

**THE EVALUATION OF ELECTRO-CHEMICALLY
ACTIVATED WATER AS AN ALTERNATIVE
DETERGENT FOR POLYAMIDE AND MACHINE
WASHABLE WOOL.**

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

Samuel Johnson

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CHAPTER 1: Introduction

1.1 General Introduction

Laundrying textile fabrics is an integral part of life as we know it and it forms part of every household (Hollis, 2002:1). Although it is a chore that is done on a daily basis, it remains a complex process (Fijan, Turk & Neral, 2007:247). Whether it is done with an automatic washing machine, by hand, with soap or with synthetic detergents (Hollis, 2002:1) the main factors contributing to this process stay the same. These factors namely; water, washing agents and mechanical action are the age old formula for washing or cleansing textile fabrics (Fijan, Turk & Neral, 2007:247).

Laundry detergents are commonly used washing agents (Hollis, 2002:1) that are consumed in almost every household in the developed world (Cameron, 2007:151). The popularity of laundry detergents is increasing more and more because it can be added automatically to the water in the washing machine (Bajpai & Tyagi, 2007:327). In addition, synthetic detergents also impart softness, antistatic properties and resiliency to fabrics (Kadolph, 2007:419; Collier & Tortora, 2001:487).

The chemicals used in laundry detergents are however 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 laundrying has been done (Stalmans, Matthijs & De Oude, 1991:115).

Taking into consideration the immense amount of laundry detergents being consumed, some environmentalists feel that we are poisoning ourselves because billions of tons 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 fresh water supplies must be protected (Bajpai & Tyagi, 2007:335).

Phosphate is one of the most important ingredients in laundry detergents, 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 which causes the water life to die (Hui & Chao, 2006:401).

As far back as the 1980's Wiechers and Heynike (1986:99-101) reported on excessive algal and plant growth experienced in reservoirs in South Africa due to eutrophication caused by phosphate. The detergent manufacturers opposed the ban of phosphate detergents 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 efficiency. Today, phosphate detergents are still consumed in South Africa. In 2007 the U.S. detergent market had virtually no phosphate formulations whereas 68% of the European powders were still phosphate based detergents and only about 50% of the detergents in Canada contained phosphate. Latin America and some of the Pacific region countries are still using phosphate based detergents (Bajpai & Tyagi, 2007:328). It is evident that the feasibility of using alternative detergents needs to be investigated.

The recent development of electrochemically activated aqueous media has become quite a phenomenon (Lobyshev, 2007:1). The aqueous media is activated by passing water through the electrochemical cells, anode and cathode. These cells or electrodes are specifically designed to activate two different media, each of which has a unique set of properties and

characteristics (Thantsha & Cloete, 2006:237). Catholyte, which is an alkaline medium, is synthesized in the cathodic electrode (cathode). Anolyte is the acidic counterpart and it is synthesized in the anodic electrode (anode) (Bakhir, 2005).

Electrochemically activated water is used in a wide range of applications including medicine, agriculture (Lobyshev, 2007:1), microbiology and the food industry (Khrapenkov & Gernet, 2002:1). It is also used as environmentally friendly anti-microbial and aqueous washing media (Bahkir, 2005). Electrochemically activated water may also provide an environmentally sensible alternative to chlorine and other solvents that are generally used (Thantsha & Cloete, 2006:237). Catholyte as an alternative to laundry detergents is promising but the feasibility thereof still needs to be established.

Polyamide, commonly known as nylon, is an important textile fibre (Kumar & Gupta, 1998:10). The most important use of the polyamide fibres is for lingerie (Kadolph, 2007:129) and hosiery products (Gruszka, Lewandowski, Benko & Perzyna, 2005:133). Chemically, this fibre is also related to wool (Kadolph, 2007:125).

Over the last few years polyamides have received a great deal of interest. This is mainly due to the outstanding properties for example, high strength, stiffness, wear resistance and dimensional stability. These favourable properties renders polyamide 6,6 suitable for a wide variety of applications (Gaitonde, Karnik, Mata & Davim, 2010:314). Polyamides are easy to care for but tend to discolour during the laundering process (Kadolph, 2007:128).

Wool is an extremely complex and versatile natural fibre which has been refined by nature over millions of years (Azoulay, 2005:25). Wool garments have very good performance characteristics and can be shaped well through tailoring. Wool fabrics are durable and very comfortable under a variety of

conditions, but it needs special care and maintenance processes (Kadolph, 2007:71).

1.2 Research Objectives

Both polyamide and wool are important fibres in the apparel industry and are being used daily. Although electrochemically activated water may be an environmentally friendly media for washing, the influence that it has on the properties of textile materials for example polyamide and wool is still only based upon speculation. Very little is known about the soil removal efficiency of this media on polyamide and wool.

1.2.1 Research Problem

Van Zyl conducted a study to determine the influence of electrochemically activated water on certain properties of cotton, polyester and a cotton/polyester blend. She also investigated the soil removal efficiency of the electrochemically activated water on the same textile fabrics (2008). Such a study is yet to be done on wool and polyamide.

In this study, it is the aim of the researcher to determine the effect of electrochemically activated water on certain important properties of polyamide 6,6 and machine washable wool fabric.

▪ **Sub Problem**

1. To evaluate the soil removal efficiency of electrochemically activated water from polyamide 6,6 and machine washable wool.

1.3 Hypotheses

Certain properties need to be evaluated in order to determine the influence that electrochemically water and detergent has on machine washable wool and polyamide 6,6 fabric.

The following hypotheses are proposed:

1. Electrochemically activated water (catholyte) will have a significant effect on the tearing strength of machine washable wool.
2. Detergent will not have a significant effect on the tearing strength of machine washable wool.
3. Electrochemically activated water (catholyte) will not have a significant effect on the tearing strength of polyamide 6,6.
4. Detergent will not have a significant effect on the tearing strength of polyamide 6,6.
5. Electrochemically activated water (catholyte) will have a significant effect on the tensile strength of machine washable wool.
6. Detergent will not have a significant effect on the tensile strength of machine washable wool.
7. Electrochemically activated water (catholyte) will not have a significant effect on the tensile strength of polyamide 6,6.
8. Detergent will not have a significant effect on the tensile strength of polyamide 6,6.

9. Electrochemically activated water (catholyte) will have a significant effect on the bending length of machine washable wool.
10. Detergent will not have a significant effect on the bending length of machine washable wool.
11. Electrochemically activated water (catholyte) will not have a significant effect on the bending length of polyamide 6,6.
12. Detergent will not have a significant effect on the bending length of polyamide 6,6.
13. Electrochemically activated water (catholyte) will have a significant effect on the wrinkle recovery of machine washable wool.
14. Detergent will not have a significant effect on the wrinkle recovery of machine washable wool.
15. Electrochemically activated water (catholyte) will not have a significant effect on the wrinkle recovery of polyamide 6,6.
16. Detergent will not have a significant effect on the wrinkle recovery of polyamide 6,6.
17. Electrochemically activated water (catholyte) will have a significant effect on the dimensional change of machine washable wool.
18. Detergent will not have a significant effect on the dimensional change of machine washable wool.
19. Electrochemically activated water (catholyte) will not have a significant effect on the dimensional change of polyamide 6,6.

20. Detergent will not have a significant effect on the dimensional change of polyamide 6,6.

Certain measurements need to be taken to determine the soil removal efficiency of electrochemically activated water and detergent from machine washable wool and polyamide 6,6.

The following hypotheses are proposed:

21. Electrochemically activated water (catholyte) will have a significant effect on the soil removal from machine washable wool.

22. Detergent will have a significant effect on the soil removal from machine washable wool.

23. Electrochemically activated water (catholyte) will have a significant effect on the soil removal from polyamide 6,6.

24. Detergent will have a significant effect on the soil removal from polyamide 6,6.

25. The temperature will not have a significant effect on the soil removal from machine washable wool.

26. The temperature will not have a significant effect on the soil removal from polyamide 6,6

1.4 Conceptual Framework

Figure 1.1 (page 8) is a flow diagram illustrating the systematic planning in order to determine the influence of catholyte, detergent and distilled water on the tearing strength, tensile strength, bending length, wrinkle recovery and

Figure 1.2 is a flow diagram illustrating the systematic planning of the soiled textile fabrics in order to determine the soil removal efficiency of catholyte, detergent and distilled water at 30°C and 40°C.

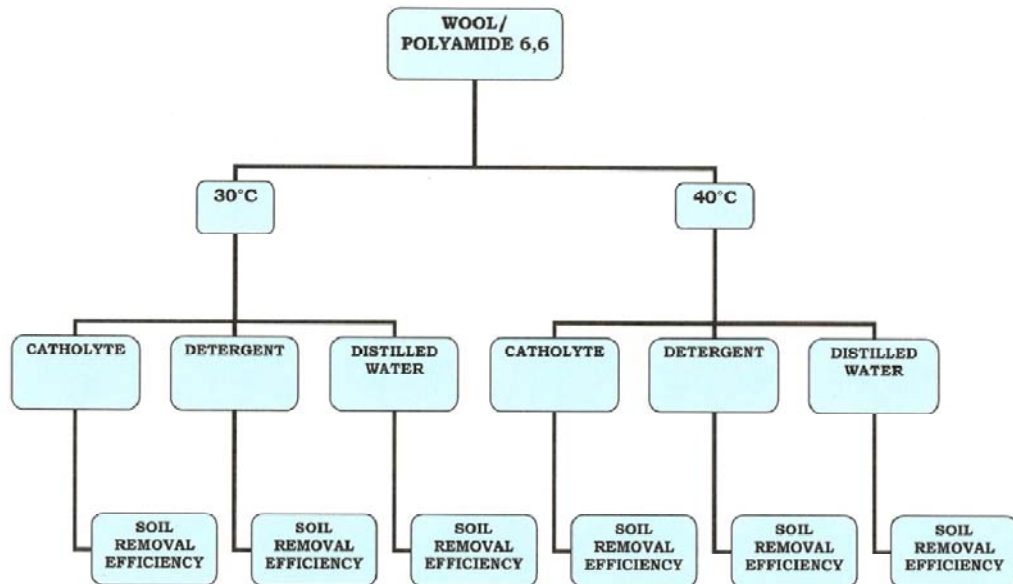


Figure 1.2: Flow Diagram of Systematic Planning for Soil Removal

1.5 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).

Bending Length: Exactly half the length of the fabric that protrudes over the edge of an apparatus and bends under its own weight (Merkel, 1991:330).

Catholyte: Alkaline water marked by the presence of HO_2^- , O_2^- and OH^- ions as a result of electrochemical exposure near the cathode in an electrochemical activation system (Bakhir, 2005).

Colorimeter: A tristimulus apparatus which has three sensors very similar to the human eye, measuring light through blue, green and red receptors (Kadolph, 1998:315).

Detergent: “A chemical compound which is formulated to remove soil or other material from textiles” (Kadolph, 2007:467).

Dimensional Change: Dimensional change is the difference between the original shape and size of the fabric and the shape and size of the fabric after it has been laundered or exposed to caring procedures (Kadolph, 2007:29).

Dimensional Stability: Dimensional stability is the ability of a certain fabric to retain its size and shape during its lifespan (Liu & Wang, 2007:958).

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

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

Eutrophication: Increased nutrient level in the water, resulting in the formation of large algae blooms causing water life to die (Köhler, 2006:58).

Laundering: The process which removes soil and/or stains by washing with an aqueous detergent solution (Merkel, 1991:373).

Stiffness: The resistance of a fabric against bending (Merkel, 1991:377).

Surfactant: Organic chemical surface active agents characterized by a heterogeneous, long-chain molecules that contains hydrophobic and hydrophilic parts (Collier & Tortora, 2001:487).

Tearing Strength: The force required to continue a tear which has already been started in a textile fabric (Kadolph, 1998:165).

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, 1998:161).

Textile: The general term used to refer to fibres, yarns and fabrics made from the fibres or yarns (Kadolph, 2007:487).

Textile Fibre: “Any substance, natural or manufactured, with a high length-to-width ratio and with suitable characteristics for being processed into a fabric” (Kadolph, 2007:470).

Van der Waals Forces: These forces are weak attractive forces between adjacent molecules that increase in strength as the molecules move closer together (Kadolph, 2007:488).

Warp: The yarns that are threaded through the loom in a woven fabric, parallel to the selvage (Kadolph, 2007:488).

Weaving: The process through which a fabric is produced by interlacing two or more yarns at right angles (Kadolph, 2007:490).

Weft: It is the yarns perpendicular to the selvage, which interlace with the warp yarns in a woven fabric (Kadolph, 2007:470).

Wrinkle Recovery: The property of a fabric enabling it to recover from folding deformations (Merkel, 1991:379).

CHAPTER 2: Review of Literature

2.1 Wool as a Natural Textile Fibre

2.1.1 Introduction

Wool is a natural protein fibre (Kadolph, 2007:62) and it is produced by a vast variety of sheep breeds (Collier & Tortora, 2001:98). The Merino breed yields the finest and most valuable fibres with good performance properties (Kadolph, 2007:63). Wool is also the fibre that is used the most out of all the protein fibres (Collier & Tortora, 2001:97).

Wool is an extremely complex but versatile fibre which has been refined by nature over millions of years. Meant originally for insulating sheep against extreme weather conditions, these properties can be used to the advantage of humans in apparel (Azoulay, 2005:25). Wool garments have very good performance characteristics and can be shaped well through tailoring. Wool fabrics are durable and very comfortable under a variety of conditions (Kadolph, 2007:71).

The use of wool is not only restricted to apparel. It is also used for furnishings, carpets, wall coverings and handcrafted wall hangings. The insulation properties of wool lead it into industry and it is often used as foundation pads for heavy machinery. Wool balls are also used to clean up oil spills because these balls can absorb up to forty times its weight in oil (Kadolph, 2007:72).

Wool has inherent antimicrobial features which increase the use of it even further (Azoulay, 2005:25). These fibres are also regarded as self-extinguishing; thus it will stop burning when it is removed from the heat source (Simpson & Crawshaw, 2002:225).

2.1.2 The Production of Wool

One of the major producers of wool is Australia, which accounts for almost half of the merino wool supply of the world (Simpson & Crawshaw, 2002:3), with a sheep population of well over 100 million (Rogers, 2006:932). Other producers of note are New Zealand, China, Eastern Europe (Kadolph, 2007:63) and South Africa (British Wool Marketing Board, 2006).

The wool fibres grow from very small oval shaped sacs situated in the skin of the sheep, called follicles (Cook, 1984:89). On average, merino sheep have 60 hair follicles per square millimetre (Rogers, 2006:932). The fibres grow in groups of 5 to 80 hairs. A typical Merino sheep can carry up to 120 million individual wool fibres. On average, these fibres grow 25mm in two months (Cook, 1984:89).

The sheep can be sheared to remove the fleece (Rogers, 2006:943). In countries like Australia and South Africa the sheep are sheared once a year (Kadolph, 2007:63). The fleece is removed in sections. The fleece from the underbelly and legs is usually of a lower quality (Tortora, 1978:70). It is of lower quality because it usually contains vegetable matter and is tangled (Collier & Tortora, 2001:99). The sheep may be allowed to graze freely in bushy areas which contribute to the fleece being contaminated with pieces of wood, leaves and burns (Tortora, 1978:70).

Other methods of fleece removal do exist (Collier & Tortora, 2001:99). The manual shearing process increases the production costs of the wool. These high costs stimulated research to find a cheaper method through biological harvesting which is also safe for the animal (Rogers, 2006:944). There are commercial harvesting procedures that are currently used. A chemical feed can be given to the sheep. This feed makes the wool brittle and it can be manually pulled off the sheep after several weeks (Kadolph, 2007:64; Collier & Tortora, 2001:99). BioClip is refined so that only a single dose of this formula

is needed so that the fleece of the sheep is shed within seven days. A body net is placed over the animal, where after the fleece is manually removed (Rogers, 2006:944).

After the fleece is removed, it is skirted. During this procedure the soiled wool are pulled away around the edges (Cook, 1984:90). After the wool is skirted it is scoured. Scouring is done to remove natural impurities (Sun & Stylios, 2006:245). Sorting takes place prior to the scouring procedure. The fleece is separated into sections of fibre of different quality (Kadolph, 2007:64). The wool is then graded, which entails the determination of the quality of the wool. The various grades are then sorted and packaged to be sent for finishing (Cook, 1984:90). The quality of the wool helps to determine its end use (Kadolph, 2007:64).

Generally the wool is then bleached to remove natural colouring matter. This procedure has an advantage in that it also enhances the fabric's wettability. If it is desired that the fabric be dyed, it is usually done at this stage, which is also the last of the processing stages (Sun & Stylios, 2006:245).

2.1.3 Morphological Structure of the Wool Fibre

2.1.3.1 Length

Merino wool fibres are regarded as relatively short (Collier & Tortora, 2001:98) varying in length between 38mm and 125mm (Kadolph, 2007:65; Cook, 1984:102). The staple length of the fibres varies considerably when it is removed from the sheep. Factors such as the breed of the sheep and the position of the fibres on the skin have an influence on the length of the fibre (Collier & Tortora, 2001:98). The wool grows continuously and is not shed during the change of seasons (Rogers, 2006:937).

2.1.3.2 Diameter

The diameter of wool ranges between 10 to 50 micrometers (Goudarzi et al., 2008:90; Kadolph, 2007:65). Collier and Tortora include a wider range from 8 to 70 micrometers (Collier & Tortora, 2001:103). Merino wool fibres have an average diameter of 15 micrometers (Kadolph, 2007:65). A fine wool fibre has a diameter of approximately 16 to 20 micrometers (Carter, 1971:73). The coarser wool fibres have a diameter of approximately 40 micrometers (Carter, 1971:73) and are generally produced by larger bodied sheep. These sheep are reared for their meat, thus the wool is only a by-product and not of high priority (Azoulay, 2005:25).

2.1.4 Physical Structure of Wool

Wool is a cellular (Goudarzi et al., 2008:90) cylindrical structure that consists of dead cells, each of which is filled with fibrous protein, known as keratin (Collier & Tortora, 2001:98). The wool has a complex (Azoulay, 2005:25; Maxwell & Huson, 2005:127) and composite structure (Leeder, 1986:4). The wool fibre consists mainly of three distinct regions, the medulla, the cortex and the cuticle (Joseph, 1986:49-50).

2.1.4.1 The Medulla

The medulla is a honeycomb-formed microscopic core (Kadolph, 2007:65) that arises from the growing root (Carter, 1971:71). The core may however, be hollow in some instances (Joseph, 1986:51; Cook, 1984:101). There are internal air spaces in the core, which makes the fibre lighter and a better thermal insulator (Kadolph, 2007:65).

When the fibre is viewed under a microscope the medulla may appear as a dark area. In most cases the medulla is absent in fine wools (Collier & Tortora, 2001:104). If the medulla is large, it makes the fibres straight, coarse and very difficult to spin (Smith & Block, 1982:90). In low quality or coarser wools,

medulla cells account for almost 15% of the total fibre mass. The food and climate also affects the forming of the medulla (Carter, 1971:72).

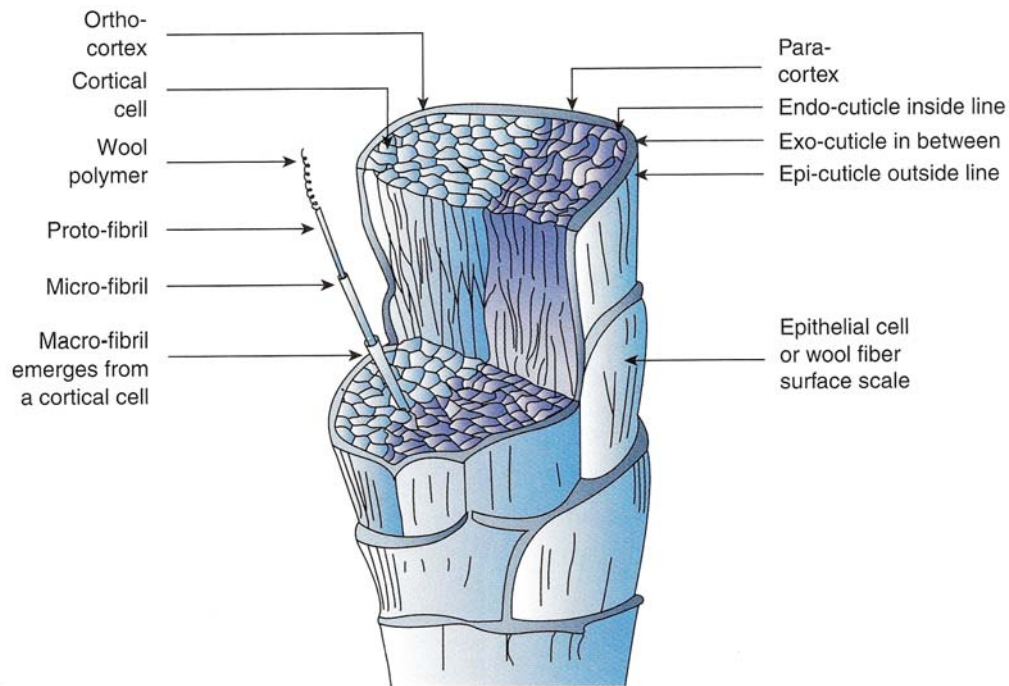


Figure 2.1: The Physical Structure of Wool (Courtesy of Gohl and Vilensky (1983) as cited in Kadolph, 2007:65)

2.1.4.2 The Cortex

The cortex is the main part of the fibre (Kadolph, 2007:65), comprising approximately 90% of the fibre (Simpson & Crawshaw, 2002:70). It consists of slightly elongated (Maxwell & Huson, 2005:127) cells which have a nucleus at the centre (Kadolph, 2007:65). These cells range from 100 to 200 micrometers in length and 2 to 5 micrometers in diameter (Cook, 1984:101).

The cuticle and cortex cells fit parallel to each other along the length of the fibre (Leeder, 1986:4). These cells are held together and separated by the cell membrane complex (CMC) (Goudarzi et al., 2008:90). This forms a continuous matrix in the keratin fibre (Horr, 1997:1). The CMC consists of intercellular

cement, lipids and minor amounts of other materials (Leeder, 1986:19). This cell membrane complex insures strong intercellular bonding through specific proteins called desmosomes (Simpson & Crawshaw, 2002:67). These cells are packed tightly together (Goudarzi et al., 2008:90).

Natural-colour wools have a colour pigment in the cortex, melanin (Kadolph, 2007:65; Tortora, 1978:75). The pigment granules are mostly embedded in the paracortex region of the fibre (Collier & Tortora, 2001:104).

2.1.4.2.1 Ortho- and Paracortex

Wool is a natural bicomponent fibre. This means that it has two different types of cells in the cortex, or two different components that exhibit different properties (Kadolph, 2007:66). The chemical composition and density of these two types of cells is also different (Feughelman, 1997:122).

The two different components are the orthocortex and paracortex. Orthocortex cells form between 60% to 90% and paracortex cells 10% to 40% of the total cortex cell population. The paracortex cells contain larger amounts of sulphur than orthocortex cells. This renders the paracortex cells more highly cross-linked (Simpson & Crawshaw, 2002:70) and resistant and the orthocortex cells less resistant (Carter, 1971:71). Paracortex cells also have more cystine than orthocortex cells (Carter, 1971:71) and are also more stable as a result (Cook, 1984:101).

The paracortex is always situated in the inner part and the orthocortex in the outer part of the fibre (Simpson & Crawshaw, 2002:71). The fibre can bend forward and backwards around its axis as a result (Kadolph, 2007:66; Smith & Block, 1982:89). The orthocortex follows the convex curve (outer side) and the paracortex the concave curve (inner side) (Rogers, 2006:938). The paracortex cells are longer than the orthocortex cells. The paracortical cells also swell

more when the fibre is wet (Carter, 1971:72). The keratin proteins of these two types of cells are organized differently (Rogers, 2006:938).

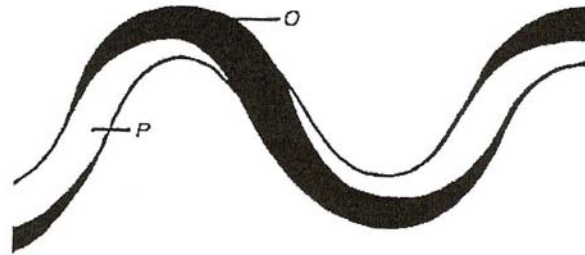


Figure 2.2: Organization of the Orthocortex (O) and Paracortex (P) of the Wool Fibre (Simpson & Crawshaw, 2002:71)

2.1.4.2.2 Crimp

The proteins in the two different parts of the cortex differ concerning their chemical and physical properties (Cook, 1984:102). These two parts, arranged in a bilateral manner, reacts differently to moisture and temperature. It is these cells that are responsible for the unique three-dimensional crimp of wool (Kadolph, 2007:66; Simpson & Crawshaw, 2002:70).

The origin of crimp is still subject to some speculation. Thibaut et al (2007:8) have suggested that it is most probably caused by asymmetric cell division in the bulb of the wool follicle. It seems likely that it is combined with the chemical events of molecular folding and cross-linking causing the differentiation (Rogers, 2006:938).

Three very important properties of wool namely: cohesiveness, elasticity and loft, is the result of the irregular waviness in the length of the fibre. Crimp helps the individual fibres cling together when yarn is produced, which also increases the durability of the yarn (Kadolph, 2007:66; Smith & Block, 1982:93). Crimp increases the elasticity because it gives the fibre the ability to

act like a spring. This unique property contributes to the loft that wool yarns exhibit (Kadolph, 2007:66; Azoulay, 2005:25). Increasing fibre crimp improves both processing behaviour and fabric quality (Collier & Tortora, 2001:104).

A lack of copper in the diet of the sheep decreases the crimp and “steely” wool is produced. Changes in the environment of the sheep or the health of the sheep also have an impact on the crimp and produce differences that adversely affect the properties of the fibre (Rogers, 2006:942).

2.1.4.2.3 Fibrils

The cortex cells consist of fibrous components namely, macro fibrils. There are 5 to 20 macro fibrils in one cell, each with a diameter ranging from 100 to 300 nanometre (nm). Micro fibrils are the fibrous component that macro fibrils consist of (Simpson & Crawshaw, 2002:72; Joseph, 1986:51). It is also sometimes referred to as sub-fibrils or proto-fibrils (Kadolph, 2007:66). These macro fibrils maintain the bonds between the cortex cells in the fibre (Smith & Block, 1982:89). The number of micro fibrils present in a macro fibril is not more than eleven (Carter, 1971:72). When it is viewed under the lens of a microscope it will appear as globular particles which are made of keratin (Cook, 1984:99).

An amorphous protein, called the matrix surrounds each micro fibril. The matrix is a cementing substance which holds the micro fibrils together (Huson, 1998:595). The micro fibrils are arranged in a helical configuration (Carter, 1971:70). It is considered that the micro fibrils in the matrix exhibit different properties when absorbing water (Nordon, 1962:561). Although it is held together it is still allowed to extend and contract when a wool fibre is stretched and relaxed. There is evidence that suggests that the matrix has especially high sulphur content. The composition of the matrix also differs from that of the micro fibrils. Micro fibrils are regarded as the crystalline units in wool fibres (Simpson & Crawshaw, 2002:74).

2.1.4.3 The Cuticle

The cells of the cuticle are flat (Maxwell & Huson, 2005:127), slightly bent with a near rectangular shape (Simpson & Crawshaw, 2002:67) and are generally known as scales (Collier & Tortora, 2001:104). It is about 20 micrometer wide and 30 micrometer long. It is 0.5 to 0.8 micrometer thick, when measured at the scale edge. The weight fraction of the cuticle cells in respect to the whole fibre is between 6 to 16% (Simpson & Crawshaw, 2002:68).

The cuticle cells are different from the cortical cells concerning their form as well as their chemical composition. Cuticle cells do not contain tyrosine (Simpson & Crawshaw, 2002:68).

Only one layer of cuticle cells surrounds the orthocortex, while two to three layers of cuticle cells surrounds the paracortex. The outer cuticle cells are thicker than the cuticle cells underneath it (Simpson & Crawshaw, 2002:68).

Each of the cuticle cells comprise of three regions or layers. The endocuticle, which is the inner layer with a low sulphur content, the exocuticle, a sulphur rich band that is central (Maxwell & Huson, 2005:127) and the epicuticle, a non-fibrous layer of scales (Kadolph, 2007:67; Smith & Block, 1982:88).

The epicuticle is perforated and it has microscopic pores. Moisture can enter the fibre through these pores. Wool fibres are therefore able to absorb moisture from the human body without letting the garment feel damp. It can also release the moisture slowly into the air (Joseph, 1986:51). The epicuticle is highly resistant to attack from alkalis, oxidizing agents and proteolytic enzymes. The epicuticle is a thin layer that covers the scales. This is a non-protein membrane. It is the only part of wool that does not consist of protein (Cook, 1984:98).

According to Maxwell and Huson (2005:127) the epicuticle is between 2 and 7nm thick, but Simpson and Crawshaw (2002:68) narrows it down to 2.5nm thick. This layer contributes to the repellency properties of wool fibres (Cook, 1984:98). It can also be easily damaged by mechanical action (Kadolph, 2007:67).

Maxwell and Huson (2005:127) believe the epicuticle consists of an outer layer of lipids bonded to the underlying layer of cystine-rich proteins. The epicuticle controls the rate of diffusion of dyes and other molecules into the fibre, thus playing an important role in many fabric properties (Carter, 1971:71). They believe that the two layers are bound by a thioester linkage called the chiral 18-methyl eicosanoic acid (18-MEA) (Maxwell & Huson, 2005:127).

Simpson and Crawshaw (2002:69) confirm that 18-MEA is a covalently bound fatty acid. This layer forms a hydrophobic barrier that has an effect on the adhesion and dye uptake of the fibre (Horr, 1997:1). When the fibre is treated with alkalis, oxidants or reducing agents, the lipid layer is stripped away, rendering a hydrophilic fibre surface (Maxwell & Huson, 2005:127).

In fine wools, the scales encircle the shaft completely and it overlaps the bottom of the previous scale (Kadolph, 2007:67). The cuticle cells arranged around the orthocortex region overlaps with each other approximately 20%. Those cells arranged around the paracortex region overlaps with 30% (Simpson & Crawshaw, 2002:69). In medium and coarse wools, the arrangement of the scales can be illustrated by looking at the arrangement of scales on a fish. The free edges of the scale face to the outside and point toward the tip of the fibre (Kadolph, 2007:67). The layer overlaps in only one direction (Simpson & Crawshaw, 2002:69).

The scales contribute to the abrasion resistant properties of wool. It also contributes to the felting properties of the wool fibre, but can irritate sensitive skin (Kadolph, 2007:67). The felting may be undesirable (Kan, Chan & Yuen, 2004:213). The layer repels water and can to a certain extent be seen as a waterproof surface agent (Cook, 1984:102). The repellency of the layer creates a barrier to dyestuffs which creates problems in the wool industry (Kan, Chan & Yuen, 2004:213).

2.1.5 Chemical Composition of Wool

Wool is a protein fibre, which is a high-molecular-weight, natural organic compound (Smith & Block, 1982:90). The fibres are formed of a cross-linked protein called keratin. It is the same protein that can be found in horns, hooves and human hair and finger nails (Kadolph, 2007:67; Cook, 1984:107). Wool contains alpha-keratins. It is protein molecules in an alpha-helix conformation that is in a complex mixture with proteins of an irregular structure (Simpson & Crawshaw, 2002:60).

Keratin consists of carbon, hydrogen, oxygen, nitrogen and sulphur (Kadolph, 2007:67; Simpson & Crawshaw, 2002:61). This composition is typical of proteins, except for the large sulphur content which is present mainly in the form of the amino acid cystine (Simpson & Crawshaw, 2002:61).

Together these elements form alpha amino acids which are glycine, alanine, valine, leucine, isoleucine, phenylalanine, proline, serine, threonine, tyrosine, aspartic acid, glutamic acid, arginine, lysine, hydroxylysine, histidine, tryptophan, cystine, methionine (Carter, 1971:68), glutamine, asparagines, thiocysteine, cycteine and cycteic acid (Simpson & Crawshaw, 2002:64).

The manner in which the amino acids are arranged within the keratin molecule and the arrangement of the molecules determine the properties of the different components of the fibre (Smith & Block, 1982:90). The amino acids are distinguished by their side chains. These side chains impart a specific property to the molecule that can be either hydrophilic or hydrophobic and acidic or basic (Simpson & Crawshaw, 2002:61).

The adjacent amino acids are connected by natural cross links, such as cystine linkages and salt bridges (Kadolph, 2007:67; Smith & Block, 1982:91). The sulphur in the composition is mainly derived from the amino acid cystine. Cystine has two sulphur atoms forming a disulphide bond (Simpson & Crawshaw, 2002:61) which means that the proteins are highly cross-linked structures (Collier & Tortora, 2001:102). This bond is the most important cross-linking element in wool (Simpson & Crawshaw, 2002:61) because highly cross-linked structures contributes to the strength and rigidity of the fibre (Smith & Block, 1982:91).

Salt bridges are a result of the high content of oppositely charged side chains of the molecules. Hence, salt bridges are sensitive to the pH-value of the fibre. A third kind of cross-link, called an isodipeptide bond is formed between a glutamic or aspartic acid and a lysine residue (Simpson & Crawshaw, 2002:62).

Hydrogen functions as stabilizing elements of wool, especially between amide groups but also between other hydrogen donating and accepting groups. The hydrogen bonds cause wool to be sensitive to hydrogen bond-breaking reagents (Simpson & Crawshaw, 2002:62).

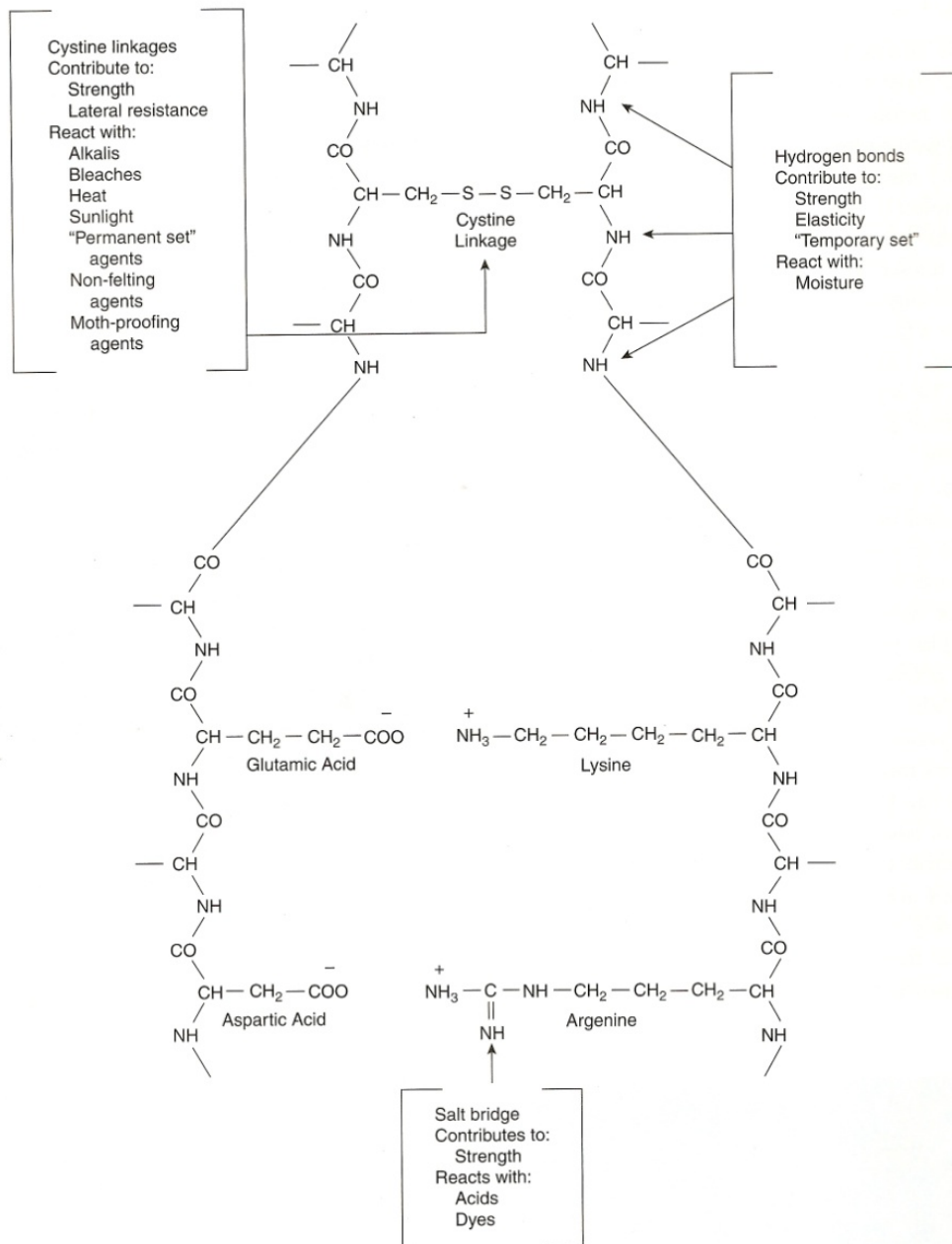


Figure 2.3: The Ladder-like Structural formula of a Wool Molecule (Kadolph, 2007:68)

With the amino acids and cross links, wool forms a ladder-like structure (Figure 2.3). This ladder-like structure forms a spiral structure (Figure 2.4). The spiral structure contributes to wool's resiliency, elongation and elastic

recovery. The cystine linkages are the most important part of the molecule. Any chemical such as an alkali, that can potentially damage these linkages, can destroy the entire structure (Kadolph, 2007:67; Smith & Block, 1982:91).

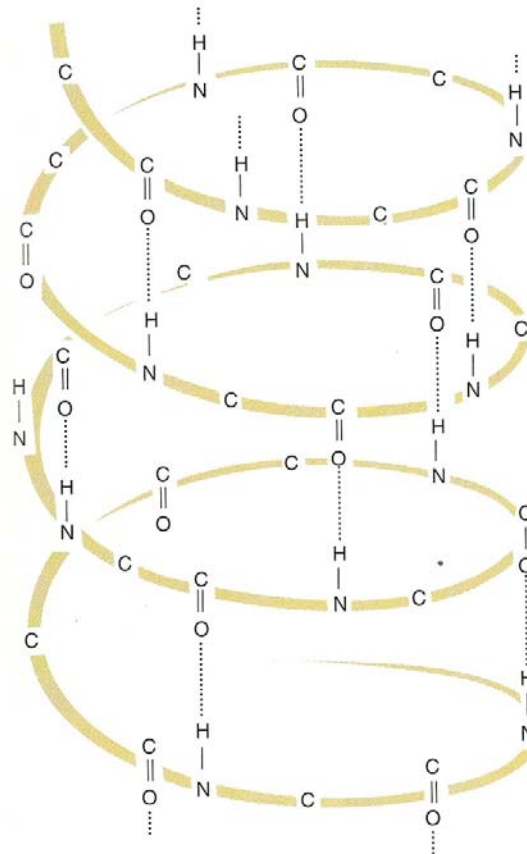


Figure 2.4: The Spiral arrangement of the Wool Molecule (Kadolph, 2007:56)

Wool fabrics can be shaped by heat and moisture. Hydrogen bonds can be broken through applying moisture (Collier & Tortora, 2001:102). The newly formed bonds retain their shape until it is exposed to high humidity. Then it will return to its original shape (Kadolph, 2007:68). Because the hydrogen bonds break when it is exposed to moist conditions, the wool will be weaker when it is wet (Collier & Tortora, 2001:102).

