A COMPARISON OF THE EFFECT OF THE MECHANICAL WASH ACTION ON TEXTILE FABRIC DETERIORATION AND SOIL REMOVAL EFFICIENCY

BY

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously submitted it in its entirety or in part at any university for a degree.

A GERICKE
December 2001

OPSOMMING

Was en skoonmaak in 'n waterige oplossing is 'n komplekse proses wat 'n interaksie tussen verskeie fisiese en chemiese prosesse behels. Ondersoeke dui aan dat verskeie van die faktore teenwoordig tydens herhaalde wasprosesse 'n nadelige effek op tekstielstowwe mag hê. Baie min is egter bekend oor die effek van die verskillende meganiese wasaksies op die degenerasie van tekstiele.

Die outomatiese wasmasjiene wat algemeen in Suid-Afrikaanse huishoudings gebruik word, word dikwels breedweg geklassifiseer as bolaaiers en voorlaaiers. By nadere ondersoek word dit egter duidelik dat daar opvallende verskille bestaan tussen die horisontale drom masjiene (*H*), die vertikale drom roerder tipe (*(V)A)*) en die vertikale drom stuwer tipe (*V(I)*) masjiene. Die effek van was op die draleeftyd van tekstielstowwe is uitvoerig ondersoek, maar daar bestaan op beide nasionale en internasionale vlak 'n ernstige behoefte aan navorsing oor die effek van die verskillende meganiese wasaksies van die verskillende wasmasjiene op tekstielstowwe. Faktore soos die aantal wasse, temperatuur van die wasoplossing, detergent tipe, water kwaliteit en tekstielstoftipe en –afwerking(s) het 'n effek of tekstieldegenerasie gedurende was. Tekstielstofeienskappe soos veranderinge in die breeksterkte van die tekstielstof of die tekstielstofmassa per eenheidsarea, agteruitgang van bedrukking, rafeling, sowel as elektronmikroskoop foto's word as aanduiding van meganiese degenerasie t.o.v. tekstiele beskou.

Die oorkoepelende doel van hierdie eksploratiewe studie was eerstens, om die effek te vergelyk van herhaalde was in verskillende outomatiese wasmasjiene (algemeen in gebruik in Suid-Afrika) op die moontlike meganiese beskadiging aan tekstielstowwe, en tweedens, om die doeltreffendheid van vuilverwydering op die wasaksies van die verskillende masjiene te vergelyk. Daar is gevolglik op 'n eksperimentele studie besluit. Die was van die tekstielstowwe, sowel as die laboratoriumtoetse, is onder gekontroleerde atmosferiese toestande in 'n laboratorium uitgevoer. Afgesien van die verskillende meganiese wasaksies van die individuele masjiene, is die effek van die veranderlikes *wastemperatuur, detergentvlak* en *aantal wasse* ook ondersoek. Dit is gedoen deur die bepaling van breeksterkte en die meting van die mate van agteruitgang van bedrukking en mate van geneigdheid tot rafeling van kledingstowwe na herhaalde was by 40°C en 60°C, met en sonder detergent in die wasvloeistof. Die kleurverandering na was is ook gemeet op laboratorium gevlekte monsters.

Die analise van die meganiese wasaksie van die sewe wasmasjiene wat in hierdie studie vergelyk is, het opvallende verskille tussen masjiene uitgewys. Daar kan tot die gevolgtrekking gekom word dat die meganiese wasaksie in kategorie *V(A)* masjiene die ergste is, wat gevolglik die grootste verlaging in breeksterkte en die meeste afteruitgang van bedrukking en rafeling veroorsaak het. Hierdie masjiene het egter nie meer doeltreffende vuilverwydering tot gevolg gehad in vergelyking met die ander kategorieë van wasmasjiene nie. Die masjiene in kategorie *H* het nie 'n betekenisvolle verskil in doeltreffenheid van vuilverwydering van dié van kategorie *V(A)* getoon nie, maar die meganiese wasaksie was minder straf. Kategorie *V(I)* masjiene het blykbaar die mees delikate wasaksie en sal moontlik die minste tekstielstof degenerasie oor die langtermyn toon, maar ongelukkig is die resultate t.o.v. die doeltreffendheid van vuilverwydering swak. Die studie bevestig dat die was van tekstielstowwe in water alleen 'n groter verlaging in breeksterkte van tekstielstowwe veroorsaak as wat die geval is wanneer met 'n detergent in die wasvloeistof gewas word.

Weens die beperkte omvang en eksploratiewe aard van die studie kon sekere aspekte van die outomatiese wasprosesse nie empiries getoets word nie. Aanbevelings vir toekomstige navorsing en implikasies vir verbruikers is geformuleer.

SUMMARY

Washing and cleansing in an aqueous washing solution is a complex process involving the interaction of numerous physical and chemical processes. Investigations indicate that various factors present during repeated laundering might have an adverse effect on textile fabrics. Little is known, however, about the effect of the different mechanical wash actions on the deterioration of textiles.

The automatic washing machines commonly used in South African households are often broadly classified as top loaders and front loaders. On closer inspection, however, it becomes clear that marked differences exist between the horizontal drum machines (*H*), vertical drum agitator type (*V(A)*) and vertical drum impeller type machines (*V(I)*). The effect of laundering on the wear life of textile fabrics has been extensively investigated, but a serious need for research on the effect of the different mechanical washing actions of the different washing machines on textile fabrics exists on both national and international level. A number of factors have an effect on textile deterioration during washing, e.g. number of washes, temperature of wash liquid, detergent type as well as fabric finishes and water quality. Fabric properties like changes in tensile strength, print deterioration and fraying, as well as electron microscope photographs, were used as indicators of mechanical deterioration to textiles.

The broad aim of this exploratory study was firstly, to compare the effect of repeated washing in different domestic automatic washing machines (commonly used in South Africa) on the possible mechanical damage to textile fabrics and, secondly, to compare the soil removal efficiency of the mechanical wash actions of the different machines. An experimental study was therefore decided on. The washing of the test fabrics, as well as the testing, was carried out under controlled conditions in a laboratory. Apart from the different mechanical wash actions of the individual machines, the effect of the variables *wash temperature, level of detergent* and *number of wash*es, was also investigated. This was done by measuring tensile strength, print deterioration and fraying propensity on samples laundered repeatedly at 40°C or 60°C, with and without detergent in the washing liquid, and comparing the colour change measured on laboratory-soiled test fabrics after washing.

Analysis of the mechanical wash actions of the seven washing machines compared in this study indicated conspicuous differences among machines. It can be concluded that the mechanical wash action in the category *V(A)* machines is the most severe, and causes the highest reduction in tensile strength, the greatest print deterioration and the highest degree

of fraying. These machines did not, however, exhibit greater soil removal efficiency than the other two categories of washing machines. The machines from category *H* did not exhibit a significantly different soil removal efficiency than those from category *V(A),* but their mechanical wash action proved to be less severe. Category *V(I)* machines seem to have the most delicate wash action and will probably cause the slightest fabric deterioration over the long term, but unfortunately produces poor soil removal efficiency results. This study also confirmed that washing fabrics in water alone causes more deterioration of tensile strength in fabrics than washing with detergent in the wash solution.

Due to the limited scope and exploratory nature of this research/study, certain aspects of automatic washing machine processes could not be tested empirically. Recommendations for future research and implications for consumers were formulated.

*Dedicated to my parents,
my husband and
my children*

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CHAPTER 1

INTRODUCTION

1.1 Introductory perspectives

The ancient Egyptians used the image of a pair of legs immersed in water as a symbol to represent a launderer. The choice was logical, as the standard method of washing textile products in those times was to tread them. The washing process at the time was not very complicated. Laundry of any kind was simply subjected to mechanical treatment consisting of beating, treading, rubbing and other similar processes. It has long been known, however, that the washing power of water can be increased in several ways. Initially, better soaps, detergents and additives were the main focus of improving laundering efficiency. The transition that was brought about by technology, from the highly labour intensive manual ways of washing textile products to machine washing was an important development (Jakobi & Löhr, 1987).

Washing and cleansing in an aqueous washing solution is a complex process involving the co-operative interaction of numerous physical and chemical processes. Physical processes refer to the mechanical wash action employed to remove soil and chemical processes can include the action of detergent or bleach components with the soil and/or textile fibres. The different soiling and ageing processes lead to five distinct categories of textile soiling. These are (a) simple coatings; (b) mechanically entrapped particles; (c) semi-liquid coatings; (d) colloidal deposits, and (e) molecular adsorption. The soil mentioned in categories (a) to (e) is progressively more difficult to remove. The objective of laundering is to remove this complex mixture of soiling materials so that the article is fit for use again (Lloyd & Adams, 1989).

The chemical removal of the soil is brought about by the use of what is commonly referred to as a detergent. The word detergent is derived from the Latin word *detergo*, which means clean (Kay, 1995:28). During the washing process, the active component in the detergent makes contact with the soil and fabric through diffusion and adheres to its surface. This is aided by agitation caused by the motion of a washing machine, or by hand scrubbing. The culmination is the lifting off of soil from the fabric. The agitation is usually strong enough to break up the suspended soil into thermodynamically more stable and smaller entities called micelles (Connor, 1981). These micelles are then emulsified (surrounded by the detergent) to keep them suspended in the washing solution. A fundamental distinction exists between the primary step, in which soil is removed from the substrate, and the secondary process where the dispersed or molecularly dissolved soil is stabilised in the washing solution (Kadolph & Langford, 1998, Jakobi & Löhr, 1987). When the fabrics are rinsed, the suspended soil and detergent are rinsed away (Tortora,1978). Cleaning is defined as "...the total soil removed from a fabric minus that deposited" (Connor, 1981: 196). The components water, detergent, soil, textile fabric type and wash action (washing equipment) thus form a vital partnership in the overall washing process. Various aspects of the first four components have been extensively researched (Brown & Cameron, 1995, Brown, *et al.*, 1993a, Brown *et al.,* 1993b, Brown *et al.*, 1991, Breen *et al.*, 1984, Lloyd & Adams, 1989, Jakobi & Löhr, 1987, Raheel, 1983, Mohamed, 1982a, Ulrich & Mohamed, 1982), but very little has been published on the effect of the wash action of domestic washing equipment.

The South African market offers a wide range of domestic automatic washing machines, but very little information is available to assist consumers in their choice of products (Erasmus, 1995). Not only must the consumer make a choice regarding the manufacturer's reliability, but features to be considered are horizontal drum (usually front loading) versus vertical drum (top loading) machine type, maximum load capacity, water consumption, washing time, range of programmes, and extra functions offered (e.g. delayed spin, "fuzzy logic" or automatic switching off at the end of the wash, etc.). Even the exterior design, colour or size of the machine combine with the rest to add to the confusion.

