 2.14 Illustration of the Hydrogen bonding between the Amide groups in polyamide 6,6 (Fried, 1995:140)

The amide groups consist of the elements carbon, oxygen, nitrogen and hydrogen. The polyamide 6,6 chains are long and straight and do not have side chains or cross-links,

thus also known as linear polyamides (Gupta, 2003:457). The cold drawing aligns the chains so that they are oriented in a highly crystalline manner (Kadolph, 2010:160). The crystallinity of the polymers can be controlled (Albano *et al.*, 2001:852).

The polar amide group (-CO-NH-), is the most important chemical group that can be found in a nylon polymer. The other important groups are the amino groups (-NH2) that are found at the ends of the polymers. These chemical groups are the groups that will form the hydrogen bonds in the polymer system (Burkinshaw, 1995:78).

The polyamide 6,6 polymer is approximately 50% to 80% crystalline, depending on the amount of drawing. Thus, the polymer is a very well-orientated polymer system (Collier & Tortora, 2001:168).

2.3.2.4 Chemical Properties

The methylene (-CH_2-) groups are not as reactive as the amide groups, therefore, the chemical properties, that polyamides exhibit, are mostly determined by the amide groups along the polymer chains. (Mather & Wardman, 2011:144).

Effect of Moisture, Water & Temperature

The amide group serves as the site for moisture absorption in these fibres which make them reasonably hydrophilic (Choudhury, 2006:30).The retention of water depends on the degree of orientation of the fibre, especially at high humidity. Water absorption occurs predominantly at the strongly hydrophilic terminal amino groups and to those amide groups that are accessible. The fibre swells very little when immersed in water and is relatively stable in water at temperatures up to boiling point, but is hydrolysed at temperatures above 150°C (Burkinshaw, 1995:79).

The exposure of polyamide 6,6 fibres for prolonged periods of time at very high temperatures, in the absence of oxygen, will cause deterioration (Mather & Wardman, 2011:145). Polyamide will burn if it is ignited, but generally it self-extinguishes when the flame is removed. The flammability of polyamide 6,6 is also less than that of wool,

cotton and silk. Removing it from the flame will, however, in these cases not prevent the fibre from melting. When it is in the molten state, it may drip on the skin and can cause serious burns and damage (Collier & Tortora, 2001:170).

There is some disagreement in the literature of the effect of water on polyamides. Stevens (1999:376) states that moisture only affects the mechanical properties of polyamide 6,6 to a low degree. Kadolph (2007:128) experienced that due to the low absorbency of the fibre, water does not have an effect on the fibre. Fried (1995:338) is concerned that all polyamides are sensitive to water because of the hydrogen bonding of the amide groups. The water acts as a plasticiser which adversely affects the properties of the polyamide. It can reduce the tensile strength (Stevens, 1999:376; Fried, 1995:338). Hatch (1993:207) experienced that there is a strong attraction between water molecules and the polar amide groups of polyamide 6,6. These polar amide groups attract more water molecules, which are noted by an increase in hydrogen bonds.

Effect of Alkali

Polyamide 6,6 has very good resistance to alkalis (Mather & Wardman, 2011:145) and the tenacity is not readily affected (Hatch, 1993:207).

Effect of Acids

Polyamide 6,6 is sensitive to acids (Mather & Wardman, 2011:145; Burkinshaw, 1995:79) because the acids hydrolyse the amide linkages along the polymer chain. Hydrolysis causes the polyamide polymer to break up into fragments; the effectiveness of the inter polymer hydrogen bonding is lost, resulting in a weaker fibre (Hatch, 1993:207). It will almost immediately dissolve in strong acids such as formic (Kadolph, 2010:163), nitric, sulphuric and hydrochloric acids (Hatch, 1993:207).

Perspiration and a polluted atmosphere, which is slightly acidic, will cause some polymer hydrolysis on the surface of the filaments. This changes the reflection properties and causes some polyamides to have a yellow hue. The yellowing of polyamide fibres can also be caused by the absorption of body oils and fat molecules (Hatch, 1993:207).

If polyamide 6,6 is treated with concentrated hydrochloric acid at high temperatures, it will break down the polymer into adipic acid and hexamethylene diamine once again (Collier &Tortora, 2001:170).

Effect of detergents and bleaches

Polyamide 6,6 fibres are not damaged by dry-cleaning solvents or the alkalinity of detergent solutions (Collier & Tortora, 2001:170; Hatch, 1993:206).

Oxygen bleaches may be used to assist in soil removal, however, the prolonged use of chlorine bleaches may cause white polyamide to discolour and become yellow (Hatch, 1993:206).

2.3.2.5 Physical Properties

The properties of polyamide 6,6 are dependent on a variety of factors. These factors include the intra-chain bonding, the nature of the backbone, processing events (Craver & Carraher, 2000:31) and conditions (Albano *et al.*, 2001:851), chain size and molecular weight distribution (Craver & Carraher, 2000:31).

Aesthetics

The end use of the fibres determines the degree of lustre (Collier & Tortora, 2001:169). The fibres can be lustrous, semi-lustrous or dull. Polyamide 6,6 with a tri-lobal shape has a pleasant lustre and is often used in upholstery and carpets because of its ability to hide soil (Kadolph, 2007:126).

Polyamide has a medium to a hard hand. This is due to the very crystalline nature of the polymer. The crystallinity and the strong hydrogen bonds cause the fabric not to give or yield readily (Hatch, 1993:206), although the texture and draping properties of the fabrics can be varied (Collier & Tortora, 2001:169).

Dimensional Stability & Appearance Retention

Polyamide 6,6 can be heat-set, thus retains its shape extremely well during usage (Kadolph, 2010:162). The fibre will stretch when it is put under stress, but it will return to its original shape when the stress is released (Hatch, 1993:204).

At moderate temperatures polyamide 6,6 will not shrink, but at high temperatures the fabrics made from this fibre may shrink a little (Collier & Tortora, 2001:171). Shrinkage due to felting does not occur in fabrics made of this fibre. This is mainly because of the low moisture regains and smooth structure of the fibre (Liu & Wang, 2007:961).

Polyamide 6,6 is very elastic and this is due to the regularity of the strong hydrogen bonds (Choudhury, 2006:30), and recovers 100% from an 8% elongation (Kadolph, 2010:162). These bonds operate over short distances, so it's able to exert the optimum strength that prevents polymer slippage and causes the polymers to return to their original position. This means that the fibres return readily to their original shape and do not wrinkle or crease easily and recover well from it (Choudhury, 2006:30). The straightening of the zigzag configuration of the polyamide polymer when it is stretched, contribute to its elasticity (Hatch, 1993:206).

Durability

Polyamide 6,6 is one of the toughest textile fibres in use. The toughness of the fibre is related to the elasticity of the polymer system (Hatch, 1993:205). These fibres exhibit excellent abrasion resistance and tenacity and recover better from high elongation than other fibres (Kadolph, 2010:161).

The good strength of polyamide 6,6 is due to its very crystalline nature (Albano *et al.*, 2001:852). It is produced in medium to high tenacities (Hatch, 1993:205).Although the higher tenacity fibres are stronger, their elongation are less than that of the regular tenacity fibres. The higher tenacity fibres are drawn to a greater degree to obtain a more orientated system which results in a more crystalline and a stronger fibre. Drawing the fibre to a greater degree means the elongation of the fibre is going to be less (Kadolph, 2010:161).

Polyamide is unsurpassed in abrasion resistance (Hatch, 1993:205), however, pilling can present a problem (Gruszka *et al.*, 2005:133). The fabric itself can however be abrasive and wear other fabrics or surfaces (Hatch, 1993:205).

Comfort and Conductivity

Polyamide 6,6 is not as comfortable to wear as natural fibres as a result of the low absorbency. Because of this low absorbency it tends to build up static electricity, especially when the humidity is low (Collier & Tortora, 2001:170). Knitted polyamide fabrics are more comfortable to wear than woven polyamide fabrics because the moisture can escape more easily (Kadolph, 2010:162).

Polyamide 6,6 is not a good electrical conductor. Fabrics made from this fibre will also hold a static charge because it does not absorb sufficient water to dissipate the accumulation of electrons, and discharge only if a good conductor is in contact (Hatch, 1993:207). Because of this property it can be used as a good insulator in electrical materials (Collier & Tortora, 2001:170).

Absorbency and Moisture Regain

Polyamide 6,6 is a hydrophilic fibre (Collier & Tortora, 2001:170). The moisture regain of polyamide 6,6 is 4 to 4.5% (Kadolph, 2010:162).

Polyamide fibres are not very absorbent as the crystalline nature of the polymer allows very few water molecules to be absorbed (Hatch, 1993:206), thus fabrics made from polyamide 6,6 fibre will dry relatively fast after laundering (Collier & Tortora, 2001:170).

Soiling and Launderability

Fabrics made from polyamide 6,6 are machine washable (Collier & Tortora, 2001:172). Fabric soiling in polyamides is related to the cross-section of the fibres. Fibres that are round magnify the soil whereas tri-lobal and square voided fibres hide the soil (Kadolph, 2010:162).

Gentle agitation and spin cycles, rather than regular washing cycles should be used. Hot water softens the polyamide too much and should, therefore, be avoided. At higher laundering temperatures, the fibre is distorted easier and the fabric is thus more likely to wrinkle. Wrinkles, that have been set by hot wash water, may be permanent (Kadolph, 2010:162).

Although the higher laundering temperatures make the polyamide softer, higher temperatures are needed for effective soil removal (Hatch, 1993:207). Ruscher (2004:61) considers a temperature of 30˚C or 40˚C as sufficient for laundering polyamide 6,6.

Aftercare

Polyamide fabrics retain their shape and appearance well during use and care, however nylon is considered to be a colour scavenger. This means that it will easily pick up colours and dirt from other fabrics that are in the wash water (Kadolph, 2010:163).

Polyamide 6,6 is resistant to the attacks of insects and fungi, but it has low resistance to sunlight. Pollutants in the atmosphere can also damage the fibre (Hatch, 1993:207).

2.3.2.6 Dyeability

Polyamide does well when dyed with acid dyes because of the significant number of accessible free amine end groups that are present in the polymer (Burkinshaw & Son, 2006:156; Gupta, 2003:496). The substantivity of these dyes towards polyamide is based mainly on the electrostatic forces of interaction operating between the sulphonate (anionic) groups in the dye and the protonated, terminal amino groups in the fibre. Hence, the adsorption of acid dyes to polyamide is site-specific (Burkinshaw & Son, 2006:156). Polyamide can also be dyed with disperse dyes (Gupta, 2003:496). Disperse dyes are unaffected by chemical variations and, therefore, yield more uniform dyeing (Choudhury, 2006:693).

Compared with other thermoplastic fibres, polyamide fibres offer a much lower choice of colourants, because these are exposed in the melt not only to high thermal energy, but also to the reducing chemical nature of polyamide 6,6 (Choudhury, 2006:699).

Fastness to laundering is not always as would be desired when dyed with acid dyes. The fibres are generally treated with a synthetic or natural tanning agent after the dye process in order to achieve higher levels of colourfastness to laundering (Akram *et al.*, 2012:29). Tannic acid and potassium antimony tartrate are successfully used as a very effective way in which the washfastness is improved. If a non-metallised acid dye is used on polyamide, an after treatment is generally necessary to achieve adequate fastness to laundering (Burkinshaw & Son, 2010:43). If the fibre has been delustered, it requires more dyestuff because it is white (Gupta, 2003:494).

2.3.2.7 Environmental Impact and Sustainability

The production of polyamide consumes more energy than the production of polyester or cotton (Kadolph, 2010:164). The raw materials used for the production of polyamides are by-products of oil refineries. These petroleum resources are non-renewable products. Concerns have also been raised about the use and the disposal of the hazardous chemicals used to produce the polyamide resin solids. Although the raw materials of polyamide are melted in an autoclave and the solutions are extruded through spinnerets, the manufacturing process still allows nitrous oxide to emit into the atmosphere. According to Chen and Burns (2006:251) nitrous oxide is one of the substances partly responsible for depleting the ozone layer of the Earth.

There are very few chemicals that are used to clean the fibre in the processing of polyamide 6,6 from raw fibre to a finished product. The main reason for this is that the fibres are not contaminated with soil or other materials like natural fibres. There is also no need to rinse chemical residues from the fibre because it is melt spun (Kadolph, 2010:164). However, dyes or chemicals may be added to the spinning solution. The purpose of the addition is to change the physical and chemical properties of the polyamide filaments before the fibres are formed. When the fibre is formed, no finishing

processes are necessary like those used on wool (Chen & Burns, 2006:251). When alpha amino acids are introduced into a polyamide 6,6 formulation, the polymer becomes biodegradable (Stevens, 1999:376).

Polyamides can be recycled, but problems can be experienced due to the other materials that are added during production. The wide variety of nylon polymers that is available in the market further complicates the recycling thereof (Kadolph, 2010:164).

2.3.3 Polyester

2.3.3.1 Production

Polyester is produced by the polymerization reaction of a diol and a diester (Freeman & Mock, 2003:505). The major polyester in use, today is polyethylene terephthalate (1-4), commonly referred to as PET (Mather & Wardman, 2011:151). It is an ester formed by step-growth polymerization of two monomers, terephthalic acid and ethylene glycol (Choudhury, 2006:31).

It is of utmost importance that the two monomers are in a 1:1 ratio. Due to this ratio, an initial reaction can be facilitated to produce bishydroxyethyl terephthalate. Terephthalic acid is formed by the oxidation of a solution of p-xylene in ethanoic acid, using oxygen, and catalytic quantities of cobalt and manganese salts, activated by bromide anions. This product, however, contains too many impurities to be used, thus it is purified (Mather & Wardman, 2011:153).

These fibres are formed by melt spinning (Freeman & Mock, 2003:505). The molten polymer is pumped directly from the final polymerization stage to the melt-spinning machine. The polymer is then extruded through filters to the spinnerette. Spin-drawing has become the generally adopted manner in which drawing takes place, because it represents major cost savings to the fibre manufacturer. Drawing the fibres also causes an increase in molecular orientation as well as crystallinity (Gupta, 2003:461).

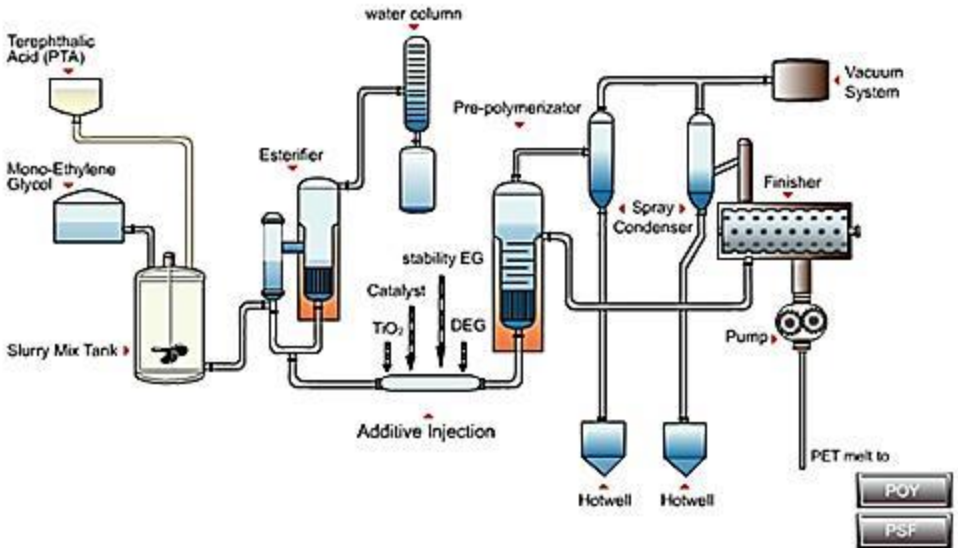


Fig. 2.15 Production process of polyester fibres (CPMA, 2013:2)

2.3.3.2 Structure

Polyester is manufactured and used in both staple and continuous filament form (Gupta, 2003:464). The fibre is smooth and generally has an even diameter (Hatch, 1993:215). The size of the fibre can be altered and is determined by the manufacturer (Gupta, 2003:493).

Polyester fibres can be produced as bright or delustered, white or solution dyed fibres. A variety of cross-sectional shapes are produced: round, trilobal, octolobal, oval, hollow, voided, hexalobal and pentalobal (Kadolph, 2010:167).

2.3.3.3 Chemical Composition

The Federal Trade Commission defines polyester fibres as “manufactured fibres in which the fibre forming substance is any long-chain synthetic polymer composed of at least 85 percent by weight of an ester of a substituted aromatic carboxylic acid, including but not restricted to substituted terephthalate units, and para substituted hydroxybenzoate units” (Kadolph, 2010:168).

There are four important chemical groups in polyester polymers, namely: methylene groups, carbonyl groups, ester links and benzene rings (Hatch, 1993:215). The chemical properties are, however, a result of the ester links in the polymer chains (Mather & Wardman, 2011:161).

Polyester has the most compact and crystalline structure of all the synthetic fibres (Fité, 1995:362). The linear molecular chains, that are packed closely together, are well oriented to the fibre axis (Hatch, 1993:215), with very strong hydrogen bonds (Kadolph, 2010:168).The orientation and crystallinity of the fibre are determining factors of the dye absorption and solubility of dyes in polyester fibres (Raslan *et al*., 2010:231).

The polyester molecular chains are stiff due to the presence of periodical phenolic groups. These fibres can be highly drawn to produce a fully oriented and highly crystalline structure. The degree of orientation can be varied over a wide range to achieve fibres with various combinations of physical properties (Choudhury, 2006:31).

2.3.3.4 Chemical Properties

Effect of Moisture, Water & Temperature

Polyester fibres are generally known to be quite hydrophobic (Choudhury, 2006:32) and can be hydrolysed by moisture at high temperatures. Significant hydrolysis of the fibres can occur at temperatures above 150°C. This reaction is catalysed by the carboxylic acid end groups, and because hydrolysis produces further carboxylic acid groups, the process is autocatalytic. Most polyesters show signs of degradation at 260°C (Mather & Wardman, 2011:162).

Effects of Alkali

Polyester has good resistance to weak alkalis and moderate resistance to strong alkalis at room temperature (Gupta, 2003:457).Hot concentrated alkali solutions hydrolyse the polymer, although this is limited to surface saponification of the fibre at temperatures up to the boil (Burkinshaw, 1995:2).Partial degradation can be ascribed to the fact that

many alkalis, such as sodium hydroxide solutions, diffuse slow, therefore only the fibre surface is attacked. The fibre cross-section is reduced, but the molar mass of the fibre stays largely unaffected (Mather & Wardman, 2011:161).

Effects of Acids

Polyester has excellent resistance to hot and cold acids (Elsasser, 2010:104) because it cannot hydrolyze the polymer chain at the ester linkages (Hatch, 1993:219). However, prolonged exposure to boiling acids can destroy or disintegrate the fibre because these acids cause hydrolysis throughout the fibre (Mather & Wardman, 2011:161).It is swollen or dissolved by phenols, chloroacetic acid or certain chlorinated hydrocarbons at elevated temperatures (Choudhury, 2006:32).

Effect of detergents and bleaches

Polyester fibres are resistant to alkaline detergent solutions. These fibres can also be bleached by both chlorine and oxygen bleaches. It should be noted that detergents are normally sufficient to remove stains, and bleaches are, therefore, not used often (Hatch, 1993:218).

2.3.3.5 Physical Properties

Aesthetics

Polyester can sometimes be described as having a hard hand. The polymer system causes stiffness because polyester polymers resist being bent. It does feel a bit waxier compared to polyamide, but that is a result of the presence of methylene groups and benzene rings in the polymer (Hatch, 1993:218).

Dimensional Stability & Appearance Retention

Because polyester has been heat set, dimensional stability and shape retention is excellent (Gupta, 2003:462). The resiliency of polyester is excellent (Elsasser,

2010:104). The crystallinity of the polymer system is largely responsible for the resilient behaviour (Hatch, 1993:218).

Pilling presents a problem in fabrics made from polyester fibres, especially those made from staple spun yarns of low twist. Pilling will develop as a result of wearing. The pills are made up of fibre ends that have worked loose from the yarn bundles as a result of surface rubbing and have wrapped around themselves. The pilling tendency of the fibre can be reduced by lowering the degree of polymerization (Gupta, 2003:495).

When polyester is exposed to temperatures greater than 195°c, drawn and heat-set fabrics will shrink (Hatch, 1993:218).

Durability

Polyester has excellent abrasion resistance (Hatch, 1993:217) and it is extremely strong fibres. The high strength is produced by hot drawing of the polymer to develop crystallinity, which also increases the molecular weight (Kadolph, 2010:169). The effective interpolymer interactions of the electrons and the benzene rings are a result of this highly crystalline polymer system (Hatch, 1993:216).

The stronger fibres have been stretched more; therefore their elongation is lower than that of the weaker fibres (Kadolph, 2010:169). The extensive interpolymer interaction of the benzene electrons along the polymer keeps the polymers from slipping (Hatch, 1993:217).

Polyester fibres do not exhibit high elastic recovery after it is subjected to high levels of stress (Hatch, 1993:217).

Comfort and Conductivity

Polyester is prone to have static problems (Kadolph, 2010:170). To a large extent, this is due to the hydrophobicity of the fibre (Hatch, 1993:218). Soil-release finishes are applied to improve the wicking characteristics of polyester, thus also improving fabric breathability and comfort (Kadolph, 2010:170).

Absorbency and Moisture Regain

Polyester is a hydrophobic fibre (Hatch, 1993:217) with very low absorbency (Elsasser, 2010:104). The low moisture regain can be attributed to the lack of polarity to attract water, the presence of benzene rings (which is hydrophobic) and the crystalline structure, which resists the entry of water molecules (Hatch, 1993:217).

Soiling and Launderability

Due to the hydrophobic nature of polyester, soil removal can present a problem, however, this problem can be overcome by vigorous laundering (Hatch, 1993:218). Warm water is generally recommended to minimise wrinkling. Hot water (49°C - 60°C) may contribute to wrinkling or colour loss (Kadolph, 2010:171).Attributing to polyesters behaviour during laundering is the fact that the fibre does not swell in water. Therefore, the mechanical properties are not significantly altered. It should be noted that polyester is not a colour scavenger (Hatch, 1993:218).

Polyester is light in weight and dries quickly. These fibres are areoleophillic and tend to retain oily soil (Kadolph, 2010:171). The presence of the benzene rings in the polymer is the most probable reason why oil adheres to the fibre (Hatch, 1993:218).

Aftercare

Low ironing temperatures should be used, as the polyester fabric will melt if the temperature is too high (Hatch, 1993:219).

2.3.3.6 Dyeability

Polyester fibres are highly crystalline and have markedly hydrophobic substrates. Therefore, it is not easily penetrable for dyes with large molecules. It also has no chemically active groups and cannot combine with dye anions or cations (Choudhury, 2006:694). This problem was overcome by introducing chemicals that added sulphonate groups to the molecule and by substituting in some cases isophthalic acid for a small portion of terephthalic acid (Gupta, 2003:465). Textiles made from these fibres

are generally dyed with disperse dyes (Ahmed & El-Shishtawy, 2010:1149) because these dyes have a very pronounced non-polar structure, causing it to have an affinity for hydrophobic fibres (Krichevskii, 2001:366).

Krichevskii (2001:364) also noted that the chemical structure of the polymer chains does not contain ionogenic and pronounced polar groups, which is the active sites of sorption of traditional dye classes (except for the terminal –COOH and –OH groups). Because of the dense structure of the fibre it is difficult to penetrate, which makes the diffusion of dyes and textile auxiliaries at a temperature below the glass transition temperature extremely difficult (Krichevskii, 2001:364). Hence, the diffusion of the dye into the fibre is extremely slow, although the exhaustion at equilibrium is good. As a result, the average temperature for dyeing polyester fibres is above 100°C. As polyester is much more thermal-stable compared to other synthetic fibres, it is possible to carry out dyeing at high temperatures (130°C) and high pressure (Choudhury, 2006:694). Increasing the temperature accelerates diffusion, which decreases the duration of the processes. Unfortunately, in some cases the non-uniformity of the temperature, results in uneven dyeing and it leads to a decrease in the quality of the colouration. However, this results in higher power consumption in comparison to most other textile fibres and the need for more complicated equipment (Krichevskii, 2001:364).

Furthermore, if the fibre has been delustered, it requires more dyestuff because it is white. It is generally accepted for polyester that the more the molecules have been organised by drawing, the slower the dyeing rate is (Gupta, 2003:494). The dyeability can be improved by the copolymerization of a third comonomer such as ethylene oxide, isophthalic acid or 4-hydroxybenzoic acid. This reduces the structural regularity of the homopolymer thereby improving the dyeability of the fibre with disperse dyes (Burkinshaw, 1995:1). Through this, the fibres are made more economical to dye because special dye bath additives, high dyeing temperatures, and high-pressure steam-print fixation usually are not required. Some polyester fibres are treated in order to be dyed with cationic dyes. Cationic dyes give brighter clearer shades than disperse dyes (Gupta, 2003:496).

2.3.3.7 Environmental Impact and Sustainability

Regardless of the fact that polyester is derived from non-renewable petroleum, the production cycle thereof is quite short. Producing polyester uses less water than cotton per kg of product and although the fibre is not biodegradable, it can be recycled. Taking a holistic view, its environmental impact can be relatively low despite the fact that it uses an energy-intensive production process (Mowbray, 2011:25).

Polyester uses less energy than the production of nylon, but more energy than the production of cotton. Some polyester is made using catalytic agents that contain heavy metal and toxic chemicals, compounds that contaminate water and soil, and have a long-term impact on the environment (Kadolph, 2010:172).

Polyester can be recycled and used to reduce landfills. It can also be produced by the recycling of bottles made of polyethylene terephthalate. An estimated 2.4 billion bottles are kept out of landfills each year in the United States alone, through the manufacturing of 100% recycled polyester (Chen & Burns, 2006:252).And because it is synthetic, it requires less hot water to wash and less energy to dry than natural fibres (Mowbray, 2011:25).

2.4 Catholyte

2.4.1 Development

The origin of electrochemically activated water can be found in the basic reaction of electrolysis, of which the principles were studied in the early 19th century. Russian academician V.V. Petrov discovered that the acidification of water near the anode and alkalization near the cathode takes place in addition to the emission of electrolytic gasses near the electrodes of a high voltage galvanic battery system which he had developed. Petrov divided the space between these electrodes (anode and cathode) with a porous diaphragm. This resulted in the first water which is characterised by the products of anodic or cathodic electrochemical reactions (Tomilov, 2002:302).

This was the foundation of Russian engineer Vitold M. Bakhir discovering the phenomenon of electrochemical activation in 1972. He also formulated the basic principles of the electrochemical activation technology (Tomilov, 2002:303). The term "electrochemical activation" first appeared in the papers of a Tashkent team of researchers who worked on this problem from 1974, of which Bakhir was the laboratory overseer (Prilutsky & Bakhir, 1997:5). Bakhir formally introduced the process of electrochemical activation, and the term was officially accepted in 1975 (Kirkpatrick, 2009:14).

2.4.2 Mechanism of Electrochemical Activation

Electrochemical activation is a physico-chemical process combining electrochemical and electrophysical actions (Lobyshev, 2007:1). The basis for this technology is the transference of aqueous media into a metastable state via an electrochemical unipolar action through the use of an element/reactor (Solovyeva & Dummer, 2000:494).

The raw products for the electrochemical activation mechanism are water and the salt dissolved in it (Marais & Brözel, 1999:155). These are generally media with low electric conductivity (Leonov, 1997:11). Freshwater and distilled water are also suitable for electrochemical activation, but requires a higher voltage which results in an unnecessary high consumption of electricity. Hence, salt is dissolved in the water for a higher content of ions and thus lower voltage for the process to take place (Tomilov, 2002:304).

Activation is the process of water transfer into a non-equilibrium thermodynamic state, and as a result there is a change in the structure of the water as it acquires a resonant microcluster structure (Aider *et al.*, 2012:4). The water is passed through the electrochemical cells anode and cathode. These cells or electrodes are specifically designed to activate the two different media, each of which has a unique set of properties and characteristics (Thantsha & Cloete, 2006:237).A reduction reaction occurs at the cathode and at the anode an oxidation reaction takes place (Aider *et al.*, 2012:39).

The processes taking place can be described in the following simplified manner:

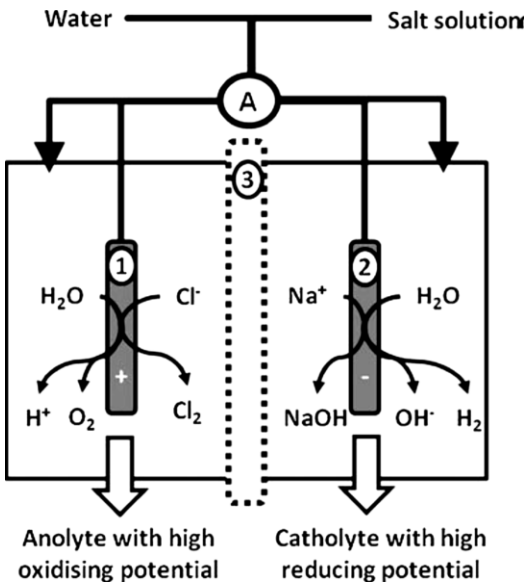
1 Oxidation of water at the anode: $2H_2O - 4e \rightarrow 4H^+ \rightarrow + O_2$
2 Reduction of water at the cathode: anode: $2H_2O + 2e \rightarrow H_2 + 2OH^-$
3 Formation of gaseous chlorine in chloride solutions at the anode: $2Cl^- - 2e \rightarrow CL_2$
4 Formation of highly active oxidants in anodic chamber: Cl_2O, ClO_2, ClO^-, HClO, Cl^+, O_2^+, O_3, HO_2, OH^+
5 Formation of highly active reductants in cathodic chamber: OH^-, $H_3^-O_2^-$, H_2, HO_2^+, HO_2^-, O_2^- (Prilutsky & Bakhir, 1997:10).

Activation is a long lasting unstable state. Therefore, structural transformations of dissolved substance molecules go on for dozens of hours and during this time the solution's reactional ability undergoes gradual changes until it finally becomes stable (Prilutsky & Bakhir, 1997:4).

The design of an electrochemical activation apparatus generally comprises of two compartments which are divided into two sections by a diaphragm. The polarity of the electrodes can be reversed and the solutions are produced inside the electrochemical reactors (Aider *et al.*, 2012:41).

The electrode chambers are elongated spaces between the cylindrical surfaces of the electrode and the diaphragm. The dimensions of these electrodes are specifically designed to ensure that the aqueous media flows through in equal quantities (Tomilov, 2002:304). The water synthesised in the cathodic electrode is named Catholyte and the term Anolyte is used for the acidic counterpart synthesised in the anodic electrode (Kirkpatrick, 2009:16), as illustrated in Figure 2.16.

During the later stages of development, similar systems were developed as the above-mentioned prototypical cell. Each system is specifically designed and developed to fulfil the need for what it is being used for (Tomilov, 2002:305). The success of this development is marked by the existence of more than 200 patents of application in different fields for these systems held by the Russian engineers (Marais & Brözel, 1999:154).



Where: (1) Anode

(2) Cathode

(3) Exchange diaphragm

(A) Electric current

Fig. 2.16 Prototypical electrochemical cell used for generating electrochemically activated solutions (Thorn *et al.*, 2011:642).

It should be noted that aqueous solutions can only be considered activated in the process of existence of anomalous properties or during relaxation period; after they are over, anomalous symptoms disappear and a classical thermodynamic equilibrium is established in the liquid medium, followed by a transition towards functional dependence of pH and oxidation-reduction potential (ORP) values typical for common (non-activated) chemical solutions (Prilutsky & Bakhir, 1997:6).

2.4.3 Properties and Characteristics of Catholyte

In the activated state, the water is marked by unusual physical and chemical parameters (Tomilov, 2002:303). This is mainly due to hydrogen along with other reactive

substances (largely antioxidants), that are generated in the cathodic chamber during activation, resulting in a decrease in the redox potential and an increased pH.

In the anodic chamber, the sodium chloride (NaCl) solution reacts at the anode surface, producing mainly chlorine and oxygen (Thorn *et al*., 2011:642). Aqueous media, which are electrochemically activated, are characterised by the metastability of the media (Lobyshev, 2007:1). The activity of electrons in the water, the electric conductivity and the pH will thus differ from the original water used for the activation (Tomilov, 2002:303).

The change in pH and redox potential is a result from stable, high-energy resonant water microclusters that are based on co-vibrating dipoles of water molecules and charged species at the electrode interfaces (Aider *et al*., 2012:40). However, this transformation is not permanent. The pH, ORP, conductivity and chloride ion concentration levels are all relatively stable during short-term storage, meaning the oxidising potential is largely retained (Thorn *et al*., 2011:642). The modified oxidation-reduction potential and altered pH of these solutions make it highly reactive and convenient for non-conventional chemical reactions. Thus, it is suitable in a wide range of applications, including the food industry and biotechnology (Aider *et al*., 2002:39).

When aqueous solutions are electrochemically activated, the physicochemical properties are changed and biological activity is imparted to it (Miroshnikov, Masalimov & Bruskov, 2004:27). Catholyte and Anolyte have different physicochemical properties, and also have different effects on biological objects. Catholyte stimulates biological growth and Anolyte inhibits it (Popova, Kiselev & Lobyshev, 1999:31).

Catholyte is alkaline with reduced redox potential which means it can give up electrons (Forostyan, Forostyan & Soroka, 1987:353) and Anolyte is more acidic with an increased redox potential. The last mentioned is dependent on the duration of the electrolysation process (Lobyshev, 2007:1) as well as the salt concentration of the initial electrolyte media. The redox potential of both the Anolyte and Catholyte solutions can be preserved by freezing it over a long period of time (Petrushanko and Lobyshev, 2001:389).

The concentration of the alkalis in Catholyte is proportional to the mineralisation of the water and the electricity consumption during the process when it was synthesised (Bakhir, 1997:39). Catholyte generally has a pH of 11.5 or higher, with surfactant and enhanced wetting properties (Kirkpatrick, 2009:17). It does not possess an obvious smell, but does have a soapy feel and is considered to be biocompatible (Gulabivala *et al.*, 2004:629). Catholyte achieves high adsorption-chemical ability and has good laundering properties (Prilutsky & Bakhir, 1997:10).

Even in its activated state, both the Anolyte and Catholyte is non-toxic to the environment. The electrochemically activated water is also easy to handle and compatible with other water treatment chemicals (Thantsha & Cloete, 2006:237). Catholyte will, however, remain in its state of metastability for a couple of days. The anomalous properties of the media disappear when it is relaxed during a long period of time (Lobyshev, 2007:1).

2.4.4 Application of Catholyte Solutions

Van Zyl (2012:126) conducted a study to determine the influence of Catholyte on the soil removal as well as on certain properties of cotton, polyester and a cotton/polyester blend. Since such a study was yet to be done on polyamide, Van Heerden, Steyn & Schall (2012:682) evaluated the soil removal efficacy of Catholyte on polyamide 6,6 and furthermore the influence of Catholyte on certain properties of polyamide 6,6 (Cronjé, Steyn & Schall, 2013:10). The above-mentioned studies indicated that Catholyte removed soil effectively without detrimental effects on textile materials.

Electrochemical activation systems are used to produce aqueous media with specific physico-chemical and biological properties (Aider *et al.*, 2012:40). ECA Technologies Africa® states that Catholyte is mainly used as a degreaser and detergent for flocculation, coagulation, washing and extraction. Furthermore, the company also claims that Catholyte can be used to wash wounds instead of using iodine (ECA Technologies Africa, 2013).

Gidarakos and Giannis (2006) reported on the removal of heavy metals such as cadmium and zinc through Catholyte. As noted previously, an acidic medium (Anolyte) is electrolysed at the anode and an alkaline medium (Catholyte) at the cathode. The H^+ ions, that are generated at the anode, moves through the soil by ion migration, pore fluid flow and diffusion.

The movement of these ions improves the desorption of the cations that adsorbed on the surface of the soil. It also forces the dissolution of precipitated contaminants. The reduction reaction, that takes place at the cathode, separates the H_2^+ and H^- ions during electrolytic dissociation. The pH value at the cathode thus increases which causes the precipitation of the metals. The electromigration of these ions contributes to the removal of contaminants. This is especially true when the concentrations of ionic contaminants are high (Gidarakos & Giannis, 2006:296).

Chartrand and Bunce (2003) reported on the utilisation of Catholyte to remove iron from acid mine drainage (AMD). AMD is an environmental problem that is caused by the microbial oxidation of iron pyrite in the presence of water and the air. This forms an acidic solution that contains toxic metals. The rise in pH of the Catholyte caused the precipitation of the iron. Once, the precipitate has settled it could be separated from the water stream.

Atlantis Activator Technologies developed the Activator™ system which is specifically designed for commercial laundering. The system relies on the electrochemical activation of Catholyte and Anolyte to produce the desired pH for laundering conditions. Traditionally chemicals would have been used to achieve the desired pH. The Anolyte and Catholyte are stored in separate tanks from where only the Catholyte is used in the laundering process. The company claims that this system offers a decrease of as much as 80% in the energy level required for processing. The system is also claimed to eliminate 60% to 75% of the need to use chemicals and detergents during laundering. The Activator™ system also contributes to a prolonged usage of textile products. In addition to the reduced water and energy consumption mentioned above, it also reduces the

environmental impact by the minimal usage of chemicals (Atlantis Activator Technologies, 2010).

2.5 General Review on Laundry Detergents

Detergents are a group of chemicals that is used for laundering clothes (Warne & Schifko, 1999:196). Kadolph (2010:480) defines a laundry detergent as "a chemical compound which is specifically formulated to remove soil or other material from textiles". Laundry detergents contain surfactants and other components that make the detergent more effective in the cleaning process (Bajpai & Tyagi, 2007:327).In addition, detergents impart softness, antistatic properties and resiliency to fabrics. It also disperses well in water and is safe to use when it comes into contact with the skin and eyes (Collier & Tortora, 2001:487).

2.5.1 Composition of Detergents

A laundry detergent comprises of a formulated mixture of raw materials that are classified into different groups (Berlow, 1994:247). The classification is based on the properties and function it fulfils in the final detergent formulation (Kadolph, 2010:484). The different raw materials that detergents comprise of are: surfactants, builders, bleaching agents, enzymes and a few other substances of minor importance that remove soil and dirt from the textiles (Khurana, 2002:1).

2.5.1.1 Surfactants

Surfactants are organic chemical surface active agents (Ivanković & Hrenović, 2010:95) that can be described as a heterogeneous, long-chain molecule that contains hydrophobic and hydrophilic parts. Through altering the hydrophilic and hydrophobic parts of the molecule, the properties may be adjusted (Bajpai & Tyagi, 2007:328).

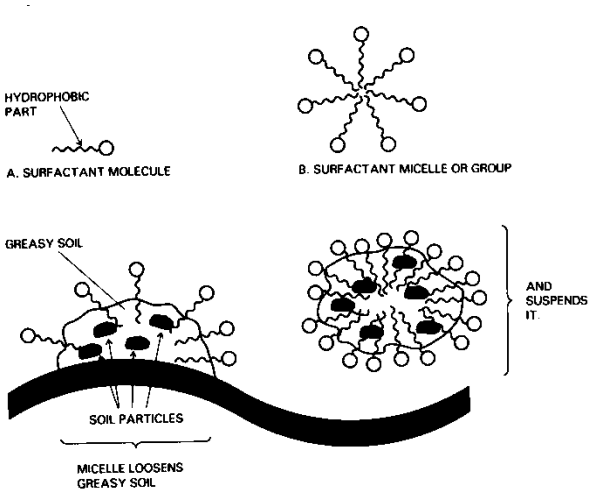


Fig. 2.17: Diagrammatic representation of Surfactant Action removing and suspending Greasy Soil (Collier & Tortora, 2001:488)

The surfactant breaks up the water molecules through its action and surrounds the soil particles as depicted in Figure 2.17. This is achieved through the surfactant lowering the surface or interface tension and thus allowing the water molecule to penetrate. Groups of surfactant molecules, called micelles, envelop the soil particle with the hydrophobic part attached to the soil. The hydrophilic part faces the water, where the particle is now suspended (Collier & Tortora, 2001:487).

Surfactants are the most important ingredient in any laundry detergent. The main reason for this is the fact that it improves the wetting ability of the water, it loosens and removes the soil with the help of the physical wash action and it emulsifies, solubilises or suspends soils in the wash solution (Ivanković & Hrenović, 2010:96).

There are different types of surfactants. The different types are categorised according to the ionic properties they exhibit in water. There are four major categories that are used in laundry detergents today namely cationic surfactants, anionic surfactants, non-ionic surfactants and amphoteric surfactants (Bajpai & Tyagi, 2007:329).

Cationic Surfactants

Cationic surfactants contain a positively charged nitrogen atom and at least one hydrophobic substituent, which is a long chain molecule (Bajpai & Tyagi, 2007:329).

These surfactants are of relative importance. The detergency of these surfactants is inferior to that of anionic and nonionic surfactants (Chupa *et al.*, 2003:1730). Cationic surfactants are limited to use in fabric softeners and disinfectants (Kadolph, 2010:484). Quaternary ammonium compounds are generally used in cationic surfactants (Bajpai & Tyagi, 2007:329).

Anionic Surfactants

Anionic surfactants are the most widely used class of surfactants (Kadolph, 2010:484). These surfactants form negative charges in water and generally most of the fabrics also carry negative charges. Because similar charges repel each other, this prevents the negatively charged enveloped soil particle from redepositing on the fabric substrate (Collier & Tortora, 2001:488).

A sodium, potassium or ammonium group often forms part of the compound. Carboxylates, sulphates, sulphonates and phosphates are hydrophilic groups that are used the most in anionic surfactants. This class of surfactants is very effective at cleaning oily soil and clay soil suspensions. The relatively low manufacturing costs of anionic surfactants and suitability for almost every type of detergent are contributing factors to its popularity (Bajpai & Tyagi, 2007:329).

Nonionic Surfactants

This type of surfactant does not ionise in the solution, hence carrying no electrical charge as it dissolves (Ivanković & Hrenović, 2010:98). Nonionic surfactants are very good at removing especially oily soil. The oily soil are removed through solubilization and emulsification. Nonionic surfactants are often used in general purpose liquid detergents. This kind of surfactant can also be mixed with anionic surfactants in some detergents (Kadolph, 2010:484).

Ethylene oxide is the most commonly used base for nonionic surfactants. It is also referred to as ethoxylated surfactants and can be further divided into a few minor groups. Polyhydroxy products like glycol esters, glycerol and sucrose esters are also an important class of non-ionic surfactants. Two minor groups, which are also used in non-ionic surfactants, are amine oxides and sulphonyl (Chupa *et al.*, 2003:1729).