In addition to proteins, wool also contains two percent of internal and external lipids. The external lipids are commonly known as wool grease. Scouring will almost completely remove the wool grease. There are many forms of wool grease, but lanolin is the most widely known. Internal lipids mainly consist of cholesterol, fatty acids and polar lipids. The polar lipids are lipids such as ceramides, cerabrosides and cholesterol sulphate (Simpson & Crawshaw, 2002:62). The lipid layer is approximately 2 to 30nm thick (Maxwell & Huson, 2005:128).

Mineral salts, nucleic acid residues and carbohydrates comprises one percent of wool's chemical composition. The nutrition the animal received determines the content of the mineral salts. Nucleic acids can be used to discriminate between sheep wool, cashmere and yak fibre. Carbohydrates originate from glycoproteins that represented former membrane proteins (Simpson & Crawshaw, 2002:67).

Studies that have been done suggest that keratin fibres is capable of altering its structure in response to changing or different environments (Maxwell & Huson, 2005:128). Keratin is shaped like a spring or a helix, and does not have an extended structure. This is known as alpha-keratin and is also the form in which it resides when the fibre is relaxed. When the fibre is stretched, the molecules form a beta-keratin. The molecules will return to their alpha-configuration when the fibre is relaxed again. It is this ability of the molecules to change configuration that imparts specific properties such as elasticity to the wool fibres (Smith & Block, 1982:91). The alpha- and beta-configurations are illustrated in figure 2.5.

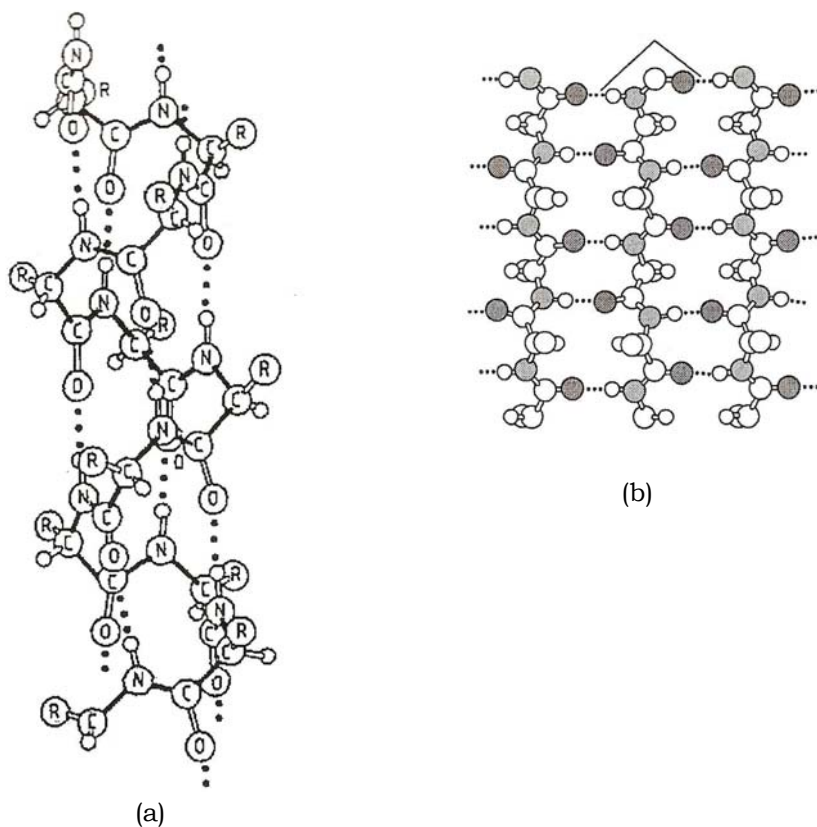


Figure 2.5: Alpha-configuration (a) and Beta-configuration (b) of the Wool Fibre (Simpson & Crawshaw, 2002:61)

2.1.6 Chemical Properties of Wool

2.1.6.1 The effect of Moisture, Water and Temperature on Wool

The hydrophilic nature of some of the functional groups of the amino acids in the wool molecule renders wool highly susceptible to humidity. Wool takes up approximately 34% to 37% of its own mass in water (Huson, 1998:595). When the wool takes up the water it swells and becomes easier to stretch (Collier & Tortora, 2001:105).

The weight of the wool also changes according to the amount of moisture that is absorbed. When the moisture is absorbed, heat is also liberated. The wool fabric will thus become warmer as it absorbs more moisture (Cook, 1984:105).

The forces that hold the molecules together in the wool fibre can be influenced if moisture is absorbed. The volume of the wool can increase by one tenth when it is soaked in water at room temperature. When it dries it will return to its original size (Cook, 1984:105).

The water molecules can penetrate between the long keratin molecules. This will loosen the mutual grip of the molecules lying next to one another. The molecules are then able to move more easily. At this stage the wool becomes softer and more plastic (Cook, 1984:110). In the presence of water, the wool fibre can be penetrated by larger molecules than in the absence of water (Huson, 1998:603).

When salt is added to the water, it lowers the activity of the water which in turn affects the relative humidity of the vapour above the water. Wool takes up less water when the relative humidity is lower. When salt is concentrated in a water solution it can have a substantial affect on the proteins in wool, in particular their solubility. The wool swells and the salt linkages are weakened (Huson, 1998:595). The viscosity and activity of the water solution also affects the penetration of ions into wool fibres (Huson, 1998:604).

There is a strong correlation between the amount of disulphide bonds that degrades and the breaking load the fibres can carry when wool is treated in water at 100°C (Feughelman, 1997:100). The predominant change that takes place is the cystyl residues that convert to lanthionyl residues when the water temperatures are between 60°C and 100°C and the pH 5.8. The lanthionyl residues form when wool is treated with water, especially when the pH value is high (Carter, 1971:77). In boiling water the fibres will lose their resiliency and become like plastic and more elastic. This causes the fibres to move easier and interlock with other fibres (Cook, 1984:106; Gohl & Vilenski, 1983:72).

2.1.6.2 The effect of Detergents on Wool

Wool should be laundered with specific detergents (Tortora, 1978:77). Swanepoel and Van Rooyen stated that detergents that are more alkaline are more suitable for wool articles (Swanepoel & Van Rooyen, 1970:519). In contradiction Kadolph, Collier and Tortora stated that the pH of the detergents used to launder wool should be near neutral or slightly acidic. Strong alkaline detergents can damage the wool (Kadolph, 2007:70; Collier & Tortora, 2001:97).

Liquid synthetic detergents are generally the safest product to use for laundering wool products. The way in which the detergent is used is just as important as the detergent itself. Solid detergents must be entirely dissolved before the wool article is put into the water. If this is not done, the undissolved particles of detergent can attach to a wool fibre and cause localised colour loss (Cook, 1984:116).

Biological detergents are a group of detergents which is commonly used in domestic laundry. The enzyme, protease, is a key component in some of these biological detergents' composition, and it causes irreversible damage to a protein fibre such as wool (Cortez, Bonner & Griffin, 2005:379). Subtilisins, which can also be included in the composition of detergents, are able to penetrate easily into the fibre and destroy the cortex. This results in a considerable loss in tensile strength (Schroeder et al., 2006:739). There are however enzymes that can be added to prevent this kind of damage. Therefore, care must be taken when biological detergents are considered (Cortez, Bonner & Griffin, 2005:379).

2.1.6.3 The effect of alkalis on wool

The physical properties of wool are adversely affected by alkalis (Carter, 1971:79). The proteins of the wool fibre are degraded by alkalis at low

concentrations and temperatures (Simpson & Crawshaw, 2002:137). Wool has poor resistance to alkalis (Joseph, 1986:46) because it attacks the disulphide bond, thus the cystine linkages, and also causes the salt linkages to break down (Carter, 1971:79).

The degree to which the properties are affected are however dependent on the type of alkali, its strength, the temperature when it is exposed to the wool, the time of exposure and how effectively it is removed after exposure (Carter, 1971:79).

When the alkali concentrations are high, the peptide chains break down (Cook, 1984:107). When wool is treated with an alkali of a pH higher than 10.5 and heated, a loss of cystine is marked (Cortez, Bonner & Griffin, 2005:380). Wool will entirely dissolve in a 5% solution of sodium hydroxide at boiling point (Joseph, 1986:46). Ammonium carbonate, borax and sodium phosphate have a minimum effect on wool. Ammonia can also be used, but extreme care must be taken (Cook, 1984:107).

Chemical groups in the wool fibre that is prone to alter their state of ionization when the pH and alkali concentrations increases are as follows: Histidine, terminal amino group, tyrosine, lysine and arginine (Simpson & Crawshaw, 2002:138).

2.1.6.4 The effect of acids on wool

Wool is more resistant to acids and weak acids do not generally harm wool (Joseph, 1986:46; Tortora, 1978:77). The acids hydrolyse the peptide bonds, but it does not hydrolyse the disulfide bonds. This only weakens the fibre (Gohl & Vilensky, 1984:81). Wool decomposes in hot concentrated sulphuric acid. However, diluted sulphuric acid is used to remove vegetable matter during carbonizing procedures. Nitric acid causes some damage because of the oxidation that takes place (Cook, 1984:107). Mineral acids that are

concentrated will damage the wool fibres irreversibly if it is left to soak in the acid for more than a few minutes (Labarthe, 1975:63).

2.1.6.5 The effect of bleaches on wool

Wool is extremely sensitive to bleaches, because it is an oxidising agent (Smith & Block, 1982:92). It is the chlorine used in the bleaches that damages the wool (Joseph, 1986:47), especially hypochlorite (Cook, 1984:116). The reaction that wool has with acids is essentially an ion-exchange. The bleaches have such an ion-exchange reaction with the disulphide bonds to produce cysteic acid (Simpson & Crawshaw, 2002:135).

Bleaches containing hydrogen peroxide and sodium perborate can be used safely on wool items (Joseph, 1986:47; Tortora, 1978:78). Wool is damaged more by oxidising bleaches than by reducing bleaches (Smith & Block, 1982:92).

2.1.7 Physical Properties of Wool

2.1.7.1 Aesthetics

The physical structure of wool contributes to the loftiness and body of fabrics (Kadolph, 2007:69). Finer wools are more lustrous than coarse wools (Joseph, 1986:50), although they still have a delicate lustre because the fibre does not reflect light very well due to the scaly and relatively rough surface (Collier & Tortora, 2001:105).

The drape, lustre, texture and hand can be varied by the choice in yarn structure, fabric structure and finish (Kadolph, 2007:69; Cook, 1984:102). The lustre is also dependant on the breed of sheep, the part of the fleece the fibre was taken from and the conditions under which the sheep was reared (Collier & Tortora, 2001:105).

2.1.7.2 Specific Gravity

The Specific Gravity of wool is 1.32 (Kadolph, 2007:70; Collier & Tortora, 2001:104). This means that wool feels light in relation to its bulk. Wool provides warmth without excessive weight (Tortora, 1978:76). Lightweight wools are very comfortable to wear during the spring and fall seasons (Kadolph, 2007:70).

2.1.7.3 Dimensional Stability

Wool is not a very dimensionally stable fibre (Goudarzi, 2008:90). This is mainly due to the physical structure of the fibres. Because of the scales wool is prone to felt and shrink, hence the poor stability (Liu & Wang, 2007:957).

There are two kinds of shrinkage: Felting shrinkage and relaxation shrinkage (Liu & Wang, 2007:957).

Felting shrinkage occurs because of mechanical action that is combined with heat and moisture. The scales of the adjacent fibres are prone to interlock with one another and then it becomes tangled and matted together. This results in fabric shrinkage. The fabric also becomes stiffer and thicker (Joseph, 1986:52).

Relaxation shrinkage is mostly due to the elongation and elasticity properties of the wool fibre. During fabric manufacturing, these properties allow the yarns to be stretched, and this stretched state is generally maintained throughout the manufacturing (Sun & Stylios, 2006:246). When the wool is exposed to moisture again, it will return to its original shape or length, which results in the fabric shrinking (Joseph, 1986:52).

Wool shrinks in a progressive manner. This means it will shrink the most during the first laundering cycles and then it will continue to shrink gradually

every time it is laundered or exposed to moisture. The shrinking will occur unless it is treated with a finish to prevent this kind of behaviour (Sun & Stylios, 2006:246; Silva et al., 2006:634). Chlorination followed by a suitable polymer coating is a treatment used to prevent shrinkage in wool fabrics. The chlorination partly removes the scales (Schindler & Hauser, 2004) and coating minimizes the friction of the wool surface and it also limits the fibres moving and interlocking in all directions (Liu & Wang, 2007:961).

External factors that also influence the degree of felting are the medium in which it is laundered (detergent, water, etc.), the pH of the medium, the temperature of the laundering and the degree of agitation it is exposed to during laundering (Liu & Wang, 2007:957).

Swanepoel and Van Rooyen (1970:516, 519) found that wool articles laundered with a detergent consisting of nearly 10% alkali (Na_2O), a non-ionic surfactant, and a foam suppressor, resulted in less felting shrinkage. The wool fabric was laundered in a standard domestic washing machine. They also found that the rate of felting at a higher pH, for example 9.5, is less than at a lower pH such as 6.5.

2.1.7.4 Durability

Wool is characterized by low strength and great extensibility. This property is mainly due to the alpha-helices that unfold when it is stretched (Ahumada et al 2004:1003). Due to the scale structure and excellent flexibility of wool, it is a very durable fibre. These properties also contribute to the moderate abrasion resistance wool exhibits. Moisture from the atmosphere helps wool retain its flexibility (Kadolph, 2007:69).

Because wool is approximately 30% crystalline, this adversely affects its strength (Collier & Tortora, 2001:103; Feughelman, 1997:35). The inherent

strength of wool fibres is less than that of synthetic fibres (Rogers, 2006:932) and cellulosic fibres like cotton (Collier & Tortora, 2001:96). It is a concern because it complicates the processing (Rogers, 2006:932). Wool's strength decreases when it is wet because the hydrogen bonds break in moist conditions. Thus care must be taken in this regard (Joseph, 1986:47).

Collier, Tortora (2001:104) and Joseph (1986:50) are all in agreement that the tensile strength of wool is 1.0 to 1.7g/d when it is dry and 0.7 to 1.5g/d when it is wet.

2.1.7.5 Comfort and Conductivity

Wool is a very comfortable fabric to wear (Kadolph, 2007:69). Protein fibres, such as wool are generally warmer than most other fibres (Joseph, 1986:46). Some people are allergic to the chemical composition of the fibres and can develop a skin irritation or they can itch or sneeze when they are wearing it. Loose ends from the more coarse and lower grade wools can irritate a person and render the apparel not wearable (Kadolph, 2007:69).

The electrical and heat conductivity of wool fibres are very low. This means that wool has the ability to trap air and thus the heat (Cook, 1984:109). The good absorbency of the wool fibres results in the ability not to build up static electricity, unless the atmosphere is very dry (Collier & Tortora, 2001:105).

2.1.7.6 Absorbency and Moisture Regain

Wool is more hygroscopic than any other fibre. This is greatly due to the number of side-chains of the molecules that attract water. The fact that the molecular structure of the wool fibre is mostly amorphous means that more water can be absorbed (Collier & Tortora, 2001:105).

The moisture regain of wool is 13% to 18% under standard conditions (Kadolph, 2007:69; Joseph, 1986:51). This property is very important when

the dye ability of wool is determined. The high moisture regain means that the fibre will absorb the dyestuff more readily (Kadolph, 2007:69). Wool will give up moisture slowly and is also water repellent (Azoulay, 2005:25; Tortora, 1978:77).

The ability of wool to absorb so much moisture contributes to the comfortability of wool in humid and cold conditions (Joseph, 1986:51). Wool also generates or produces heat as part of the moisture absorption (Azoulay, 2005:25). As the wool begins to dry the heat is absorbed by the fibre due to the evaporation. This is referred to as hygroscopic behaviour (Joseph, 1986:51).

When the behaviour of wool concerning moisture is considered it can be summarized by saying that wool is water repellent, but with prolonged exposure to moisture the fibre does absorb large quantities of water. The surface of the fibre does, however, feel dry because the moisture is contained in the fibre (Collier & Tortora, 2001:105).

2.1.7.7 Appearance Retention

The elasticity and resilience of wool are excellent (Joseph, 1986:50; Tortora, 1978:76). The elasticity of wool fabrics is not affected by, or sensitive to, finishing processes such as scouring, desizing or bleaching (Sun & Stylios, 2006:248).

The fibre has an elastic recovery of 99% when it is stretched 2%. Even when it is stretched 10%, it has a recovery of more than 50% (Kadolph, 2007:69; Joseph, 1986:51). At break the elongation of wool is 25% to 35% under standard atmospheric conditions and 25% to 50% when it is wet (Cook, 1984:104).

It has good resistance against wrinkling and recovers well from it (Collier & Tortora, 2001:105). The existence of a network of flexible molecules in wool is the main factor contributing to wool's wrinkle recovery properties. These bonds are believed to stretch when the fabric is deformed and also assist when it recovers (Kim & Kang, 2002:118). Wool retains its shape well during its lifetime. Wool apparel items retain their size and shape well when it is dry-cleaned (Kadolph, 2007:70). Wrinkles will hang out of wool garments, especially if it is hung in a damp environment (Tortora, 1978:76).

Wool has excellent resiliency because of its unique crimp characteristics (Azoulay, 2005:25; Collier & Tortora, 2001:105).

2.1.7.8 Care

Wool is susceptible to damage when it is wet, therefore it must be handled with extreme care when it is wet. When wool is wet, the tenacity, resiliency and elastic recovery drastically decline while the breaking elongation increases with 35% (Kadolph, 2007:70). Dry-cleaning is recommended for most wool items. Some wool items can be washed by hand, but the correct procedure must be followed. In order to reduce the risk of felting, wool should be washed in warm water and agitation should be limited. It must be dried flat and cannot be tumble dried (Kadolph, 2007:70).

Chlorine bleaches damage wool (Kadolph, 2007:70; Smith & Block, 1982:93). The chlorine attacks the exocuticle and loosens the top layer which then comes off. Wool is also very sensitive to alkalis (Kadolph, 2007:70; Smith & Block, 1982:93). When alkalis are used on white wool, it will discolour to yellow; thereafter it will become a jelly-like substance and dissolve (Kadolph, 2007:70).

Wool is attacked by moth larvae and other insects. The repeated use of mothballs is not recommended because it can be toxic (Collier & Tortora, 2001:106). It must be used if there are signs of an insect infestation.

Wool burns slowly and is self-extinguishing. Wool is seen as a flame-resistant fibre (Kadolph, 2007:70; Tortora, 1978:77).

2.1.7.9 Washability

Wool does not soil easily, and when it does happen it can be removed easily. Grease and oils will not stain wool as easily as it does other fabrics (Von Bergen, 1970:182). Wool items do not necessarily have to be washed or dry-cleaned after every time it has been used (Kadolph, 2007:70). The desoiling properties of wool are superior to most of the other fibres (Swanepoel & Van Rooyen, 1970:520).

The stirring and tumbling of washing machines are not ideal for wool articles (Cook, 1984:117), because felting shrinkage is a concern with pure wool articles (Collier & Tortora, 2001:108).

Temperatures for washing wool should be kept warm and not hot (Joseph, 1986:53). Temperatures not exceeding 40°C are considered as warm (ASTM D3136) and temperatures exceeding 50° to 60°C are regarded as hot but wool is rarely washed at these temperatures (Swanepoel & Van Rooyen, 1970:520). The normal domestic washing temperature for wool is 40°C (Vasconcelos et al., 2006:729), although Cook considered the ideal temperature 38°C (Cook, 1984:116). The temperatures should also be kept constant throughout the washing cycle (Joseph, 1986:53).

2.1.8 Environmental impact of wool

Because wool is a natural fibre, some consumers regard it as environmentally friendly. Although wool is a renewable source, it cannot be produced without any impact on the environment (Chen & Burns, 2006:250). Sheep sometimes graze pastures so closely that erosion can occur if care is not taken to avoid overgrazing. The disposal of animal waste is another concern. It is general

practice that sheep manure is spread over the ground to return nutrients to the soil. The excessive application of the manure may contaminate runoff when it rains (Kadolph, 2007:71).

Sheep is also susceptible to diseases that can be transmitted to humans (Smith & Block, 1982:183). Most of these diseases are not a threat for consumers, but caution should be exercised on wool that is imported from Third World countries, especially on behalf of the textile workers (Kadolph, 2007:71).

When wool is processed, soap and alkaline solutions are used to remove the impurities and grease from the fibres. Chemicals are also used on wool to limit shrinking and ensure it is machine washable (Chen & Burns, 2006:250). The immense amount of water, energy and chemicals that is used to apply dyes to wool fibres should also be taken into consideration (Kadolph, 2007:71). The use of coloured wool can be a feasible way to eliminate the dyeing of wool. This is achieved through selective breeding of sheep with natural pigmentation. However, the amount of coloured wool that is used today is not as common in comparison to conventional wool (Chen & Burns, 2006:250).

Most wool products must be dry-cleaned. Some of the solvents that are used in the dry-cleaning process have been identified as carcinogens. Restrictions regarding the exposure to these solvents in the workplace exist (Kadolph, 2007:71).

2.2 Polyamide 6,6 as a Textile Fibre

2.2.1 Introduction

Polyamides, commonly known as nylon, are an important class of condensation polymers (Kumar & Gupta, 1998:10). Polymers are materials of very high molecular weight (Kadolph, 2007:123). These polymers are obtained through chemical reactions of monomers. Monomers are very small molecular compounds (Kumar & Gupta, 1998:1). Condensation polymers are formed from bi- or polyfunctional monomers. Polyamide is formed by a reaction between amine and acid groups (Kumar & Gupta, 1998:11).

In 1939 polyamide 6,6 was the first synthetic fibre introduced to the world (Kadolph, 2007:123) and it is still a very important commercial polymer (Kumar & Gupta, 1998:92). It was first used in women's hosiery and it was tremendously successful in this respect (Kadolph, 2007:123). The name nylon was derived from "no-run". It was thought of by the inventors to emphasise the durability of the hosiery (Gohl & Vilensky, 1983:104). Today, a wide range of these fibres is available (Ruchser, 2004:61).

Different types of polyamides are manufactured. Polyamide 6, polyamide 6,6, polyamide 11 and polyamide 6,10 are some of the important polyamides manufactured (Cook, 1984:29). The notation at the end of polyamide terms is an indicator of the number of carbon atoms in the starting material (Craver & Carraher, 2000:50). This implies that there are two monomers present in polyamide 6,6 and each contains six carbon atoms (Gohl & Vilensky, 1983:104).

Polyamide is a versatile fibre that has many applications (Gruszka, Lewandowski, Benko & Perzyna, 2005:133; Dasgupta, Hammond & Goddard III, 1996:12291). The most important use of the polyamide fibres is for lingerie (Kadolph, 2007:129), hosiery products and carpets (Gruszka, Lewandowski,

Benko & Perzyna, 2005:133). It can be used for fashion items, functional sportswear, and can even be used in automotive tyres (Ruchser, 2004:61) and airbags for automobiles (Anon, 2004:49). The fabrics made from these fibres are easy-care and they have very good wear properties (Ruchser, 2004:61). Polyamide 6,6 can also be used for making piping, insulation, zippers and brush bristles when it is in a plastic form (Stevens, 1999:364).

Polyamide 6,6 is one of the most used polymers in the engineering industry (Albano et al., 2001:852; Fried, 1995:338). Polyamide 6 and polyamide 6,6 accounts for approximately 80% of the total polyamide production. A decade ago Stevens found that 80 to 90% of this total was used as fibres. He also estimated that at that time polyamide fibres roughly represented 25% of the total fibre production (Stevens, 1999:364).

2.2.2 The Production of Polyamide 6,6

Polyamide 6,6 is an aliphatic semi-crystalline polyamide (Clark JR., Kander & Sauer, 1999:27) that is formed by the polymerisation of diamine (hexamethylene diamine) and dicarboxylic acid (adipic acid) (Collier & Tortora, 2001:166; Craver & Carraher, 2000:50; Kumar & Gupta, 1998:92).

Polyamide 6,6 is produced through the linear polymerisation process (Joseph, 1986:103) in two stages (Figure 2.6). During the first stage the monomers, hexamethylene diamine and adipic acid, are combined in a solution to form 1-aminohexamethylene adipamide. Last mentioned is sometimes referred to as nylon 6,6 salt (Kumar & Gupta, 1998:92; Joseph, 1986:103). The salt is a compound and not a polymer (Collier & Tortora, 2001:167).

The water molecule is given off as a by-product when the diamine and acid molecules join together. The adipic acid can be produced from cyclohexane

and hexamethylene diamine from benzene. The cyclohexane is generally derived from the distillation of petroleum (Joseph, 1986:103).

The salt is then purified and polymerised in an autoclave in an atmosphere of nitrogen (Joseph, 1986:103). Thereafter it is extruded in a ribbon form and cut into smaller pieces, called chips (Collier & Tortora, 2001:167).

The spinning process used when manufacturing polyamide 6,6 is called melt spinning. After the ribbon is extruded and has been cut, the chips are heated on a grid. The freshly cut chips cannot pass through this grid unless it is melted. Once it is melted, the chips are passed through a filter which removes any impurities (Collier & Tortora, 2001:168). The polymer chips are then extruded through spinnerets into cool air where the polyamide filament will be formed (Joseph, 1986:103). 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, it is stretched or cold-drawn so that the molecules can be oriented and fibre strength and fineness can be developed (Joseph, 1986:103). 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, increasing the lustre and tensile strength (Collier & Tortora, 2001:168).

High-tenacity fibres are stronger than regular tenacity polyamide fibres because it is drawn to a greater degree than the regular fibres. First mentioned fibres are therefore more crystalline and oriented (Kadolph, 2007:126).

Polyamide may also contain a plasticizer. A plasticizer is a material that makes another material softer or more flexible when it is added to that material and may be added to the fibre during the manufacturing process. Sulphonamides

are the plasticizer usually used with polyamide (Craver & Carraher, 2000:157, 172).

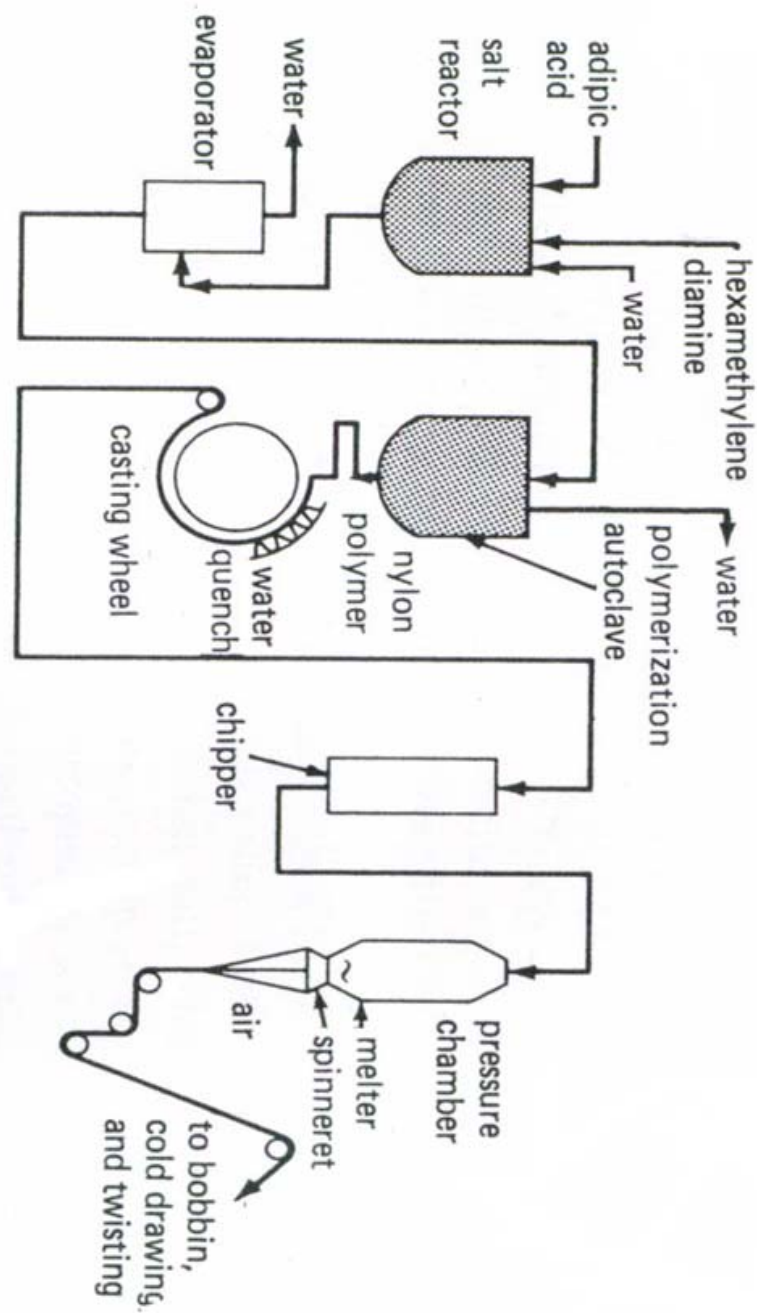


Figure 2.6: Flow Diagram of the Manufacturing Process of Polyamide 6,6 (Joseph 1986:102)

2.2.3 Morphological Structure of Polyamide 6,6

2.2.3.1 Length

The length of the fibres is determined by the manufacturer (Joseph, 1986:103). It can be manufactured as staple fibre or continuous filament (Gruszka, Lewandowski, Benko & Perzyna, 2005:133).

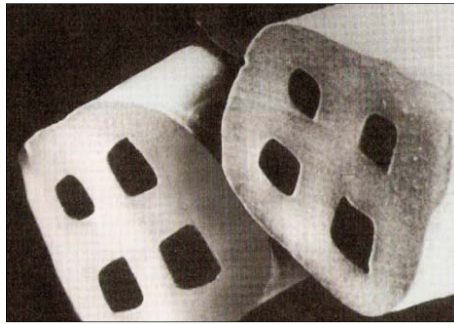
2.2.4 Physical Structure of Polyamide 6.6

The diameter of polyamide filaments or staple fibres varies between 14 to 24 micrometers. The diameter is usually determined by the requirements of the end-use of the fabric. The fibre length to breadth ratio generally is more than 2000:1 (Gohl & Vilensky, 1983:104).

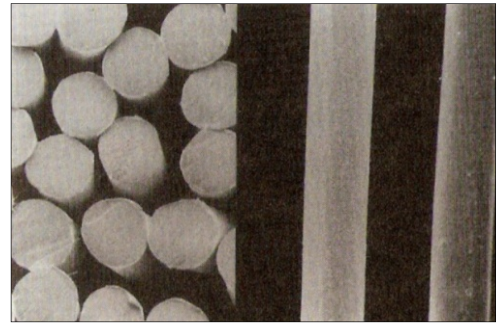
Polyamide is available in a variety of forms. It can be multifilament, monofilament, staple or tow. It is also available in a wide range of deniers and shapes and can be partially drawn or completely finished filaments (Kadolph, 2007:124). It can also be round, tri-lobal or square (Ruchser, 2004:61; Joseph, 1986:103).

Varying degrees of polymerisation and strengths can also be produced. Seen under the microscope, the fibres look like very fine glass rods. They are generally transparent, unless it was delustered or solution-dyed (Kadolph, 2007:124).

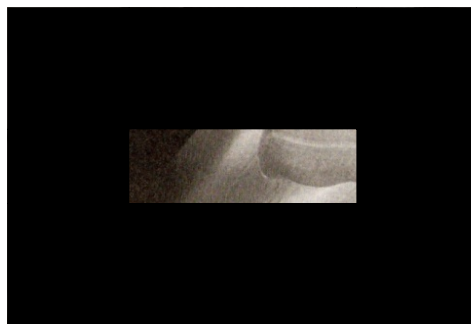
There is a combination of factors contributing to this seemingly featureless appearance of polyamide. It is influenced by the viscosity of the spinning solution, the nature of the polyamide material as well as the rate of coagulation in cold air of the extruded stream of polymers. This causes the filament to retain the shape of the spinneret orifice (Gohl & Vilensky, 1983:105). Tri-lobal polyamide may have longitudinal striations (Gohl & Vilensky, 1983:106).



(a)



(b)



(c)

Figure 2.7: 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, 2007:125)

Initially the uniform shape of polyamide was expected to be an advantage over natural fibres such as wool and cotton, but this uniformity produced woven fabrics with a very unattractive feel. This is the reason for polyamide being produced in various shapes. The fibre retains the shape of the spinneret hole (Kadolph, 2007:124).

The fibres can be produced in different degrees of lustre (Kadolph, 2007:124). Titanium dioxide is used to control the lustre of the fibres (Joseph, 1986:103). 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).

2.2.5 Chemical Composition of Polyamide 6,6

The specific arrangement of the chain structure has a definite effect on the properties of this polymer. This specific arrangement is the sequence of monomer units in the polymer as well as the general chemical composition of the polymer (Fried, 1995:10).

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, 2007:125; Collier & Tortora. 2001:165).

Nylon 6,6 is a linear (Gohl & Vilensky, 1983:106) polyamide. These polymers are composed of polyethylene segments which are separated by peptide units. These units can either be parallel or antiparallel (Dasgupta, Hammond & Goddard III, 1996:12291).

The amide groups consist of the elements carbon, oxygen, nitrogen and hydrogen. The polyamide 6,6 chains are long and straight and does not have side chains or cross links. The cold drawing aligns the chains so that they are oriented in a highly crystalline manner (Kadolph, 2007:125). The crystallinity of the polymers can be controlled (Dasgupta, Hammond & Goddard III, 1996:12291). The carbon atoms however, have a linear, but zigzag arrangement (Gohl & Vilensky, 1983:106).

Polyamide 6,6 has an all aliphatic backbone (Fried, 1995:338) and is an aliphatic semi-crystalline polyamide (Clark jr., Kander & Sauer, 1999:27). 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 (Gohl & Vilensky, 1983:107).

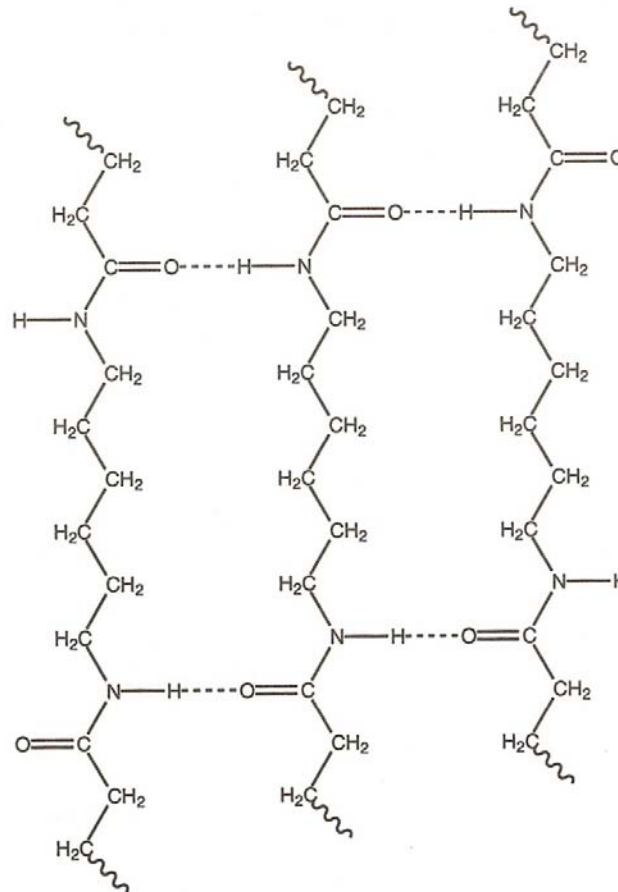


Figure 2.8: Illustration of the Hydrogen bonding between the Amide groups in polyamide 6,6 (Fried, 1995:140)

The polyamide 6,6 polymer is approximately 65% to 85% crystalline and 35% to 15% amorphous. Thus the polymer is a very well orientated polymer system (Gohl & Vilensky, 1983:107). It consists of hundreds of molecules of adipic acid and hexamethylene diamine that is linked together to form a macromolecule (Joseph, 1986:103). The hydrocarbon parts of the fibre are hydrophobic, and the amide groups are hydrophilic (Smith & Block, 1982:122).

The melting point of polyamides can significantly be reduced through the substituent groups on the polymer backbone. Introducing alpha-methyl groups to the carboxyl portion of the polymer reduces the melting temperature to 166°C (Stevens, 1999:376).

2.2.6 Chemical Properties of Polyamide 6,6

2.2.6.1 The effect of Moisture, Water & Temperature on Polyamide 6,6

Aliphatic polyamides, such as polyamide 6,6, have a hydrophilic nature (Khanna, Han & Day, 1996:1745). These polymers contain very strong hydrogen bonds, and when the fabric becomes wet the water molecules hydrolyse a significant amount of the hydrogen bonds in the amorphous areas of the polymer. This results in a considerable loss of strength (Gohl & Vilensky, 1983:108).

When excessive heat is applied to polyamide materials, it will melt. The heat causes the polymers to become so excited that a breakdown of inter-polymer bonding occurs. However, when the heat is applied under controlled conditions, the fabric can be heat set. This process breaks the hydrogen bonds under conditions of strain, which means the polyamide can be moulded into the desired shape and the bonds reformed (Gohl & Vilensky, 1983:110).

Polyamide 6,6 melts at approximately 265°C and can withstand temperatures up to 150°C without being damaged (Stevens, 1999:374). At temperatures higher than 150°C the fibres will discolour. The fibres will soften between temperatures of 177°C and 205°C. The ideal temperatures for ironing polyamide 6,6 are between 150°C and 175°C. At temperatures above 530°C, the polyamide will ignite (Joseph, 1986:105).

The exposure of polyamide 6,6 fibres for prolonged periods of time at very high temperatures will cause deterioration. Permanent losses in tensile strength, breaking elongation and toughness are marked. Apart from the deterioration of these properties, the increase of temperature also results in a decrease in tenacity and an increase in elongation (Cook, 1984:242).

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 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 plasticizer which adversely affects the properties of the polyamide. It can reduce the tensile strength (Stevens, 1999:376; Fried, 1995:338). Gohl and Vilensky (1983:109) 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 is noted by an increase in hydrogen bonds.

2.2.6.2 The effect of Detergents and Bleaches on Polyamide 6,6

Polyamide 6,6 fibres are not damaged by soaps and synthetic detergents (Joseph, 1986:106). Polyamide 6,6 can be dry-cleaned as the solvents used during the process are not harmful to the fibre (Collier & Tortora, 2001:170).

Polyamide fabrics are originally white and do not require extensive bleaching before dyeing. Oxidising bleaches that are used under slight alkaline conditions does the least amount of damage to the fibres. The most common bleaches used are peracetic acid, hydrogen peroxide and sodium chloride (Gohl & Vilensky, 1983:110).

Polyamide 6,6 fabrics that are treated with bleaches are more prone to discolour than polyamide 6,6 fabrics that have not been treated with bleaches (Gohl & Vilensky, 1983:110). The prolonged use of chlorine bleaches may however cause white polyamide to discolour and become yellow (Kadolph, 2007:128).