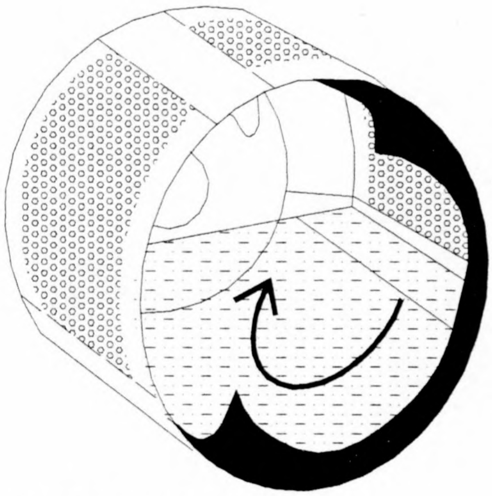
Washing machines have a life span of well in excess of ten years, making it even more important for the consumer to make the right choice when buying a domestic washing machine (Erasmus, 1995). In a study that was done on consumer laundering habits, washing machine owners listed value for money, load capacity, economy (water and electricity consumption) and the variety of programmes that machines offer as important motivations for purchases. When asked to indicate factors that lead to their awareness of machine type, factors indicated were television advertisements (65%), in-store advice (61%), word-of-mouth (53%), and magazines (40%) (Lever Pond's, 1999). The effect of the different mechanical wash actions on deterioration of textile fabrics, especially after repeated washing, is often underestimated and usually unknown. Information on the efficiency with which washing is cleaned is often hard to come by or based on unscientific sources. A serious need for research on the effect of the different mechanical washing actions of the different washing machines on the clothes in the wash exists on both national and international levels. Information on the cleaning efficiency of the different types of washing machines from which consumers have to choose, will also be of great value.

The automatic washing machines commonly used in South African households are often broadly classified as top loaders and front loaders (Plumbley, 1999, Lever Pond's, 1999, Lever Bros, 1995). On closer inspection, however, it becomes clear that a finer distinction is necessary. The group referred to as front loaders washes washing in a drum than turns around a horizontal axis. Some horizontal drum machines, however, open from the top (with the washing being loaded through the side of the drum) and not the front. It is therefore technically more correct to refer to the group as horizontal drum machines, in stead of front loaders (Jakobi & Löhr, 1987). In top loader machines, the drum has a vertical axis, which is the reason for the group being classified as vertical drum machines. In the vertical drum machines the mechanical wash action can be brought about either by a device situated in the centre of the base of the drum, called an agitator, or by an impeller in either the base or side of the drum. The difference between the two devices makes it imperative to divide the group into two further categories. Table 1.1 illustrates and explains the mechanical wash actions of the three categories of domestic automatic washing machines, while Figure 1.1 shows illustrations of the mechanical wash actions of the machines. The drastic differences in the actions, with which these machines clean laundry, are obvious.

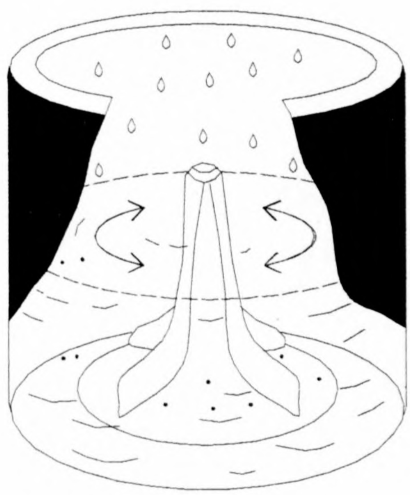
TABLE 1.1: BROAD EXPLANATION OF MECHANICAL WASH ACTIONS OF DOMESTIC AUTOMATIC WASHING MACHINES AVAILABLE IN SOUTH AFRICA

	DOMESTIC AUTOMATIC WASHING MACHINES		
	HORIZONTAL DRUM MACHINES (FRONT LOADERS)	VERTICAL DRUM MACHINES (TOP LOADERS)	
		Agitator Type Machines	Impeller Type Machines
Mechanical wash action:	A horizontal perforated inner drum rotating on its axis in alternating directions inside a larger drum (which holds the bulk of the water) is responsible for the wash action. The washing is lifted by fins on the sides of the inner drum and then allowed to fall back into the wash liquor, causing agitation to loosen soil.	An agitator fitting into the bottom of a perforated drum causes the wash action. The rhythmic motion of the agitator arms moves the washing around for the duration of the wash, creating friction among the articles in the wash load and between the articles and the sides of the drum.	An impeller in the form of a ribbed disk is fitted, either at the base or on the side of the drum. The mechanical wash action is caused by the accelerated water movement, which swirls the washing around in the drum. This washing action is enhanced in some models by the drum also rotating in alternate directions.
Temperature control:	The wash liquor is heated internally by electrical heating coils, usually thermostatically controlled.	The machines are connected to hot and cold water supplies and the desired wash temperature selected is achieved by automatic mixing of the two inlet sources.	

(a) Category: horizontal drum machines



(b) Category vertical drum agitator type machines



(c) Category vertical drum impeller type machines

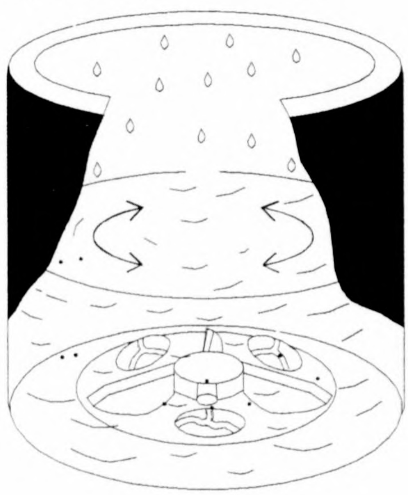


FIGURE 1.1: ILLUSTRATION OF THE BASIC MECHANICAL WASH ACTIONS OF THE THREE CATEGORIES OF WASHING MACHINES

In practice, washing machine manufacturers constantly change the construction details of washing machines. Old models are phased out and new models introduced every year. According to the American Association of Textile Chemists and Colorists (AATCC), the new models being developed in the United States since 1990 are made more energy efficient and involve direct drive machines replacing the old belt drive machines. Model changes in the old belt type machines had little influence on soil removal efficiency and fabric properties. The new direct drive machines, however, provide a lot more mechanical agitation per minute than did the older units and cannot be regarded as comparable to the older units. The greater mechanical agitation in direct drive machines speeds up soil removal, but negatively affects the appearance of some fabrics (Merkel, 1991). This was confirmed in a study by Shiraiwa and Yamada (1993). With new machines constantly appearing on the market, it is thus imperative that research must be done to investigate the effect of different degrees of mechanical agitation on textile fabrics during washing.

Deterioration of textile fabrics involves the pervasive change in textile structure, reducing its life expectancy. Researchers like Ulrich and Mohamed (1982: 38) reported that 50% of the damage that occurs throughout a garment's wear life, is caused by abrasion during laundering. Lord (1971) came to the conclusion that, with respect to damage, conditions during the laundering and use of textiles are more important than the type of fabric or fibre it is made of. Chemical damage and ***mechanical action*** are the main causes of textile degradation during laundering (Slater, 1991). This gave rise to the question ***whether a difference would be found in the mechanical degradation of fabrics after repeated washing in domestic automatic washing machines where the wash programmes and mechanical wash actions differ.*** Deterioration of textiles, with specific focus on textile properties that can be negatively affected by different mechanical wash actions, will be discussed in the successive paragraphs.

Degradation manifests itself in a variety of ways. Loss of colour and change in tensile strength are considered the main effects of degradation (De Villiers, 1998). Fabric abrasion is defined as "...the wearing away of any part of a material by rubbing against another surface" (Merkel, 1991:195). During laundering, fabrics are continually flexed and straightened and submitted to wet abrasion as they rub against other fabrics in the wash and the sides of the washing machine or wash tub. When the lint filters of a washing machine or dryer are cleaned, the bits of fibre in the mat of lint are direct evidence of fibre breakage. An added consideration is that fibres, especially natural fibres, have a fibrillar internal structure, which, under some circumstances, can split up during wash and wear. Splitting is experienced under wet conditions, as the water molecules fill interfibrillar spaces in between the fibrils (Merkel, 1991). Furthermore, most wash liquors are alkaline and together with the temperature of the wash liquor, cause wool and cotton fibres to swell significantly. The swollen fibres are easily distorted and damaged by mechanical action. Cotton fibres in particular suffer from fibrillation (Lloyd & Adams, 1989).

Loss of weight is also listed as an indication of fabric deterioration, but colour changes, as well as changes in fabric strength, can usually be seen even when the weight change is still very small. A problem with weight measurements is that the fabric may shrink during use and care, causing an increase in the weight per unit area even while the weight of the entire specimen decreases (Merkel, 1991).

The ***tensile strength*** of a fabric is affected to some degree by almost every feature of fabric construction or finish. Any drop in tensile strength signals a possible change in the fabric, which makes tensile strength especially useful in comparative tests (e.g. for research purposes) (Merkel, 1991, Kadolph, 1998).

Visual changes in fabric appearance due to abrasion includes frosting, pilling, snagging, mussing, and yarn distortion (Merkel, 1991). Of these, frosting and yarn distortion are the two most likely to happen to printed cotton fabric during laundering. Frosting is defined as "...a change in colour caused by localized abrasive wear" (Merkel, 1991:372). In laundering, frosting may manifest itself as the abrading away or loss of surface colour in a pigment printed fabric. Pigment printing involves the application of pigments to the fabric surface as a means of colouration. Pigments are insoluble particles that are held mechanically on a fibre surface by a binder. The pigment is retained on a fabric as long as the binders remain intact. Mechanical agitation such as that which occurs during laundering can cause pigment binding strength to deteriorate, which may cause colour loss and lead to a fabric getting a faded appearance (Kadolph & Langford, 1998, Smith & Block, 1982, Hall, 1978). From here on the above will be referred to as ***print deterioration***.

Yarn distortion in a washed fabric may become a problem when an unfinished edge of a fabric in a wash is exposed to mechanical agitation. This is referred to as ***fraying*** and defined as the loss of threads from a raw edge cut parallel to the threads (Taylor, 1990). Fraying may occur when a garment is cut or torn during use and the tear is not mended before washing. The severity of the wash action will determine the degree of fraying that will be caused during the wash. ***Degree of fraying*** could also be used in a test as a direct indication of the severity of the wash action of a washing machine.