Amphoteric Surfactants

Amphoteric surfactants contain anionic and cationic groups. The most common amphoteric surfactants are known as N-alkyl betaines, which are derivatives of trimethyl glycine (Chupa *et al.*, 2003:1730). The behaviour of amphoteric surfactants is dependent on the pH of the solution they are dissolved in (Leidreiter, Gruning & Kaseborn, 2008:242).

This is also the main characteristic by which this type of surfactant is known. When it is dispersed into acid solutions, it will behave like a cationic surfactant due to the acquisition of a positively charged ion. In alkaline solutions, the surfactant becomes negatively charged and thus behaves like an anionic surfactant. Properties such as the wetting ability, detergency and foaming of amphoteric surfactants are affected by change in charge with a specific pH (Bajpai & Tyagi, 2007:330).

2.5.1.2 Builders

The purpose of builders is to enhance the cleaning efficiency of the surfactant that is being used in the detergent. Therefore, it is the second most important ingredient in any detergent formulation (Collier & Tortora, 2001:488). Builders are used in general purpose liquid and powder detergents. The function of builders can be summarised as follows:

- It softens the water through binding all the hard water minerals
- It prevents the forming of water hardness ions
- It assists in the removing of soil from fabrics by helping the surfactants concentrating on the soil
- It enhances the efficiency of the surfactants
- It disperses and suspends the soils so it cannot redeposit on the fabric or clothing
- It provides a desirable level of alkalinity, which assists in the process of cleaning (Bajpai & Tyagi, 2007:330)

Builders soften the water through sequestering (separation), precipitation or ion exchange (Kadolph, 2010:484). Alkaline conditions are desirable when cleaning. The alkalinity conveys negative charges to the soils and substrates (Kissa, 1987:331). Sodium

carbonate and sodium silicates are commonly used to fulfil the purpose of an alkaline agent in laundry detergents (Bajpai & Tyagi, 2007:330).

There are three types of builders:

Sequestering Builders

Polyphosphates and citrate are sequestering builders. The polyphosphates inactivate the mineral ions which cause the water to be hard, and are able to suspend them in the solution (Edser, 2007:1). Citrate is not as strong as the polyphosphates, but it has a desirable effect. Citrate also contributes to the detergency performance of the liquid detergents (Bajpai &Tyagi, 2007:330).

The effect of phosphates on the environment has been a discussion topic for decades (Knud-Hansen, 1994:2). The environmental impact of these phosphates is discussed under heading 2.5.3.

Precipitating Builders

Sodium carbonate and sodium silicate are considered as precipitating builders. It is able to suspend the soil and prevent it from redepositing on the fabric surface (Chupa *et al.*, 2003:1732). Silicates soften the water by forming a precipitant with the hardness ions which can be washed away when the fabric is rinsed. This is an irreversible reaction which is extremely effective on calcium ions (Bajpai & Tyagi, 2007:330). Sodium carbonate provides high alkalinity in addition to forming a precipitant with calcium and magnesium carbonates (Chupa *et al.*, 2003:1732).

Zeolite

Zeolite is a sequestering agent for multivalent metal ions (Kadolph, 2010:485). It sequesters the multivalent ions and also the anionic surfactants from precipitating out of the solution (Bajpai & Tyagi, 2007:330). Zeolite is successfully used to replace sodium tripolyphosphate (STPP). STPP has a detrimental effect on the environment which stimulated the usage of zeolite as an alternative builder (Hui & Chao, 2006:401). Replacing STPP with zeolite does not have a damaging effect on textile fabrics (Pillay, 1994:32).

2.5.1.3 Anti-Redeposition Agents

Anti-redeposition agents prevent the loosened dirt and soil from redepositing on the clean garment or fabric. Although anionic surfactants also fulfil the function of an anti-redeposition agent, other agents are still added none the less (Collier &Tortora, 2001:489).

The most popular anti-redeposition agent used in liquid detergents is carboxymethyl cellulose. It is derived from natural cellulose and is very soluble in water (Miller & Raney, 1993:174). These agents adsorb to the soil or substrate and convey a negative charge to it. The soil will not redeposit on the fabric surface due to this negative charge (Kadolph, 2007:420).

2.5.1.4 Corrosion Inhibitors

Corrosion inhibitors help to protect the washing machine during laundering. It protects the mechanical parts of a washing machine against corrosion. Sodium silicate is often used as a corrosion inhibitor (Collier & Tortora, 2001:489).

2.5.1.5 Processing Aids

These agents are added to the laundry detergent to provide the detergent with the desirable physical properties for the use which it is intended. For example, when sodium sulphate is added, it helps to provide crisp and free-flowing powders (Kadolph, 2010:485). Alcohols are used as solvents for all the ingredients in liquid detergents. Alcohol also helps to adjust the viscosity and prevent separation within the product (Bajpai & Tyagi, 2007:330).

2.5.1.6 Colourants

Colourants are added to impart a certain distinguished look or individuality to the product (Edser, 2007:2).

2.5.1.7 Fragrances

Fragrances have three functions in any laundry detergent formulation:

- It covers the chemical odour of the detergent
- It covers the odour of the soils and substrates in the washing solution
- Its imparts a pleasant scent to the fabrics (Collier & Tortora, 2001:489)

These three functions stay the same in the laundry detergents, regardless of the scent or type of fragrance used (Bajpai & Tyagi, 2007:331).

2.5.1.8 Bleaches

Oxygen Bleaches

Oxygen bleaches provide laundry detergents with a bleaching action for the removal of soils and stains, which can be used on all fabrics (Moe, 2000:79). Oxygen bleaches in liquid laundry detergents come in the form of hydrogen peroxide. In these liquid forms, the oxidising agent (which bleaches) is supplied directly. The hydrogen peroxide breaks up the soil and organic material in the washing solution (Kadolph, 2010:485). In addition to the last mentioned, it also offers colourfastness to the fabric (McLean, 1999:42). Hydrogen peroxide is gentler than sodium hypochlorite which is used in chlorine bleaches (Bajpai & Tyagi, 2007:331). Sodium percarbonate or sodium perborate is bleaches often used as these agents (Collier & Tortora, 2001:489).

2.5.1.9 Opacifiers

Opacifiers contribute to the rich opaque appearance of liquid detergents (Kadolph, 2010:485).

2.5.1.10 Enzymes

In recent years it has become very popular to add enzymes to detergent formulations (Bajpai& Tyagi, 2007:331). When enzymes are present in the detergent formulation, it has the added benefit that the laundering can be done at lower temperatures with improved cleaning (Vasconcelos *et al*., 2006:725; Schroeder *et al*., 2006:738). Protease is an enzyme used in laundry detergents and it helps to break down complex protein soils like blood, grass and milk (Bajpai & Tyagi, 2007:331). Amylases, lipases, cellulases and mannanases are other enzymes that are also used. Proteases are however one of the most important groups (Schroeder *et al*., 2006:738).

Protease can also hydrolyse natural protein fibres, for example, wool. This causes irreversible damage to the fabric and clothing made from this fibre (Vasconcelos *et al*., 2006:726). Some of the protease enzymes that are used can penetrate the wool fibre without much difficulty and are able to destroy the cortex. This results in reduced tensile strength (Schroeder *et al*., 2006:739).

2.5.1.11 Other Ingredients

Sometimes other ingredients (which are not mentioned in the above list) are added to laundry detergents to provide special outcomes which are desired by the consumer. One such example is the addition of optical brighteners. These brighteners are essentially dyes that absorb light at one wavelength and re-emit it at another. Consequently, the brighteners cover the soil and make yellow fabrics appear white (Kadolph, 2010:485).

2.5.2 Phosphate Based Detergents

Phosphate based detergents are used to soften hard water and assist in suspending the dirt. This kind of detergent contains phosphates and it is highly caustic (Bajpai & Tyagi, 2007:327). The typical formulation for a standard phosphate-based detergent is depicted in Table 2.1.

Phosphate not only binds hardness causing ions, but it also fulfils other functions that are critical for efficient soil removal. These functions include pH buffering and breakup of soil (Kissa, 1987:333). Phosphates thus remove calcium and magnesium from the water to help the surfactants in suspending and emulsifying the soils (Hui & Chao, 2006:401).

Table 2.1: Composition of a typical phosphate-based detergent (Khurana, 2002:3)

Components	**Conventional Powders (%)**	**Compact Powders (%)**
Sodium Tripolyphosphate (STPP)	20 to 25	50
Organic phosphates	0 to 0.2	0
Sodium silicate	6	5
Sodium carbonate	5	4
Surfactants	12	14
Sodium perborate	14	10
Activator	0 to 2	3
Sodium sulphate	1 to 24	4
Enzymes	1	0.8
Anti-redeposition agents	0.2	1
Optical brightening agents	0.2	0.3
Perfume	10	0.2
Water	0	8

2.5.3 Environmental Impact of Detergents

Laundry detergents are used by every household, hotel, hospital, nursing home, prison and military base in the developed world. The chemicals used in laundry detergents are non-renewable, in other words, it can only be used once (Bajpai & Tyagi, 2007:335). Those chemicals are drained directly into the sewage systems after the laundering has been done (Ivanković & Hrenović, 2010:95).

Some laundry detergents leave chemical residues on clothes if it is not dissolved properly. These residues can enter the body through the skin or lungs, causing health problems, including allergies and skin infections in the worst scenario. Some fragrances used in the detergents can also be an irritation to the lungs, causing problems for people who already have asthma (Khurana, 2002:3). Detergents not containing phosphate are less of a threat to the environment than those that do contain phosphate (Warne & Schifko, 1999:204).

Taking into consideration the amount of laundry detergents being used, some environmentalists feel that we are poisoning ourselves because billions of tonnes of these chemicals are being pumped back into the water systems. Water is one of the most critical elements for humans to survive. Therefore, it is important that the freshwater supplies must be protected (Bajpai & Tyagi, 2007:335).

Phosphate is an important part of any detergent formulation, but it is also associated with environmental issues. One such issue is eutrophication. Eutrophication occurs when the nutrient level in the water increases, causing the formation of large algae blooms. This causes slow moving water and non-moving masses of water to turn murky and it may even become toxic (Köhler, 2006:58). Eutrophication of our natural water resources is a serious problem. This causes the water life to die (Hui & Chao, 2006:401).

As far back as the 1980's Wiechers and Heynike (1986:100) reported on excessive algal and plant growth experienced in reservoirs in South Africa due to eutrophication caused by phosphate. During that period countries such as USA, Canada, the Netherlands, Switzerland and Japan have already banned phosphate as an ingredient for detergents. The detergent manufacturers opposed the ban in South Africa stating that it was going

to be to the detriment of the consumer. At that stage, they could not produce a phosphate-free product with equal washing efficiency. Replacing the phosphate would have increased the cost to the consumer and decreased soil removal efficacy (Wiechers & Heynike, 1986:99-101). In 1994, Pillay, confirmed these findings (Pillay, 1994:2).

In 2007, there were virtually no phosphate formulations on the U.S. detergent market, but 68% of the European and approximately 50% of the Canadian detergents contained phosphate. Furthermore, Latin America and some of the Pacific region countries are still using phosphate-based detergents (Bajpai & Tyagi, 2007:335). As of 30 June 2013, the European Union has subsequently limited laundry detergent phosphorus content to 0.5g as the recommended quantity to be used in a standard washing machine (European Union Regulation, 2012).

In contrast, there is no regulation introduced in South Africa to limit the phosphorus content in detergents. However, the Water Research Commission undertook pilot studies regarding the different eutrophication-management options to determine their effectiveness and applicability for implementation (Van Ginkel, 2011:698). The most recent of these was to investigate the consequences of introducing zero-phosphate detergents into South Africa. They concluded that the projected reduction in phosphate concentration loading due to the introduction of zero-phosphate detergents is significant, although being extremely costly (Quayle *et al.*, 2010). It is evident that alternative detergents need to be investigated.

CHAPTER 3

METHODOLOGY

3.1 Materials

3.1.1 Textile Fabrics

The purpose of this study was to determine what effect Catholyte had on the colourfastness and tensile strength of dyed cotton, polyamide 6,6 and polyester fabric. In order to conduct these tests, the study was divided into three main categories, each of which is comprised of a different set of textile fabrics, described in the following table:

Table 3.1: Description of dyed cotton, polyamide 6,6 and polyester textile fabrics used in this research study.

	Dyestuff	**Colour**	**Textile Fabric**	**Product Code**
Textile fabric set 1	Sulphur	Black	100% cotton	AISE 01
	Direct	Black	100% cotton	AISE 12
	Reactive	Black	100% cotton	AISE 20
Textile fabric set 2	Disperse	Red	100% polyester	AISE 30
	Acid	Red	100% polyamide 6,6	AISE 39
	Azoic	Orange	100% cotton	AISE 07
	Direct	Red	100% cotton	AISE 16
	Reactive	Red	100% cotton	AISE 13
Textile fabric set 3	Reactive	Blue	100% cotton	AISE 24
	Reactive	Violet	100% cotton	AISE 26
	Reactive	Green	100% cotton	AISE 23

NOTE: All fabrics were purchased from Center for Testmaterials, Vlaardingen, Netherlands.

3.1.2 Catholyte

A ROX-1-WB-E electrolyser unit from Hoshizaki Electric Co. was used to convert the 5% NaCl concentration, filtered water solution to its "active" metastable state, producing Anolyte and Catholyte. The Anolyte and Catholyte were produced at 1-1.5 L/min. The prepared Catholyte had a pH of between 11 and 12 and was used within 1 hour of preparation.

The tap water used for the electrolysis was passed through a filtering system to ensure suitable softness properties, as per the instructions of the manufacturer. The composition of the Catholyte and filtered water is depicted in Table 3.2.

For each laundered sample, 150ml of the prepared Catholyte was used.

Table 3.2: The composition of Catholyte and filtered water, as provided by the Institute for Groundwater Studies, University of the Free Sate.

Determinant	Units	Filtered Water	Catholyte
Free Chlorine	Mg/L	<0.01	0.04
Calcium as Ca	Mg/L	2.845	8.004
Magnesium as Mg	Mg/L	1.259	2.726
Sodium as Na	Mg/L	53.6	300.9
Potassium as K	Mg/L	0.143	0.274
Aluminium as Al	Mg/L	0.013	0.017
Iron as Fe	Mg/L	0.055	0.101
Manganese as Mn	Mg/L	0.002	0.003
Copper as Cu	Mg/L	0.010	0.024
Nickel as Ni	Mg/L	0.010	,0.010
Zinc as Zn	Mg/L	0.013	0.128
Sulfate as SO4	Mg/L	21.54	15.69
Barium as Ba	Mg/L	0.004	0.011
Stronsium as Sr	Mg/L	0.004	0.010
Silicon as Si	Mg/L	3.552	2.710

3.1.3 Non-Phosphate Detergent

The ECE Non-Phosphate Reference Detergent Type A (706-652) without optical brighter was purchased from Dutest Agencies, Cape Town, South Africa. The composition of the detergent is shown in Table 3.3.

For each laundered sample, 150ml filtered water and 0.23 g of the detergent powder was used, as stated by the test method used (refer to section 3.2.1.1).

Table 3.3: The composition of the ECE Non-Phosphate Reference Detergent Type A as provided by the manufacturer.

Ingredient name	Contents
SODIUM CARBONATE	5-15%
Foam Inhibitor	5-15%
Sodium Dodecyl Benzene Sulphonate	5-15%
Ethoxylated Fatty Alcohol C12-18 (7E/O)	1-5%

3.1.4 Filtered Water

The tap water was passed through a four-phase filtering system, containing 5 micron filters and carbon filters. The measured pH of the filtered water was between 7.61 – 7.96.

3.2 Methods of Testing

3.2.1 Colourfastness

In order to assess colourfastness of the textile fabrics used in this study, wash fastness, staining and colourfastness to rubbing was measured.

3.2.1.1 Wash fastness

The laundering was conducted using an Atlas Launder-Ometer (Atlas Electric Devices Co.) and AATCC Test method 61-2009. Test IIA was used for this study.

Half (1475) of the samples were laundered at 40°C with three different washing liquors (Catholyte, detergent or filtered water) for five, ten, twenty or fifty cycles. The remainder of the samples (1475) was laundered at 60°C with Catholyte, detergent or filtered water for five, ten, twenty or fifty cycles.

Fifty stainless steel balls were placed in each stainless steel canister, as well as 150ml of the washing liquor in accordance with the test method. The balls were counted after each laundering cycle to ensure all the samples were subjected to the same degree of agitation. One test specimen per canister was allowed.

After laundering, the test specimens were rinsed for one minute in individual glass beakers containing 150ml filtered water in a water bath at 40°C. The samples were left to dry indoors before it was laundered again. No artificial light source (i.e. fluorescent lighting) was used during these procedures.

Colour Change:

The colour change, that each test specimen exhibited, was measured (AATCC Evaluation Procedure 6-2008) instrumentally with a Spectrophotometer 2300d using illuminant $D_{65}10°$ standard observer before subjected to laundering (refer to calculation on p77). Colour measurements of each specimen were taken again after laundering. Five samples per textile material were used for each treatment, number of laundering cycles and temperature combination. Five readings per sample were taken. The change in colour was determined according to AATCC Evaluation Procedure 7-2006.

The CIE L*a*b* colour space was used (Figure 3.1). L* defines the lightness, a* conveys the red/green value and b* the yellow/blue value. On the a* axis, which runs from left to right, a movement in the direction of –a indicates a shift towards green and a measurement in the direction of +a indicates a shift towards red. A movement towards –b on the b* axis depicts a shift towards blue and a movement towards +b depicts a shift

towards yellow. On the L* axis L = 100 at the top of the axis, which is white or total reflection. At the bottom of the L* axis L = 0, which is black or total absorption.

The L* value of the colour measurement is taken and not manipulated or altered. The a* and b* values however are merely co-ordinates and need to be interpreted by the computer programme accompanying the apparatus with which the readings were taken with. The differences in colours can be expressed numerically by calculating ΔE. The ΔE* indicates the size of the colour difference. It does not determine the way in which the colours are different (Konika Minolta, 1998:22).

The calculation of ΔE is done using the following formula:

$$\Delta E = \sqrt{\Delta a*^{2} + \Delta b*^{2} + \Delta L*^{2}}$$

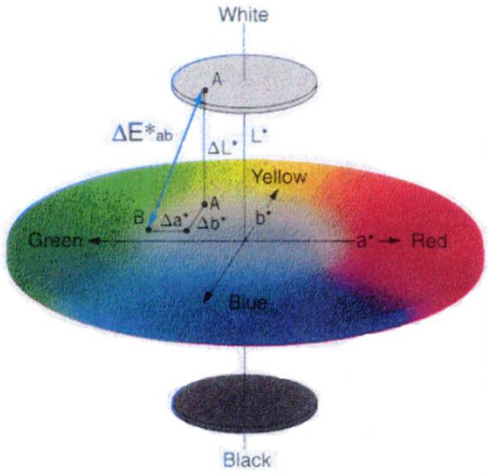


Fig. 3.1 The L*a*b* Colour Space (Konika Minolta, 1998:22)

The colorimetric (L*a*b*) data obtained from the instrumental evaluation was then converted to Gray Scale equivalents according to the appropriate evaluation procedure (table 3.4). The calculations were made using the following formulae:

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

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

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

$$\Delta H_K = \Delta H^*_{ab} - D$$

$$\Delta C_K = \Delta C^*_{ab} - D$$

$$D = (\Delta C^*_{ab} \cdot C_m \cdot e^{-x}) \,/\, 100$$

$$x = [(h_M - 280) \,/\, 30]^2$$

$$C^*_{ab} = (a^{*2} + b^{*2})^{1/2}$$

$$h^*_{ab} = \arctan(b^*/a^*)$$

The samples were conditioned for a minimum of 24 hours at 21° ± 1°C and 65% ± 2% relative humidity before the tests were conducted.

Table 3.4: Gray Scale Colour Change Step Values

ΔE_F		GSc
	< 0.40	5
≥ 0.40	< 1.25	4-5
≥ 1.25	< 2.10	4
≥ 2.10	< 2.95	3-4
≥ 2.95	< 4.10	3
≥ 4.10	< 5.80	2-3
≥ 5.80	< 8.20	2
≥ 8.20	< 11.60	1-2
≥ 11.60		1

Colour Strength:

Colour Strength values (expressed as a K/S value) of the samples were also measured. The K/S value at one wavelength interval (520nm) was calculated, according to the Kubelka-Munk equation:

$$K/S = ((1.0 - R_\lambda)^2 / (2.0\ R_\lambda)$$

Where:

R_λ is the absorption coefficient of the sample

λ is the specified wavelength, 520nm.

K is the absorption coefficient

S is the scattering coefficient

3.2.1.2 Staining

Staining was determined in accordance with AATCC Test Method 61-2009. Bleached cotton test fabric (5cm x 5cm) was sewn onto the short edge of the samples. Colour measurements of the cotton test fabric were taken before and after laundering for each individual sample. Three readings per sample were taken. The change in colour (staining) was determined according to AATCC Evaluation Procedure 12-2010. The colorimetric data obtained was converted to Gray Scale for Staining Step Values as specified by the evaluation procedure. The following calculations were used:

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

Staining-scale grade (SSG) was calculated, using the following equation:

$SSG = 6.1 - 1.45 * \ln(\Delta E_{GS})$

If SSG was greater than 4, it was recalculated using the following equation:

$SSG = 5 - 0.23 * \Delta E_{GS}$

Table 3.5: Gray Scale Staining Step Values

ΔE_F	GSs
5.00 to 4.75	5
4.74 to 4.25	4-5
4.24 to 3.75	4
3.74 to 3.25	3-4
3.24 to 2.75	3
2.74 to 2.25	2-3
2.24 to 1.75	2
1.74 to 1.25	1-2
Less than 1.25	1

Measuring took place after the samples had been dried and conditioned for a minimum of 24 hours at 21° ± 1°C and 65% ± 2% relative humidity.

3.2.1.3 Colourfastness to Rubbing: Dry & Wet

AATCC Test Method 8-2007 was used to determine the colourfastness to rubbing, for both wet and dry.

Dry:

Each sample was placed on the base of the Crockmeter, resting flat on the abrasive cloth. A white test cloth square (5cm x 5cm), with weave parallel to the direction of the rubbing, was placed over the end of the finger. The test square was secured in place using a spiral wire. The test square was rubbed for 10 complete turns at the rate of one turn per second and removed afterwards. The test squares were evaluated using AATCC Evaluation Procedure 12 (refer to section 3.2.1.2).

Wet:

The test square was weighed, and 0.16mL (0.65 times its weight) water was applied using a graduated pipette. The square was weighed again and the wet pickup determined, where after the above-mentioned procedure was followed.

Five samples per fabric (Table 3.1) with dimensions 50mm x 130mm, were cut with the long dimension on the bias of the fabric. The raw edges of the fabric were over-locked to avoid fraying during the laundering. The width of the overlock edges was taken into consideration when the samples were prepared, so that the dimensions of the samples still met the test specifications. The samples were conditioned for a minimum of 24 hours at 21° ± 1°C and 65% ± 2% relative humidity before the tests were conducted.

3.2.2 Tensile Strength

The tensile strength tests were conducted with the Instron Tensile Tester and SANS 1092:2007 test method was used. This test determines the maximum force before the fabric breaks and the elongation at maximum force.

The samples were carefully and accurately prepared so that their dimensions were 290mm x 70mm. A total of six samples per textile fabric (table 3.1) were prepared, with

their long sides parallel to the warp. Before the testing took place, samples were conditioned for a minimum of 24 hours at 21 ± 1°C and 65% ± 2% relative humidity.

The gauge length of the Instron (testing machine) was set at 200mm ± 1mm. The rate of extension was set at 100 mm/min. The ramp rate of the apparatus was 20 N/min. The samples were placed in the clamps with about zero force (pretension mounting). The sample was clamped with the middle of the sample in line with the centre point of the jaw edges. The test was started and the movable clamp extended until the fabric ruptured. The maximum force in Newton (a) and the percentage extension at break were recorded (b). Any readings were disregarded if the sample slipped during the testing period.

3.2.3 Statistical Analysis

3.2.3.1 Colour change and staining

All variables (L*; a*; b*; Delta-E colour difference; Delta-E staining) were calculated as the difference of the respective "after" and "before" values; thus, for example L*-difference was calculated as:

L*-colour difference = L*-after colour difference – L*-before colour difference

The dependent variables were analysed separately for the 11 textiles using an analysis of variance (ANOVA) fitting the factors treatment (Catholyte, detergent, filtered water), temperature (40 degrees Celsius, 60 degrees Celsius), and number of cycles (five, ten, twenty and fifty cycles), as well as all two-factor and interactions and the three-factor interaction. F-tests and associated p-values for the effects in the model were obtained from the ANOVA. This analysis excluded the control data because the control data was not part of the factorial design of the study.

Furthermore, least squares means for all treatments, temperatures, cycles, and for all two and three-factor combinations of treatments, temperature, and cycles were calculated, together with their standard errors. Estimates of the differences between

least squares means, associated 95% confidence intervals and p-values were reported for all main effects and two-factor combinations.

3.2.3.2 Colour strength, colourfastness to rubbing and tensile strength

Note: The variables Delta-E dry rubbing and Delta-E wet rubbing were analysed after averaging six replicate readings of each measurement.

The dependent variables (K/S value; Delta-E dry rubbing; Delta-E wet rubbing; Maximum load at break; Displacement at break) were analysed separately for the 11 textiles using an analysis of variance (ANOVA) fitting the factors treatment (Catholyte, detergent, filtered water), temperature (40 degrees Celsius, 60 degrees Celsius), and number of cycles (five, ten, twenty and fifty cycles), as well as all two-factor and interactions and the three-factor interaction. F-tests and associated p-values for the effects in the model were obtained from the ANOVA. This analysis excluded the control data because the control data was not part of the factorial design of the study.

Furthermore, least squares means for all treatments, temperatures, cycles, and for all two and three-factor combinations of treatments, temperature, and cycles were calculated, together with their standard errors. Estimates of the differences between least squares means, associated 95% confidence intervals and p-values were reported for all main effects and two-factor combinations.

Comparison to control (Maximum load at break and displacement at maximum load):

In addition to the above analysis, the 24 cell means of the data from the factorial experiment (associated with the 24 combinations of the three design factors) were compared to the control data using a one-way analysis of variance fitting a factor treatment with 25 levels (24 combinations of the three design factors, plus the control level). Estimates of the differences between the 24 cell means and the control mean, associated 95% confidence intervals and p-values were reported (SAS Version 9.2, Proc GLM).

CHAPTER 4

COLOURFASTNESS AND TENSILE STRENGTH OF COTTON DYED BLACK WITH SULPHUR, DIRECT AND REACTIVE DYESTUFF LAUNDERED WITH CATHOLYTE, DETERGENT AND FILTERED WATER

4.1 Introduction

Colourfastness is one of the most important considerations for consumers, when taking laundry practices into consideration (Alam *et al.*, 2008:58). It can be described as the resistance of a textile material to a change in any of its colour characteristics (Schindler & Hauser, 2004:144). During daily use of the textile materials, it is exposed to a variety of treatments that can cause these colour changes. Changes occur because the dye molecules decompose in the fabric, or it is removed into an external medium (Hunger, 2003:348). Staining, which is the transfer of colour to a secondary, accompanying textile material, can also occur (Schindler & Hauser, 2004:144).

Black is the most commonly used colour for textile materials. Sulphur black and reactive black is generally used on cotton because of its high colourfastness to laundering. Direct black is also used, although poor colourfastness can be expected (Fu *et al.*, 2013:3101). In this section the colourfastness (washfastness, staining, colourfastness to rubbing) and tensile strength (maximum load at break and displacement at maximum load) of cotton dyed with sulphur, direct and reactive black dyestuffs, will be evaluated, and discussed.

4.2 Colourfastness

In this study, the colour measurement was done instrumentally before laundering, as well as after the laundering process. The ΔE differences were calculated and converted to Gray scale ratings (AATCC, 2011:379) as to be compatible with results obtained in other research. These ratings can be expressed as numbers, ranging from 5 to 1: where a value of 5 indicates unchanged colour (optimum colourfastness) and a value of 1 indicates major colour change and poor colourfastness (Schindler & Hauser, 2004:144; Hunger, 2003:348). Additionally, colour strength (K/S values) at a single wavelength was determined for the dyed textile fabrics.

Differences in ΔE values indicate overall colour change and do not differentiate between strength, saturation, and shade changes (Oakes, Gratton & Dixon, 2004:279b). Therefore, the K/S values and individual colorimetric parameters, L*, a* and b* values were reported. On the a* axis (left to right), a movement in the direction of –a indicates a shift towards green and a measurement in the direction of +a indicates a shift towards red. A movement towards –b on the b* axis depicts a shift towards blue and a movement towards +b depicts a shift towards yellow. On the L* axis, L = 100 at the top of the axis, which is white or total reflection. At the bottom of the L* axis, L = 0, which is black or total absorption (Konika Minolta, 1998:22).

4.2.1 Wash fastness

4.2.1.1 Colour Change

Sulphur black dyed cotton

The sulphur black dyed cotton samples were laundered with Catholyte, detergent and filtered water for five, ten, twenty, or fifty cycles at 40°C or 60°C respectively. The measured colorimetric data (L*, a*, and b*) before and after laundering, colour

Table 4.1: Colorimetric data, colour strength (K/S) and Gray Scale values of sulphur black dyed cotton as a result of change caused by laundering treatment, -temperature and number of laundering cycles.

	Before					After					(Difference : After – Before)					
	L*	a*	b*	ΔE	K\S Value	L*	a*	b*	ΔE	K\S Value	ΔL*	Δa*	Δb*	ΔE	K\S Value	Gray Scale Value
TREATMENT																
Catholyte	22.12	1.59	0.36	22.18	14.31	21.95	0.57	-1.38	22.01	12.73	-0.17*	-1.02*	-1.74*	-0.17*	-1.58*	4
Detergent	22.09	1.59	0.33	22.15	14.31	21.65	0.80	-1.06	21.70	13.00	-0.44*	-0.80*	-1.38*	-0.45*	-1.31*	4-5
Filtered Water	22.09	1.60	0.37	22.16	14.31	20.92	0.95	-0.84	20.97	14.16	-1.17*	-0.64*	-1.21*	-1.19*	-0.15*	4
TEMPERATURE																
40°C	22.15	1.58	0.37	22.21	14.31	21.30	0.83	-1.07	21.35	13.48	-0.85*	-0.76*	-1.41*	-0.86*	-0.83*	4
60°C	22.05	1.60	0.34	22.11	14.31	21.72	0.72	-1.14	21.77	13.12	-0.34*	-0.88*	-1.48*	-0.35*	-1.19*	4
CYCLES																
Five	22.16	1.58	0.33	22.22	14.31	20.96	1.11	-0.51	21.00	14.13	-1.20*	-0.48*	-0.83*	-1.22*	-0.18*	4
Ten	22.00	1.61	0.38	22.06	14.31	20.94	0.97	-0.79	20.98	14.02	-1.06*	-0.64*	-1.16*	-1.08*	-0.29*	4
Twenty	22.13	1.58	0.32	22.19	14.31	21.28	0.71	-1.25	21.33	13.41	-0.85*	-0.88*	-1.57*	-0.86*	-0.90*	4
Fifty	22.11	1.59	0.39	22.19	14.31	22.85	0.30	-1.82	22.93	11.60	0.73*	-1.29*	-2.21*	0.74*	-2.71*	3-4

*Statistically significant ($p < 0.05$)

strength (K/S values), the statisticially analysed differences, as well as the Gray scale ratings are depicted in Table 4.1.

The differences in colour change caused by laundering the samples with Catholyte (ΔE=-0.17), detergent (ΔE=-0.45) or filtered water (ΔE=-1.19) were all statistically significant. However, according to the Gray scale values, only a slight change in colour (GSC=4-5) could be observed for the samples laundered with detergent, while the samples laundered with Catholyte and filtered water obtained readings in the same proximity (GSc=4), still indicating excellent colourfastness. Gray scale values experienced in studies conducted by other researchers (Fu, *et al.*, 2013:3108; Xiao, Zhang & Yang, 2007:195; Burkinshaw, Chevli & Marfell, 2000:70) are within the range of 4 to 4-5, which is similar to results obtained in this study and confirms that sulphur black has good colourfastness. From these results it can be deduced that Catholyte performed well in comparison with detergent and filtered water, with regards to preserving the colour of the laundered textile fabric.

Although the samples laundered with Catholyte showed the least decrease in lightness (ΔL*=-0.17), as opposed to those laundered with detergent (ΔL*=-0.44) and filtered water (ΔL*=-1.17), these samples exhibited the greatest values shifting towards green (Δa*=-1.02) and blue (Δb*=-1.74) in the colour space, adversely affecting the overall ΔE value. This corresponds with the colour strength of the samples laundered with Catholyte, decreasing the most with -1.58, whilst the samples laundered with detergent (K/S=-1.31) and filtered water (K/S=-0.15) decreased less in colour strength.

The fact that filtered water showed the least decrease in colour strength is expected, as samples laundered with filtered water is considered the control. This is in contradiction to the Gray Scale value which is less than the samples laundered with detergent. It is important to note that the Gray Scale value is calculated from colorimetric data which indicates overall colour change. When studying the individual readings it is evident that the samples laundered with filtered water showed the greatest decrease in lightness, but the smallest shift towards blue and green compared to the samples laundered with the detergent and Catholyte. As the L*-value decreases, the K/S value decreases, resulting in a duller shade. This happens because the lightness of the sample decreases, and

consequently, the inherent colour strength also. Because the lightness decreases the shift towards more light being absorbed rather than reflected, renders the textile duller (Ali *et al.*, 2015:276).

The difference in colour change caused by the laundering temperatures was statistically significant, although the differences were a ΔE value of less than 1: -0.86 and -0.35 for 40°C and 60°C, respectively. Aside from the fact that the difference in the change of colour was significant for both temperatures, the Gray Scale values still indicate excellent colourfastness (GSc=4). Interestingly, it seems as though the samples laundered at 60°C showed the least decrease in lightness (ΔL*=-0.34), however, the samples laundered at this temperature showed the greatest shifts towards green (Δa*=-0.88) and blue (Δb*=-1.48), when compared to the samples laundered at 40°C. Although the samples laundered at the lower temperature appeared to have become lighter, the colour strength of these samples decreased less (K/S=-0.83), than those laundered at 60°C (K/S=-1.19). This implies that the samples laundered at 60°C had a duller shade than those laundered at 40°C, which correlates to findings that indicate that colour change is greater as the laundering temperature increases (Laitala, Boks & Klepp, 2011:260; Alam, *et al.*, 2008:63).

Laundering the sulphur dyed cotton samples for five, ten, twenty, and fifty cycles respectively caused a significant change in colour. Initially, the ΔE value decreased, where after, the lightness progressively increased slightly as the number of laundering cycles increased. As is the pattern with the preceding discussion, the samples became lighter (+ΔL*), greener (-Δa*) and bluer (-Δb*), which adversely affected the calculated ΔE values. However, the difference in colour strength seemed to increase as the number of laundering cycles increased, resulting in declining colour strength as the laundering cycles increased. Apart from these findings, Gray Scale values obtained is still within good and acceptable fastness to laundering (GSc=4 – 3-4) and is similar to results that suggests sulphur dyes have good to excellent colourfastness to laundering (Radhika & Moses, 2014:31).

Direct black dyed cotton

Laundering the direct black dyed samples with Catholyte, detergent and filtered water statistically had a significant influence on the difference in colour change (Table 4.2).

From the Gray scale values, it is evident that the wash fastness is still of an acceptable standard, varying from 3-4 – 4. The lightness increased considerably for the samples laundered with detergent and Catholyte, but decreased when the samples were laundered with filtered water. The last mentioned samples also exhibited the smallest shift towards the green (Δa*=-0.22) and the blue (Δb*=-1.12) colour spaces. The corresponding colour strength values indicate that colour strength decreased the least when the samples were laundered with filtered water (K/S=-0.31), but decreased significantly more when laundered with Catholyte (K/S=-3.23) and detergent (K/S=-2.59). The decrease in colour strength when laundered with Catholyte and detergent, most probably is due to the physical losses, arising from the bleeding of dye into the wash liquor (which is confirmed by the staining observed, discussed in section 4.2.1.2) and chemical losses, due to the action of Catholyte and the detergent (Philips *et al*, 2000:234).

Laundering the samples at a higher temperature resulted in a greater change in colour than laundering at the lower temperature (40°C). Gray Scale values indicate that only a slight change in colour could be observed (GSc=4), whereas a moderate change in colour was observed when laundered at 60˚C (GSc=3-4), although the change was considered statistically significant. The samples laundered at 40˚C seemed to have decreased in lightness, whilst shifting towards green (-Δa*) and blue (-Δb*) in the colour spaces. When laundered at 60˚C, the samples increased in lightness, but the Δa* and Δb* parameters also shifted towards the green and blue colour spaces, respectively. This could possibly be justified by the fact that the dye molecules do not disperse at lower temperatures, but that it might have been the case that after the initial laundering at 40˚C, some of the dye redeposited on the surface of the sample, consequently decreasing the lightness of the sample slightly (ΔL*=-0.37). At a higher temperature, the dissolution of the dye particles from the fibre surface takes place. More dye particles are

Table 4.2: Colorimetric data, colourstrength (K/S) and Gray Scale values of direct black dyed cotton as a result of change caused by laundering treatment, -temperature and number of laundering cycles.

	Before					After					(Difference : After – Before)					
	L*	a*	b*	ΔE	K\S Value	L*	a*	b*	ΔE	K\S Value	ΔL*	Δa*	Δb*	ΔE	K\S Value	Gray Scale Value
TREATMENT																
Catholyte	21.35	-0.22	-0.53	21.36	14.48	22.91	-1.37	-2.71	23.12	11.25	1.56*	-1.16*	-2.18*	1.76*	-3.23*	3-4
Detergent	21.36	-0.20	-0.52	21.36	14.48	22.00	-1.06	-2.48	22.17	11.89	0.65*	-0.86*	-1.96*	0.81*	-2.59*	4
Filtered Water	21.35	-0.23	-0.57	21.36	14.48	20.27	-0.45	-1.68	20.34	14.17	-1.08*	-0.22*	-1.12*	-1.01*	-0.31*	4
TEMPERATURE																
40°C	21.37	-0.21	-0.52	21.38	14.48	21.00	-0.68	-2.03	21.12	13.19	-0.37*	-0.47*	-1.51*	-0.26*	-1.29*	4
60°C	21.33	-0.22	-0.56	21.34	14.48	22.45	-1.24	-2.55	22.64	11.69	1.12*	-1.01*	-1.99*	1.30*	-2.79*	3-4
CYCLES																
Five	21.36	-0.20	-0.55	21.37	14.48	20.70	-0.53	-1.79	20.79	13.49	-0.67*	-0.33*	-1.24*	-0.59*	-0.99*	4
Ten	21.35	-0.22	-0.52	21.36	14.48	20.80	-0.73	-2.04	20.92	13.41	-0.55*	-0.52*	-1.52*	-0.44*	-1.07*	4
Twenty	21.35	-0.23	-0.56	21.36	14.48	21.68	-1.05	-2.45	21.85	12.30	0.33*	-0.82*	-1.89*	0.50*	-2.18*	4
Fifty	21.34	-0.22	-0.53	21.35	14.48	23.73	-1.52	-2.87	23.96	10.55	2.39*	-1.30*	-2.34*	2.61*	-3.93*	3

*Statistically significant ($p < 0.05$)

thus washed off, which might also explain the increase in lightness. As more of the black (absorbing) particles are removed, the more light the sample will reflect (Alam, *et al.*, 2008:63). However, the colour strength decreased significantly as the laundering temperature increased, which is a result of the above-mentioned dissolution of the dye particles.

An initial decrease in colour change (ΔE=21.37 to ΔE=20.79) was observed when the samples were laundered for five cycles. After the initial decrease, the ΔE value increased significantly although the difference in ΔE decreased, from twenty cycles as the laundering cycles increased. This is mainly due to the change in lightness (+ΔL*) that exhibited the same behaviour, influencing the overall colour change (ΔE). The a* and b* parameters shifted progressively towards the green (-Δa*) and blue (-Δb*) colour spaces, respectively as the number of laundering cycles increased (Table 4.2). As explained previously, the initial decrease in lightness is caused by the wash-off and redepositing of the dye particles, but as the laundering progressed; the samples became increasingly lighter as more of the dye molecules dissipated. The Gray scale values are, however, of an acceptable standard (GSc=4), except for those laundered for fifty cycles, which exhibited undesirable wash fastness (GSc=3). The colour strength decreased as the number of launderings increased. This is not unexpected, because the forces between the fibre and dye are weak when immersed in water (Horrocks & Anand, 2000:196), thus repeated laundering will tend to cause greater colour loss as the number of cycles increases.

Reactive black dyed cotton

Colour change that was caused when the reactive black dyed cotton samples were laundered with Catholyte, detergent and filtered water for five, ten, twenty or fifty cycles at 40°C or 60°C respectively, are depicted in Table 4.3.

Laundering the samples with Catholyte caused the least difference in colour change (ΔE=-0.32), and obtained a Gray Scale value of 5, which indicates optimum

Table 4.3: Colorimetric data, colourstrength (K/S) and Gray Scale values of reactive black dyed cotton as a result of change caused by laundering treatment, -temperature and number of laundering cycles.

	Before					After					(Difference : After – Before)					
	L*	a*	b*	ΔE	K\S Value	L*	a*	b*	ΔE	K\S Value	ΔL*	Δa*	Δb*	ΔE	K\S Value	Gray Scale Value
TREATMENT																
Catholyte	49.16	-7.90	-15.69	52.21	1.39	48.81	-7.73	-15.81	51.89	1.32	-0.35*	0.17*	-0.12*	-0.32*	-0.07*	5
Detergent	49.19	-7.80	-15.74	52.19	1.39	48.44	-7.88	-15.78	51.55	1.34	-0.71*	-0.08*	-0.04*	-0.64*	-0.05*	4-5
Filtered Water	49.15	-7.90	-15.43	52.23	1.39	48.09	-7.83	-15.84	51.23	1.37	-1.07*	0.07*	-0.40*	-1.00*	-0.02*	4-5
TEMPERATURE																
40°C	49.15	-7.88	-15.71	52.20	1.39	48.34	-7.84	-15.81	51.46	1.36	-0.81*	0.04*	-0.10*	-0.74*	-0.03*	4-5
60°C	49.16	-7.86	-15.53	52.22	1.39	48.56	-7.78	-15.80	51.65	1.32	-0.60*	0.08*	-0.27*	-0.57*	-0.07*	4-5
CYCLES																
Five	49.20	-7.93	-15.74	52.26	1.39	48.16	-7.85	-15.84	51.30	1.36	-1.05*	-0.08*	-0.10*	-0.96*	-0.03*	4-5
Ten	49.10	-7.85	-15.48	52.16	1.39	48.32	-7.88	-15.79	51.44	1.35	-0.78*	0.03*	-0.31*	-0.71*	-0.04*	4-5
Twenty	49.09	-7.82	-15.54	52.16	1.39	48.33	-7.83	-15.87	51.47	1.35	-0.76*	0.01*	-0.33*	-0.69*	-0.04*	4-5
Fifty	49.21	-7.88	-15.72	52.27	1.39	48.98	-7.68	-15.73	52.02	1.31	-0.23*	-0.20*	-0.01*	-0.25*	-0.08*	4-5

*Statistically significant ($p < 0.05$)

washfastness. When the samples were laundered with filtered water, the greatest difference in colour change (ΔE=-1.07) could be observed, although a Gray Scale value of 4-5 was calculated, which is considered excellent washfastness. Only a slight change in colour could be observed for the samples laundered with detergent (GSc=4-5), achieving a difference in colour change (ΔE) of only -0.64. It is also true for all the samples laundered with Catholyte, detergent and filtered water, that it decreased in lightness (-ΔL*), and shifts towards red (+Δa*) and yellow (+Δb*) was observed, in the same sequence as mentioned earlier. Consequently the colour strength decreased the most for the samples laundered with Catholyte (K/S=-0.07), detergent (K/S=-0.05), as opposed to those samples laundered with filtered water, which decreased the least (K/S=-0.02). As explained previously, the decrease in lightness is directly proportional to the decrease in colour strength (page 97), therefore, Catholyte exhibited the least decrease in lightness, but the greatest decrease in colour strength. Furthermore, good washfastness is expected of reactive dyed fabrics as their covalent nature of bonding with cellulosic fabrics ensures optimum fastness (Samanta *et al.*, 2004:230). Catholyte showed to be superior with regards to preserving the colour of the reactive black dyed samples.