Polyamide 6,6 yarns may deteriorate if it is treated with bleaches repeatedly. The degree of deterioration is dependent on some key factors which are controllable. The type and concentration of the bleach, the pH of the bleach bath, the temperature of the treatment and the amount of time the polyamide is exposed are the key factors contributing to the deterioration (Cook, 1984:245).

2.2.6.3 The effect of Alkalis on Polyamide 6,6

Polyamide 6,6 has very good resistance to alkalis (Kadolph, 2007:128; Cook, 1984:247). Alkali hydrolysis will however occur when it is frequently exposed to alkali. The fabric weakens as a result. The prolonged exposure of polyamide 6,6 to alkali causes white polyamide fabrics to yellow and coloured polyamide 6,6 fabrics to become dull (Gohl & Vilensky, 1983:110).

2.2.6.4 The effect of Acids on Polyamide 6,6

Polyamide 6,6 is less resistant to acids than it is to alkalis. The amide groups in the fibre are more easily hydrolysed in acidic conditions. Hydrolysis causes the polyamide polymer to break up into fragments. The effectiveness of the

hydrogen bonds is thus lost and the result is a weakened fibre (Gohl & Vilensky, 1983:110).

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 (Gohl & Vilensky, 1983:110).

Nitric and sulphuric acid are mineral acids that will cause polyamide 6,6 to disintegrate almost immediately at immersion. Solutions of 3 percent strength of these acids at room temperature also have a noticeable effect on the fibre. Formic acid at room temperature and at concentrations will also dissolve the polyamide 6,6 (Joseph, 1986:106). Oxalic acid at room temperature in a 3.0 percent concentration will also cause some damage to the fibre (Cook, 1984:245).

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).

2.2.7 Physical Properties of Polyamide 6,6

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).

2.2.7.1 Aesthetics

The end use of the fibres determines the degree of lustre (Collier & Tortora, 2001:169). It can be lustrous, semi-lustrous or dull. Polyamide 6,6 with a tri-lobal shape has a pleasant lustre (Kadolph, 2007:126).

Polyamide has a medium to 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 (Gohl & Vilensky, 1983:108). The texture and draping properties of the fabrics can be varied (Collier & Tortora, 2001:169).

Polyamide 6,6 fibres that does not have a round shape, like the voided and tri-lobal shapes, are often used in upholstery and carpets for they hide soil which is an advantage (Kadolph, 2007:126).

2.2.7.2 Specific Gravity

Polyamide 6,6 is a low density fibre (Collier & Tortora, 2001:169). Fabrics made of polyamide fibres are very light because the density of the fibre is 1.14gm/cc (Kadolph, 2007:127; Fried, 1995:339). Although the fabrics made from this fibre are very light, it still has good strength (Collier & Tortora, 2001:169).

2.2.7.3 Dimensional Stability

Polyamide 6,6 can be heat-set, it retains its shape extremely well during usage (Kadolph, 2007:127). The fibre will stretch when it is put under stress, but it will return to its original shape when the stress is released (Joseph, 1986:104).

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). Polyamide 6,6 is not prone to felt. 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).

2.2.7.4 Durability

Polyamide 6,6 is one of the toughest textile fibres in use today. The toughness of the fibre is related to the elasticity polymer system (Gohl & Vilensky, 1983:108). Polyamide 6,6 has excellent abrasion resistance (Kadolph, 2007:126; Anon, 2004:49) and it is also ten times higher than the abrasion resistance of wool (Gruszka, Lewandowski, Benko & Perzyna, 2005:133).

The fabric itself can however be abrasive and wear other fabrics or surfaces (Joseph, 1986:106). Polyamide 6,6 tends to pill, which is a disadvantage (Gruszka, Lewandowski, Benko & Perzyna, 2005:133).

Polyamide 6,6 has excellent strength (Collier & Tortora, 2002:169). 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. The tenacity of polyamide 6,6 is 4.6 to 5.8 grams per denier, when it is regular strength. For high tenacity fibres it is 5.8 to 9.0 grams per denier (Joseph, 1986:103). Simpson, Southern and Ballman (1981:97) reported that tenacity is exponentially correlated to the amorphous orientation of the fibre. They noted that polyamide 6,6 with a tenacity of 1765N and 5.4% elongation is achievable.

Although the higher tenacity fibres are stronger, their elongation is less than that of the regular tenacity fibres. The reason can be found in the manufacturing process. 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, 2007:126). When it is wet, the strength may be reduced by 10% to 20% (Joseph, 1986:103).

2.2.7.5 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, 2002:170). Knitted polyamide fabrics are more comfortable to wear than woven polyamide fabrics because the moisture can escape more easily (Kadolph, 2007:127).

Polyamide 6,6 is not a good electrical conductor. It will also hold static charge until it can be discharged to a good conductor (Joseph, 1986:106). Because of this property it can be used as a good insulator in electrical materials (Collier & Tortora, 2001:170).

2.2.7.6 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, 2007:127). This moisture regain is one of the highest of synthetic fibres, but it is still not as comfortable to wear as natural fibres such as wool (Kadolph, 2007:127).

Polyamide fibres are not very absorbent as the crystalline nature of the polymer allows very few water molecules to be absorbed. Thus these types of fabrics are prone to build up static electricity, because there is not a sufficient amount of water molecules present to dissipate the build-up of it (Gohl & Vilensky, 1983:109; Joseph, 1986:104). Fabrics made from polyamide 6,6 fibre will dry relatively fast after it has been laundered (Collier & Tortora, 2001:170).

2.2.7.7 Appearance Retention

Polyamide 6,6 is very elastic and this is due to the regularity of the strong hydrogen bonds. These bonds operate over short distances, so it's able to exert 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 does not wrinkle or crease easily (Gohl & Vilensky,

1983:108) and recovers well from it (Joseph, 1986:104). The straightening of the zigzag configuration of the polyamide polymer when it is stretched, contribute approximately 22% to its elasticity (Gohl & Vilensky, 1983:108).

Polyamide is very elastic and the recovery from a 4% elongation is 100%. This is a contributing factor to the good shape retention that these fabrics exhibit (Kadolph, 2007:128; Joseph, 1986:104). Even if it is stretched for a few days, it will recover approximately 50% of its length almost immediately (Cook, 1984:241). Polyamide 6,6 also has good recovery from compression, hence the usage thereof in carpets (Collier & Tortora, 2001:170).

The break elongation of polyamide 6,6 is relatively high (Collier & Tortora, 2002:170) and can be stretched up to 300% before it breaks (Fried, 1995:339). Polyamide 6,6 is very flexible because it has low resistance to bending (Collier & Tortora, 2002:170).

2.2.7.8 Care

Polyamide fabrics retain their shape and appearance well during use and care. When washed in hot water, wrinkling may be caused. Nylon is considered to be a colour scavenger. This means that it will easily pick up colours and dirt from other fabrics that is in the wash water (Kadolph, 2007:128).

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 (Kadolph, 2007:129).

Polyamide 6,6 fibres are characterized by a predominantly acidic surface (Tate, Kamath, Wesson & Ruetsch, 1996:587). Food soils may attract insects. 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, 2007:129).

2.2.7.9 Washability

Fabrics made from polyamide 6,6 are machine washable (Collier & Tortora, 2001:172). Ruscher (2004:61) considers a temperature of 30°C or 40°C as sufficient for laundering polyamide 6,6 while Cook (1984:253) states that white polyamide goods should be laundered at 60°C.

Laundering in warm water with gentle agitation helps to prevent wrinkling. Wrinkles that have been set by hot wash water may be permanent (Kadolph, 2007:128).

2.2.8 Environmental Impact of Polyamide 6,6

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, 2007:129). 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, 2007:129).

2.3 Electrochemically Activated Water

2.3.1 Introduction

As early as the 19th century, in 1802, Russian academician V.V. Petrov discovered that the acidification of water near the anode and alkalization near the cathode happens in addition to the emission of electrolysis 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 characterized 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. This discovery was initiated by Bakhir mentioning a previously unknown fact: that the physical and chemical properties of anolyte and catholyte generated through a diaphragm type electrochemical activator differed considerably from the anolyte and catholyte prepared through the dissolution of chemicals and water. This discovery allowed Bakhir to deem the anolyte and catholyte as electrochemically activated water. He also formulated the basic principles of the electrochemical activation technology (Tomilov, 2002:303).

Today electrochemically activated water is used in a wide range of applications including medicine, agriculture, industry (Lobyshev, 2007:1), microbiology and the food industry (Khrapenkov & Gernet, 2002:1). In addition, electrochemically activated water is used in the processes of water purification and decontamination. It is also used as environmentally friendly anti-microbial and washing aqueous media (Bahkir, 2005). Electrochemically activated water may also provide an environmentally sensible alternative to chlorine and other solvents that are generally used (Thantsha & Cloete, 2006:237).

2.3.2 Mechanism of Electrochemical Activation

Electrochemical activation is a physical and chemical (physico-chemical) process combining electrochemical and electrophysical actions (Lobyshev, 2007:1; Tomilov, 2002:303). Exposure of the water to electrochemical activation results in the altering of the molecular state of the water from stable into metastable (activated) aqueous media (Bakhir, 2005; Khrapenkov & Gernet, 2002:1). In the activated state, the water is marked by unusual physical and chemical parameters (Tomilov, 2002:303). Through electrochemical activation it is possible to purposefully change the acid-base and oxidative-reductive properties of the water (Bakhir, 2005).

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). Fresh water 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).

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). The electrodes are unipolar with a double electric layer near the surface of the electrode (Leonov, 1997:11).

Flow-through electrochemical modular (FEM) cells are generally used for electrochemical activation. Figure 2.9 is an illustration of what the FEM-cell looks like. These cells can be connected in a parallel manner. This enables the circuit to be switched from bipolar to a monopolar electrolyser without having to change the hydraulic configuration of the system (Tomilov, 2002:304).

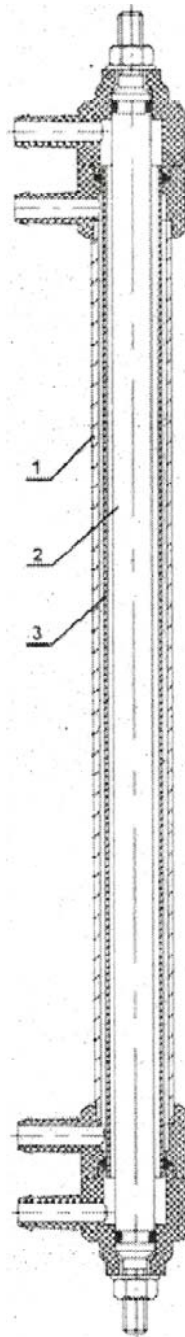


Figure 2.9: Illustration of the FEM-Cell used for Electrochemical Activation

- Where
- 1 : Cathode
 - 2 : Anode
 - 3 : Diaphragm (Tomilov, 2002:304)

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 synthesized in the cathodic electrode is named catholyte and the term anolyte is used for the acidic counterpart synthesized in the anodic electrode (Bakhir, 2005).

These FEM-Cells are specifically designed for the electrochemical activation of water. Conventional electrolyzers are not suitable for the electrolysis of water because it is designed to optimize the processes of conventional electrochemical activation. In 1974 Bakhir and his colleague, Y.G. Zadorozhnyi, developed the first diaphragm type electrochemical reactors. The result was the FEM-Cell mentioned above (Tomilov, 2002:305).

During the later stages of development, other similar cell systems were developed. Each system is specifically designed and developed to fulfill 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).

2.3.3 Properties and Characteristics of Electrochemically Activated Water

Aqueous media which are electrochemically activated are characterized by the metastability of the media (Lobyshev, 2007:1). Metastability merely means that the media, in this case water, exhibits anomalous (unnatural) values of its physical and chemical parameters (Khrapenkov & Gernet, 2002:1). 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).

Catholyte will 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. The physico-chemical properties of the anolyte and catholyte differ from one another as well as their biological properties.

The differences in physico-chemical properties of the anolyte and catholyte are determined mainly through three parameters namely: pH, redox potential and electric conductivity. 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. Last mentioned is depended 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).

Catholyte stimulates biological cell growth while anolyte inhibits the growth (Lobyshev, 2007:1). Catholyte is also negatively charged (Thantsha & Cloete, 2006:237).

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).

Lobyshev (2007:1) found that catholyte contains hydrogen peroxide at a concentration of 10^{-7} M. The catholyte also has high Na and K concentrations in comparison with the initial water (Forostyan, Forostyan & Soroka, 1987:353). Annandale, Schulman and Kirkpatrick (2008:36) reported that the pH of catholyte is between 12 and 13.

The concentration of the alkalis in catholyte is proportional to the mineralization of the water and the electricity consumption during the process when it was synthesized (Bakhr, 1997:39).

2.3.4 Application of Catholyte Solutions

Electrochemical activation is an attractive technology because it simplifies, accelerates and reduces the price of some routine technological processes. It also increases the product quality and it decreases the wastewater contamination (Bakhr, 2005).

Gidakos 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 contribute to the removal of contaminants. This is especially true when the concentrations of ionic contaminants are high (Gidakos & Giannis, 2006:296).

Chartrand and Bunce (2003) reported on the utilization 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 air. This forms an acidic solution that contains toxic metals. The rise in pH of the catholyte caused the precipitation of the iron. The precipitate settled and 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 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 (Standard Textile Inc. 2010).

2.4 General Review on Laundry Detergents

2.4.1 Introduction

Laundrying dirty clothes is an integral part of life as we know it and it is part of every household. Whether it is done with an automatic washing machine, by hand, with soap or with synthetic detergents, are dependent upon the conditions of every household. This mere fact reiterates the importance of detergents in the functioning of every household (Hollis, 2002:1).

Detergents are a group of chemicals that is used for laundrying clothes (Warne & Schifko, 1999:196). Kadolph (2007:467) defines a laundry detergent as “a chemical compound which is specifically formulated to remove soil or other material from textiles”. These detergents are added to the washing water of laundry (Berlow, 1994:247). Laundry detergents contain surfactants and other components that make the detergent more effective in the cleaning process (Bajpai & Tyagi, 2007:327).

Laundry detergents are becoming more and more popular due to the fact that it can be added automatically to the water in the washing machine (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 (Kadolph, 2007:419; Collier & Tortora, 2001:487).

There are a variety of laundry detergent brands and kinds available on today's market (Bajpai & Tyagi, 2001:327). Traditionally laundry detergents were only available in a powdered or solid granular form. The use of liquid laundry detergents has however gradually increased over the years. There are a few companies that even manufacture laundry detergent in tablets and dissolvable sachets, to eliminate the need to measure the correct amount of detergent for each load of washing (Hollis, 2002:1).

2.4.2 History of the Development of Detergents

The first synthetic detergent was developed in 1916. The shortage of fats for the manufacturing of soap during World War I stimulated this development and production (Collier & Tortora, 2001:486). The branched-chain alkyl benzene sulphonates and short-chain alkyl naphthalene sulphonates were produced in Germany. These first synthetic detergents also took hard minerals out of the water that left it soft, like the soap. Before this breakthrough development, laundry products mainly comprised of sodium and potassium neutralized fatty acid soaps (Berlow, 1993:247).

During the 1930's long chain alkyl aryl sulphonates were introduced and by 1945 it was the main component of synthetic laundry detergents. Built detergents were first introduced in 1947 in the United States with sodium diphosphate as the builder (Bajpai & Tyagi, 2007:328).

Phosphates were added to detergents because the straight chain detergents did not work in hard water. Hard water is water that is rich in minerals such as calcium, magnesium, iron and manganese (Berlow, 1993:247). Phosphates are very good at softening the water, but it is also an extremely good fertilizer for algae. This resulted in algae blooms which in turn diminished the oxygen supply in the water, thus killing the fish and having a considerable effect on the eutrophication of waterways. As a result the fate of phosphate was raised as an environmental concern. Sodium carbonate and EDTA were later used as water softeners to replace phosphate (Hui & Chao, 2006:401).

Reacting benzene with propylene tetramer formed an alkyl aryl group which was then sulphonated. This reaction was used to form surfactants that were used in early synthetic detergents (Collier & Tortora, 2001:486). These materials were non-biodegradable and highly branched. In 1965 these

surfactants were voluntarily withdrawn from the market and were replaced with biodegradable linear chain analogs (Bajpai & Tyagi, 2007:328).

The use of zeolites and ion exchange materials as builders in detergents contributed to the gradual movement away from the use of phosphates in the mid 1970's (Hui & Chao, 2006:401). In 2007 the U.S. detergent market had virtually no phosphate formulations whereas 32% of the European powders converted to zeolite based detergents and Canada had only converted about 50%. Latin America and some of the Pacific region countries are still using phosphate based detergents (Bajpai & Tyagi, 2007:328).

2.4.3 Composition of Detergents

A laundry detergent comprises of a formulated mixture of raw materials that are classified into different groups (Berlow, 1993:247). The classification is based on the properties and function it fulfils in the final detergent formulation (Kadolph, 2007:419). The different raw materials 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).

2.4.3.1 Surfactants

Surfactants are organic chemical surface active agents (Collier & Tortora, 2001:487) 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).

The characteristic property of surfactants is the fact that they adsorb at the surface mostly in an oriented manner. The orientation is a deciding factor concerning whether the surface will exhibit hydrophilic or hydrophobic

properties (Anon, 2002:5). The surfactant breaks up the water molecules through its action and surrounds the soil particles as depicted in figure 2.10. 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).

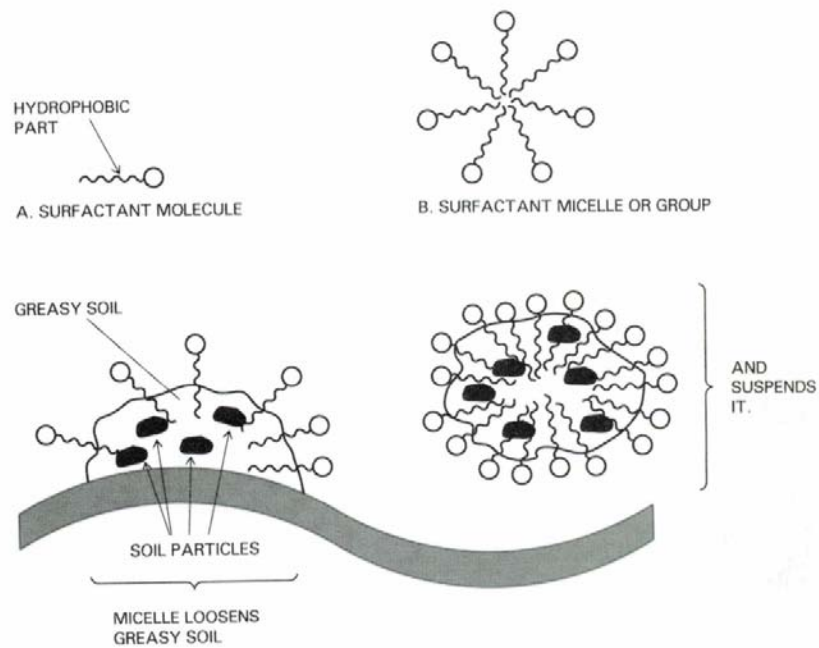


Figure 2.10: Diagrammatic representation of Surfactant Action removing and suspending Greasy Soil (Collier & Tortora, 2001:488)

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 (Kissa, 1981:2256).

There are different types of surfactants. The different types are categorized 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).

2.4.3.1.1 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 (Davidsohn & Milwidsky, 1972:23). Cationic surfactants are limited to use in fabric softeners and disinfectants (Kadolph, 2007:419). Quaternary ammonium compounds are generally used in cationic surfactants (Bajpai & Tyagi, 2007:329).

2.4.3.1.2 Anionic Surfactants

Anionic surfactants are the most widely used class of surfactants (Kadolph, 2007:419; Davidsohn & Milsidsky, 1972:488). 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).

2.4.3.1.3 Nonionic Surfactants

This type of surfactant does not ionize in the solution, hence carrying no electrical charge as it dissolves (Collier & Tortora, 2001:488). Nonionic surfactants are very good at removing especially oily soils. The oily soils 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, 2007:419).

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 is also an important class of non-ionic surfactants. Two minor groups which are also used in non-ionic surfactants are amine oxides and sulphonyl (Davidsohn & Milwidsky, 1972:24).

2.4.3.1.4 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 (Davidsohn & Milwidsky, 1972:33). 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).

2.4.3.2 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 summarized 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)

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 fulfill the purpose of an alkaline agent in laundry detergents (Bajpai & Tyagi, 2007:330).

Builders soften the water through sequestering (separation), precipitation or ion exchange (Kadolph, 2007:419). There are three types of builders:

2.4.3.2.1 Sequestering Builders

Polyphosphates and citrate are sequestering builders. The polyphosphates inactivate the mineral ions which causes 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 2.4.5.

2.4.3.2.2 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 (Davidsohn & Milwidsky, 1972:46). 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 (Davidsohn & Milwidsky, 1972:48).

2.4.3.2.3 Zeolite

Zeolite is a sequestering agent for multivalent metal ions (Kadolph, 2007:419). 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).

2.4.3.3 Anti-Redeposition Agents

Anti-redeposition agents prevent the loosened dirt and soil from redepositing on the clean garment or fabric. Although anionic surfactants also fulfill 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).

2.4.3.4 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).

2.4.3.5 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, 2007:420). Alcohols are used as solvents for all the ingredients in liquid detergents. It also helps to adjust the viscosity and prevent separation within the product (Bajpai & Tyagi, 2007:330).

2.4.3.6 Colourants

Colourants are added to impart a certain distinguished look or individuality to the product (Edser, 2007:2; Bajpai & Tyagi, 2007:330)

2.4.3.7 Fragrances

Fragrances have three functions in any laundry detergent formulation:

- It covers the chemical odor of the detergent
- It covers the odor 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).

2.4.3.8 Bleaches

Bleaching agents are added to detergent formulations to make especially white clothes clean (Collier & Tortora, 2001:489).

2.4.3.8.1 Oxygen Bleaches

Oxygen bleaches provides 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 comes in the form of hydrogen peroxide. It supplies the oxidising agent (which bleaches) directly. The hydrogen peroxide breaks up the soil and organic material in the washing solution (Kadolph, 2007:420). In addition to 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).

2.4.3.8.2 Bleaching Agents

Due to different consumer demands and the development of new technology, laundry detergents with built-in bleaching agents made its appearance (McLean, 1999:42). Sodium percarbonate or sodium perborate is bleaches often used as these agents (Collier & Tortora, 2001:489).

2.4.3.9 Opacifiers

Opacifiers contribute to the rich opaque appearance of liquid detergents (Bajpai & Tyagi, 2007:331; Kadolph, 2007:420).

2.4.3.10 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., 2005:738). 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., 2005:738).

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., 2005:739).

2.4.3.11 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 a dye that absorb light at one wavelength and re-emits it at another. These brighteners cover the soil and makes yellow fabrics appear white (Kadolph, 2007:420).

2.4.4 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 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

2.4.5 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 (Stalmans, Matthijs & De Oude, 1991:115).

Taking into consideration the amount of laundry detergents being used, some environmentalists feel that we are poisoning ourselves because billions of tons 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 fresh water 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) 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).

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).

2.5 Soil Removal

2.5.1 Introduction

The laundering of textiles is a complex process that has been the subject of intensive study over a few decades. The efficiency of the laundering process is dependent on a few factors. The chemical structure of the textile fabric as well as the construction thereof, the type of soil, the structure and concentration of the surfactant and all the other ingredients present in a detergent formulation, are factors to be considered. The conditions in which the laundering takes place are also of great importance (Ilec, Simoncic & Hladnik, 2009:318).

Soil accumulating on textile products is one of the main factors causing the fabric to deteriorate. Spilling food on the fabric is one such an example. It makes the fabric, usually not attractive for insects, attractive because of the organic substrate on it. Dirt that has been rubbed into the fabric causes an increase in the abrasion of the yarns as the soils rub against the fibre. This eventually causes the fibres to break which in turn renders the fabric damaged (Collier & Tortora, 2001:485).

Soil removal plays a vital role in caring for fabrics. Effective soil removal contributes to maintaining the fabric in a good condition for prolonged use (Kadolph, 2007:420).

The soil that is deposited on the fabrics generally consists of different ingredients or materials. Some types of soil are soluble and others are insoluble. Organic acids, mineral acids, alkaline substances, blood, starches and sugars are all materials that can be found in soluble dirt. These materials can all be dissolved in cool or warm water, and does not present difficulty when fabrics with these soil stains are cleaned. Sometimes it will however be necessary to use special stain-removal techniques or substances (Collier & Tortora, 2001:485).

Insoluble soils may bind to the fabric due to physical attraction or in greases, oils and films. While water may be enough to remove soluble soil, it is not enough to remove the insoluble soils. Special materials or solutions are necessary to assist in the removal process of these insoluble soils (Collier & Tortora, 2001:485).

The degree to which a textile fabric can be soiled is related to the hydrophilic nature of the fibres, as well as their negative charge. The electrostatic charge on the fibres, the smoothness of the yarn and the fabric surface also contributes to the soil resistance of a textile fabric (Ilec, Simoncic & Hladnik, 2009:318).

2.5.2 Mechanism of Soil Removal by Laundry Detergents or Surfactants

Surfactants can remove the soil in three different ways, namely the roll-up mechanism, emulsification or solubilization (Bajpai & Tyagi, 2007:332).

2.5.2.1 Roll-Up Mechanism

The roll-up of oily soil from the fibre surface is a result of tension at the interface between the oil, water and the fibre. When a surfactant is present the adhesion angle of the oil increases from 0° to 90° and 180° , causing the oily soil to roll up. The surfactant does this by lowering the tension between the water/fibre and water/oil interfaces (Miller & Raney, 1993:174).



Figure 2.11: The Roll-Up Mechanism of Oily Soil Removal (Kissa, 1981:2255)

The soil will roll up completely when the resultant force of the interfacial tension is positive. If the resultant force becomes zero before the adhesion angle has increased to 180°, the roll up will stop immediately. When this occurs an external force has to be applied to complete the roll up and hence the removal of the soil (Kissa, 1981:2256).

The optimum conditions for removing oily soil is when the surface of the fibre is oleophobic and hydrophilic. This happens when the interfacial tension between the fibre and water is small, the interfacial tension between the oil and fibre is large and when the interfacial tension between the wash solution and oil is also small (Kissa, 1981:2256).

It should also be mentioned that a positive resultant force of interfacial tensions are not sufficient for the oil to roll up. The viscosity of the oily soil is also a determining factor in the rate of roll up of the oil. If the viscosity of the oily soil is higher than the resultant interfacial forces, an external force will be needed to remove the soil (Bajpai & Tyagi, 2007:332).

2.5.2.2 Emulsification

Emulsification is one of the most important factors where oil recovery and detergency is concerned (Huang et al., 1999:93). It is the main application of surfactant absorption at liquid/liquid interfaces. An emulsified mixture of water in oil is generally referred to as a mousse (Bajpai & Tyagi, 2007:333).

The detergent acts as an emulsifier during the laundering procedure. It stabilizes the emulsion and lowers the oil/solution interfacial tension, which enables easy emulsification of the oily soils. Because the surfactants in the detergent have hydrophobic and hydrophilic regions, it can absorb to polar and non-polar materials at the same time. This makes surfactants a very valuable part of the detergent formulation (Huang et al., 1999:93). During the laundering procedure, the non-polar materials are kept in emulsions in the

wash solution and it is removed when rinsing takes place (Shahidzadeh, Bonn & Meunier, 1997:459).

Surfactants also increase the kinetic stability of the emulsions in such a way that the emulsion does not change significantly. The detergents interact with the oil and the water, thus stabilizing the interface between the oil or water droplets that are in suspension (Bajpai & Tyagi, 2007:333).

2.5.2.3 Solubilization

Scott defines solubilization as “the process of incorporation of an insoluble substance into surfactant micelles” (Scott, 1963:134). Solubilization is the process where the co-solute is transferred from its pure state, which is either solid or liquid, to the micelles. The co-solute may be polar or non-polar (Bajpai & Tyagi, 2007:333).

The solubility increases when the critical micelle concentration is reached. This increase of the solubility of the solute can be ascribed to the solubilization of the substrate molecules into the micelles (Scott, 1963:135-136).

The soluble detergent enhances the water in order to wash the laundry better. This is done along with agitation or tumbling. The detergent fulfills its function in the initial wash cycle, where it separates the soil and dirt from the fabric. The rinse that usually follows thereafter ensures that the detergent residue is rinsed away from the fabric and also to remove the dirt suspended in the wash water (Bajpai & Tyagi, 2007:334).

2.5.3 Kinetics of the Soil Removal Process

Removing the soils from the fibre or fabric surface is the essence of the cleansing or soil removal process. This process requires energy because it is the reverse action of coagulation and adhesion (Bajpai & Tyagi, 2007:334).

The soil must be moved from a lower energy state (attached to the fabric surface) to an elevated energy state (separated in the aqueous media). This energy is generally supplied by an external source, such as the human hand or a washing machine. The detergent merely serves to reduce the amount of energy that the external source has to supply (Collier & Tortora, 2001:486).

The removing of solid soil particles was first formulated by Lange (Bajpai & Tyagi, 2007:334). Figure 2.12 schematically illustrates the soil removal process.

STEP I: Soil particle (P) was attached to a fabric substrate (S). The soil particle (P) spontaneously separated from the substrate (S) at a very short distance (δ) in the presence of a detergent solution. This proceeds by the surfactant molecules adsorbing to the soil particle and suspends the particle. The energy that was needed ($A_1 = V_{II} - V_I$) in step one was spontaneously supplied by the adsorption process.

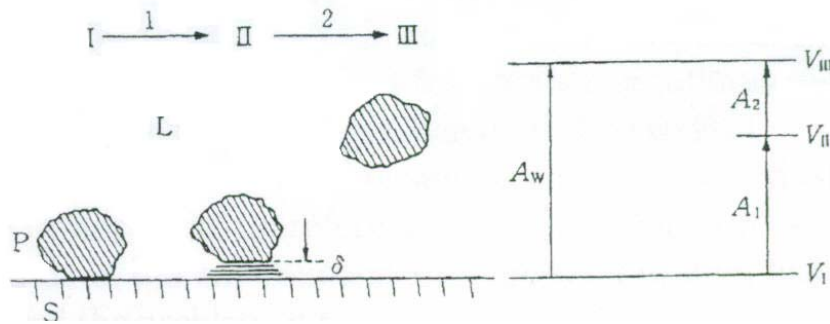


Figure 2.12: Schematic Representation of the Removal Process of Solid Soil Particles (P) from a Fabric Substrate (S) (Cutler & Kissa, 1987:195)

Where : VI, VII & VIII are Potential Energies in Steps I, II & III respectively
: A1 & A2 is the work needed to separate the particle in Steps I, II & III

STEP II: Step two is to increase the distance (δ) and carry the soil particle away from the substrate infinitely. The energy needed for this step can be calculated by the following: $A_2 = V_{III} - V_{II}$.

STEP III: Figure 2.13 illustrates the potential energy as a function of distance between the soil particle and the substrate. The soil particle that is on the substrate is subject to Van der Waals forces. The potential energy of the Van der Waals forces is V_A . The double electrical repulsion layer is V_R . The resultant force (V) is determined by $V = V_A + V_R$. The energy barrier (E) is illustrated by the curve. The height of this curve is dependant on the zeta potential of the fibre and the soil particle. The height of this barrier is extremely important because it controls the kinetics of the removal as well as the redeposition of the soil particle. The soil particle must go over the potential barrier for this step to be successful (Bajpai & Tyagi, 2007:334).

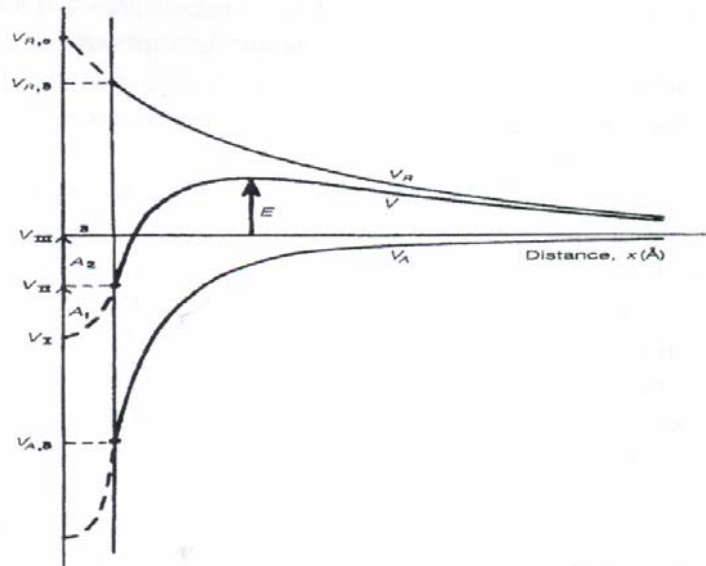


Figure 2.13: The Potential Energy as a Function of Distance between a Soil Particle and a Substrate (Cutler & Kissa, 1987:196)

2.5.4 Assessment of Soil Removal Efficiency

The soil removal efficiency can be determined by assessing it as a colour and assigning a numerical value to that specific colour. These colorimetrically determined numerical values are compared to the numerical value obtained before the soil removal was done. This enables researchers to determine the efficiency with which the soil was removed. The numerical value is expressed as ΔE^* . The higher the difference in ΔE^* value is between the compared readings, the more efficiently soil was removed (Ilec, Simoncic & Hladnik, 2009:319).

Assessing colour and expressing it, is dependent on individual interpretation thereof. Each individual defines and interprets colour according to personal references. When colours are compared, the same is true. The solution for a standardised colour assessment relies upon the instrumental assignment of numerical values to differentiate it from one another (Minolta, 1998:1).

Commonly used instruments for the assessment of colour include spectrophotometers, colorimeters and densitometers. These instruments measure reflected and transmitted light. Spectrophotometers measure the percentage of light that has been reflected or transmitted by the surface. This results in a curve which serves as a fingerprint for that specific colour. A colorimeter is a tristimulus which has three sensors very similar to the human eye. The light is measured through the blue, green and red receptors (Kadolph, 1998:315). Densitometers are similar to colorimeters. It is designed for measuring more specific materials like printing inks and photographic dyes (Minolta, 1998:29).

The uniqueness of each colour is due to a combination of three very important elements namely hue, lightness and saturation. Hue is used as classification for colour red, orange, blue etcetera, which is generally depicted on a

colourwheel. This element is mainly concerned with how colour is perceived. Lightness conveys the brightness or darkness intensity of the specific colour. Saturation describes how dull or vivid a colour is. This indicates how close the specific colour is to grey or a pure hue (Minolta, 1998:13).

In 1905 the American artist Albert H. Munsell devised a method for expressing colours by way of a numerical system. This system is still in use today. This system assigns a numerical value to each of the elements which combine to form a colour. The hue (Munsell Hue), lightness (Munsell Value) and saturation (Munsell Chroma) is generally expressed as a number/letter combination. In addition to the ground breaking work of Munsell, other methods to express colour have also been developed. The *Commission Internationale de l'Eclairage* (CIE) or International Commission of Illumination translated in English, developed the CIELAB (CIE 1976 L*a*b*) and CIELUV (CIE 1976 L*u*v*) colour scales. This was done to provide more uniform colour differences in relation to visual differences (Minolta, 1998:16).

The L*a*b* colour scale is the most popular scale for assessing colour. Figure 2.14 illustrates the L*a*b* colour scale. 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.

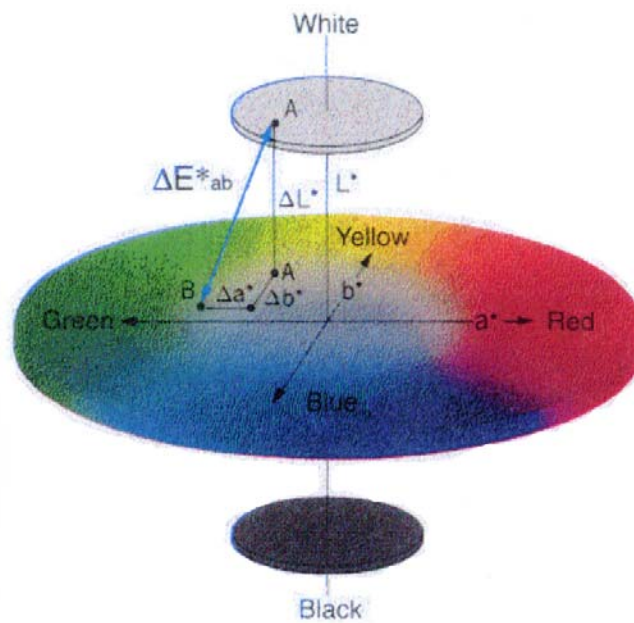


Figure 2.14: The L*a*b* Colour Space (Minolta, 1998:22)

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 program accompanying the apparatus with which the readings were taken with. The differences in colours can be expressed numerically by calculating ΔE^* .

The calculation of ΔE^* is done by the following formula:

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

The ΔE^* indicates the size of the colour difference. It does not determine the way in which the colours are different (Minolta, 1998:22).

CHAPTER 3: Materials and Methods

3.1 Materials

3.1.1 Textile Materials

The primary focus of this study was to determine what effect the electrochemically activated water (catholyte) had on some of the important properties of polyamide 6,6 and machine washable wool. The other component of this study was to determine the soil removal efficiency of the catholyte on the polyamide 6,6 and machine washable wool. In order to conduct the tests, four sets of woven textile fabrics were needed. Standard polyamide 6,6 and wool fabric, and standard soiled polyamide 6,6 and wool fabric as described in the following section were used for this study.

The laundering, tearing strength, tensile strength, bending length, wrinkle recovery and dimensional stability tests were conducted on the standard machine washable wool and polyamide 6,6 textile fabrics described below:

3.1.1.1 Wool

ISO standard adjacent single fibre machine washable worsted merino wool challis (style #537; lot #0107) was purchased from Testfabrics, Inc., West Pittston, Pennsylvania. The yarns of the fabric were machine spun and it was woven using a plain weave construction. The fabric weighed 125 gm/m² with 22 warp yarns and 21 weft yarns per 10mm distance.

3.1.1.2 Polyamide 6,6

The standard unsoiled, undyed polyamide 6,6 (style #361; lot #1421) fabric was purchased from Testfabrics, Inc., West Pittston, Pennsylvania. It was made from 100% machine spun Du Pont type polyamide 6,6 yarns meeting the ISO 105 standard. The fabric was woven using a plain weave construction with a weight of 124 gm/m² and 22 warp yarns and 21 weft yarns per 10mm distance.

The soil removal tests were conducted on the standard soiled machine washable wool and polyamide 6,6 textile materials described below:

3.1.1.3 Soiled Wool

Standard soiled machine washable merino wool (style STC TF #530) was purchased through Dutest Agencies, Milnerton, South Africa from Testfabrics, Inc., West Pittston, Pennsylvania. The yarns of the fabric were machine spun and it was weaved using a plain weave construction. The wool was not dyed but chemicals were applied and it underwent processes which rendered it machine washable.

NOTE: The components for the soiling of the standard soiled fabrics are keltex, corn starch, mialral oil, oleic acid, morpholine, vegetable fat, butanol, solvesso 150 and water.

3.1.1.4 Soiled Polyamide 6,6

The standard soiled, undyed polyamide 6,6 (style STC TF #361) fabric was purchased through Dutest Agencies, Milnerton, South Africa from Testfabrics, Inc., West Pittston, Pennsylvania. It was made from 100 percent machine spun Du Pont type polyamide 6,6 yarns. The fabric was weaved using a plain weave construction.