The term soiling implies overall contamination or discolouration of a fabric, whereas staining implies a local contamination or discolouration. The subject of fabric soil and stain removal has become a major concern in textile testing, because of consumer and industry complaints. The term **soil removal efficiency** refers to the efficiency with which a washing machine removes soil from a fabric surface during washing. The effectiveness of different washing machines with regard to soil removal efficiency can thus be compared by washing a laboratory-soiled test fabric in each and evaluating the colour change in the test fabric, either visually or with a colour spectrophotometer or colorimeter (Merkel, 1991). The main purpose of a washing machine is to clean soiled fabric. This study would therefore not be meaningful unless the ***soil removal efficiency*** of the machines is also compared.

From the above it was concluded that the textile properties of tensile strength, print deterioration, degree of fraying, and soil removal efficiency can be used as valid indicators to compare the severity of the mechanical wash action of different washing machines and their effect on textile fabric deterioration during laundering.

1.2 Problem statement

The effect of laundering on the wear life of textile (especially cotton) fabrics has been extensively researched. Results show that the decrease in fabric strength, due to laundering treatments, is a result of the combined effect of mechanical and chemical damage to textile fibres or yarns. Researchers indicate that a number of factors may have an effect on textile deterioration during washing. These factors are number of washes, temperature of wash liquid, fabric finishes and water quality (Lloyd & Adams, 1989, Jakobi & Löhr, 1987, Raheel, 1983a, Mohamed, 1982b, Ulrich & Mohamed, 1982). It was also established that detergent type, number of washes, water quality, as well as finishes applied to cotton fabrics, are important factors in the deterioration of fabric colour (Lord, 1971, Ulrich & Mohamed, 1982, Mohamed 1982b). Fabric properties like changes in tensile strength, fabric mass per unit area, print deterioration and fraying, as well as electron microscope photographs, were used as indicators of mechanical damage to textiles (Booth, 1968, Goynes & Rollins, 1971, Higgenbotham, 1976, Shiraiwa & Yamada, 1993, Slater, 1991, Ulrich & Mohamed, 1982).

The above-mentioned investigations indicate that various factors present during repeated laundering may have an adverse effect on textile fabrics. Little is known, however, about the effect of the different mechanical wash actions on the deterioration of textiles. The only research found in this regard was by Shiraiwa and Yamada (1993). They compared an impeller type washing machine with increased mechanical action to a standard mechanical action washing machine of the same type. Improved detergent efficiency, but more pronounced felting shrinkage (with wool samples) and fraying were detected than in the case of the standard machine. It is an accepted fact that greater mechanical action in washing machines accelerates soil removal, but could negatively affect the appearance and strength of some fabrics. It should be noted that new developments in washing machine programmes provide more severe mechanical action per minute compared to the previous designs (Merkel, 1991).

From the above, it is clear that there is a need to investigate

(1) Whether the variety of wash actions of different domestic automatic washing machines (explained in Table 1.1) have different mechanical degradation effects on the tensile strength, print deterioration and degree of fraying of textiles being washed, and

(2) whether there is a difference in the soil removal efficiency of the machines that relates to the different wash actions.

The results of this study will contribute to establishing much needed scientific information, based on empirical research, to help consumers with the selection of washing machines. Although this investigation should be considered an exploratory study, it is designated to serve as a point of departure and a scientific model for future research in this field, which could be of academic as well as industrial worth.

1.3 Research objectives

The broad aim of the research was to compare the effect of repeated washing in different domestic automatic washing machines (commonly used in South Africa) on the possible mechanical damage to textile fabrics and also to compare the soil removal efficiency of the mechanical wash actions of the different machines. The effect on mechanical damage of textile fabrics would be established by comparing the tensile strength, print deterioration and degree of fraying of test samples that were repeatedly washed in the various machines. Seven different washing machines, representing three categories, were used in the study. Soil removal efficiency would be compared by assessing colour change in laboratory-soiled test fabrics after washing.

More specifically stated, the objectives were:

1. To assess and compare the effect of repeated washing in the seven *washing machines* on the *tensile strength*, *print deterioration* and *fraying* of a textile fabric;

2. To assess and compare the effect of repeated washing in the *three categories* of washing machines on the *tensile strength*, *print deterioration* and *fraying* of a textile fabric;

3. To assess whether there is a difference in the *tensile strength* of a textile fabric after repeated washing

   3.1 at $40^{o}C$ or $60^{o}C$, in the different machines, and

   3.2 with or without detergent (from here on referred to as *level of detergent*) in the different machines;

4. To assess whether there is a difference in the *soil removal efficiency* of the seven *washing machines*, based on colour change in laboratory-soiled test fabrics;

5. To assess whether there is a difference in the *soil removal efficiency* of the *three categories* of washing machines, based on colour change in laboratory-soiled test fabrics.

1.4 Hypotheses

The following null hypotheses were formulated for the study:

$H1_0$ There will be no difference in the effect of the variable, *washing machine*, on the *tensile strength* of samples of a 100% cotton fabric washed respectively 10, 20, 30, 40 and 50 times in the seven different washing machines.

$H2_0$ There will be no difference in the effect of the variable, *category of washing machine*, on the *tensile strength* of samples of a 100% cotton fabric washed respectively 10, 20, 30, 40 and 50 times in the seven different washing machines.

$H3_0$ There will be no difference in the effect of the variable, *washing machine*, on the *print deterioration* measured on samples of a pigment-printed 100% cotton fabric washed 10 and 20 times without detergent at 40°C in the seven different washing machines.

$H4_0$ There will be no difference in the effect of the variable, *category of washing machine*, on the *print deterioration* measured on samples of a pigment-printed 100% cotton fabric washed 10 and 20 times without detergent at 40°C in the seven different washing machines.

$H5_0$ There will be no difference in the effect of the variable, *washing machine*, on the *degree of fraying* assessed on samples of a pigment-printed 100% cotton fabric washed once, three and five times without detergent at 40°C in the seven different washing machines.

$H6_0$ There will be no difference in the effect of the variable, *category of washing machine,* on the *degree of fraying* assessed on samples of a pigment-printed 100% cotton fabric washed once, three and five times without detergent at 40°C in the seven different washing machines.

$H7_0$ There will be no difference in the effect of the variable, *wash temperature*, on the *tensile strength* of 100% cotton fabric washed 10, 20, 30, 40 and 50 times in the seven different washing machines.

$H8_0$ There will be no difference in the effect of the variable, *level of detergent*, on the *tensile strength* of 100% cotton fabric washed 10, 20, 30, 40 and 50 times in the seven different washing machines.

$H9_0$ There will be no difference in the *soil removal efficiency* of the seven different *washing machines*.

$H10_0$ There will be no difference in the *soil removal efficiency* of the three *categories of washing machines*.

1.5 Conceptual framework

Based on the above, the independent variables identified for this research project were seven different washing machines, three categories of washing machines, number of washes (refer operational definition 1.6.21) carried out, wash temperature, and level of detergent. The dependent variables were changes in tensile strength, print deterioration, degree of fraying, and soil removal efficiency. The relationship between the dependent and independent variables relevant to this study is illustrated in the conceptual framework (Figure 1.2).

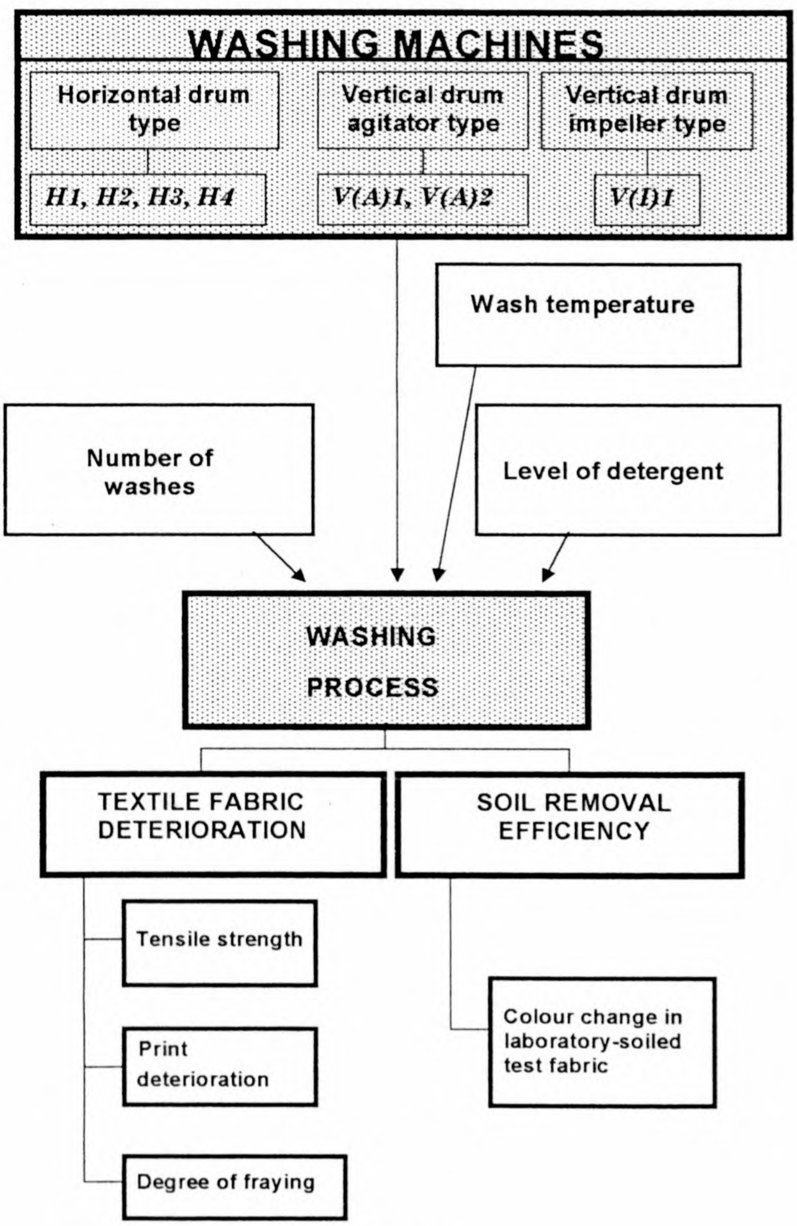


FIGURE 1.2: CONCEPTUAL FRAMEWORK

1.6 Operational definitions

For the purpose of this study, the following definitions apply:

1.6.1 Cleaning efficiency (see *soil removal efficiency*)

1.6.2 Conditioning of textiles (see *standard condition for physical testing*)

1.6.3 Deterioration of textile fabrics

Deterioration of cotton fabrics refers to a pervasive change in textile structure that reduces its life expectancy. Mechanical and chemical damage are the main causes of textile deterioration during laundering (Slater, 1991). Deterioration manifests itself in a variety of ways. Loss or change of colour and change of tensile strength are considered to be some of the main effects of deterioration (De Villiers, 1998).