The difference in colour change observed was slightly higher at 40°C (ΔE=-0.74) than at 60°C (ΔE=-0.57), although the Gray Scale values for both temperatures indicate excellent washfastness (GSc=4-5). The colour strength appears to have decreased less at the lower temperature (K/S=-0.03%), than laundering at the higher temperature (K/S=-0.07%). The fact that wash fastness did not decrease considerably when laundered at a higher temperature, attests to the nature of the covalent bonds of reactive dyes being able to withstand repeated laundering at higher temperatures (Farrell *et al.*, 2011:9).

Although laundering the samples for five, ten, twenty and fifty cycles respectively caused a significant difference in overall colour change, the Gray Scale values indicated that the dye exhibited excellent washfastness (GSc=4-5). The lightness of the samples increased progressively as the number of laundering samples increased, corresponding to the colour strength (K/S values) that decreased as the laundering cycles increased. No notable pattern could be observed concerning the individual a* and b* parameters.

Initially it seemed that the samples shifted towards the red (+Δa*) and blue (-Δb*) colour spaces as the cycles increased, however, when laundered for fifty cycles, a shift towards the green (-Δa*) and yellow (+Δb*) colour spaces, beyond the initial shift experienced after laundering for five cycles, was observed. This anomaly could not be explained, but it is presumed that the composition of the dye, because it is not pure but rather a mixture of colours, possibly could have become unstable after fifty cycles. It is not characteristic for reactive dyes, but possible, especially if the exact dye structure is not known (Doyal & Warnock, 2005:264). Fu and fellow researchers (2013:3107) reported reactive dyed black cotton having a Gray Scale value of 4-5, which is comparable with results obtained in the present study.

4.2.1.2 Staining

Sulphur black dyed cotton

It is evident from Table 4.4 that the samples laundered with detergent, appeared to have stained the least (GSs=4-5). The samples laundered with Catholyte and filtered water caused moderate staining, obtaining Gray Scale values of 3 and 3-4, respectively. The corresponding ΔE values indicate the same pattern: the samples laundered with detergent resulted in the smallest difference (ΔE=-2.95), as opposed to the samples laundered with filtered water (ΔE=-5.81) and Catholyte (ΔE=-7.01). According to the individual parameters, the samples shifted towards the green (-Δa*) and yellow (+Δb*) colour spaces respectively, and the lightness decreased significantly. This is true for all the samples laundered with Catholyte, detergent and filtered water. The shift was proportionate and in the same sequence as first mentioned.

Boardman and Jarvis (2000:63) found that cotton dyed with sulphur dyes can be a major source of staining. The fact that the samples laundered with detergent exhibited the least staining, could be explained by the interaction between sulphur dyes and surfactants. Oakes, Gratton and Dixon (2004:270a) found that staining was greater in the absence of an anionic surfactant. Therefore, they concluded that anionic

Table 4.4: Colorimetric data and Gray Scale equivalents of staining caused by sulphur, direct and reactive black dyed cotton as a result of laundering treatment, -temperature and number of laundering cycles.

	Sulphur Black					Direct Black					Reactive Black				
	ΔL*	Δa*	Δb*	ΔE	Gray Scale Value	ΔL*	Δa*	Δb*	ΔE	Gray Scale Value	ΔL*	Δa*	Δb*	ΔE	Gray Scale Value
TREATMENT															
Catholyte	-6.93*	-0.55*	1.91*	-7.01*	3	-11.71*	-0.78*	-0.21*	-11.67*	3	-1.79*	-0.37*	1.24*	-0.77*	4-5
Detergent	-2.91*	-0.24*	0.81*	-2.95*	4-5	-21.86*	-4.42*	-1.57*	-21.60*	2	-0.65*	-0.22*	0.83*	-0.36*	5
Filtered Water	-5.75*	-0.37*	1.41*	-5.81*	3-4	-11.29*	-0.81*	-0.63*	-11.22*	3	-1.20*	-0.19*	0.99*	-0.90*	4-5
TEMPERATURE															
40°C	-4.98*	-0.38*	1.38*	-5.04*	3-4	-11.94*	-1.27*	-0.49*	-11.86*	2-3	-1.10*	-0.22*	1.04*	-0.67*	4-5
60°C	-5.41*	-0.39*	1.37*	-5.47*	3-4	-17.96*	-2.74*	-1.11*	-17.80*	2	-1.32*	-0.29*	1.00*	-0.69	4-5
CYCLES															
Five	-2.94*	-0.22*	1.07*	-2.99*	4-5	-13.75*	-1.37*	-0.32*	-13.71*	2-3	-0.91*	-0.15*	0.91*	-0.72*	5
Ten	-4.38*	-0.31*	1.17*	-4.43*	4	-13.78*	-1.85*	-0.93*	-13.71*	2-3	-0.92*	-0.16*	0.85*	-0.67*	5
Twenty	-6.02*	-0.45*	1.46*	-6.09*	3-4	-15.688	-2.27*	-0.95*	-15.55*	2	-1.75*	-0.39*	0.88*	-0.54*	4-5
Fifty	-7.45*	-0.58*	1.79*	-7.52*	3	-16.58*	-2.54*	-1.00*	-16.43*	2	-1.28*	-0.34*	1.44*	-0.78*	4-5

*Statistically significant ($p < 0.05$)

surfactants inhibit the transfer of sulphur dye onto adjacent textile. The observed staining may also be attributed to the anionicity of sulphur dye products coupled with the hydrophilic, absorptive character of the cotton fibres (Burkinshaw & Paraskevas, 2010:231).

The difference in colour change (ΔE) significantly increased as the temperature increased. The Gray Scale values indicate that laundering at both 40°C and 60°C had a similar influence (GSs=3-4). The staining experienced was moderate, but still within acceptable standards. The samples exhibited the same yellowing (+Δb*) and shift towards the green (-Δa*) colour space, whilst the lightness decreased (-ΔL*). Because colour change is generally greater at a higher temperature, the dye molecules staining adjacent fabrics are also reported to be higher (Radhika & Moses, 2014:31).

The colour change (ΔE) became greater, as the number of laundering cycles increased, subsequently also causing the Gray Scale values to decrease with a progressive increase in launderings. A Gray Scale value of 4-5 was obtained after five washes, which indicates that only slight staining took place. This is confirmed by similar results obtained by Xiao and co-workers (2007:195), indicating the same Gray Scale value for staining when sulphur black dyed samples were laundered. The Gray Scale value decreased, to indicate moderate staining when the samples were laundered for fifty cycles (GSs=3). Correspondingly, the samples showed shifts towards the green (-Δa*) and yellow (+Δb*) colour spaces, whilst also decreasing in lightness (-ΔL*). As the number of laundering cycles increase, it is expected that the staining will also increase as more of the dye dissipates from the fabric surface, and deposits on to the adjacent fabric (Fu, *et al*., 2013:3108).

Direct black dyed cotton

Staining that was observed as a result of laundering the direct black dyed cotton samples with Catholyte, detergent and filtered water at 40°C or 60°C for five, ten, twenty and fifty cycles respectively, is depicted in Table 4.4. It is evident that laundering with detergent resulted in the greatest staining (ΔE=-21.60) and Gray Scale value of 2.

Laundering with Catholyte caused moderate staining (GSs=3), with a ΔE value of -11.67. Laundering the samples with filtered water caused the least staining, a change in ΔE value of -11.22, although the Gray Scale value is equivalent to the samples laundered with Catholyte. The samples laundered with detergent exhibited a substantial shift toward the green (Δa*=-4.42) and blue (Δb*=-1.57) colour spaces, whilst decreasing in lightness significantly (ΔL*=-21.86). The same pattern could be observed with the samples laundered with Catholyte and filtered water, but the changes being significantly smaller. Generally, direct dyes are considered the most likely source of staining during laundering. It is due to the relative ease by which direct dyes can be displaced from cotton, especially when wash-off after dyeing was not effective. Furthermore, these dyes have been designed to be intrinsically substantive to cotton fibres (being linear, coplanar and conjugated aromatic in nature) and thus may readily redeposit (Boardman & Jarvis, 2000:64).

It is evident that staining was greater at the higher temperature, causing a change in ΔE value of -17.80, as opposed to laundering at 40°C, which caused a change in ΔE of -11.86. The corresponding Gray Scale values indicate major staining, with values of 2-3 and 2 for 40°C and 60°C respectively. As is the case with previously mentioned individual parameters, the samples showed a significant decrease in lightness (-ΔL*), and shifts towards the green (-a*) and blue (-b*) colour spaces, respectively. The great degree of staining is not unexpected as it is generally accepted that the dissolution of the dye particles takes place from the fibre surface at higher temperatures. More dye particles are thus washed off, which causes greater staining at the higher temperature (Alam, *et al.*, 2008:63).

The change in ΔE significantly increased as the number of laundering cycles increased. The Gray Scale values indicated greater staining as the number of cycles increased, resulting in values of 2-3 and 2 when laundered for five and ten, and twenty and fifty cycles respectively. In line with the two aforementioned paragraphs, the stained samples were greener (-Δa*) and blue (-Δb*), and significantly less light (-ΔL*) than before laundering. Because the forces between the fibre and dye are weak when immersed in water (Horrocks & Anand, 2000:196), repeated laundering will tend to cause greater colour loss and hence greater staining, as the number of cycles increases. Al Mamun and

fellow researchers (2014:1070) obtained similar results, reporting staining of 2-3, which is comparable with results in the present research.

Reactive black dyed cotton

Staining, that took place, was the greatest when laundering with Catholyte (Table 4.4), resulting in a change of ΔE value of -1.77, but indicating only slight staining (GSs=4-5). Laundering with detergent seems to have caused the least change (ΔE=-0.36), with resultant miniscule staining. Laundering the samples with filtered water also caused only slight staining (ΔE=-0.90 and GSs=4-5). Subsequent shifts towards green (-Δa*) and yellow (+Δb*), as well as a decrease in lightness (-ΔL*) was observed with all samples laundered with Catholyte, filtered water and detergent. Fu and co-workers (2013:3108) reported reactive dyed black cotton having a staining value of 4-5, thus these results are well within range and acceptable. The fact that detergent performed better might be because anionic surfactants aids in preventing dye particles from redepositing on adjacent textile fabrics. Catholyte and filtered water did not contain surfactants, which did not inhibit dye particles from redepositing, thus resulting in lower staining values.

Staining values (GSs=4-5) were the same whether laundered at 40°C or 60°C indicating only slight staining, although statistically, the change in colour was significant for laundering at both temperatures. A slight decrease in lightness (-ΔL*), and shifts towards the green (-Δa*) and yellow (+Δb*) colours spaces was evident. This is comparable to the previous results indicating that the colour change of reactive dyed samples laundered at the same temperatures, was not great (GSc=4-5). Consequently, because dye loss was not considerable, the staining was not prominent.

When laundered for five and ten cycles, minuscule staining was observed (GSs=5), whereas slight staining was observed when the samples was laundered for twenty and fifty cycles (GSs=4-5). Although significant, changes in the ΔE values were less than 1. The lightness of the samples decreased as the number of laundering cycles increased whilst slight shifts to green and yellow colour spaces was observed. The nature of the

covalent bonds of reactive dyes are able to withstand repeated laundering at higher temperatures (Farrell *et al*., 2011:9). It is also true that reactive dyes have less tendency to be transferred since they are smaller and have lower substantivity for cotton (Oakes, 2005:2).

4.2.1.3 Fastness to rubbing: Dry & Wet

Appearance retention is an important consideration with regards to the longevity and use of textile materials (Sonaje & Chougule, 2013:29). Consequently, rubbing fastness tests continue to form one of the most important evaluations when the dyeing of textile fibres is considered, as it is a good indication of the level of dyeing for cotton (Mohsin *et al*, 2013:344). The rubbing off behaviour depends on a great variety of factors, of which the type of dye is one. When fastness to rubbing is tested, the degree of staining is assessed using Gray Scale for staining (GSs). The changes are graded with values of 1–5, where a rating of 5 signifies negligible change and a rating of 1 denotes maximum change (Suganuma, 2013:443).

The Gray Scale values obtained as a result of the sulphur, direct and reactive black dyed samples subjected to the rubbing fastness tests, both dry and wet, are depicted in Table 4.5.

Sulphur black dyed cotton

It is evident from Table 4.5, that the Gray Scale values (GSs=4) obtained for colourfastness to dry rubbing, is similar for all the treatments, which is comparable to results obtained by Xiao and fellow researchers (2007:195). It can thus be safely concluded that Catholyte can be used to launder sulphur black dyed cotton, without any great reduction in rubbing fastness. Very poor colourfastness to wet rubbing was observed for samples laundered with all the treatments, resulting in Gray Scale values of 1 for the samples laundered with detergent and filtered water, and 1-2 for the samples laundered with Catholyte. Radhika and Moses (2014:34) also experienced poor fastness

Table 4.5: Gray Scale values of colourfastness to rubbing, dry and wet, for sulphur, direct and reactive black dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Dry			Wet		
	Sulphur Black	**Direct Black**	**Reactive Black**	**Sulphur Black**	**Direct Black**	**Reactive Black**
TREATMENT						
Catholyte	4	4-5	4-5	1-2	3	4-5
Detergent	4	4-5	4-5	1	3	4-5
Filtered Water	4	4-5	4-5	1	2-3	4-5
TEMPERATURE						
40°C	4	4-5	4-5	1-2	3	4-5
60°C	4	4-5	4-5	1	2-3	4-5
CYCLES						
Five	4	4-5	4-5	1	2-3	4-5
Ten	4	4-5	4-5	1	2-3	4-5
Twenty	4	4-5	4-5	1-2	3	4-5
Fifty	4	4-5	4-5	2	3	4-5

to wet rubbing. The fastness to rubbing is very much dependent on the fabric itself, its preparation, and the dyeing process, especially the efficiency of rinsing before oxidation (Choudhury, 2006:589). Parmar and Gurumoorthi (2011:2) reported that the substantial negative charge of the wet cotton used during wet rubbing might cause rubbing off of the dye particles that is already displaced. Thus, the Gray Scale values fastness to wet rubbing of sulphur dyes can be expected to be poor. Notably, the wet fastness of sulphur dyes are also less resistant to laundering, particularly above 50°C (Choudhury, 2006:589).

Laundering the sulphur black dyed samples at both 40°C and 60°C, resulted in good colourfastness to dry rubbing (GSs=4). Fastness to wet rubbing is very poor, resulting in Gray Scale values of 1-2 and 1 for 40°C and 60°C, respectively. Because the entrapment of sulphur dyes in cotton is greatly dependant on dipole-dipole interactions, the Van der Waals forces may become weaker at a higher temperature, causing the dye molecules to be displaced from the textile surface, and subsequently rubbed off (Jang, Ko & Carr, 2001:139).

The sulphur black dyed samples exhibited good colourfastness to dry rubbing, with Gray Scale values of 4 for the samples laundered for five, ten, twenty and fifty cycles. When the samples were laundered for five and ten cycles, fastness to wet rubbing was 1, where after the values increased half a value on the Gray Scale until the samples were laundered for fifty cycles. A probable explanation could be sought in the increase in staining. As the staining increased due to an increased number of laundering cycles (Table 4.4), more dye particles redeposited on the adjacent fabric. Because the majority of the dye particles that dissipated already deposited onto this fabric, the dye that could rub off, were reduced.

Direct black dyed cotton

Laundering the direct black dyed samples with Catholyte, detergent and filtered water resulted in equivalent Gray Scale values of 4-5 for fastness to dry rubbing, which indicates excellent fastness (Table 4.5). Mohsin and fellow researchers (2013:345) reported similar values when they investigated the fastness to dry rubbing for direct black dyed cotton. However, fastness to wet rubbing is only moderate, with Gray Scale values of 3 when laundered with Catholyte and detergent, and 2-3 when laundered with filtered water. Direct dyed cotton fabric typically exhibits one of the lowest wet fastness properties and was demonstrated in the current research (Mohsin *et al.*, 2013:345).

Laundering at both 40°C and 60°C, resulted in excellent fastness to dry rubbing (GSs=4-5). Fastness to wet rubbing is only moderate, with a value of 3 when laundered at 40°C, and slightly lower (GSs=2-3) when laundered at 60°C. Direct dyes are known to

exhibit better fastness to dry rubbing (Inglesby & Zeronian, 2002:19), as opposed to wet rubbing, particularly at higher temperatures (Oakes, 2005:2).

Regardless of the number of laundering cycles, fastness to dry rubbing is excellent, obtaining Gray Scale values of 4-5. However, laundering the samples for five and ten cycles resulted in fastness to wet rubbing of 2-3 and 3 when laundered for twenty and fifty cycles. As mentioned previously, the increasing staining values as the number of laundering cycles increased could be the probable explanation. Most likely because more dye particles redeposited on the adjacent fabric, thus less could rub off.

The fact that fastness to wet rubbing was moderate and unsatisfactory, could be due to the wet cotton that was used to do the test. The cotton develops a negative charge, which might cause excessive rubbing off of the already displaced dye particles (Jang, Ko & Carr, 2001:143).

Reactive black dyed cotton

The reactive black dyed samples that were laundered with Catholyte, detergent and filtered water exhibited excellent fastness to dry rubbing, as well as wet rubbing, obtaining Gray Scale values of 4-5 (Table 4.5). Radhika and Moses (2014:34) reported superior fastness to rubbing for reactive dyes (GSs=4-5), and states that it is due to the strong covalent bonds that exist between dyes and cotton. Catholyte obtained similar values as those samples laundered with detergent and filtered water, thus it can be concluded that Catholyte can be used to launder reactive black dyed cotton without adversely affecting its fastness to rubbing.

Laundering the samples at 40°C as well as 60°C, resulted in excellent fastness to both wet and dry rubbing (GSs=4-5). As the covalent bonds should generally be stable, regardless of the temperature, it is not surprising that the fastness for dry and wet rubbing was very good. Mazumder and Haque (2011:46) reported fastness to dry and wet rubbing values of 4-5, which is comparable to the results obtained in this study.

The number of laundering cycles did not seem to have a significant influence on the dry and wet rubbing fastness of the reactive black samples as all the samples exhibited excellent fastness (GSs=4-5). The bonds, that hold the dye inside the fibre, are generally stable with regards to wet treatments and are fast to repeated laundering (Choudhury, 2006:516). Mohsin and fellow researchers (2013:347) observed fastness to rubbing, both wet and dry, values of 4-5 for reactive dyed samples laundered repeatedly.

4.3 Tensile Strength

Tensile strength of a woven fabric is one of the most important properties, as it is a good indicator of fabric performance (Wu & Pan, 2005:789). The wet processing, dyeing among others, could be a possible contributing factor towards decreasing tensile strength. However, in most instances, this is overcome in the textile dye industry by cross-linking textiles and fixatives added to dye baths (Doh, 2004:26). Tensile strength is the strength of a textile under tension and is expressed in terms of the force necessary to break it. Maximum load at break is the force needed to rupture a fabric, whereas elongation at break is the elongation exhibited by the textile, which corresponds to the breaking force. It describes the increase in the sample's length that had occurred up to rupture and it is usually expressed as a percentage (Kadolph, 2007:156). In this section the tensile strength results of the sulphur, direct and reactive black dyed cotton that were subjected to different laundering conditions are discussed.

The tensile strength (maximum load at break and displacement at maximum load) statistics for this research was done in two separate sets. The first set (Analysis 1) of data determined the p-values and significance in change of the samples laundered with Catholyte, detergent and filtered water at 40°C or 60°C for five, ten, twenty or fifty cycles respectively when compared to the untreated samples (control). The second set (Analysis 2) of data determined the p-values and significance when the different laundering treatments (Catholyte, detergent and filtered water), laundering temperatures (40°C and 60°C), and laundering cycles (five, ten, twenty and fifty) were compared.

4.3.1 Maximum Load at Break

Sulphur black dyed cotton

The statistical data obtained for both analysis 1 and analysis 2 of the sulphur black dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles is depicted in Table 4.6.

Table 4.6: Difference (relative to control) in maximum load (Newton and %) carried before break and p-values of the sulphur black dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		Analysis 2 (Comparison with resultant p-values)			
	N	**%**				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	-6.66	-1.01		0.6902	0.0135*	
Detergent	-10.97	-1.66	0.6902		0.0044*	
Filtered Water	-0.60	-0.09	0.0135*	0.0044*		
TEMPERATURE			**40°C**	**60°C**		
40°C	-7.92	-1.20		0.0468*		
60°C	-10.23	-1.55	0.0468*			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	-2.23	-0.34		0.1061	0.0025*	<.0001*
Ten	-4.76	-0.72	0.1061		0.1462	<.0001*
Twenty	-6.52	-0.99	0.0025*	0.1462		0.0073*
Fifty	-38.79*	-5.89	<.0001*	<.0001*	0.0073	

*Statistically significant ($p < 0.05$)

The sulphur black dyed samples laundered with filtered water showed to have decreased the least in terms of the maximum load before break. The decrease of 0.60N was negligible and less than 1%. Laundering the samples with Catholyte resulted in a decrease in maximum load carried of 6.66N, which is equivalent to a decrease of only 1.01%. Laundering with detergent seemed to have caused the greatest decrease in maximum load carried (10.97N), although the decrease of 1.66% was not significant. Anionic surfactants can have an adverse effect on dyed cotton textiles (Ghorabi *et al.*, 2012:126), if the chain length is longer, a corresponding increase in free energy of binding to fixative, through an increase in hydrophobic interactions is observed. This can weaken the intermolecular forces, (Oakes, Gratton & Dixon 2004:273a), resulting in a decreased load the textile can carry before breaking, which might explain the decrease caused by detergent.

When maximum load carried by the samples laundered with filtered water are compared with those laundered with Catholyte and detergent, both the differences were statistically significant. However, the decrease in maximum load before break carried by the samples laundered with Catholyte did not differ significantly from those laundered with detergent. This indicates that the effect on breaking load of sulphur black dyed cotton will be similar when detergents are replaced with Catholyte.

Laundering the sulphur black dyed samples at 40°C resulted in a decrease in maximum load carried before it broke of 7.92N. This is a decrease of only 1.20%, and not significant. Laundering the samples at a higher temperature, resulted in a further decrease in maximum load carried (10.23N), although this difference was not significant with regards to the unlaundered textile. It was, however, significantly different when compared to laundering at the lower temperature. According to Usluoglu and Arabaci (2014:366), the optimal laundering temperature for the tensile strength of cotton was found to be 40°C. An increase in laundering temperature resulted in a subsequent decrease in tensile strength. Weakening or disintegration of the cotton fabric may also be caused if the dye is not properly applied (Ahmed & El-Shishtawy, 2010:1145).

Laundering the sulphur dyed black samples for five, ten and twenty cycles resulted in an insignificant decrease in maximum load carried as the number of laundering cycles

increased. However, laundering the samples for fifty cycles caused a significant decrease in maximum load carried of 38.79N, causing the strength to decrease by 5.89%. In this research, it was found, laundering the samples for five and ten cycles did not differ significantly with regards to the decrease in maximum load carried. However, when laundering for twenty and fifty cycles, the decrease seemed to be significant. Laitala, Boks and Klepp (2011:260) also found that tensile strength of cotton decreased as the number of laundering cycles increased. This could be as a result of the change in the fabric structure due to the repeated laundering action the samples were subjected to. The mechanical action of laundering causes friction between the yarns, which decreases some fabric properties such as maximum load before break (Choi *et al.*, 2004:294).

Direct black dyed cotton

The statistical data obtained for both analysis 1 and analysis 2 of the direct black dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles is represented in Table 4.7.

Laundering the direct black dyed cotton samples with Catholyte, detergent and filtered water significantly decreased the maximum load it could carry before break. It is evident that laundering the samples with Catholyte resulted in the greatest decrease in maximum load carried at break (114.15N), with a resultant weakening effect of 13.62%.

Laundering the samples with filtered water caused the least decrease in maximum load at break (92.37N), although still a significant reduction of 11.02% when compared to the untreated samples. Laundering the direct dyed samples with detergent resulted in a decrease of 94.64N in maximum load carried, which is an 11.29% reduction. The decrease in maximum load caused by Catholyte differs significantly when compared to the decrease caused by laundering the samples with detergent and filtered water. A higher alkali concentration and temperature can cause higher loss in strength if reactivity is low, which is the case with direct dyes (Singha, 2013:4). As Catholyte had the highest alkalinity (pH=$\geq$11 and $\leq$12), this might be a feasible explanation of the occurrence exhibited here.

Table 4.7: Difference (relative to control) in maximum load (Newton and %) carried before break and p-values of the direct black dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		Analysis 2 (Comparison with resultant p-values)			
	N	**%**				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	-114.15*	-13.62		0.0235*	0.0122*	
Detergent	-94.64*	-11.29	0.0235*		0.7913	
Filtered Water	-92.37*	-11.02	0.0122*	0.7913		
TEMPERATURE			**40°C**	**60°C**		
40°C	-85.38*	-10.19		<.0001*		
60°C	-115.40*	-13.77	<.0001*			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	-72.37*	-8.64		0.0803	0.0008*	<.0001*
Ten	-89.68*	-10.70	0.0803		0.0927	<.0001*
Twenty	-106.45*	-12.70	0.0008*	0.0927		0.0082*
Fifty	-133.06*	-15.88	<.0001*	<.0001*	0.0082*	

*Statistically significant ($p < 0.05$)

Laundering the direct dyed cotton samples at 40°C and 60°C caused a significant decrease in the maximum load carried by the samples. When the samples were laundered at 40°C, a decrease of 85.38N was noted, indicating a decline of 10.19%. Laundering the direct dyed cotton at 60°C resulted in an even higher decrease in maximum load carried, of 115.4N and a corresponding 13.77%. When a comparison was made concerning the influence that the different temperatures had, it is evident that the

influence differs significantly. The forces of interaction that operate between direct dyes and cotton fibres are predominantly van der Waal's forces (Burkinshaw, 1995:130). These forces may become weaker at a higher temperature, causing the dye molecules to be displaced from the textile surface, especially if the wash-off was not effective (Jang, Ko & Carr, 2001:139). Doh (2004:25) did report that the disrupted system, especially, affecting the crystallinity of the fibres, might be the cause for a greater decrease at a higher temperature.

A notable decrease in maximum load carried was observed as the number of laundering cycles increased. Laundering the samples for five cycles resulted in a decrease of maximum load carried of 72.37N, which increased the difference to 89.68 after laundering for ten cycles. Laundering for twenty cycles further decreased the maximum load to a difference of 106.45N until it reached a peak of 133.06N when laundered for fifty cycles, which had a 15.88% weakening effect on the fabric. The increase in the percentage of decline in maximum load (8.64% to 15.88%), is proportionate to the increase in number of laundering cycles. When compared, there was no significant difference in decrease of maximum load carried between laundering the samples for five and ten cycles. Comparing the samples laundered for fifty cycles to the samples laundered for five cycles, there seems to have been a significant difference in decreasing maximum load. Laundering direct dyed cotton textile fabrics repeatedly will result in significant damages to the tensile properties of the fibres (Laitala, Boks & Klepp, 2011:260; Doh, 2004:16). This is most probably due to the gradual degradation of fibres along the spiral plane, contributing to tensile strength loss. Once the fissures reach the lumen, further degradation in strength occurs rapidly (Saravanan, Vasanthi & Ramachandran, 2009:5).

Reactive black dyed cotton

The statistical data obtained for both analysis 1 and analysis 2 of the reactive black dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles is depicted in Table 4.8.

Table 4.8: Difference (relative to control) in maximum load (Newton and %) carried before break and p-values of the reactive black dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		Analysis 2 (Comparison with resultant p-values)			
	N	**%**				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	-53.20*	-6.66		0.6059	0.3945	
Detergent	-56.63*	-7.09	0.6059		0.7317	
Filtered Water	-58.94*	-7.38	0.3945	0.7317		
TEMPERATURE			**40°C**	**60°C**		
40°C	-56.17*	-7.03		0.9752		
60°C	-56.34*	-7.05	0.9752			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	-22.29*	-2.79		0.0131*	<.0001*	<.0001*
Ten	-41.74*	-5.23	0.0131*		0.0010*	<.0001*
Twenty	-67.96*	-8.51	<.0001*	0.0010*		0.0015*
Fifty	-93.03*	-11.65	<.0001*	<.0001*	0.0015*	

*Statistically significant ($p < 0.05$)

Laundering the reactive black dyed samples with Catholyte, detergent and filtered water resulted in a significant decrease in maximum load for all the treatments. Laundering the samples with filtered water resulted in the greatest decrease of 58.94N, which is a significant reduction of 7.38% in strength. Laundering the reactive dyed black samples with Catholyte, exhibited the least decrease in maximum load carried (53.20N), which is a decrease of 6.66% in strength. Laundering the samples with detergent resulted in a

similar reduction of 56.63N and 7.09%. According to the statistical analysis, there was no significant difference in reduction when laundering with Catholyte, detergent and filtered water was compared. Therefore, it can be concluded that the reaction between Catholyte and reactive black dyed samples are similar and can be used safely when laundering these textiles, as it will not cause more weakening than laundering with detergent or filtered water. The same pattern is exhibited when the fastness to laundering was evaluated. Samanta and fellow researchers (2004:229) experienced an appreciable reduction in maximum load carried and greater breaking extension, when laundering reactive dyed cotton.

The maximum load carried when laundering the samples at 60°C decreased slightly more (56.34N) than compared to the samples laundered at 40°C (56.17N), although this difference was statistically not significant. The reduction in maximum load carried by the textile fabrics, 7.03% and 7.05% for 40°C and 60°C respectively, was most likely due to changes in the fibres of the textiles as a result of laundering at a higher temperature, rather than weakening by the dyestuff itself (Was-Gubala, 2009:165). This conclusion is drawn from the fact that reactive dye is held in place by the fibre as long as the covalent bond is intact. These bonds are generally stable under higher temperatures and repeated laundering (Choudhury, 2006:516).

Laundering the samples for five, ten, twenty and fifty cycles lead to a significant decrease in maximum load it could carry, as the number of laundering cycles increased. Consequently, laundering the samples for fifty cycles caused the greatest decrease in maximum load of 93.0.N, which is an 11.65% decline in tensile strength. The decrease in maximum load caused as a result of the number of laundering cycles, differed significantly when each combination was compared (Table 4.8). Declining tensile strength as the number of laundering cycles increased, might be expected because of inherent fibre qualities degrading as repeated mechanical agitation, heat and water is applied (Rizk, Ibrahim & El-Borai, 2015:91; Doyal & Warnock, 2005:264).

4.3.2 Displacement at Maximum Load

Sulphur black dyed cotton

The difference (relative to control) in displacement at maximum load (% and mm) and the p-values of the sulphur black dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles are depicted in Table 4.9.

Table 4.9: Difference (relative to control) in displacement at maximum load (% and mm) and p-values of the sulphur black dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		Analysis 2 (Comparison with resultant p-values)			
	%	mm				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	0.06*	11.33		<.0001*	0.0021*	
Detergent	0.05*	10.03	<.0001*		0.2454	
Filtered Water	0.05*	10.38	0.0021*	0.2454		
TEMPERATURE			**40°C**	**60°C**		
40°C	0.05*	10.15		0.0007*		
60°C	0.06*	11.01	0.0007*			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	0.04*	8.03		<.0001*	<.0001*	<.0001*
Ten	0.05*	9.78	<.0001*		<.0001*	<.0001*
Twenty	0.06*	12.10	<.0001*	<.0001*		0.4051
Fifty	0.06*	12.40	<.0001*	<.0001*	0.4051	

*Statistically significant ($p < 0.05$)

It is evident from Table 4.9 that the percentage (%) displacement observed when the sulphur black dyed samples were laundered with Catholyte, detergent and filtered water was significant. The displacement increased the most when laundered with Catholyte (0.06%), as opposed to laundering the samples with detergent and filtered water, causing an increase of 0.05%. Statistically, the increase in displacement at maximum load caused as a result of laundering with Catholyte, differed significantly, although the difference only a miniscule 0.01%. However, the difference caused in displacement at maximum load caused by laundering with detergent and filtered water did not differ significantly.

Laundering the sulphur black dyed samples at 60°C resulted in a slightly increased displacement at maximum load of 0.01%, compared to laundering at 40°C. The difference in displacement at maximum load differed significantly when compared to the untreated samples, and comparing the difference caused as a result of laundering at the different temperatures, also caused a significant increase in displacement at maximum load.

As the number of laundering cycles increased, the displacement at maximum load also increased significantly, when compared to the untreated samples. The displacement increased from 0.04% (laundered for five cycles) to 0.05% after laundering for ten cycles. This further increased to 0.06% after laundering for twenty cycles, but platoed at 0.06% after laundering the samples for fifty cycles. It seems that the difference caused when laundering the samples for five, ten and twenty cycles, was significant when the comparisons are made. It is apparent that the difference in displacement at maximum load caused when the samples laundered for twenty cycles are compared to those laundered for fifty, does not seem to be significant. However, comparing those samples laundered for fifty cycles to those laundered for five and ten seems to differ significantly.

In all the cases, the elongation at maximum load percentage seems to have increased proportionately to the decrease in maximum load carried by the textile (as discussed and explained in section 4.3.1). Samanta and fellow researchers (2004:229) reported elongation at maximum load of sulphur dyed cotton to be 21.44%. The lesser extent of the influence of the treatments, temperatures, and laundering cycles experienced in this

research project, might be due to only slight influence of the treatment on the crystallinity index of the fibres. The mechanical properties of textile fibres depend not only on the degree of crystallinity of fibres but also on the various secondary valency forces that operate in the polymer. It can be concluded that the resistance power to deform the material with higher inter-chain bonds was not influenced. Consequently, also causing the fibres not to be displaced to a great extent under stress (Yu *et al*, 2014:4).

Direct black dyed cotton

The difference (relative to control) in displacement at maximum load (% and mm) and p-values of the direct black dyed cotton samples as a result of laundering treatment, - temperature and number of laundering cycles are depicted in Table 4.10.

Laundering the direct dyed black samples with Catholyte, detergent and filtered water caused significant increases in displacement at maximum load. Laundering the samples with Catholyte caused the greatest increase in displacement (0.06%), although it did not differ significantly from the increase caused when the samples were laundered with detergent and filtered water (0.05%).

A slight, although significant (0.01%), increase in displacement at maximum load was observed when the samples were laundered at 60°C as opposed to 40°C. When compared to the unlaundered samples, the increase in displacement at maximum load was also significant.

As the number of laundering cycles increased, the displacement at maximum load increased with 0.01%, until displacement at maximum load of 0.07% at fifty laundering cycles was reached. According to the statistical analysis, these increases were significant when compared to the untreated direct black dyed fabric, but also when compared to the different number of laundering cycles.

Table 4.10: Difference (relative to control) in displacement at maximum load (% and mm) and p-values of the direct black dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		Analysis 2 (Comparison with resultant p-values)			
	%	mm				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	0.06*	11.19		0.0692	0.1136	
Detergent	0.05*	10.65	0.0692		0.8110	
Filtered Water	0.05*	10.72	0.1136	0.8110		
TEMPERATURE			**40°C**	**60°C**		
40°C	0.05*	10.33		<.0001*		
60°C	0.06*	11.38	<.0001*			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	0.04*	8.26		<.0001*	<.0001*	<.0001*
Ten	0.05*	10.01	<.0001*		<.0001*	<.0001*
Twenty	0.06*	11.42	<.0001*	<.0001*		<.0001*
Fifty	0.07*	13.73	<.0001*	<.0001*	<.0001*	

*Statistically significant ($p < 0.05$)

The increase in displacement at maximum load for all the direct black dyed samples laundered with Catholyte, detergent and filtered water, at 40°C and 60°C, for five, ten, twenty and fifty cycles respectively was proportionate to the decrease in maximum load at break (discussed and explained in section 4.3.1). It is expected that displacement at maximum load increase when subjected to treatments. This might be due to formation of any surface resin (which acts as a bodying agent), as a result of impurities in the treatments, and fills the gaps between the threads and prevents the movement of the

yarns and fibres, resulting in only a slight increase in displacement at maximum load (Sun & Stylios, 2012:1055).

Reactive black dyed cotton

The difference (relative to control) in displacement at maximum load (% and mm) and the p-values of the reactive black dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles are depicted in Table 4.11.

As is evident from Table 4.11, laundering the reactive black dyed samples with Catholyte, detergent and filtered water, resulted in significant increases in displacement at maximum load when compared to the untreated samples. Laundering the samples with filtered water and detergent seems to have caused the least increase in displacement at maximum break, both only 0.05%. The displacement caused when the samples were laundered with Catholyte was significantly different from those laundered with detergent and filtered water.

Laundering the reactive black dyed samples at both 40°C and 60°C resulted in significant increases in displacement at maximum load when compared to the untreated samples.

As the number of laundering cycles increased, the displacement at maximum load also increased significantly, when compared to the untreated samples. The displacement increased from 0.04% (laundered for five cycles) to 0.06% after laundering for fifty cycles. It is apparent that the difference caused when laundering the samples for five, ten and twenty cycles, was significant when the different cycles are compared.

Displacement at maximum load significantly increased for all the reactive dyed black samples that were subjected to the above-mentioned discussion. This happened proportionally to the decrease in maximum load the fabric could carry before break as discussed and explained in section 4.3.1. According to Samanta fellow researchers (2004:229) it is most probably due the possible change in internal orientation of the

fibre matrix as a result of degradation caused by the laundering treatments, temperature and cycles.

Table 4.11: Difference (relative to control) in displacement at maximum load (% and mm) and p-values of the reactive black dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		Analysis 2 (Comparison with resultant p-values)			
	%	mm				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	0.06*	11.19		<.0001*	<.0001*	
Detergent	0.05*	10.09	<.0001*		0.0871	
Filtered Water	0.05*	9.73	<.0001*	0.0871		
TEMPERATURE			**40°C**	**60°C**		
40°C	0.05*	10.96		<.0001*		
60°C	0.05*	9.71	<.0001*			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	0.04*	8.01		<.0001*	<.0001*	<.0001*
Ten	0.05*	9.88	<.0001*		<.0001*	<.0001*
Twenty	0.06*	11.03	<.0001*	<.0001*		<.0001*
Fifty	0.06*	12.42	<.0001*	<.0001*	<.0001*	

*Statistically significant ($p < 0.05$)

CHAPTER 5

COLOURFASTNESS AND TENSILE STRENGTH OF ACID, DISPERSE, AZOIC, DIRECT AND REACTIVE DYED POLYESTER, POLYAMIDE 6,6 AND COTTON TEXTILE FABRICS LAUNDERED WITH CATHOLYTE, DETERGENT AND FILTERED WATER

5.1 Introduction

Wash fastness of textiles is of great importance when evaluating the performance of dyed textiles (Chowdhury, Butola & Joshi, 2013:232). One of the most important difficulties that might arise in the laundering is the formulation of wash liquors, causing the possible transfer of dyes from dyed fabrics in the washing bath. The result is that the dyed fabric changes colour and other fabrics may be stained due to the transfer (or migration) of dyes (Carrion, 2014:150).

Disperse dyes are generally employed to dye polyester (Oakes, 2005:2) and acid dyes are mostly used to dye polyamide 6,6 (Burkinshaw & Son, 2006:156). Reactive dyes are extensively used to dye cotton fabrics (Rizk, Ibrahim & El-Borai, 2015:86), and is deemed as the most important dye class for this fibre (Ristić & Ristić, 2012:113). Another class of dye, of great commercial importance is direct dyes, which is also used to dye cotton (Hauser & Tabba, 2001:282). Azoic dyes, although generally used for printing cotton, is considered a viable option to dye cotton fabrics if a deep red or orange shade is required (Choudhury, 2006:601).

As red is one of the primary colours, it plays an important role in the dyeing industry (Fu, *et al*., 2013:3101). Thus, different red dyestuffs, with affinity for specific fibres were used in this section. Subsequently, the colourfastness (wash fastness, staining, colourfastness to rubbing) and tensile strength (maximum load at break and displacement at maximum load) of disperse red dyed polyester, acid red dyed polyamide 6,6, and azoic orange, reactive and direct red dyed cotton, will be evaluated, and discussed.

5.2 Colourfastness

As mentioned in the previous chapter, the instrumentally measured ΔE differences were calculated and converted to Gray scale ratings, in order to ensure compatibility with results observed in other research studies. Because differences in ΔE values indicate overall colour change and do not differentiate between strength, saturation, and shade changes, the individual colorimetric parameters, L*, a* and b* are also discussed where applicable. Additionally, the colour strength (K/S values) at a single wavelength was determined for the dyed textile fabrics to facilitate and enhance the discussion on colour change.

5.2.1 Wash fastness

5.2.1.1 Colour Change

Disperse red dyed polyester

The disperse red polyester samples were laundered with Catholyte, detergent and filtered water for five, ten, twenty, or fifty cycles at 40°C or 60°C respectively. The colorimetric data (L*, a*, and b*) before and after laundering, colour strength (K/S values), the statistically analysed differences, as well as the Gray scale ratings are depicted in Table 5.1.

The samples laundered with detergent, seems to have undergone the greatest overall colour change (ΔE=0.53), causing a significant decrease in colour strength (K/S value) of -1.01. These samples also exhibited the highest increase in lightness, but moderate shifts towards the red (Δa*=0.43) and blue (Δb*=-0.13) colour spaces. Laundering the disperse red dyed polyester samples with Catholyte did not cause a significant decrease in colour strength (K/S=-0.45), although a significant increase in overall colour change (ΔE=0.51) was experienced. Laundering the samples with Catholyte seems to have caused the greatest shifts towards the red (Δa*=0.46) and blue (Δb*=-0.15) colour spaces, but only causing a moderate increase in lightness (ΔL*=0.29). The samples that

Table 5.1: Colorimetric data, colourstrength (K/S) and Gray Scale values of disperse red dyed polyester as a result of change caused by laundering treatment, -temperature and number of laundering cycles.