NOTE: The components for the soiling of the standard soiled fabrics are keltex, corn starch, mialral oil, oleic acid, morpholine, vegetable fat, butanol, solvesso 150 and water.

3.1.2 Detergent

The ECE Phosphate Reference Detergent Type B without optical brightener was purchased from James H. Heal & Co. Ltd, Halifax, England. The detergent (code 706-736) meets the ISO 105 standard for testing. The composition of the detergent is depicted in table 3.1.

Table 3.1: The composition of the ECE Phosphate Detergent as provided by James H. Heal & CO. LTD

Component	Quantity (% mass)
Linear sodium alkyl benzene sulphonate (mean length of alkane chain C _{11.5})	8
Ethoxylated tallow alcohol (14 EO units)	2.9
Sodium soap, chain length C ₁₂₋₁₆ 13% - 26% : C ₁₈₋₂₂ 74% - 87%	3.5
Sodium tripolyphosphate	43.7
Sodium silicate(SiO ₂ :Na ₂ O ₂ = 3.3 : 1)	7.5
Magnesium silicate	1.9
Carboxy methyl cellulose(CMC)	1.2
Ethylene diamine tetra acetic acid (EDTA), tetra sodium salt	0.2
Sodium sulphate	21.2
Water	9.9
TOTAL	100

3.1.3 Electrochemically Activated Water

The electrochemically activated water (catholyte) was prepared by the electrolysis of a 5% NaCl concentration distilled water solution. The electrolysis was carried out under uniform conditions of a continuous electric current of twelve ampere and pressure of seventy five kilo-Pascal. The electrolysis was continued until the catholyte reached a pH between 12 and 13 (Annandale, Schulman & Kirkpatrick, 2008:36; Petrushanko and Lobyshev, 2001:389).

The catholyte was used within eight hours after preparation. The composition of the electrochemically activated water is depicted in table 3.2. The analysis was done by the Institute for Groundwater Studies, University of the Free State.

Table 3.2: The composition of Electrochemically Activated Water as provided by the Institute for Groundwater Studies, University of the Free State

		Anolyte	Catholyte
Determinant	Units	Value	Value
Electrical Conductivity	mS/m	7955	16117
Ca	mg/l	4.95	2.5
Mg	mg/l	1.06	<1
Na	mg/l	15188	22482
K	mg/l	5.67	8.68
Cl	mg/l	27578	26506
PO ₄	mg/l	41.94	4.74
SO ₄	mg/l	2131	1034
Aluminium	mg/l	0.057	0.063
Copper	mg/l	0.375	0.073
Fe	mg/l	0.057	0.105
Manganese	mg/l	0.007	<0.01
Ni	mg/l	<0.1	<0.1
Zn	mg/l	0.184	0.042

3.2 Methods of Testing

3.2.1 Laundering

The laundering was conducted using an Atlas Launder-Ometer (Atlas Electric Devices Co.) and AATCC Test method 61-1975. Test IIA was used for this study.

3.2.1.1 Preparation and Laundering of the fabric intended for the tearing strength, tensile strength, bending length, wrinkle recovery and dimensional stability tests:

The samples were cut to meet the dimensional specifications of the tests being conducted on it. All samples covered an area of 7500mm².

The raw edges of the fabric were over-locked to avoid fraying during the laundering. The width of the over-lock edges was taken into consideration when the samples were prepared, so that the dimensions of the samples still met the different test specifications.

Table 3.3 illustrates the division of the samples and the variables each set was exposed to.

Half of the samples were laundered at 30°C with three different washing solutions (catholyte, detergent or distilled water) for five, ten, twenty or fifty cycles. The other half of the samples was laundered at 40°C with catholyte, detergent or distilled water for five, ten, twenty or fifty cycles. Table 3.3 illustrates how the samples were divided into sets and what variable each set was exposed to.

Table 3.3: Illustration of the division of the sample sets and the variables each set was exposed to

Set #	Type of Cleaning Liquor	Temperature	Number of cycles
Set 1-1(a)	Catholyte	30°C	5
Set 1-1(b)	Catholyte	30°C	10
Set 1-1(c)	Catholyte	30°C	20
Set 1-1(d)	Catholyte	30°C	50
Set 1-2(a)	Catholyte	40°C	5
Set 1-2(b)	Catholyte	40°C	10
Set 1-2(c)	Catholyte	40°C	20
Set 1-2(d)	Catholyte	40°C	50
Set 2-1(a)	Detergent	30°C	5
Set 2-1(b)	Detergent	30°C	10
Set 2-1(c)	Detergent	30°C	20
Set 2-1(d)	Detergent	30°C	50
Set 2-2(a)	Detergent	40°C	5
Set 2-2(b)	Detergent	40°C	10
Set 2-2(c)	Detergent	40°C	20
Set 2-2(d)	Detergent	40°C	50
Set 3-1(a)	Distilled Water (Control)	30°C	5
Set 3-1(b)	Distilled Water (Control)	30°C	10
Set 3-1(c)	Distilled Water (Control)	30°C	20
Set 3-1(d)	Distilled Water (Control)	30°C	50
Set 3-2(a)	Distilled Water (Control)	40°C	5
Set 3-2(b)	Distilled Water (Control)	40°C	10
Set 3-2(c)	Distilled Water (Control)	40°C	20
Set 3-2(d)	Distilled Water (Control)	40°C	50

3.2.1.2 Preparation and Laundering of the fabric intended for the soil removal tests:

The fabric samples were cut 75mm x 100mm and the raw edges were overlocked to avoid fraying during the laundering. One group of the samples was laundered for five cycles of 45 minutes at 30°C with three different washing agents (catholyte, detergent or distilled water). The other group was laundered at 40°C with catholyte, detergent or distilled water for five cycles. Twelve samples were prepared per set as depicted in table 3.4.

Table 3.4: Illustration of the division of the soiled fabric sample sets and the variables each set was exposed to

Set #	Type of Cleaning Liquor	Temperature
Set 4(a)	Catholyte	30°C
Set 4(b)	Catholyte	40°C
Set 5(a)	Detergent	30°C
Set 5(b)	Detergent	40°C
Set 6(a)	Distilled Water (Control)	30°C
Set 6(b)	Distilled Water (Control)	40°C

3.2.1.3 Procedure

This procedure is applicable to the fabric samples mentioned in 3.2.1.1 and 3.2.1.2.

Fifty stainless steel balls were placed in each stainless steel cylinder as well as 150ml of the washing solution in accordance with the IIA test in AATCC Test Method 61-1975. The balls were counted after each laundering cycle to ensure all the samples were subjected to the same degree of agitation. One sample per cylinder was allowed.

After laundering, the samples were rinsed for one minute in individual glass beakers containing 150ml distilled water in a water bath of the same temperature as the laundering temperature. The samples were left to dry naturally before it was laundered again.

3.2.2 Tearing Strength

The tearing strength tests were conducted with the Elmendorf Tearing Strength tester as per ASTM Test Method D 1424 - 63. Tearing strength is expressed as tearing force which is the average force that is required to continue a tear in the fabric.

The samples were prepared to be 100mm x 63mm. Four samples with their long sides parallel to the warp and four samples with their long sides parallel to the weft were prepared per set as outlined in table 3.3. This was done on both the wool and polyamide 6,6 fabrics. The samples were conditioned for a minimum of 24 hours at $21 \pm 1^\circ\text{C}$ and $65 \pm 2\%$ relative humidity before they were tested.

Before the test commenced, it was checked that the apparatus was level. The pendulum was raised to its starting position and the pointer was set against its stop. The conditioned sample was fastened securely in the clamps with its upper edge parallel to the clamps and the yarns to be torn, perpendicular to it. The blade knife was used to cut a slit in the fastened sample. The pendulum was released and the tear continued until the fabric ruptured. The reading was recorded in milli-Newton (mN), which expressed the tearing force. Any readings were disregarded if the sample slipped in the jaw or if puckering occurred.

NOTE: The warp yarns of the samples cut parallel to the weft of the fabric was torn and the weft yarns of the samples cut parallel to the warp of the fabric was torn.

3.2.3 Tensile Strength

The tensile strength tests were conducted with the Instron Tensile Tester and ISO/SANS 13934-1:1999 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 100mm x 50mm. A total of ten samples per set (table 3.3) were prepared, five samples with their long sides parallel to the warp and five samples with their long sides parallel to the weft. This was done on both the wool and polyamide 6,6 fabrics. The samples were conditioned for a minimum of 24 hours at $21 \pm 1^{\circ}\text{C}$ and $65 \pm 2\%$ relative humidity before the tests were conducted.

The gauge length of the Instron (testing machine) was set at $100\text{mm} \pm 1\text{mm}$. The rate of extension was set at 100 mm/min. The ramp rate of the apparatus was 20 kN/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 extension in millimetres were recorded (b). Any readings were disregarded if the sample slipped during the testing period.

NOTE: Due to the dimensional changes (shrinkage) that took place during the laundering of the fabrics the thread count per 10mm^2 increased. The number of threads in the test dimensions of the sample was thus more than before it was laundered and so the tensile strength of the fabric was adversely influenced. The test method was adjusted to accurately convey the tensile strength of the fabric used in this study. The adjustment was done by using a formula after the tests were carried out.

The following formula was used:

$$TS = O \times \frac{X}{Y}$$

Where TS : Altered tensile strength value in Newton (N) as used in the results of this study

O : Original tensile strength value in Newton (N)

X : Number of threads per 10mm² before the fabric laundering

Y : Number of threads per 10mm² after fabric laundering

3.2.4 Bending Length

The bending length was determined by using the Shirley Stiffness tester and British Standard Test Method 3356:1961. Bending length is a very simple and accurate way in which the stiffness of a fabric can be expressed. It is the length a test sample has to overhang to produce a deflection through a predetermined angle.

The samples were prepared so that their dimensions were 25mm x 150mm. A total of eight samples per set (table 3.3) were prepared, four samples with their long sides parallel to the warp and four samples with their long sides parallel to the weft. This was done on both the wool and polyamide 6,6 fabrics. The samples were conditioned for a minimum of 24 hours at 21 ± 1°C and 65 ± 2% relative humidity before the tests were carried out.

Before the test commenced, it was checked that the test apparatus was level on the work bench. The sample was placed horizontally on the platform of the apparatus with the weight on top of it so that the edges at the front coincide. The weight was slid carefully and slowly whilst the front edges started to project beyond the platform edge. The eyes were held in a position so that the

two lines on the tester formed one when looking in the mirror. The sample was slid until the tip of the protruding edge touched the line.

Four readings from each sample were taken. It was taken with each side up; first the one end and then the other end. The readings were recorded in centimetres and were deemed as the bending length of the fabric. When the fabric twisted, as it tends to do, the reference point at the centre of the edge was taken. If the sample twisted more than 45°, the reading was not recorded.

3.2.5 Wrinkle Recovery

The wrinkle recovery tests were conducted with the Shirley Crease Recovery tester and AATCC Test Method 66. The wrinkle recovery from creasing and compressing under controlled conditions are determined through measuring the recovery angle.

The samples were prepared so that their dimensions when tested were 15mm x 40mm. Three samples with their long sides parallel to the warp and three samples with their long sides parallel to the weft were prepared per set as outlined in table 3.3. This was done on both the wool and polyamide 6,6 fabrics. The samples were conditioned flat without wrinkles for a minimum of 24 hours at $21 \pm 1^\circ\text{C}$ and $65 \pm 2\%$ relative humidity before it was tested.

The sample was folded in half, edge on edge with tweezers taking great care not to grip it near the area intended to be wrinkled. The sample was placed on the marked area of the apparatus platform. The 500 gram load was gently applied for 5 minutes \pm 5 seconds. When the time expired, the load was removed without delay. The sample was transferred to the tester disk holder with the tweezers, again taking care not to disturb the area that was wrinkled. The sample was placed in the tester disk with one leg clasped in the holder and the other protruding from the clasp and hanging free. The dial was adjusted so that the free leg was aligned vertically with the vertical guide line and was left to recover for 5 minutes. The final adjustment was made just before the time

expired and the reading was recorded in degrees as on the dial. This reading is the wrinkle recovery of the fibre.

3.2.6 Dimensional Change

The dimensional change was determined by counting the threads in a determined dimension before and after laundering and calculating the recorded readings in a percentage (%) value.

A determined area of 25mm x 25mm was marked on each sample. Before the laundering of the samples (table 3.3) commenced, the number of threads in the specific area was counted and recorded. After the laundering of the samples was complete, the threads in the specific area was counted and recorded again. A thread counter with a magnifying glass was placed on the sample in order to make the counting easier and more accurate.

The recorded readings were calculated in percentage. The following formula was used for the calculation:

$$\% \text{ Dimensional Change} = \frac{A-R}{A} \times \frac{100}{1}$$

Where A : Thread count before laundering

 R : Thread count after laundering

3.2.7 Soil Removal

AATCC Test Method 135-1985 for the Instrumental Colour Measurement of Textiles was used to determine the difference in colour between the laundered fabrics. The difference in colour indicated the degree to which the soil removal took place. The samples were prepared as mentioned in 3.2.1.2.

A colorimeter that was calibrated before conducting the tests was used to measure the colour difference. The CIE 1976 L*a*b* colour scale formula was

used to calculate the difference in shade. L^* defines the lightness, a^* conveys the red/green value and b^* the yellow/blue value. The measure of the colour lightness was given as a direct reading, however the a^* and b^* values coordinates on each respective axis that indirectly reflect hue and chroma. The differences in colour were expressed as a numerical value by calculating (delta-E) ΔE . The calculation of ΔE^* is done by the following formula:

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

The ΔE^* indicates the size of the colour difference. It does not determine the way in which the colours are different. Three measurements per sample were taken.

3.2.8 Statistical Analysis

The dependent variables, tearing strength, tensile strength, bending length, wrinkle recovery and dimensional stability, were analyzed separately for the four combinations of two textile materials, polyamide 6,6 and machine washable wool, and two directions of measurement, warp and weft. The analysis of variance (ANOVA) model fitted the factors treatment (catholyte, detergent, distilled water), temperature (30 degrees Celsius, 40 degrees Celsius), and cycle (5, 10, 20, 50), as well as all two-factor interactions and the three factor interaction between these variables. F-tests and associated P-values for all effects in the model were obtained from the ANOVA.

Furthermore, least squares means for all treatments, temperatures, cycles and combinations of these three factors were calculated, together with their standard errors. Estimates of the differences between least squares means, associated 95% confidence intervals and P-values were also reported.

NOTE: A probability value of 0.05 or less leads to the conclusion that the effect is significant.

CHAPTER 4: Results and Discussion

4.1 Tearing Strength

This test measures the force required to continue a tear which has already been started in the fabric. The force is increased on the tear until the fabric ruptures (Kadolph, 1998:165). The average force necessary for the continuation of the tear is noted and an average for the samples are calculated (ASTM D1424 – 63; p325). Tearing strength is one of the most important strength parameters when the durability properties of a particular textile fabric are analyzed (Witkowska & Frydrych, 2004:42).

The results obtained when the tearing strength tests were conducted on the polyamide 6,6 and machine washable wool fabrics used in this study are discussed in the following section:

4.1.1 The influence of detergent, catholyte and distilled water on the tearing strength of polyamide 6,6 and machine washable wool fabric

The influence of detergent, catholyte and distilled water on the tearing force needed to rupture the warp and weft yarns of the polyamide 6,6 fabric is shown in figure 4.1. The tearing force needed to rupture the weft yarns of polyamide 6,6 fabric laundered in distilled water did not differ significantly from the tearing force needed to rupture the weft yarns of the fabric before it was laundered. Although the force required to tear the weft of the fabric laundered in catholyte decreased from 998mN to 977mN, it is not considered as a significant difference. Laundering the fabric with detergent lowered the tearing force of the weft yarns even further to 950mN, a significant difference. The influence of the catholyte on the force needed to rupture the weft yarns of the polyamide 6,6 fabric was not significantly different from the influence that the

detergent had on the force needed to rupture the weft yarns of the same fabric. The p-values of the compared treatments are depicted in table 4.1.

The tearing force needed to rupture the weft yarns of the polyamide 6,6 fabric was higher than the tearing force needed to rupture the warp yarns of the same fabric. This is an unexpected outcome as the warp yarns of a fabric are usually the stronger yarns (Kadolph, 2007:222). The difference in tearing force was the highest between the weft and warp yarns of the polyamide 6,6 fabric laundered with detergent.

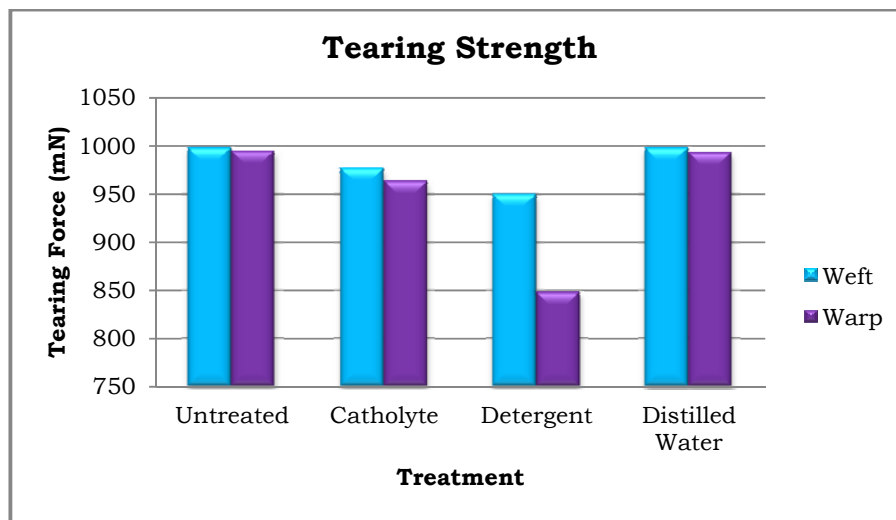


Figure 4.1: The influence of Detergent, Catholyte and Distilled Water on the Tearing Strength of Polyamide 6,6 fabric

Table 4.1: P-Values of Compared Treatment Combinations for the Weft of the Polyamide 6,6 fabric

TREATMENT	Catholyte	Detergent	Distilled Water
Catholyte		0.0777	0.1733
Detergent	0.0777		0.0028
Distilled Water	0.1733	0.0028	

From figure 4.1 it is evident that the tearing force needed to rupture the warp yarns of the polyamide 6,6 fabric laundered with catholyte and detergent respectively were significantly lower compared to the tearing force needed to rupture the warp yarns of the same fabric before it was laundered and when it was laundered with distilled water. The tearing force needed to rupture the warp yarns of polyamide 6,6 fabric laundered with detergent was the lowest. The tearing force decreased from 995mN to 848mN which was a significant difference. The tearing force needed to rupture the warp yarns of the polyamide 6,6 fabric laundered with catholyte (963.75mN) was lower than the force needed to rupture the warp yarns of the same fabric laundered in distilled water (993.44mN), but higher than the force needed to rupture the warp yarns of the polyamide 6,6 fabric laundered with detergent (848.13mN). Table 4.2 depicts the p-values of the compared treatments.

Table 4.2: P-Values of Compared Treatment Combinations for the Warp of the Polyamide 6,6 fabric

TREATMENT	Catholyte	Detergent	Distilled Water
Catholyte		<.0001	0.0346
Detergent	<.0001		<.0001
Distilled Water	0.0346	<.0001	

The fact that the detergent and catholyte had a significant influence on the polyamide 6,6 fabric may be contradictory to the literature stating that polyamide 6,6 generally has good resistance to alkali (Kadolph, 2007:128; Collier & Tortora, 2001:170; Cook, 1984:247). Gohl and Vilensky (1983:110) did however note that the polyamide fibre may weaken if it is frequently exposed to alkalis. Taking into consideration that the fabric was laundered for up to fifty cycles, the frequency of the exposure to the alkalis may explain the decline in tearing force.

The calculated average pH of the detergent liquor used during the laundering of the polyamide 6,6 fabric was 9.65, and the average of the catholyte used during the laundering of the fabric 12.78. From the results discussed on the previous pages it is evident that the polyamide 6,6 fabric laundered with detergent needed the lowest force to rupture the weft and warp yarns of the fabric. The tearing force needed to rupture the weft and warp yarns of the polyamide 6,6 fabric laundered with catholyte was higher than the force needed to rupture the fabric laundered with detergent. The pH of the detergent was also lower on the alkaline pH range than the pH of the catholyte. It can therefore be concluded that the pH of the detergent liquor is not the sole cause of the decline in tearing force of the fabric. One or more ingredients in the detergent might be responsible for the damage.

The distilled water did not have a significant influence on the tearing force of the polyamide 6,6 fabric as the tearing force remained in the vicinity of the tearing force needed to rupture the yarns of the unlaundered fabric. This is expected as the distilled water was merely used as a control to the polyamide 6,6 fabric laundered with catholyte and detergent.

As stated previously (page 101) the polyamide 6,6 fabric was stronger in the weft than the same fabric in the warp. This is in contradiction to what is generally accepted as the warp of a fabric is usually stronger than the weft of the fabric, due to the fact that the warp yarns have to withstand abrasion and tension on the loom while the fabric is woven (Kadolph, 2007:222).

Catholyte and detergent had a significant influence on the tearing force of machine washable wool. Figure 4.2 illustrates the influence that catholyte, detergent and distilled water had on machine washable wool fabric. Laundering the fabric with distilled water resulted in the least amount of decrease in the tearing force needed to rupture the weft yarns. The tearing force of these samples declined from 537.50mN to 534.38mN, an insignificant difference of only 3.13mN. A further decrease of 5.63mN was noted when the

machine washable wool fabric was laundered with detergent. Laundering the fabric with catholyte resulted in the lowest tearing force in the weft noted by a significant decline of 48.75mN when compared to the force needed to rupture the weft yarns of the fabric before it was laundered. The mean tearing force values (mN) needed to rupture the weft yarns of the machine washable wool fabric when laundered with catholyte, detergent and distilled water is depicted in table 4.3.

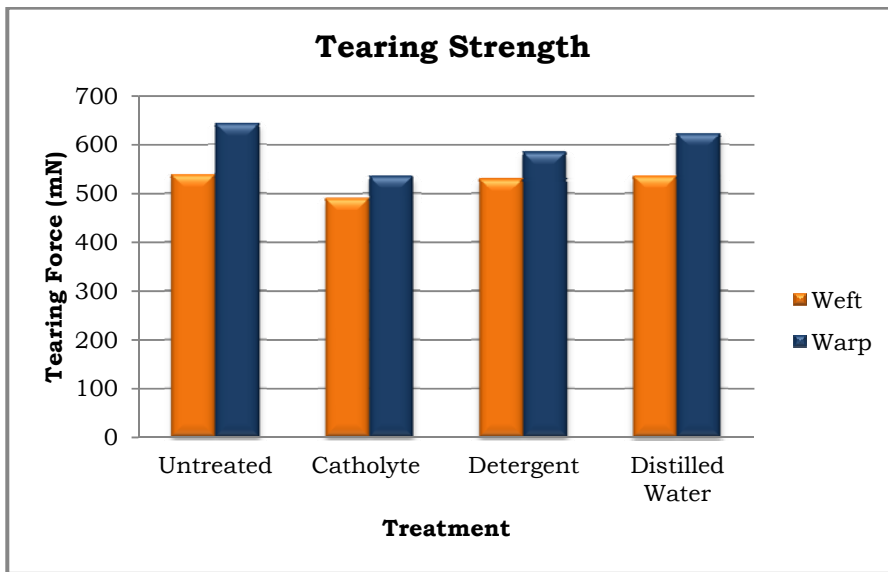


Figure 4.2: The influence of Detergent, Catholyte and Distilled Water on the Tearing Strength of Machine Washable Wool fabric

Table 4.3: Tearing force means (mN) for Machine Washable Wool fabric laundered with Catholyte, Detergent and Distilled Water

TREATMENT	Mean (Weft)	Mean (Warp)
Untreated	537.500000	642.500000
Catholyte	488.750000	534.583333
Detergent	528.750000	583.750000
Distilled water	534.375000	621.770833

As is evident from figure 4.2, the tearing force needed to rupture the warp yarns of the machine washable wool fabric was higher than the tearing force needed to rupture the weft yarns of the same fabric. Generally the warp of a fabric is superior in strength to that of the weft. The warp yarns are stronger because these yarns have to withstand abrasion and tension on the loom while the fabric is woven (Kadolph, 2007:222).

Laundering the machine washable wool with distilled water seems to have caused the least loss in tearing force needed to rupture the warp yarns, marked by a significant decrease of 20.73mN. Before the fabric was laundered a tearing force of 642.50mN was needed to rupture the yarns and laundering the machine washable wool with distilled water resulted in a decrease of tearing force to 621.77mN. Laundering the fabric with detergent further decreased the tearing force of the warp with 38.02mN and laundering the fabric with catholyte significantly decreased the tearing force in the warp, again with 38.02mN resulting in a significant difference. Laundering the machine washable wool fabric with catholyte resulted in the highest loss of tearing force needed to rupture the warp yarns.

The significant decline in tearing force in the warp and weft yarns of machine washable wool that was laundered with catholyte and detergent can be ascribed to the alkaline nature of these laundering liquors. Proteins of the wool fibre are degraded by alkali (Simpson & Crawshaw, 2002:137). Wool has poor resistance to alkali (Joseph, 1986:46) because it attacks the disulphide bond, thus the cystine linkages, and also causes the salt linkages to break down (Carter, 1971:79). This results in a loss of strength (Simpson & Crawshaw, 2002:137).

As expected the distilled water caused the least loss in tearing force as it was merely used as a control to the fabric treated with catholyte and detergent. The water molecules can penetrate between the long keratin molecules. This alters the structural arrangement of the molecule. The molecules are then able

to move more easily (Feughelman, 1997:64). At this stage the wool becomes softer, more plastic and weaker (Cook, 1984:110). In the wet state while the fabric was exposed to agitation, damage was most probably caused to the fabric structure resulting in the slight decrease of tearing force.

4.1.2 The influence of laundering temperature on the tearing strength of polyamide 6,6 and machine washable wool fabric

Figure 4.3 illustrates the influence of laundering temperature on the tearing force of the polyamide 6,6 fabric. Laundering the fabric at 40°C lowered the tearing force needed to rupture the weft yarns from 998mN to 976.05mN and laundering the polyamide 6,6 fabric at 30°C lowered the tearing force further to 973.82mN. The tearing force needed to rupture the weft yarns of the polyamide 6,6 fabric laundered at 30°C was slightly lower than force needed to rupture the weft yarns of the fabric laundered at 40°C. The difference was insignificant.

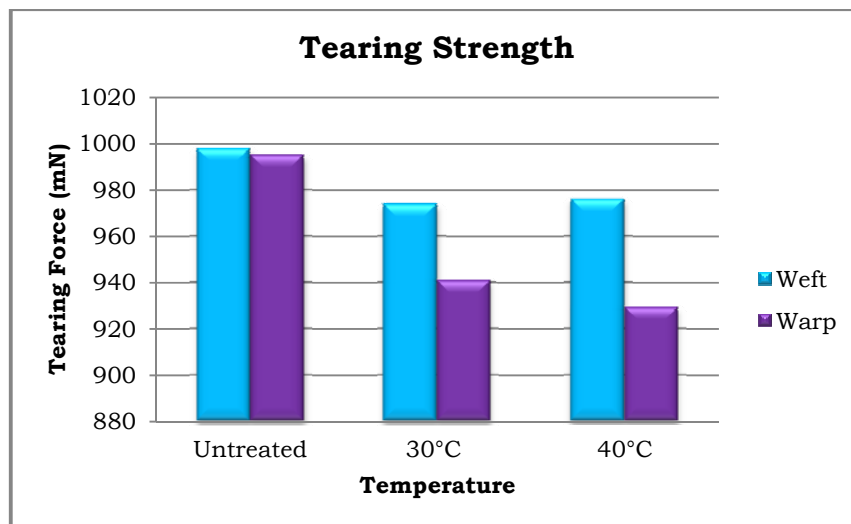


Figure 4.3: The influence of Temperature on the Tearing Strength of the Polyamide 6,6 fabric

Laundering the polyamide 6,6 fabric at 30°C resulted in a tearing force of 940.83mN in the warp which was 54.17mN lower than before the fabric was

laundered. Laundering the polyamide 6,6 fabric at 40°C lowered the tearing force needed to rupture the warp yarns to 929.38mN. The difference in the tearing force needed to rupture the warp yarns of the polyamide 6,6 fabric laundered at 30°C and 40°C was insignificant.

From figure 4.3 it is also evident that the tearing force needed to rupture the warp yarns of the fabric was lower than the tearing force needed to rupture the weft yarns of the polyamide 6,6 fabric.

Although a decrease in tearing force was noted, the laundering temperature was not considered as a significant influence. These results are valuable as 30°C and 40°C are regarded as standard temperatures for laundering polyamide 6,6 fabric (Ruchser, 2004:61).

Figure 4.4 illustrates the influence that the laundering temperatures had on the tearing force of the machine washable wool fabric. Laundering the machine washable wool fabric at 30°C and 40°C had a significant influence on the tearing force needed to rupture the weft and warp yarns of the fabric.

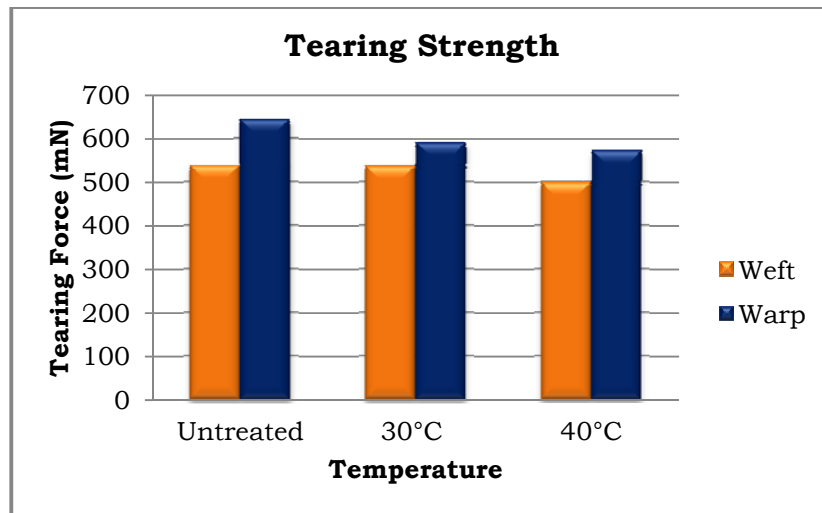


Figure 4.4: The influence of Temperature on the Tearing Strength of Machine Washable Wool fabric

The tearing force needed to rupture the weft yarns of the machine washable wool fabric laundered at 30°C decreased slightly from 537.50mN (unlaundered) to 536.04mN. Laundering the machine washable wool fabric at 40°C lowered the tearing force needed to rupture the weft yarns of the fabric significantly to 498.55mN, the difference between the forces needed to rupture the yarns being 37.50mN.

Laundering the machine washable wool fabric at 30°C resulted in the tearing force in the warp being 53.47mN less than before it was laundered. The tearing force thus significantly decreased from 642.50mN to 589.03mN. Laundering the fabric at 40°C decreased the tearing force in the warp further to 571.04mN.

From figure 4.4 a noticeable difference in tearing force is evident between the weft and warp of machine washable wool fabric that were laundered at 40°C in comparison with the fabric laundered at 30°C. The tearing force of the fabric laundered at 40°C is less than the machine washable wool fabric laundered at 30°C. The tearing force decreased as the temperature increased. Temperatures for laundering wool should not be warm or hot (Kadolph, 2007:70; Joseph, 1986:53). Temperatures not exceeding 40°C are considered as warm (ASTM D3136) and temperatures exceeding 50-60°C are regarded as hot, but wool should not be washed at these temperatures. Temperatures not exceeding 30°C are regarded as cold (ASTM D3136). Although the normal domestic washing temperature for wool is considered 40°C (Vasconcelos et al., 2006:729), from the results discussed in this section it is evident that the wool laundered at 30°C can withstand a higher force before it ruptures than the wool laundered at 40°C. Therefore wool should rather not be laundered at a temperature of 40°C.

4.1.3 The influence of the number of laundering cycles on the tearing strength of polyamide 6,6 and machine washable wool fabric

Figure 4.5 illustrates the influence that five, ten, twenty and fifty laundering cycles respectively had on the tearing force of polyamide 6,6 fabric. Laundering the polyamide 6,6 fabric for five cycles lowered the tearing force in the weft from 998mN (before laundering) to 985.56mN. Laundering the fabric for ten cycles is marked by an insignificant decrease in tearing force of only 0.56mN. When the polyamide 6,6 fabric was laundered for four cycles, a further decrease in the tearing force needed to rupture the weft yarns of the fabric of was noted. Laundering the fabric for fifty cycles resulted in the lowest tearing force value in the weft of 962.92N. The statistical analysis supports the conclusion that the number of laundering cycles did not have a significant influence on the tearing force needed to rupture the weft yarns of polyamide 6,6 fabric.

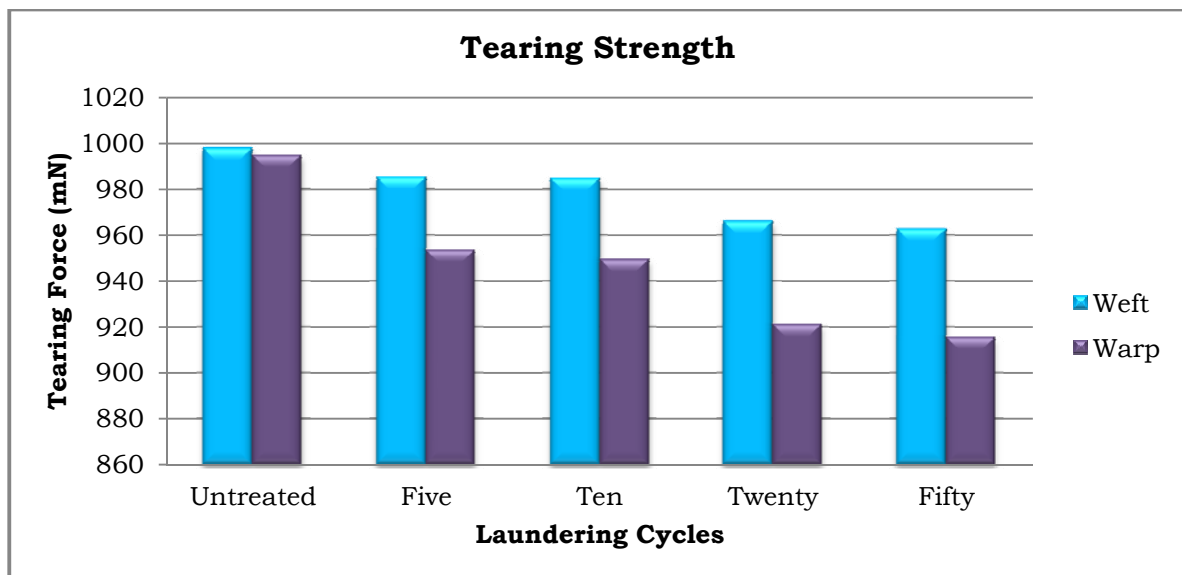


Figure 4.5: The influence of the Number of Laundering Cycles on the Tearing Strength of Polyamide 6,6 fabric

Table 4.4 depicts the tearing force means (mN) of the polyamide 6,6 fabric that was laundered for five, ten, twenty and fifty cycles respectively. From figure 4.5 it can be concluded that the tearing force of both the weft and the warp of polyamide 6,6 fabric decreased as the number of laundering cycles increased.

It is evident that the tearing force needed to rupture the weft yarns of the polyamide 6,6 fabric was higher than the tearing force needed to rupture the warp yarns of the fabric. This is unusual as the warp of a fabric is generally stronger than the weft of the fabric. This is mainly because the warp yarns are manufactured to be stronger enabling it to withstand abrasion and tension on the loom while the fabric is woven (Kadolph, 2007:222).

The tearing force needed to rupture the warp yarns of the polyamide 6,6 fabric laundered for five cycles was 953.75mN. Laundering the fabric for ten cycles lowered the tearing force in the warp to 949.58mN. Laundering the polyamide 6,6 fabric for twenty cycles lowered the tearing force needed to rupture the warp yarns further to 921.25mN and laundering fabric for fifty cycles resulted in the lowest tearing force in the warp of 915.83mN. The number of laundering cycles had a significant influence on the tearing force needed to rupture the warp yarns of polyamide 6,6 fabric.

Table 4.4: Tearing Force means (mN) for Polyamide 6,6 fabric laundered for Five, Ten, Twenty and Fifty Cycles respectively

NUMBER OF CYCLES	Mean (Weft)	Mean (Warp)
Five	985.555556	953.750000
Ten	985.000000	949.583333
Twenty	966.250000	921.250000
Fifty	962.916667	915.833333

As stated previously, polyamide 6,6 generally has good resistance to alkalis (Collier & Tortora, 2001:170). Gohl and Vilensky (1983:110) did however note that the polyamide fibre may weaken if it is frequently exposed to alkalis. This may explain the decrease in tearing force as the number of laundering cycles, thus the frequency of exposure, increased.

Figure 4.6 illustrates the influence that the number of laundering cycles had on the tearing force of machine washable wool fabric. When the machine washable wool was laundered for five cycles, a decrease in the tearing force of 33.33mN was noted compared to the force needed to rupture the weft yarns of the unlaundered fabric. Laundering the machine washable wool fabric for ten cycles resulted in an increase of tearing force in the weft of 10.42mN. Laundering the fabric for twenty cycles significantly increased the tearing force in the weft to 534.17mN but laundering the fabric for fifty cycles decreased the tearing force in the weft to 516.25mN.

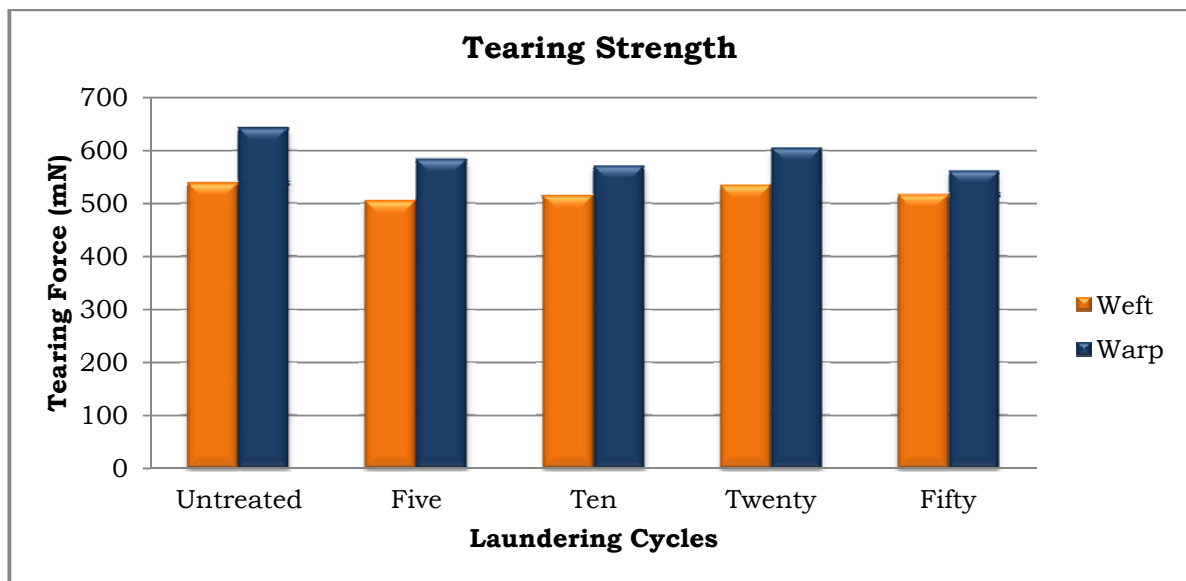


Figure 4.6: The influence of the Number of Laundering Cycles on the Tearing Strength of Machine Washable Wool fabric

Laundrying the machine washable wool fabric for five cycles decreased the tearing force needed to rupture the warp yarns of the fabric from 642.50mN to 583.06mN. Laundrying the fabric for ten cycles decreased the tearing force in the warp slightly to 570.83mN but laundrying the machine washable wool fabric for twenty cycles increased it again to 604.58mN. The tearing force needed to rupture the warp yarns of the machine washable wool fabric significantly decreased to 561.67mN when the fabric was laundryed for fifty cycles. As is evident from figure 4.6 the number of laundrying cycles had a significant influence on the tearing force of the machine washable wool fabric.