1.6.4 Domestic automatic washing machine

A washing machine (intended mainly for domestic use) designed to complete a full wash programme, including water intake, wash cycle, rinse cycle(s) and spin cycle(s), of which the time, action and water consumption are automatically controlled according to the programme selected. (The programmes selected will be discussed in Chapter 3).

1.6.5 Fabric (see *textile fabric*)

1.6.6 Fraying

Fraying is the loss of threads from a raw edge cut parallel to the threads in the fabric (Taylor, 1990). For the purpose of this investigation degree of fraying will be assessed visually and rated on a five-point ordinal scale (Refer Addendum E).

1.6.7 Laundering

Laundering is a process intended to remove soils and/or stains by treatment (washing) with an aqueous detergent solution and normally includes subsequent rinsing, extraction and drying (Merkel, 1991)

1.6.8 Launderer

The launderer is the person carrying out the laundering process.

1.6.9 Level of detergent

The level of detergent refers to the concentration of detergent present in the washing solution during the wash cycle. For this study, the two levels used were nil and the amount described in 3.6 (Refer Chapter 3).

1.6.10 Print deterioration

Print deterioration is the deterioration in surface appearance of a printed fabric, with normally acceptable print quality, after being subjected to mechanical agitation as would occur during washing in a washing machine. It is evaluated for the purpose of this project by comparing colorimeter lightness measurements taken on the plain areas of the print before and after washing.

1.6.11 Rinse cycle

The rinse cycle refers to the intake of clean (usually cold) water in a washing machine, followed by a mechanical rinse action. The purpose of rinsing is to remove the remaining detergent from the wash load. The cycle can be followed by a spin cycle and is usually repeated several times, depending on the washing programme of the washing machine.

1.6.12 Soil removal efficiency

The soil removal efficiency is the efficiency with which soiled fabrics are cleaned during washing. Soil removal efficiency will be measured by assessing the colour change in standardised laboratory-soiled test fabrics before and after washing.

1.6.13 Spin cycle

The draining of the remaining water from the wash load by centrifugal force is referred to as the spin cycle. The drum spinning at high speed develops this force. The specific washing programme of the washing machine determines the duration of the spin as well as the speed.

1.6.14 Standard atmosphere for testing textiles

The standard atmosphere for testing textiles refers to an atmosphere in which a relative humidity of 65$\pm$2 percent and a temperature of 21$\pm$1^{o}C (ASTM) is maintained (Kadolph, 1998:86, Merkel, 1991:376) (Refer Addendum A).

1.6.15 Standard condition for physical testing

A textile fabric is in a standard condition (or is "conditioned") for physical testing when it has been kept at the standard atmosphere for testing until it has reached equilibrium with regard to humidity content and temperature (Textile Terms and Definitions Committee, 1988) (Refer Addendum A).

1.6.16 Tensile strength

The tensile strength is the maximum resistance of a material to deformation in a tensile test carried to rupture; that is, the breaking load or force per unit cross-sectional area of the unstrained specimen (Merkel, 1991) (measured in Newton per 50mm fabric width for the purpose of this investigation).

1.6.17 Textile fabric, textiles, fabrics

These terms refer to a manufactured assembly of fibres and/or yarns in a planar structure. The structure should have sufficient mechanical strength to provide the assembly inherent cohesion. Generally, textile fabrics are knitted or woven, but other structures like lace, net, felt or nonwovens are also implied (Kadolph & Langford, 1998, Textile Terms and Definitions Committee, 1988).

1.6.18 Washing cycle

The washing cycle refers to the intake and heating (where applicable) of water, followed by a mechanical wash action. The washing cycle ends with the draining of the water and is followed by rinse and spin cycles. If detergent is used to enhance cleaning, it is added at the beginning of the washing cycle and removed with the draining of the wash water and during the rinse cycles that follow.

1.6.19 Washing*

The washing refers to the textile products that make up the wash load.

*when used as a noun

1.6.20 Wash load

The textile fabrics being washed in one washing machine at a certain time is called the wash load.

1.6.21 Wash* or wash programme

A sequence of actions carried out by an automatic washing machine is called a wash or a wash programme. It usually includes water intake, one or more wash cycle(s), rinse cycle(s) and spin cycle(s), of which the time, action and water consumption are automatically controlled according to the programme selected.

*when used as a noun

1.6.22 Wash temperature

The wash temperature refers to the highest temperature that the water in the washing machine will reach during the wash cycle.

1.7 Research report sequence

Chapter 1 provides an introduction to the research problem, motivation for the study and relevance of the problem. In the second chapter, a review of the factors that may influence the effect of the mechanical wash action on fabric deterioration and soil removal efficiency are included. This chapter is concluded with a description of methods used for assessing tensile strength, print deterioration, degree of fraying, and soil removal efficiency. Chapter 3 describes the research methodology used for the empirical part of the study. This is discussed in terms of choice of washing machines, test fabrics and test procedures, measurements taken and data analyses. The results of the study are discussed in Chapter 4.

In the final chapter, conclusions are drawn, based on the literature review and results of the empirical part of the study. Possible limitations of the study are indicated and broad guidelines for further investigations are given.

CHAPTER 2

EFFECT OF MECHANICAL WASH ACTION ON TEXTILE FABRIC DETERIORATION AND SOIL REMOVAL EFFICIENCY

2.1 Introduction

A literature study was conducted to provide insight into the mechanical actions by which washing machines remove soil from soiled textile fabrics. This would serve as reference to help find possible explanations for the results obtained in the empirical study described in Chapter 3. It was also used as point of departure in planning the investigation.

This chapter provides a review of literature related to laundering of textile fabrics in domestic automatic washing machines. It starts with a classification of washing machines and a discussion on mechanical wash actions. This is followed by an overview of the process of soil removal and the factors that influence soil removal, as well as methods of assessing soil removal efficiency. Research on the effect of laundering on textile deterioration and the factors that influence it, is also discussed, with special reference to the deterioration of cotton fibres during laundering. The chapter is concluded with a description of the methods followed to assess fabric deterioration, especially after repeated laundering.

2.2 Washing machines

2.2.1 Classification of washing machines

Hand washing of textile fabrics is the process by which soil may be manually removed from products such as clothes through the use of water, detergent and agitation. A care label with the instruction "hand wash only" usually implies a gentle squeezing action. In South Africa, a fairly large portion of the population still uses hand washing as the only method of cleaning clothes.

A washing machine is a machine designed for the purpose of removing soil from textile products through the use of water, detergent and agitation. The term *domestic* washing machines refers to washing machines intended for use in a domestic environment, whereas *commercial or industrial* washing machines are manufactured with the purpose of washing larger wash loads, at higher temperatures and/or with special additives (Kadolph & Langford, 1998, Lloyd & Adams, 1989).

Domestic washing machines were first marketed about a century ago and are now used for the bulk of home laundry in most developed countries. In these countries, hand washing is reserved for delicate items or articles with deep shades which might otherwise introduce dye-staining problems (Lloyd & Adams, 1989). In South Africa (generally still regarded as a Third World country) automatic washing machines are used in about 20% of households, but this figure has been increasing since 1990 (SAARF, 1998).

Washing machine manufacturers, in collaboration with detergent manufacturers, have made considerable effort to improve the economic and functional performance of washing machines, taking into account the different properties of textile fibres as well as consumer preferences. Examples of these are wash cycles specifically designed for woollens, easy care fabrics, etc. (Lloyd & Adams, 1989). Today's washing machine manufacturers must meet the challenge of merging safety, ease-of-use and environmental concerns to satisfy consumers. This resulted in the development of higher efficiency in machines – especially with regard to energy and water consumption (Rasdal, 1995). Other new developments include pre-set programmes, for which the user selects the programme (e.g. "*40^oC cottons* ") and the machine controls the whole sequence of functions, and "fuzzy logic", a function in which the machine can sense the size of a wash load and adjust the wash cycle accordingly (Anon., 1999). Weiser (1996) advises prospective buyers of washing machines to consider aspects like the finish of the machine, outside and inside, flexibility in water level controls, choice of water temperatures, energy usage and service requirements as important when deciding on which machine to buy.

Domestic washing machines can be subdivided into semi-automatic machines and fully automatic machines. The semi-automatic group is generally referred to as *twin-tubs* and requires the operator to add water and detergent and drain the water after the wash cycle, and to control the rinse and spin cycles in a similar way. To operate a fully automatic washing machine, the operator is only required to select a wash programme (and sometimes a wash temperature) and start the machine. It will then proceed through the cycles in the wash programme by itself.

There are numerous ways in which to classify domestic automatic washing machines. Jakobi and Löhr (1987) use a broad classification, dividing automatic machines into two main groups. The first group includes the horizontal drum type machines in which the laundry is usually loaded from the front, but they can also have a door at the top of the drum. Despite the latter, this group is often referred to as "front loaders". The water is heated by internal heating means in these machines and the mechanical action is brought about by the rotation of the drum. The second group, generally known as top loaders, can be described as vertical drum type machines. In these, the washing is loaded from the top into a drum with a vertical axis. The mechanical wash action can be provided either by a rotating agitator in the centre of the drum, or an impeller at the bottom or side of the drum. The machine must be connected to an external source of hot water if heated wash solution is required.

A more accurate classification would thus allow for three categories[1]:

- horizontal drum machines or front loaders (*H*)

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[1] For the rest of this document the abbreviations *H*, *V(A)* and *V(I)* will refer to the three categories of washing machines.

- vertical drum agitator type machines or agitator type top loaders (*V(A)*)
- vertical drum impeller type machines or impeller type top loaders (*V(I)*)

Lloyd and Adams (1989) classified the machines according to the countries where they were most popular at the time:

Japan:	impeller-type top loaders
Western Europe:	horizontal drum-type front loaders
North America:	agitator-type top loaders

It is interesting to note that more recent literature shows a shift in this traditional classification. Horizontal drum machines, often referred to as "high-efficiency washers" are being reintroduced to the American market (Kenner & Greer, 1998:28). The machines are very popular due to the low water and energy consumption (approximately 40% less water per wash than top loaders). The tumbling action of the machines is reported to be gentle to clothing, causing less pilling and colour loss and allowing clothes to look new longer and have a longer wear life. The machines also have more rinse cycles than the top loaders, leading to better removal of detergent residues, as well as reducing greying and the development of slight odours in the clothes (Kenner & Greer, 1998, Rasdal, 1995).