	Before					After					(Difference : After – Before)					
	L*	a*	b*	ΔE	K\S Value	L*	a*	b*	ΔE	K\S Value	ΔL*	Δa*	Δb*	ΔE	K\S Value	Gray Scale Value
TREATMENT																
Catholyte	39.69	62.10	14.07	75.03	21.31	39.98	62.56	13.92	75.54	20.86	0.29*	0.46*	-0.15*	0.51*	-0.45	5
Detergent	39.69	62.12	14.06	75.05	21.31	40.06	62.55	13.93	75.58	20.30	0.37*	0.43*	-0.13*	0.53*	-1.01*	5
Filtered Water	39.57	61.99	13.95	74.86	21.31	39.65	62.24	13.83	75.08	21.20	0.08*	0.25*	-0.12*	0.22*	-0.11	5
TEMPERATURE																
40°C	39.70	62.12	14.07	75.05	21.31	39.92	62.47	14.01	75.44	20.87	0.22*	0.35*	-0.06*	0.39*	-0.44	5
60°C	39.61	62.02	13.99	74.91	21.31	39.88	62.43	13.78	75.35	20.70	0.27*	0.41*	-0.20*	0.45*	-0.61	5
CYCLES																
Five	39.65	62.07	14.04	74.98	21.31	39.81	62.28	13.92	75.22	20.80	0.16*	0.21*	-0.12*	0.24*	-0.51	5
Ten	39.63	62.03	14.06	74.94	21.31	39.83	62.33	13.93	75.27	20.79	0.20*	0.30*	-0.13*	0.33*	-0.52	5
Twenty	39.70	62.14	14.02	75.06	21.31	40.00	62.61	13.99	75.60	20.79	0.30*	-0.47*	-0.03*	0.54*	-0.52	5
Fifty	39.63	62.04	13.99	74.93	21.31	39.95	62.58	13.74	75.50	20.77	0.32*	0.54*	-0.25*	0.57*	-0.54	5

*Statistically significant ($p < 0.05$)

were laundered with filtered water exhibited the least increase in overall colour change (ΔE=0.22), and lightness (ΔL*=0.08), although still significant when compared to the parameters before laundering. The subsequent decrease in colour strength (K/S=0.11) was not significant. Shifts towards the red (+Δa*) and blue (-Δb*) colour spaces exhibited by these samples was also the least. Regardless of the above-mentioned changes that occurred, the Gray Scale values observed when the samples were laundered with Catholyte, detergent or filtered water was 5, which indicates optimum wash fastness.

Other researchers, obtained similar results to the results found in this study, indicating Gray Scale values of 5 when wash fastness of disperse red polyester was evaluated (Carpignano *et al.,* 2010:206; Carrión-Fité, 2014:6). The nature of interaction between disperse dyes and polyester, due to the hydrophobic and crystalline nature of the textile, contributes to excellent fastness to laundering (Koh, 2011:200). An increase in lightness and shift towards the red colour space might indicate that residual dye was washed off after initial laundering, contributing to the desired (bright red) colour of the textile (Burkinshaw & Katsarelias, 1997:249). From these findings, it can be concluded that Catholyte performed well when used as wash liquor, and did not seem to influence the wash fastness of these particular samples considerably than when laundering with detergent.

Laundering the samples at both 40°C and 60°C caused a significant increase in overall colour change, with observed ΔE values of 0.39 and 0.45, respectively. Although the overall colour change was significant, the resultant decrease in colour strength of 0.44 (40°C) and -0.61 (60°), was not significant. As the laundering temperature increased, subsequent changes of the samples becoming lighter (+ΔL*), redder (+Δa*) and bluer (-Δb*) occurred. Due to the strength of dye solution formed inside the fibres, disperse dyes generally do not present a problem when laundered at higher temperatures (Oakes, 2005:2). De Giorgi and fellow researchers (2000:78) did not observe a decrease in wash fastness as the temperature increased and reported Gray Scale values of 5 for both disperse red dyed polyester at both temperatures. However, Carrión-Fité (2014:6) did report a slight decrease in colour strength as the temperature increased.

As is evident from Table 5.1, an increase in the number of laundering cycles caused a significant increase in the difference of the overall colour change (+ΔE), which can be seen in the increase in lightness the samples exhibited. The colour strength decreased from 0.51 after being laundered for five cycles, to 0.52 when laundered for ten and twenty cycles, and exhibiting a decrease in colour strength of only 0.54 after laundering for fifty cycles, which is not significant. The samples became significantly lighter, with the initial difference 0.16 after laundering for five cycles, but increased to 0.32 when laundered for fifty cycles. Increasing shifts towards the red (+aΔ) and blue (-Δb*) colour spaces could be observed as the number of laundering cycles increased. No change in the Gray Scale values could be observed with the increasing number of laundering cycles, all still indicating optimum wash fastness (GSc=5). Oakes, Gratton and Dixon (2004:281b) did report a slight decrease in colour strength with increase in laundering cycles, which could be due to unfixed dye being washed off. Xie and co-workers (2007:296) experienced no decrease in wash fastness as the laundering cycles increased. As mentioned earlier, the distinct behaviour of disperse dyes when applied to polyester, contributes to the excellent wash fastness properties of this dye-fibre combination. Mainly because the dye is physically bonded to the fibre, therefore very stable (Van der Kraan *et al.*, 2007:470; Johnson & Cohen, 2010:157).

Acid red dyed polyamide 6,6

The colorimetric data, K/S values and Gray Scale values obtained when acid red dyed polyamide textile fabric was laundered with Catholyte, detergent and filtered water at 40°C or 60°C for five, ten, twenty, or fifty cycles respectively, is given in Table 5.2.

From this Table it can be seen that laundering with filtered water caused the greatest difference in overall colour change (ΔE=-0.48) but the least decrease in colour strength (K/S=-0.10). These samples exhibited the greatest shift towards the green (Δa*=-0.32) colour space and smallest shift towards the blue (Δb*=-0.46) colour space, whilst decreasing in lightness. Laundering the samples with Catholyte caused the least change in colour (ΔE=-0.23) and the greatest decrease in colour strength (K/S=-0.69), whereas

Table 5.2: Colorimetric data, colourstrength (K/S) and Gray Scale values of acid red dyed polyamide as a result of change caused by laundering treatment, -temperature and number of laundering cycles.

	Before					After					(Difference : After – Before)					
	L*	a*	b*	ΔE	K\S Value	L*	a*	b*	ΔE	K\S Value	ΔL*	Δa*	Δb*	ΔE	K\S Value	Gray Scale Value
TREATMENT																
Catholyte	31.40	45.30	23.31	59.84	24.75	31.77	45.05	22.67	59.61	24.06	0.37*	-0.25*	-0.64*	-0.23*	-0.69	5
Detergent	31.55	45.48	23.62	60.18	24.75	31.85	45.30	22.94	59.94	24.07	0.30*	-0.18*	-0.68*	-0.24*	-0.68	5
Filtered Water	31.48	45.39	23.51	60.04	24.75	31.37	45.07	23.05	59.56	24.65	-0.11*	-0.32*	-0.46*	-0.48*	-0.10	5
TEMPERATURE																
40°C	31.45	45.34	23.39	59.90	24.75	31.50	45.09	23.10	59.60	24.74	0.05*	-0.25*	-0.29*	-0.30*	-0.01	5
60°C	31.50	45.44	23.57	60.14	24.75	31.93	45.18	22.67	59.80	23.91	0.43*	-0.26*	-0.90*	-0.34*	-0.84	4-5
CYCLES																
Five	31.49	45.42	23.49	60.05	24.75	31.32	45.16	23.23	59.67	24.00	-0.17*	-0.26*	-0.26*	-0.38*	-0.75	5
Ten	31.48	45.39	23.46	60.02	24.75	31.31	45.16	22.99	59.70	23.93	-0.17*	-0.23*	-0.47*	-0.32*	-0.82	5
Twenty	31.46	45.38	23.46	60.00	24.75	31.39	45.12	22.36	59.88	23.60	-0.07*	-0.26*	-1.10*	-0.12*	-1.15	5
Fifty	31.46	45.38	23.51	60.02	24.75	31.64	45.21	22.97	59.97	22.77	0.18*	-0.26*	-0.54*	-0.04*	-1.98	4-5

*Statistically significant ($p < 0.05$)

laundering with detergent resulted in a similar difference in colour change (ΔE=-0.24) and decrease in colour strength (K/S=-0.68), although not significant for both these treatments. The samples laundered with Catholyte and detergent both exhibited an increase in lightness (+ΔL*) and similar shifts towards the green (-Δa*) and blue (-Δb*) colour spaces. The resultant Gray Scale values for the samples laundered with Catholyte, detergent and filtered water indicates optimum wash fastness (GSc=5).

The decrease in lightness and colour strength caused due to laundering the samples with filtered water, resulted in duller samples. However, it seems that laundering the acid red dyed polyamide samples with detergent and Catholyte contributed to lighter samples, with a miniscule decrease in inherent colour strength. Burkinshaw and Son (2006:158) also experienced an increase in lightness after laundering. They concluded that it is excess dye that is washed off, rather than a change in shade due to the alkalinity of the wash liquors. Alkaline treatments are employed for initial wash-off after the dyeing procedure because alkaline mediums are known for detergency properties, but also for preserving the colour of dyed textiles (Boardman & Jarvis, 2000:65).

Other studies done on the wash fastness of acid red dyed polyamide indicated similar results (GSc=5) of optimum wash fastness (Burkinshaw & Son, 2006:158; Hauser & Tabba, 2001:287). The good wash fastness of acid dyes on polyamide is due the electrostatic interactions between the dye and the polymer, as well as the Van der Waals forces that bind the dye to the matrix (Hauser & Tabba, 2001:287). From these results, it can be concluded that Catholyte can be used to launder acid red polyamide textile fabrics without causing major colour change and still maintain optimum wash fastness.

Laundering the samples at 40°C caused less colour change (ΔE=-0.30) as opposed to laundering at 60°C, which caused greater colour change (ΔE=-0.34). Although the colour change experienced as a result of laundering at both 40°C and 60°C was significant, the colour strength did not decrease significantly. Laundering at 40°C, caused a negligible decrease of -0.01 in colour strength (K/S-value), whereas laundering at 60°C caused a decrease of -0.84. The results still indicate excellent wash fastness for both temperatures, obtaining Gray Scale values of 5 and 4-5 for 40°C and 60°C, respectively.

It is evident that the samples increased slightly in lightness (ΔL*=0.05) when laundered at the lower temperature, whilst difference in lightness increased further (ΔL*=0.43) after laundering at the higher temperature. It is true for both the a*- and b*-axis, that the samples shifted towards the green and blue colour spaces as the laundering temperature increased. Burkinshaw and Son (2010:135) experienced inferior wash fastness at 60°C. It was also observed that at the higher temperature the samples became lighter (+ΔL), which might be attributed to surplus dye having not been removed from the dyeings at the end of the dyeing process (Burkinshaw & Son, 2010:134). This might be ascribed to the interaction between the alkaline wash liquor and temperature, which could be more effective at higher temperatures (Van Heerden, 2010:174).

Laundering the acid red dyed polyamide samples for consecutive laundering cycles, caused the difference in colour change to decrease significantly as the number of laundering cycles increased. Laundering the samples for five cycles caused a decrease in difference in overall colour change of 0.38, and continually decreasing to 0.32 after laundering for ten cycles, and 0.12 after twenty cycles finally reaching 0.04 after fifty laundering cycles. This can be ascribed to the lightness initially decreasing (ΔL*=-0.17) after five laundering cycles, but thereafter steadily increasing as the number of laundering cycles increased, adversely affecting the ΔE value. The colour strength (K/S-value) decreased more with the increasing number of laundering cycles, although not significantly. The total decrease in colour strength was 1.98 after laundering for fifty cycles. Excellent wash fastness was still achieved when laundering the samples for five (GSc=5), ten (GSc=5), twenty (GSc=5) and fifty (GSc=4-5) cycles.

The lightness (ΔL*) of the samples increased gradually from -0.17 after laundering for five and ten cycles, to -0.07 after twenty cycles and reaching a value of +0.18 after fifty cycles. The movement on the a*-axis was observed to be relatively stagnant with the exception of laundering for ten cycles, where the difference seems to have decreased, but then increased again after laundering for twenty and fifty cycles. No real pattern could be observed for shifts along the b*-axis, although initially there was a shift towards blue, but later moving towards yellow again. Burkinshaw, Son and Chevli (2000:47) reported similar findings. In their research, the colour strength decreased as the number of

laundering cycles increased and the lightness increased as the number of laundering cycles increased. In another study, researchers found the a*-values to have stayed more or less the same and the b* values shifted towards the left (-Δb*) (Burkinshaw & Son, 2010:135). They also reported that the extent of dye loss that occurred during repeated washing was low and the shade of the dyeings was little changed as a result of the repeated laundering (Burkinshaw & Son, 2010:136; Burkinshaw, Son & Chevli, 2000:47). As the colour change was not significant according to the statistical analysis, the same can be assumed for this study.

Azoic orange dyed cotton

The colorimetric data, K/S values and Gray Scale values obtained when the azoic orange dyed cotton was laundered with Catholyte, detergent and filtered water at 40°C or 60°C for five, twenty and fifty cycles, are given in Table 5.3.

Laundering the azoic orange dyed cotton samples with detergent caused the greatest overall change in colour (ΔE=3.62), as well as a slight increase in colour strength. (K/S=0.03). Laundering the samples with Catholyte caused a significant change in colour resulting in a ΔE difference of 1.98 and a decrease in colour strength of 0.20. It is apparent that laundering the samples with filtered water caused the least difference in colour change (ΔE=1.59), however, causing a significant increase in colour strength (K/S=1.92). Laundering with Catholyte and detergent exhibited very good wash fastness (GSc=4) and a slightly higher value when laundering with filtered water (GSc=4-5). The lightness (ΔL*) significantly increased for all the samples laundered with Catholyte (ΔL*=1.24), detergent (ΔL*=1.69) and filtered water (ΔL=0.42). The samples laundered with all the mentioned treatments, also exhibited marginal shifts towards the red (+Δa*) and yellow (+Δb*) colour spaces, proportionate to the increase in lightness. Gharanjig and co-workers (2010:35) reported similar wash fastness (GSc=4) values when azoic orange cotton fabric was laundered.

Most synthetic dyes, especially azoic dyes, have significant structural variations but will be stable under general domestic laundering conditions (Julkapli, Bagheri & Hamid,

2014:9). The increase in lightness could, therefore, indicate that not all the unfixed dye was washed off after the dyeing process. This has been known to cause a decrease in wash fastness (Terinte *et al.*, 2014:132). However, the colour strength, that increased, might indicate that shrinkage took place, which has been reported to make the colour appear more intense (Doyal & Warnock, 2005:264). Generally it is accepted that dyed cotton should not exhibit significant shrinkage because it has been subjected to wet processing, therefore already allowing for relaxation shrinkage and dimensional changes. Insofar as the present study, no significant shrinkage was observed with the reactive and direct dyed cottons. The explanation for this occurrence might lie in the dyeing procedure itself. It is reported that with the application of reactive and direct dyes, up to six wash-off procedures are done to remove unfixed dye. Although not all unfixed dye is removed, relaxation shrinkage can occur, therefore reducing the occurrence of shrinking significantly when laundered domestically. When azoic dyes are applied a maximum of three wash-off procedures are applied, thus the textile can still exhibit shrinkage when laundered (Terinte *et al.*, 2014:132). Furthermore, it can be concluded that Catholyte can be used as a suitable alternative washing agent to launder azoic orange dyed cotton as it caused only a slight decrease in colour strength, although still resulting in very good wash fastness.

Laundering the azoic orange dyed cotton samples at 40°C resulted in an increase in overall colour change of 1.82, as well as an increase in colour strength of 1.21, however, still exhibiting excellent wash fastness. Laundering the samples at 60°C caused a decrease in colour change of 0.05 and resultant wash fastness level of 4, which still indicates excellent fastness. As the temperature increased, the samples became lighter (ΔL^*), redder ($+\Delta a^*$) and more yellow ($+\Delta b$). After the initial increase in colour strength (K/S=1.21), laundering at a higher temperature did cause a considerable decrease in colour strength. Was-Gubala and Grzesiak (2010:58) also found that laundering at temperatures above 40°C might intensify colour change, thus explaining the marginal shifts experienced with all the parameters. Wang and fellow researchers (2008:644) reported Gray Scale ratings of 4 when azoic dyed cotton was laundered at 60°C, which is comparable to results obtained in this study.

Table 5.3: Colorimetric data, colourstrength (K/S) and Gray Scale values of azoic orange dyed cotton as a result of change caused by laundering treatment, -temperature and number of laundering cycles.

	Before					After					(Difference : After – Before)					
	L*	a*	b*	ΔE	K\S Value	L*	a*	b*	ΔE	K\S Value	ΔL*	Δa*	Δb*	ΔE	K\S Value	Gray Scale Value
TREATMENT																
Catholyte	35.03	55.54	32.01	73.05	27.28	36.27	56.91	32.78	75.03	27.08	1.24*	1.37*	0.76*	1.98*	-0.20*	4
Detergent	35.10	55.54	31.94	73.06	27.28	36.78	58.18	33.77	76.67	27.31	1.69*	2.64*	1.83*	3.62*	0.03*	4
Filtered Water	35.06	55.52	31.97	73.03	27.28	35.48	56.87	32.79	74.62	29.20	0.42*	1.35*	0.82*	1.59*	1.92*	4-5
TEMPERATURE																
40°C	35.10	55.60	32.03	73.14	27.28	45.86	57.07	32.79	74.96	28.49	0.76*	1.47*	0.76*	1.82*	1.21*	4-5
60°C	35.02	55.46	31.92	72.95	27.28	36.49	57.56	33.43	75.92	27.23	1.47*	2.10*	1.51*	2.97*	-0.05*	4
CYCLES																
Five	35.06	55.52	31.95	73.02	27.28	35.55	56.85	32.76	74.63	28.63	0.49*	1.33*	0.81*	1.60*	1.35*	4-5
Ten	35.08	55.56	32.00	73.09	27.28	35.90	57.26	33.17	75.29	28.55	0.82*	1.70*	1.17*	2.20*	1.27*	4-5
Twenty	35.03	55.52	31.98	73.03	27.28	36.34	57.49	33.33	75.74	27.78	1.31*	1.97*	1.35*	2.72*	0.50*	4
Fifty	35.07	55.53	31.98	73.05	27.28	36.91	57.68	33.19	76.10	26.47	1.84*	2.15*	1.21*	3.05*	-0.81*	4

*Statistically significant ($p < 0.05$)

After the initial increase in overall colour change(ΔE=1.60), colour strength (K/S=1.35) and lightness (ΔL*=0.49), after laundering for five cycles, the samples consecutively decreased in these parameters as the number of laundering cycles increased. The decrease being significant and finally exhibiting an overall colour change of 3.05, colour strength decrease of 0.81 and increase in lightness of 1.84 after laundering for fifty cycles. The samples thus became lighter, but also redder (+Δa*) and more yellow (+Δb*) as the laundering cycles increased. Regardless of the changes, very good wash fastness values were still achieved (GSc=4-5 and 4). It has been reported that with the increase in the number of laundering cycles, colour changes can be marginally intensified and consequent wash fastness values of 4 was observed (Was-Gubala & Grzesiak, 2010:58).

Direct red dyed cotton

The corresponding colorimetric data (L*, a*, and b*), before and after laundering, colour strength (K/S values), the statistically analysed differences, and Gray scale ratings when the direct red dyed cotton samples were laundered with Catholyte, detergent and filtered water for five, ten, twenty, or fifty cycles at 40°C or 60°C respectively, is depicted in Table 5.4.

Laundering the direct red dyed cotton samples with detergent seems to have caused the greatest difference in colour change (ΔE=8.95), which is indicative of poor wash fastness (GSc=1-2), and resulting in a significant decrease in colour strength of 5.49. When the samples were laundered with Catholyte, a colour change difference of 7.01 was observed, with a subsequent decrease in colour strength of 4.40, also resulting in poor wash fastness (GSc=2). Laundering the samples with filtered water seems to have caused the least difference in colour change (ΔE=3.09) and decrease in colour strength (K/S=-1.96), although significant and indicating moderate wash fastness (GSc=3). The lightness increased marginally for the samples laundered with Catholyte (ΔL*=6.74) and detergent (ΔL*=8.64), and moderately for those samples laundered with filtered water (ΔL*=2.60). Significant shifts, proportional to the change in colour, was experienced towards the red (+Δa*) and blue (-Δb*) colour spaces. The increase in lightness renders

the textile brighter, although the decrease in colour strength implies that the inherent colour of the textile is weaker, although the sample is brighter (Ali *et al.*, 2015:276).

Other researchers (Burkinshaw & Gotsopoulos, 1999:188; Hauser & Tabba, 2001:285) experienced similar results when direct red dyed cotton was laundered in their respective studies (GSc=2-3), with similar shifts towards the red and blue colour spaces. The poor performance of direct red dyed cotton might be due to untreated cotton (no added cationic dye sites), where no fixative agents were used during dyeing (Hauser & Tabba, 2001:285). Furthermore, Oakes, Gratton and Dixon (2004:273a) concluded that an increase in the chain length of a surfactant can cause colour loss to increase. This may be due to a corresponding increase in free energy of binding to fixative, through an increase in hydrophobic interactions, which also explains the occurrence of detergent causing the greatest difference in colour change experienced in this study.

Laundering the samples at 40°C caused a significant increase in colour change of 4.15 and subsequent decrease in colour strength of 2.63. Laundering at the higher temperature, caused an even greater increase in colour change (ΔE=8.55) and decrease in colour strength (K/S=-5.28). It is apparent that laundering at the lower temperature resulted in moderate wash fastness (GSc=3) whereas laundering at the higher temperature resulted in poor wash fastness (GSc=1-2). Major shifts towards the red ($+\Delta a^*$) and blue ($-\Delta b^*$) colour spaces were observed, increasing as the temperature increased. Results obtained in this study is similar to results obtained by Jang, Ko and Carr (2001:143), who found the wash fastness of direct red dyed cotton to be 1-2 at higher temperatures. According to these authors, the decreased wash fastness at higher temperatures can be found in the interaction between dye and textile. These interactions are dependent upon hydrogen bonding and Van der Waal's forces. At higher temperatures, it becomes weaker, because of the dipole-dipole interactions.

According to Table 5.4, the difference in colour change significantly increased as the number of laundering cycles increased. Laundering the direct red dyed cotton for five cycles, resulted in a colour change of 3.54, and decrease in colour strength (K/S=-2.05), where after the difference in colour change increased (ΔE=4.98) and colour strength decreased further to 3.11 after laundering for ten cycles. Laundering the samples for

Table 5.4: Colorimetric data, colourstrength (K/S) and Gray Scale values of direct red dyed cotton as a result of change caused by laundering treatment, -temperature and number of laundering cycles.

	Before					After					(Difference : After – Before)					
	L*	a*	b*	ΔE	K\S Value	L*	a*	b*	ΔE	K\S Value	ΔL*	Δa*	Δb*	ΔE	K\S Value	Gray Scale Value
TREATMENT																
Catholyte	32.63	35.64	-3.72	48.46	13.38	39.36	38.47	-6.12	55.47	8.98	6.74*	2.83*	-2.40*	7.01*	-4.40*	2
Detergent	32.55	35.72	-3.60	48.46	13.38	41.19	39.4	-3.36	57.41	7.89	8.64*	3.68*	-2.76*	8.95*	-5.49*	1-2
Filtered Water	32.51	35.34	-3.58	48.41	13.38	35.11	37.27	-5.47	51.51	11.42	2.60*	1.93*	-1.89*	3.09*	-1.96*	3
TEMPERATURE																
40°C	32.56	35.46	-3.58	48.45	13.38	36.14	37.80	-5.42	52.60	10.75	3.58*	2.35*	-1.84*	4.15*	-2.63*	3
60°C	32.57	35.67	-3.68	48.44	13.38	40.97	38.95	-6.54	57.00	8.10	8.41*	3.28*	-2.86*	8.55*	-5.28*	1-2
CYCLES																
Five	32.51	35.63	-3.64	48.37	13.38	35.35	37.65	-5.19	51.92	11.33	2.84*	2.02*	-1.55*	3.54*	-2.05*	3
Ten	32.60	35.68	-3.68	48.47	13.38	36.89	38.22	-5.69	53.44	10.27	4.30*	2.54*	-2.01*	4.98*	-3.11*	2-3
Twenty	32.58	35.70	-3.64	48.47	13.38	38.98	38.80	-6.10	55.37	9.13	6.40*	3.10*	-2.46*	6.90*	-4.25*	2
Fifty	32.56	35.25	-3.57	48.47	13.38	43.00	38.84	-6.95	58.45	6.98	10.43*	3.59*	-3.38*	9.98*	-6.40*	1-2

*Statistically significant ($p < 0.05$)

twenty cycles increased the difference in colour change to 6.90 and caused a further decrease in colour strength (K/S=-4.25). Finally, it escalated to where the significant difference in colour change was 9.98 and the decrease in colour strength was 6.40. Shifts towards the red (+Δa*) and blue (-Δb*) colour spaces was experienced, and significantly continued to shift as the number of laundering cycles increased. The wash fastness after laundering for five cycles was moderate (GSc=3), however increasing the number of laundering cycles to ten caused wash fastness to decrease to 2-3. Further increasing the number of laundering cycles to twenty caused wash fastness of 2, whilst laundering the samples for fifty cycles caused very poor wash fastness of 1-2. Doyal and Warnock (2005:264) obtained similar results concerning wash fastness, concluding that repeated laundering caused direct red dyed cotton to fade. Cotton fabrics dyed with direct dyes can be affected by dye desorption during laundering, as a result of the washing ingredients, thus causing dye to be removed from the textile fabric (Carrion, 2014:150).

Reactive red dyed cotton

The colorimetric data (L*, a*, b*, ΔE), colour strength (K/S values) and Gray Scale values obtained when reactive red dyed cotton samples were laundered with Catholyte, detergent and filtered water at 40°C or 60°C, for five, ten, twenty and fifty cycles respectively, is represented in Table 5.5.

Laundering the samples with filtered water seems to have caused the greatest difference in colour change (ΔE=-0.83), but the least decrease in colour strength (K/S=-0.09). Laundering the samples with Catholyte caused the greatest decrease in colour strength (K/S=-0.82) and a moderate difference in colour change (ΔE=-0.24). As a result of laundering the samples with detergent, a moderate decrease in colour strength (K/S=-0.19) and a slight change in colour (ΔE=-0.09) was observed. Although a decrease in colour strength was evident, Gray Scale values indicated excellent wash fastness (GSc=4-5). When laundered with detergent (ΔL*=0.52) and Catholyte (ΔL*=0.42), the lightness increased significantly, although laundering with filtered water (ΔL*=-0.38) caused a significant decrease in lightness. Laundering with all the treatments caused

Table 5.5: Colorimetric data, colourstrength (K/S) and Gray Scale values of reactive red dyed cotton as a result of change caused by laundering treatment, -temperature and number of laundering cycles.

	Before					After					(Difference : After – Before)					
	L*	a*	b*	ΔE	K\S Value	L*	a*	b*	ΔE	K\S Value	ΔL*	Δa*	Δb*	ΔE	K\S Value	Gray Scale Value
TREATMENT																
Catholyte	62.99	-33.67	-29.38	77.26	10.91	63.41	-33.13	-28.50	77.02	10.09	0.42*	0.54*	0.88*	-0.24*	-0.82*	4-5
Detergent	62.95	-34.03	-29.44	77.38	10.91	63.47	-33.56	-28.62	77.29	10.72	0.52*	0.47*	0.82*	-0.09*	-0.19*	4-5
Filtered Water	62.91	-33.99	-29.44	77.33	10.91	62.53	-33.22	-28.96	76.50	10.82	-0.38*	0.77*	0.47*	-0.83*	-0.09*	4-5
TEMPERATURE																
40°C	62.99	-34.03	-29.40	77.32	10.91	62.92	-33.30	-28.75	76.78	10.77	0.44*	0.46*	0.80*	-0.24*	-0.14*	4-5
60°C	62.91	-33.76	-29.44	77.33	10.91	63.35	-33.31	-28.64	77.09	10.32	-0.07*	0.73*	0.65*	-0.54*	-0.59*	4-5
CYCLES																
Five	62.83	-33.56	-29.51	77.30	10.91	63.67	-32.86	-28.23	77.02	10.90	0.84*	0.70*	1.28*	-0.28*	-0.02*	4-5
Ten	62.97	-34.01	-29.39	77.37	10.91	63.15	-33.30	-28.79	76.98	10.86	0.18*	0.71*	0.60*	-0.39*	-0.05*	4-5
Twenty	62.94	-34.04	-29.39	77.26	10.91	62.93	-33.52	-28.83	76.84	10.64	-0.01*	0.52*	0.56*	-0.42*	-0.27*	4-5
Fifty	63.05	-33.99	-29.38	77.36	10.91	62.79	-33.54	-28.92	76.91	9.77	-0.27*	0.45*	0.46*	-0.45*	-1.14*	4-5

*Statistically significant ($p < 0.05$)

significant shifts towards the red (+Δa*) colour space, laundering with filtered water more so than laundering with Catholyte and detergent. Shifts towards the yellow (+Δb*) colour space were also experienced, laundering with Catholyte causing the greatest shift. Mohsin and coworkers (2013:346) reported wash fastness of 4-5 when reactive red dyed cotton was laundered, which is similar to results obtained in this study.

When the samples were laundered with Catholyte and detergent, the lightness increased, whereas laundering with filtered water decreased the lightness. The increase in lightness renders the textile brighter, and although a decrease in colour strength is observed the inherent colour of the textile is weaker, although the sample still appears brighter. A decrease in lightness indicates that the textile became duller (Ali *et al.*, 2015:276). The alkalinity of the Catholyte and detergent may be the explanation of this occurrence. Alkaline treatments are employed for initial wash-off after the dyeing procedure because alkaline mediums are known for detergency properties, but also preserving the colour of reactive dyed textiles (Boardman & Jarvis, 2000:65). From these findings, it can be concluded that Catholyte is suitable to be used as a wash liquor when laundering reactive red dyed cotton, as the wash fastness obtained when laundered with Catholyte, was excellent.

Laundering the reactive red dyed samples at 40°C resulted in a decrease in colour change of 0.24 and a significant decrease in colour strength of 0.14. Laundering the samples at a higher temperature (60°C) caused a decrease in colour difference of 0.54 and colour strength decrease of 0.59, also significant. However, the wash fastness still indicates optimum wash fastness (GSc=4-5). The lightness increased after laundering at the lower temperature (ΔL*=0.44) and decreased after laundering at the higher temperature (ΔL*=-0.07). It seems that the samples shifted towards the red (+Δa) colour space as the laundering temperature increased. Initially after laundering at 40°C, the samples shifted towards the yellow colour space (Δb*=0.80), but laundering at the higher temperature caused them to shift towards the blue colour space (Δb*=0.65). The washfastness observed at both temperatures is excellent (GSc=4-5). Alam and fellow researchers (2008:64) obtained wash fastness results similar to what were found in this study. They stated that wash fastness tends to decrease as temperature increases. At the higher temperature, the dissolution of the dye particles from the fibre surface takes

place and hence more dye particles are easily washed off the fabric (Alam *et al.*, 2008:64). Moreover, the lightness decreasing at the higher temperature indicates that the shade became duller, confirmed by the subsequent decrease in colour strength. This is comparable to findings that that indicate that colour change is greater as the laundering temperature increases (Laitala, Boks & Klepp, 2011:260).

It is evident from Table 5.5 that the difference in colour change increased as the number of laundering cycles increased. Laundering for five cycles caused a difference in overall colour change of -0.28, which increased to -0.39 after laundering for ten cycles. Increasing the number of laundering cycles to twenty resulted in an overall colour difference of -0.42, and lead to a decrease of -0.45 after laundering for fifty cycles. The colour strength decreased significantly as the number of laundering cycles increased, resulting in a decrease of 1.14 after laundering for fifty cycles. The colour strength significantly decreased as the number of laundering cycles increased. Although these changes occurred, the wash fastness values observed, irrespective of the number of laundering cycles, were excellent (GSc=4-5). The lightness initially increased after laundering for five cycles (ΔL^*=0.84), where after it decreased as the number of laundering cycles increased. The samples also exhibited initial subsequent shifts towards the red (+Δa^*) and yellow (+Δb^*) colour spaces after laundering for five cycles. However, increasing the number of laundering cycles from five to ten, twenty and fifty, caused significant shifts towards the green (-Δa^*) and blue (-Δb) colour spaces. It should be noted that the shifts of these two colour parameters resulted in changes after laundering for fifty cycles, which is similar to the initial parameters before treatment. Therefore, it can be concluded that the initial shifts in lightness, redness and yellowness was a result of unfixed dye being washed off, but not adversely affecting the overall colour shade of the samples, although the inherent strength of the colour did decrease. These findings can be compared to research done by Burkinshaw and co-workers (2011:137) who found that repeated laundering of reactive red dyed cotton did not have a great effect on the change in hue of the fabric. In another research study, the wash fastness of reactive red dyed cotton was observed to be 4-5 (Cai, Pailthorpe and David, 1999:445).

5.2.1.2 Staining

Staining that was observed as a result of laundering the disperse red dyed polyester and the acid red dyed polyamide samples with Catholyte, detergent and filtered water at 40°C or 60°C for five, ten, twenty and fifty cycles respectively, is depicted in Table 5.6.

Disperse red dyed polyester

Laundering the disperse red dyed polyester samples with Catholyte and detergent seems to have resulted in equivalent overall colour change of the evaluated stained samples (ΔE=-0.57). Laundering with filtered water caused less staining (ΔE=-0.31), although the overall effect was still significant. Regardless of what wash liquor was used to launder the samples, Gray Scale values for staining of 5 was obtained, indicating that there was almost no change in appearance of the adjacent fabric that was evaluated for staining. The stained samples all decreased in lightness, those laundered with detergent more so than those laundered with Catholyte and filtered water. Shifts towards the red (+Δa*) colour space was observed for all samples, whilst a shift towards the yellow colour space was experienced for the samples laundered with Catholyte (Δb*=1.00) and filtered water (Δb*=0.78). Laundering the samples with detergent, caused a slight shift towards the blue colour space (Δb*=-0.05). Gharanjig and fellow researchers (2010:40) reported staining of 4-5 when disperse red dyed polyester was evaluated. The high wash fastness qualities of the polyester fabrics dyed with disperse dyes can be attributed to the high crystalline structure and fine porosities of the polyester fibres. Because of the excellent wash fastness, no major wash-off of unfixed dye is experienced and therefore subsequent staining is less. Favourable results with regards to laundering with Catholyte was observed and indicates that laundering with this wash liquor does not cause more staining than laundering with detergent.

Laundering at 40°C caused the least overall colour change (ΔE=-0.13), decrease in lightness (ΔL*=-0.09), and shifts toward the red (Δa*=0.17) and yellow (Δb*=0.31) colour spaces of the stained samples. Increasing the laundering temperature increased the movement of all these parameters to an overall colour change -0.84 and consequent

Table 5.6: Colorimetric data and Gray Scale equivalents of staining caused by disperse red dyed polyester and acid red dyed polyamide as a result of laundering treatment, -temperature and number of laundering cycles.

	Disperse Red on Polyester					Acid Red on Polyamide				
	ΔL*	Δa*	Δb*	ΔE	Gray Scale Value	ΔL*	Δa*	Δb*	ΔE	Gray Scale Value
TREATMENT										
Catholyte	-0.55	0.59	1.00	-0.57*	5	-1.03	0.95	1.71	-1.08*	4-5
Detergent	-0.64	1.41	-0.05	-0.57*	5	-0.60	0.49	0.75	-0.63*	5
Filtered Water	-0.28	0.57	0.78	-0.31*	5	-1.06	1.20	1.56	-1.09*	4-5
TEMPERATURE										
40°C	-0.09	0.17	0.31	-0.13*	5	-0.58	0.38	1.11	-0.62*	5
60°C	-0.89	1.54	0.84	-0.84*	5	-1.21	1.38	-2.63	-1.24*	4-5
CYCLES										
Five	-0.59	1.04	0.38	-0.58*	5	-0.76	0.59	1.06	-0.80*	4-5
Ten	-0.24	0.16	0.38	-0.58*	5	-0.82	0.72	1.27	-0.85*	4-5
Twenty	-0.24	0.16	0.36	-0.35*	5	-0.92	1.02	1.39	-0.95*	4-5
Fifty	-0.28	0.21	0.36	-0.34*	5	-1.08	1.20	1.65	-1.12*	4-5

*Statistically significant ($p < 0.05$)

decrease in lightness (ΔL*=-0.89), and shifts towards the red (Δa*=1.54) and yellow (Δb*=0.84) colour spaces. However, optimum staining values were still achieved (GSs=5), indicating that the stained samples differed very little in colour in comparison of its untreated state. According to Huang and co-workers (2011:889), polyester dyed with disperse dyestuff should not be affected by temperature to a great extent. This is partly due to the stability of the hydrophobic fibre at a higher temperature, and the stability of the specific dyestuff in the textile substrate, regardless of the temperature. Thus implying, staining should also be less of a concern with regards to temperature (Oakes 2005:2). Jihong and Shuilin (2005:79) observed similar results as is found in this study when staining of disperse red polyester was examined at different temperatures.

Regardless of the number of laundering cycles, the staining observed for the disperse red dyed polyester was optimum (GSs=5). Although the difference in overall colour change of the stained samples decreased as the number of laundering cycles increased, no real pattern could be observed for the individual redness (Δa*) parameter. The lightness seemed to have decreased after five laundering cycles (ΔL*=-0.59), but decreasing less after ten, twenty (ΔL*=-0.24) and fifty cycles (ΔL*=-0.28). The samples showed similar shifts towards the yellow colour space (+Δb*) irrespective of the number of laundering cycles. This could be indicative that after laundering for five cycles, most of the unfixed dye was washed-off, and thereafter no major changes could be observed for the individual parameters as most of the staining causing particles have been eliminated. Jihong and Shuilin (2005:79) did not observe major staining when disperse red dyed polyester was laundered for different numbers of laundering cycles (GSs=4-5). These results are comparable with results found in this study.

Acid red dyed polyamide 6,6

It is evident from Table 5.6 that laundering with filtered water caused the greatest staining (GSs=4-5) and significant overall colour change (ΔE=-1.09) of the stained samples. Laundering with Catholyte resulted in similar staining results (GSs=4-5 and ΔE=-1.08). Laundering with detergent caused the least staining, (GSs=5) with an overall

colour change of ΔE=-0.63 of the stained samples. Irrespective of all the changes discussed excellent staining values were observed. The samples exhibited decreases in lightness when laundered with Catholyte (ΔL*=-1.03), detergent (ΔL*=-0.60) and filtered water (ΔL*=-1.06). Shifts towards the red (+Δa*) and yellow (+Δb*) colour spaces could be observed for all the samples, proportionate to the change in colour with regards to the treatment used. If acid dyes are pre-metallised, excellent staining fastness can be expected (Burkinshaw, Chevli & Marfell, 2000:72). Akram and co-workers (2012:33) found the staining of acid red dyed polyamide to be 4. The results in this study were slightly better. The staining can be attributed to the loss of dye molecules during washing (Akram *et al*., 2012:33). The fact that detergent caused the least staining could be attributed to the surfactant present in the detergent formulation. Anionic surfactants have been found to inhibit the transfer of acid dye to adjacent fabrics (Oakes, Gratton and Dixon, 2004:270a). However, these results may still be regarded as favourable because laundering with Catholyte did not cause major staining to take place.

As the laundering temperature increased, the staining also increased. The resultant Gray Scale values of 5 and 4-5 for laundering at 40°C and 60°C respectively was still indicative of excellent staining fastness. Increasing the laundering temperature from 40°C to 60°C, caused the initial decrease in lightness (ΔL*=-0.58) to decrease further (ΔL*=-1.21) at the higher temperature. The acid red dye polyamide samples also became redder (+Δa*) as the temperature increased. Interestingly, laundering at 40°C caused a shift toward the yellow (Δb*=1.11) colour space, whereas laundering at 60°C caused a shift towards the blue (Δb*=-2.63) colour space. Oakes (2005:2) found that staining was greater at higher temperatures, attributing it the method of application of acid dyes, causing it to transfer to adjacent textile materials, particularly at higher temperatures. Hence, explaining the lower Gray Scale value at the higher temperature. Chu and Tang (2014:238) found the staining of acid red dyed polyamide to be 4-5, which is comparable to results obtained in the present research.

As the number of laundering cycles increased, the overall change in colour of the stained samples also increased. A change of -0.80 was noted after laundering for five cycles, which increased to -0.85 after laundering for ten cycles. Laundering for twenty cycles further increased the change in colour of the stained samples to -0.95. Increasing the

number of laundering cycles to fifty resulted in a ΔE value of -1.12. The number of laundering cycles did not play a role in the Gray Scale values obtained (GSs=4-5) for all the cycles, although the ΔE value decreased significantly.

The samples decreased in lightness (-ΔL*) and shifted towards the red (+Δa*) and yellow (+Δb*) colour spaces continuously as the number of laundering cycles increased. Lee, Lee and Kim (2013:2023) also reported Gray Scale values of 4-5 for staining, regardless of the number of laundering cycles. They also stated that the low staining can be attributed to the excellent wash fastness of acid dyed. As not much of unfixed dye is washed off, less is available to redeposit on adjacent textiles, for example, cotton.

Azoic orange dyed cotton

Staining that was observed as a result of laundering the azoic orange, direct red and reactive red dyed cotton samples with Catholyte, detergent and filtered water at 40°C or 60°C for five, ten, twenty and fifty cycles respectively, is depicted in Table 5.7.

Laundering the azoic orange dyed cotton samples with Catholyte caused the greatest staining, resulting in an overall colour change of ΔE=-3.52 of the stained samples, although the Gray Scale value obtained is very good (GSs=4). Laundering the samples with detergent and filtered water resulted in similar overall colour changes (ΔE=-1.54), with excellent Gray Scale (GSs=4-5) values observed. A decrease in lightness was noted when the samples were laundered with Catholyte (ΔL*=-3.64), detergent (ΔL*=-1.55) and filtered water (ΔL*=-2.52). The samples exhibited marked shifts towards the red (+Δa*) and yellow (+Δb*) colour spaces respectively, proportionate to the ΔE values. Although these changes occurred, very good staining values were still obtained. Phillips and fellow researchers (2001:10) reported similar values of staining (GSs=4-5) when azoic orange dyed cotton was laundered. They also stated that good washfastness is expected, because of the molecular size of the dye inside the fibre. It cannot easily be removed from the dye-fibre substrate, although residual dye may be washed off. Thus, staining will also be limited and exhibit favourable results. An explanation as to why the Catholyte caused more staining than detergent and filtered water, eludes the researcher,

although it can be assumed that an unknown interaction between the specific dye-fibre matrix and the Catholyte exist. However, the staining observed when laundered with Catholyte is still within the acceptable range and is suitable to use to launder azoic orange dyed cotton.