As evident from figure 4.6 the tearing force needed to rupture the warp yarns of the machine washable wool was higher than the tearing force needed to rupture the weft yarns of the same fabric. The machine washable wool fabric used in this study had more warp yarns than weft yarns per ten millimetre distance (for it was counted). The higher density of the warp yarns and the fact that warp yarns are generally stronger may be the reason that the warp yarns had higher tearing force values.

The tearing force needed to rupture the weft as well as the warp yarns of the machine washable wool fabric laundryed for twenty cycles was significantly higher than the tearing force needed to rupture the weft and warp yarns of the fabric laundryed for five, ten and fifty cycles. No explanation can be given for these results.

A decrease in the force needed to rupture the warp yarns of the machine washable wool laundryed for five, ten and fifty cycles was noted as the number of cycles increased. The decrease in tearing force was expected as the continuous exposure to the alkaline media is bound to weaken the fibre. As stated previously, wool has poor resistance to alkali (Joseph, 1986:46) because the alkali attacks the disulphide bond, damaging the cystine linkages, and also causes the salt linkages to break down (Carter, 1971:79).

However, as the number of laundering cycles increased from five to ten to fifty, the force needed to rupture the weft yarns of the fabric also increased. The increase in tearing force for the fabric was unlikely. A feasible explanation would be that the fabric started to felt as the agitation was repeated. By combining mechanical action, such as agitation, with heat and moisture, the adjacent scale edges interlock (Liu & Wang, 2007:957; Joseph, 1986:48). This keeps the fibre from returning to its original position and it also results in shrinkage of the fabric (Kadolph, 2007:67). The shrinkage that occurred due to felting may also be an explanation for the higher tearing force as the laundering cycles increased. The felting results in a denser fabric which also increases the tearing force. This rare incident was reported in an earlier study which was also conducted on machine washable wool fabric (Loubser, 1983:57).

4.2 Tensile Strength

Tensile strength is the strength of a textile material under tension. It measures the resistance of a textile fabric to stretching in one specific direction (Collier & Tortora, 2001:52). The tensile properties of a textile material and specifically the tensile strength is an important characteristic in determining the performance of the textile material. The breaking force is the force required to rupture or break the fabric (Kadolph, 1998:161). The breaking force in this study is expressed in Newton (N) as measured by the Instron Tensile Tester.

The results obtained when the tensile strength tests were conducted on the polyamide 6,6 and machine washable wool fabrics used in this study are discussed in the following section:

4.2.1 The influence of detergent, catholyte and distilled water on the tensile strength of polyamide 6,6 and machine washable wool fabric

Figure 4.7 illustrates the influence that catholyte, detergent and distilled water had on the maximum load the weft and warp yarns of polyamide 6,6 fabric could carry before breaking.

Laundrying the polyamide 6,6 fabric with catholyte resulted in the least decrease of the maximum load the weft yarns could carry, compared to the maximum load the weft yarns of the unlaundered fabric could carry. The maximum load it could carry was 674.40N. Laundrying the fabric with detergent decreased the maximum load the weft yarns could carry slightly with 7.31N to 667.07N.

Laundrying the polyamide 6,6 fabric with distilled water resulted in loss in tensile strength as the maximum load the weft yarns could carry decreased from 724.77N to 620.52N, a difference of 104.15N. The mean maximum loads

(N) of the weft and warp yarns that polyamide 6,6 could carry is depicted in table 4.5.

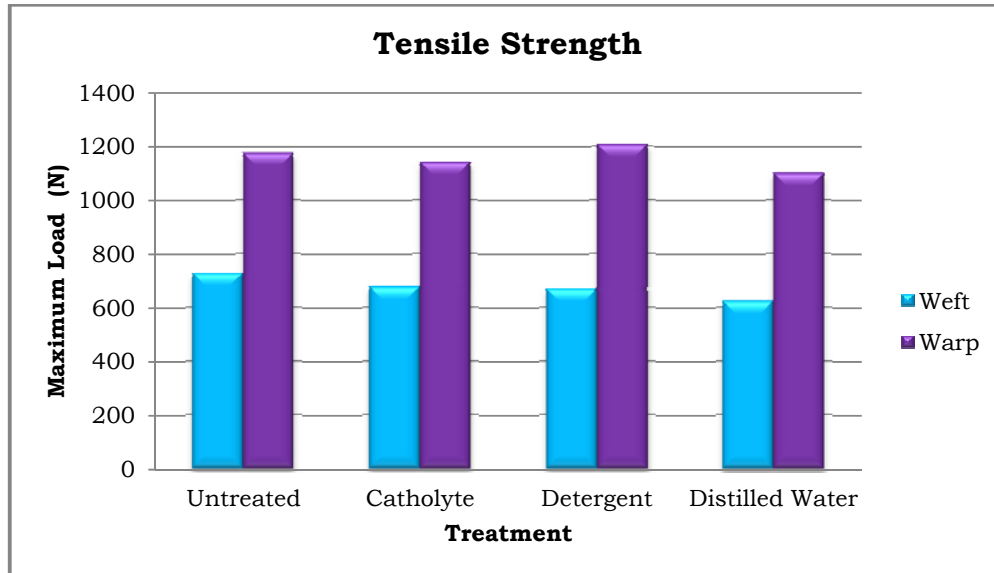


Figure 4.7: The influence of Catholyte, Detergent and Distilled Water on the Maximum Load of Polyamide 6,6 fabric

From figure 4.7 it is evident that the maximum load carried by the warp yarns of polyamide 6,6 before breaking were significantly higher than the maximum load the weft yarns could withstand before it broke. Although catholyte, detergent and distilled water did not have a significant influence on the maximum load that the weft yarns could carry before breaking, it had a significant effect on the maximum load the warp yarns could carry. It is expected that the warp yarns can withstand a higher maximum load as stronger yarns are selected for warp yarns to withstand the stress of the weaving process (Kadolph, 2007:222).

As illustrated by figure 4.7, it seems that laundering the polyamide 6,6 fabric with detergent increased the maximum load the warp yarns could carry. This is concluded as the unlaundered warp yarns could carry a maximum load of 1173.18N and the maximum load the warp yarns laundered with detergent

could carry was 1204.19. The difference was an insignificant increase of 31.01N.

The warp yarns of the polyamide 6,6 fabric laundered with catholyte carried a maximum load of 1138.46N. This is insignificantly different from the maximum load (667.083N) the warp yarns of polyamide 6,6 laundered with detergent could carry. Laundering the polyamide 6,6 fabric with distilled water caused the warp yarns to carry a significantly lower maximum load than when laundered with detergent. No explanation could be given for this result.

Table 4.5: Mean Maximum Loads (N) carried by the Weft and Warp yarns of Polyamide 6,6 fabric laundered with Catholyte, Detergent and Distilled Water

TREATMENT	Mean (Weft)	Mean (Warp)
Untreated	724.660000	1173.180000
Catholyte	674.395000	1138.46000
Detergent	667.082500	1204.18750
Distilled Water	620.515000	1097.82750

The insignificant influence of catholyte, detergent and distilled water can be interpreted as a positive result. These results were not unexpected as it is generally accepted that polyamide 6,6 has good resistance to alkalis (Collier & Tortora, 2001:170).

Simpson, Southern and Ballman (1981:97) reported polyamide 6,6 fibres to have a tenacity of 1765N and that the tensile strength of these fibres are correlated exponentially to the amorphous orientation of the fibre. This is considerably higher than the tenacity exhibited by the polyamide 6,6 fibres in this study. This may be explained through the fact that the fabric in this study was a lightweight polyamide 6,6.

Figure 4.8 illustrates the influence that detergent and distilled water had on the maximum load the weft and warp yarns of machine washable wool fabric could carry before breaking. The influence that catholyte had on the maximum load of the weft and warp yarns of machine washable wool is not illustrated. This is due to the fact that the fabric disintegrating during the laundering procedure. Therefore a statistically accurate mean for this treatment could not be determined.

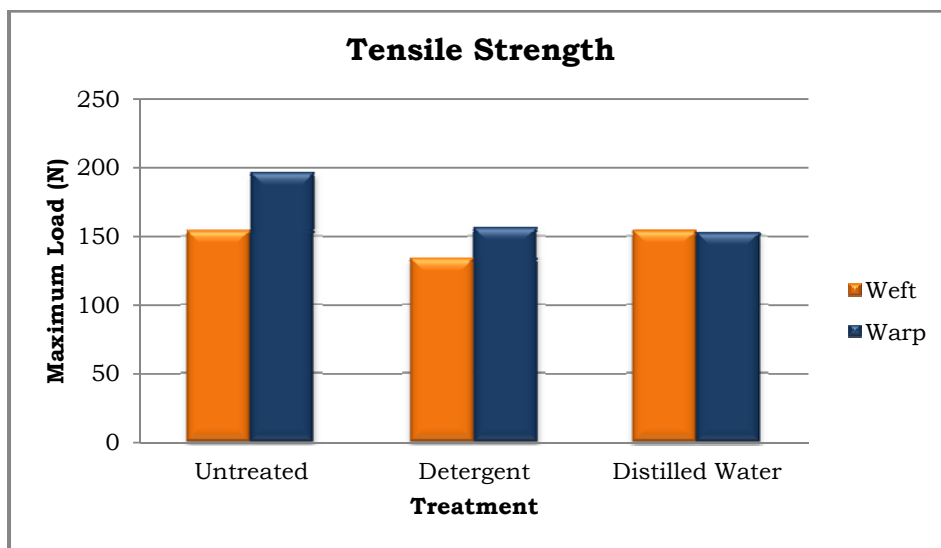


Figure 4.8: The influence of Detergent and Distilled Water on the Maximum Load of Machine Washable Wool fabric

As is evident from figure 4.8 there was a significant difference between the influence that the detergent and the distilled water had on the maximum load the weft yarns of the machine washable wool fabric could carry. The maximum load the weft yarns of the fabric laundered with distilled water could carry was 154.09N and laundering the fabric with detergent lowered the maximum load the weft yarns could carry to 133.63N. Laundering the fabric with distilled water resulted in a negligible increase in the maximum load (0.11N) that the weft yarns could carry when it is compared to the maximum load the weft yarns of the fabric could carry before it was laundered. The mean maximum

loads (N) the weft and warp yarns of machine washable wool could carry are depicted in table 4.6.

Table 4.6: Mean Maximum Loads (N) carried by the Weft and Warp yarns of Machine Washable Wool fabric laundered with Detergent and Distilled Water

TREATMENT	Mean (Weft)	Mean (Warp)
Untreated	153.980000	196.200000
Detergent	133.625000	156.310000
Distilled Water	154.092500	152.610000

The maximum load the warp yarns of the unlaundered fabric (196.20N) could carry was 39.89N more than the load carried (152.61N) by the warp yarns of the fabric laundered with detergent. The difference between the maximum load carried by the warp yarns of the machine washable wool fabric laundered with detergent and the warp yarns of the fabric laundered with distilled water was insignificant.

The slight increase of the maximum load the weft yarns of the machine washable wool fabric laundered with distilled water could carry can be explained by the felting propensity of wool fibres. The scales of adjacent fibres interlocked and felted as a result. The shrinkage that took place caused a denser fabric with a higher maximum load before it broke. Similar results were also reported by Liu and Wang (2007:957).

The South African Bureau of Standards (1261-3:2002) determined that the standard tensile strength for textiles used in apparel in South Africa be no less than 330N (2002:4). The tensile strength of the machine washable wool fabric in this project is a lightweight wool fabric and the lower values are still acceptable.

The weft and warp yarns of the machine washable wool fabric laundered with catholyte disintegrated after twenty laundering cycles. This can be explained by wool's response to alkalis. When highly alkaline liquors are used on white wool, it will discolor to yellow; where after it becomes a jelly-like substance (Kadolph, 2007:70). This happens because the alkali causes the disulphide bonds to break and the breakage of these bonds results in the wool dissolving (Feughelman, 1997:14).

4.2.2 The influence of laundering temperature on the tensile strength of polyamide 6,6 and machine washable wool fabric

Figure 4.9 illustrates the influence of laundering temperature on the maximum load the weft and warp yarns of polyamide 6,6 could carry. As is evident from figure 4.9, laundering the polyamide 6,6 fabric at both 30°C and 40°C did not have a significant influence on the maximum load the weft yarns could carry. Laundering the fabric at 30°C decreased the maximum load the weft yarns could carry to 654.27N and laundering polyamide 6,6 at 40°C decreased the maximum load the weft yarns could carry insignificantly to 653.73N.

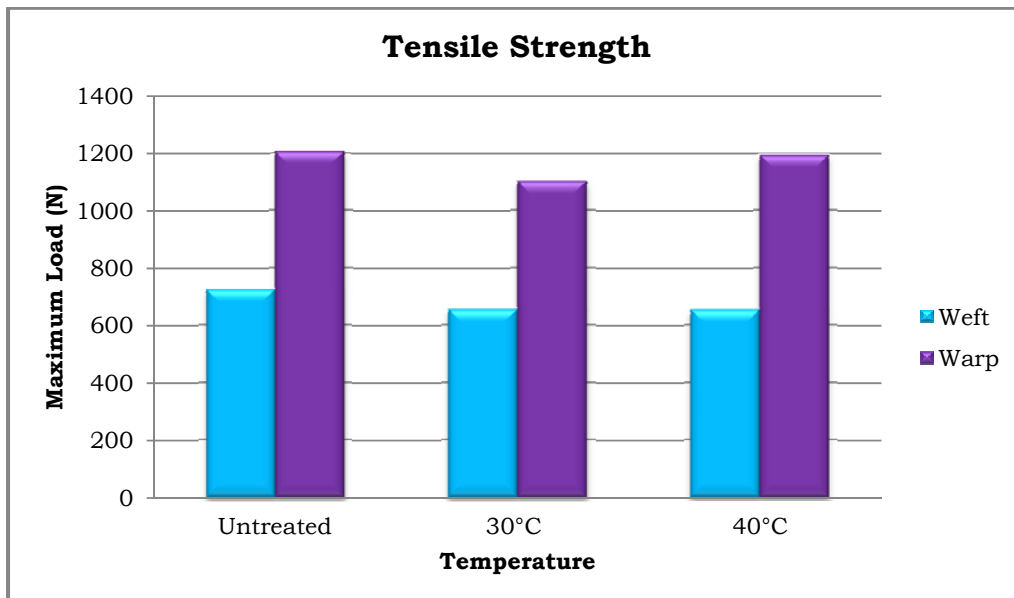


Figure 4.9: The influence of Temperature on the Maximum Load of Polyamide 6,6 fabric

Table 4.7 depicts the mean maximum loads (N) the weft and warp yarns of the polyamide 6,6 fabric laundered at 30°C and 40°C could carry. Laundering the fabric at 40°C resulted in an insignificant decrease of 13.51N concerning the maximum load the warp yarns could carry compared to the maximum load the warp yarns of the unlaundered fabric could carry. Laundering the polyamide 6,6 fabric at 30°C decreased the maximum load the warp yarns of the fabric could carry significantly with 90.66N.

Table 4.7: Mean Maximum Loads (N) carried by the Weft and Warp yarns of Polyamide 6,6 fabric laundered at 30°C and 40°C

TEMPERATURE	Mean (Weft)	Mean (Warp)
Untreated	724.66000	1205.66000
30°C	654.261667	1101.49500
40°C	653.733333	1192.15500

Figure 4.10 illustrates the influence of temperature on the maximum load carried by the weft and warp yarns of machine washable wool fabric. It is evident from figure 4.10 that the temperature did have a significant influence on the maximum load carried by the weft and warp yarns of machine washable wool fabric laundered with catholyte. Laundering the machine washable wool fabric with catholyte at 30°C resulted in a maximum load of 93.27N carried by the weft yarns and 110.80N carried by the warp yarns. It is worth mentioning again that the weft and warp yarns of the machine washable wool fabric disintegrated when it was laundered at 40°C with catholyte. Thus both the temperature and treatment had a significant influence on the maximum load that the yarns could carry.

Laundering the machine washable wool fabric with detergent at 30°C caused the weft yarns to carry a maximum load of 130.74N and the warp yarns to carry a maximum load of 163.14N. When the fabric was laundered at 40°C

with detergent, the weft yarns could carry a maximum load of 136.51 and the warp yarns carried a maximum load of 149.49N before breaking.

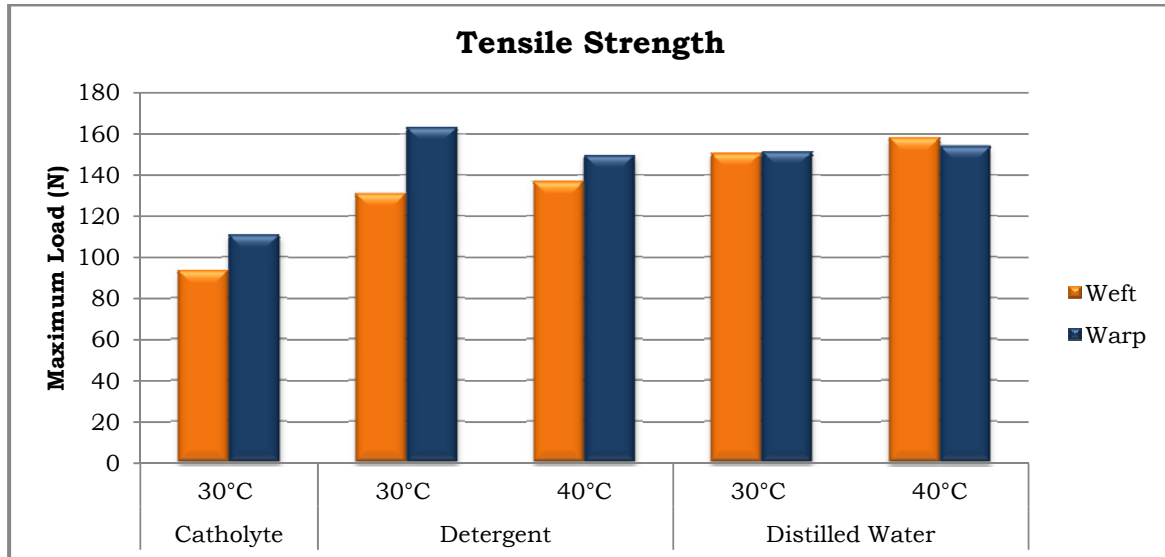


Figure 4.10: The influence of Temperature on the Maximum Load of Machine Washable Wool fabric

When the machine washable wool fabric was laundered at 30°C with distilled water, the maximum load the weft yarns could carry was 150.36N and the maximum load the warp yarns could carry was 151.33N. Laundering the machine washable wool fabric with distilled water at 40°C caused the weft yarns to carry a maximum load of 157.83N and the warp yarns to carry a maximum load of 153.90N.

Feughelman (1997:100) did report on the correlation between the decrease in breaking load and the amount of disulphide bonds that break when wool is exposed to high temperatures. The disulphide bonds are the bonds mainly responsible for the strength of wool as well as the cystine linkages. When these links are degraded due to exposure to alkali or temperature, a loss in tensile strength is noted. This would explain the deterioration of the machine washable wool fabric in the catholyte at 40°C. As already stated in the

previous section, it seems like the wool is damaged more at 30°C than at 40°C when laundered with detergent and distilled water, although Vasconcelos et al (2006:729) regards 40°C as a suitable temperature for the home laundering of wool fabric.

It is possible that the dimensional change in the structure as a result of the higher temperature, might have increased the number of yarns in a unit to such an extent that the higher temperature seems to carry a higher load before breaking.

4.2.3 The influence of the number of laundering cycles on the tensile strength of polyamide 6,6 and machine washable wool fabric

Figure 4.11 illustrates the influence of the number of laundering cycles on the maximum load carried by the weft and warp yarns of polyamide 6,6 fabric. The number of laundering cycles did not have a significant influence on the maximum load that the weft and warp yarns of polyamide 6,6 could carry.

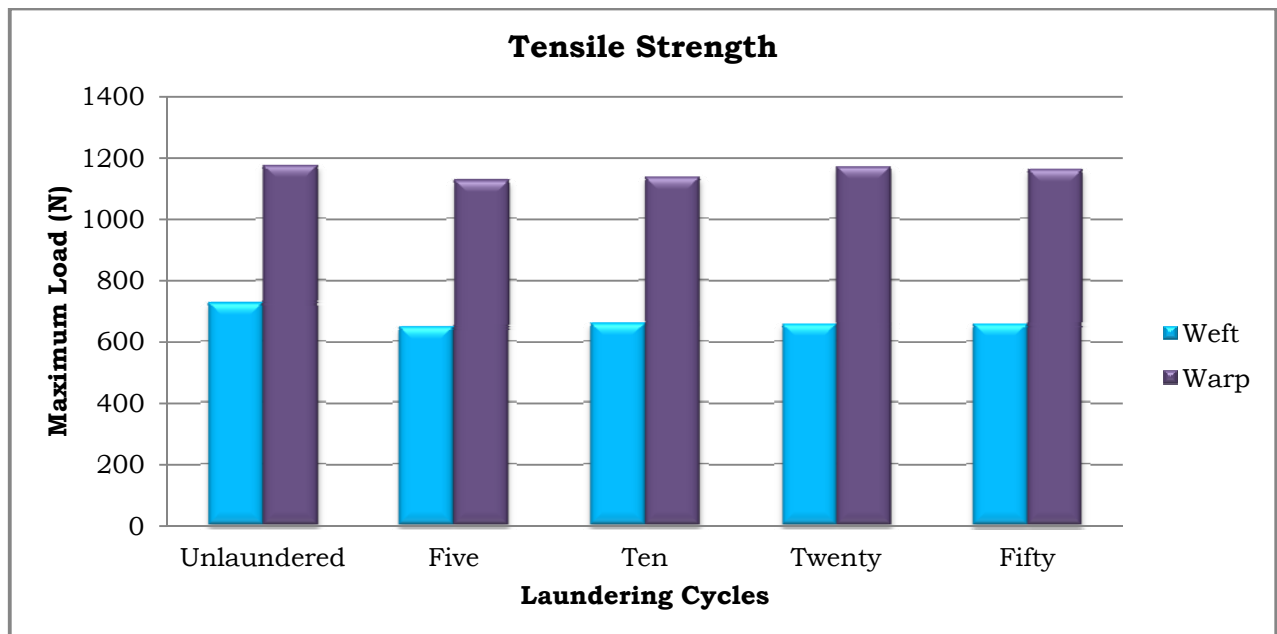


Figure 4.11: The influence of the Number of Laundering Cycles on the Maximum Load of Polyamide 6,6 fabric

Laundering the polyamide 6,6 fabric for five cycles decreased the maximum load the weft yarns could carry from 724.66N to 646.09N. According to the statistical analysis this was an insignificant decrease of 78.57N. Laundering the polyamide 6,6 fabric for ten cycles seemingly increased the maximum load the weft yarns could carry with an insignificant 12.35N. When the fabric was laundered for twenty cycles, it resulted in another insignificant decrease of 2.75N. Laundering the polyamide 6,6 fabric for fifty cycles surprisingly increased the maximum load the weft yarns could carry with a negligible 0.06N. Table 4.8 depicts the statistically determined p-values when the maximum loads carried by the weft yarns of polyamide 6,6 laundered for five, ten, twenty and fifty cycles are compared.

Table 4.8: P-Values of Compared Maximum Loads (N) carried by the Weft yarns of Polyamide 6,6 laundered for Five, Ten, Twenty and Fifty cycles

NUMBER OF CYCLES	Five	Ten	Twenty	Fifty
Five		0.7417	0.7977	0.7964
Ten	0.7417		0.9416	0.9429
Twenty	0.7977	0.9416		0.9987
Fifty	0.7964	0.9429	0.9987	

As is evident from figure 4.11, the warp yarns could carry higher maximum loads than the weft yarns of the polyamide 6,6 fabric. Laundering the polyamide 6,6 fabric for five cycles reduced the maximum load the warp yarns could carry from 1173.18N to 1124.36N. This is an insignificant decrease of 48.82N. Laundering the polyamide 6,6 fabric for ten cycles again resulted in a slight increase of 10.25N in the load the warp yarns could carry. Laundering the fabric for twenty cycles increased the maximum load the warp yarns could carry insignificantly with 34.14N. When the polyamide 6,6 fabric was laundered for fifty cycles the maximum load the warp yarns could carry decreased with 9.19N. Table 4.9 depicts the statistically determined p-values

when the maximum loads carried by the warp yarns of polyamide 6,6 laundered for five, ten, twenty and fifty cycles are compared.

Table 4.9: P-Values of Compared Maximum Loads (N) carried by the Warp yarns of Polyamide 6,6 laundered for Five, Ten, Twenty and Fifty cycles

NUMBER OF CYCLES	Five	Ten	Twenty	Fifty
Five		0.8316	0.3583	0.4659
Ten	0.8316		0.4795	0.6051
Twenty	0.3583	0.4795		0.8489
Fifty	0.4659	0.6051	0.8489	

Figure 4.12 illustrates the influence the number of laundering cycles had on the maximum load carried by the weft and warp yarns of the machine washable wool fabric laundered with catholyte, detergent and distilled water. The number of cycles had a significant influence on the maximum load carried by the weft and warp yarns of machine washable wool fabric laundered with catholyte. Laundering the machine washable wool fabric for five cycles with catholyte caused the weft yarns to carry a maximum load of 100.02N. Laundering the fabric for another five cycles with catholyte decreased the maximum load carried by the weft yarns to 86.80N.

Laundering the machine washable wool fabric with catholyte for five cycles resulted in the warp yarns carrying a maximum load of 113.70N. Laundering the fabric for ten cycles reduced the load carried by the warp yarns to 93.40N. The weft and warp yarns of the machine washable wool disintegrated after laundering the fabric with catholyte for twenty cycles. This is mainly due to the effect a alkali such as catholyte has on the wool fibre, as discussed in section 4.2.1 (page 119).

The number of cycles had a significant influence on the maximum load carried by the weft and warp yarns of machine washable wool fabric laundered with detergent. When the fabric was laundered for five cycles with detergent, the weft yarns could carry a maximum load of 123.12N. Laundering the machine washable wool with detergent for another five cycles increased the maximum load the weft yarns could carry slightly to 129.19N. Laundering the fabric for twenty cycles lead to another increase in the maximum load the weft yarns could carry (139.22N). When the machine washable wool fabric was laundered for fifty cycles with detergent, the maximum load the weft yarns could carry was 142.97N. The maximum load the weft yarns of the fabric laundered with detergent could carry increased as the number of laundering cycles increased.

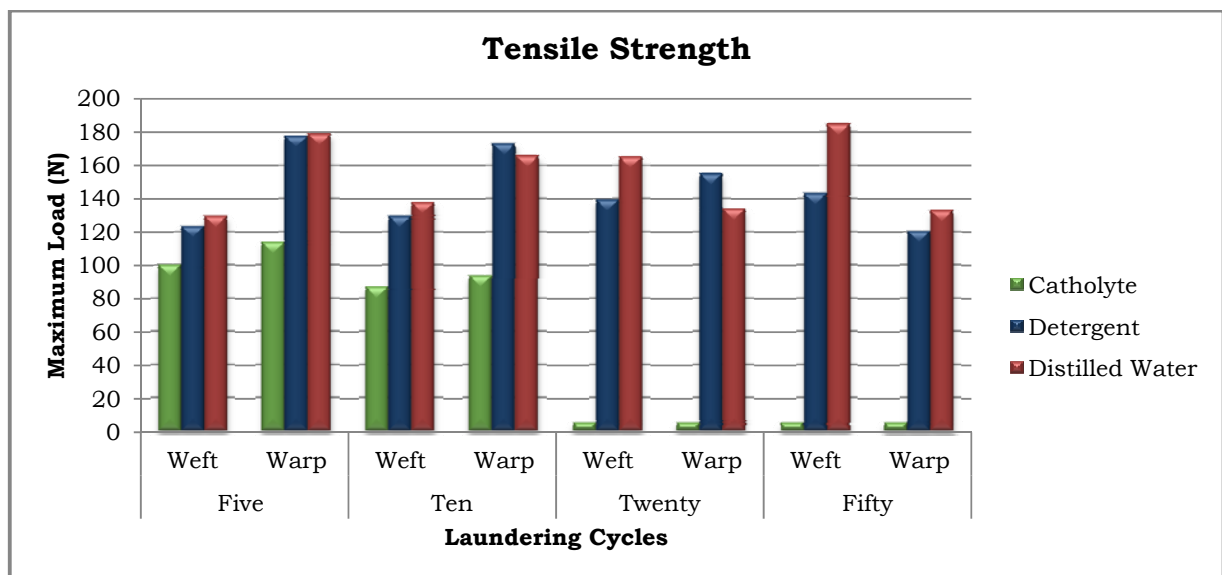


Figure 4.12: The influence of the Number of Laundering Cycles on the Maximum Load of Machine Washable Wool fabric

Laundering the machine washable wool fabric for five cycles with detergent caused the warp yarns to carry a maximum load of 177.54N but laundering the fabric for ten cycles decreased the maximum load carried by the warp yarns to 172.76N. When the fabric was laundered with detergent for twenty cycles the warp yarns could carry a maximum load of 154.82N. Laundering the machine

washable wool fabric for fifty cycles decreased the maximum load carried by the warp yarns to 120.12N. From figure 4.12 it can be concluded that the maximum load carried by the warp yarns of machine washable wool laundered with detergent decreased as the number of laundering cycles increased.

Laundering the machine washable wool fabric with distilled water for five cycles resulted in the least decrease in the maximum load carried by the weft yarns. These weft yarns could carry a maximum load of 129.22 and laundering the fabric for another five cycles increased the maximum load the weft yarns could carry to 137.52N. Laundering the machine washable wool fabric for twenty cycles in distilled water resulted in a maximum load of 139.22 carried by the weft yarns. Laundering the fabric for fifty cycles significantly increased the maximum load carried by the weft yarns to 184.63N. The maximum load the weft yarns could carry increased as the number of laundering cycles increase when the machine washable wool was laundered with distilled water.

Laundering the machine washable wool for five cycles with distilled water caused the warp yarns to carry a maximum load of 178.74N. When the fabric was laundered for ten cycles, the maximum load the warp yarns could carry decreased to 165.60N and laundering the fabric for another ten cycles decreased the maximum load carried by the warp yarns further to 133.55N. Laundering the machine washable wool fabric for fifty cycles resulted in a slight decrease in the maximum load carried by the warp yarns to 132.55N. It is evident from figure 4.12 that the maximum load carried by the warp yarns of the machine washable wool fabric laundered with distilled water decreased as the number of laundering cycles increased. These results indicate that the machine washable wool fabric deteriorated with agitation in water even without the presence of chemical substances of a higher pH.

It is evident from figure 4.12 that the warp yarns could carry a higher maximum load than the weft yarns. As previously stated, warp yarns are

manufactured to be stronger than weft yarns, because it has to withstand more abrasion during the weaving process on the loom (Kadolph, 2007:222). The fact that the maximum load carried by the weft yarns of the machine washable wool fabric laundered with detergent and distilled water increased as the number of laundering cycles increased might be due to the fact that the weft yarns of the fabric were thinner and therefore more yarns felted together per unit increasing the maximum load.

4.2.4 Displacement and stress-strain curves of polyamide 6,6 and machine washable wool fabric

The displacement of the yarns before breakage occurred is correlated to the breaking force or the maximum load the yarns could carry before it broke. A stress-strain curve is the graphical representation of the textile fabric's resistance to deformation and elongation caused by an external force (Kadolph, 1998:161).

Figures 4.13 and 4.14 illustrates the displacement and maximum load before breakage of the weft and warp yarns of the polyamide 6,6 fabric, respectively. (The remainder of the graphs similar to above figures 4.13 and 4.14 are bound as an appendix to this document).

The stress-strain curve of the polyamide 6,6 fabric (figures 4.13 & 4.14) observed in this study is similar to what Nasri, Lallam and Bunsell (2001:461) experienced in their study on the tensile behaviour of polyamide 6,6. There is a quasi-linear elasticity zone where the stress and strain are related by Hook's law. The yarns harden after the inflection point, which leads to a small strain for a large increase in stress. This happens because of a new arrangement in the macromolecular chains of the fibre. The last part of the curve is marked by a definite decrease in the slope. This is due to the chains breaking which results in the yarn rupturing.

Weft yarns of the Polyamide 6,6 fabric:

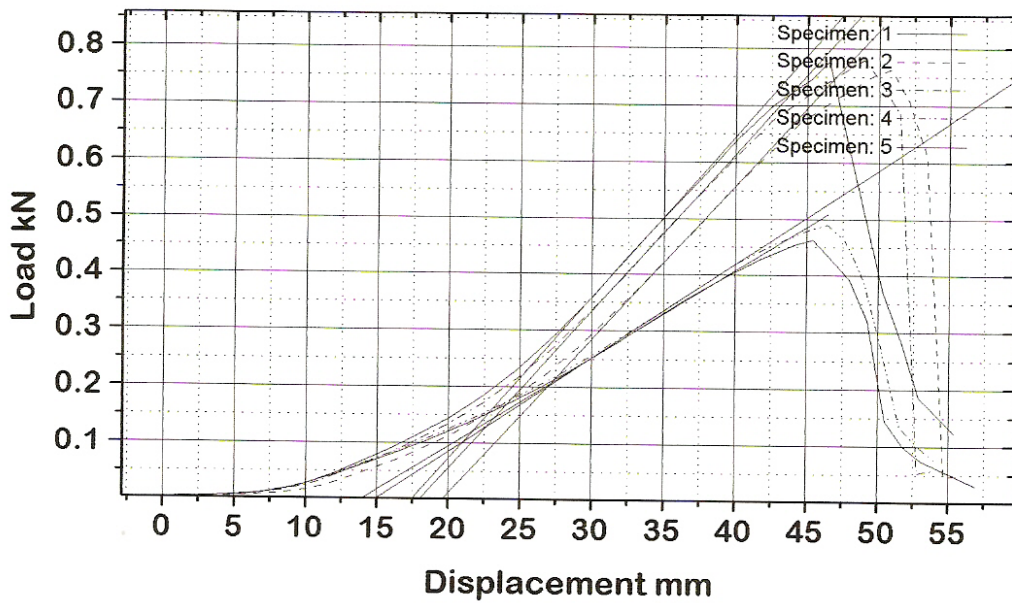


Figure 4.13: The displacement and maximum load of the Weft yarns of Polyamide 6,6 fabric laundered at 30°C for Five Cycles with Distilled Water

Warp yarns of the Polyamide 6,6 fabric:

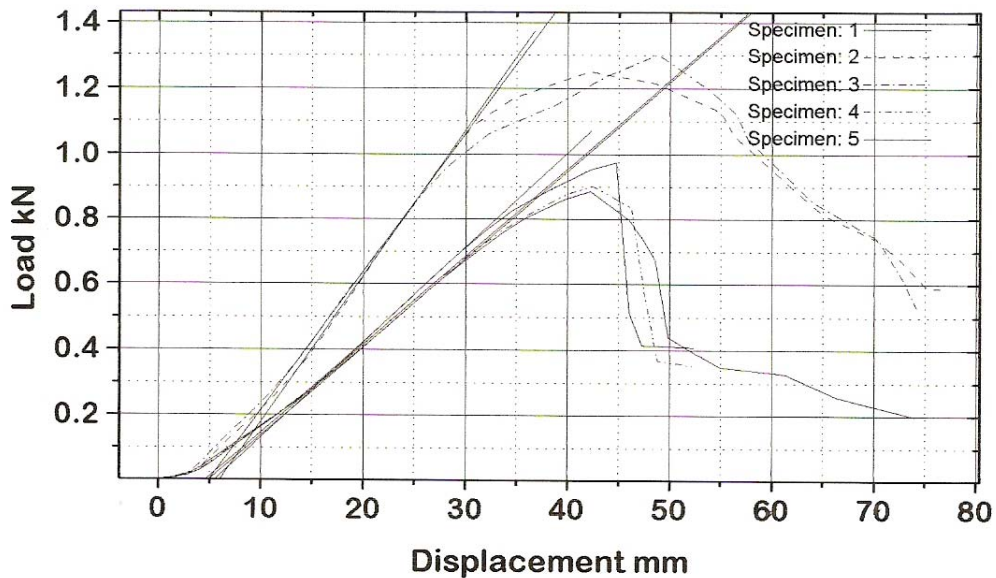


Figure 4.14: The displacement and maximum load of the Warp yarns of Polyamide 6,6 laundered at 30°C for Five Cycles with Distilled Water

Figure 4.15 illustrates the influence of catholyte, detergent and distilled water on the displacement at maximum load of the weft and warp yarns of the polyamide 6,6 fabric. Table 4.10 depicts the displacement means for the weft and warp yarns laundered with catholyte, detergent and distilled water. The displacement at maximum load for the weft yarns of the polyamide 6,6 fabric ranges from 49.25mm to 50.26mm. The difference of 1.01mm is negligible. The displacement at maximum load for the warp yarns ranges from 47.62mm to 48.67mm, also a negligible difference of only 1.06mm.

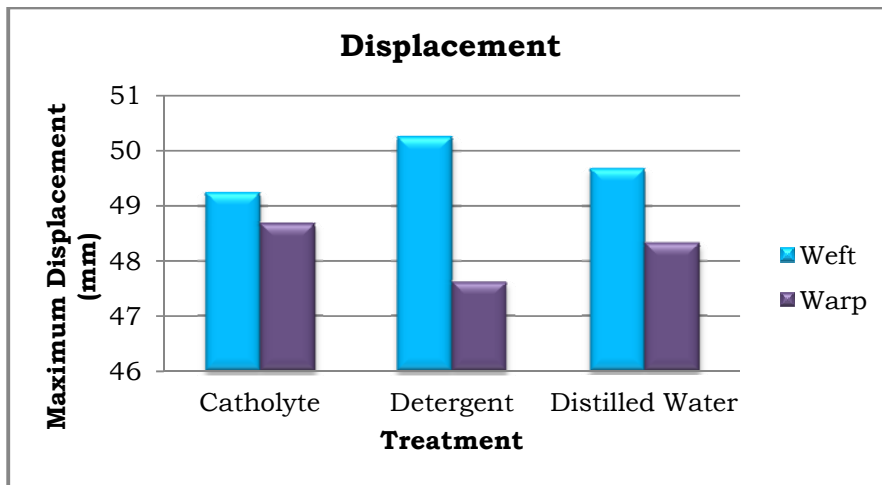


Figure 4.15: Influence of Catholyte, Detergent and Distilled Water on the Displacement at Maximum Load of Polyamide 6,6 fabric

Table 4.10: Mean Displacement (mm) at Maximum Loads of the Weft and Warp yarns of Polyamide 6,6 laundered with Catholyte, Detergent and Distilled Water

TREATMENT	Mean (Weft)	Mean (Warp)
Catholyte	49.246750	48.674250
Detergent	50.258000	47.615250
Distilled Water	49.681750	48.319500

The elongation at break for the polyamide 6,6 fabric is correlated to the amorphous orientation of the fibre (Simpson, Southern & Ballman, 1981:97).