In South Africa both the vertical drum (top loader) and horizontal drum (front loader) machines are popular. When compared, the 1998 AMPS data (SAARF 1998) show greater growth in the number of households using vertical drum machines than those using horizontal drum machines (Refer Figure 2.1). The reason could be found in the fact that the top loaders sold in South Africa are usually designed for larger wash loads than the horizontal drum machines. In a recently completed study on consumer preferences in South Africa, respondents listed capacity as one of the main reasons for buying top loaders (Lever Pond's, 1999).

FIGURE 2.1: WASHING MACHINE USE IN SOUTH AFRICA.
Source: AMPS data (SAARF, 1998)

2.2.2 Mechanical wash action

Traditionally the term horizontal drum washing machine (front loader) implies a washing machine in which the laundry is placed in a horizontal, perforated drum, which rotates on its axis in alternative directions. Usually only the lower third of the drum is filled with wash solution, which means that, in contrast with vertical drum machines, all the laundry is never fully submerged. The wash solution is heated internally by electrical heating coils. As the drum turns, laundry items in the wash load are repeatedly lifted by paddles or fins located on the sides of the drum and then dropped back into the wash solution for renewed soaking, rubbing and compacting. The mechanical wash action thus consists of the washing being lifted as the drum turns and then a free fall to the bottom when it reaches the top of the drum (Jakobi & Löhr, 1987, Lord, 1971). For a constant wash load, the free fall distance is directly dependent on the drum size, as well as the level of water in the drum. According to Penney (1999) the wash action is more effective if the free-fall distance is longer (Jakobi & Löhr, 1987, Lord, 1971). Modern washing machines have two drums. The washing is placed into a perforated stainless steel drum, which is surrounded by a larger second drum. The second drum is not positioned evenly around the first, providing a wider gap between the two at the bottom. This is where the heating coils are positioned for heating the water without direct contact with the wash load (Penney, 1999, Lloyd & Adams, 1989).

When comparing machines, especially when it comes to spin cycles, it is important to note that the speed of drum rotation, as well as drum size, must be taken into account. A larger drum can rotate at a slower speed and achieve the same centrifugal force as a smaller drum (Penney, 1999).

The domestic vertical drum washing machines (top loaders) available in South Africa differ with regard to their mechanical wash actions. One type creates a wash action by means of an agitator and the other works with an impeller. Both types have a metal laundry tub described as "vertical" because it has a vertical axis and opens at the top. The tub is usually enamelled or made of stainless steel, with an open perforated basket, into which the washing is loaded, inside it. The laundry tub is filled with enough water to cover the wash load and allow laundry articles to move around freely in the wash solution. The volume is thus dependent on the amount of washing being laundered. Machines of this type normally have two water connections, one for hot water and one for cold water. The desired wash temperature is selected by proper setting of the controls, and the selected temperature is achieved by automatic mixing of water from the two input sources. After the water has been introduced, the agitator or impeller begins to function and the laundry is swirled, agitated or pushed around in the wash liquid for the correct wash time (depending on the programme selected). When the wash cycle is complete, the used wash solution is drained off. The machine then begins a series of spray rinses and spins, whereby fresh cold water is sprayed on to the load to remove detergent and pumped or drained off, followed by a spin. Water is sometimes allowed to fill the tub again for a second brief rinse, followed by a final spin (Jakobi & Löhr, 1987). In the United States, these machines usually have a capacity of 2-3 kg (Jakobi & Löhr, 1987:205), although larger machines and machines that can operate with larger or smaller wash loads are now readily available (Rasdal, 1995). In South Africa manufacturers claim capacities varying from 5,5kg to 8,5 kg or more[2].

In the agitator type machines, the agitator in the centre of the drum or tub either performs a rhythmic motion with the agitator "arms" turning backwards and forwards, or it can turn continuously in one direction for the duration of the wash cycle. The washing is physically moved around by the action of the agitator, while the drum, in most cases, remains stationary during the wash cycle. Impeller-type washing machines were originally introduced by the Japanese. These machines have a rotating ribbed disk mounted, either in the base of the tub or on its side, as source of mechanical action. Washing is thus swirled around in the drum by the accelerated movement of the water (Jakobi & Löhr, 1987). In the newest automatic types that are appearing on the South African market, the impeller is usually situated at the bottom of the drum and the mechanical action is sometimes enhanced by rotation of the drum.

Both of the above two top loading types (*V(A)* and *V(I)*) have much larger capacities than the front loaders (*H*) - usually in excess of 8,5 kg. Impeller type machines with a capacity of 5 or 6 kg are also found, but the larger ones seem to be more popular[3].

From the above it is clear that washing machines can be classified into three main categories according to the mechanical wash actions that they employ to remove soil from soiled textile fabrics, namely horizontal drum machines, vertical drum agitator type machines and vertical drum impeller type machines. When the descriptions of these wash actions are taken into account, it is obvious that the wash actions differ in severity. Whenever individual washing machines are discussed, its classification should be kept in mind to explain the severity of its wash action. Whether the effect of the difference in severity of the wash actions

[2] Information obtained from leading retailers in the Western Cape.
[3] Information obtained from leading retailers in the Western Cape.

on textile fabrics being laundered is significant, and whether there are differences among individual machines, as well as among categories, at this stage remains to be investigated.

2.3 Soil removal

The main purpose of a washing machine remains the removal of soil from soiled textile fabrics. As explained in Chapter 1, the mechanical wash action is not the only factor that influences soil removal efficiency. To understand the full effect of this complicated process better, a review of literature on the soil removal process and factors influencing soil removal is presented in the following paragraphs.

2.3.1 Soil removal process

The soil removal process generally consists of three major stages, namely

- breakdown of soil aggregates and a reduction of soil/fibre adhesion,
- detachment of loosened soil from the points of contact and
- transport of the detached soil into the general wash solution and maintaining it there until it can be rinsed away.

Water and mechanical action alone (the most primitive cleaning process) will remove some soil, but the cleaning effect will not be very efficient and will be confined mainly to loose surface soils. The process can only be effectively accomplished through a combination of chemical and mechanical processes.

The most common combination of ingredients found in laundry products, such as detergents or soaps, is surface active agents, also referred to as "surfactants", water softeners, alkaline buffers, and polymeric soil suspension aids. During the soil removal process, the wet fabric is agitated through the motion of the washing machine or by hand scrubbing. The soil is broken into smaller particles and surrounded (emulsified) by the detergent and then lifted off the fabric by the action of the detergent. The detergent surrounding the soil particles prevents it being redeposited on to the fabric as the washing progresses. In all this, the mechanical action employed by the washer plays an important role. When fabrics are rinsed, the suspended soil and detergent are washed away (Tortora, 1978).

Matching the correct combination of detergent ingredients with the right mechanical cleaning action, wash temperature and wash length is important for ensuring maximum effectiveness (Lloyd & Adams, 1989). If one aspect of soil removal is decreased, another or others have to be increased for the cleaning process to be as effective (Kadolph & Langford, 1998). Jakobi and Löhr (1987) identified textile fabrics, soil, detergent, water and wash action as the six major factors that affect the wash process. These factors will be discussed in that order.

2.3.2 Factors that affect soil removal

2.3.2.1 *Textile fabrics*

A textile fabric being washed can affect the efficacy of soil removal in several ways. Fabrics are extremely variable with regard to fibre composition, finish and construction and different fabric properties can affect the efficiency of the wash process differently.

The chemical composition of a fibre determines which chemical groups are present in the fibre. Cotton, for example, contains many hydroxyl groups, which improves its affinity for water molecules. This improves its ability to absorb water, which in turn has an influence on the fibre's ability to absorb soil in a water medium. At the same time it influences its cleaning ability, as it can easily absorb water, which acts as a medium to bring the detergent into contact with the soil (Gohl & Vilensky, 1983, Kadolph & Langford, 1998).

The crystallinity of the chemical structure of a fibre determines how effectively a small molecule (like that of water) can penetrate the fibre's structure. A highly crystalline structure, such as found in synthetic fibres, not only allows little opportunity for penetration by soil in a water medium, but also prevents water as a cleaning medium from assisting the soil removal process (Gohl & Vilensky, 1983). Highly oriented (crystalline) fibres include polyester, nylon and aramid and are also referred to as hydrophobic. Textile fibres with amorphous regions in their molecular structure, such as cotton and viscose rayon, allow water to move freely within the structure, and enhance the soil removal process by allowing dissolved soil to be rinsed out. These fibres are referred to as hydrophylic (Kadolph & Langford, 1998). Hydrophobic fibres also absorb oily soils readily, but at the same time make it difficult for water and detergent to penetrate the fibre's structure to remove these soils (Kadolph & Langford, 1998, Gohl & Vilensky, 1983).

Soil removal is dependent on a fabric's capacity to retain moisture. The higher its moisture regain capacity, the lower a fibre's soil retention. Both polyester and acrylic fibres have a moisture regain capacity of below 2% (Kadolph & Langford, 1998:110,120). Both show a high tendency to retain soil. Cotton has a moisture regain capacity of 7-11% (Kadolph & Langford, 1998:39) and is effectively cleaned in water. Viscose fibres can have a moisture regain of up to 12,5%, but although soil can be effectively removed from these fibres in an aqueous medium, the fabrics lose up to 50% of their strength in water and must therefore be handled with care when washed. The loss in strength is due to the amorphous regions within the fibre, causing the molecular chains to separate as the fibre swells, breaking the hydrogen bonds and distorting the chains (Kadolph & Langford, 1998:85).

Textile fibres that tend to build up static electricity carry a charge on the surface, which attracts soil and lint and causes dark colours especially to become unsightly. Fabrics that fall into this category are mainly those with low moisture regain capacity and silk.

The microstructure of the fibres in a fabric also plays a role in soiling and soil removal. A fibre with an uneven cross-section and irregular surface contour provides uneven areas where soil can adhere. Surface contours can be smooth, serrated, striated or rough, and have a direct effect on the texture and soiling of a fabric. Cotton is an example of a fibre with an irregular bean-shaped cross-section, a flat, ribbon like structure with convolutions along its length, making it prone to soiling. The convolutions can be a disadvantage, as dirt sand and soil collect in the twists, which then require rigorous washing to be removed. Synthetic fibres with a smooth cross-section collect less soil, but in nylon the smooth round cross-section tends to magnify soil and cause the fabrics to appear soiled (Kadolph & Langford, 1998, Smith & Block, 1982).