Laundering the samples at 40°C resulted in a staining value of 4-5 and a significant overall colour change of -2.45. Laundering at a 60°C caused a slight increase in the difference in overall colour change (ΔE=-2.55), although the staining value remained the same. The samples decreased in lightness as the temperature was increased from 40°C (ΔL*=-2.50) to 60°C (ΔL*=-2.64) and subsequently shifted towards the red (+Δa*) and yellow (+Δb*) colour spaces. Wang and co-workers (2008:644) reported that staining of azoic dyes might be directly proportionate to the wash fastness exhibited by these dyes with regards to cotton. As more dye is washed off, more molecules are available to redeposit, which might account for the slight increase in the individual parameters. Kim and Jeon (2013:109) observed similar Gray Scale values of staining (GSs=4-5) when azoic orange cotton was laundered at different temperatures, which is comparable to results obtained in this study.

The overall colour change (ΔE) increased as the number of laundering cycles increased, although still obtaining very good staining values of 4-5 for all the laundering cycles. This indicates that only slight staining was visible. Continuous decrease in lightness (-ΔL) could be observed as the number of laundering cycles increased. The samples exhibited a marginal shift towards the red (Δa*=3.62) colour space after laundering for five cycles, where after a shift towards the green colour space could be observed when the samples were laundered for ten (Δa*=3.72), twenty (Δa*=3.74) and fifty (Δa*=3.76) cycles. No pattern could be observed on the blue-yellow axis. The samples initially shifted towards the yellow colour space after five (Δb*=1.77) laundering cycles, but towards the blue colour space after laundering for ten and twenty cycles, as the Δb*-parameter decreased, and increasing again after laundering for fifty cycles, indicating a shift towards the yellow colour space. Al-Mousawi and El-Apasery (2013:8840) reported similar staining values for azoic dyed cotton (GSs=4-5). In their opinion, the relatively big size of the dye molecule and the good intra-fibre diffusion of the dye molecules

Table 5.7: Colorimetric data and Gray Scale equivalents of staining caused by azoic orange, direct red and reactive red dyed cotton as a result of laundering treatment, -temperature and number of laundering cycles.

	Azoic Orange					Direct Red					Reactive Red				
	ΔL*	Δa*	Δb*	ΔE	Gray Scale Value	ΔL*	Δa*	Δb*	ΔE	Gray Scale Value	ΔL*	Δa*	Δb*	ΔE	Gray Scale Value
TREATMENT															
Catholyte	-3.64	5.11	2.54	-3.52*	4	-17.05	24.63	-6.88	-12.19*	2	-3.06	4.11	-0.63	-2.91*	4
Detergent	-1.55	2.30	1.22	-1.54*	4-5	-16.90	24.54	-6.51	-11.96*	2	-1.18	1.58	-0.23	-1.14*	4-5
Filtered Water	-2.52	3.72	1.23	-1.54*	4-5	-23.02	28.00	-5.64	-15.61*	1-2	-5.02	6.98	-1.17	-4.05*	4
TEMPERATURE															
40°C	-2.50	3.54	1.55	-2.45*	4-5	-18.85	24.58	-5.98	-13.14*	2	-2.03	2.94	-0.23	-1.92	4-5
60°C	-2.64	3.88	1.78	-2.55*	4-5	-19.13	26.86	-6.71	-13.38*	2	-4.14	5.54	-0.29	-3.48	4
CYCLES															
Five	-2.37	3.62	1.77	-2.31*	4-5	-17.90	23.07	-5.51	-12.53*	2	-2.13	2.71	0.19	-2.05*	4-5
Ten	-2.57	3.72	1.45	-2.48*	4-5	-18.80	25.98	-6.56	-13.13*	2	-2.26	3.27	-0.23	-2.13*	4-5
Twenty	-2.66	3.74	1.61	-2.60*	4-5	-18.80	26.17	-6.62	-13.15*	2	-2.91	4.05	-0.26	-2.73*	4-5
Fifty	-2.68	3.76	1.82	-2.61*	4-5	-20.46	27.64	-6.69	-14.20*	2	-5.06	6.87	-0.73	-3.90*	4

*Statistically significant ($p < 0.05$)

inside the fabrics, renders it very stable under domestic laundering conditions, especially repeated laundering.

Direct red dyed cotton

Laundering the direct red dyed cotton with Catholyte, detergent and filtered water caused major staining (Table 5.7). It is evident that laundering with filtered water caused the greatest staining, (ΔE=15.61) and a resultant Gray Scale value of 1-2. Laundering the samples with detergent (ΔE=-11.96) and Catholyte (ΔE=-12.19) caused similar staining, resulting in Gray Scale values of 2. The samples decreased in lightness considerably, those laundered with filtered water (ΔL*=-23.02), more so than the samples laundered with detergent (ΔL*=-16.90) and Catholyte (ΔL*=-17.05). The direct red dyed cotton samples also became redder (+Δa*) and bluer (-Δb*), proportionate to the ΔE values. Jang, Ko and Carr (2001:143) found the staining of direct red dyed cotton to be 2. Direct dyes are known for causing major staining during laundering. It is due to the relative ease by which direct dyes can be displaced from cotton, especially when wash-off after dyeing was not effective. These dyes have been designed to be intrinsically substantive to cotton fibres, and therefore may readily redeposit (Boardman & Jarvis, 2000:64). Laundering the samples with Catholyte did not cause more staining than laundering with detergent and can hence be interpreted as a positive result.

The staining slightly increased as the laundering temperature increased. Laundering at 40°C resulted in a decrease in ΔE of 13.14 whereas laundering at 60°C resulted in a ΔE decrease of 13.38. Laundering at both temperatures caused poor Gray Scale staining values (GSs=2). The decrease in lightness was marginal for both temperatures and decreased slightly more when the laundering temperature was increased from 40°C (ΔL*=-18.85) to 60°C (ΔL*=-19.13). The samples also indicated shifts towards the red (+Δa*) colour space as the laundering temperature increased, which indicated that dye particles washed off from the samples redeposited on the adjacent textiles. The samples continually shifted towards the blue (-Δb*) colour space as the laundering temperature increased. As mentioned previously, direct dyes are prone to be less fast at higher temperatures as a result of the weakened hydrogen bonding and Van der Waal's forces.

Consequently, more dye particles are redeposited on adjacent textile fabrics because more particles are available for redepositing. Bafrooei, Malek and Mazaheri (2014:384) reported similar staining values (GSs=2) at higher laundering temperatures.

The staining became greater with the increasing number of laundering cycles. The ΔE value initially decreased with 12.53 after five laundering cycles, decreasing further with 13.13 after ten laundering cycles, continuing to exhibit this behaviour after twenty (ΔE=-13.15) and fifty (ΔE=-14.20) laundering cycles. As a result, the lightness (ΔL*) decreased marginally, but not significantly, as the number of laundering cycles increased. The direct red dyed samples became redder (+Δa*) and more blue (-Δb*), the more it was laundered. Burkinshaw and Gotsopoulos (1999:188) observed that staining remained at a Gray Scale value of 2, regardless of the number of laundering cycles. Although, the above changes significantly changed the colour of the stained sample, the Gray Scale value remained 2 irrespective of the number of laundering cycles. Thus, it is comparable with the results of Burkinshaw and Gotsopoulos. Direct dyed cotton fabrics can be affected by dye desorption during washing, depending on the washing ingredients. The process can also continue as the number of washings increases (Carrion, 2014:150).

Reactive red dyed cotton

According to Table 5.7, laundering the reactive red dyed cotton with filtered water caused the greatest staining, although the Gray Scale value is still considered very good (GSs=4). Laundering with Catholyte caused a moderate change in colour (ΔE=-2.91) of the stained samples and Gray Scale equivalent of those samples laundered with filtered water. Laundering with detergent caused the least staining (GSs=4-5) and colour change of -1.14, regarding the stained samples. All the samples exhibited shifts towards the red (+Δa*) and blue (-Δb*) colour spaces, proportionate to the ΔE values. The samples decreased in lightness (-ΔL*), especially those laundered with filtered water. Burkinshaw and fellow researchers (2011:137) observed staining Gray Scale values of 4 for reactive red dyed cotton. The results obtained in the current research are, therefore, comparable. According to Fu and co-workers (2013:3108) reactive dyes have been known to have good staining values because dye does not readily dispose from the fabric

surface during laundering, therefore less dye particles are available to redeposit on adjacent fabric. Moreover, Oakes, Gratton and Dixon (2004:281b) stated that the presence of an anionic surfactant can prevent the staining on adjacent textile fabrics, as a result of inhibiting the particles from redepositing. Therefore, laundering textiles dyed with certain dyestuffs, with detergent will cause less staining. Catholyte still performed well not causing major staining, and thus can be regarded as a suitable wash liquor to launder reactive red dyed cotton with.

Increasing the laundering temperature seems to have increased the staining that had occurred. Laundering at 40°C caused the stained samples to change colour equivalent to -1.92, which further decreased to -3.48 when these samples were laundered at 60°C. As a result, the lightness decreased (-ΔL*) more as the laundering temperature increased. The samples exhibited continuous shifts towards the red (+Δa*) and blue (-Δb*) colour spaces as the laundering temperature was increased from 40°C to 60°C. In another study, laundering the reactive red dyed cotton samples resulted in Gray Scale staining values of 4-5 at 60°C (Burkinshaw *et al.*, 2011;137).

Increasing the number of laundering cycles resulted in an increase in staining with resultant Gray scale values values of 4-5 to 4. The lightness decreased as the number of laundering cycles increased whilst shifts towards the red (+Δa*) colour space could be observed, increasing as the number of laundering cycles increased. Initially, a shift towards the yellow colour space could be observed after laundering for five cycles (Δb*=0.19), however, as the laundering cycles increased the samples shifted towards the blue (-Δb*) colour space. If wash-off was not done effectively, washfastness could decrease because unfixed dye is still being removed from the fabric. The removed dye then redeposit on the adjacent fabric, causing staining (Burkinshaw *et al.*, 2011:137). Hauser and Tabba (2001:117) observed Gray Scale staining values of 4-5 when reactive red dyed cotton was laundered.

5.2.1.3 Fastness to rubbing: Dry & Wet

The Gray Scale values obtained as a result of subjecting the disperse red dyed polyester, acid red dyed polyamide, azoic orange, direct red and reactive red dyed cotton samples to the rubbing fastness tests, both dry and wet, are depicted in Table 5.8. These samples were laundered with Catholyte, detergent and filtered water at 40°C or 60°C for five, ten, twenty and fifty cycles respectively.

Disperse red dyed polyester

From Table 5.8 it can be seen that laundering the disperse red dyed polyester samples with detergent and filtered water, resulted in optimum colourfastness to dry rubbing (GSs=5). Laundering the samples with Catholyte caused excellent colourfastness to dry rubbing obtaining a Gray Scale value of 4-5. Laundering with Catholyte, detergent and filtered water resulted in excellent colourfastness to wet rubbing, obtaining Gray Scale values of 4-5 for all the treatments. Many attempts have been made to determine the relationship between the chemical structure of a dye and its fastness properties. Such inter-relationships can be very complex. Satisfactory fastness to washing and rubbing a characteristic for disperse dyes, especially when applied to polyester; because of its more crystalline and hydrophobic structure (Koh, 2011:200). The same researcher reported fastness to dry and wet rubbing, to be 4-5. This is similar to results obtained in this study. Furthermore, it is positive that Catholyte did not have an adverse effect on the rubbing fastness, and can be used to launder disperse red dyed polyester fabric.

Laundering the disperse red dyed polyester samples at 40°C and 60°C resulted in excellent colourfastness for both dry and wet rubbing. Fastness to dry rubbing was superior with an optimum Gray Scale value of 5, when laundered at 40°C. Gray Scale values of 4-5 was observed for fastness to dry rubbing when the samples were laundered at 40°C and for both fastness to dry and wet rubbing when the samples were laundered at 60°C. Xie and co-workers (2007:296)observed no change in rubbing fastness when they increased the temperature and obtained fastness values of 4-5 for both wet and dry rubbing.

Irrespective of the number of laundering cycles, disperse red dyed polyester samples performed well and obtained excellent colourfastness with regards to both dry and wet rubbing, obtaining Gray Scale values of 4-5 for all the cycles. As mentioned previously the high rubbing fastness qualities of the polyester fabrics dyed with disperse dyes can be attributed to the high crystalline structure and fine porosities of the polyester fibres. It is stable to repeated laundering under general domestic laundry practices (Gharanjig *et al.*,2010:40). These authors also reported rubbing fastness of 4-5 for both dry and wet rubbing. The observed fastness values in the present research is comparable with the aforementioned results.

Acid red dyed polyamide 6,6

Laundering the acid red dyed polyamide samples with Catholyte, detergent and filtered water resulted in excellent fastness to both dry and wet rubbing (GSs=4-5). The excellent rubbing fastness of acid dyed polyamide can be attributed to the presence of the carboxylic acid and hydroxyl groups in the dye molecules. The presence of these groups in the dye molecule causes the easy hydrolysis of the adsorbed dyes on fibres and then being converted into water solubilized dye. This results in less unfixed dye, and the unfixed dye that is present is washed off during laundering. The stable fixation and less unfixed dye results in the high rubbing fastness, to both wet and dry samples (Sadeghi-Kiakhani *et al.*, 2011:3394). They observed fastness to rubbing, wet and dry, of 4 in their study. The similar results of the samples laundered with Catholyte and detergent leads to the conclusion that Catholyte is suitable to be used on acid red dyed polyamide without adversely affecting the rubbing fastness of the textile.

From Table 5.8, it is clear that the laundering temperature did not have an influence in the rubbing fastness of acid red dyed polyamide as it remained 4-5 at both temperatures. This is true for the samples subjected to the dry rubbing, as well as the wet rubbing tests. A Gray Scale value of 4-5 is indicative of excellent fastness to rubbing. Chu and Tang (2014:234) reported that an increase in temperature did not change the Gray Scale value observed for colourfastness to both dry and wet rubbing (GSs=4-5).

Table 5.8: Gray Scale values of colourfastness to rubbing, dry and wet, for disperse red dyed polyester, acid red dyed polyamide, azoic orange dyed cotton, direct red dyed cotton and reactive red dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Dry					Wet				
	Disperse Red	**Acid Red**	**Azoic Orange**	**Direct Red**	**Reactive Red**	**Disperse Red**	**Acid Red**	**Azoic Orange**	**Direct Red**	**Reactive Red**
TREATMENT										
Catholyte	4-5	4-5	4-5	4	4-5	4-5	4-5	2-3	3-4	4
Detergent	5	4-5	4-5	4-5	4-5	4-5	4-5	2-3	4	4
Filtered Water	5	4-5	4-5	4-5	4-5	4-5	4-5	2-3	3-4	4
TEMPERATURE										
40°C	5	4-5	4-5	4-5	4-5	4-5	4-5	2-3	4	4
60°C	4-5	4-5	4-5	4-5	4-5	4-5	4-5	2-3	3-4	4
CYCLES										
Five	4-5	4-5	4-5	4-5	4-5	4-5	4-5	2-3	3-4	4
Ten	4-5	4-5	4-5	4-5	4-5	4-5	4-5	2-3	3-4	4
Twenty	4-5	4-5	4-5	4-5	4-5	4-5	4-5	2-3	4	4
Fifty	4-5	4-5	4-5	4-5	4-5	4-5	4-5	2-3	4	4

Irrespective of the number of laundering cycles, the colourfastness to rubbing, both dry and wet, remained excellent with observed Gray Scale values of 4-5. Burkinshaw and Son (2010:137) experienced similar results with the Gray Scale values remaining 5, even though the number of laundering cycles was increased. They stated that the superior fastness properties of acid dyes could be related to the polar groups in the dye's molecular structure, with minimal dye being available for desorption and redepositing.

Azoic orange dyed cotton

Laundering the azoic orange dyed cotton samples with Catholyte, detergent and filtered water resulted in similar values of fastness, indicating excellent fastness to dry rubbing. However, laundering the samples with the same treatments resulted in moderate fastness to wet rubbing of Gray Scale values of 2-3 for all the treatments. Koh, Yoo and Kim (2004:160) reported fastness to dry rubbing as 4-5 and fastness to wet rubbing as 3. It is comparable to the results found in this study. Elsasser (2010:204) did observe that azoic dyes have a tendency to crock/rub off onto other fabrics if the after treatment process was not effective. The moderate performance when the azoic orange dyed cotton was subjected to the wet rubbing test could be attributed to the low water solubility of the dye, due to its higher molecular weight, as well as the intramolecular hydrogen bonding between the azo and alkyl groups, which makes it less accessible to hydrolysis. However, this characteristic leads to the dye being redeposited on the wet cotton, resulting in the subsequent transfer of colour to the white cotton (Mokhtari *et al.*, 2008:199). Furthermore, the similar results obtained from Catholyte and detergent, could be interpreted as positive, leading to the conclusion that Catholyte can be used to launder azoic dyed cotton as it will not cause the textile fabric to be less colourfast to rubbing.

Increasing the laundering temperature from 40°C to 60°C, did not adversely affect the colourfastness to dry or wet rubbing, as the Gray Scale values stayed the same for both temperatures. Fastness to dry rubbing was excellent, and Gray Scale staining values of 4-5 was observed. Fastness to wet rubbing is only moderate, with values of 2-3being observed for both temperatures. Mokhtari and fellow researchers (2008:199) observed

similar results (GSs=2-3) when they evaluated the wet rubbing fastness of azoic dyed cotton. However, the results they observed for fastness to dry rubbing was slightly higher (GSs=5), indicating optimum fastness. The difference in fastness might be due to the structural variation of the exact dye as it has been known to vary depending on the exact structure (Ingamells, 1993:105). The specific structure of this azoic dye is not known to the researcher.

Laundering the azoic dyed cotton for any number of laundering cycles, did not change the Gray Scale staining value obtained for both dry and wet rubbing. Subjecting the azoic dyed cotton to the dry rubbing test resulted in excellent fastness values of 4-5, irrespective of the number of laundering cycles the samples were exposed to. The fastness to wet rubbing was only moderate, achieving values of 2-3 for all the laundering cycles. Shamey and Hussein (2005:38) did note that samples exposed to the wet fastness tests can result in poor wash fastness. Moreover, repeated laundering should not have a significant effect on the rubbing fastness as the naphthol is insoluble in water and therefore cannot continually be removed from the dye-fibre substrate, resulting in poor wash and rubbing fastness. Only the unfixed dye that was not removed by the wash-off after dyeing can be present and slightly alter these fastness values.

Direct red dyed cotton

Laundering the direct red dyed cotton with Catholyte resulted in very good colourfastness to dry rubbing (GSs=4), whereas laundering the samples with detergent and filtered water resulted in excellent colourfastness to dry rubbing (GSs=4-5). Colourfastness to wet rubbing observed was moderate to good when the samples were laundered with Catholyte and filtered water (GSs=3-4), and good when laundered with detergent (GSs=4). Mohsin and co-workers (2013:346) observed the colourfastness to dry rubbing of direct red dyed cotton to be 4-5, and the fastness to wet rubbing 3-4. The results obtained by these researchers are comparable with the results obtained in this study. Laundering the samples with Catholyte did seem to result in a slightly lower fastness to rubbing value, although it is still considered acceptable. Direct dyed cotton

generally is not expected to exhibit good wet fastness, as a result of the physico-chemical manner in which the dye is bonded to the fibre substrate. These bonds are not as strong as covalent bonds. Consequently, the dye can easily be redisposed when submerged in water and rubbed off (Boardman & Jarvis, 200:63).

It seems that the colourfastness to dry rubbing was not affected by an increase in temperature, indicating excellent fastness of 4-5. However, increasing the laundering temperature indicated that the colourfastness to wet rubbing decreased half a level on the Gray Scale, from 4 to 3-4, although still indicating good colourfastness to wet rubbing. Yin, Wang and Wang (2008:311) reported the fastness to dry rubbing of acid red dyed cotton to be 4, and 2-3 when subjected to the wet rubbing test. They did not note a change in Gray Scale value as the temperature increased.

The colourfastness to dry rubbing was unaffected by the increase in the number of laundering cycles and maintained excellent fastness values (GSs=4-5). Laundering the samples for five and ten cycles resulted in moderate to good colourfastness to wet rubbing, however, it seems that increasing the number of laundering cycles to twenty and fifty, subsequently increased the colourfastness to wet rubbing. As mentioned previously, the increasing staining values as the number of laundering cycles increased could be the probable explanation. Most likely because more dye particles redeposited on the adjacent fabric, thus less could rub off. Jang, Ko and Carr (2001:143) observed colourfastness to dry rubbing of direct red dyed cotton to be 5, and Gray Scale values of 4 for wet rubbing, regardless of the number of laundering cycles. The results in this study are comparable, although not identical. This could be ascribed to the variation in dye structure, which can alter some of the fastness properties, especially with regards to the chromophore used (Ingamells, 1993:90).

Reactive red dyed cotton

From Table 5.8, it is evident that the laundering with Catholyte, detergent and filtered water resulted in excellent colourfastness to dry rubbing (GSs-4-5). Laundering the samples with the same treatments resulted in very good fastness to wet rubbing, all

achieving Gray Scale staining values of 4. Jang, Ko and Carr (2001:145) found that reactive red exhibited very good (GSs=4-5) colourfastness to both dry and wet rubbing. This can be expected as the covalent bonds that hold the reactive dye in place, are very strong, and will seldom be broken by friction caused as a result of rubbing (Boardman and Jarvis, 2000:63). Laundering the samples with Catholyte resulted in fastness properties equivalent to those samples laundered with detergent. Therefore, it can safely be concluded that Catholyte can be used to launder reactive red dyed cotton, without adversely affecting the fastness properties of the textile material.

The increase in temperature did not seem to affect the colourfastness to rubbing, as the observed values remained the same. Laundering at both 40°C and 60°C resulted in colourfastness to dry rubbing of 4-5 and colourfastness to wet rubbing of 4. Sonaje and Chougule (2013:35) reported the rubbing fastness of reactive red dyed cotton for dry and wet tests to be 4. In the present study, the fastness to dry rubbing was slightly higher, whereas the fastness to wet rubbing is identical. Reactive dyed cotton have been known to be stable under higher laundering temperatures, however, the chromophore present in the molecular structure of reactive red might be the reason for a slightly lower fastness value to wet rubbing. Some researchers speculate that certain chromophores are more stable under different temperatures than others (Hauser & Tabba, 2001:117).

The increase in laundering cycles did not seem to affect the colourfastness to rubbing to a great extent. Laundering the reactive red dyed samples for five, ten, twenty, and fifty cycles resulted in fastness values of 4-5 when subjected to dry rubbing tests. Increasing the laundering cycles from five to fifty also did not change the fastness to rubbing observed towards wet rubbing, although the Gray Scale value was slightly lower (GSs=4). Other researchers obtained similar results as was found in this study. They reported fastness values of 4-5 for dry rubbing and 4 when evaluating fastness to wet rubbing. They also noted no change in the fastness value as the laundering cycles increased. (Mohsin *et al.*, 2013:346; Hauser and Tabba, 2001:117; Jang, Ko & Carr, 2001:145).

5.3 Tensile Strength

The maximum load at break and displacement at maximum load statistics for this research was reported in two sets. Analysis 1 was the data of the determined p-values and significance in change of the samples laundered with Catholyte, detergent and filtered water at 40°C or 60°C for five, ten, twenty, or fifty cycles respectively when compared to the untreated samples (control). Analysis 2 was the determined p-values and significance when the different laundering treatments (Catholyte, detergent and filtered water), laundering temperatures (40°C and 60°C), and laundering cycles (five, ten, twenty and fifty) were compared.

5.3.1 Maximum Load at Break

Disperse red dyed polyester

The statistical data obtained for both the analysis of the disperse red dyed polyester samples as a result of laundering treatment, -temperature and number of laundering cycles is depicted in Table 5.9.

Laundering the samples with Catholyte caused the greatest difference, resulting in a decrease in maximum load carried of 27.48N, which is equivalent to a decrease of 6.28%. Laundering the samples with detergent caused a decrease in maximum load carried before break of 25.34N (5.79%). The decrease caused as a result of laundering with these two treatments, did not differ significantly. Laundering with filtered water caused the least decrease in maximum load carried 10.19N (2.33%). The decrease in maximum load carried by the samples when laundered with Catholyte, detergent, and filtered water was not significant when compared to the untreated samples. The decrease caused by laundering with filtered water differed significantly from the effect that detergent and Catholyte had. The fact that the decrease in maximum load carried by the samples when laundered with detergent did not differ significantly from the decrease caused when laundering with Catholyte can be interpreted as favourable results. Jahagirdar and Tiwari (2004:2019) did note a decrease in maximum load

carried of disperse red dyed polyester, although not significant. It could be due to laundering with alkaline media, as Lin and fellow researchers (2002:181) did report that laundering polyester with detergent could increase fibre mobility, which results in slippage and the reduction of fabric strength.

Table 5.9: Difference (relative to control) in maximum load (Newton and %) carried before break and p-values of the disperse red dyed polyester samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		**Analysis 2 (Comparison with resultant p-values)**			
	N	**%**				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	-27.48	-6.28		0.4477	<.0001*	
Detergent	-25.34	-5.79	0.4477			
Filtered Water	-10.19	-2.33	<.0001*	<.0001*	<.0001*	
TEMPERATURE			**40°C**	**60°C**		
40°C	-18.23	-4.17		0.0179*		
60°C	-23.78	-5.44	0.0179*			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	-14.39	-3.29		0.0801	0.0453*	<.0001*
Ten	-20.11	-4.60	0.0801		0.7968	0.0116*
Twenty	-20.95	-4.79	0.0453*	0.7968		0.0225*
Fifty	-28.56	-6.53	<.0001*	0.0116*	0.0225*	

*Statistically significant ($p < 0.05$)

Laundering at 60°C, seems to have caused a greater decrease in maximum load carried by the samples (23.78N) in comparison to laundering at 40°C (18.23N). Although maximum load carried decreased, it was not significant when compared to the untreated samples. When compared, the effect, that the two different temperatures had on the maximum load carried by the reactive red dyed samples, differed significantly from one another. Samanta and fellow researchers (2003:80) also reported disperse red dyed polyester to have a decreased maximum load carried at break when laundering at a higher temperature. However, the decrease in maximum load carried can be attributed to the increase in laundering temperature, combined with the laundering action that can cause damage to the fibres, rather than the dye itself (Laitala, Boks & Klepp, 2011:260; Choi *et al.*, 2004:292).

The maximum load that the samples could carry decreased as the number of laundering cycles increased. It should be noted, that although it decreased, when compared to the untreated samples, it was not a significant decrease. Laundering the disperse red dyed polyester samples for five cycles caused a decrease of 14.39N (3.29%), further decreasing to 20.11N (4.60%) when laundered for ten cycles. Laundering the samples for twenty cycles caused a further reduction of 20.95N (4.79%) in maximum load that the samples could carry before break, leading to a decrease in maximum load carried before break of 28.56N, which is equivalent to a reduction 6.53% after laundering for fifty cycles. The decrease in maximum load carried caused when laundering for five cycles, compared to laundering for ten cycles is not significant. However, the decrease in maximum load carried caused when laundering for twenty and fifty cycles, did differ significantly. This differs from the results and explanation of Huang and co-workers (2010:889) who found that repeated laundering at very high temperatures can be harmful to the strength of disperse dyed polyester, although not as significant at 60°C. Polyester fibres are very hydrophobic, therefore, they absorb only a very small amount of water and there is no significant change in their tensile properties when they are wetted. This contributes to retaining their strength after being subjected to wet treatments such as repeated launderings (Koh, 2011:200).

Acid red dyed polyamide 6,6

Table 5.10 depicts the statistically analysed differences in maximum load carried (N and %) when the acid red dyed polyamide was laundered with Catholyte, detergent and filtered water at 40°C or 60°C for five, ten, twenty and fifty cycles respectively, as well as the comparisons of the variables and p-values.

Laundering the acid red dyed polyamide samples with Catholyte caused the greatest decrease in maximum load carried (33.50N), which is 4.94%. When this reduction is compared to the maximum load the untreated samples could carry, it does not differ significantly. Laundering the samples with filtered water caused the least decrease in maximum load carried before break, 0.52N, which is equivalent to 0.08%, and also not significant. Laundering acid red dyed polyamide with detergent caused an insignificant decrease in maximum load carried before break of 2.02N (0.30%). Comparing the decrease in maximum load caused by laundering with Catholyte, with the decrease caused as a result of laundering with detergent and filtered water, it differed significantly. Although the decrease in maximum load carried before break due to laundering with detergent and filtered water, did not differ significantly when compared. Laundering the acid red dyed polyamide samples with Catholyte, detergent and filtered water did not cause a significant decrease in maximum load carried before break, when compared to the untreated samples. Polyamide is a crystalline fibre and the fibre swells very little when immersed in water, therefore, it is relatively stable in water at temperatures up to boiling point (Burkinshaw, 1995:79). Textiles made from these fibres are resistant to alkalis (Collier & Tortora, 2001:172). Due to the inherent substantivity of acid dyes towards polyamide fibres, no significant decrease in tensile strength have been reported as a result of dyeing the textile with acid dyes (Kiumarsi & Parvinzadeh, 2010:3145). Therefore, it can be concluded that the slight decrease caused was as a result of the mechanical action during laundering. Van Heerden (2010:115) also reported that Catholyte caused a greater decrease in maximum load carried than laundering with detergent. This could possibly be due to an unknown interaction between the constituents in the Catholyte and the polyamide polymer.

Table 5.10: Difference (relative to control) in maximum load (Newton and %) carried before break and p-values of the acid red dyed polyamide samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		Analysis 2 (Comparison with resultant p-values)			
	N	**%**				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	-33.50	-4.94		<.0001*	<.0001*	
Detergent	-2.02	-0.30	<.0001*		0.8183	
Filtered Water	-0.52	-0.08	<.0001*	0.8183		
TEMPERATURE			**40°C**	**60°C**		
40°C	-8.52	-1.26		0.1908		
60°C	-15.51	-2.29	0.1908			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	-6.73	-0.99		0.8381	0.5565	0.0460*
Ten	-8.27	-1.22	0.8381		0.0725	0.1562
Twenty	-11.16	-1.65	0.5565	0.0725		0.7010
Fifty	-21.88	-3.23	0.0460*	0.1562	0.7010	

*Statistically significant ($p < 0.05$)

The decrease in maximum load carried before break when the samples were laundered at 40°C did not differ significantly from the decrease caused when laundering the samples at 60°C. Laundering at 40°C caused a decrease in maximum load carried before break of the samples of 8.52N (1.26%), whereas laundering at the higher temperature caused a decrease of 15.51 N, which is equivalent to 2.29%. Researchers in other studies also observed a slight decrease in maximum load carried by polyamide when the

temperature was increased (Usluoglu & Arabaci, 2014:366; Laitala, Boks & Klepp, 2011:260). The fact that the increase in temperature did not have a significant influence on the maximum load carried by the fabric, as well as the insignificant difference between the effect of the two temperatures attests to the stability of acid red dyed polyamide under laundering conditions (Ingamells, 1993:80).

The maximum load the samples could carry before break decreased as the number of laundering cycles increased. Although these decreases were not significant when compared to the untreated samples, laundering for fifty cycles resulted in a decrease of 21.88N (3.23%), which differed significantly from the decrease observed when the samples were laundered for five cycles, 6.73N (0.99%). The difference in decrease of maximum load caused when laundering for ten, twenty, and fifty cycles did not differ significantly when compared to one another. Lipus, Ačko and Neral (2013:378) observed a slight decrease in tensile strength with repeated laundering of polyamide. They attributed the findings to some mechanical damage as a result of the agitation and friction during the laundering procedure, rather than the degradation of the textile due to the dyeing procedure or inherent weakness.

Azoic orange dyed cotton

The statistical data obtained for both the analysis of the azoic orange dyed cotton samples as a result of laundering with Catholyte, detergent and filtered water at 40°C or 60°C for five, ten, twenty and fifty cycles is depicted in Table 5.11.

It is evident that laundering with Catholyte caused the least decrease in maximum load before break carried by the samples, although still a significant reduction of 140.60N (9.20%). Laundering with detergent caused the greatest decrease in maximum load carried before break by the samples, of 168.58N (11.03%). Filtered water caused a decrease in maximum load carried before break of 144.23N (9.44%). When the decrease caused by laundering with Catholyte is compared to the decrease caused by laundering with filtered water, it was not significant. However, the decrease that laundering with detergent caused differed significantly from the decrease in maximum load carried

Table 5.11: Difference (relative to control) in maximum load (Newton and %) carried before break and p-values of the azoic orange dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		Analysis 2 (Comparison with resultant p-values)			
	N	**%**				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	-140.60*	-9.20		0.0214*	0.7631	
Detergent	-168.58*	-11.03	0.0214*		0.0446*	
Filtered Water	-144.23*	-9.44	0.7631	0.0446*		
TEMPERATURE			**40°C**	**60°C**		
40°C	-139.19*	-9.11		0.0162*		
60°C	-163.08*	-10.67	0.0162*			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	-118.72*	-7.77		0.0130*	0.0078*	<.0001*
Ten	-153.67*	-10.06	0.0130*		0.1100	0.8555
Twenty	-156.19*	-10.22	0.0078*	0.1100		0.1560
Fifty	-175.97*	-11.52	<.0001*	0.8555	0.1560	

*Statistically significant ($p < 0.05$)

before break that laundering with either Catholyte or filtered water caused. Literature differs on the effect that laundering treatments have on azoic dyed cotton. However, the significant decrease in maximum load carried by the samples could be attributed to the gradual degradation of fibres along the spiral plane contributes to the initial tensile strength loss and once the fissures reach the lumen, further degradation in strength can occur rapidly (Saravanan, Vasanthi & Ramachandran, 2009:5). Azoic dyes applied on

cotton have not been known to have an influence on the tensile properties, as the molecules are trapped within the fibre. Any weakening of the fabric may be attributed to the inherent fibre properties or other after treatment processes, for example, crease resistant finishes or cationic cross-linking (Choudhury, 2006:601). The decrease in maximum load carried before break caused when the samples were laundered with Catholyte was less than the decrease caused due to laundering with detergent. Thus, it can be safely concluded that Catholyte is suitable to be used to launder azoic orange dyed cotton.

When compared to the untreated samples, the temperature caused a significant decrease in maximum load that the azoic orange dyed cotton samples could carry. The decrease caused, as a result of laundering at 40°C and 60°C differed significantly when compared. Laundering at 40°C caused a decrease of 139.19N, which is equivalent to a decrease of 9.11% in maximum load carried, whereas laundering at 60°C, caused a reduction of 163.08N (10.67%) in maximum load carried before break. Although the increase in temperature did cause a significant decrease in maximum load carried before break, it was not more than the decrease caused as a result of laundering with Catholyte, detergent and filtered water. Therefore it can be concluded that the initial decrease can be attributed to the degradation of the fibres along the spiral plane, and that the increase in temperature have caused degradation but not more so than the treatments (Kothari, Ishtiaque & Ogale, 2002:50).

Laundering the azoic orange dyed cotton for five, ten, twenty or fifty cycles caused a significant progressive decrease in maximum load carried by the samples as the number of laundering cycles increased. The initial decrease in maximum load carried before break after laundering for five cycles was 118.72N (7.77%), which increased to 153.67N (10.06%) after laundering for ten cycles. Laundering the azoic orange dyed samples for twenty cycles resulted in a decrease in maximum load carried of 156.19N (10.22%). Subjecting the samples to fifty laundering samples resulted in the greatest decrease in maximum load carried (175.97N; 11.52%). When comparing the decrease caused after laundering for five cycles, to the decrease caused as a result of laundering for ten, twenty and fifty cycles, it was significantly different. However, the difference between laundering for ten, twenty or fifty cycles did not differ significantly. Lipus, Ačko and

Neral (2013:378) did observe major mechanical damage to cotton textiles which was laundered for more than 25 cycles. The damage adversely affected the tensile strength, causing a significant decrease. Kim and Jeon (2013:108) concluded that azoic colorants used to dye cotton fabric do not cause a weakening in the fibre structure.

Direct red dyed cotton

The statistical data obtained for both analysis when the direct red dyed cotton was laundered with Catholyte, detergent and filtered water at 40°C or 60°C for five, ten, twenty and fifty cycles is given in Table 5.12.

From Table 5.12, it can be seen that laundering the direct red dyed cotton samples with Catholyte caused the least decrease in maximum load carried before break, causing a decrease of 88.27N (10.92%). Laundering with both detergent and filtered water caused a decrease of 12.59%, which is equivalent to 101.76N and 101.79N, respectively. When compared to the untreated cotton the decreases in maximum load carried before break was significant, however, the decrease caused by each treatment (Catholyte, detergent, filtered water) did not differ significantly from another. It was concluded by Singha (2013:4) that a higher alkali concentration and temperature can cause higher loss in strength if reactivity is low, which is the case with direct dyes. From the different treatments Catholyte had the highest alkalinity (pH=$\geq$11 and $\leq$12), therefore it is unexpected that laundering with Catholyte caused the least decrease in maximum load carried, although considered as a positive result in the current research. A full explanation eludes the researcher.

With an increase in temperature, the maximum load carried by the samples decreased significantly when compared to the unlaundered samples. Laundering at 40°C caused a significant decrease of 87.85N (10.87%), and laundering at 60°C caused a decrease of 106.70N (13.20%). Comparing the decrease in maximum load carried when the samples were laundered at 40°C and the decrease caused when laundering at 60°C, the difference in decrease was not significant. As mentioned previously the forces of interaction that operate between direct dyes and cotton fibres are predominantly van

der Waal's forces (Burkinshaw, 1995:130). Doh (2004:25) observed that the higher temperature causing the Van der Waal's forces to weaken could disrupt the system, affecting the crystallinity of the fibres. This might be the cause of the decrease in maximum load carried at the higher temperature.

Table 5.12: Difference (relative to control) in maximum load (Newton and %) carried before break and p-values of the direct red dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		**Analysis 2 (Comparison with resultant p-values)**			
	N	**%**				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	-88.27*	-10.92		0.2872	0.2892	
Detergent	-101.76*	-12.59	0.2872		0.9984	
Filtered Water	-101.79*	-12.59	0.2892	0.9984		
TEMPERATURE			**40°C**	**60°C**		
40°C	-87.85*	-10.87		0.0710		
60°C	-106.70*	-13.20	0.0710			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	-73.32*	-9.07		0.6663	0.0673	<.0001*
Ten	-79.67*	-9.86	0.0673		0.1644	<.0001*
Twenty	-100.23*	-12.40	0.1644	0.1644		0.0159*
Fifty	-135.89*	-16.81	0.0002*	<.0001*	0.0159*	

*Statistically significant ($p < 0.05$)

The increase in number of laundering cycles caused a continual significant decrease in maximum load that the samples could carry before break. The decrease in maximum load carried was initially 73.32N (9.07%) after laundering for five cycles, but increased

to 79.67N (9.86%) after laundering for twenty cycles. Laundering the direct red dyed cotton samples for twenty cycles caused a significant decrease in maximum load carried of 100.23N (12.40%), which further decreased to 135.89N (16.81%) after laundering for fifty cycles. The decrease in maximum load carried caused as a result of laundering for fifty cycles, was significantly more than the decrease caused when laundering the samples for five, ten or twenty cycles. However, the difference between the maximum load carried before break after five, ten and twenty cycles did not differ significantly. Laundering direct dyed cotton for prolonged periods can cause a significant decrease in tensile properties (Abdel-Mohsen *et al.*, 2012:114). This can be attributed to the degradation of fibres along the spiral plane, contributing to tensile strength loss. Once the fissures reach the lumen, further degradation in strength occurs rapidly (Saravanan, Vasanthi & Ramachandran, 2009:5), which explains the significant decrease in maximum load carried after laundering for fifty cycles.

Reactive red dyed cotton

From Table 5.13 (depicting the statistically analysed difference in means) it can be seen that laundering with filtered water caused the least decrease in maximum load carried before break of the samples, only decreasing 26.66N (3.46%), which was also not significant when compared to the maximum load carried by the untreated samples.

Laundering the reactive red dyed cotton with detergent seems to have caused a decrease in maximum load carried of 33.98N (4.41%). Laundering with Catholyte caused a significant decrease of 52.59N (6.83%). The decrease in maximum load caused as a result of laundering with both detergent and filtered water did not differ significantly when compared. However, the decrease in maximum load before break carried by the samples when laundered with Catholyte was significantly different when compared to both filtered water and detergent. Laundering the cotton at a higher pH (Catholyte) might have caused greater loss in tensile strength due to the degree of orientation and rearrangement, which was lessened as a result of exposure to the high alkali. As alkalis generally do not harm cotton it might be concluded that the cellulose behaves as a polyhydric alcohol and most reactive dyes react with it only under alkaline condition

(Slater, 2003:81). Therefore, the very high pH, could have triggered an unfavourable reaction leading to Catholyte causing a greater decrease in maximum load carried as opposed to laundering with detergent or filtered water. It should be noted that the decrease, however, was still less than 10%.

Table 5.13: Difference (relative to control) in maximum load (Newton and %) carried before break and p-values of the reactive red dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		**Analysis 2 (Comparison with resultant p-values)**			
	N	**%**				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	-52.59*	-6.83		0.0059*	0.0002*	
Detergent	-33.98	-4.41	0.0059*		0.2749	
Filtered Water	-26.66	-3.46	0.0002*	0.2749		
TEMPERATURE			**40°C**	**60°C**		
40°C	-32.14	-4.17		0.0416*		
60°C	-43.35	-5.63	0.0416*			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	-11.16	-1.45		0.0500	<.0001*	<.0001*
Ten	-26.45	-3.43	0.0500		0.0021*	<.0001*
Twenty	-50.79	-6.60	<.0001*	0.0021*		0.1265
Fifty	-62.58	-8.13	<.0001*	<.0001*	0.1265	

*Statistically significant ($p < 0.05$)

The maximum load, that the samples could carry after laundering at 40°C, when compared to the maximum load carried after laundering at 60°C was statistically

significantly different. Laundering at the higher temperate causing a greater decrease in maximum load carried by the reactive red dyed samples of 43.35N (5.63%) when compared to laundering the samples at 40°C, which caused a decrease in maximum load carried of 32.14N (4.17%), which is a significant difference. The maximum load carried before break was not significantly lower when compared to the untreated samples, as the decreases were less than 10%. It was most likely due to changes in the fibres of the textiles as a result of mechanical damage during laundering at a higher temperature, rather than weakening caused by the dyestuff itself (Was-Gubala, 2009:165). This conclusion is drawn from the fact that reactive dye is held in place by the fibre as long as the covalent bond is intact. These bonds are generally stable under higher temperatures (Choudhury, 2006:516).