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 (Kadolph, 2007:126). This probably explains the difference in the stress-strain graphs of the weft and warp yarns of polyamide 6,6 fabric.

Figures 4.16 and 4.17 are illustrations of the stress-strain curve as well as displacement and maximum load before breakage of machine washable wool observed in this study.

Weft yarns of Machine Washable Wool fabric:

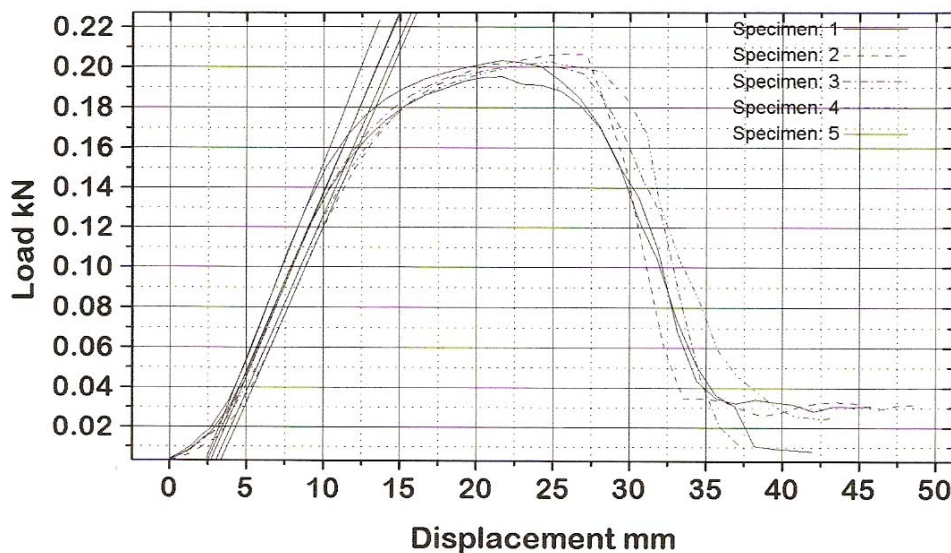


Figure 4.16: The displacement and maximum load of the Weft yarns of Machine Washable Wool fabric laundered at 30°C for Five Cycles with Distilled Water

The stress-strain curve of wool described in the literature is marked by three distinct regions. The stress-strain curve is characterized by an initial Hookean region. The alpha-helices are under strain in the Hookean region and during the yield region these helices unfold and during the post-yield region the bonds break down and the yarns rupture (Feughelman, 1997:29). The stress-strain curve of the warp yarns differ from the curve of the weft yarns. The warp yarns

are more tightly twisted to produce a stronger yarn with less elongation and that can explain the difference between the two curves.

Warp yarns of Machine Washable Wool fabric:

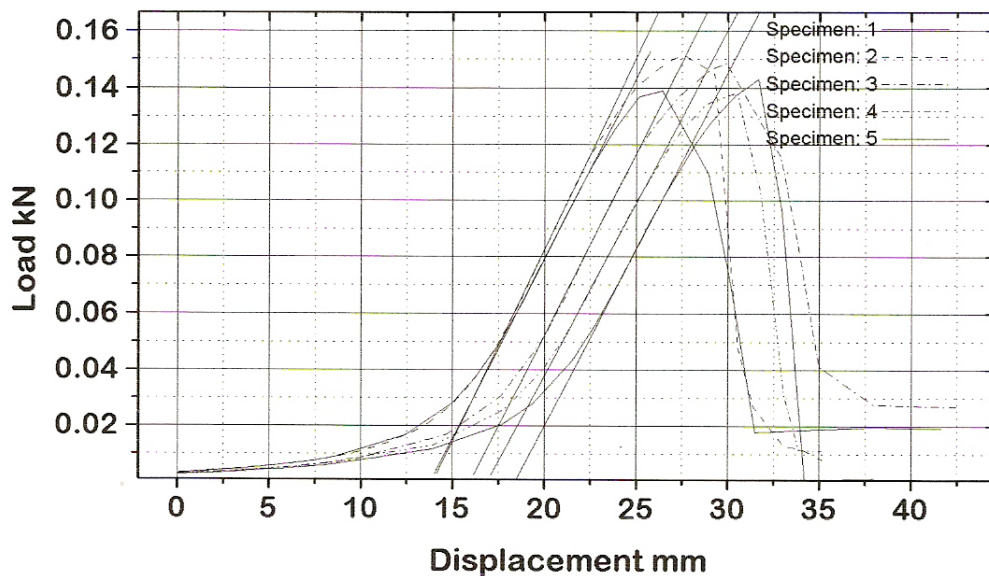


Figure 4.17: The displacement and maximum load of the Warp yarns of Machine Washable Wool fabric laundered at 30°C for Five Cycles with Distilled Water

Wool is characterized by low strength and great extensibility, which is obvious in figure 4.16. This property is mainly due to the alpha-helices that unfold when it is stretched (Ahumada et al, 2004:1005). The lower tenacity of wool can be explained by the large amount of amorphous areas in the fibre. Wool is approximately only 30% crystalline. The amorphous areas contain bulky molecules that cannot form hydrogen bonds. There is less cystine and this renders the fibre weaker (Feughelman, 1997:35).

Figure 4.18 illustrates the influence of detergent and distilled water on the displacement at maximum load of the weft and warp yarns of machine washable wool fabric. The displacement at maximum load for the machine washable wool laundered with catholyte could not be determined as the fabric

disintegrated after 20 laundering cycles. The displacement at maximum load for the weft yarns of the machine washable wool fabric ranges from 29.64mm to 30.95mm. The difference of 1.31mm is insignificant.

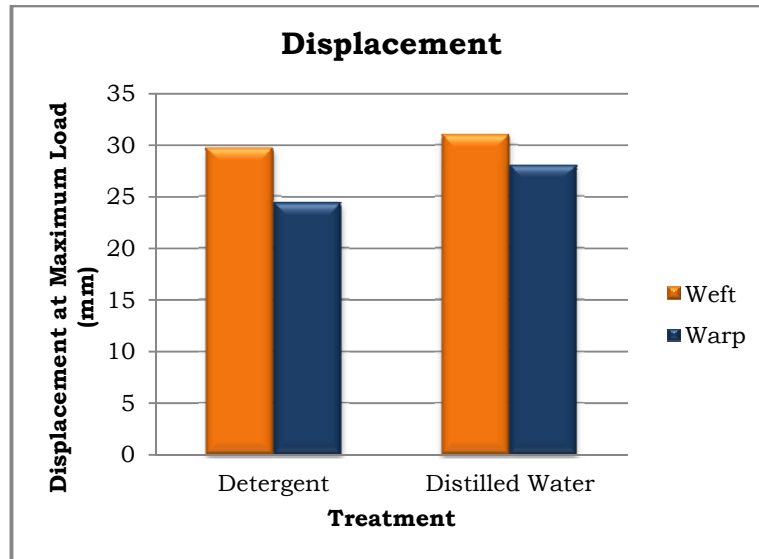


Figure 4.18: Influence of Detergent and Distilled Water on the Displacement at Maximum Load of Machine Washable Wool fabric

The displacement at maximum load for the warp yarns ranges from 24.34mm to 27.99mm, a negligible difference of only 3.65mm. Table 4.11 depicts the displacement means (mm) for the weft and warp yarns of machine washable wool laundered with detergent and distilled water. From these results it can be concluded that laundering in distilled water and with detergent did not influence the displacement of the machine washable wool fabric.

Table 4.11: Mean Displacement (mm) at Maximum Loads of the Weft and Warp yarns of Polyamide 6,6 laundered with Catholyte, Detergent and Distilled Water

TREATMENT	Mean (Weft)	Mean (Warp)
Detergent	29.63925	24.33825
Distilled Water	30.94775	27.99125

4.3 Bending Length (Stiffness)

Bending length is a typical property of a textile fabric. It is mainly dependent on the energy that is required to produce a deformation due to its own weight (Yüsekaya, Howard & Adanur, 2008:263). Bending length is a simple and accurate way in which the stiffness of a fabric is expressed (BS 3356:61). A fabric's bending properties are important because they contribute towards drape and hand and it influences fabric deformation (Kadolph, 2007:27). The deformation usually occurs in the yarns of the fabric. The stiffer the fabric, the longer the bending length in centimetres will be (Kadolph, 1998:213).

The results obtained when the bending length tests were conducted on the polyamide 6,6 and machine washable wool fabrics used in this study are discussed in the following section:

4.3.1 The influence of detergent, catholyte and distilled water on the bending length of polyamide 6,6 and machine washable wool fabric

Figure 4.19 illustrates the influence of catholyte, detergent and distilled water on the bending length of polyamide 6,6. The bending length of the unlaundered polyamide 6,6 fabric in the weft direction was 2.35cm. Laundering the polyamide 6,6 fabric with catholyte resulted in a bending length of 3.53cm in the weft direction. This was significantly different from the bending length (3.83cm) in the weft direction of the polyamide 6,6 fabric laundered with detergent. The bending length in the weft direction of the polyamide 6,6 fabric laundered with distilled water was 3.48cm. This was significantly lower than the bending length in the weft direction of the polyamide 6,6 fabric laundered with detergent. It is evident that catholyte, detergent and distilled water had a significant influence on the bending length of polyamide 6,6 causing the fabric to be more rigid or stiff in the weft direction.

The bending length in the warp direction of the unlaundered polyamide 6,6 fabric was 2.58cm. The bending length in the warp direction of the polyamide 6,6 fabric laundered with catholyte was 3.22cm, which is significantly different from the bending length in the warp direction of the unlaundered fabric. When the polyamide 6,6 fabric was laundered with the detergent the bending length in the warp direction was 3.77cm, which was significantly higher than the bending length in the warp direction of the polyamide 6,6 fabric laundered with distilled water. Catholyte, detergent and distilled water had a significant influence on the bending length of polyamide 6,6 causing the fabric to be more rigid or stiff in the warp direction.

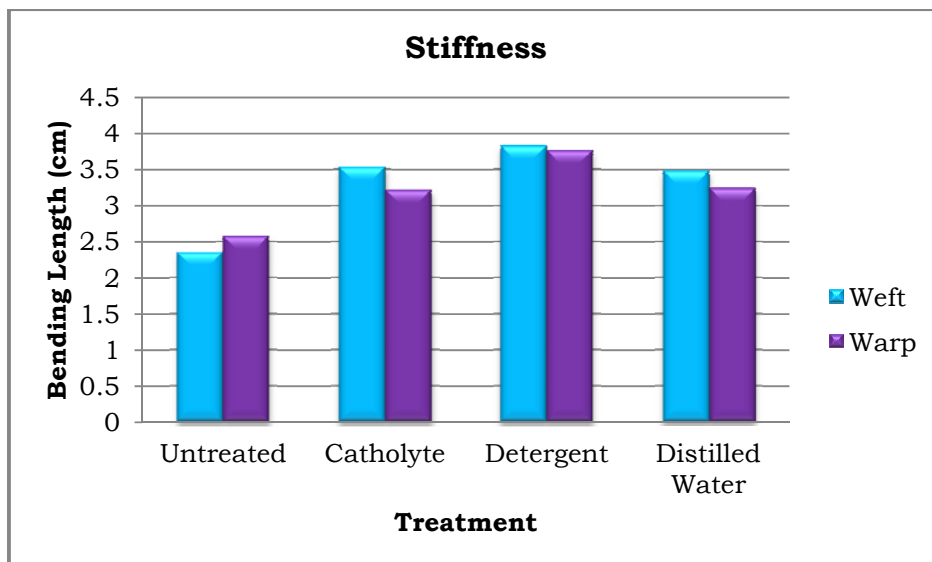


Figure 4.19: The influence of Catholyte, Detergent and Distilled Water on the Bending Length of Polyamide 6,6 fabric

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 (Gohl & Vilensky, 1983:109). The reason for the polyamide 6,6 fabric stiffening might be due to the increased amount of hydrogen bonds. Because no pressure was applied after the laundering of the fabric enabling the bonds to reform, the

fabric dried containing the increased amounts of hydrogen bonds. This resulted in a stiffer fabric.

Figure 4.20 illustrates the influence that catholyte, detergent and distilled water had on the bending length of machine washable wool fabric. The bending length in the weft direction of the unlaundered machine washable wool fabric was 2.65cm. Laundering the machine washable wool fabric with detergent had the least influence on the bending length of the fabric in the weft direction. Laundering the machine washable wool fabric with detergent resulted in a bending length distance of 2.86cm in the weft direction, which is significantly different from the bending length (3.23cm) in the weft direction of the fabric laundered with catholyte. When the machine washable wool fabric was laundered with distilled water, the bending length in the weft direction was 2.97cm.

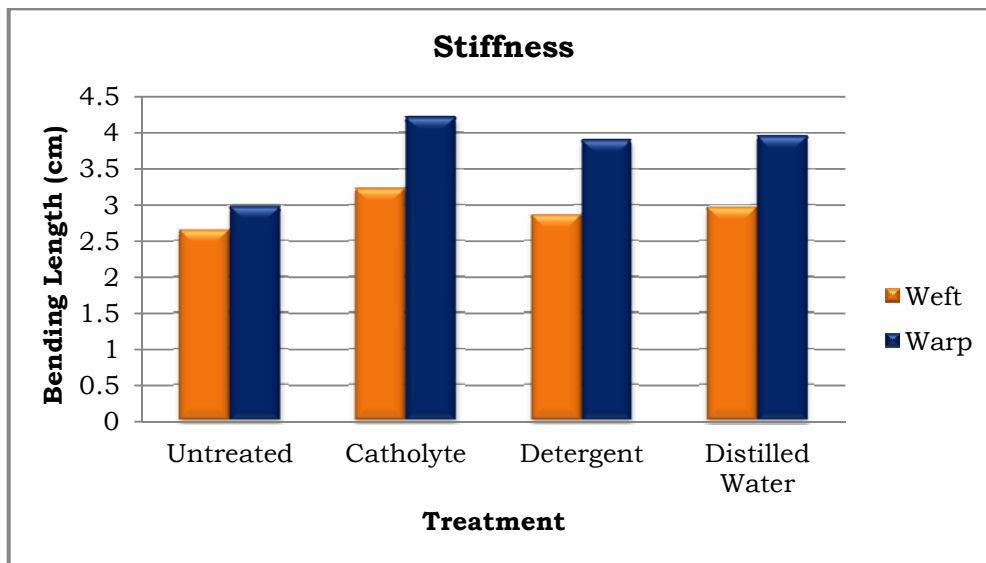


Figure 4.20: The influence of Catholyte, Detergent and Distilled Water on the Bending Length of Machine Washable Wool fabric

It is evident from figure 4.20 that catholyte had the greatest influence on the bending length of machine washable wool in the weft direction. Catholyte, detergent and distilled water had a significant influence on the bending length

of the machine washable wool fabric, causing it to be more rigid and stiff. Table 4.12 depicts the p-values when the bending length in the weft direction of machine washable wool laundered with catholyte, detergent and distilled water are compared.

Table 4.12: P-Values of Compared Treatment Combinations of the Bending Length in the Weft direction of Machine Washable Wool fabric

TREATMENT	Catholyte	Detergent	Distilled Water
Catholyte		<.0001	<.0001
Detergent	<.0001		0.0804
Distilled Water	<.0001	0.0804	

It is evident from figure 4.20 that the bending length in the warp direction was higher than the bending length values in the weft direction of the machine washable wool fabric. The bending length in the warp direction of the unlaundered machine washable wool fabric was 2.98cm. Laundering the machine washable wool fabric with detergent resulted in the least influence on the bending length distance (3.90cm) in the warp direction, although it is still significant. Laundering the fabric with distilled water resulted in a bending length distance of 3.95cm in the warp direction. Laundering the machine washable wool fabric with catholyte seemed to have the most influence on the bending length of the fabric in the warp direction, resulting in a bending length value of 4.22cm. Table 4.13 depicts the p-values of the compared treatments. It is also evident from table 4.13 that catholyte, detergent and distilled water had a significant influence on the bending length in the warp direction of machine washable wool.

Table 4.13: P-Values of Compared Treatment Combinations of the Bending Length in the Warp direction of Machine Washable Wool fabric

TREATMENT	Catholyte	Detergent	Distilled Water
Catholyte		<.0001	<.0001
Detergent	<.0001		0.3190
Distilled Water	<.0001	0.3190	

Wool has moderate bending qualities (Tortora, 1978:76), which is confirmed by the results obtained in this study.

4.3.2 The influence of temperature on the bending length of polyamide 6,6 and machine washable wool fabric

Figure 4.21 illustrates the influence of temperature on the bending length in the weft and warp direction of the polyamide 6,6 fabric. The bending length of the unlaundered fabric in the weft direction was 2.35cm. Laundering the polyamide 6,6 fabric at 30°C resulted in the highest bending length value in the weft direction of 3.73cm. The polyamide 6,6 fabric laundered at 40°C seemed to be influenced the least by temperature, having a bending length value of 3.49cm in the weft direction. It can be concluded that temperature had a significant influence on the bending length in the weft direction of polyamide 6,6 fabric causing the fabric to be more rigid and stiff.

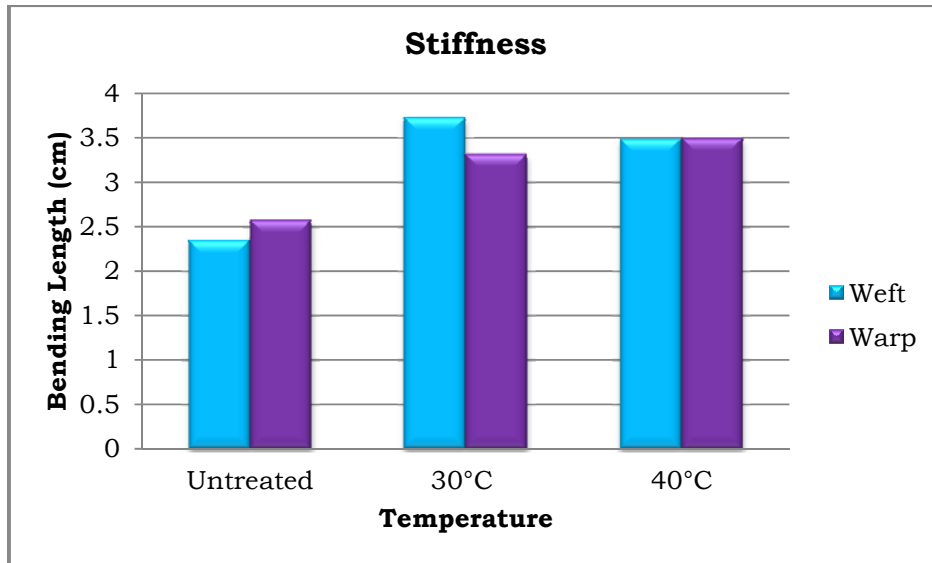


Figure 4.21: The influence of Temperature on the Bending Length of Polyamide 6,6 fabric

The bending length in the warp direction of the unlaundered polyamide 6,6 fabric was 2.58cm. Laundering the polyamide 6,6 fabric at 30°C seemed to have the least influence, resulting in a bending length value of 3.31cm in the warp direction of the fabric. Laundering the warp yarns at 40°C resulted in the highest bending length distance in the warp direction of 3.49cm. The temperature had a significant influence on the bending length of the polyamide 6,6 fabric in the warp direction. The higher the temperature the more stiff the fabric became.

The fact that the bending length of the polyamide 6,6 yarns was influenced when laundering took place at 40°C was somewhat unexpected as polyamide 6,6 is not generally influenced by a temperature such as 40°C (Nasri, Lallam & Bunsell, 2001:465).

Figure 4.22 illustrates the influence of temperature on the bending length in the weft and warp direction of machine washable wool. The bending length in the weft direction of the unlaundered machine washable wool fabric was

2.65cm. Laundering the machine washable wool at 30°C resulted in a bending length of 2.89cm in the weft direction of the fabric. The bending length in the weft direction of the machine washable wool fabric laundered at 40°C was 3.14cm.

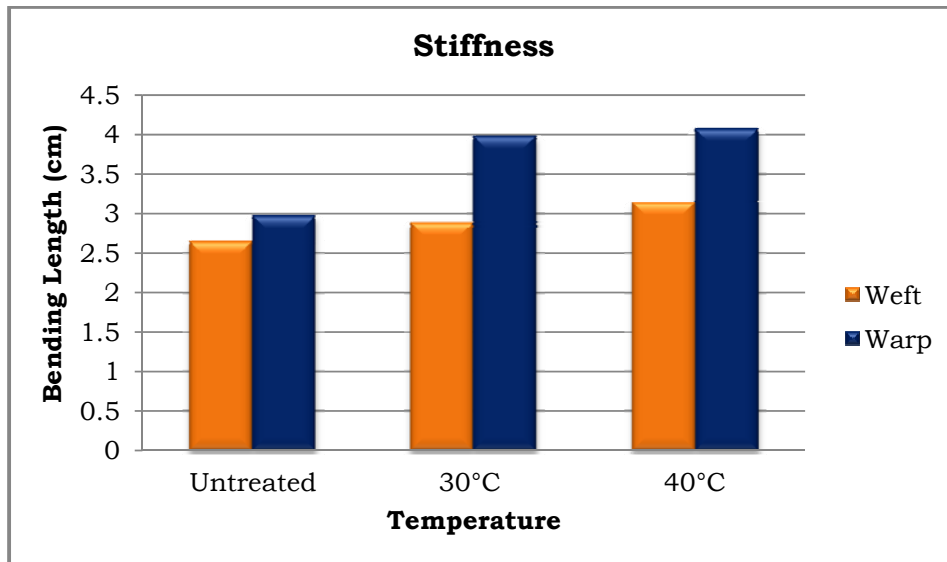


Figure 4.22: The influence of Temperature on the Bending Length of Machine Washable Wool fabric

The bending length of the unlaundered machine washable wool fabric in the warp direction was determined to be 2.98cm. Laundering the machine washable wool at 30°C caused a bending length of 3.98cm in the warp direction. When the machine washable wool fabric was laundered at 40°C, the bending length distance in the warp direction was 4.07cm, which is significantly different from the bending length in the warp direction of the fabric laundered at 30°C. It is evident that the temperature had a significant influence on the bending length in both the warp and weft direction of the machine washable wool, causing the fabric to become stiffer as it was laundered at 40°C.

4.3.3 The influence of the number of laundering cycles on the bending length of polyamide 6,6 and machine washable wool fabric

Figure 4.23 illustrates the influence of the number of laundering cycles on the bending length in the weft and warp direction of polyamide 6,6 fabric. The bending length in the weft direction of the unlaundered polyamide 6,6 fabric was 2.35cm. Laundering the polyamide 6,6 fabric for five cycles resulted in a significantly higher bending length in the weft direction of 3.34cm. When the polyamide 6,6 fabric was laundered for ten cycles, the bending length in the weft direction was 3.90cm. Laundering the polyamide 6,6 fabric for another ten cycles, resulted in a bending length in the weft direction of 3.66cm. Laundering the polyamide 6,6 fabric for fifty cycles caused the bending length in the weft direction to be 3.55cm. The bending length means (cm) in the weft and warp direction for the polyamide 6,6 fabric laundered for five, ten, twenty and fifty cycles are depicted in table 4.14.

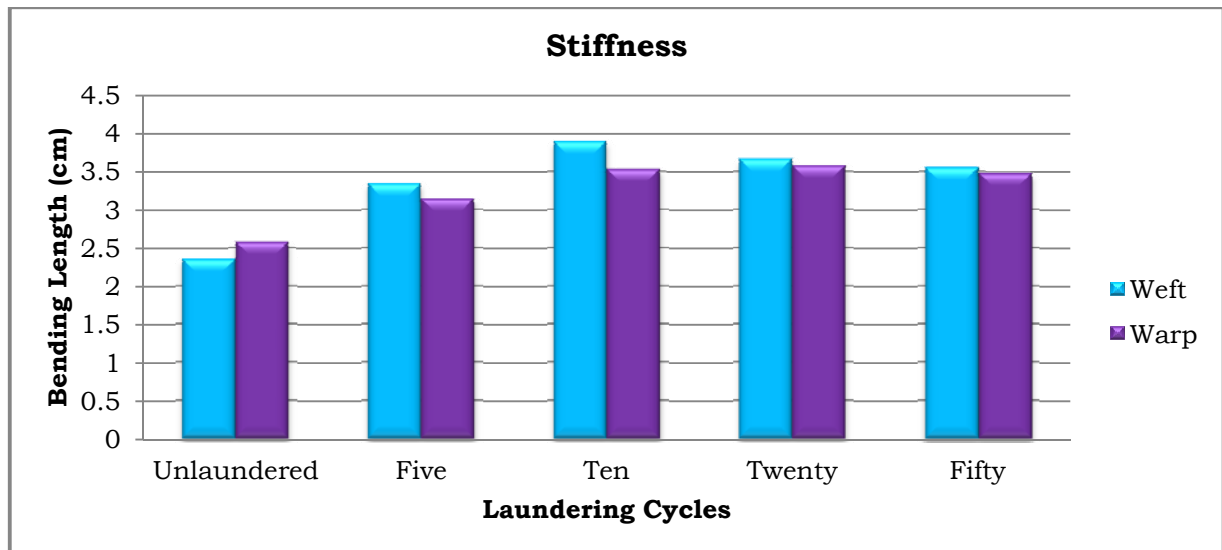


Figure 4.23: The influence of the Number of Laundering cycles on the Bending Length of Polyamide 6,6 fabric

Table 4.14: Bending length means (cm) in the Weft and Warp direction of Polyamide 6,6 fabric laundered for Five, Ten, Twenty and Fifty cycles

NUMBER OF CYCLES	Mean (Weft)	Mean (Warp)
Five	3.337500	3.137500
Ten	3.891667	3.525000
Twenty	3.658333	3.570833
Fifty	3.550000	3.470833

The unlaundered polyamide 6,6 fabric had a bending length distance of 2.58cm in the warp direction. Laundering the polyamide 6,6 fabric for five cycles, resulted in a bending length distance of 3.14cm in the warp direction, which is significantly higher than the bending length in the warp direction of the unlaundered fabric. The bending length in the warp direction of the polyamide 6,6 fabric laundered for ten cycles was 3.53cm. Laundering the polyamide 6,6 fabric for twenty cycles resulted in an insignificantly higher bending length in the warp direction of 3.57cm. When the polyamide 6,6 fabric was laundered for fifty cycles, the bending length in the warp direction was 3.47cm. It is evident that the number of laundering cycles had a significant influence on the bending length in the weft and warp direction of the polyamide 6,6 fabric by first increasing the stiffness and then decreasing the stiffness.

Figure 4.24 illustrates the influence of the number of laundering cycles on the bending length in the weft and warp direction of machine washable wool fabric. The unlaundered machine washable wool fabric had a bending length of 2.65cm in the weft direction. When the machine washable wool fabric was laundered for five cycles, it resulted in a bending length distance of 2.92cm. Laundering the fabric for another five cycles caused the bending length in the weft direction to be 2.97cm. Laundering the machine washable wool fabric for twenty cycles resulted in a higher bending length in the weft direction of 3cm. When the fabric was laundered for fifty cycles the bending length in the warp

direction was 3.19cm. The number of laundering cycles had a significant influence on the bending length in the weft direction of the machine washable wool fabric as it caused the fabric to become stiffer as the number of laundering cycles increased.

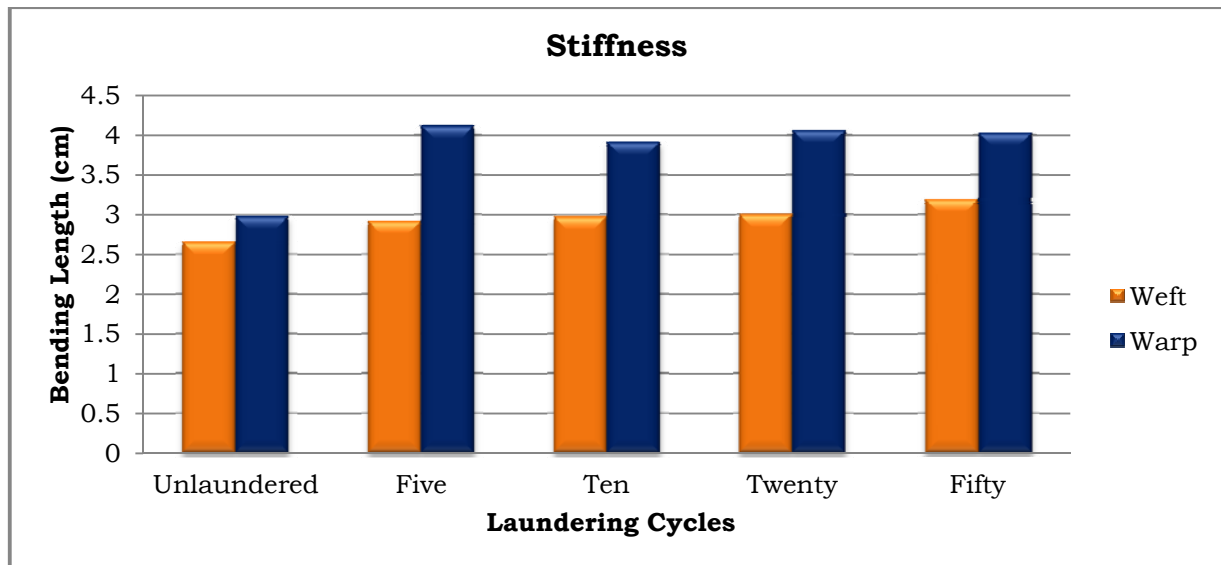


Figure 4.24: The influence of the Number of Laundering cycles on the Bending Length of Machine Washable Wool fabric

Table 4.15 depicts the bending length means (cm) in the weft and warp direction of the machine washable wool fabric laundered for five, ten, twenty and fifty cycles. The bending length of the unlaundered machine washable wool fabric in the warp direction was 2.98cm. Laundering the fabric for five cycles resulted in a bending length value of 4.11cm, which was significantly higher than the bending length in the warp direction of the unlaundered fabric. When the machine washable wool fabric was laundered for ten cycles the bending length was 3.90cm. Laundering the fabric for fifty cycles resulted in a bending length distance of 4.03cm. The number of cycles had a significant influence on the bending length of machine washable wool. A significant increase in stiffness is noted after the machine washable wool was laundered,

but the number of laundering cycles did not significantly influence the stiffness of the fabric.

Table 4.15: Bending length means (cm) in the Weft and Warp direction of Machine Washable Wool fabric laundered for Five, Ten, Twenty and Fifty cycles

NUMBER OF CYCLES	Mean (Weft)	Mean Warp
Five	2.912500	4.112500
Ten	2.966667	3.904167
Twenty	2.995833	4.058333
Fifty	3.187500	4.025000

An explanation for the increase in stiffness as the laundering cycles increase may be explained by the structural changes that took place. As the laundering cycles increased, the fabric became denser due to felting shrinkage. This caused the fabric to be stiffer. This may have caused the fabric to have more resistance against bending, and increased the bending length as a result.

4.4 Wrinkle Recovery

All fabrics bend and fold (wrinkling) during its lifetime of usage. One of the factors contributing to the quality of any fabric is the ability of that fabric to recover from these induced wrinkles (Xu & Cuminato, 1998:901). Wrinkles are in essence deformations that are dependent on the elastic properties of the fibre (Kim, 1999:860). The wrinkle recovery of a fabric is determined in the angle of recovery between 0° and 180° (Merkel, 1991:237). A weight is applied to the area where the crease is applied and left to rest on it for a predetermined time. When the weight is removed the fabric is left to recover for the same amount of time. The measurement in degrees (°) is then noted and an average for the samples is determined (AATCC 66:286). Recovering 100% from the wrinkle would be a wrinkle recovery angle of 180° (Kim, 1999:865). An angle higher than 120° is considered a good recovery from wrinkles (Merkel, 1991:237).

The results obtained when the wrinkle recovery of the polyamide 6,6 and machine washable wool fabrics used in this study were determined, are discussed in the following section:

4.4.1 The influence of detergent, catholyte and distilled water on the wrinkle recovery of polyamide 6,6 and machine washable wool fabric

Figure 4.25 illustrates the influence of catholyte, detergent and distilled water on the wrinkle recovery in the weft and warp direction of polyamide 6,6. The highest wrinkle recovery was achieved in the weft direction of the fabric laundered in distilled water. These yarns recovered 121.33° as opposed to a significantly different recovery of 115.71° of the weft yarns of the fabric laundered with detergent. The weft direction of the fabric laundered with catholyte recovered 118.38° from the induced wrinkles. The wrinkle recovery of

the weft direction of the polyamide 6,6 fabric laundered with catholyte, detergent and distilled water differed significantly from each other.

Catholyte, detergent and distilled water did however not have a significant effect on the wrinkle recovery in the warp direction of the polyamide 6,6 fabric. Laundering the fabric with distilled water resulted in the highest wrinkle recovery of 120.96° in the warp. The warp yarns of the fabric laundered with catholyte recovered 117.13°, significantly lower than those laundered with distilled water. Laundering the fabric with detergent resulted in wrinkle recovery of 118.67° in the warp.

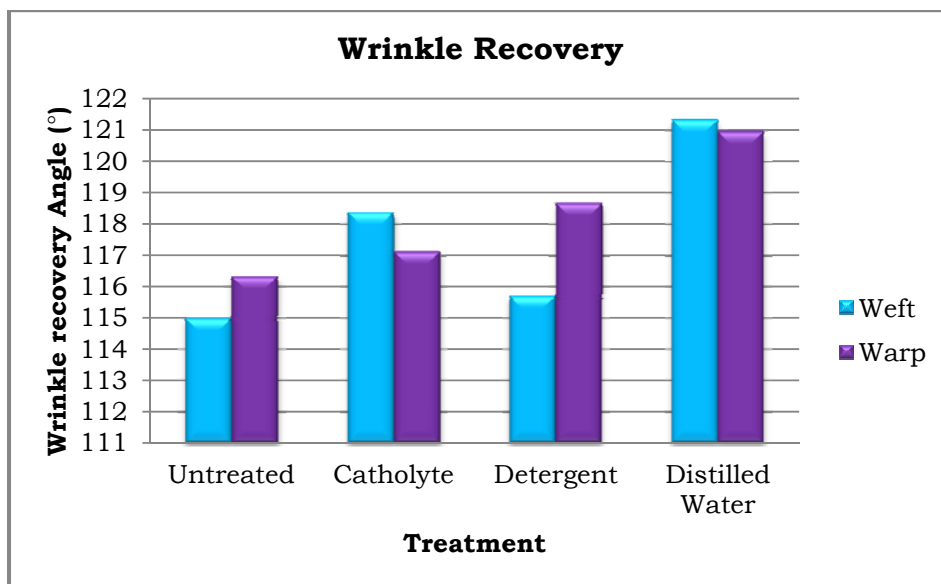


Figure 4.25: The influence of Detergent, Catholyte and Distilled Water on the Wrinkle Recovery of Polyamide 6,6 fabric

Both the weft and warp directions of the polyamide 6,6 fabric laundered with distilled water had the highest wrinkle recovery. Laundering the fabric with detergent resulted in wrinkle recovery of only 2.96° less in the weft than in the warp of the fabric laundered with detergent. The differences in wrinkle recovery between the weft and warp direction of polyamide 6,6 fabric laundered with catholyte is only 1.25°.

Polyamide 6,6 is a very elastic fibre mainly due to the regularity of the strong hydrogen bonds. These bonds operate over short distances, enabling it to exert 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 does not wrinkle or crease easily (Gohl & Vilensky, 1983:108) and recovers well from it (Joseph, 1986:104). The fact that polyamide recovers well from wrinkles is confirmed by the results obtained in this study.

The fact that the laundering of the polyamide 6,6 fabric with detergent and catholyte resulted in a lower wrinkle recovery in the weft of the fabric, lead to the assumption that ingredients in the detergent and the alkaline pH inhibits the recovery of the polymers from distortion.

As noted with polyamide 6,6 that catholyte, detergent and distilled water only had a significant influence in the weft direction of the fabric, the same is evident with the machine washable wool fabric:

The influence of catholyte, detergent and distilled water on the wrinkle recovery in the weft and warp directions of machine washable wool is illustrated in figure 4.26. Laundering the wool fabric with distilled water resulted in wrinkle recovery of 137.67° in the weft direction. This is 3.71° more than the wrinkle recovery in the weft of the machine washable wool fabric laundered with detergent and 8.30° more in the weft direction of the machine washable wool fabric laundered with catholyte. The statistical analysis supports the conclusion that these values differ significantly from each other. Table 4.16 depicts the p-values of the different treatment comparisons. Catholyte, detergent and distilled water had a significant influence on the wrinkle recovery in the weft direction of the machine washable wool fabric.

Table 4.16: P-Values of Compared Treatment Combinations in the Weft direction of Machine Washable Wool fabric

TREATMENT	Catholyte	Detergent	Distilled Water
Catholyte		0.0777	0.1733
Detergent	0.0777		0.0028
Distilled Water	0.1733	0.0028	

The difference in wrinkle recovery in the warp direction of the machine washable wool fabric laundered with catholyte, detergent and distilled water was not significant.

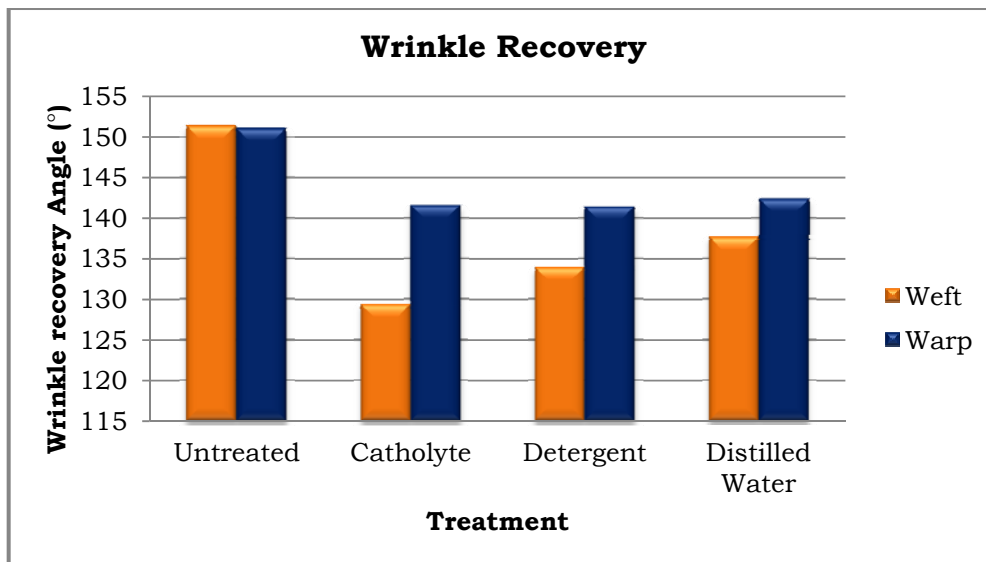


Figure 4.26: The influence of Detergent, Catholyte and Distilled Water on the Wrinkle Recovery of Machine Washable Wool fabric

The existence of a network of flexible molecules in wool is the main factor contributing to wool's wrinkle recovery properties. These bonds are believed to stretch when the fabric is deformed and also assist when it recovers (Kim & Kang, 2002:118). The significant influence of catholyte and detergent on the wrinkle recovery of the wool yarns in the weft direction may be explained by the reaction of the salt bridges in the wool molecule to changes in pH. Feuhgelman

(1997:33) reported that salt bridges in the wool molecule contribute to the resistance to mechanical distortion for example wrinkling. These interactions are however influenced by a change in pH. The presence of OH^- ions present in a higher pH (especially catholyte) causes the interactions to disappear, which decreases the wrinkle recovery of the yarns. The warp direction did not show any significant difference in wrinkle recovery between laundering the fabric with catholyte, detergent and distilled water, most probably as a result of the structure of the warp yarns.