Soiling and soil removal are also affected by yarn construction. Factors like distance between fibres and protruding ends play a role in the ease with which soil collects on the yarn surface. Loosely twisted, bulky yarns, as well as textured yarns, are easily penetrated by soil or staining agents. Such systems are more open, with a coarser surface than untextured or tighter yarns. Tightly twisted or plied yarns will more readily shed soil (Smith & Block, 1982). The same applies to textile fabrics. A compact surface of a twill fabric will, for example, be more soil resistant than weave constructions with a more textured surface, but its soil removal propensity will be equivalent to a plain weave (Kadolph & Langford, 1998). In knitted fabrics, a smoother surface, such as found in tricot knits, reduces soiling. Because of the movability of the interlooped yarns in a knit structure, soil removal is relatively easy. In weft knit fabrics, as in loosely woven fabrics or fabrics with a low yarn count, care must be taken during laundering to prevent yarn distortion (Smith & Block, 1982).

Textile finishes also affect soilability and soil removal. Some are specifically designed to reduce the degree of soiling of a fabric by repelling the soil or preventing formation of a bond between the soil and the fabric. These fabrics would thus be easier to clean. Fluoro-chemicals are common, durable and effective soil release finishes. They improve a fabric's performance in resisting soil, releasing soil and retaining whiteness by resisting redeposition of soil in the wash water (Kadolph & Langford, 1998).

Fibre blending could influence soil removal. A blend is a mixture of two or more fibre types, for example cotton and polyester, in one fabric or yarn (Smith & Block, 1982). Fabrics that are mixtures of, for example, bulk-filament yarns and spun yarns are also produced. A fabric could have spun yarns in the warp and textured filament yarns in the weft, or bands of different yarn types in one direction to create a design in a fabric (Kadolph & Langford, 1998). These yarns have different soiling properties, and thereby complicate the cleaning process.

It is clear that textile fabrics as a factor in the wash process plays a complex and sometimes unpredictable role in soil removal. One element that may seem unimportant, may have a profound effect on soiling or soil release. A seemingly simple wash load can be made up of a complex mixture of fibres, textures, constructions and finishes (Steyn, 1994).

2.3.2.2 *Soil type*

There are many ways in which textiles become soiled in the home, some being unavoidable consequences of normal usage. The human body itself is a major source of soiling on clothing, towels and other textile fabrics that come into contact with it. Emulsions of blood, bodily excretions and saliva, together with dead skin cells and the output of sebaceous glands, contribute proteins, lipids, inorganic electrolytes and simple compounds such as urea to this soiling. Other causes are accidental and arise from contact with foods, drinks, cosmetics, mud and a host of other materials encountered in daily life, including the deposition of airborne particulate matter such as dust and smoke (Ford, 1991, Lloyd & Adams, 1989). The different soiling and ageing processes lead to the classification of different categories of textile soiling. Connor (1981) classified soils into three main categories:

- soluble soil
- insoluble oily/fatty soil
- insoluble particulate soil

Lloyd and Adams (1989) suggested the following classifications:

- simple coatings
- mechanically entrapped particles
- semi-liquid coatings
- colloidal deposits
- molecular adsorption

From the first to the last, the categories of soiling are progressively more difficult to remove. The objective of laundering is not only to remove this complex mixture of materials, but also to recover fabric handle, texture and comfort so that the article is clean and fit for use again (Ford, 1991, Lloyd & Adams,1989).

2.3.2.3 *Detergents*

Many new types of laundry products have been developed in response to consumer trends towards using lower wash temperatures, changes in consumer life styles and concern over the impact of detergent ingredients, particularly phosphate, on the environment (Lloyd & Adams, 1989). Washing powders remain the dominant product, but consumers at present have a choice between powders developed for specific purposes, specific washing machine types and concentrated powders. Detergents are also available in liquid form, and even in sachets (Lloyd & Adams, 1989, Swaine, 1993) or preformed pellets (Plumbley, 1999).

A detergent is a cleansing agent. The three main properties that a detergent should have are wetting power, dirt removing power, and an emulsifying and soil suspending power. Chemically, detergent molecules consist of a hydrophobic (water-repellent) part and a hydrophilic (water attraction) part (Gohl & Vilensky, 1983). The addition of detergent to water lowers the surface tension so that water can penetrate the fabric that has to be cleaned more effectively. This occurs because the soil, forming a thin layer (film) over the fabric surface, attracts the hydrophobic parts of the detergent molecules. The water molecules in turn are attracted by the hydrophilic parts of the detergent molecules, so enabling them to penetrate the fabric. Because of this action, all detergents are called surface-active agents. They act to remove soil by decreasing interfacial tension and allowing the water to penetrate in between the dirt and the fabric, causing the dirt to float away. Agitation will assist this process (Gohl & Vilensky, 1983).

Kadolph and Langford (1998) describes this process from a different perspective: A soap or detergent molecule consists of an organic "tail" that has an affinity for organic soils and a polar "head" that has an affinity for the solvent. Thus the two parts literally dislodge the soil from the fabric. Agitation breaks the soil into very tiny globules that are held in suspension until they are rinsed away (Figure 2.2).

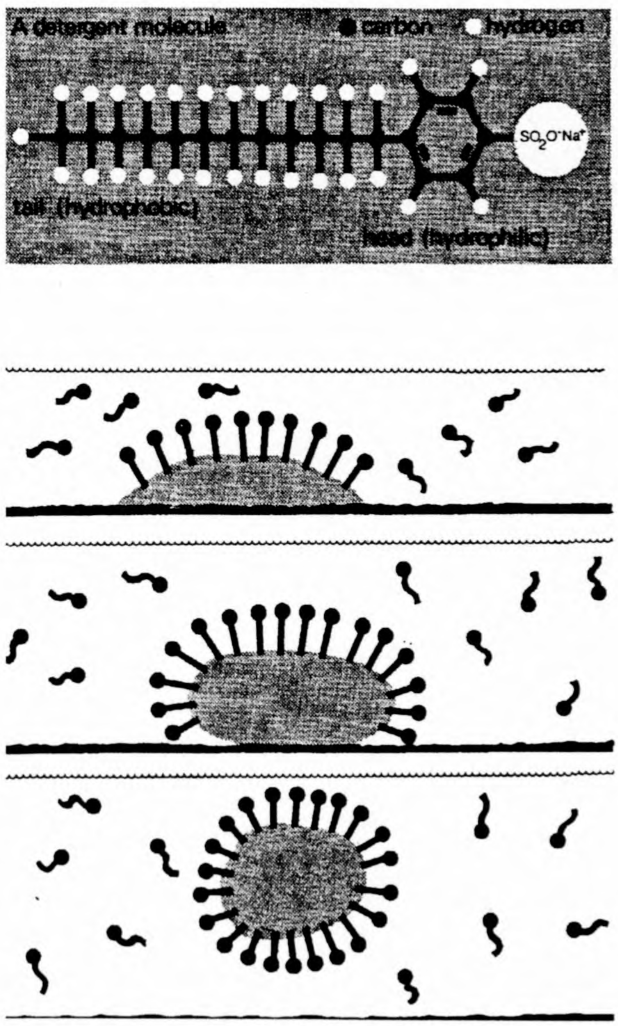

FIGURE 2.2: MECHANISM OF SOIL REMOVAL: DETERGENT SURROUNDS AND LIFTS SOIL OFF THE FABRIC (Gostelow & Dean, 1971:8)

A detergent or washing powder is a mixture of many components and no two brands of detergents or washing powders are exactly the same. Some of the major components and their functions are briefly described below.

A *surfactant* is the key ingredient of any washing powder. Surfactant is short for surface-active agent and its main function is to improve the wetting ability of water. It loosens and removes dirt, emulsifies and helps suspend soil in the water and prevents redeposition. A detergent may contain more than one kind of surfactant and different types use different surfactants. Surfactants can be classified according to their ionic character in water: anionic, nonionic or cationic (Freemantle, 1996b).

A *builder* in a detergent is the second major component, which enhances or "builds" the effect of the surfactant by deactivating calcium and magnesium ions, which would otherwise use up surfactant molecules. Builders therefore are water-softeners and they work by complexation (sequestration), precipitation or ion exchange. An example of a builder is sodium tripolyphosphate (TPP). It works by complexing the unwanted ions, but its use has been curtailed because of the contribution of waste phosphates to eutrophication. In countries or states where the use of phosphates in detergents has been banned, manufacturers have to revert to alternative builders. Sodium carbonate softens water by precipitating calcium or magnesium carbonate. The most common builders used today are synthetic zeolites, which are solid ion exchangers that trap the divalent ions inside the solid particles. Most of the builders also provide alkaline solutions which enhance cleaning, as most detergents work most effectively around pH 10-11. Sodium carbonate can also be added to raise the pH.

Fillers and *processing aids* are added to detergents to alter the physical properties of the detergent liquid. Sodium sulphate is added to make the materials flow freely. Alcohols in liquid detergents keep everything in solution and alter the freezing point. Borax aids water absorption and produce free-flowing powders (Freemantle, 1996b).

Bleaches commonly used are compounds of hydrogen peroxide (e.g. sodium perborate or sodium percarbonate), but these only function optimally at temperatures above 60°C. Other compounds are added to lower the temperature at which the bleach works. TAED (tetra-acetylethylene-diamine) is such an additive, which acts as a catalyst, that enables washing to be performed at 40°C. A manganese catalyst which reduces the bleaching temperature, even to room temperature, has been developed (Freemantle, 1996a, Freemantle, 1996b).

There are a number of minor components in detergents, which, although small in bulk, are important for the functioning of the detergent. *Fluorescers* or optical brighteners are organic molecules that adsorb on fabrics like dyes. They absorb UV light and re-emit white light, thus brightening the fabric. *Enzymes* are added to biological detergents as catalysts to help break down biological stains like blood and grass. *Fabric softeners* impart softness by controlling static electricity. *Corrosion inhibitors* like sodium silicate reduce corrosion inside the washing machines. *Antifoaming agents* are added to control the amount of foam produced during the wash. *Colourants and fragrances* may be added as desired (Freemantle, 1996b, Gostelow & Dean, 1971, Kadolph & Langford, 1998).

From the above, it is clear that a detergent is a mixture of substances and not a pure compound. A detergent powder is made by combining the ingredients, often in the form of a slurry, which is spray-dried to yield free flowing granules. No two brands are the same, and the same brand name in different countries may have different compositions (Freemantle, 1996b, Lloyd & Adams, 1989). Continuous research and developmental work done on the subject also allows for continuous variation in the products available to consumers (Plumbley, 1999).

2.3.2.4 *Water*

Water can be classified as a cleansing agent, but not a very efficient one. One of the main reasons for this is the high surface tension of water, which renders it a poor wetting agent. It's ability to remove dirt and grease (soil) is greatly improved when used in conjunction with a soap or soapless detergent (Gostelow & Dean, 1971). The mixture of water and detergent is referred to as detergent solution (Ford, 1991). The main inorganic variables in wash water are calcium and magnesium ions, which determine the hardness of the water (Carty, 1983).