Increasing the number of laundering cycles, lead to a continual decrease in maximum load carried before break by the samples, although not significant. After five laundering cycles the maximum load decreased with 11.16N (1.45%). An increase in the number of laundering cycles to ten resulted in the maximum load further decreasing with 26.45N (3.43%), and reaching a decrease of 50.79N after laundering for twenty cycles. After fifty laundering cycles, the maximum load decreased with 62.58N (8.13%). The decrease in maximum load carried after five cycles did not differ significantly from the decrease caused after laundering for ten cycles. There was a significant difference in decrease caused after laundering for five cycles when compared to twenty and fifty cycles. Doyal and Warnock (2005:264) reported a decrease in tensile strength as the number of laundering cycles increased, although not significant. They found that it was most probably due to mechanical degradation of the cotton polymer because of prolonged exposure to wet treatments.

5.3.2 Displacement at Maximum Load

Disperse red dyed polyester

The displacement at maximum load of the disperse red polyester samples as a result of laundering with Catholyte, detergent and filtered water at 40°C or 60°C for five, ten, twenty or fifty cycles are depicted in Table 5.14.

Laundering the samples with Catholyte and detergent caused a significant increase in displacement at maximum load. Laundering with Catholyte, caused the greatest increase in displacement (0.08%), whereas laundering with detergent caused the less displacement (0.06%). Laundering the disperse red dyed polyester with filtered water caused an increase in displacement of 0.01%, which was insignificant. Comparing the displacement caused by all the treatments, the comparisons differed significantly.

Laundering at 60°C caused significantly greater displacement of 0.09% as opposed to the insignificant increase in displacement (0.01%) when the disperse red polyester was laundered at 40°C. Consequently, the displacement caused when laundering at 40°C and laundering at 60°C was compared, differed significantly.

As the number of laundering cycles increased, the displacement at maximum load increased as well. The displacement increased significantly after laundering for five (0.03%), ten (0.05%), twenty (0.05%) and fifty (0.07%) cycles. The displacement caused after laundering for five cycles was significantly different from the displacement caused after laundering for twenty and fifty cycles, although not statistically different from laundering for ten cycles. No significant difference in displacement caused was found when laundering for ten, twenty and fifty cycles were compared.

Lin and fellow researchers (2008:181) and Jahagirdar and Tiwari (2004:2019) found significant increases in displacement at maximum load when disperse red dyed polyester was laundered. This occurrence might be attributed to the amorphous areas present in the polyester matrix, and as the fabric was stretched, the areas became less amorphous contributing to the increase of displacement at maximum load (Samanta *et*

al., 2003:79). The displacement can be correlated to the decrease in maximum load carried by the samples before break which was discussed in the previous section.

Table 5.14: Difference (relative to control) in displacement at maximum load (% and mm) and p-values of the disperse red dyed polyester samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		Analysis 2 (Comparison with resultant p-values)			
	%	mm				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	0.08*	3.81		0.0170*	<.0001*	
Detergent	0.06*	2.92	0.0170*		<.0001*	
Filtered Water	0.01	0.60	<.0001*	<.0001*		
TEMPERATURE			**40°C**	**60°C**		
40°C	0.01	0.26		<.0001*		
60°C	0.09*	4.63	<.0001*			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	0.03*	1.58		0.0112*	0.1161	0.0002*
Ten	0.05*	2.25	0.0112*		0.3216	0.0215
Twenty	0.05*	2.68	0.1161	0.3216		0.1783
Fifty	0.07*	3.27	0.0002*	0.0215	0.1783	

*Statistically significant ($p < 0.05$)

Acid red dyed polyamide 6,6

The difference (relative to control) in displacement at maximum load (% and mm) and p-values of the acid red dyed polyamide samples as a result of laundering treatment,

-temperature and number of laundering cycles are depicted in Table 5.15. Three decimal places after the comma was used in this Table, as the changes were minuscule.

Table 5.15: Difference (relative to control) in displacement at maximum load (% and mm) and p-values of the acid red dyed polyamide samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		Analysis 2 (Comparison with resultant p-values)			
	%	mm				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	0.028	5.56		0.0001*	<.0001*	
Detergent	0.001	0.21	0.0001*		0.0087*	
Filtered Water	0.021	4.13	<.0001*	0.0087*		
TEMPERATURE			**40°C**	**60°C**		
40°C	0.002	0.40		0.1804		
60°C	0.006	1.22	0.1804			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	0.002	0.31		0.2815	0.6717	0.8056
Ten	0.002	0.41	0.2815		0.0821	0.1345
Twenty	0.004	0.72	0.6717	0.0821		0.5033
Fifty	0.011	2.25	0.8056	0.1345	0.5033	

*Statistically significant ($p < 0.05$)

Laundering the acid red dyed polyamide samples with Catholyte, detergent or filtered water did not cause a significant increase in displacement at maximum load. Laundering the samples with detergent caused an increase of 0.001%, which is negligible. Laundering the polyamide with Catholyte and filtered water resulted in displacement at

maximum load of 0.028% and 0.021% respectively. The displacement caused by laundering with either of the treatments differed significantly when compared.

Laundering the polyamide samples at 40°C caused an increase in displacement at maximum load of the fabric of 0.002%. Whilst laundering at the higher temperature caused displacement at maximum load of 0.006%. The effect, which the temperature had on the displacement, was significant when the pair is compared.

The displacement at maximum load increased as the number of laundering cycles increased. After laundering for fifty cycles, the displacement at maximum load was 0.011%, which is not significant. Comparisons made between the displacement at maximum load as a result of laundering at five, ten, twenty and fifty cycles did not differ significantly when compared.

The elongation at break for the polyamide fabric is correlated to the amorphous orientation of the fibre. If the fibre is drawn to a higher degree in order to manufacture a stronger fibre, there are less amorphous parts in the fibre but more crystalline parts. The higher number of crystalline parts lowers the elongation of the fibre (Usluoglu & Arabaci, 2014:366). This is the most probable explanation for the insignificant increase in displacement at maximum load observed for the acid red dye polyamide samples. The displacement at maximum load can be proportionately correlated to the maximum load carried before break of the textile fabric, which was explained in section 5.3.1 of this chapter.

Azoic orange dyed cotton

The difference (relative to control) in displacement at maximum load (% and mm) and p-values of the azoic orange dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles are depicted in Table 5.16.

Laundering azoic orange dyed cotton with Catholyte caused the least increase in displacement at maximum load (0.05%), although significant. Laundering with filtered water and detergent caused similar displacement at maximum load (0.06%). When the

displacement caused as a result of laundering with Catholyte is compared to the displacement caused when laundering with filtered water it was not significant. However, laundering with Catholyte did cause significantly less displacement when compared to the displacement caused when laundering with detergent.

Increasing the temperature did not seem to cause a significant increase in the displacement at maximum load. Displacement for laundering at both 40°C and 60°C was 0.06%.

Table 5.16: Difference (relative to control) in displacement at maximum load (% and mm) and p-values of the azoic orange dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		**Analysis 2 (Comparison with resultant p-values)**			
	%	**mm**				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	0.05*	10.95		<.0001*	0.7100	
Detergent	0.06*	12.64	<.0001*		<.0001*	
Filtered Water	0.06*	11.01	0.7100	<.0001*		
TEMPERATURE			**40°C**	**60°C**		
40°C	0.06*	11.46		0.2929		
60°C	0.06*	11.61	0.2929			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	0.05*	9.33		<.0001*	<.0001*	<.0001*
Ten	0.05*	10.80	<.0001*		<.0001*	<.0001*
Twenty	0.06*	12.02	<.0001*	<.0001*		<.0001*
Fifty	0.07*	13.98	<.0001*	<.0001*	<.0001*	

*Statistically significant ($p < 0.05$)

It is evident from Table 5.16 that increasing the number of laundering cycles caused a significant increase in the displacement at maximum load of the azoic orange dyed cotton samples. Laundering for five and ten cycles increased the displacement to 0.05%. Increasing the number of cycles to twenty increased the displacement to 0.06% and laundering the samples for fifty cycles, caused the displacement at maximum load of 0.07%. The displacement at maximum load each number of laundering cycles caused was significantly different when compared to any of the other number of laundering cycles.

The results discussed above are proportionate to the maximum load carried before break of the same samples discussed earlier in this chapter.

Direct red dyed cotton

The difference (relative to control) in displacement at maximum load (% and mm) and the statistically compared p-values of the direct red dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles are depicted in Table 5.17.

Laundering the direct red dyed cotton samples with Catholyte, detergent and filtered water resulted in similar results with regards to displacement at maximum load. Laundering with each of these treatments caused displacement at maximum load of the yarns to be 0.06%, which according to the statistical analysis, is significant. Consequently, the effect, that the different treatments had on the displacement at maximum load, was also not significant when compared pairwise.

The effect, that both temperatures had, was significant, although not differing from one another significantly. Thus increasing the temperature did not seem to have an effect on the displacement, resulting in displacement at maximum load of 0.06%.

Increasing the number of laundering samples caused a significant increase in displacement at maximum load. Initially after laundering for five cycles, the displacement at maximum load was 0.05%. After laundering for ten cycles, the

displacement increased to 0.06%, further increasing to 0.07% after laundering for twenty cycles. When the direct red dyed cotton samples were laundered for fifty cycles, the displacement at maximum load increased with a significant 0.08%. Comparisons made between all the number of laundering cycles indicates that each number of cycles caused a significantly different increase when compared to any of the other number of cycles.

Table 5.17: Difference (relative to control) in displacement at maximum load (% and mm) and compared p-values of the direct red dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		**Analysis 2 (Comparison with resultant p-values)**			
	%	**mm**				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	0.06*	12.71		0.7909	0.6283	
Detergent	0.06*	12.62	0.7909		0.8252	
Filtered Water	0.06*	12.54	0.6283	0.8252		
TEMPERATURE			**40°C**	**60°C**		
40°C	0.06*	12.27		0.0150*		
60°C	0.06*	12.98	0.0150*			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	0.05*	9.96		0.0002*	<.0001*	<.0001*
Ten	0.06*	11.57	0.0002*		<.0001*	<.0001*
Twenty	0.07*	13.45	<.0001*	<.0001*		<.0001*
Fifty	0.08*	15.52	<.0001*	<.0001*	<.0001*	

*Statistically significant ($p < 0.05$)

Moreover, the results obtained for displacement at maximum load for the direct red dyed cotton samples are correlated to the results obtained when the maximum load carried at break was evaluated (explained and discussed in section 5.3.1).

Reactive red dyed cotton

The displacement at maximum load of the reactive red dyed cotton as a result of laundering with Catholyte, detergent and filtered water at 40°C or 60°C for five, ten, twenty or fifty cycles are depicted in Table 5.18.

Laundering with Catholyte, detergent and filtered water lead to similar results when the displacement at maximum load was evaluated. Irrespective of the laundering treatment the reactive red dyed cotton was subjected to, the displacement at maximum load exhibited a significant increase of 0.06%. The increase in maximum load of each treatment did not differ significantly when compared to the increase caused by laundering with the other treatments.

The increase in displacement at maximum load caused as a result of laundering at both 40°C and 60°C, was statistically significant (0.06%), although not differing significantly when compared. Increasing the temperature did not seem to have an adverse effect on the displacement at maximum load.

Increasing the number of laundering samples caused a significant increase in displacement at maximum load. The displacement at maximum load increasing from 0.05%, after laundering for five and ten cycles, to 0.06% after laundering for twenty cycles and peaking at 0.07% after laundering for fifty cycles. Each number of cycles resulting in a significant increase in displacement at maximum load, when compared to increase caused by any of the other number of laundering cycles.

These results are proportionately comparable to the maximum load carried at break of the laundered reactive red dyed cotton, discussed in 5.3.1.

Table 5.18: Difference (relative to control) in displacement at maximum load (% and mm) and p-values of the reactive red dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		Analysis 2 (Comparison with resultant p-values)			
	%	mm				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	0.06*	11.95		0.5688	0.1914	
Detergent	0.06*	11.76	0.5688		0.4571	
Filtered Water	0.06*	11.50	0.1914	0.4571		
TEMPERATURE			**40°C**	**60°C**		
40°C	0.06*	11.69		0.7473		
60°C	0.06*	11.78	0.7473			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	0.05*	9.43		0.0107*	<.0001*	<.0001*
Ten	0.05*	10.47	0.0107*		<.0001*	<.0001*
Twenty	0.06*	12.76	<.0001*	<.0001*		0.0003*
Fifty	0.07*	14.28	<.0001*	<.0001*	0.0003*	

*Statistically significant ($p < 0.05$)

The azoic orange, direct and reactive red dyed cotton exhibited similar behaviour, hence the same conclusion can be drawn for these three textiles. Moreover, it was proved in the previous discussion that decrease in tensile strength was not as a direct result of the dyestuff used, rather as a function of the textile. Literature indicates that displacement at maximum load can be expected to increase when subjected to laundering treatments. It could be due to formation of any surface resin, as a result of impurities in the treatments, and fills the gaps between the threads and prevents the movement of the

yarns and fibres, resulting in only a slight increase in displacement at maximum load. Furthermore, the mechanical properties of textile fibres depend not only on the degree of crystallinity of fibres but also on the various secondary valency forces that operate in the polymer. It can be concluded that the resistance power to deform the material with higher interchain bonds was not influenced. Consequently, also causing the fibres not to be displaced to a great extent under stress (Yu *et al.*, 2014:4; Sun & Stylios, 2012:1055; Samanta *et al.*, 2004:229).

CHAPTER 6

COLOURFASTNESS AND TENSILE STRENGTH OF REACTIVE DYED COTTON LAUNDERED WITH CATHOLYTE, DETERGENT AND FILTERED WATER

6.1 Introduction

Cotton is a dominant textile fibre that is used extensively worldwide, with a share of 50% in total fibre consumption (Ali *et al.*, 2015:271). The colourfastness of textiles is a very important consideration for consumers (Alam *et al.*, 2008:58). Cotton is predominantly dyed with reactive dyes, because it produces bright colours with excellent colourfastness to laundering (Elsasser, 2010:204). These dyes are also extensively used in the textile industry (Rizk, Ibrahim & El-Borai, 2015:86), because it is ideal for products, which are often dyed to heavy depths of shade and are likely to be frequently washed (Mather & Wardman, 2011:38).

As chromophores (colour bearing part) present in the reactive dye molecules differ as different colours are combined (Farrell *et al.*, 2011:89), it would be interesting to evaluate what behaviour the different coloured dyes exhibits when laundered, especially with Catholyte. Thus, reactive blue, violet, and green dyed cotton was used in this section. Blue is a primary colour, and therefore is considered a pure colour (Choudhury, 2006:260). Both violet and green are combined colours, and consequently are not regarded as pure. In the following discussion the colourfastness (wash fastness, staining, colourfastness to rubbing – both wet and dry) and tensile strength (maximum load at break and displacement at maximum load) of reactive blue, violet and green dyed cotton will be evaluated and discussed.

6.2 Colourfastness

In chapters 4 and 5 of this research project, it was explained that the ΔE differences were calculated and converted to Gray scale ratings, in order to be comparable with results observed in other research studies. Because differences in ΔE values indicate overall colour change and do not differentiate between strength, saturation, and shade changes, the individual colorimetric parameters, L*, a* and b* were also reported and discussed where applicable. These individual parameters were measured instrumentally with a spectrophotometer. Additionally, the colour strength (K/S values) at a single wavelength was determined for the dyed textile fabrics to facilitate the discussion on colour change.

6.2.1 Wash fastness

6.2.1.1 Colour Change

Reactive blue dyed cotton

The reactive blue dyed cotton samples were laundered with Catholyte, detergent and filtered water for five, ten, twenty, or fifty cycles at 40°C or 60°C respectively. The measured colorimetric data (L*, a*, b*) before and after laundering, colour strength (K/S values), the statistically analysed differences, as well as the Gray scale values are depicted in Table 6.1.

It seems that laundering the reactive blue dyed cotton with filtered water resulted in the greatest overall colour change (ΔE=-0.83), although the colour strength did not seem to be affected (K/S=0.00) greatly. Laundering the samples with Catholyte resulted in a moderate difference in colour change of -0.24, and an insignificant decrease in colour strength of -0.02. Laundering the samples with detergent caused the greatest decrease in colour strength (K/S=-0.03) and the least difference in colour change (ΔE=-0.09). It

Table 6.1: Colorimetric data, colourstrength (K/S) and Gray Scale values of reactive blue dyed cotton as a result of change caused by laundering treatment, -temperature and number of laundering cycles.

	Before					After					(Difference : After – Before)					
	L*	a*	b*	ΔE	K\S Value	L*	a*	b*	ΔE	K\S Value	ΔL*	Δa*	Δb*	ΔE	K\S Value	Gray Scale Value
TREATMENT																
Catholyte	62.99	-33.67	-29.38	77.26	0.28	63.41	-33.13	-28.50	77.02	0.26	0.42*	0.58*	0.88*	-0.24*	-0.02	4-5
Detergent	62.95	-34.03	-29.44	77.38	0.28	63.47	-33.56	-28.62	77.29	0.25	0.52*	0.47*	0.82*	-0.09*	-0.03*	4-5
Filtered Water	62.91	-33.99	-29.44	77.33	0.28	62.53	-33.22	-28.96	76.50	0.28	-0.38*	0.77*	0.47*	-0.83*	0.00	4-5
TEMPERATURE																
40°C	62.99	-34.03	-29.40	77.32	0.28	62.92	-33.30	-28.75	76.78	0.27	-0.07	0.73*	0.65*	-0.54*	-0.01	4-5
60°C	62.91	-33.76	-29.44	77.33	0.28	63.35	-33.31	-28.64	77.09	0.26	0.44*	0.46*	0.80*	-0.24*	-0.02*	4-5
CYCLES																
Five	63.05	-33.99	-29.38	77.26	0.28	62.79	-33.54	-28.92	76.84	0.27	-0.27	0.45*	0.46*	-0.42*	-0.01	4-5
Ten	62.94	-34.04	-29.39	77.36	0.28	62.93	-33.52	-28.83	76.91	0.27	-0.01	0.52*	0.56*	-0.45*	-0.01	4-5
Twenty	62.97	-34.01	-29.39	77.37	0.28	63.15	-33.30	-28.79	76.98	0.26	0.18*	0.71*	0.60*	-0.39*	-0.02*	4-5
Fifty	62.83	-33.56	-29.51	77.30	0.28	63.67	-32.86	-28.23	77.02	0.25	0.84*	0.70*	1.28*	-0.28*	-0.03*	4-5

*Statistically significant ($p < 0.05$)

is evident that laundering with either Catholyte, detergent or filtered water resulted in excellent wash fastness (GSc=4-5). It is also apparent that laundering with Catholyte and detergent caused a significant increase in lightness (ΔL*=0.42 & 0.52 respectively), whereas laundering with filtered water caused a decrease in lightness (ΔL*=-0.38). Shifts towards the red colour space were observed for all the treatments, more so when laundering with filtered water (Δa*=0.77), than laundering with Catholyte (Δa*=0.58) and detergent (Δa*=0.47). As some of the unfixed blue dye was washed off, the samples subsequently became yellower (+Δb*) when laundered with all the treatments. From these results, it can be concluded that Catholyte did not cause a significant decrease in colour strength and resulted in excellent wash fastness results when used to launder reactive blue dyed cotton.

The fact that reactive dyes are highly water soluble (Epolitio *et al.*, 2005:35), might be an explanation for the filtered water causing greater overall change in colour and decrease in lightness. Initial wash-off of unfixed dye also contributes to duller fabrics. The decrease in lightness rendered the samples duller, although the inherent colour strength remained unchanged when laundered with filtered water. Burkinshaw and co-workers (2000:266) also reported greater colour change in cotton dyed with reactive blue in the absence of a washing agent. The samples became lighter when laundered with detergent and Catholyte, which might be due to initial unfixed dye being washed off by the alkaline media (Ali *et al.*, 2015:277). It can also serve as an explanation as to why the filtered water caused a decrease in lightness and the alkaline wash liquors an increase. Wash-off contributes to lighter samples rather than rendering it duller. The samples were thus brighter, and slightly less blue after laundering with these wash liquors.

Although the difference in overall colour change was greater when laundering at 40°C (ΔE=-0.54) than at 60°C (ΔE=-0.24), both these changes were significant, although exhibiting excellent wash fastness (GSc=4-5). The colour strength decreased as the laundering temperature increased, only decreasing significantly when laundering at 60°C (K/S=-0.02). Laundering at the lower temperature resulted in an insignificant decrease in lightness (ΔL*-0.07), whereas laundering at the higher temperature contributed to a significant increase in lightness (ΔL*=0.44). Interestingly the samples

shifted towards the red colour space after laundering at 40°C (Δa*=0.73), but shifted slightly towards the green colour space after laundering at 60°C (Δa*=0.46). The samples continued to become more yellow (+Δb*) as the temperature increased.

The fact that wash fastness did not decrease considerably as a result of laundering at a higher temperature, attests to the nature of the covalent bonds of reactive dyes being able to withstand repeated laundering at higher temperatures (Farrell *et al.*, 2011:9). The most probable explanation for the anomaly regarding the slight shift towards the green colour space when laundering at the higher temperature, could be that the interactions between the higher temperature and the washing liquor had a different influence on the dyed cotton than the lower temperature. Ahmed (2005:225) reported a slight decrease in colour strength as the laundering temperature increased, however, the Gray Scale values remained 4-5 indicating excellent wash fastness. These findings are comparable with results observed in this study.

According to Table 6.1, it seems that the difference in overall colour changed significantly after laundering for five (ΔE=-0.42) and ten (ΔE=-0.45) cycles, but less when laundering for twenty (ΔE=-0.39) and fifty (ΔE=-0.28) cycles, although still significant. This is a result of the calculated ΔE value being adversely affected by the lightness indicator. It is apparent that the lightness initially decreased after laundering for five cycles (ΔL*=-0.27), but continually increased after laundering for ten (ΔL*=-0.01), twenty (ΔL*=0.18) and fifty cycles (ΔL*=0.84). A slight decrease in colour strength (K/S=-0.01) could be observed after laundering for five and ten cycles, and decreased further after laundering for twenty (K/S=-0.02) and fifty (K/S=-0.03) cycles. The samples shifted more towards the yellow (+Δb*) colour space as the number of laundering cycles increased. The reactive blue dyed cotton samples also became redder (+Δa*) as the number of laundering cycles increased, until reaching fifty laundering cycles. Laundering for fifty cycles resulted in a similar shift towards the red (Δa*=0.70) colour space as laundering for twenty cycles (Δa*=0.71). Regardless of the above-mentioned changes, the wash fastness observed for all the laundering cycles was excellent (GSc=4-5).

The initial decrease in lightness after laundering for five cycles indicates that the samples became duller as the colour strength also decreased. This is probably due to unfixed dye that was removed from the fabric surface, causing the fabric to be duller (Agrawal, 2014:27). However, the samples became lighter and the colour strength decreased, which could indicate that a minuscule amount of the dye could have dissipated from the fibre-dye matrix, resulting in a lighter textile with decreased colour strength. Ali and fellow researchers (2015:277) and Doyal and Warnock (2005:516) reported the wash fastness of reactive blue dyed cotton as 4-5, subjected to repeated laundering.

Reactive violet dyed cotton

The reactive violet dyed cotton was laundered with Catholyte, detergent and filtered water at 40°C and 60°C for five, ten, twenty and fifty cycles. The individual L*, a*, b* and ΔE parameters, as well as the statistically analysed differences, colour strength values and calculated Gray Scale values are depicted in Table 6.2.

From Table 6.2 it can be seen that laundering the reactive violet dyed cotton samples with Catholyte, caused the least colour change (ΔE=-0.16), but a significant decrease in colour strength (K/S=-0.10). Laundering the samples with filtered water caused the greatest colour change (ΔE=-0.76), although only a slight decrease in colour strength (K/S=-0.01). The samples, that were laundered with detergent, resulted in an overall colour change of -0.34 and decrease in colour strength of 0.06. Laundering the samples with Catholyte resulted in an increase in lightness (ΔL*=0.07), whilst laundering with detergent (ΔL*=-0.46) and filtered water (ΔL*=-1.00) caused a decrease in lightness. A significant shift towards red was observed when the samples were laundered with detergent (a*=0.14) and filtered water (a*=0.44), and the samples laundered with Catholyte exhibited a shift towards the green colour space (Δa*=-0.36). The reactive violet dyed cotton laundered with Catholyte and filtered water showed shifts towards the yellow (+Δb*) colour space, although laundering with detergent resulted in a shift towards the blue colour space. Mohsin and co-workers (2013:346) reported the wash fastness of reactive violet dyed cotton to be 4-5. It is apparent that laundering with

Catholyte, detergent and filtered water resulted in excellent fastness to washing, obtaining Gray Scale values of 4-5 for all treatments, which is similar to what Mohsin and co-workers found.

The decrease in lightness caused when laundering with detergent and filtered water resulted in duller samples, which is most likely due to washed-off unfixed dye (Boardman & Jarvis, 2000:63). The fact that Catholyte caused an increase in lightness, might be due to an unfavourable effect that it has on the dye-fibre matrix, which might be enhanced due to the high alkalinity thereof. The different behaviour with regards to the shade changes on the a*- and b*- axis, exhibited by the reactive violet dyed cotton could be as a result of the composition of the dye molecule. This is because the dye is derived from combining different chromophores in its molecular structure in order to obtain a violet colour (Farrell *et al.*, 2011:89; Choudhury, 2006:265). Catholyte caused the greatest decrease in colour strength, which might be attributed to the high alkalinity of the wash liquor compared to that of detergent and filtered water. This conclusion is drawn based on observations that chromophores are sensitive to alkalis and acids, and therefore will react differently, exhibiting different behaviour (Mohsin *et al.*, 2013:345). Catholyte exhibited wash fastness equivalent to the sample that were laundered with detergent, which can be interpreted as a good result.

Laundering the samples at 40°C resulted in an overall decrease in colour change 0.60 and a decrease in colour strength of 0.05. Increasing the laundering temperatures resulted in a decrease in overall colour change (ΔE=-0.24) and a decrease in colour strength of 0.07. The lightness significantly decreased as a result of laundering at both 40°C (ΔL*=-0.66) and 60°C (ΔL*=-0.26). As the laundering temperature increased the samples shifted towards the red colour space (+Δa*). After initially shifting towards the yellow colour space (Δb*=0.12) when laundered at 40°C, the samples shifted towards the blue colour space (Δb*=0.10) when laundered at 60°C. Insofar as the wash fastness according the Gray Scale, it was excellent (GSc=4-5).

The initial decrease in lightness, which resulted in duller samples, could be as a result of

Table 6.2: Colorimetric data, colourstrength (K/S) and Gray Scale values of reactive violet dyed cotton as a result of change caused by laundering treatment, -temperature and number of laundering cycles.

	Before					After					(Difference : After – Before)					
	L*	a*	b*	ΔE	K\S Value	L*	a*	b*	ΔE	K\S Value	ΔL*	Δa*	Δb*	ΔE	K\S Value	Gray Scale Value
TREATMENT																
Catholyte	59.34	21.77	-22.08	66.96	1.24	59.41	21.41	-21.73	66.80	1.14	0.07	-0.36*	0.34*	-0.16*	-0.10*	4-5
Detergent	59.26	21.89	-22.08	66.92	1.24	58.80	22.03	-22.16	66.59	1.18	-0.46*	0.14*	-0.08*	-0.34*	-0.06*	4-5
Filtered Water	59.43	21.75	-22.04	67.02	1.24	58.43	22.19	-21.96	66.25	1.23	-1.00*	0.44*	0.08*	-0.76*	-0.01	4-5
TEMPERATURE																
40°C	59.36	21.83	-22.05	66.98	1.24	58.70	21.90	-21.93	66.38	1.19	-0.66*	0.07*	0.12*	-0.60*	-0.05*	4-5
60°C	59.33	21.77	-22.08	66.95	1.24	59.06	21.85	-21.98	66.71	1.17	-0.26*	0.08*	0.10*	-0.24*	-0.07*	4-5
CYCLES																
Five	59.38	21.78	-22.06	66.99	1.24	58.62	21.95	-22.04	66.36	1.22	-0.76*	0.17*	0.01	-0.62*	-0.02	4-5
Ten	59.27	21.80	-22.09	66.91	1.24	58.62	22.00	-22.10	66.40	1.21	-0.65*	0.19*	-0.01	-0.51*	-0.03*	4-5
Twenty	59.30	21.84	-22.10	66.95	1.24	58.70	22.05	-22.06	66.48	1.20	-0.60*	0.21*	0.01	-0.47*	-0.04*	4-5
Fifty	59.42	21.79	-22.03	67.01	1.24	59.58	21.50	-21.62	66.94	1.11	0.16	-0.28*	0.41*	0.07	-0.13*	4-5

*Statistically significant ($p < 0.05$)

unfixed dyed washed off. After laundering at the higher temperature, it seems that the lightness increased at the higher temperatures. As discussed previously, the covalent bonds binding the reactive dyes to the fibre substrate are generally stable under laundering conditions and higher temperatures (Choudhury, 2006:260), which is confirmed by the excellent wash fastness values (GSc=4-5) at both temperatures. However, it could be possible that a few of the bonds could have weakened at the higher temperature, and resulted in a very small amount of the dye dissipating from the dye-fibre matrix, causing the increase in lightness (Agrawal, 2014:29). The last mentioned author also found the colour strength of reactive violet cotton to decrease as the temperature increased.

As the number of laundering cycles increased, the colour strength decreased significantly. Laundering the reactive violet cotton for five cycles, resulted in an overall colour change of -0.62 and colour strength decrease of 0.02. Increasing the number of laundering cycles to ten caused a difference in colour change of -0.51 and decrease in colour strength of 0.03. After laundering the samples for twenty cycles, the colour change was -0.47 and the colour strength -0.04. Further increasing the laundering cycles to fifty caused a difference in change of colour of 0.07 and decrease in colour strength of 0.13. It is thus evident that after the initial decrease in colour change, it steadily increased as the number of laundering cycles increased as a result of the change in lightness. The lightness decreased with 0.76 after five laundering cycles, but the difference decreased after laundering for ten (ΔL^*=-0.65), twenty (ΔL^*=-0.60) and fifty (ΔL^*=0.16) cycles. The blueness (Δb^*) parameter remained relatively static until the samples were laundered for fifty cycles, resulting in a significant shift towards the yellow colour space. On the a*-axis the samples initially shifted towards red colour space after five (Δa^*=0.17), ten (Δa^*=0.19) and twenty (Δa^*=0.21) laundering cycles, but shifting significantly towards the green colour space after fifty cycles. Although, there was a decrease in colour strength noted, the wash fastness is considered excellent (GSc=4-5). Mohsin and fellow researchers (2013:346) reported the wash fastness of reactive dyed violet to be 4-5 after multiple laundering cycles.

After laundering for five cycles, the samples became duller, as a result of the decrease in colour strength and lightness. As mentioned previously, this is most likely due to

unfixed dye that was removed from the fabric surface (Agrawal, 2014:27). However, the samples became lighter and the colour strength decreased as the number of laundering cycles increased which might be attributed to a very small amount of the dye that could have dissipated from the fibre-dye matrix.

Reactive green dyed cotton

The reactive green dyed cotton samples were laundered with Catholyte, detergent and filtered water for five, ten, twenty, and fifty cycles at 40°C or 60°C, respectively. The measured colorimetric data (L*, a*, b*) before and after laundering, colour strength (K/S values), the statistically analysed differences, as well as the Gray scale values are depicted in Table 6.3.

Laundering the reactive green dyed cotton samples with Catholyte resulted in a decrease in colour strength of 0.05, and a difference in overall colour change of 0.50. Laundering the samples with detergent caused a colour change of 0.85 and subsequent decrease in colour strength of 0.06. Laundering with filtered water caused a miniscule decrease in colour strength of 0.01 and colour change of 0.85. Laundering the reactive green dyed cotton with filtered water caused a decrease in lightness (ΔL^*=-0.75), whilst laundering with Catholyte (ΔL^*=1.42) and detergent caused a significant increase in lightness (ΔL^*=1.37). The samples laundered with Catholyte and filtered water exhibited shifts towards the red (Δa^*= 0.79 & 0.58 respectively) colour space, whereas laundering with detergent caused a shift towards the green colour space. Shifts towards the yellow colour spaces were observed when the samples were laundered with Catholyte (Δb^*=1.76) and detergent (Δb^*1.50). Laundering the samples with filtered water resulted in a shift towards the blue colour space. The wash fastness values obtained when the reactive green dyed cotton was laundered with Catholyte and detergent was very good (GSc=4) and laundering with filtered water resulted in excellent wash fastness (GSc=4-5).

Table 6.3: Colorimetric data, colourstrength (K/S) and Gray Scale values of reactive green dyed cotton as a result of change caused by laundering treatment, -temperature and number of laundering cycles.

	Before					After					(Difference : After – Before)					
	L*	a*	b*	ΔE	K\S Value	L*	a*	b*	ΔE	K\S Value	ΔL*	Δa*	Δb*	ΔE	K\S Value	Gray Scale Value
TREATMENT																
Catholyte	65.60	-37.03	-16.94	77.21	0.21	67.02	-36.23	-15.18	77.71	0.16	1.42*	0.79*	1.76*	0.50*	-0.05*	4
Detergent	65.59	-36.67	-16.92	77.20	0.21	66.96	-37.00	-15.42	78.06	0.15	1.37*	-0.33*	1.50*	0.85*	-0.06*	4
Filtered Water	65.57	-36.89	-17.18	77.17	0.21	64.82	-36.31	-17.45	76.32	0.20	-0.75*	0.58*	-0.27*	-0.85*	-0.01	4-5
TEMPERATURE																
40°C	65.65	-36.98	-17.17	77.28	0.21	65.82	-36.74	-16.32	77.14	0.18	0.18*	0.24*	0.85*	-0.14*	-0.03*	5
60°C	65.52	-36.74	-16.86	77.11	0.21	66.71	-36.29	-15.71	77.58	0.16	1.19*	0.45*	1.15*	0.47*	-0.05*	4-5
CYCLES																
Five	65.59	-36.94	-16.96	77.16	0.21	65.59	-36.85	-16.59	77.05	0.18	0.00	0.09*	0.37*	-0.12*	-0.03*	5
Ten	65.58	-36.46	-17.01	77.18	0.21	65.89	-36.78	-16.25	77.20	0.17	0.31*	-0.31*	0.76*	0.02	-0.04*	5
Twenty	65.52	-37.08	-17.02	77.19	0.21	66.25	-36.68	-16.06	77.46	0.17	0.73*	0.40*	0.95*	0.27*	-0.04*	4-5
Fifty	65.65	-36.96	-17.07	77.25	0.21	67.34	-35.75	-15.15	77.74	0.16	1.69*	1.20*	1.91*	0.49*	-0.05*	4

*Statistically significant ($p < 0.05$)

The decrease in lightness when samples were laundered with filtered water rendered the samples duller, although the inherent colour strength changed little. Burkinshaw and co-workers (2000:266) reported greater colour change in cotton dyed with reactive green in the absence of a washing agent. The samples became lighter when laundered with detergent and Catholyte. Wash-off contributes to lighter samples rather than rendering it duller. The samples were thus brighter, and slightly less green after laundering with these wash liquors, which might be due to initial unfixed dye being washed off by the alkaline media (Ali *et al.*, 2015:277). The different behaviour of the reactive green dyed cotton towards the different wash liquors might be due to the instability of the specific chromophore used in the molecular structure of the dye molecule (Ingamells, 1993:40). Regardless of all the changes that occurred with regards to the colour of the textiles, the wash fastness obtained was good. Chowdhury, Butola and Joshi (2013:237) reported excellent (GSc=4-5) wash fastness of laundered reactive green dyed cotton.

As the temperature increased the colour strength decreased significantly. Laundering the samples at 40°C resulted in a decrease in colour strength of 0.03 and an overall change of colour of -0.14. Laundering the samples at the increased temperature caused a colour strength decrease of 0.05 and overall colour change of 0.47. It seems that increasing the laundering temperature resulted in the sample becoming continually lighter (+ΔL*), redder (+Δa*) and yellower (+Δb*). The wash fastness when laundering at 40°C was optimum (GSc=5) and excellent when laundering at 60°C (GSc=4-5). Mazumder and Haque (2011:45) reported the wash fastness of reactive dyed green cotton to be 4-5, at different temperatures. Interestingly, the lightness did not decrease after the initial laundering, as was the case with the previously discussed dyestuffs. The conclusion drawn is that the initial wash-off after dyeing was effective, in that a negligible amount of dye was washed off, therefore, the samples were not duller. The lightness increased as the temperature increased, which could indicate that, some of the dye dissipated from the dye-fibre matrix, causing the increase in lightness (Agrawal, 2014:29). It has been reported that the colour strength decreased as the temperature increased when laundering reactive green dyed cotton (Mazumder and Haque, 2011:45).

The increase in number of laundering cycles caused a subsequent increase in the overall colour difference and decrease in colour strength. After five laundering cycles, the colour strength decreased with 0.03 and overall colour change was -0.12. Laundering for ten cycles caused a decrease in colour strength of 0.04 and colour change of 0.02. After twenty laundering cycles, the colour change still only decreased with 0.04, and the colour change was 0.27. After fifty laundering cycles, the decrease in colour strength was 0.05 and colour change was 0.49. As the number of laundering cycles increased the samples became lighter (+ΔL*) and yellower (+Δb*). The redness was unstable as it became redder after five laundering cycles, reverting to green after ten, but increasingly became redder after increasing the number of laundering cycles. The wash fastness observed ranged from optimum after five and ten laundering cycles (GSc=5), to very good after twenty cycles (GSc=4-5) and good after fifty cycles (GSc=4-5). Chowdhury, Butola and Joshi (2012:237) reported wash fastness of 4-5 when evaluating reactive green dyed cotton, as well as colour strength decreasing as the number of laundering cycles increased. As mentioned previously the increase in lightness is an indicator of more light being reflected, therefore, more dye that is being dissipated from the dye-fabric matrix (Agrawal, 2014:29).

6.2.1.2 Staining

Colorimetric data and Gray Scale equivalents of staining caused by reactive blue, violet and green dyed cotton as a result of laundering with Catholyte, detergent and filtered water, at 40°C and 60°C, for five, ten, twenty and fifty laundering cycles is depicted in Table 6.4.

Reactive blue dyed cotton

Laundering the reactive blue dyed cotton samples with Catholyte caused the greatest staining (ΔE=-1.28) although obtaining a very good rating (GSs=4). Laundering with filtered water caused staining equivalent to a colour change of -1.08 and observed Gray

Table 6.4: Colorimetric data and Gray Scale equivalents of staining caused by reactive blue, violet and green dyed cotton as a result of laundering treatment, -temperature and number of laundering cycles.

	Reactive Blue					Reactive Violet					Reactive Green				
	ΔL*	Δa*	Δb*	ΔE	Gray Scale Value	ΔL*	Δa*	Δb*	ΔE	Gray Scale Value	ΔL*	Δa*	Δb*	ΔE	Gray Scale Value
TREATMENT															
Catholyte	-1.29	-1.41	0.03	-1.28*	4	-0.75	0.13	0.64	-0.77*	4-5	-1.12	-1.48	0.02	-1.11*	4-5
Detergent	-0.79	-0.68	-0.10	-0.78*	4-5	-0.36	0.26	0.14	-0.36*	5	-0.50	-0.93	0.09	-0.50*	4-5
Filtered Water	-1.07	-0.96	0.11	-1.08*	4-5	-0.89	0.03	0.43	-0.90*	4-5	-0.89	-1.68	0.11	-0.89*	4-5
TEMPERATURE															
40°C	-1.00	-0.92	0.17	-1.00*	4-5	-0.66	0.08	0.31	-0.67*	4-5	-0.80	-1.20	0.19	-0.80*	4-5
60°C	-1.10	-1.11	-0.08	-1.09*	4-5	-0.67	0.17	0.50	-0.69*	4-5	-0.87	-1.53	-0.04	-0.87*	4-5
CYCLES															
Five	-1.19	-1.02	-0.04	-1.18*	4-5	-0.77	-0.05	0.20	-0.78*	4-5	-0.89	-1.28	0.16	-0.89*	4-5
Ten	-1.08	-1.12	-0.02	-1.07*	4-5	-0.71	0.21	0.31	-0.72*	4-5	-0.87	-1.25	0.01	-0.86*	4-5
Twenty	-0.98	-0.96	0.10	-0.98*	4-5	-0.65	0.19	0.43	-0.67*	4-5	-0.83	-1.49	0.05	-0.82*	4-5
Fifty	-0.95	-0.97	0.11	-0.95*	4-5	-0.52	0.16	0.66	-0.54*	4-5	-0.75	-1.42	0.07	-0.75*	4

*Statistically significant ($p < 0.05$)

Scale rating of 4-5. Laundering with detergent resulted in an excellent Gray Scale value (GSs=4-5), and a ΔE equivalent to -0.78. The stained samples decreased in lightness equivalent to the colour change. The reactive blue dyed cotton also exhibited marked shifts towards the green (-Δa*) colour space, proportionate to the change in colour. Laundering with Catholyte and filtered water caused shifts towards the yellow (+Δb*) colour space, whereas laundering with detergent caused a shift towards the blue (-b*) colour space. The staining observed when laundering with Catholyte, detergent and filtered water was significant. Although the most staining was experienced when laundering with Catholyte, very good results were still observed (GSs=4).

The temperature did not seem to affect the Gray Scale values of staining, remaining at a value of 4-5 when laundered at both temperatures, indicating only a slight change in colour of the stained samples. Increasing the laundering temperature from 40°C to 60°C seems to have caused an increase in the difference in colour change (ΔE=-1.00 to -1.09), lightness (ΔL*=-1.00 to -1.10), and greater shift toward green (Δa*=-0.92 & -1.11) respectively. The samples initially shifted towards the yellow colour space after laundering at 40°C (Δb*=0.17), but after laundering at 60°C shifted towards the blue colour space (Δb*=-0.08).

Increasing the number of laundering cycles did not adversely affect the Gray Scale staining value, remaining at 4-5 regardless of the number of laundering cycles. The lightness and colour change increasing slightly after the initial decrease in lightness. These two parameters exhibited similar behaviour, when the samples where laundered for five (ΔL*=-1.19 & ΔE=-1.18), ten (ΔL*=-1.08 & ΔE=-1.07), twenty (ΔL*=-0.98 & ΔE=-0.98) and fifty (ΔL*=-0.95 & ΔE=-0.95) laundering cycles. Initially the colour shifted towards the green colour space after laundering for five (Δa*=-1.02) and ten (Δa*=-1.12) cycles, thereafter shifting towards the red colour space after laundering for twenty (Δa*=-0.96) and fifty (Δa*=-0.97) cycles. On the blue-yellow axis the samples became bluer after laundering for five cycles (Δb*=-0.04), but continued to shift towards the yellow colour spaces, after laundering for ten (Δb*=-0.02), twenty (Δb*=0.10) and fifty (Δb*=0.11) laundering cycles.