4.4.2 The influence of temperature on the wrinkle recovery of polyamide 6,6 and machine washable wool fabric

Figure 4.27 illustrates the influence temperature had on the wrinkle recovery in the weft and warp direction of polyamide 6,6. The weft yarns of the fabric laundered at 40°C had a wrinkle recovery angle of 118.83°. This was only 0.72° higher than the wrinkle recovery in the weft of the fabric laundered at 40°C, an insignificant difference. The statistical analysis support the conclusion that temperature did not have a significant influence on the wrinkle recovery of the weft yarns of the polyamide 6,6 fabric.

From figure 4.27 it is evident that there was a significant difference between the wrinkle recovery of the warp yarns of the fabric laundered at 30°C and the recovery angle of the warp yarns of the fabric laundered at 40°C. The warp yarns of the polyamide 6,6 fabric laundered at 30°C had the highest wrinkle recovery angle of 121.75°. Laundering the polyamide 6,6 fabric at 40°C significantly lowered the wrinkle recovery of the warp yarns with 5.67°.

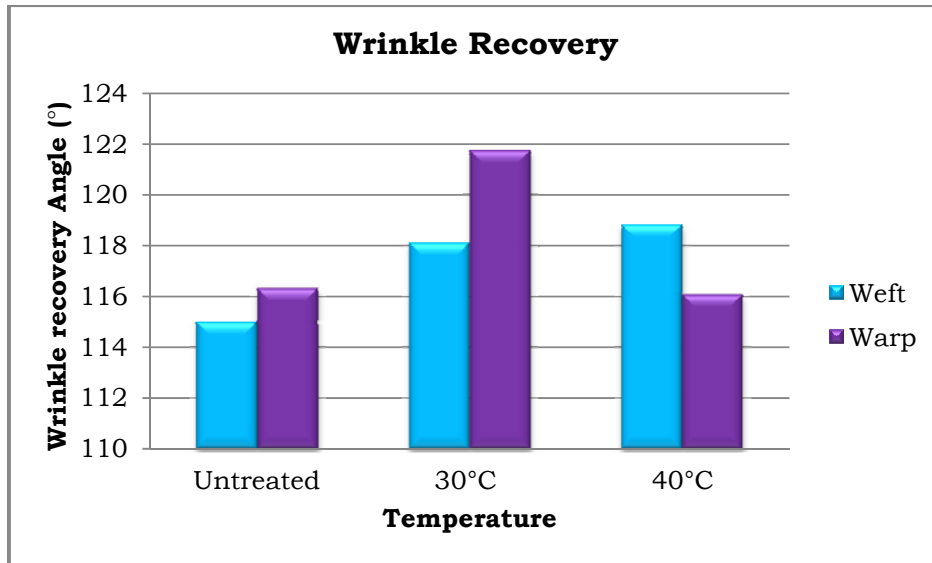


Figure 4.27: The influence of Temperature on the Wrinkle Recovery of Polyamide 6,6 fabric

Wrinkling and wrinkle recovery are dependent on the visco-elastic properties of textile fabrics (Kim, 199:860). The fact that the wrinkle recovery of the polyamide 6,6 yarns was influenced when laundering took place at 40°C was somewhat unexpected as the visco-elastic properties of polyamide 6,6 are not generally influenced by a temperature like 40°C (Nasri, Lallam & Bunsell, 2001:465).

Figure 4.28 illustrates the influence of temperature on the wrinkle recovery in the weft and warp directions of the machine washable wool fabric. Evidently from figure 4.28, the wrinkle recovery angle of the warp yarns of the machine washable wool were higher than the wrinkle recovery of the weft yarns of the same fabric. Laundering the machine washable wool fabric at 30°C resulted in a wrinkle recovery angle of 133.64° in the weft direction. The recovery angle of the weft yarns increased slightly to 133.69° when the fabric was laundered at 40°C. This was an insignificant difference.

The machine washable wool fabric laundered at 30°C had a mean wrinkle recovery angle of 142.03° in the warp direction. Laundering the fabric at 40°C decreased the wrinkle recovery angle of the warp yarns slightly to 141.47°. That was an insignificant difference of 0.56°.

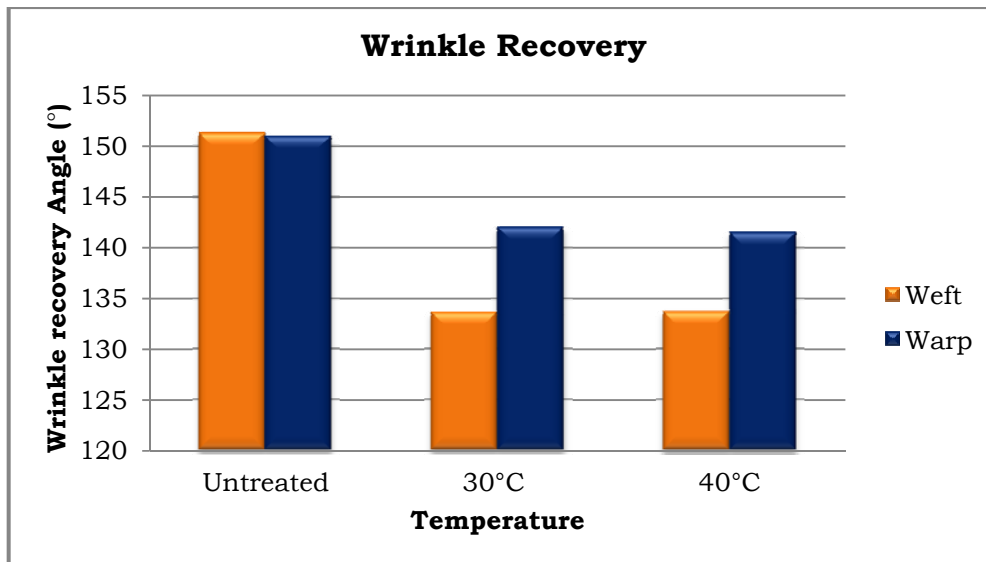


Figure 4.28: The influence of Temperature on the Wrinkle Recovery of Machine Washable Wool fabric

Temperature did not have a significant influence on the wrinkle recovery in the weft and warp direction of machine washable wool, as supported by the statistical analysis. This may be due to the fact that the bonds in the structure of wool contributing to wrinkle recovery are more pH sensitive than it is temperature sensitive (Feughelman, 1997:33). Dong et al. (2002:12) and Menefee et al. (1982:86) reports that it is related to the glass transition temperature of wool, which has an effect on the visco-elastic properties of wool that influences wrinkle recovery.

4.4.3 The influence of the number of laundering cycles on the wrinkle recovery of polyamide 6,6 and machine washable wool fabric

Figure 4.29 illustrates the influence that the number of laundering cycles had on the wrinkle recovery angle in the weft and warp direction of polyamide 6,6 fabric. Laundering the fabric for five cycles resulted in a wrinkle recovery angle of 123.22° for the weft yarns. Laundering the fabric for ten cycles, lead to a decrease in the wrinkle recovery angle of the weft yarns. The angle decreased insignificantly with 3.33° to 119.89°.

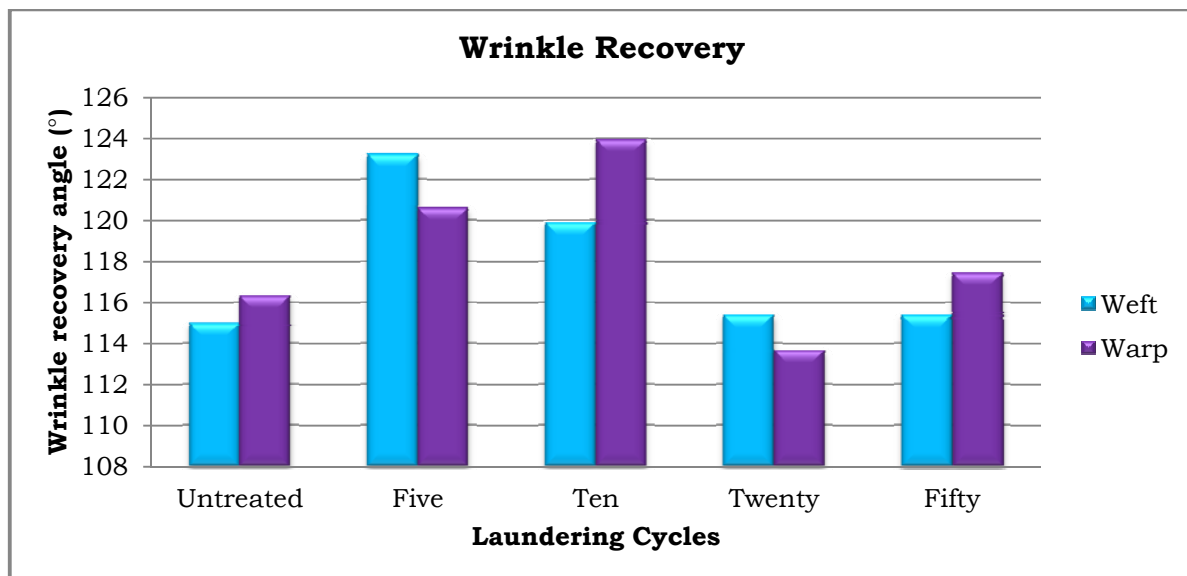


Figure 4.29: The influence of the Number of Laundering Cycles on the Wrinkle Recovery of Polyamide 6,6 fabric

Laundering the fabric for twenty cycles decreased the wrinkle recovery to 115.39°, a significant difference of 4.5°. The yarns of the fabric laundered for fifty cycles exhibited exactly the same wrinkle recovery angle of 115.39° than those laundered for twenty cycles did. The statistically determined p-values of the compared number of laundering cycles of the weft yarns of polyamide 6,6 fabric are depicted in table 4.17.

Table 4.17: P-Values of Compared Number of Laundering Cycles in the Weft direction of Polyamide 6,6 fabric

NUMBER OF CYCLES	Five	Ten	Twenty	Fifty
Five		0.1804	0.0025	0.0025
Ten	0.1804		0.0727	0.0727
Twenty	0.0025	0.0727		1.0000
Fifty	0.0025	0.0727	1.0000	

Table 4.18 depicts the p-values of the comparisons of the number of laundering cycles in the warp direction of polyamide 6,6. Laundering the fabric for five cycles resulted in a wrinkle recovery angle of 120.61° in the warp direction. Laundering the fabric for ten cycles insignificantly increased the angle of the warp yarns to 123.94°. Laundering the polyamide 6,6 fabric for twenty cycles significantly decreased the wrinkle recovery angle of the warp yarns with 10.28°. When the fabric was laundered for fifty cycles, the wrinkle recovery of the warp yarns increased again with 3.78°. Thus a steadily lowering of the wrinkle recovery with the increase in the number of laundering cycles was noted. The number of laundering cycles had a significant influence on the wrinkle recovery in the weft as well as the warp directions of polyamide 6,6 fabric.

Table 4.18: P-Values of Compared Number of Laundering Cycles in the Warp direction of Polyamide 6,6 fabric

NUMBER OF CYCLES	Five	Ten	Twenty	Fifty
Five		0.1257	0.0021	0.1452
Ten	0.1257		<.0001	0.0038
Twenty	0.0021	<.0001		0.0837
Fifty	0.1452	0.0038	0.0837	

Polyamide 6,6 is a very elastic fibre mainly due to the regularity of the strong hydrogen bonds. These bonds operate over short distances, so it is able to exert 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 does not wrinkle or crease easily (Gohl & Vilensky, 1983:108) and recovers well from it (Joseph, 1986:104). The hydrogen bonds may be hydrolyzed at the frequent exposure to alkali which may explain the lowering in wrinkle recovery that is experienced with the increase in the number of laundering cycles.

As stated previously, polyamide 6,6 generally has good resistance to alkalis (Collier & Tortora, 2001:170). Gohl and Vilensky (1983:110) did however note that the polyamide fibre may weaken if it is frequently exposed to alkalis.

Figure 4.30 illustrates the influence of the number of laundering cycles on the wrinkle recovery angle of machine washable wool. Laundering the wool fabric for five cycles resulted in a wrinkle recovery angle of 133.28° in the weft yarns. Laundering the fabric for ten cycles increased the wrinkle recovery angle to 136.56° , but laundering it for twenty cycles decreased it insignificantly to 131.11° . The weft yarns of the fabric laundered for fifty cycles had a wrinkle recovery angle of 133.50° . The wrinkle recovery angle fluctuated regardless of the number of laundering cycles; therefore a definite pattern could not be determined. Despite the fluctuating of the wrinkle recovery angle, the angle remained high.

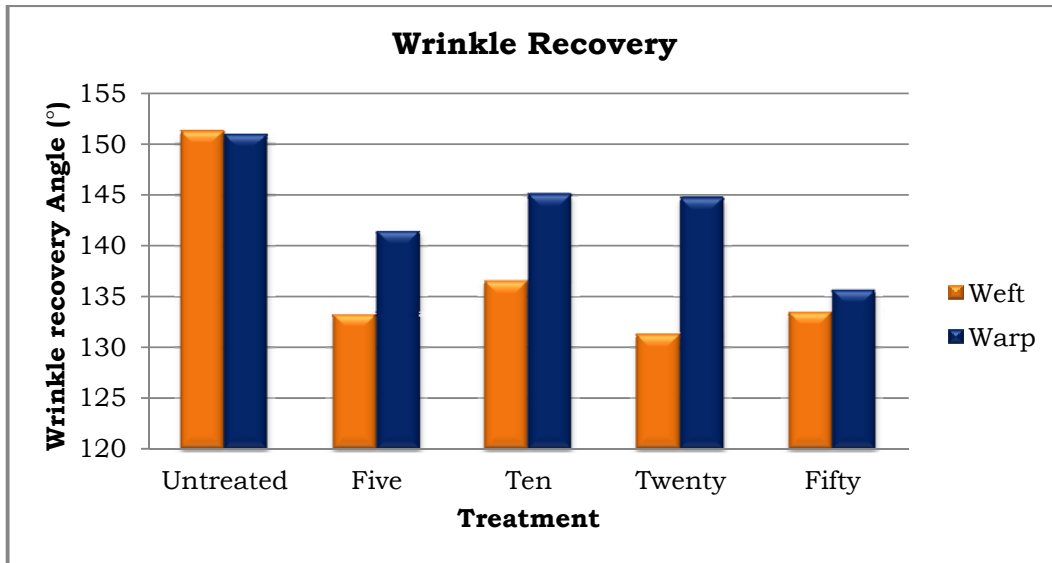


Figure 4.30: The influence of the Number of Laundering Cycles on the Wrinkle Recovery of Machine Washable Wool fabric

Table 4.19 depicts the p-values of the compared number of laundering cycles for the weft yarns of machine washable wool. It is also evident from table 4.19 that the number of laundering cycles had a significant influence on the wrinkle recovery angle of the weft yarns of machine washable wool.

Table 4.19: P-Values of Compared Number of Laundering Cycles in the Weft direction of Machine Washable Wool fabric

NUMBER OF CYCLES	Five	Ten	Twenty	Fifty
Five		0.0353	0.2048	0.8838
Ten	0.0353		0.0012	0.0490
Twenty	0.2048	0.0012		0.1586
Fifty	0.8838	0.0490	0.1586	

Laundering the machine washable wool for fifty cycles resulted in the lowest wrinkle recovery angle of 135.67° for the warp yarns. Laundering the fabric for five cycles increased the recovery angle of the warp yarns with 5.78° to

141.44°. Laundering the fabric for twenty cycles increased the wrinkle recovery angle of the warp yarns again to 144.78°. Laundering the machine washable wool for ten cycles resulted in the highest wrinkle recovery angle of the warp yarns of 145.11°. The statistically determined p-values of the compared number of laundering cycles of the warp yarns of machine washable wool are depicted in table 4.20. As is evident from table 4.20, the number of laundering cycles had a significant influence on the wrinkle recovery angle in the warp direction of machine washable wool fabric.

Table 4.20: P-Values of Compared Number of Laundering Cycles in the Warp direction of Machine Washable Wool fabric

NUMBER OF CYCLES	Five	Ten	Twenty	Fifty
Five		0.0487	0.0722	0.0025
Ten	0.0487		0.8549	<.0001
Twenty	0.0722	0.8549		<.0001
Fifty	0.0025	<.0001	<.0001	

The fluctuation in the wrinkle recovery of the machine washable wool fabric may be explained in the structural changes that took place as a result of the laundering cycles.

4.5 Dimensional Change

Dimensional stability is the ability of a certain fabric to retain its size and shape during its lifespan. Dimensional change is the difference between the original shape and size of the fabric and the shape and size of the fabric after it has been laundered or exposed to caring procedures (Kadolph, 2007:29). The dimensional change that took place is calculated by using a specific formula and it is expressed in percentage (%) (Liu & Wang, 2007:958).

The results obtained when the dimensional change was determined on the polyamide 6,6 and machine washable wool fabrics used in this study are discussed in the following section:

4.5.1 The influence of detergent, catholyte and distilled water on the dimensional change of polyamide 6,6 and machine washable wool fabric

The influence of detergent, catholyte and distilled water on the dimensional change in the warp and weft direction of the polyamide 6,6 fabric is shown in figure 4.31. It is evident that the warp direction showed the highest percentage of dimensional change, but still a very low level of shrinkage. The dimensional change in the warp direction when the polyamide 6,6 fabric was laundered with detergent was the highest at 1.2%. The fabric laundered with catholyte had a lower dimensional change in the warp direction. The dimensional change that took place when the fabric was laundered with distilled water was 0.06%.

The dimensional change in the weft direction of the polyamide 6,6 fabric was the lowest. The fabric laundered with distilled water exhibited the most dimensional change with 0.4% in the weft direction. Laundering with catholyte caused shrinkage of 0.2% in the weft direction. The fabric laundered with detergent showed the least dimensional change with only 0.1% change in the weft direction. The percentage means for the influence of catholyte, detergent and distilled water are summarized in table 4.21.

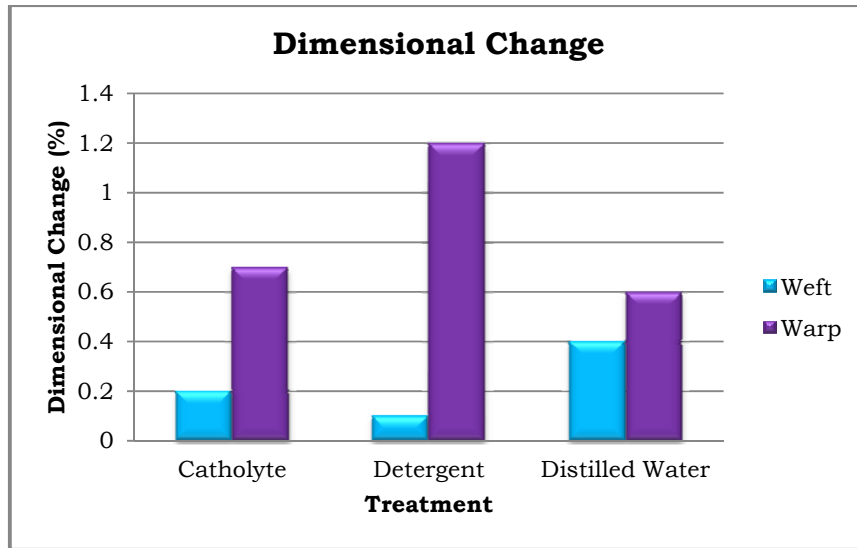


Figure 4.31: The influence of Detergent, Catholyte and Distilled Water on the Dimensional Change of Polyamide 6,6 fabric

Table 4.21: Percentage Means for the influence of Detergent, Catholyte and Distilled Water on the Dimensional Change in the warp and weft direction of Polyamide 6,6 fabric

TREATMENT	Mean (Warp)	Mean (Weft)
Catholyte	0.70000000	0.20000000
Detergent	1.20000000	0.10000000
Distilled Water	0.60000000	0.40000000

Generally polyamide 6,6 fabrics retain its shape well throughout the usage thereof, mainly because it can be heat-set (Joseph, 1986:104). At moderate temperatures polyamide 6,6 is not prone to show dimensional change or shrinkage, but at high temperatures the fabrics made from the polyamide 6,6 fibre may shrink (Collier & Tortora, 2001:171). Although the fabric did change in the weft and warp directions, the change was not enough to deem it as significant. This is supported by the statistical analysis of the compared treatment combinations as depicted in tables 4.22 and 4.23. Therefore it can be concluded that catholyte, detergent and distilled water did not have a

significant effect on the dimensional change of the polyamide 6,6 fabric. Kadolph (2007:128) and Joseph (1986:104) stated that polyamide 6,6 is dimensionally stable.

Table 4.22: P-Values of Compared Treatment Combinations in the Weft direction of Polyamide 6,6 fabric

TREATMENT	Catholyte	Detergent	Distilled Water
Catholyte		0.6754	0.4029
Detergent	0.6754		0.2106
Distilled Water	0.4029	0.2106	

Table 4.23: P-Values of Compared Treatment Combinations in the Warp direction of Polyamide 6,6 fabric

TREATMENT	Catholyte	Detergent	Distilled Water
Catholyte		0.1948	0.7946
Detergent	0.1948		0.1205
Distilled Water	0.7946	0.1205	

Catholyte, detergent and distilled water did however have a significant effect on the dimensional change of the wool fabric as seen in figure 4.32. The wool laundered with catholyte showed the highest dimensional change. The machine washable wool laundered with catholyte shrunk 18.6% in the warp direction. The shrinkage in the warp direction of the machine washable wool laundered with detergent and distilled water was considerably lower than the wool fabric laundered with catholyte. The mean percentages of the laundered wool warp yarns are depicted in table 4.21 below.

Table 4.24: Percentage Means for the influence of Detergent, Catholyte and Distilled Water on the Dimensional Change in the warp and weft direction of Machine Washable Wool fabric

TREATMENT	Mean (Warp)	Mean (Weft)
Catholyte	18.6000000	17.5000000
Detergent	10.0000000	9.7000000
Distilled Water	9.1000000	8.6000000

The weft direction of the wool fabric laundered with catholyte had the highest dimensional change percentage (17.5%). The percentage lowered when the fabric was laundered with detergent and it was the lowest when the fabric was laundered with distilled water. The percentage means for the dimensional change in the weft direction of machine washable wool are depicted in table 4.24.

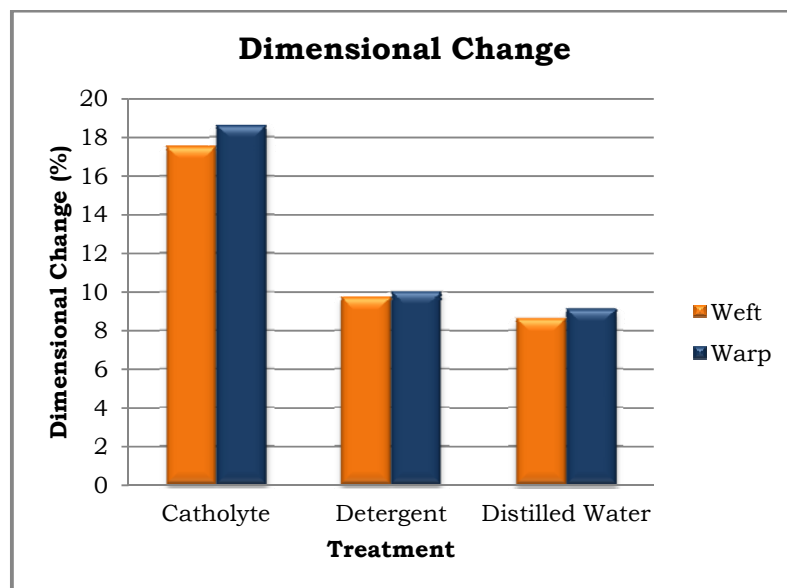


Figure 4.32: The influence of Detergent, Catholyte and Distilled Water on the Dimensional Change of Machine Washable Wool fabric

The catholyte had a significant influence on the dimensional change of the wool fabric. The dimensional change in the weft direction of the fabric laundered

with catholyte was 7.8% higher than the change in the weft direction of the fabric laundered with detergent and 8.9% higher than the change in the weft direction of the fabric that was laundered with distilled water. The fabric laundered with detergent had a dimensional change of 7.8% less in the warp direction than the fabric laundered with catholyte. The fabric laundered with distilled water showed a dimensional change of 9.5% less in the warp direction than those laundered with catholyte. The detergent and distilled water also had a significant influence on the dimensional stability of the wool fabric. There was however no significant difference between the influence that the detergent had on the wool and the influence that the distilled water had on the wool.

Wool is not dimensionally stable (Joseph, 1986:51). Because of the physical structure of the fibres, wool is prone to felting and shrinkage. This implies that the dimensional stability of wool is poor (Sun & Stylios, 2006:246). Felting shrinkage is a unique property of wool that is based on the structure of the wool fibre. By combining mechanical action, such as agitation, friction and pressure, with heat and moisture, the adjacent scale edges interlock (Joseph, 1986:48). This keeps the fibre from returning to its original position and it also results in shrinkage of the fabric. Relaxation shrinkage is another factor that needs to be considered here (Kadolph, 2007:67). Relaxation shrinkage is mostly due to the elongation and elasticity properties of the wool fibre. During fabric manufacturing, these properties allow the yarns to be stretched, and this stretched state is generally maintained throughout the manufacturing (Sun & Stylios, 2006:246). When the wool is exposed to moisture again, it will return to its original shape or length, which results in the fabric shrinking (Joseph, 1986:52).

It is evident that the dimensional changes that took place in the wool fabric were not surprising. It was alarming that the dimensional changes exceeded 10%, which is the generally expected percentage wool usually shrinks (Liu & Wang, 2007:958). As stated the wool in this study exhibited dimensional

changes up to 18.6%. However, it must be noted that the dimensional change values obtained for the fabric laundered with detergent and distilled water are in line with the 10% Liu and Wang (2007:958) mentioned.

The fact that the wool exhibited such dimensional change may be due to the highly alkaline pH (12.78) of the catholyte. The alkalinity does play a role in the felting shrinkage of wool fabrics (Sun & Stylios, 2006:246). The wool fabric laundered with detergent exhibited an accepted dimensional change percentage not exceeding 10%. Swanepoel and Van Rooyen (1970:519) did note that at a pH of 9.5, the dimensional change of wool is more controllable. As expected the wool fabric laundered with the distilled water exhibited dimensional change to a reasonable degree.

4.5.2 The influence of laundering temperature on the dimensional change of polyamide 6,6 and machine washable wool fabric

Figure 4.33 illustrates the dimensional change of polyamide 6,6 laundered at 30°C and 40°C. It is evident from figure 4.33 that the polyamide 6,6 fabric exhibited the highest dimensional change in the warp direction, although it was still a low shrinkage value of 1%.

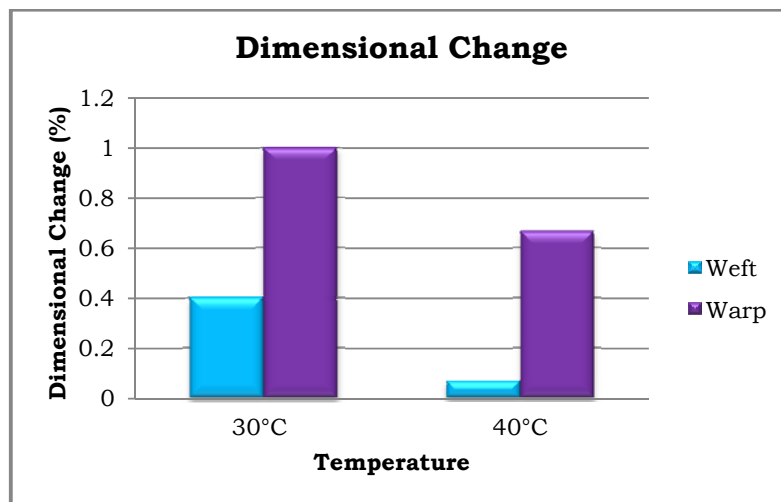


Figure 4.33: The influence of Temperature on the Dimensional Change of Polyamide 6,6 fabric

Although dimensional change did take place, it was not enough to regard it as a significant influence. Therefore it can be concluded that the temperature did not have a significant influence on the dimensional change of the polyamide 6,6 fabric as the statistically determined p-value is 0.896 in the weft direction and 0.2891 in the warp direction.

Table 4.25: Percentage Means for the influence of the Laundering Temperature on the Dimensional Change in the warp and weft direction of Polyamide 6,6 fabric

TEMPERATURE	Mean (Warp)	Mean (Weft)
30°C	1.00000000	0.40000000
40°C	0.66666667	0.06666667

The biggest change took place in the warp direction of the fabric (Table 4.25). This may be explained by the immense amount of stress the warp yarns are put under during the construction of the fabric. It will stretch when it is put under stress, but it will return to its original shape when the stress is released (Joseph, 1986:104) as would happen in the presence of water.

Collier and Tortora stated that the polyamide 6,6 fabric will not shrink at moderate temperatures (Collier & Tortora, 2001:171). The literature is supported in this study by the fact that the temperature did not have a significant effect on the polyamide 6,6 fabric.

Figure 4.34 illustrates the influence of temperature on the dimensional change of the wool fabric used in this study. It can be seen that the highest dimensional change took place in the warp direction when the fabric was laundered at 40°C. Laundering the fabric at 30°C caused a dimensional change of 12.20% in the weft direction, the difference being only 0.73%. Thus as the temperature increased the dimensional change also increased slightly, although not significantly.

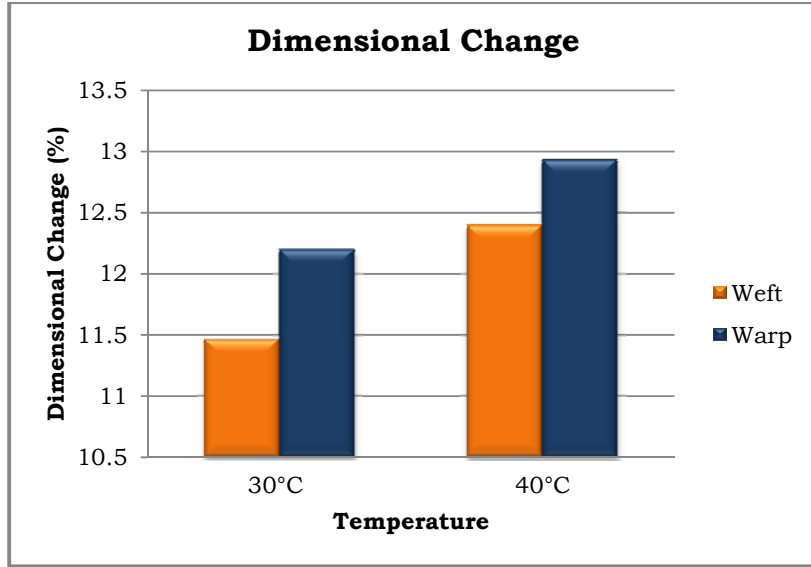


Figure 4.34: The influence of Temperature on the Dimensional Change of Machine Washable Wool fabric

The fabric showed a dimensional change of 11.47% in the weft direction at 30°C. Laundering the fabric at 40°C increased the dimensional change in the weft direction further to 12.40%. It can be concluded that as the temperature increased, the dimensional change in the weft direction also slightly increased.

Table 4.26: Percentage Means for the influence of the Laundering Temperature on the Dimensional Change in the warp and weft direction of Machine Washable Wool fabric

TEMPERATURE	Mean (Warp)	Mean (Weft)
30°C	12.2000000	11.4666667
40°C	12.9333333	12.4000000

Table 4.26 depicts the percentage means for the influence of the laundering temperature on the dimensional change in the weft and warp direction of the machine washable wool. At both 30°C and 40°C the fabric exhibited the highest dimensional change in the warp direction. When the fabric was laundered at 30°C, the dimensional change in the weft direction was 11.47%

compared to 12.20% dimensional change in the warp direction. Laundering the fabric at 40°C resulted in a 12.40% dimensional change in the weft direction and a 12.93% dimensional change in the warp direction; the differences both being only 0.53% which is not significant.

The dimensional change that took place in the warp direction of the wool fabric was the highest, and the dimensional change also increased for both the weft and warp directions as the temperature increased. Although literature states that 40°C is the normal domestic washing temperature for wool (Vasconcelos et al., 2006:729), in this study it was experienced that the least amount of damage was done at 30°C as discussed throughout this chapter. It must be considered that wool is susceptible to damage at higher temperatures (Carter, 1971:76).

4.5.3 The influence of the number of laundering cycles on the dimensional change of polyamide 6,6 and machine washable wool fabric

The number of laundering cycles did not have a significant influence on the dimensional change of polyamide 6,6 as depicted in figure 4.35. Laundering polyamide 6,6 for fifty cycles resulted in the highest dimensional change in the warp direction. The change of 1.60% was however not significant. The dimensional change in the warp direction did not exceed 0.80%, when the fabric was laundered for five, ten and twenty cycles respectively. Table 4.27 depicts the percentage means of the dimensional change that took place in the weft and warp direction of the polyamide 6,6 fabric laundered for five, ten, twenty and fifty cycles.

Laundering the polyamide 6,6 fabric for fifty cycles resulted in the highest dimensional change in the weft direction. Although it was the highest, the change of 0.53% was not significant. The dimensional change of the fabric in the weft direction laundered for five, ten and twenty cycles respectively did not exceed 0.27%. The change is not considered to be significant.

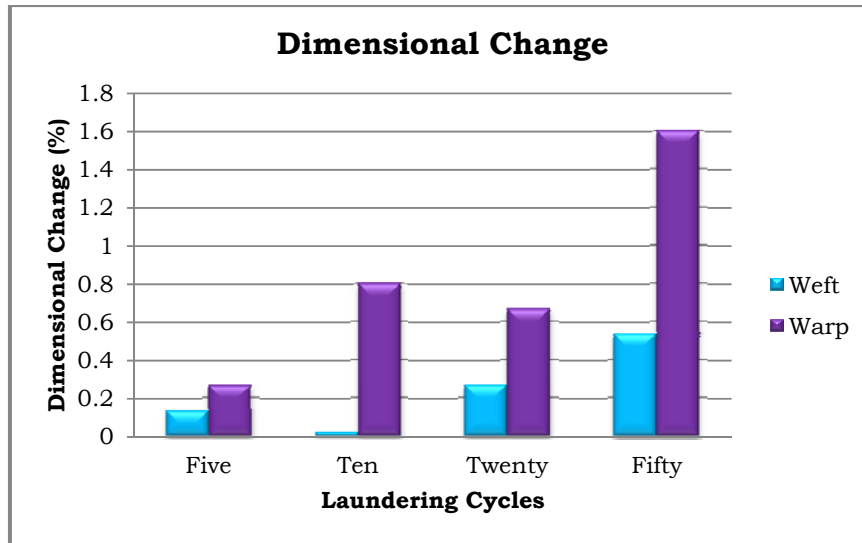


Figure 4.35: The influence of the number of Laundering Cycles on the Dimensional Change of Polyamide 6,6 fabric

Table 4.27: Percentage Means for the influence of Five, Ten, Twenty and Fifty Laundering Cycles on the Dimensional Change in the warp and weft direction of Polyamide 6,6 fabric

NUMBER OF CYCLES	Mean (Warp)	Mean (Weft)
Five	0.26666667	0.13333333
Ten	0.80000000	0.00000000
Twenty	0.66666667	0.26666667
Fifty	1.60000000	0.53333333

Figure 4.36 illustrates the influence that the number of laundering cycles had on the dimensional stability of machine washable wool. The lowest dimensional change (11.33%) happened in the warp direction of the wool fabric laundered for five cycles. Laundering the fabric for ten cycles resulted in a slightly lower dimensional change in the warp direction than when it was laundered for five cycles. The dimensional change increased again when fabric was laundered for twenty cycles.

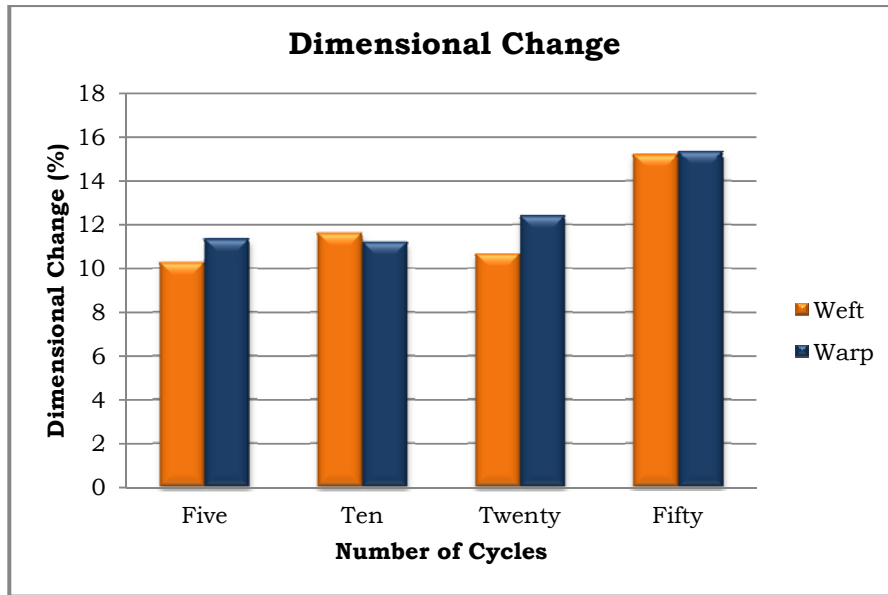


Figure 4.36: The influence of the number of Laundering Cycles on the Dimensional Change of Machine Washable Wool fabric

Laundering the machine washable wool fabric for twenty cycles increased the dimensional change in the warp direction with 1.20% and laundering it for fifty cycles increased the dimensional change with another 2.93%. The dimensional change in the warp direction of the fabric laundered for fifty cycles differed significantly from the change in the warp direction of the fabric laundered for five, ten and twenty cycles respectively. Laundering the machine washable wool fabric for fifty cycles also exhibited the greatest dimensional change in the warp direction with a percentage of 15.33. The dimensional change increased with 4% as the number of laundering cycles increased from five to fifty.