Water volume is important in the wash process. Washing is most effective when there is a free flow of detergent solution through the textile material. When such materials are washed, it is necessary that they move relatively to each other and the detergent solution. Washing methods are only satisfactory if they ensure that liquor passes through and not only over the surface of the textile materials. A fabric contains innumerable interstices and the liquor in a washing machine will partly be deflected to pass over the fabric surface and will partly pass through the interstices - much will depend on the force of the moving liquor and also on the compact nature of the fabric (Hall, 1978). The wetted fabric is then agitated by the motion of the washing machine, the soil is broken into smaller particles and surrounded (emulsified) by the detergent, then lifted off the fabric by the action of the detergent and agitation. When fabrics are rinsed, the rinse water carries away the emulsified and suspended soil and remaining detergent (Tortora, 1978).

Water volume is important in order to allow for agitation, to remove soil and keep soil suspended, and to avoid excessive wrinkling of items in the wash load (Kadolph & Langford, 1998). This is of particular importance in the case of agitator and impeller type washing machines, where the items being washed are immersed and swirled around in water. In the case of horizontal drum type washing machines, the mechanical wash action consists of the washing being lifted out of the water by the paddles or fins, when the drum rotates, and free-falling to the bottom when it reaches the top of the drum. In this case the wash action is more effective if the free-fall distance is larger, with the latter depending directly on the volume of water in the drum and the drum size. A smaller volume of water in the drum or a bigger drum will thus directly affect the free fall distance and influence the effectiveness of soil removal. In these machines the volume of the rinse water plays an important role, as suspended and emulsified soil must be removed during the rinses (Penney, 1999).

Electrostatic forces hold onto soils such as lint and dust. If the electrostatic force is neutralised, the soil can be removed. Because water is an excellent conductor of electricity, immersing the fabric in water, as is done in laundering, neutralises any static charge on the surface of the fabric. Water-soluble soils such as coffee, sodas and sugar are absorbed by hydrophilic fibres. When the fabric is immersed in water, the water dissolves these soils, allowing them to be rinsed out. Organic soils such as grease, oil and gravy can be absorbed by oleophilic fibres. They require the assistance or chemical action of a detergent or solvent other than water to be removed (Kadolph & Langford, 1998).

2.3.2.5 *Water temperature during washing*

The temperature of the wash solution is important in determining the effectiveness of the cleaning additives used. Some additives are more effective at certain temperatures. Water temperature is also important for effectively removing some soils, e.g. stains of oleophilic nature. As temperature decreases, cleaning power decreases. If water temperature during the wash cycle is thus decreased, either more agitation or more detergent will be required for the cleaning process to be effective (Kadolph & Langford, 1998).

Carty (1983:184) investigated whether washing at 40°C could produce the same results as washing at 50°C. He found that the same performance could only be achieved at 40°C when washing is combined with a pre-soak period in the detergent liquid. Enzymes in detergent also function best under these conditions. Although perborate bleach functions best at temperatures in excess of 50°C, the rate of oxygen release at 40°C is sufficient under the above conditions. He mentioned, though, that perborate bleach activators were being developed (Carty, 1983). These bleach activators were made commercially available in 1994 (Freemantle, 1996a:58).

Sodium perborate, the main fabric-safe bleach found in washing powders, functions effectively at temperatures from 50-60°C (Lloyd & Adams, 1989:77). Consumer trends, however, dictate that clothes be washed at lower temperatures, such as 40° (Lever Bros, 1995, Lever Pond's, 1999). In 1992, 95% of the wash loads in the United Kingdom were washed at 60°C and below (Swaine, 1993:4). Another trend is for consumers to wash clothes at a lower temperature to freshen them up, rather than use hot water to remove stains (Anon., 1998).

As mentioned, Unilever announced a new product to improve bleaching at lower temperatures in 1994. It was called Persil Power TM and had a new accelerator containing manganese as main ingredient. This would act as a catalyst to activate bleaches at 40°C (Freemantle, 1996a:56). Products with this ingredient have also become available in South Africa (Plumbley, 1999). Enzymes in detergents remain active only up to about 60°C. In hotter water, they become ineffective (Gostelow & Dean, 1971:12).

2.3.2.6 *Mechanical wash action*

The role of mechanical action in laundering cannot be disregarded. Jakobi and Löhr (1987) state that the physico-chemical principles discussed above are augmented by taking advantage of hydrodynamic effects. Soil is trapped in the interstices between the fibres and yarns and is held on by mechanical and electrostatic forces. Some of these soils, such as gums, mud or waxes, are held on mechanically and can be removed by scraping or agitation. An increase in mechanical force has a significant soil-removing effect on larger particles. For this reason, some washing machines employ abrupt changes in direction of mechanical movement to achieve adequate turbulence near substrate surfaces.

Different washing machines employ varying mechanical actions to achieve this turbulence and movement of the washing in the wash solution. It must be kept in mind, though, that excessive agitation can abrade fabrics and cause deterioration (Hatch, 1993, Kadolph & Langford, 1998).

2.3.3 Assessment of soil removal efficiency

In expressing the colour of an object verbally, one person's response will most probably vary from that of another, as each observer interprets colour according to personal references and defines it individually. The same is true for the comparison of colours. The solution is a measuring instrument that explicitly identifies colour and assigns a numeric value to it to differentiate it from others. Today the most commonly used instruments for measuring colour are spectrophotometers, colorimeters and densitometers. All three types of instruments measure reflected or transmitted light. A spectrophotometer measures light at many points on the visual spectrum, which results in a curve. A colorimeter (tristimulus), on the other hand, measures light much like the human eye, using red, green and blue receptors. A densitometer is similar to a colorimeter except that its responses are designed from measuring specific materials such as printing inks and photographic dyes (X-Rite, 1996, Datacolor, 2000).

Each colour has its own distinct appearance, based on three elements: hue, value and chroma. Hue has to do with how we perceive colour: "Red", "green", "blue", etc. These colours can be depicted on a colour wheel. Value describes a colour's luminous intensity – that is, its degree of "lightness". The third characteristic, chroma, describes a colour's vividness or dullness, indicating how close it is to either grey or the pure hue.

In 1905, artist Albert H. Munsell originated a colour ordering system, or colour scale, which is still in use today. The Munsell system assigns numerical values to the three properties of colour: hue, value and chroma, on the basis of a "colour tree" or scale. Today, colour systems rely on instrumentation, utilising mathematics rather than physical samples like the Munsell scale. In 1931 the *Commission Internationale de l'Eclairage* (translated as the International Commision of Illumination), or CIE, standardised colour order systems by specifying the light source (or illuminants), the observer and the methodology through which to derive values for describing colour. In short, it represents specific numerical values for the responses of the average person to different wavelengths of light. It provides a means for converting any spectral colour curve into three numbers, known as tristimulus values XYZ, that can identify any colour. To overcome the limitations of chromatical diagrams, the CIE recommended two, alternative, uniform colour scales: CIE 1976 (L*a*b*) or CIELAB and CIE 1976 (L*u*v*) or CIELUV (Datacolor, 2000, Minolta, 1998, X-Rite, 1996).

The L*a*b* colour space is one of the most popular colour spaces for measuring object colour at present and is widely used in all fields. When a colour is expressed in CIELAB, L* defines lightness, a* denotes the red/green value and b* the yellow/blue value. Figure 2.3 shows the colour plotting diagrams for L*a*b*. The a* axis runs from left to right. A colour measurement movement in the –a direction depicts a shift towards green and a +a movement depicts a shift towards red. Along the b* axis, -b movement represents a shift towards blue and +b a shift towards yellow. the centre L* axis shows L = 100 (white or total reflection) at the top and L=0 (black or total absorption) at the bottom. The measure of a colour's lightness (L*), is correctly reported without further manipulation, but a* and b* are merely coordinates that indirectly reflect hue and chroma, but are difficult to interpret separately and require some computation to yield explicit values for hue and chroma (Datacolor, 2000, Minolta, 1998, X-Rite, 1996, McGuire, 1992, Angliss, 1991). In the L*a*b* colour space, differences can be expressed numerically by calculating ΔE* (pronounced as delta-E). ΔE* indicates the size of a colour difference, but not the way in which the colours are different. It is calculated as a single numerical value with the following formula (Minolta, 1998:22, X-Rite, 1996:13):

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

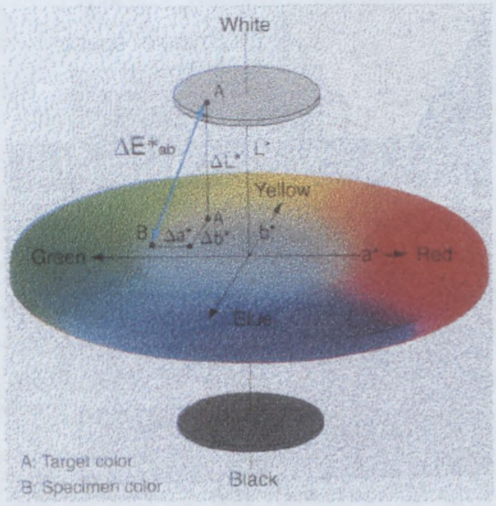

FIGURE 2.3: L*a*b* COLOUR SPACE AND COLOUR DIFFERENCE (ΔE*) (Minolta, 1998:22)

2.4 Effect of soil removal processes on textile durability

2.4.1 Textile durability

Durability of a textile article can be influenced to a substantial degree by how the item is used, cleaned and stored. Hence, durability is difficult to define in absolute terms. Measures of strength and structural integrity are often used to assess durability, but other factors may be equally important in determining the lifespan of a textile article. An attribute that may be deemed of little importance in influencing initial consumer satisfaction may be of great importance in producing dissatisfaction (Kadolph 1998).

Aspects of textile care and durability go hand in hand. Care describes how a product responds to the procedures recommended for returning a soiled item to its clean and as near-to-new as possible condition. The effect of cleaning on a product can be evaluated from many perspectives. Changes in product dimensions or colour, pilling, snagging, fabric distortion, as well as yarn slippage can occur during care as a result of the abrasion that fabrics are subjected to during agitation (Kadolph, 1998). Most wash solutions are alkaline and cause some fibre types, like cotton, to swell significantly. The swollen fibres can be easily distorted and damaged by mechanical action. Problems such as shrinking, felting, creasing, and stretching arise when wet fabrics are subjected to excessive mechanical action or temperatures. Cotton fibres, in particular, suffer from fibrillation. This increases inter fibre hydrogen bonding, which in turn can lead to an unacceptably harsh feel and a considerable loss in fabric bulk during drying (Lloyd & Adams,1989).