Reactive violet dyed cotton

It is evident from Table 6.4, that laundering with filtered water caused the greatest staining (ΔE=-0.90), although significant, still resulting in an excellent Gray Scale value (GSs=4-5). Laundering the samples with detergent resulted in the least staining (ΔE=-0.36) and almost no change in colour of the stained samples (GSs=5) although the change in colour is considered statistically significant. Laundering with Catholyte resulted in very good staining (GSs=4-5) and a significant change in colour of the stained samples (ΔE=-0.77). The samples decreased in lightness almost equivalent to change in colour when laundered with Catholyte, detergent or filtered water. It was observed that the samples became redder (+Δa*) and yellower (+Δb*) proportionate to the change in colour. Laundering reactive dyed violet with Catholyte resulted in a good staining value, and it can be concluded that Catholyte can be successfully used to launder this textile.

Laundering the samples at 40°C resulted in a significant difference in colour change of -0.67, which is equivalent to a Gray Scale value of 4-5. When the samples were laundered at 60°C, the resultant Gray Scale value (GSs=4-5) was unchanged, but the colour change (ΔE=-0.69) slightly decreased. The decrease in lightness was almost equivalent to the colour change laundering at both 40°C (ΔL*=-0.66) and 60°C (ΔL*=-0.67). The samples became redder (+Δa*) and yellower (+Δb*) as the temperature increased.

Initially the lightness and colour change significantly decreased, however, after the initial decrease the difference in lightness and colour change seems to have become similarly less as the number of laundering cycles increased. Regardless if the reactive violet dyed samples were laundered for five (ΔE=-0.78), ten (ΔE=-0.72), twenty (ΔE=-0.67) or fifty (ΔE=-0.54) cycles, the Gray Scale values remained 4-5, indicating that no great staining took place. The samples initially shifted towards the green colour space after five cycles (Δa*=-0.05) thereafter to the red after ten laundering cycles (Δa*=0.21). As the laundering cycles increased from ten to twenty to fifty, the samples exhibited shifts toward the red colour space (+Δa*), but less than the initial shift after ten laundering cycles. It was observed that the samples became continually yellower (+Δb*) as the laundering cycles increased.

Reactive green dyed cotton

From Table 6.4 it can be seen that laundering with Catholyte caused the greatest staining (ΔE=-1.11), although significant, still resulting in a good Gray Scale value (GSs=4-5). Laundering the samples with detergent caused a colour change of -0.50, which is also similar to Gray Scale rating of 4-5. Laundering with filtered water caused a similar Gray Scale rating and significant colour change in the stained samples of -0.89. As was the case with the reactive violet dyed cotton, the samples decreased in lightness almost equally, to what the colour change was found to be. Laundering the reactive green dyed samples with Catholyte (Δa*=-1.48), detergent (Δa*=-0.93) and filtered water (Δa*=-1.68) resulted in shifts towards the green colour space. The samples also exhibited shifts towards the yellow colour space (+Δb*). Laundering the reactive green dyed cotton samples with Catholyte resulted in a Gray Scale value of staining equivalent to what laundering with detergent caused. This can be interpreted as a positive result, concluding that laundering with Catholyte does not result in more staining than laundering with detergent.

The increase in laundering temperature caused a significant increase in colour change, although the Gray Scale value remained the same (GSs=4-5). Laundering at both 40°C (ΔE=-0.80; ΔL*=-0.80) and 60°C (ΔE=-0.87; ΔL*=-0.87) resulted in almost equivalent decreases with regards to the overall colour change of the stained samples, as well as the lightness indicator. The samples became continually greener (-Δa*) as the temperature increased. After laundering the reactive dyed violet samples at 40°C the samples shifted towards the yellow (Δb*=0.19) colour space, however, increasing the temperature to 60°C resulted in a shift towards the blue (Δb*=-0.04) colour space.

After laundering the samples for five cycles, the colour change and lightness decreased significantly (ΔE=-0.89 & ΔL*=-0.89), however after laundering for ten (ΔE=-0.86 & ΔL*=-0.87), twenty (ΔE=-0.82 & ΔL*=-0.83) and fifty (ΔE=-0.75 & ΔL*=-0.75) cycles the difference decreased as the number of laundering cycles increased. No pattern could be ascertained with regards to the green-red axis. After five laundering cycles the samples became greener (Δa*=-1.28), shifting slightly towards the red colour space after ten laundering cycles (Δa*=-1.25), although shifting more towards the green colour space (Δa*=-1.49) after twenty laundering

cycles, but again in the direction of the red (Δa*=-1.42) colour space after fifty laundering cycles. The same pattern was observed with regards to the blue-yellow axis, shifting back and forth towards blue and yellow after five (Δb*=0.16), ten (Δb*=0.01), twenty (Δb*=0.05) and fifty (Δb*=0.07) laundering cycles. Irrespective if the reactive green dyed cotton was laundered for five, ten or twenty cycles, the resultant Gray Scale value was 4-5, whereas laundering the samples for fifty cycles, resulted in Gray Scale value of 4. These values indicate very good fastness towards staining.

The reactive blue, violet and green dyed cotton exhibited similar behaviour regarding staining observed on the adjacent textile fabrics. In all instances, the detergent caused less staining than laundering with both filtered water and Catholyte. This might be contributed to the formulation of the detergent. Findings indicate that staining was greater in the absence of an anionic surfactant. Therefore, they concluded that anionic surfactants inhibit the transfer of reactive dye onto adjacent textiles (Oakes, Gratton & Dixon, 2004:270a). Furthermore, literature indicates that the staining values obtained in this study are similar to findings in other research studies when staining of reactive blue, violet and green dyed cotton was evaluated (Agrawal. 2014:16; Mohsin *et al.*, 2013:346; Abdel-Mohsen *et al.*, 2012:115).

In all instances, when the influence on the temperature was evaluated, only a slight change in the colour of the stained samples could be observed, increasing slightly as the temperature increased. The covalent bonds binding the reactive dye to the fibre substrate are generally stable under domestic laundering conditions and higher temperatures (Choudhury, 2006:260). With regards to the wash fastness of the reactive blue, violet and green dyed cotton, the wash fastness remained 4-5 at both temperatures, except for the reactive violet dyed samples where the wash fastness was higher (GSc=5) at 40°C than laundering at 60°C (GSc=4-5). This could be related to the staining, as only a miniscule amount of dye was dissipated or washed-off from the fabric surface, only a small amount of dye was available for redeposition on adjacent fabrics causing staining. Radhika and Moses (2014:31) found that staining could be higher at higher temperatures, although not significantly.

In all the instances the colour change on the stained samples was the greatest after laundering for five cycles, thereafter exhibiting a decrease in the difference colour

change difference. This is most likely due to the lightness increasing, which indicates that miniscule amounts of the dyes could have dissipated from the fabric surface, being available for redeposition on adjacent textile fabrics (Mazumder & Haque, 2011:45). The last mentioned authors also found the staining of reactive dyed samples to remain (4-5) the same after repeated laundering.

The distinctly different behaviour that the dyed fabrics exhibited with regards to the colour shifts on the green-red and blue-yellow axis, could be as a result of the type of chromophores used in the molecular structure of the dye (Farrell *et al.*, 2011:89).

6.2.1.3 Fastness to rubbing: Dry & Wet

Reactive blue dyed cotton

The colourfastness to rubbing, for both dry and wet tests, as a result of subjecting the reactive blue dyed cotton to laundering with Catholyte, detergent and filtered water, at 40°C or 60°C for five, ten, twenty and fifty cycles, are depicted in Table 6.5.

Laundering the reactive blue dyed cotton samples with Catholyte resulted in excellent colourfastness to dry rubbing (GSs=4-5). However, laundering the samples with detergent and filtered water resulted in optimum fastness to dry rubbing, exhibiting a Gray Scale value of 5. Laundering with either Catholyte, detergent or filtered water resulted in fastness to wet rubbing of 4-5. Although Catholyte resulted in slightly less dry rubbing fastness value, it is still excellent. Fastness to wet rubbing is equivalent to the values observed when laundering with detergent and filtered water, which can be interpreted as a positive result.

It is apparent that the temperature at which the samples were laundered did seem to affect the colourfastness to rubbing for both the dry and wet tests. Fastness to dry rubbing indicated optimum fastness (GSs=5), indicated that almost no colour rubbed off. Colourfastness to wet rubbing was excellent (GSs=4-5) for laundering at both 40°C and 60°C.

The number of laundering cycles had a similar effect on the colourfastness to rubbing of the reactive blue dyed cotton. Increasing the number of laundering cycles did not

result in more colour rubbing off. Colourfastness to dry rubbing was observed to be optimum (GSs=5) for the samples laundered for five, ten, twenty and fifty cycles. Excellent colourfastness to wet rubbing (GSs=4-5) was observed for the samples, irrespective of the number of laundering cycles it was laundered for.

Table 6.5: Gray Scale values of colourfastness to rubbing, dry and wet, for reactive blue, violet and green dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Dry			Wet		
	Reactive Blue	**Reactive Violet**	**Reactive Green**	**Reactive Blue**	**Reactive Violet**	**Reactive Green**
TREATMENT						
Catholyte	4-5	5	4-5	4-5	4-5	4-5
Detergent	5	4-5	5	4-5	4-5	4-5
Filtered Water	5	5	4-5	4-5	4-5	4-5
TEMPERATURE						
40°C	5	5	4-5	4-5	4-5	4-5
60°C	5	5	4-5	4-5	4-5	4-5
CYCLES						
Five	5	5	4-5	4-5	4-5	4-5
Ten	5	5	4-5	4-5	4-5	4-5
Twenty	5	5	4-5	4-5	4-5	4-5
Fifty	5	5	4-5	4-5	4-5	4-5

Reactive violet dyed cotton

The reactive violet dyed cotton that were laundered with Catholyte and filtered water exhibited optimum fastness (GSs=5) to dry rubbing. Excellent fastness (GSs=4-5) to dry rubbing was observed when the samples were laundered with detergent.

Subjecting the samples to laundering with Catholyte, detergent and filtered water, resulted in excellent fastness to wet rubbing, obtaining Gray Scale values of 4-5 (Table 6.5). It is evident that laundering with Catholyte did not cause more dye to rub off in both dry and wet instances, than when laundering with detergent. It can thus be safely concluded that Catholyte can be safely used to launder reactive violet dyed cotton without causing excessive rub off of the dye.

Laundering the reactive violet dyed samples at both 40°C and 60° did not seem to adversely affect the colourfastness to dry rubbing of the reactive violet dyed cotton, indicating optimum fastness (GSs=5). Excellent colourfastness to wet rubbing (GSs=4-5) was also observed when the samples were laundered, regardless of the laundering temperature.

The increase in number of laundering cycles did not cause change in the Gray Scale value obtained for fastness to both dry and wet rubbing. A value of 5 was obtained for colourfastness to dry rubbing, indicating optimum fastness for all the laundering cycles. Excellent fastness to wet rubbing (GSs=4-5) was observed when the samples were laundered for five, ten, twenty and fifty cycles.

Reactive green dyed cotton

Laundering the reactive green dyed cotton samples with detergent resulted in optimum colourfastness to dry rubbing (GSs=5), however, laundering the samples with Catholyte and filtered water resulted in excellent colourfastness to dry rubbing. Subjecting the samples to wet rubbing tests indicate that excellent fastness (GSs=4-5) to rubbing was obtained, whether the samples were laundered with Catholyte, detergent or filtered water. Laundering the samples with Catholyte resulted in excellent colourfastness to both dry and wet rubbing. Hence, it can be assumed that reactive green dyed cotton can be laundered with Catholyte without adversely affecting the rubbing fastness thereof.

Laundering the samples at both temperatures, 40°C and 60°C, resulted in excellent colourfastness to both dry and wet rubbing. Regardless of the number of laundering

cycles, the colourfastness to dry and wet rubbing indicated excellent fastness (GSs=4-5).

The above discussed results are comparable to other research which indicates that the colourfastness to dry and wet rubbing of reactive blue, violet and green dyed cotton is 4-5 – 5 (Agrawal, 2014:25 Mohsin *et al.*, 2013:346; Abdel-Mohsen *et al.*, 2012:115; Mazumder & Haque, 2011:45). In some instances, the treatment the samples were subjected to, caused a different rating with regards to colourfastness to dry rubbing. In the case of both reactive blue and green, the fastness to dry rubbing was slightly less in comparison with the samples laundered with detergent. This could be due to an unknown interaction between one or more of the constituents present in Catholyte and the interaction thereof with the specific dye structure. In the case of reactive violet dyed cotton, the detergent exhibited slightly less colourfastness to rubbing. This can most probably be attributed to the action of the surfactant present in the detergent (Hauser & Tabba, 2001:117). The interaction between the detergent and the specific molecular dye structure was not favourable, although excellent fastness was still observed.

The same researchers mentioned above did not note a significant decrease in rubbing fastness as the temperature increased or due to repeated laundering. This can be expected as the covalent bonds that hold the reactive dye in place, are very strong, and will seldom be broken by friction caused as a result of rubbing (Boardman and Jarvis, 2000:63).

From the above-discussed results and Table 6.5, it is evident that the colourfastness to dry rubbing of reactive violet and blue dyed cotton is superior to the dry rubbing fastness of reactive green dyed cotton. However, the colourfastness to wet rubbing of reactive blue, violet and green dyed cotton are equivalent whether it is laundered with Catholyte, detergent or filtered water, at 40°C or 60°C , or for five, ten, twenty or fifty cycles.

6.3 Tensile Strength

As mentioned in the previous chapters, the maximum load at break and displacement at maximum load statistics for this research was reported in two sets. Analysis 1 represents the data of the determined p-values and significance in change of the samples laundered with Catholyte, detergent and filtered water at 40°C or 60°C for five, ten, twenty, and fifty cycles respectively when compared to the untreated samples (control). Analysis 2 represents the determined p-values and significance when the different laundering treatments (Catholyte, detergent and filtered water), laundering temperatures (40°C and 60°C), and laundering cycles (five, ten, twenty and fifty) were compared.

6.3.1 Maximum Load at Break

Reactive blue dyed cotton

It is evident from Table 6.6 that laundering the reactive blue dyed cotton samples with Catholyte caused a greater decrease in the maximum load carried when compared to the untreated samples. The decrease of 3.87% (29.33N), was significant. Laundering the samples with detergent seems to have caused the least decrease in maximum load carried before break (0.36%; 2.75N). Laundering the samples with filtered water caused a decrease of 0.68% (5.12N), which was not significant. The difference in decrease of maximum load carried at break when detergent and filtered water are compared is not significant. However, the difference in decrease in maximum load carried before break caused, when Catholyte is compared to filtered water and detergent, was statistically significant.

Laundering reactive blue dyed cotton samples at 40°C caused a decrease in maximum load carried of 5.66N (0.75%), whereas laundering the samples at 60°C caused a decrease in maximum load carried by the samples of 12.31N (1.62%). When compared to the untreated samples, the decreases caused in maximum load carried as a result of the laundering temperature was not significant. The difference in

decrease in maximum load carried before break, when both laundering temperatures are compared, was not significant.

Table 6.6: Difference (relative to control) in maximum load (Newton and %) carried before break and p-values of the reactive blue dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		Analysis 2 (Comparison with resultant p-values)			
	N	%				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	-29.33*	-3.87		0.0436*	0.0093*	
Detergent	-2.75	-0.36	0.04368*		0.5471	
Filtered Water	-5.12	-0.68	0.0093*	0.5471		
TEMPERATURE			**40°C**	**60°C**		
40°C	-5.66	-0.75		0.5332		
60°C	-12.31	-1.62	0.5332			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	-0.27	-0.04		0.1657	0.0006*	<.0001*
Ten	-1.63	-0.21	0.1657		0.0335*	0.0077*
Twenty	-22.62*	-2.98	0.0006*	0.0335*		0.1906
Fifty	-42.43*	-5.59	<.0001*	0.0077*	0.1906	

*Statistically significant ($p < 0.05$)

The maximum load carried before break of reactive blue dyed cotton decreased as the number of laundering cycles increased. Laundering the samples for five cycles resulted in an insignificant decrease of maximum load carried of 0.27N (0.04%). Increasing the number of laundering cycles to ten (1.63N; 0.21%), twenty (22.62N;

2.98%), and fifty (42.43N; 5.59%) cycles resulted in a further decrease in maximum load carried before break. The decreases observed after laundering for twenty and fifty cycles were significant. The difference in decrease in maximum load carried at break caused when the samples were laundered for five and ten cycles, did not differ significantly, however, comparing the decrease caused when laundering for twenty and fifty cycles, differed significantly from laundering for five cycles.

Reactive violet dyed cotton

The reactive violet dyed cotton was laundered with Catholyte, detergent and filtered water at 40°C or 60°C for five, ten, twenty and fifty cycles. The statistical data obtained for analysis 1 and 2 are depicted in Table 6.7.

The greatest decrease in maximum load carried was caused by laundering with detergent, causing a decrease of 92.89N (11.84%). Laundering with filtered water caused a decrease of 88.43N (11.27%) and laundering with Catholyte caused a decrease of 80.45N (10.25%). Compared to the unlaundered samples, decreases observed when laundering with either Catholyte, detergent or filtered water was significant. The differences in the decrease of maximum load carried at break caused when the different treatments are compared, did however not differ significantly. Hence, it can be safely concluded that laundering with Catholyte will not cause a significantly different decrease when compared to laundering with detergent.

Laundering the reactive dyed violet samples at both 40°C and 60°C caused a significant decrease in maximum load carried before break. The maximum load carried at break decreased as the temperature increased from 40°C (71.57N; 9.12%) to 60°C (102.94; 13.12%). When comparing the decrease in maximum load caused when laundering at the lower temperatures, to laundering at the higher temperature, the difference in decrease was statistically significant.

The maximum load carried by the samples decreased significantly as the number of laundering cycles increased. Initially, a decrease of 42.72N (5.44%) was observed after laundering for five cycles, which increased to 84.92N (10.82%) after laundering the reactive violet dyed samples for ten cycles. Increasing the number of laundering

cycles to twenty, resulted in a decrease in maximum load of 101.96N (12.99%), and when laundered for fifty cycles the decrease was 119.43N (15.22%). The decrease caused when laundering for five cycles was significantly different from the decrease caused when laundering at ten, twenty, and fifty cycles. It is evident from Table 6.7 that laundering the samples for twenty and fifty cycles, did not result in significantly different decreases in maximum load carried at break of the reactive violet dyed cotton samples.

Table 6.7: Difference (relative to control) in maximum load (Newton and %) carried before break and p-values of the reactive violet dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		**Analysis 2 (Comparison with resultant p-values)**			
	N	**%**				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	-80.45*	-10.25		0.3601	0.5569	
Detergent	-92.89*	-11.84	0.3601		0.7422	
Filtered Water	-88.43*	-11.27	0.5569	0.7422		
TEMPERATURE			**40°C**	**60°C**		
40°C	-71.57*	-9.12		0.0054*		
60°C	-102.94*	-13.12	0.0054*			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	-42.72*	-5.44		0.0080*	0.0002*	<.0001*
Ten	-84.92*	-10.82	0.0080*		0.2781	0.0292*
Twenty	-101.96*	-12.99	0.0002*	0.2781		0.2661
Fifty	-119.43*	-15.22	<.0001*	0.0292*	0.2661	

*Statistically significant ($p < 0.05$)

Reactive green dyed cotton

Table 6.8 depicts the statistical data for analysis 1 and 2 of the reactive green dyed cotton laundered with Catholyte, detergent and filtered water, at 40°C or 60°C for five, ten, twenty and fifty cycles, respectively.

Laundering the samples with Catholyte and detergent caused similar significant decreases in maximum load carried by the samples of 90.81N (10.90%) and 90.68N (10.89%), respectively. When compared, the effect of these treatments on the maximum load carried before break of the laundered samples did not differ significantly. Laundering with filtered water resulted in a decrease in maximum load carried of (80.56N; 9.67%), which is the least decrease, although it does not differ significantly from the decrease that laundering with Catholyte and detergent caused. It can be interpreted as a positive result that Catholyte did not cause a significantly different decrease in maximum load carried by the laundered samples, when compared to detergent.

Laundering at 40°C, caused a significant decrease in maximum load carried before break, of 80.42N (9.66%), whereas laundering at 60°C caused a significant decrease of 94.28N (11.32%). Increasing the temperature thus adversely affects the maximum load the samples can carry before break. The decrease caused also differed significantly when laundering at 40°C and 60°C are compared.

Laundering the reactive green dyed cotton samples for five cycles, resulted in a decrease of 63.59N (7.64%) in maximum load carried before break. Increasing the number of laundering cycles to ten, resulted in a decrease of 69.96N (8.40%) in maximum load carried. Laundering for twenty cycles caused a decrease of 95.89N (11.52%) and laundering for fifty cycles significantly decreased the maximum load carried before break of the samples with 119.95N (14.40%). The difference in maximum load carried before break when laundering for five and ten cycles, does not differ significantly. However, the difference in decrease of maximum load carried at break when laundering for twenty and fifty cycles, compared to laundering for five cycles, does differ significantly.

Table 6.8: Difference (relative to control) in maximum load (Newton and %) carried before break and p-values of the reactive green dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		Analysis 2 (Comparison with resultant p-values)			
	N	**%**				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	-90.81*	-10.90		0.9883	0.2268	
Detergent	-90.68*	-10.89	0.9883		0.2324	
Filtered Water	-80.56*	-9.67	0.2268	0.2324		
TEMPERATURE			**40°C**	**60°C**		
40°C	-80.42*	-9.66		0.0462*		
60°C	-94.28*	-11.32	0.0462*			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	-63.59*	-7.64		0.5148	0.0012*	<.0001*
Ten	-69.96*	-8.40	0.5148		0.0085*	<.0001*
Twenty	-95.89*	-11.52	0.0012*	0.0085*		0.0143*
Fifty	-119.95*	-14.40	<.0001*	<.0001*	0.0143*	

*Statistically significant ($p < 0.05$)

It is evident from the above discussed results that laundering the reactive violet and green dyed cotton with either Catholyte or detergent did not result in significant differences with regards to decrease in maximum load carried at break when comparing these two treatments. The difference in decrease in maximum load carried at break when laundering the reactive blue dyed cotton with Catholyte and detergent was significant. Reactive red dyed cotton exhibited the same behaviour as reactive blue dyed cotton. It might be assumed that the pure colours (primary

colours, i.e. blue and red) exhibit the same behaviour towards laundering with Catholyte. A probable explanation might be the high alkalinity of the Catholyte. Laundering with this wash liquor might have caused greater loss in tensile strength due to the degree of orientation and rearrangement, which was lessened as a result of exposure to the high alkali. As alkalis generally do not harm cotton it might be concluded that the cellulose behaves as a polyhydric alcohol and most reactive dyes react with it only under alkaline condition (Slater, 2003:81). This can only be concluded for reactive blue and red dyed cotton laundered with Catholyte. The insignificant difference caused when laundering the reactive violet and green dyed cotton can be ascribed to observations that chromophores are sensitive to alkalis and acids, and therefore will react differently, exhibiting different behaviour (Mohsin *et al.*, 2013:345). The reactive violet and green dyed cotton samples also exhibited similar behaviour towards the decrease in maximum load, which was significant. Agrawal (2014:27) reported the tensile strength of reactive dyed green and blue samples to decrease, and Uğur and co-workers (2011:194) reported the same for reactive violet dyed cotton.

The significant reduction in maximum load carried at break as a result of laundering at 40°C and 60°C when laundering the reactive dyed blue, violet and green was most likely due to changes in the fibres of the textiles as a result of mechanical damage during laundering at a higher temperature (Uğur *et al.*, 2011:194; Was-Gubala, 2009:165).

In all instances, for the reactive blue, violet and green dyed cotton samples the maximum load carried at break decreased as the number of laundering cycles increased. Lau and fellow researchers (2002:934) and Shurkian, Amirbayat and Gong (2002:2) reported similar findings of reactive dyed cotton to decrease in strength as the number of laundering cycles increased. They concluded that it might be expected because of inherent fibre qualities degrading as repeated mechanical agitation, heat and water is applied

Although not stated in literature, from these results it is evident that reactive violet and green dyed cotton exhibited significantly more weakening of tensile properties than reactive dyed blue cotton. As the exact molecular structures of the dyes were not available, it is difficult to draw a conclusion and indicate what might have affected

the considerable decrease in strength, apart from the influences of general domestic laundering conditions.

6.3.2 Displacement at Maximum Load

Reactive blue dyed cotton

Table 6.9: Difference (relative to control) in displacement at maximum load (% and mm) and p-values of the reactive blue dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		Analysis 2 (Comparison with resultant p-values)			
	%	mm				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	0.06*	11.92		0.0201*	0.4068	
Detergent	0.06*	11.07	0.0201*		0.1338	
Filtered Water	0.06*	11.62	0.4068	0.1338		
TEMPERATURE			**40°C**	**60°C**		
40°C	0.05*	11.00		0.0004*		
60°C	0.06*	12.08	0.0004*			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	0.04*	8.98		0.0155*	<.0001*	<.0001*
Ten	0.05*	10.02	0.0155*		<.0001*	<.0001*
Twenty	0.06*	12.35	<.0001*	<.0001*		<.0001*
Fifty	0.07*	14.80	<.0001*	<.0001*	<.0001*	

*Statistically significant ($p < 0.05$)

It is evident from Table 6.9 that laundering the reactive blue dyed cotton with either Catholyte, detergent or filtered water, resulted in a similar significant increase in displacement at maximum load (0.06%).

Although the statistical analysis indicates a significant difference in displacement when laundering with Catholyte and detergent are compared (based on the mm), percentage wise it is similar. From this Table it can be safely concluded that the increase in displacement at maximum load as a result of laundering with either Catholyte or detergent was significant.

The displacement at maximum load increased slightly, but significantly, from 0.05% to 0.06% when the laundering temperature was increased from 40°C to 60°C. The increase in displacement at maximum load was significant when compared to the untreated samples.

As the number of laundering cycles increased, the displacement at maximum load increased with 0.01%, until displacement at maximum load of 0.07% after fifty laundering cycles was reached. According to the statistical analysis, these increases were significant when compared to the untreated reactive blue dyed fabric, but also to the values reached after the different number of laundering cycles.

Reactive violet dyed cotton

As seen in Table 6.10, the displacement at maximum load observed when the samples were laundered with Catholyte, detergent and filtered water, was similar (0.05%). The increase in displacement was significant compared to the unlaundered samples. The increase caused when laundering with either of the treatments did not differ significantly.

Increasing the temperature from 40°C to 60°C resulted in a slight increase in displacement although the percentage (0.05%) remained the same. Based on the displacement (mm) the increase caused when laundering at the two temperatures differed significantly.

Table 6.10: Difference (relative to control) in displacement at maximum load (% and mm) and p-values of the reactive violet dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		Analysis 2 (Comparison with resultant p-values)			
	%	mm				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	0.05*	10.29		0.5659	0.1807	
Detergent	0.05*	10.47	0.5659		0.0574	
Filtered Water	0.05*	9.86	0.1807	0.0574		
TEMPERATURE			**40°C**	**60°C**		
40°C	0.05*	10.02		0.1568		
60°C	0.05*	10.39	0.1568			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	0.04*	7.35		<.0001*	<.0001*	<.0001*
Ten	0.05*	9.46	<.0001*		<.0001*	<.0001*
Twenty	0.06*	11.08	<.0001*	<.0001*		<.0001*
Fifty	0.06*	12.94	<.0001*	<.0001*	<.0001*	

*Statistically significant ($p < 0.05$)

Laundering the reactive violet dyed samples for five cycles resulted in an increase in the displacement at maximum load of 0.04%, and increasing the number of laundering cycles to ten, increased the displacement further to 0.05%. Laundering the samples for twenty and fifty laundering cycles resulted in displacement at maximum load of 0.06%. The displacement caused as a result of each number of laundering cycles, differing significantly when compared to any of the number of laundering cycles.

Reactive green dyed cotton

It is evident from Table 6.11 that laundering with either Catholyte, detergent or filtered water resulted in similar (0.06%) results for displacement at maximum load. The difference in displacement caused also did not differ significantly compared to the different treatments were compared.

Table 6.11: Difference (relative to control) in displacement at maximum load (% and mm) and p-values of the reactive green dyed cotton samples as a result of laundering treatment, -temperature and number of laundering cycles.

	Analysis 1 (Difference: After-Before)		**Analysis 2 (Comparison with resultant p-values)**			
	%	**mm**				
TREATMENT			**Catholyte**	**Detergent**	**Filtered Water**	
Catholyte	0.06*	12.34		0.0650	0.0345	
Detergent	0.06*	11.84	0.0650		0.7743	
Filtered Water	0.06*	11.76	0.0345	0.7743		
TEMPERATURE			**40°C**	**60°C**		
40°C	0.06*	11.64		0.0024*		
60°C	0.06*	12.33	0.0024*			
CYCLES			**Five**	**Ten**	**Twenty**	**Fifty**
Five	0.05*	9.46		<.0001*	<.0001*	<.0001*
Ten	0.06*	11.43	<.0001*		0.0059*	<.0001*
Twenty	0.06*	12.30	<.0001*	0.0059*		<.0001*
Fifty	0.07*	14.74	<.0001*	<.0001*	<.0001*	

*Statistically significant ($p < 0.05$)

It seems that an increase in temperature only caused a slight increase in displacement at maximum load, when considering the millimetres displaced. The percentage remained 0.06% when laundering at both temperatures. The statistical analysis indicates that the displacement caused when laundering at 40°C did not differ significantly from the displacement caused when laundering at 60°C.

Laundering the reactive green dyed samples for five cycles, resulted in observed displacement at maximum load of 0.05%. Laundering the samples for ten and twenty cycles, resulted in displacement of 0.06%, whilst an increase in displacement to 0.07% was observed when the samples were laundered for fifty cycles.

The above-discussed results for displacement at maximum load of reactive blue, violet and green dyed cotton are proportionately comparable to the maximum load carried at break of the laundered reactive red dyed cotton, discussed in 6.3.1.

Because the same textile material was used, and the same dyestuff, only different colours, similar results were observed with regards to displacement at maximum load of the reactive blue, violet and green dyed samples. Displacement at maximum load significantly increased for all the samples that were subjected to the above-mentioned treatments, temperatures and laundering cycles. This is most probably due to the possible change in internal orientation of the fibre matrix as a result of degradation caused by the laundering treatments, temperature and cycles (Shurkian, Amirbayat & Gong, 2002:2; Chowdhury, Butola & Joshi, 2013:232).

CHAPTER 7

CONCLUSION & RECOMMENDATION

7.1 Conclusion

It was the purpose of this study to determine what effect Catholyte had on the colourfastness and tensile strength of dyed cotton, polyamide 6,6 and polyester fabric. This was achieved by laundering the dyed cotton, polyamide 6,6 and polyester fabric with Catholyte, detergent and filtered water, at 40°C and 60°C, for five, ten, twenty and fifty cycles, respectively. The colorimetric data (ΔE, L*, a*, b*) obtained was converted to Gray Scale values (GSc=5 indicates excellent fastness; GSc=1 indicates poor fastness). Additionally, colour strength (K/S values) was also determined to assist in the discussion of the wash fastness results. Based on the research objectives outlined in chapter 1 and the results discussed in chapters 4, 5 and 6, the following conclusions were drawn:

Objective 1: To compare the influence of Catholyte versus detergent on the wash fastness of sulphur, direct and reactive black dyed cotton.

When the influence of Catholyte and detergent on the wash fastness of sulphur and direct black dyed cotton was evaluated, it was observed that laundering with Catholyte (GSc=4; 3-4, respectively) caused slightly more colour loss and a greater decrease in colour strength as opposed to laundering with detergent (GSc= 4-5; 4, respectively). The wash fastness observed when the reactive black dyed samples were laundered with Catholyte was higher (GSc=5) and also resulted in less loss in colour strength than laundering with detergent (GSc=4-5). The L*, a* and b* parameters indicated similar results proportionate to the above mentioned observations.

Objective 2: To compare the influence of Catholyte versus detergent on the wash fastness of disperse red dyed polyester, acid red dyed polyamide 6,6, azoic orange, direct red and reactive red dyed cotton.

Evaluating the influence of Catholyte and detergent on the wash fastness of disperse red dyed polyester, acid red dyed polyamide 6,6, azoic orange, and reactive red dyed cotton, indicated excellent wash fastness (GSc=5; 5; 4; 4-5, respectively) for both treatments. Direct dyed cotton was less colourfast, when laundered with detergent (GSc=1-2) as opposed to laundering with Catholyte (GSc=2), although it is considered as poor wash fastness. Laundering the disperse red dyed polyester, acid red dyed polyamide 6,6, azoic orange, and direct red dyed cotton with Catholyte resulted in less loss in colour strength when compared to laundering these textiles with detergent. However, laundering the reactive red dyed cotton with Catholyte resulted in a greater loss in colour strength in comparison to laundering with detergent. Similar results, which were proportionate to the above mentioned, was observed for the individual L*, a* and b* parameters.

Objective 3: To compare the influence of Catholyte versus detergent on the wash fastness of reactive blue, violet and green dyed cotton.

Laundering the reactive blue and violet dyed cotton with both Catholyte and detergent, resulted in excellent wash fastness (GSc=4-5). Laundering the reactive green dyed cotton also resulted in very good wash fastness (GSc=4) when laundered with both treatments. Laundering the reactive blue and green dyed cotton with Catholyte resulted in less loss in colour strength when compared to laundering with detergent. Whereas laundering the reactive violet dyed cotton with detergent resulted in less loss in colour strength in comparison to laundering with Catholyte. The L*, a* and b* parameters indicated similar results proportionate to the above mentioned observations.

Objective 4: To compare the influence of Catholyte versus detergent on the staining of sulphur, direct and reactive black dyed cotton.

When the influence of Catholyte and detergent on the staining of sulphur and reactive black dyed cotton, was compared, it was observed that laundering with

detergent resulted in less staining (GSs=4-5; 5, respectively) than laundering with Catholyte (GSs=3; 4-5, respectively), although little staining was observed for both treatments. Laundering the direct black dyed cotton with detergent resulted in greater staining (GSs=2) than laundering with Catholyte (GSs=3), but it is considered excessive staining for both treatments. The individual L*, a* and b* parameters support these findings.

Objective 5: To compare the influence of Catholyte versus detergent on the staining of disperse red dyed polyester, acid red dyed polyamide 6,6, azoic orange, direct red and reactive red dyed cotton.

Laundering the disperse red dyed polyester and direct red dyed cotton with Catholyte (GSs=5) and detergent (GSs=2) indicated a variation from very little staining to excessive staining, although both treatments exhibited similar results. Laundering the acid red dyed polyamide, azoic orange, and reactive red dyed cotton resulted in slightly less staining when laundered with detergent (GSs=5; 4-5; 4-5, respectively) as opposed to laundering with Catholyte (GSs=4-5; 4; 4, respectively), although only little staining for both treatments was observed. The individual L*, a* and b* parameters support these findings.

Objective 6: To compare the influence of Catholyte versus detergent on the staining of reactive blue, violet and green dyed cotton.

When comparing the influence of Catholyte versus detergent on the staining of reactive blue and violet dyed cotton, it was observed that laundering with detergent caused less staining (GSs=4-5; 5, respectively) in comparison to laundering with Catholyte (GSs=4; 4-5, respectively), although very little staining was caused as a result of laundering with both treatments. However, laundering reactive green dyed cotton resulted in very little staining when laundered with either Catholyte or detergent (GSs=4-5). The individual L*, a* and b* parameters support these findings.

Objective 7: To compare the influence of Catholyte versus detergent on the colourfastness to dry and wet rubbing of sulphur, direct and reactive black dyed cotton.

The influence of both Catholyte and detergent on the colourfastness to dry rubbing of sulphur, direct and reactive black dyed cotton was very good (GSs=4; 4-5; 4-5, respectively). Laundering the direct and reactive black dyed cotton with Catholyte and detergent resulted in acceptable to very good colourfastness to wet rubbing (GSs=3; 4-5, respectively), whereas laundering the sulphur black dyed cotton with detergent resulted in poor colourfastness (GSs=1) and only slightly better when laundered with Catholyte (GSs=1-2).

Objective 8: To compare the influence of Catholyte versus detergent on the colourfastness to dry and wet rubbing of disperse red dyed polyester, acid red dyed polyamide 6,6, azoic orange, direct red and reactive red dyed cotton.

Laundering the acid red dyed polyamide 6,6, azoic orange and reactive red dyed cotton with Catholyte and detergent resulted in very good colourfastness to dry rubbing when laundered with both Catholyte and detergent (GSs=4-5, respectively). Laundering the disperse red dyed polyester and the direct red dyed cotton, resulted in slightly better colourfastness when laundered with detergent (GSs=5; 4-5, respectively) when compared to laundering with Catholyte (GSs=4-5; 4, respectively), although the colorfastness observed was very good. Laundering the disperse red dyed polyester, acid red dyed polyamide 6,6, and reactive red dyed cotton with Catholyte and detergent resulted in very good colourfastness to wet rubbing for both treatments (GSs=4-5; 4-5; 4, respectively). The direct red dyed cotton was the exception, exhibiting better colourfastness to wet rubbing when laundering with detergent (GSs=4) as opposed to laundering with Catholyte (GSs=3-4). Laundering the azoic orange dyed cotton resulted in poor colourfastness to wet rubbing when it was laundered with both Catholyte and detergent.

Objective 9: To compare the influence of Catholyte versus detergent on the colourfastness to dry and wet rubbing of reactive blue, violet and green dyed cotton.

When the influence of Catholyte and detergent on the colourfastness to dry rubbing of reactive blue and green dyed cotton was evaluated, it was observed that laundering with detergent resulted in better colourfastness to dry rubbing (GSs=5, respectively) when compared to laundering with Catholyte (GSs=4-5), although the results indicate excellent colourfastness. Laundering the reactive violet dyed cotton with Catholyte resulted in better colourfastness to dry rubbing (GSs=5) when compared to laundering with detergent (GSs=4-5). Laundering the reactive blue, violet and green dyed cotton with both Catholyte and detergent resulted in very good colourfastness to wet rubbing (GSs=4-5).

Objective 10: To compare the influence of Catholyte versus detergent on the tensile strength of sulphur, direct and reactive black dyed cotton.

Laundering sulphur black dyed cotton with detergent, caused greater loss in tensile strength (10.97N), when compared to laundering with Catholyte (56.320N). Laundering the reactive black dyed cotton also resulted in a greater loss in tensile strength when laundered with detergent (6.66N) when compared to laundering with Catholyte (53.20N). Although, laundering the direct black dyed cotton with Catholyte caused greater loss in tensile strength (114.15N) when compared to laundering with detergent (94.64N).

Objective 11: To compare the influence of Catholyte versus detergent on the tensile strength of disperse red dyed polyester, acid red dyed polyamide 6,6, azoic orange, direct red and reactive red dyed cotton.

Laundering the disperse red dyed polyester, acid red dyed polyamide 6,6 and reactive red dyed cotton with Catholyte, resulted in greater loss of tensile strength (27.48N; 33.50N; 52.59N, respectively) when compared to laundering with detergent (25.34N; 2.02N; 33.98N, respectively). However, laundering the azoic orange and direct red dyed cotton resulted in greater loss of tensile strength when laundered

with detergent (168.58N and 101.76N, respectively) as opposed to laundering with Catholyte (140.60N and 88.27N, respectively).

Objective 12: To compare the influence of Catholyte versus detergent on the tensile strength of reactive blue, violet and green dyed cotton.

Comparing the influence of Catholyte and detergent on the tensile strength of reactive blue and green dyed cotton, it was evident that laundering with Catholyte caused greater loss in tensile strength (29.33N and 90.81N, respectively) than laundering with detergent (2.75N and 90.68N). Laundering the reactive violet dyed cotton with detergent resulted in greater loss of tensile strength (92.89N) than laundering with Catholyte (80.45).

7.2 Recommendation

As no literature could be found on the influence of Catholyte on dyed textile materials, it is recommended that research with dyestuffs not included in this study and a broader colour range be conducted. Furthermore, it is also recommended that interactions between the dyestuffs and Catholyte be studied on molecular level to better explain and understand the mechanism of interaction.

REFERENCES

AATCC. 2011. *Technical Manual of the American Association of Textile Chemists and Colorists*. Volume 86. Research Triangle Park: American Association of Textile Chemists and Colorists.

Abdel-Mohsen, A.M., Aly, A.S., Hrdina, R., Montaser, A.S., & Hebeish, A. 2012. Biomedical Textiles Through Multifunctioalization of Cotton Fabrics Using Innovative Methoxypolyethylene Glycol-N-Chitosan Graft Copolymer. *Journal of Polymers and the Environment*, 20:104-116.

Agrawal, B.J. 2014. Improved Dyeing of Cotton Substrate with Vinyl Sulfone Based Reactive Dyes – An Eco-Friendly Approach. *Progress in Chemical Engineering*, 1(1):22-30.

Ahmed, N.S.E. 2005. The use of sodium edate in the dyeing of cotton with reactive dyes. *Dyes and Pigments*, 65:221-225.

Ahmed, N.S.E. & El-Shishtawy, R.M. 2010. The use of new technologies in coloration of textile fibers. *Journal of Materials Science*, 45(5):1143-1153.

Aider, M., Gnatko, E., Benali, M., Plutakhim, G. & Kastyuchik, A. 2012. Electro-activated aqueous solution: Theory and application in the food industry and biotechnology. *Innovative Food Science and Emerging Technologies*, 15:38-49.

Akram, M., Ali, S., Shahid, S.A., Ullah, I., Nadeem, M. & Shafeeq, A. 2012. A study on the after-treatment of metallised acid dye on nylon 6,6 by using reactive fixing agent. *Journal of Quality and Technology Management*, 8(1):29-40.

Alam, S., Khan, F.M.A., Razzaque, S.M.A., Hossain, M.J. & Minhaz-ul-Haque, M. 2008. Dyeing of cotton fabrics with reactive dyes and their physico-chemical properties. *Indian Journal of Fibre & Textile Research*, 33:58-65.

Albano, C., Sciamanna, R., Gónzalez, R., Papa, J. & Navarro, O. 2001. Analysis of nylon 66 solidification process. *European Polymer Journal*, 37:851-860.

Ali, S., Mighal, M.A., Shoukat, U., Balock, M.A. & Kim, S.H. 2015. Cationic Starch (Q-TAC) Pre-Treatment of Cotton Fabric: Influence on dyeing with reactive dye. *Carbohydrate Polymers*, 117:271-278.

Al Mamun, A.A., Rahman, M., Asif, A.H. & Sarkar, P. 2014. Effects of Dyeing Parameters on Color Strength and Fastness Properties of Cotton Knitted Fabric Dyed with Direct Dyes. *International Journal of Current Engineering and Technology,* 4(2):068-1072.

Al-Mousawi, S.M. & El-Apasery, M.A. 2013. Synthesis of Some Monoazo Disperse Dyes Derived from Aminothienochromene. *Molecules*, 18:8837-8844.