The weft direction of the wool fabric exhibited slightly less dimensional change than the warp direction. Although the weft direction of the wool fabric laundered for five cycles showed the least amount of dimensional change, it was still a significant influence causing a change of 10.27%. No significant dimensional changes occurred after ten and twenty cycles, but increasing the laundering cycles to fifty resulted in the shrinkage increasing to 15.2%. The dimensional change in the weft direction increased with 4.93% as the number

of laundering cycles increased from five to fifty. The number of cycles had a significant influence on the dimensional stability of the machine washable wool as supported by the results. Table 4.28 depicts the percentage means of the dimensional change that took place in the weft and warp direction of the machine washable wool fabric laundered for five, ten, twenty and fifty cycles.

Table 4.28: Percentage Means for the influence of Five, Ten, Twenty and Fifty Laundering Cycles on the Dimensional Change in the warp and weft direction of Machine Washable Wool fabric

NUMBER OF CYCLES	Mean (Warp)	Mean (Weft)
Five	11.3333333	10.2666667
Ten	11.2000000	11.6000000
Twenty	12.4000000	10.6666667
Fifty	15.3333333	15.2000000

Wool shrinks in a progressive manner. It will shrink the most during the first laundering cycles and then it will continue to shrink gradually every time it is laundered or exposed to moisture (Sun & Stylios, 2006:246; Silva et al., 2006:634). Therefore it is considered no surprise for the increase of dimensional change as the number of laundering cycles was also increased.

4.6 Soil Removal

Soil accumulating on textile products is one of the main factors causing the fabric to deteriorate (Collier & Tortora, 2001:485). Soil removal plays a vital role in caring for fabrics. Effective soil removal contributes to maintain the fabric in a good condition for prolonged use (Kadolph, 2007:420). A colorimeter and the CIE 1976 L*a*b* colour scale formula were used to calculate the difference in shade (AATCC 135-1985) before and after soil removal. The differences in colour were expressed as a numerical value by calculating (delta-E) ΔE . The ΔE^* indicates the size of the colour difference (Minolta, 1998:22). The higher the ΔE^* value the higher the soil removal efficiency (Ilec, Simoncic & Hladnik, 2009:319).

The results obtained when the degree of soil removal from the soiled polyamide 6,6 and machine washable wool fabrics used in this study were determined, are discussed in the following section:

4.6.1 The soil removal efficiency of detergent, catholyte and distilled water from the polyamide 6,6 and machine washable wool fabric

Figure 4.37 illustrates the influence of the catholyte, detergent and distilled water on the soil removal from the soiled machine washable wool and polyamide 6,6 fabrics used in this study. The laundered polyamide 6,6 and machine washable wool fabrics were compared against the unlaundered polyamide 6,6 and machine washable wool fabric. The polyamide 6,6 and machine washable wool fabrics that were not laundered shows the lowest delta E (ΔE^*) value. Last mentioned delta E value indicates the numerical value of the original fabric before soil removal, and thus the higher the delta E value, the more soil was removed. It is evident that laundering the machine washable wool and polyamide 6,6 fabric with detergent was the most effective for

removing the soil. The catholyte removed the soil to a better degree from the polyamide 6,6 fabric than from the machine washable wool fabric.

Laundering the polyamide 6,6 fabric with detergent showed to be the most effective for soil removal with the highest delta E value of 64.92 in comparison with the unlaundered fabric which had a delta E value of 42.30. Catholyte was less effective than the detergent, but effective enough to make a significant difference when compared to the unlaundered fabric. Laundering the polyamide 6,6 fabric with distilled water was the least effective means of removing the soil with the lowest delta E value of 49.32.

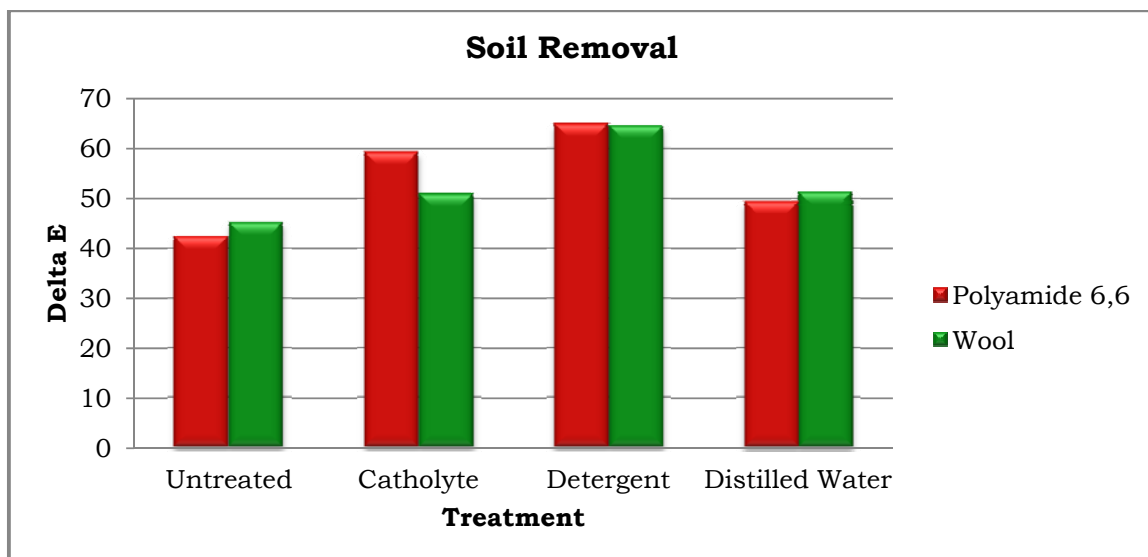


Figure 4.37: The Soil Removal Efficacy of Detergent, Catholyte and Distilled Water from Polyamide 6,6 and Machine Washable Wool fabric

Laundering the machine washable wool fabric with catholyte, detergent and distilled water was an effective means of soil removal from the machine washable wool fabric as the influence that it had on the soiled fabric was significant. It is evident when looking at figure 4.37 that detergent had the most effective influence on the soil removal from machine washable wool fabric. Laundering the fabric in distilled water increased the delta E value from 45.20 to 51.28, but laundering the machine washable wool in detergent increased it

to 64.58. Thus it can be concluded that the soil removal efficacy of the distilled water was also lower than that of the detergent. The soil removal efficacy of the distilled water from machine washable wool seems to be better than that of catholyte. The soil removal when laundering the machine washable wool with catholyte and distilled water did not differ significantly as is evident from figure 4.37 and also table 4.30 which depicts the p-values of the catholyte, detergent and distilled water when it is compared. The delta E values of the fabric laundered with catholyte and distilled water were higher than that of the unlaundered wool fabric.

Table 4.30: P-Values of Compared Treatment Combinations for the Soil Removal from Machine Washable Wool fabric

TREATMENT	Catholyte	Detergent	Distilled Water
Catholyte		<.0001	0.6331
Detergent	<.0001		<.0001
Distilled Water	0.6331	<.0001	

The low efficiency of the distilled water is expected because the distilled water has little soil removal qualities. The removal of soil is greatly dependant on the surface charges of the soil, fabric and wash solution used (Bajpai & Tyagi, 2007:331). Distilled water has fewer ions which influences the charge of the distilled water. The pH of the distilled water is usually also near seven, which is neutral. This adversely affects the soil removal of the particular solution. This is the reason for using it as a control.

In this study the soil removal efficiency of the detergent was better than that of the catholyte on both the machine washable wool and polyamide 6,6 fabrics. In a previous study done on the soil removal efficiency of catholyte, in some instances the detergent also removed the soil better than the catholyte. In that particular study a 50/50 solution of catholyte and detergent proved to be the

most efficient solution for removing soil from cotton and polyester (Van Zyl, 2008). Phosphate in detergents not only binds hardness ions but it also fulfils other functions that are critical to efficient soil removal. These functions include pH buffering and soil peptization or breakup (Bajpai & Tyagi, 2007:328). Phosphate does not form part of the constitution of catholyte, and that may be the reason for the better soil removal efficiency of the detergent on both the fabrics.

The fact that there was no significant difference between the soil removal efficiency of the catholyte and distilled water from machine washable wool, is in contradiction to the literature. Literature cited states that the desoiling of wool is more at a higher pH (Swanepoel & Van Rooyen, 1970:519). The pH of the catholyte was considerably higher than the pH of the distilled water, which was near neutral. The soil resistance of a fabric is related to the hydrophilic nature of the fibres, as well as their negative charge (Swanepoel & Van Rooyen, 1970:516, 519). The reduced redox potential and charge of the catholyte may be the reason for the soil removal efficiency being lower and not significantly different from that of the distilled water.

Another explanation might be that the higher pH-value might have caused the wool to shrink more and therefore concentrating the remaining soil on the fabric which then seems to be more.

4.6.2 The influence of the laundering temperature and temperature/treatment interaction on the soil removal efficiency from polyamide 6,6 and machine washable wool fabric

The soil removal from the machine washable wool and polyamide 6,6 fabrics was higher at both 30°C and 40°C compared to the fabrics before it was laundered. It is evident from figure 4.38 that the soil removal was the highest when the soiled polyamide 6,6 fabric was laundered at 40°C. The delta E value of the polyamide 6,6 fabric laundered at 40°C (58.06) was only 0.44 higher than the same fabric laundered at 30°C (57.62) and is therefore not significant.

It can be concluded that the temperature did not have a significant influence on the soil removal from the polyamide 6,6 fabric. The influence of the laundering temperature on the soil removal from machine washable wool was the lowest.

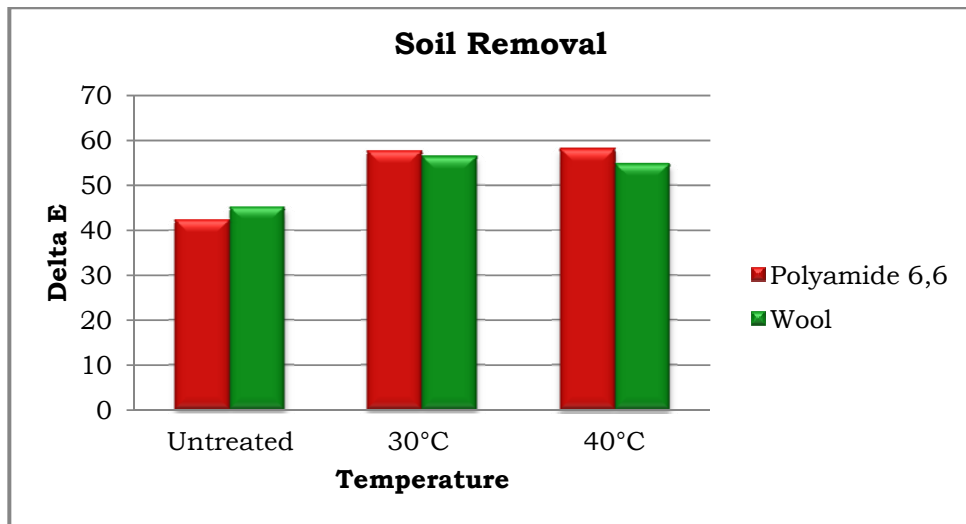


Figure 4.38: The Influence of Temperature on Soil Removal from Polyamide 6,6 and Machine Washable Wool fabric

As is evident when looking at figure 4.38, the soil was removed more from the machine washable wool at 30°C than at 40°C. Once again it might be as a result of the compacting of the yarns due to shrinkage that occurred. The delta E value lowered from 56.38 when it was laundered at 30°C to 54.80 when it was laundered at 40°C. The delta E value increased from 45.20 of the unlaundered fabric to 56.38 and 54.80 for 30°C and 40°C respectively. This influence was significant as the p-value is less than 0.05 as determined by the statistical analysis.

The interaction that took place between the temperature and the treatment with which the soiled fabric was laundered, had an influence on the soil removal of the fabric. Figure 4.39 illustrates the influence of the treatment/temperature interaction on the soil removal from the machine washable wool and polyamide 6,6 fabric.

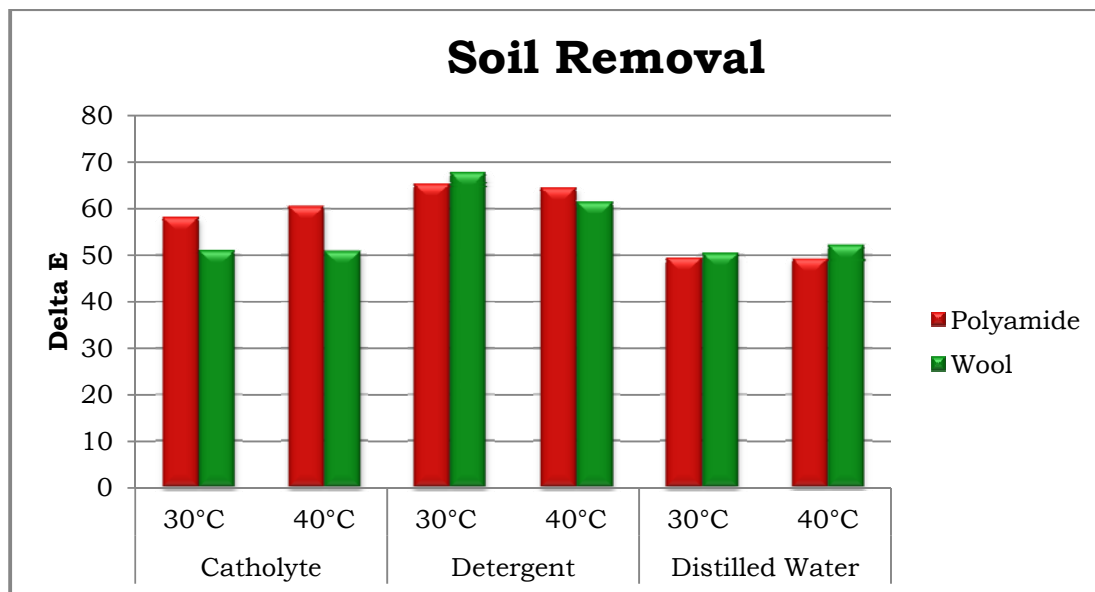


Figure 4.39: Influence of the Treatment/Temperature Interaction on the Soil Removal from Polyamide 6,6 and Machine Washable Wool fabric

The treatment/temperature interaction is compared for the polyamide 6,6 and machine washable wool fabrics in figure 4.39. Laundering both the wool and polyamide 6,6 fabrics with detergent at 30°C seems to be the most effective means for removing soil as is evident from figure 4.39. Laundering the fabrics with detergent at 40°C is also effective, but the delta-E values are slightly lower than when it was laundered at 30°C.

It is evident when looking at figure 4.39 that the soil removal of the polyamide 6,6 fabric laundered with catholyte at 30°C was less effective than the same fabric laundered with catholyte at 40°C. Laundering the fabric with detergent at 30°C and 40°C is still more effective though. There was however no great difference in the delta E values for the fabric laundered with detergent at 30°C and 40°C respectively. Laundering the polyamide 6,6 fabric with distilled water at both 30°C and 40°C respectively proves to not be so effective. The delta E means for the treatment/temperature interactions are depicted in table 4.31.

Table 4.31: Delta-E means for the Treatment/Temperature Interaction for the Soil Removal from Polyamide 6,6 fabric

TREATMENT	Delta-E Mean (30°C)	Delta-E Mean (40°C)
Catholyte	58.0953195	60.4877822
Detergent	65.3238108	64.5034333
Distilled Water	49.4395034	49.1998565

Looking at figure 4.39, laundering the wool with detergent at both 30°C and 40°C respectively is most effective for removing soil. The delta-E value decreased considerably from laundering the fabric with detergent at 30°C and 40°C respectively to laundering it with catholyte and distilled water at 30°C and 40°C respectively. The difference in the delta-E value between the wool fabric laundered with catholyte at 30°C and the wool fabric laundered with catholyte at 40°C is only 0.13. This is not a significant difference as was supported by the statistical analysis. This means that the soil removal efficacy of the catholyte when used on wool is not dependant on the temperature as is the case with the polyamide 6,6. For the fabric laundered with distilled water there is also no significant difference between the two temperatures. The delta E means for the treatment/temperature interactions are depicted in table 4.32.

Table 4.32: Delta-E means for the Treatment/Temperature Interaction for the Soil Removal from the Machine Washable Wool fabric

TREATMENT	Delta-E Mean (30°C)	Delta-E Mean (40°C)
Catholyte	50.9662425	50.8398279
Detergent	67.7494566	61.4007877
Distilled Water	50.4161902	52.1433272

It can be concluded that temperature as a main factor does not have a significant effect on polyamide 6,6, but rather the interaction with a treatment.

The treatment as a main factor has a significant soil removal effect on the samples. This means that the cleaning efficacy of the treatment is not dependent on the temperature but rather that the efficacy of the temperature is dependent on an interaction with the treatment.

Both temperature and treatment as main factors have a significant soil removal effect on wool. The interaction between the temperature and treatment also has a significant effect on the soil removal of the wool samples.

CHAPTER 5: Conclusion and Recommendation

5.1 Conclusion

In this study, it was the primary aim of the researcher to determine the effect of electrochemically activated water (catholyte) on certain important properties of polyamide 6,6 and machine washable wool fabric. This was achieved by laundering the fabric with catholyte, detergent or distilled water for five, ten, twenty or fifty cycles at 30°C or 40°C. After the laundering was completed tearing strength, tensile strength, bending length, dimensional change and wrinkle recovery tests were conducted on the fabrics.

From the results obtained of the tests conducted, conclusions are drawn on the base of the hypotheses stated in the introduction which relates to the aim of the study.

When the machine washable wool fabric was laundered with catholyte, a significant decrease in tearing strength of the weft and the warp of the fabric was noted. The decrease in tearing strength caused by the catholyte was significantly different to the influence that detergent had on the tearing strength of the fabric. Laundering the machine washable wool with detergent only caused a slight decrease in tearing strength. This was confirmed by the fact that the decrease in tearing strength caused by the detergent did not differ significantly from the decrease caused by the distilled water. Therefore hypothesis 1 is accepted as it stated that catholyte will have a significant effect on the tearing strength of machine washable wool. Furthermore hypothesis 2 is also accepted because it stated that laundering the fabric with detergent will not have a significant influence on the tearing strength of the machine washable wool fabric.

It is evident from the results obtained that the number of laundering cycles as well as the temperature at which the machine washable wool fabric was laundered significantly decreased the tearing strength of the machine washable wool fabric.

The tearing strength of the polyamide 6,6 fabric was significantly lower after laundering with catholyte. This is evident as the tearing force needed to rupture the weft and warp yarns of the fabric, significantly decreased when the fabric was exposed to catholyte. It is interesting to note that laundering the polyamide 6,6 fabric with detergent caused more damage than the catholyte as the tearing strength was lower than when the fabric was laundered with catholyte.

According to hypothesis 3, the catholyte will not have a significant effect on the tearing strength of polyamide 6,6 fabric and according to hypothesis 4 the detergent will also not have a significant effect on the tearing strength of the polyamide 6,6 fabric. Hypotheses 3 and 4 are therefore partly rejected because laundering the polyamide 6,6 fabric with catholyte, significantly decreased the tearing strength of the warp yarns of the fabric. This conclusion can be drawn as the number of cycles the fabric was laundered seems to have had a negative influence on the tearing strength of the warp yarns of the fabric. The number of laundering cycles caused fluctuation in the tearing strength of the warp yarns, resulting in a significantly lower tearing strength of these yarns after the fiftieth laundering cycle. The number of laundering cycles caused a slight decrease in the tearing strength of the weft yarns of the polyamide 6,6 fabric. The temperature at which the fabric was laundered seems to have had no significant influence on the tearing strength of the polyamide 6,6.

Laundering the machine washable wool fabric with catholyte at 30°C caused the tensile strength to be significantly lower than the unlaundered fabric. The machine washable wool fabric laundered with catholyte at 40°C disintegrated

after twenty laundering cycles. Although the detergent caused a significant lowering of the tensile strength of the fabric, it did not cause the fabric to disintegrate. This indicates that the decrease in tensile strength caused by detergent was significantly different from the decrease in tensile strength that was caused by the catholyte on machine washable wool fabric. The catholyte caused more damage than the detergent.

Hypothesis 5 stated that catholyte will have a significant effect on the tensile strength of machine washable wool fabric. Therefore hypothesis 5 is accepted as the maximum load carried by the weft and warp yarns of the machine washable wool fabric significantly decreased. According to hypothesis 6 the detergent will not have a significant influence on the tensile strength of the machine washable wool fabric. Hypothesis 6 is rejected because laundering the machine washable wool fabric with detergent caused a significant decrease in the maximum load the weft and warp yarns of the fabric could carry. Both the temperature and the number of laundering cycles also caused a significant decrease in tensile strength of the machine washable wool fabric.

The tensile strength of the polyamide 6,6 fabric decreased when it was laundered with catholyte. The decrease in tensile strength was significant in the warp yarns of the fabric although it was not considered as a significant decrease in the weft yarns of the fabric. Laundering the polyamide 6,6 fabric with detergent also resulted in a loss of tensile strength, although not significant. It seems that the decrease caused when laundering the fabric with catholyte is not significantly different from the decrease experienced when laundering with detergent.

According to hypothesis 7 laundering with catholyte will not have a significant effect on the tensile strength of the polyamide 6,6 fabric. Therefore hypothesis 7 is accepted for the weft yarns of the polyamide 6,6 fabric but rejected for the warp yarns of the polyamide 6,6 fabric. Hypothesis 8 stated that the detergent

will not have a significant effect on the tensile strength of the polyamide 6,6 fabric and in light of the results it is accepted. The number of laundering cycles did not significantly decrease the tensile strength of the weft and warp yarns of the fabric. The temperature did however cause a significant decrease in the tensile strength of the warp yarns, but did not significantly decrease the tensile strength of the weft yarns of the same fabric.

Laundering the machine washable wool fabric with catholyte caused the fabric to be stiffer. This is concluded as the bending length in both the warp and weft direction of the fabric laundered with catholyte, significantly increased. Laundering the machine washable wool fabric with detergent caused the fabric to become significantly stiffer, but not as stiff as when the fabric was laundered with catholyte. The influence of detergent on the increase of bending length of the fabric was significantly different from the increase in bending length that laundering with catholyte caused.

According to hypothesis 9, laundering the machine washable wool fabric with catholyte will have a significant effect on the bending length of the fabric. Hypothesis 9 is therefore accepted because laundering the machine washable wool fabric with catholyte resulted in a significantly higher bending length distance, causing the fabric to be stiffer. According to hypothesis 10 the detergent will not have a significant effect on the bending length of the machine washable wool fabric. Hypothesis 10 is therefore rejected because laundering the machine washable wool fabric with detergent caused the fabric to become significantly stiffer. The temperature at which the fabric was laundered caused the bending length to increase significantly as the temperature increased. The number of laundering cycles caused the machine washable wool to become slightly stiffer as the number of laundry cycles increased.

Laundering the polyamide 6,6 fabric with catholyte caused a significant increase in bending length in both the weft and warp directions. This resulted

in a stiffer fabric; however laundering with detergent caused the fabric to be even stiffer. The bending length significantly increased when the polyamide 6,6 fabric was laundered with detergent. The increase in bending length resulting from laundering the fabric with detergent was significantly different from the increase caused by the catholyte.

Hypothesis 11 states that catholyte will not have a significant influence on the bending length of polyamide 6,6 fabric and hypothesis 12 states that detergent will not have a significant influence on the bending length of polyamide 6,6 fabric. Hypotheses 11 and 12 are therefore rejected because laundering the polyamide 6,6 fabric with catholyte or detergent resulted in a significant increase in bending length, causing the fabric to be stiffer. The number of laundering cycles as well as the temperature at which the laundering took place significantly increased the bending length, also causing the fabric to become stiffer.

Laundering the machine washable wool fabric with catholyte resulted in a significantly lower wrinkle recovery angle in the weft direction; although the recovery angle in the warp direction was not significantly lower. When the fabric was laundered with detergent the wrinkle recovery angle also significantly decreased. The decrease in the recovery angle when laundering the polyamide 6,6 with catholyte and detergent, did not differ significantly from one another. Although the decrease in wrinkle recovery in the weft of the fabric was significant, it is still regarded as a good recovery value.

According to hypothesis 13 the wrinkle recovery of machine washable wool will be significantly influenced when the fabric is laundered with catholyte and according to hypothesis 14 the wrinkle recovery of machine washable wool will not be significantly influenced when the fabric is laundered with detergent. Hypotheses 13 and 14 are accepted for the weft direction of the fabric because the wrinkle recovery angle of the machine washable wool fabric in the weft

laundered with catholyte or detergent decreased significantly. However hypotheses 13 and 14 are rejected for the warp direction of the machine washable wool as the wrinkle recovery in that direction did not significantly decrease as a result of laundering with catholyte or detergent.

The number of cycles the fabric was laundered for caused significant fluctuations on the wrinkle recovery angle of the fabric in both the weft and warp direction. The temperature at which the fabric was laundered caused no significant decrease in the wrinkle recovery angle in the weft and warp direction of the machine washable wool fabric as the recovery angle in the weft direction negligibly increased and the recovery angle in the warp direction insignificantly decreased.

Polyamide 6,6 fabric laundered with catholyte resulted in higher wrinkle recovery values in both the weft and the warp directions of the fabric, although not significant. Laundering the polyamide 6,6 fabric with detergent increased the wrinkle recovery values as well. It is noted that laundering the fabric with detergent caused a higher wrinkle recovery value in the warp direction but lower wrinkle recovery value in the weft direction when compared to the recovery value of the fabric laundered with catholyte. These differences are however not significant.

Hypothesis 15 stated that catholyte will not have a significant effect on the wrinkle recovery of polyamide 6,6 fabric. According to hypothesis 16 the wrinkle recovery of polyamide 6,6 fabric will not be significantly influenced when laundered with detergent. Therefore hypotheses 15 and 16 are accepted for the polyamide 6,6 fabric because laundering the fabric with catholyte or detergent resulted in an insignificant increase in the wrinkle recovery angle. Although the catholyte and detergent did not cause a significant increase in the wrinkle recovery, the temperature at which the fabric was laundered caused a significant decrease in the wrinkle recovery in the warp direction as the

temperature increased. The temperature did not cause a significant decrease in the wrinkle recovery in the weft direction.

According to the results the dimensional change that took place when the machine washable wool was laundered with catholyte was significant. It can thus be concluded that catholyte caused the fabric to shrink significantly. Laundering the machine washable wool fabric with detergent, resulted in significant shrinkage as well, however not as severe as when the fabric was laundered with catholyte. The shrinkage caused by laundering the fabric with detergent was significantly different from the shrinkage caused by laundering the fabric with catholyte.

Hypothesis 17 stated that laundering the machine washable wool with catholyte will have a significant influence on the dimensional change of the fabric. Therefore hypothesis 17 is accepted as laundering the machine washable wool with catholyte caused the fabric to shrink significantly in both the warp and weft directions. Hypothesis 18 stated that laundering the machine washable wool fabric with detergent will not have a significant effect on the dimensional change of the fabric. Hypothesis 18 is rejected because laundering the machine washable wool fabric with detergent had a significant effect on the dimensional change of the fabric. The number of laundering cycles caused the fabric to shrink more as the laundering cycles increased. The temperature only caused a slight increase in shrinkage of the fabric as the temperature increased.

Laundering the polyamide 6,6 fabric with catholyte did not cause significant shrinkage in either the weft or warp directions. Laundering the polyamide 6,6 fabric with detergent did not cause significant shrinkage and it is also not significantly different from the influence of laundering the fabric with catholyte.

According to hypothesis 19 catholyte will not have a significant influence on the dimensional change of the polyamide 6,6 fabric and according to hypothesis 20 detergent will not have a significant influence on the dimensional change of the polyamide 6,6 fabric. Therefore hypotheses 19 and 20 are accepted as laundering polyamide 6,6 with catholyte did not cause significant shrinkage. The temperature and the number of laundering cycles did not cause significant shrinkage of the polyamide 6,6 fabric.

The secondary aim of the study was to determine the soil removal efficiency of electrochemically activated water (catholyte) from soiled polyamide 6,6 and soiled machine washable wool fabric. This was achieved by laundering the fabric with catholyte, detergent or distilled water for five cycles at 30°C or 40°C. After the laundering was completed the soil removal was determined by using the colorimeter.

It is evident from the results that catholyte proved to be an effective washing agent for removing soil after five launderings. Although it was effective, the efficiency of the phosphate detergent proved to be better. According to hypothesis 21 catholyte will have a significant effect on the soil removal from machine washable wool fabric. Hypothesis 22 states that detergent will have a significant effect on the soil removal from machine washable wool. The results indicate that catholyte as well as the detergent had a significant influence on the soil removal from machine washable wool fabric, therefore hypotheses 21 and 22 are accepted.

Hypothesis 23 states that catholyte will have a significant influence on the soil removal from polyamide 6,6 fabric. According to hypothesis 24 the detergent will have as significant influence on the soil removal from polyamide 6,6 fabric. Laundering the polyamide 6,6 fabric with catholyte resulted in the soil being significantly removed. The detergent proved to be more efficient at removing soil from the polyamide 6,6 fabric than the catholyte. It is interesting to note

that catholyte removed soil to a higher degree from the polyamide 6,6 fabric than from the machine washable wool. Hypotheses 23 and 24 are therefore accepted as the catholyte had a significant influence on the soil removal from the polyamide 6,6 fabric.

Laundrying the machine washable wool fabric at 30°C caused a significant amount of soil to be removed from the fabric. Laundrying the fabric at 40°C also caused a significant amount of soil to be removed, although it was less than laundrying the fabric at 30°C. According to hypothesis 25 the temperature will not have a significant effect on the soil removal from machine washable wool. Hypothesis 25 is thus rejected because laundrying the machine washable wool fabric at 30°C and 40°C did have a significant effect on the soil removal from the fabric.

Laundrying the polyamide 6,6 fabric at 30°C and 40 °C resulted in a significant amount of soil being removed. The difference in the soil removal efficiency at the different temperatures was however negligible. Hypothesis 26 states that the temperature will not have a significant effect on the soil removal from polyamide 6,6. According the results the soil was significantly removed from the polyamide 6,6 fabric, therefore hypothesis 26 is rejected.

It can be concluded that catholyte is a suitable alternative detergent for polyamide 6,6 fabric. The influence that it has on the properties examined in this project was not to the detriment of the fabric. Catholyte is however not suitable to use on machine washable wool as it had a severe negative influence on the properties of wool.

The soil removal efficiency of catholyte was also more effective on the polyamide 6,6 fabric than on the machine washable wool fabric. However, the soil removal of catholyte from machine washable wool was also significantly efficient. It is evident that a phosphate based detergent is superior in soil

removal efficiency, it must however be noted that catholyte is still considered as efficient in removing soil from polyamide 6,6 and machine washable wool fabric.

Catholyte as an environmentally friendly washing agent is an attractive alternative to conventional laundry detergents because it removes soil efficiently from polyamide 6,6 fabric without causing damage to the fabric and minimalises the impact on the environment. The laundering of textile fabrics with electrochemically activated water would contribute to the more green approach of consumers and manufacturers experienced across the world.

5.2 Recommendation

This research project highlighted the effect of catholyte on some properties of polyamide 6,6 and machine washable wool fabric. It emphasized the need for more investigation into the influence that catholyte might have on other fibres and properties.

It is recommended that the influence of catholyte on the colourfastness of fabrics be determined for information concerning the influence of catholyte is currently lacking.

Determining the influence of catholyte on certain properties of machine washable wool may also be conducted by activating catholyte at different pH-values which are more in the region of the pH of conventional detergents.

The relatively easy manner in which the water is manufactured may prove to be a convenient way in which the consumer can do laundry in the future. However, the sustainability thereof still needs to be established and it can also be viewed as a stimulant for more in-depth investigation and research in this particular field.

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OPSOMMING

Die elektrochemiese aktivering van vloeistowwe is 'n relatiewe nuwe tegnologie. Die alkaliese deel van die geaktiveerde vloeistof, bekend as *catholyte*, word vir 'n verskeidenheid toepassings gebruik, onder andere as wasmiddel weens die goeie skoonmaakvermoë daarvan. Die standaard fosfaat bevattende detergent wat tans gebruik word het 'n negatiewe impak op die omgewing. *Catholyte* is 'n alternatiewe oplossing omdat die pH daarvan na neutraal terugkeer binne 'n bestek van 48 uur na aktivering.

Al word *catholyte* beskou as 'n omgewingsvriendelike alternatiewe wasmiddel, is die effek wat dit op sekere belangrike eienskappe van tekstielstowwe soos byvoorbeeld wol en poliamiede het, steeds net gebaseer op spekulasie. Baie min is ook bekend oor die skoonmaakvermoë van *catholyte* op wol en poliamiede.

Die doel van hierdie studie was om die invloed van *catholyte* op sekere belangrike eienskappe van tekstielstowwe te bepaal, om sodoende te evalueer of dit as 'n alternatiewe wasmiddel vir masjienwasbare wol en poliamiede 6,6 gebruik kan word.

Die masjienwasbare wol en poliamiede 6,6 tekstielstowwe is gewas by 30°C en 40°C met *catholyte*, detergent of gedistilleerde water vir vyf, tien, twintig of veertig wassiklusse onderskeidelik.

Die standaard toetsmetodes vir was (AATCC 61) en die bepaling van skeursterkte (ASTM D1424), treksterkte (ISO/SANS 13934-1), kreukelherstel (AATCC 66), buiglengte (BS 3356), skoonmaakvermoë (AATCC 135) en krimpings is gebruik. Variansie analise (ANOVA) is gebruik vir die statistiese interpretasie van die resultate.

Catholyte, detergent en gedistilleerde water het 'n betekenisvolle afname in die skeursterkte van die poliamiede 6,6 en wolstof veroorsaak. Die wastemperatuur het geen beduidende invloed op die skeursterkte van poliamiede 6,6 getoon nie, alhoewel dit 'n betekenisvolle afname in die skeursterkte van wol veroorsaak het. Die hoeveelheid wassiklusse het 'n noemenswaardige afname in die skeursterkte van die skeringdrade van poliamiede 6,6 asook die inslag en skeringdrade van wol veroorsaak. Dit het geen beduidende invloed op die skeursterkte van die inslagdrade van poliamiede 6,6 getoon nie.

Catholyte, detergent en gedistilleerde water asook die wastemperatuur en die hoeveelheid siklusse het nie 'n betekenisvolle invloed op die treksterkte van die inslagdrade van poliamiede 6,6 getoon nie. Dit het wel 'n betekenisvolle afname in die treksterkte van die skeringdrade van poliamide 6,6 en die inslag en skeringdrade van wolstof veroorsaak.

Catholyte, detergent en gedistilleerde water asook die wastemperatuur en die hoeveelheid siklusse het 'n betekenisvolle invloed op die buig lengte (styfheid) van die poliamiede 6,6 en wolstof getoon. Bogenoemde invloede het veroorsaak dat albei die stowwe stywer geword het.

Catholyte, detergent en gedistilleerde water het 'n betekenisvolle toename in die kreukelherstel in die inslagrigting van poliamiede 6,6 en 'n afname in die kreukelherstel in die inslagrigting van wol veroorsaak. Dit het nie 'n beduidende invloed in die skeringrigting van wol en poliamiede 6,6 getoon nie. Die wastemperatuur het nie 'n betekenisvolle invloed op die kreukelherstel van die wolstof en die kreukelherstel in die inslagrigting van poliamiede 6,6 getoon nie. Dit het egter 'n noemenswaardige wisseling in die kreukelherstel van die poliamiede 6,6 en wolstof veroorsaak het.

Catholyte, detergent en gedistilleerde water, wastemperatuur en die hoeveelheid siklusse het nie 'n beduidende invloed op die dimensionele stabiliteit van die poliamiede 6,6 stof getoon nie. Dit het egter veroorsaak dat die wolstof noemenswaardig gekrimp het.

Die skoonmaakvermoë van *catholyte* en detergent is betekenisvol ten opsigte van die vuilverwydering vanaf die poliamide 6,6 en wolstof. Die wastemperatuur het slegs 'n betekenisvolle invloed getoon ten opsigte van die vuilverwydering vanaf die wolstof.

Sleutelterm: Masjienwasbare wolstof, poliamiede 6,6, elektrochemiese aktivering, *catholyte*, skeursterkte, treksterkte, buiglengte, kreukelherstel, krimping, skoonmaakvermoë.

ABSTRACT

The electro-chemical activation of aqueous media is relatively new technology. The alkaline part of the activated media (catholyte) is used in a wide variety of applications due to outstanding detergency properties. The standard phosphate based detergents currently used by consumers cause a negative impact on the environment. Catholyte provides an environmental friendlier alternative as it returns to be neutral water within 48 hours after activation.

Although catholyte may be an environmentally friendly medium for washing, the influence that it has on the properties of textile materials, for example wool and polyamide is still only based upon speculation. Little is also known about the soil removal efficiency of this medium on wool and polyamide.

The aim of this study was to evaluate electro-chemically activated water (catholyte) as an alternative detergent for machine washable wool and polyamide 6,6. This was done by determining the influence of catholyte on certain important properties of these textile fabrics as well as the soil removal efficiency.

The machine washable wool and polyamide 6,6 textile fabrics were laundered at 30°C and 40°C with catholyte, phosphate detergent or distilled water for five, ten, twenty or fifty laundering cycles respectively.

The standard test methods for laundering (AATCC 61) and measuring the tearing strength (ASTM D1424), tensile strength (ISO/SANS 13934-1), wrinkle recovery (AATCC 66), bending length (BS 3356), soil removal (AATCC 135) and dimensional change were used. Analysis of variance (ANOVA) was used for the statistical interpretation of the results obtained.

Catholyte, detergent and distilled water caused a significant decrease in the tearing strength of both the polyamide 6,6 and wool fabrics. The temperature had no significant influence on the tearing strength of polyamide 6,6 fabric although it caused a significant decrease in the tearing strength of wool. The number of laundering cycles caused a significant decrease in the tearing strength of the warp yarns of polyamide 6,6 as well as the weft and warp yarns of wool, however it did not have a significant influence on the weft yarns of polyamide 6,6.

Catholyte, detergent and distilled water as well as the temperature and number of laundering cycles did not have a significant influence on the tensile strength on the weft yarns of the polyamide 6,6. It did however cause a significant decrease in tensile strength of the warp yarns of polyamide 6,6 and the weft and warp yarns of wool.

Catholyte, detergent and distilled water as well as the temperature and number of laundering cycles had a significant influence on the bending length (stiffness) of polyamide 6,6 and wool, causing the fabric to become stiffer.

Catholyte, detergent and distilled water caused a significant increase in the wrinkle recovery in the weft of polyamide 6,6 and decrease in wrinkle recovery in the weft of wool. It did not have a significant influence in the warp of wool and polyamide 6,6. The temperature had no significant influence on the wrinkle recovery of the wool and weft of polyamide, although it caused a significant fluctuation in the warp of polyamide 6,6. The number of laundering cycles caused a significant fluctuation in the wrinkle recovery of the polyamide 6,6 and wool fabrics.

Catholyte, detergent and distilled water, as well as the temperature and number of laundering cycles did not have a significant influence on the

dimensional stability of polyamide 6,6. It did however cause the wool fabric to shrink significantly.

Catholyte and detergent proved to be significantly effective in removing soil from polyamide 6,6 and wool. The temperature only had a significant influence on soil removal from the wool.

Key terms: Machine washable wool, polyamide 6,6, electro-chemical activation, catholyte, tearing strength, tensile strength, bending length, wrinkle recovery, dimensional change, soil removal.