Asif, M. 2010. Genomic Analysis for Quality Traits in Cotton (*Gossypiumhirsutum*L.) by DNA Fingerprinting Technology. Doctor of Philosophy. Plant Biotechnology Division, National Institute for Biotechnology and Genetic Engineering (NIBGE), Faisalabad & Institute of Pure and Applied Biology, Bahauddin Zakariya University (BZU): Multan.

Asif, M., Mirza, J.I. & Zafar, Y. 2008. Genetic analysis for fiber quality traits of some cotton genotypes. *Pakistan Journal of Botany*, 40(3):1209-1215.

Atlantis Activator Technology. 2010. *Activator™*. Standard Textile, http://www.standardtextile.com/healthcare/innovations/centium-core-technology.htm (accessed December, 2010).

Bafrooei, F.K., Malek, R.M.A. & Mazaheri, F. 2014. The Effect Of Dendrimer On Cotton Dyeability With Direct Dyes. *Chemical Industry & Chemical Engineering Quarterly*, 20(3):379-385.

Bajpai, D. & Tyagi, V. K. 2007. Laundry Detergents: An Overview. *Journal of Oleo Science* 56(7):327-340.

Bakhir, V. M. 2005. *Electrochemical activation: a key to ecologically pure technologies of water Treatment*. Vitold Bakhir Institute, http://www.vbinstitute.org/terms/.html (Accessed 28 September 2013).

Bakhir, V. M. 1997. *Electrochemical activation: Theory and Practice*. First International Symposium on Electrochemical Activation, Moscow, p38–45.

Berlow, L. 1994. How products are made. *AATCC review*, 1:247-251.

Boardman, C. & Jarvis, A.N. 2000. The prevention of in-wash dye transfer. *Coloration Technology*, 30(1):63–66.

Broughton, K. 2001. *Textile Dyeing*. Massachusetts:Rockport Publishers.

Burkinshaw, S.M. 1995. *Chemical Principles of Synthetic Fibre Dyeing*. Glasgow:Blackie Academic & Professional.

Burkinshaw, S.M., Chevli, S. N. & Marfell, D.J. 2000. The dyeing of nylon 6,6 with sulphur dyes. Dyes and Pigments, 45:65-74.

Burkinshaw, S.M. & Gotsopoulos, A. 1999. Pretreatment of cotton to enhance its dyeability; Part 2 Direct Dyes. *Dyes and Pigments*, 42:179-195.

Burkinshaw, S.M., Howroyd, J., Kumar, N. & Kabambe, O. 2011. The wash-off of dyeings using interstitial water part 2: Bis(aminochlorotriazine) reactive dyes on cotton. *Dyes and Pigments,* 91:134-144.

Burkinshaw, S.M. & Katserelias, D. 1997. The Wash-off of Reactive Dyes on Cellulosic Fibres. Part 4: The Use of Different Alkalis with Monochlorotriazinyl Dyes on Cotton. *Dyes and Pigments,* 35:249-259.

Burkinshaw, S.M., Mignanelli, M., Froehling, P.E. & Bide, M.J. 2000. The use of dendrimers to modify the dyeing behaviour of reactive dyes on cotton. *Dyes and Pigments*, 47:259-267.

Burkinshaw, S.M. & Pareskevas, M. 2010. The dyeing of silk Part 1: Low temperature application of solubilised sulphur dyes using sodium thioglycolate. *Dyes and Pigments*, 87:225-233.

Burkinshaw, S.M. & Son, Y.A. 2010. The dyeing of supermicrofibre nylon with acid and vat dyes. *Dyes and Pigments*, 87:132-138.

Burkinshaw, S.M. & Son, Y.A. 2006. A comparison of the colour strength and fastness to repeated washing of acid dyes on standard and deep dyeable nylon 6,6. *Dyes and Pigments*, 70:156-163.

Burkinshaw, S.M., Son, Y.A. & Chevli, S.N. 2000. The fastness, to repeated washing, of reactive dyes and pre-metallised acid dyes on nylon 6,6. *Dyes and Pigments*, 45:43-49.

Cai, Y., Pailthorpe, M.T. & David, S.K. 1999. A New method for improving the dyeability of Cotton with Reactive Dyes. *Textile Research Journal*, 69(6):440-446.

Cameron, B.A. 2007. Laundering in Cold Water: Detergent Considerations for Consumers. *Family and Consumer Sciences Research Journal*, 36(2):151-162.

Can, O.T., Kobya, M., Demirbas, E. & Bayramoglu, M. 2006. Treatment of the textile wastewater by combined electrocoagulation. *Chemosphere*, 62:181-187.

Carpignano, R., Parlati, S., Piccinini, P., Savarino, P., De Giorgi, M.R. & Fochi, R. 2010.Use of ß-cyclodextrin in the dyeing of polyester with low environmental impact. *Coloration Technology*, 126:201-208.

Carrion, F.J. 2014. Influence of the dye transfer inhibitors for the washing of softened cotton fabric. *The Journal of The Textile Institute*, 105(2):150-155.

Carrion-Fité, F.J. 2014. Colour change of polyester dyed fabric during washing by ecological surfactants. *The Journal of The Textile Institute*, 105(4):1-7.

Chartrand, M.M.G. & Bunce, N.J. 2003. Electrochemical remediation of acid mine drainage. *Journal of Applied Electrochemistry*, 33:259–264.

Chen, H. & Burns, L. 2006. Environmental Analysis of Textile Products. *Clothing and Textiles Research Journal*, 24(3):248-261.

Chequer, F.M.D., De Oliveira, G.A.R., Ferraz, E.R.A., Cardoso, A.C., Zanoni, M.V.B. & De Oliveira, D.P. 2013. Textile Dyes: Dyeing Process and Environmental Impact. *In* Günay, M. (ed.) *Eco-Friendly Textile Dyeing and Finishings*. InTech, http://www.intechopen.com/books/eco-friendly-textile-dyeing-and-finishing/textile-dyes-dyeing-process-and-environmental-impact (Accessed October, 2014).

Choi, K., Cho, G., Kim, P. & Cho, C. 2004. Thermal Storage/Release and Mechanical Properties of Phase Change Materials on Polyester Fabrics. *Textile Research Journal,* 74:292-296

Choudhury, A.K.R. 2006. *Textile Preparation and Dyeing*. New Hampshire:Science Publishers.

Chowdhury, M.A., Butola, B.S. & Joshi, M. 2013. Application of thermochromic colorants on textiles: temperature dependence of colorimetric properties. *Coloration Technology*, 129:232-237.

Chu, P. & Tang, R. 2014. Acid and cationic dyeing of nylon/cationic dyeable nylon mixture. *Industria Textilă*, 65(4):233-238.

Chupa, J., Misner, S., Sachdev, A. & Smith, G.A. 2003. Soap, Fatty Acids, and Synthetic Detergents. *In* Kent, J.A. (ed.) *Riegel's Handbook of Industrial Chemistry*. 10thed. New York: Kluwer Academic/Plenum Publishers. 1694-1741.

Collier, B.J. & Tortora, P.G. 2001. *Understanding Textiles*. 7th Ed. New Jersey:Prenctice Hall.

Cotton Incorporated. 2011. The life cycle inventory & life cycle assessment of cotton fiber & fabric. *Eco Textile News*, 45. Supplementary leaflet.

CPMA. 2013. *Production Technologies*, Chemicals & Petrochemicals Manufacturers' Association India, http://cpmaindia.com/nfy_about.php (accessed October, 2013).

Craver, C.D. & Carraher, C.E. 2000. *Applied Polymer Science: 21st Century*. Amsterdam:Elsevier.

Cronjé, N., Steyn, H.J.H & Schall, R. 2013. A Comparison Of The Influence Of Catholyte Vs Phosphate Detergent On The Mechanical Properties Of Polyamide 6,6 Woven Fabric. *South African Journal of Family Ecology and Consumer Sciences*, 41:1-11.

De Giorgi, M.R., Cadoni, E., Maricca, D. & Piras, A. 2000. Dyeing polyester Fibres with disperse dyes in supercritical CO_2. *Dyes and Pigments*, 45:75-79.

Doh, S.J. 2004. A Study On The Effects Of Textile Processing On Tensile Properties Of Single Cotton Fibers - From Raw Cotton To Washed Garments. Doctor of Philosophy. Fiber and Polymer Science, North Carolina State University.

Doyal, M. & Warnock, M. 2005.Effects of Laundering on Reactive- and Direct-Dyed Cotton Fibers. *Summaries of Arkansas Cotton Research 2005*: Research Series 543:263-265.

Edser, C. 2007. Let's concentrate on laundry detergents. *Focus on surfactants*, June:1-2.

ECA Technoloiges Africa. 2013. Electrolysed Water solutions of ECA Technologies Africa® units.

Eco Textile. 2011. Benchmark cotton LCA launched. *Eco Textile News*, 45:32-33.

Elsasser, V.H. 2010. *Textiles : concepts and principles*. 3rd Ed. New York: Fairchild books.

Epolito, W.J,, Lee, Y.H., Bottomley, L.A. & Pavlostathisa, S.G. 2005. Characterization of the textile anthraquinone dye Reactive Blue 4. *Dyes and Pigments*, 67:35-46.

European Union. 2012. Regulation (EU) No 259/2012 of the European Parliament and of the Council of 14 March 2012. Official Journal of the European Union, L 94/16-L 94/21.

Farrell, M., Smith, B., May, R. & Abbot, M. 2011. Real-Time Monitoring For Sustainable Fiber Reactive Dyeing Processes. *AATCC Review*, September:44-48.

Ferus-Comelo, M. 2009. Dye demand/supply ratio as a predictor for the unlevelness of disperse-dyed polyester. *Coloration Technology*, 125:352-356.

Fité, F.J.C. 1995. Dyeing polyester at Low Temperatures: Kinetics of Dyeing with Disperse Dyes. *Textile Research Journal*, 65(6):362-368.

Forostyan, Y.N., Forostyan, E.I. & Soroka, I.I. 1987. Influence of Electrochemically activated water on lignin. *Chemistry of Natural Compounds*, 23(3):353-354.

Freeman, H.S. & Mock, G.N. 2003. Dye Application, Manufacture of Dye Intermediates and Dyes. *In* Kent, J.A. (ed.) *Riegel's Handbook of Industrial Chemistry*. 10thed. New York: Kluwer Academic/Plenum Publishers. 499-590.

Fried, J. R. 1995. *Polymer Science and Technology*. Prentice Hall. New Jersey.

Fu, S. Hinks, D., Hauser, P. & Ankeny, M. 2013.High efficiency ultra-deep dyeing of cotton via mercerization and cationization. *Cellulose*, 20:3101-3110.

Fung, K.Y., Ng, K.M. & Tsui, W.T.M. 2011. Toward Zero Water Consumption in Dyeing Plants. *AATCC Review*, 11(2):41-45.

Gharanjig, K., Sadeghi-Kiakhani, M., Arami, M., Mahmoodi, N.M. & Khosravi, A. 2010. Solubilisation kinetics of some monoazonaphthalimeddisperse dyes containing butyric acid and investigation of fastness properties of the dyes on polyester. *Coloration Technology*, 126:37-41.

Ghorabi, S., Rajabi, L., Madaeni, S.S., Zinadini, S. & Derakhshan, A.A. 2012. Effects of three surfactant types of anionic, cationic and non-ionic on tensile properties and fracture surface morphology of epoxy/MWCNT nanocomposites. *Iranian Polymer Journal*, 21:121–130.

Gidarakos, E. & Giannis, A. 2006. Chelate agents enhanced electrokinetic remediation for removal cadmium and zinc by conditioning Catholyte pH. *Water, Air, and Soil Pollution*, 172:295-312.

Gong, Y. & Yang, G. 2009. Manufacturing and physical properties of all-polyamide composites. *Journal of Materials Science*, 44(17):4639-4644.

Goodpaster, J.V. & Liszewski, E.A. 2009. Forensic analysis of dyed textile fibers. A*nalytical and bioanalytical chemistry,* 394:2009-2018.

Gruszka, I., Lewandowski, S., Benko, E. & Perzyna, M. 2005. Structure and Mechanical Properties of Polyamid Fibres. *Fibres & Textiles in Eastern Europe*, 13(5):133-136.

Gulabivala, K., Stock, C.J.R., Lewsey, J.D., Gori, S., Ng, Y. & Spratt, D.A. 2004. Effectivenss of electrochemically activated water as an irrigant in an infected tooth model. *International Endodontic Journal*, 37:624-631.

Gupta, B.S. 2003. Manufactured Textile Fibres. *In* Kent, J.A. (ed.) *Riegel's Handbook of Industrial Chemistry*. 10thed. New York: Kluwer Academic/Plenum Publishers. 431-498.

Hatch, K.L. 1993. *Textile Science*. West Publishing Co:St. Paul.

Hauser, P.J. & Tabba, A.H. 2001. Improving the environmental and economic aspects of cotton dyeing using a cationised cotton. *Coloration Technology*, 117:282-288.

Hollis, G. 2002. Surfactants in the Global World. *Focus on Surfactants*, 11:1-1.

Horrocks, A.R. & Anand, S.C. 2000. *Handbook of Technical Textiles*. Elsevier.

Huang, H., Ma, W., Zhang, S. & Lu, R. 2011. Optimal Dyeing Systems for Resistance to the Physical Strength Loss of the PLA/cotton Blended Fabric. *Journal of Applied Polymer Science*, 120:886–895.

Hui, K.S. & Chao, C.Y.H. 2006. Pure, single crystalline, chamfered-edge zeolite 4A synthesized from coal fly ash for use as a builder in detergents. *Journal of Hazardous Materials*, 137:401-409.

Humphries, M. 2009. *Fabric Reference*. 4th Ed. New Jersey: Prentice Hall.

Hunger, K. 2003. *Industial Dyes: Chemistry, Properties, Applications*. Hoboken: John Wiley & Sons.

Ingamells, W. 1993. *Colour for textiles: A user's handbook*. West Yorkshire: Society of Dyers and Colourists.

Inglesby, M.K. & Zeronian, S.H. 2002.Direct dyes as molecular sensors to characterize cellulose substrates. *Cellulose*, 9:19-29.

Ivanković, T. & Hrenović, J. 2010. Surfactants in the environment. *Archives of Industrial Hygiene an Toxicology,* 61:95-110

Jackman, D., Dixon, M. & Condra, J. 2003. *The Guide to Textiles for Interiors*. 3rd ed. Winnipeg: Portage & Main Press.

Jahagirdar, C.J. & Tiwari, L.B. 2004. Study of Plasma Polymerization of Dichloromethane on Cotton and Polyester Fabrics. *Journal of Applied Polymer Science*, 94: 2014–2021.

Jang, J., Ko, S.W. & Carr, C.M. 2001. Investigation of the improved dyeability of cationised cotton via photografting with UV active cationic monomers. *Coloration Technology*, 117:139-146.

Jihong, Y.Z. & Shuilin, C. 2005. Dyeing of polyester using micro-encapsulated disperse dyes in the absence of auxiliaries. *Coloration Technology*, 121:76-80.

Johnson, I. & Cohen, A. 2010. *J. J. Pizzuto's Fabric Science*. 9thed. New York: Fairchild Books.

Julkapli, N.M., Bagheri, S. & Hamid, S.B.A. 2014. Recent Advances in Heterogeneous Photocatalytic Decolorization of Synthetic Dyes. *Scientific World Journal*, 2014:1-25.

Jung, J. & Sun, G. 2001.Recovery of Sodium Sulfate from Farm Drainage Salt for use in Reactive Dyeing of Cotton. *Environmental Science and Technology*, 35(16):3391-3395.

Kadolph, S. J. 2010. *Textiles*. New Jersey: Pearson Education LTD.

Kadolph, S.J. 2007. *Quality assurance for textiles and apparel*. New York: Fairchild.

Karahan, H.A., Özdoğan, E., Demir, A., Ayhan, H. & Seventekin, N. 2008. Effects of atmospheric plasma treatment on the dyeability of cotton fabrics by acid dyes. *Coloration Technology*, 124:106-110.

Khurana, R. 2002. Detergents: Counting the cost of cleanliness. *Toxics Link Factsheet*, 16:1-6.

Kim, T & Jeon, S. 2013. Coloration of Ultra High Molecular Weight Polyethylene Fibers Using Alkyl-substituted Monoazo Yellow and Red Dyes. *Fibers and Polymers*, 14(1):105-109.

Kiumarsi, A. & Parvinzadeh, M. 2010. Enzymatic Hydrolysis of Nylon 6 Fiber Using Lipolytic Enzyme. Journal ofApplied Polymer Science,116:3140–3147.

Kissa, E. 1987. Kinetics and Mechanism of Soiling Detergency. Detergency: Theory and Technology. Marcel Dekker: New York.

Kirkpatrick, R.D. 2009. The mechanism of antimicrobial activity of Electro-Chemically Activated (ECA) water and its healthcare applications. Doctor of Philosophy. Faculty of Natural and Agricultural Sciences, University of Pretoria: Pretoria.

Knud-Hansen, C. 1994. Historical Perspective of the Phosphate Detergent Conflict. *Conflict Research Consortium*, February, Working Paper.

Koh, J. 2011. Dyeing with Disperse Dyes. *In* Hauser, P.J. (ed.) *Textile Dyeing*. InTech, Available from: http://www.intechopen.com/books/textile-dyeing/dyeing-with-disperse-dyes.

Koh, J., Yoo, Y.H. & Kim, J.P. 2004. One-bath dyeing of poly(ethylene-terephthalate)/cotton blends with alkali-clearable azo disperse dyes containing a fluorosulphonyl group. *Coloration Technology*. 120:156-160.

Köhler, J. 2006. Detergent phosphates: an EU policy assessment. *Journal of Business Chemistry* 3(2):15-30.

Konika Minolta. 1998. Precise Color Communication: Color control from Perception to Instrumentation.

Kothari, V.K., Ishtiaque, S.M. & Ogale, V.G. 2002. Tensile properties of polyester/cotton blended yarns. *Indian Journal of Fibre & Textile Research*, 27:48-51.

Kulkarni, V.G. 2005. Recent advances in colour and functional masterbatches for man-made fibers. *Chemical Fibers International*, 6:379-381.

Kumar, A. & Gupta, R.K. 1998. *Fundamentals of Polymers*. New York: McGraw-Hill.

Krichevskii, G.E. 2001. Textile materials made from polyester fibres – A most difficult material to color. *Fibre Chemistry*, 33(5):364-367.

Laitala, K., Boks, C. & Klepp, I.G. 2011.Potential for environmental improvements in laundering. *International Journal of Consumer Studies*, 35:254-264.

Lau, L., Fan, J., Siu, T. & Siu, L.Y.C. 2002. Effects of Repeated Laundering on the Performance of Garments with Wrinkle-Free Treatment. *Textile Research Journal,* 72: 931-937.

Lee, SK., Lee, H.Y., Kim, S.D. 2013. Dyeing Properties of Mixture of Ultrafine Nylon and Polyurethane with Different Types of Dye. *Fibers and Polymers*, 14(12):2020-2026.

Leidreiter, H.I., Gruning, B. & Kaseborn, D. 2008. Amphoteric Surfactants: Processing, product composition and properties. *International Journal of Cosmetic Science*, 19(5):239-253.

Leonov, B. I. 1997. Electrochemical activation of water and aqueous solutions; Past, present and future. First International Symposium on Electrochemical Activation, Moscow, p11-27.

Lewis, D.M. & Vo, L.T.T. 2007. Dyeing cotton with reactive dyes under neutral conditions. *Coloration Technology*, 123:306-311.

Lin, J., Winkelmann, C., Wordley, S.D., Kim, J., Wei, C-I., Cho, U., Broughton, R.M., Santiago, J.I. & Williams, J.F. 2002. Biocidal Polyester. *Journal of Applied Polymer Science*, 85: 177–182.

Lipus, L.C., Ačko, B., Neral, B. 2013. Influence of magnetic water treatment on fabrics' characteristics. *Journal of Cleaner Production*, 52:374-379.

Liu, X. & Wang, X. 2007. A Comparative Study on the Felting Propensity of Animal Fibers. *Textile Research Journal*, 77(12):957-963.

Lobyshev, V.I. 2007. Electrochemically Activated Water. Second Annual Conference on *The Physics, Chemistry and Biology of Water*, October, p1.

Marais, J.T. & Brözel, V.S. 1999. Electro-chemically activated water in dental unit water lines. *British Dental Journal*, 187:154-158.

Mather, R.R. & Wardman, R.H. 2011. *The Chemistry of Textile Fibres*. RSC Publishing: Cambridge.

Mazumder, S. & Haque, M. 2011. Importance of fixing agent on the colour fastness of reactive dyestuff orignated from various dye manufacturers. *Dyeing Printing Finishing*, 44-47.

McLean, R.J. 1999. Understanding Interactions between Detergents with Bleach and Textiles. *Textile Chemist and Colorist & American Dyestuff Reporter*, 1(4):42-45.

Moe, K. 2000. With Bleach Detergents: How They Work. *AATCC Review*, 32(8):79-81.

Miller, C.A. & Raney, K.H. 1993. Solubilization —emulsification mechanisms of detergency. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 74(2-3):169-215.

Min, L., Xiaoli, Z. & Shuilin, C. 2003. Enhancing the wash fastness of dyeings by a sol-gel process. Part 1: Direct dyes on cotton. *Coloration Technology*, 119:297-300.

Miroshnikov, A.I., Msalimov, Z.K., & Bruskov, V.I. 2004. Concentration of Hydrogen Peroxide in Electrochmically Activated solutions and Study of Its Effect on *Escherichia coli* Growth. *Biophysics*, 49(1):27-32.

Mohsin, M., Rasheed, A., Farooq, A., Ashraf, M. & Shah, A. 2013. Environment friendly finishing of sulphur, vat, direct and reactive dyed cotton fabric. *Journal of Cleaner Production*, 53:341-347.

Mokhtari, J., Gharanjig, K., Arami, M. & Mahmoodi, N.M. 2008. Novel hydrolysable azo disperse dyes based on N-ester-1,8-naphthalimide: dyeing of polyester–cotton blends. *Coloration Technology*, 124:295-300.

Mowbray, J. 2011. Naturally synthetic. *Eco Textile News*, August/September, 44:23-26.

Munshi, V.G., Ukidve, A.V., Raje, C.R., Bhaskar, P. & Pai, S.D. 1992.Effect of laundering on the mechanical properties of apparel fabrics. *Resume of papers: Technological conference*, February:177-179.

Nielsen, J.D. & Munk, S. 2009. Low temperature laundering: life cycle assessment. *IOP Conference Series: Earth and Environmental Science* 6:202024.

Oakes, J. 2005. Formulation of colour-care and heavy-duty detergents: a review. *Coloration Technology*, 121:1-6.

Oakes, J., Gratton, P., Dixon, S. 2004a. Solubilisation of dyes by surfactant micelles. Part 5: Durability of dye fixatives. *Coloration Technology*, 120:276-283.

Oakes, J., Gratton, P., & Dixon, S. 2004b. Solubilisation of dyes by surfactant micelles. Part 4: Influence of dye fixatives. *Coloration Technology*, 120:267-275.

Parmar, S. & Gurumoorthi, E. 2011. *Study of the Variation of results in Color Fastness to Rubbing Test*. Fibre 2 Fashion, http://www.fibre2fashion.com/industry-article/34/3333/study-of-variation-of-results-in-color-fastness-to-rubbing-test1.asp (accessed October, 2014).

Parvinzadeh, M. 2007. The Effects of Softeners on the Properties of Sulfur-Dyed Cotton Fibers. *Journal of Surfactants and Detergents*, 10:219-223.

Patterson, P. 2011. The pollution solution. *Eco Textile News*, August/September, 44:50-52.

Petrushanko, I. & Lobyshev, V.I. 2001. Nonequilibrium state of electrochemically activated water and its biological activity. *Biofizika*, 46(2):389-401.

Phillips, D., Taylor, J., Lakhanpal, R., Scotney, J. & Bevan, G. 2001. Comparison of the performance of zeolite-containing and phosphate-containing ECE reference deterents in three different wash fastness tests. *Coloration Technology*, 117:6-12.

Phillips, D., Taylor, J., Lakhanpal, R., Hall, R., Bailey, J., Bevan, G., Lloyd, J., Hoffmeister, J. & McKelvey, D. 2000. The color fastness of optionally aftertreated direct dyes on cotton during washing in an activated oxygen bleach-containing detergent. *Journal of the Society of Dyers and Colorists*, 116:229-235.

Prilutsky, V.I. and Bakhir, V.M. 1997. Electrochemically Activated Water: Anomalous properties, Mechanism of biological action. *All Russian Scientific Research and Experimental Institute of Medical Engineering* (VNIIIMT), UDK 621.357:541.13.

Popova, I.Y., Kiselev, V.I. & Lobyshev, V.I. 1999. On the nature of Biological activity of water and aqueous solutions after treatment in the diaphragm electrolyser. Conference on Biophotons, 31-32.

Pillay, M. 1994. Detergent Phosphorus in South Africa: Impact on Eutrophication with Specific Reference to the Umgeni Catchment. Master of Science: Engineering, University of Natal.

Quayle, L.M., Dickens, C.W.S, Graham, M., Simpson, D., Goliger, A., Dickens, J.K., Greese, S. & Blignaut, J. 2010. Investigation of the positive and negative consequences associated with the introduction of zero-phosphate detergents into South Africa. *Institute of Natural Resources*, Technical Report TT446/10.

Radhika, R. & Moses, J.J. 2014. Study On Dyed And Finished Modal, Cotton And Modal/Cotton (50:50) Blend Fabrics For Their Color Strength And Fastness Properties. *International Journal of Engineering Research and Science & Technology*, 3(2):24-37.

Raslan, W.M., Bendak, A., Khalil, E.M. & Fawzi, T. 2010. Modification of polyester fabric by chemical/thermal treatment to improve dyeing ability. *Coloration Technology*, 126:231-236.

Ristić, N. & Ristić, I. 2012. Cationic Modification of Cotton Fabrics and Reactive Dyeing Characteristics. *Journal of Engineered Fibers and Fabrics,* 7(4):113-121.

Rizk, H.F., Ibrahim, S.A. & El-Borai, M.A. 2015. Synthesis, fastness properties, color assesment and antimicrobial activity of some azo reactive dyes having pyrazole moiety. *Dyes and Pigments*, 112:86-92.

Ruscher, T. 2004. Polyamide – A Versatile Fiber That Places High Demands on Textile Finishers. *Asian Textile Business*, February, 591:61-63.

Sadeghi-Kiakhani, M., Gharanjig, K., Arami, M. & Khosravi, A. 2011. Dyeing and Fastness Properties of Polyamide Fabrics Using Some Acid-Based Monoazo Disperse Dyes. *Journal of Applied Polymer Science*, 122:3390–3395.

Samanta, A.K., Mitra, S., Singhee, D. & Parekh, S. 2004. Efficacy of selective surfactants/detergents as washing agents on soiled white and dyed cotton fabrics. *Indian Journal of Fibre & Textile Research*, 29:223-332.

Samanta, A.K., Chattopdhyay, D.P., Konar, A. & Sharma, D.N. 2003. Selective chemical pretreatments and post-treatments on microdenier polyester fabric for improving surface depth of colour. *Indian Journal of Fibre & Textile Research*, 28:76-85.

Saravan, D., Vasanthi, N.S. & Ramachandran, T. 2009. A review on influential behaviour of biopolishing on dyeability and certain physico-mechanical properties of cotton fabrics. *Carbohydrate Polymers* 76:1–7.

SAS Institute Inc. *SAS/STAT 9.2 User's Guide, Second Edition*. Cary, NC: SAS Institute Inc, 2009

Schindler, W.D. & Hauser, P.J. 2004. *Chemical finishing of textiles*. Cambridge:Woodhead Publishing Limited.

Schroeder, M., Lenting, H.B.M., Kandelbauer, A., Silva, C.J.S.M., Cavao-Paulo, A. & Gubitz, G.M. 2006. Restricting detergent protease action to surface of protein fibres by chemical modification. *Applied Microbiology and Biotechnology*, 72(4):738-744.

Senthilkumar, M. & Selvakumar, N. 2011. A study on the effect of bulk water content and drying temperature on the colour of dyed cotton fabrics. *Coloration Technology*, 127:145-152.

Shamey, R. & Hussein, T. 2005. Critical Solutions in the Dyeing of Cotton Textile Materials. *Textile Progress*, 37:1-84.

Shurkian, O., Amirbayat, J. & Gong, R.H. 2002. Effects of Repeated Laundering and Crease-Resistant Treatment on Fabric Properties. *Journal of Textile Engineering*, 48(1):1-4.

Singa, K. 2013. Characterization of Dyeing P/C Blends Fabric: a Thermodynamic View. *International Journal of Textile Science* 2(1):1-6.

Sirianuntapiboon, S. & Srisornsak, P. 2007. Removal of disperse dyes from textile wastewater using bio-sludge. *Bioresource Technology*, 98:1057-1066.

Slater, K. 2003. *Environmental Impact of Textiles: Procuction, processes and protection*. Cambridge: Woodhead Publishing Ltd.

Solovyeva, A.M. & Dummer, P.M.H. 2000. Cleaning effectiveness of root canal irrigation with electrochemically activated anolyte and catholyte solutions: a pilot study. *International Endodontic Journal*, 33:494-504.

Sonaje, N.P., & Chougule, M.B. 2013. Experimental Analysis of Washing and Rubbing Fastness of Cotton Fabric Processed With Recycled Wastewater Using Different Dyes. *International Journal of Emerging Science and Engineering*, 1(10):29-37.

Stevens, M.P. 1999. *Polymer Chemistry: An Introduction*. New York: Oxford University Press.

Suganuma, K. 2013. Effect of the rubbing force on dry rubbing fastness with various white cloths. *Coloration Technology*, 129:443–447.

Sun, D. & Stylios, G.K. 2012. Cotton Fabric Mechanical Properties Affected by Post-finishing Processes. *Fibers and Polymers*, 13(8)1050-1057.

Taylor, J.A., Pasha, K. & Phillips, D.A.S. 2001.The dyeing of cotton with hetero bi-functional reactive dyes containing both a monochlorotriazinyl and a chloroacetylamino reactive group. *Dyes and Pigments*, 51:145-152.

Terinte, N., Manda, B.M.K., Taylor, J., Schuster, K.C. & Patel, M.K. 2014. Environmental assessment of coloured fabrics and opportunities for value creation: spin-dyeing versus conventional dyeing of modal fabrics. *Journal of Cleaner Production,* 72:127-138.

Thantsha, M.S. & Cloete, T.E. 2006. The effect of sodium chloride and sodium bicarbonate derived anolytes, and anolyte-catholyte combination on biofilms. *Water SA*, 32(2):237-242.

Thorn, R.M.S., Lee, S.W.H., Robinson, G.M., Greenman, J. & Reynolds, D.M. 2011. Electrochemically activated solutions: evidence for antimicrobial efficacy and applications in healthcare environments. *European journal of clinical microbiology & infectious diseases*, 31(5):641-653.

Tomilov, A.P. 2002. Electrochemical Activation: a New Trend in Applied Electrochemistry. *Zhizn & Bezopasnost (Russian Life and Safety)*, 3:302-307.

Uğur, S.S., Saruşik, M. Usluoglo, A.H.A. 2011. Nano-TiO2 Based Multilayer Film Deposition on Cotton Fabrics for UV-Protection. *Fibers and Polymers*, 12(2):190-196.

Usluoglu, A. & Arabaci, G. 2014. Bleaching of Cotton/polyamide fabrics with enzymes and peracetic acid. *Asia-Pacific Journal Of Chemical Engineering*, 9:364–367.

Van der Kraan, M., Fernandez Cid, M.V., Woerlee, G.F., Veugelers, W.J.T. & Witkamp, G.J. 2007. Dyeing of natural and synthetic textiles in supercritical carbon dioxide with disperse reactive dyes. *Journal of Supercritical Fluids*, 40:470-476.

Van Ginkel, C.E. 2011. Eutrophication: Present reality and future challenges for South Africa. *Water SA* 37(5): 693-702.

Van Heerden, N., Steyn, H.J.H & Schall, R. 2012. Soil Removal Efficacy of Catholyte on Polyamide 6,6 Fabric. *Chinese Business Review*, 11(7):682-689.

Van Heerden, N. 2010. The Evaluation Of Electro-Chemically Activated Water As An Alternative Detergent For Polyamide And Machine Washable Wool. Master of Science. Faculty of Natural and Agricultural Sciences, University of the Free State: Bloemfontein.

Van Zyl, J.S. 2012. Katoliet as detergent vir katoen-, poliëster en poliësterkatoenmengelstof. Magister Scientiae. Fakulteit Natuur en Landbouwetenskappe, Universiteit van die Vrystaat: Bloemfontein.

Vasconcelos, A., Silva, C.J.S.M., Schroeder, M., Guebitz, G. M. & Cavaco-Paulo, A. 2006. Detergent formulations for wool domestic washings containing immobilized enzymes. *Biotechnology Letters*, 28(10):725-731.

Wang, L., Pan, X., Wang, F., Yang, L. & Liu, L. 2008. Structure-properties relationships investigation on the azo dyes derived from benzene sulfonamide intermediates. Dyes and Pigments, 76:636-645.

Warne, M.J. & Schifko, A. D. 1999. Toxicity of Laundry Detergent Components to a Freshwater Cladoceran and Their Contribution to Detergent Toxicity. *Ecotoxiocology and Environmental Safety*, 44:196-206.

Was-Gubala, J. 2009. The kinetics of colour change in textiles and fibres treated with detergent solutions Part I – Colour perception and fluorescence microscopy analysis. *Science and Justice,* 49:165–169.

Was-Gubala, J. & Grzesiak, E. 2010. The kinetics of colour change in textiles and fibres treated with detergent solutions Part II – Spectrophotometric measurements. *Science and Justice*, 50:55-58.

Wiechers, H.N.S. & Heynike, J.C. 1986. Sources of phosphorus which give rise to eutrophication in South African waters. *SA Water*, 12(2):99-102.

Wu, J. & Pan, N. 2005. Grab and Strip Tensile Strengths for Woven Fabrics: An Experimental Verification. *Textile Research Journal*, 75(11):789-796.

Wynne, A. 1997. *Textiles*. Oxford: Macmillan.

Xiao, J., Zhang, S. & Yang, J. 2007. Studies on dyeing method and dyeing properties of a sulphur black dye containing carboxylic acid groups on cotton. *Coloration Technology*, 123:191-196.

Xie, K., Hou, A., Shi, Y. & Xie, J.Y. 2007. The surface polymerising of fluoromonomer and the shade-darkening effect on dyed polyester microfibre fabric. *Coloration Technology*, 123:293–297,

Yin, Y., Wang, C. & Wang, C. 2008. An evaluation of the dyeing behavior of sol–gel silica doped with direct dyes. *Journal of Sol-Gel Science and Technology,* 48:308–314.

Yu, H., Wang, Y., Zhong, Y., Mao, Z. & Tan, S. 2014. Foam properties and application in dyeing cotton fabrics with reactive dyes. *Coloration Technology*, 130:1-7.

ABSTRACT

Colour is one of the most significant factors in the appeal and marketability of textile products. Cotton, polyester and polyamide 6,6 are the most prominent groups of fibres used in the world. A Life Cycle Assessment done on textile products revealed that the area of greatest environmental impact is the consumer use phase, due to the laundering habits for the care of these products over its life span. With the development of electrochemically activated water (Catholyte) and some research done to suggest it might be an environmentally friendly alternative detergent for laundering; the environmental impact during the consumer phase can therefore be considerably scaled down. The influence of Catholyte on the colourfastness of textiles is, however, unknown. Thus it was the aim of this study to determine the influence of Catholyte on certain colourfastness properties of dyed cotton, polyester and polyamide 6,6 textile fabrics.

The sulphur, direct, reactive and azoic dyed cotton, disperse dyed polyester and acid dyed polyamide 6,6 textile fabrics were laundered (AATCC 61) with Catholyte, detergent and filtered water at 40°C and 60°C for five, ten, twenty or fifty cycles respectively. Wash fastness and staining (AATCC Evaluation Procedure 6) were measured instrumentally with a Konika Minolta Spectrophotometer 2300d using illuminant $D_{65}10°$ standard observer. Colourfastness to rubbing, dry and wet (AATCC 8), as well as tensile strength (SANS 1092) was also evaluated. The colorimetric data obtained was converted to Gray scale ratings (AATCC Evaluation Procedure 12).

The results indicate that laundering with Catholyte caused slightly less Gray scale values as opposed to laundering with detergent, with regards to sulphur and direct black dyed cotton. Higher wash fastness was observed when reactive black and direct red dyed cotton samples were laundered with Catholyte, as opposed to laundering with detergent. When laundering disperse red dyed polyester, acid red dyed polyamide, azoic orange, reactive red, blue, violet and green dyed cotton, with both Catholyte and detergent indicated similar wash fastness results.

Staining results indicate that laundering sulphur black, reactive black, red, blue and violet, azoic orange dyed cotton and acid red dyed polyamide with detergent resulted in less staining than laundering with Catholyte. Laundering direct black dyed cotton resulted in less staining when laundered with Catholyte, compared to laundering with detergent. Regardless of laundering the disperse red dyed polyester, direct red and reactive green dyed cotton with either Catholyte or detergent, similar staining results were observed.

The influence of both Catholyte and detergent on the colourfastness to dry rubbing of sulphur black, direct black and reactive black and red, azoic orange dyed cotton and acid red dyed polyamide were similar. Laundering the disperse red dyed polyester and the direct red, reactive green and blue dyed cotton, resulted in slightly higher colourfastness to dry rubbing when laundered with detergent. Laundering the reactive violet dyed cotton with Catholyte resulted in better colourfastness to dry rubbing when compared to laundering with detergent.

Laundering the direct black, reactive black, red, blue, violet and green, azoic orange dyed cotton, disperse red dyed polyester and acid red dyed polyamide with Catholyte and detergent resulted in similar colourfastness to wet rubbing. Laundering the sulphur black and direct red dyed cotton with detergent resulted in slightly less colourfastness to wet rubbing when compared to laundering with Catholyte.

Laundering sulphur black, reactive black and violet, direct red and azoic orange dyed cotton with detergent, caused greater loss in tensile strength as opposed to laundering with Catholyte. Laundering the direct black and reactive red, blue and green dyed cotton, disperse red dyed polyester, acid red dyed polyamide with Catholyte, caused greater loss in tensile strength.

Key words: Catholyte, wash fastness, colourfastness, tensile strength, textiles dyes

OPSOMMING

Kleur is een van die belangrikste faktore in die aanloklikheid en bemarking van tekstielprodukte. Katoen, poliëster en poliamied 6,6 is die prominentste groepe van vesels wat in die wêreld gebruik word. 'n Lewensiklus-analise wat op tekstielprodukte gedoen is, dui aan dat die verbruikersfase die grootste aandeel in omgewingsimpak het. Dit sluit wasgewoontes en versorging van tekstielprodukte in. Die ontwikkeling van elektrochemies-geaktiveerde water (Catholyte), tesame met navorsing wat aandui dat dit moontlik 'n omgewingsvriendelike alternatief tot wasdetergente kan wees; kan dalk die omgewingsimpak gedurende die verbruikersfase aansienlik verminder. Die invloed van Catholyte op die kleurvastheid van tekstiele is egter onbekend. Dit was dus die doel van hierdie studie om die invloed van Catholyte op sekere kleurvastheid eienskappe van gekleurde katoen, poliëster en poliamied 6,6 tektielstowwe te bepaal.

Die swael-, direk-, reaktief- en aso gekleurde katoen, dispersie gekleurde poliëster en suur gekleurde poliamied 6,6 tekstielstowwe is met Catholyte, detergent en filtreerde water by 40°C en 60°C vir vyf, tien, twintig of vyftig siklusse, onderskeidelik gewas (AATCC 61). Wasvastheid en vlekkking (AATCC Evaluasie Prosedure 6) is instrumenteel met 'n Konika Minolta Spektrofotometer 2300d gemeet, en 'n illuminant $D_{65}10°$ standaard observeerder is gebruik. Kleurvastheid tot afvrywing, droog en nat (AATCC 8), asook treksterkte (SANS 1092) is geëvalueer. Die kolometriese data wat verkry is, is omgeskakel na Grysskaal waardes (AATCC Evaluasie Prosedure 12) toe.

Die resultate dui aan dat om met Catholyte te was, effense laer Grysskaal waardes in vergelyking met detergent, ten opsigte van swael- en direk swart gekleurde katoen tot gevolg het. Hoër wasvastheid is opgemerk wanneer reaktief swart- en direk rooi gekleurde katoen met Catholyte gewas is, in vergelyking met dit wat met detergent gewas is. Wanneer dispersie rooi gekleurde poliëster, suur rooi gekleurde poliamied, aso oranje-, reaktief rooi-, blou-, violet- en groen gekleurde katoen, met beide Catholyte en detergent gewas is, is soortgelyke wasvastheid ondervind.

Vlekresultate dui aan dat die swael swart-, reaktief swart-, rooi-, blou- en violet-, aso oranje gekleurde katoen en suur rooi gekleurde poliamied met detergent te was, minder gevlek het as om dit met Catholyte te was. Om direk swart gekleurde katoen met Catholyte te was het minder vlekking veroorsaak as om met detergent te was. Soortgelyke resultate is verkry deur dispersie rooi gekleurde poliëster, direk rooi en reaktief groen gekleurde katoen met Catholyte of detergent te was.

Die invloed van Catholyte en detergent op die kleurvastheid tot afvrywing, droog, vir swael swart-, direk swart- en reaktiewe swart- en rooi-, en aso oranje gekleurde katoen was soortgelyk. Om die dispersie rooi gekleurde poliëster en direk rooi gekleurde, reaktief groen- en blou gekleurde katoen met detergent te was het beter kleurvastheid tot gevolg gehad. Om die reaktief violet gekleurde katoen met Catholyte te was het beter kleurvastheid tot afvrywing, droog, gehad vergeleke met detergent.

Om die direk swart-, reaktief swart-, rooi-, blou-, violet- en groen-, aso oranje gekleurde katoen, dispersie rooi gekleurde poliëster en suur rooi gekleurde poliamied met Catholyte en detergent te was het soortgelyke vastheid tot afvrywing, nat, gehad. Om die swael swart- en direk swart gekleurde katoen met detergent te was het effens minder kleurvastheid tot afvrywing, nat, gehad in vergelyking om met Catholyte te was.

Om die swael swart-, reaktief swart- en violet-, direk rooi- en aso oranje gekleurde katoen met detergent te was, het ‘n groter verlies in trektsterkte tot gevolg gehad as wanneer dit met Catholyte gewas is. Om die direk swart- en reaktief rooi-, blou- en groen gekleurde katoen, dispersie rooi gekleurde poliëster, suur rooi gekleurde poliamied met Catholyte te was, het ‘n groter verlies in treksterkte veroorsaak as om met detergent te was.

Sleutelwoorde: Catholyte, wasvastheid, kleurvastheid, treksterkte, tekstiel kleurstowwe