Appearance retention describes the degree to which a textile product retains its original appearance during, for instance, cleaning and care. Performance characteristics include resistance to colour change regardless of any degradation factors to which the product may be exposed (Kadolph, 1998). It thus is important when washing or care conditions are evaluated that aspects like the above be addressed.

Durability testing evaluates how the various materials in a product perform when subjected to conditions that are assumed to measure their durability. These measurements are an indication of how a fabric withstands the various forces applied to it. Results, for instance, will often reflect the amount of force the fabric withstands at failure. The practice of testing fabrics until they fail is used in two areas of testing, i.e. in durability and safety. Acceptable or unacceptable performances are described as pass/fail results and fabrics are usually measured against minimum performance specifications. These measurements, however, are also valuable for comparing fabric behaviour (Kadolph, 1998).

2.4.2 Durability of cotton fibres and fabrics

The cotton fibre is a single plant cell, consisting of a lumen, well developed primary and secondary walls and a distinct cuticle on the outside. The cuticle is the waxy outer layer or "skin" of the cotton fibre, and only a few molecules thick. Its waxy nature enables it to adhere tenaciously to the primary wall of the fibre. The inert nature of the cotton wax could protect the rest of the fibre from chemical and other degrading agents, but scouring and bleaching during cotton finishing removes much of it. Subsequent laundering will remove most of the remaining cuticle. As the area of the cuticle is decreased further, deterioration of the cotton textile fabric increases (Gohl & Vilensky, 1983, Hatch, 1993, Kadolph & Langford, 1998).

The primary cell wall, which is about 200 nm thick, is composed of very fine cellulose structures called fibrils. The fibrils spiral at a 20° to 30° angle to the fibre axis. The spiralling imparts strength to the primary cell wall and hence to the fibre (Gohl & Vilensky, 1983:44, Hatch, 1993:64, Trotman, 1990:31). Boylston and Hebert (1995) studied cotton samples of varying maturity and reported that primary wall cellulose was two and a third times less crystalline than the secondary wall cellulose and the fibrillar diameter of the primary wall approximately one and a half times that of the secondary cell wall. This confirms their previous results indicating lower molecular weight, crystalline size and extent of crystallinity within the primary wall of the textile fibre. Cotton fibre primary wall morphology is important to consider when doing wash tests because this structural component is the first contact that textile processing or cleaning makes with the fibre. The degree of crystallinity of a fibre, or region within a fibre, influences the amount of bonding among the polymer chains and has direct bearing on its strength, rigidity, elastic recovery, abrasion resistance, etc. In less crystalline regions, the polymers are not packed together as closely and less bonding occurs (Hatch, 1993, Kadolph & Langford, 1998).

The secondary cell wall is made up of layers of cellulose. The layers deposited at night differ from those deposited by day, which results in growth rings and can be seen in the cross-section of the fibre. The bundles of cellulose (fibrils) are arranged spirally and in a reverse direction at some points. These reverse spirals are important in the development of convolutions in the fibre that contribute to elastic recovery and elongation of the fibre. Whenever the fibrils change the direction of their spiral, a weak area occurs in the secondary wall structure. In these weak areas, the fibre alters the direction of twist and it can be 15-30% weaker than the rest of the secondary cell wall (Gohl & Vilensky, 1983:44, Hatch, 1993:64, Kadolph & Langford, 1998:36). Despite these weak spots, cotton fibres launder well and withstand fairly rough handling (Corbman, 1983).

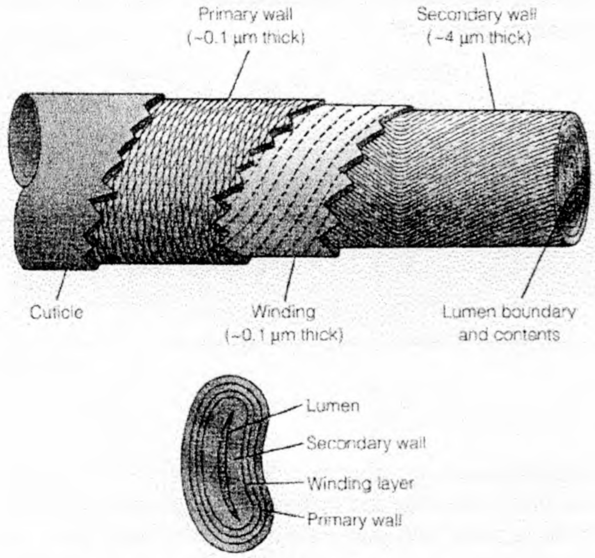

FIGURE 2.4: MORPHOLOGICAL STRUCTURE OF THE COTTON FIBRE (Hatch, 1993:165)

In their natural state, cotton fibres exhibit neither shrinkage nor stretching. Woven or knitted cotton fabrics show signs of dimensional change during the first few launderings because laundering in a water medium releases tensions in the fabric and yarns that are created during weaving, knitting or finishing processes. The relaxation of these tensions may cause changes in the fabric dimensions (Tortora, 1978). Dimensional change refers to any alteration or modification of the dimensions of a material, component or product during finishing, manufacturing or care. It can refer to either an increase or a decrease in dimensions. A positive percentage indicates a dimensional increase and a negative percentage indicates shrinkage.

Dimensional change manifests itself as relaxation shrinkage, progressive shrinkage or a combination of the two (Kadolph & Langford, 1998). The dimensional changes that occur after the first wash due to relaxation of tensions that developed during processing, is called relaxation shrinkage. However, because not all relaxation shrinkage occur during the first wash cycle, it may be necessary to evaluate residual shrinkage, which might occur after subsequent wash cycles (Kadolph & Langford, 1998).

Dimensional stability problems may not be uniform in both lengthwise and crosswise directions or consistent from one part of the material to another. Dimensional stability can also be significantly affected by heat, degree of agitation, type of washing machine and dryer. Poor dimensional stability can lead to problems with product fit and appearance as well changes in fabric density and drape. Textile fabrics may become compact and stiff when they shrink (Kadolph & Langford, 1998).

2.4.3 Deterioration of textile fabrics during laundering

Deterioration is defined as a pervasive change in the textile structure that is inevitable and universal. Whether it will affect the life expectancy of the article or the comfort and/or satisfaction of the consumer, will depend on the type of deterioration that takes place. Deterioration cannot be avoided. It may be accelerated or decelerated, but never halted completely (Slater, 1991).

Elder (1978:1) defines "wear" as the "...ability of a material to withstand a variety of mechanical actions in different chemical and physical environments." Once a textile article is placed into service it must be maintained at an acceptable level. Maintenance can involve laundering, dry-cleaning, bleaching, brushing or other procedures that subject the article to mechanical and chemical action. Laundering, probably the most universal maintenance process to which textiles are subjected, involves a combined mechanical and chemical treatment. Detergents used to change the surface condition so that soil particles can be removed by the flow of water over them, are normally alkaline in nature and contain a combination of chemical compounds which can affect fibres in an adverse manner and lead to a deterioration. The action of the water itself, especially at the elevated temperatures sometimes used in laundering, can also not be ignored.

The mechanical action of laundering is a result of deliberate agitation to ensure thorough mingling of the water and fibres to enhance the process of separation of soil from fabric. During this process, textile fabric comes into contact with the sides of the drum of the washing machine or other container, with the device that is used to bring about the agitation and with other fabrics in the wash. All of these involve abrasive contact, leading to degradation by removal of tiny particles of fibre from the textile (Slater, 1991, Elder, 1978). Degradation may manifest itself in a variety of ways during the useful life of a textile article. The most obvious ones are those that are readily apparent, like visually or potentially destructive changes. Examples of these are loss or change of colour by fading, crocking or running during laundering. Changes in mechanical properties such as loss of tear or tensile strength, abrasion resistance, elasticity, etc., can also lead to a reduced wear life or the article being rejected as unfit for further use (Slater 1991). The abrasion that textiles are subjected to during use and care not only removes tiny fragments from fibres but also tends to pull fibres out of the fabric structure, making them more susceptible to damage.

The basic cause of deterioration lies at the fibre molecular level. In general, only three types of deterioration occur, namely chemical modification of the substituent groups in the structure, removal of side chains or minor bonds and scission of main chain bonds. These changes are brought about by a variety of mechanical and chemical mechanisms (Slater, 1991). Shortening of the fibre chain molecules reduces the coherence between them and hence the strength of the fibre as a whole.

Laundering during use and care results in two types of deterioration, i.e. mechanical stresses, essentially due to abrasion in the wet state, as well as chemical damage due to laundering, especially bleaching (Handu *et al.*, 1967). Several researchers have investigated the effect of laundering on fabric deterioration and their findings are very relevant to this study. A review of some of these studies will be reported below in the form of brief descriptions.

Higginbotham (1976) compared two studies in which the effect of laundering and wear was investigated. In the first (where the detergent contained bleaching agents) chemical and mechanical damage contributed about equally to the deterioration. In the second (where little or no bleaching agent was used) deterioration due to mechanical action was greater. (The above was washed commercially and the wear trials carried out in a school and hoste, respectively) Higginbotham concluded that domestic conditions for washing are much more variable than commercial processes and generalizations should not be made. Chemical damage during use partly results from laundering; no finishing treatment will afford significant protection and certain minimum care finishes can aggravate the problem.

Chemical damage will mainly depend on the composition of the detergent and whether it contains bleach or not. Mechanical damage in domestic laundering will vary considerably according to the type of washing machine used. Lord (1971) confirmed that mechanical and chemical damage occur in laundering as well as in use (with wide fluctuations) and criticized the practice of predicting performance solely on laundering trials because of this.

The major source of deterioration in washable textiles, however, is the washing process rather than service wear. Slightly more than half the damage in a test series was attributed to mechanical damage and about half of this occurred during laundering. Used trouser cuffs made of sheeting fabrics were used to examine mechanical damage to cotton fibres after laundering. The cuffs were laundered in a top loading agitator type machine, with a laundry detergent, until damage occurred. Fibres were examined under the transmission electron microscope. The rate of abrasion in the laundered cuffs was higher than in the unwashed cuffs. The two most conspicuous points of damage in all samples were broken fibre ends and damage along the fibre axis. The type of damage observed in washer-abraded fabric was quite different from that in dryer-abraded fabrics. Fibres from fabric that was treated with cross-linking agents, exhibited more excessive abrasion damage, but even the untreated cotton fibres showed signs of abrasion after 40 wash cycles. Surface fibres appeared stringy and peeled and showed extensive fibrillation. The structure of the fibres was disrupted by the pulling of fibres and bundles of fibrils from their normal position in the fibre. This wet abrasion in the washing machine can be attributed to the swelling of fibres in water and the mechanical action of the machine tearing the fibrils apart. Any rough surface in the interior of the machine may contribute to this wear (Goynes & Rollins, 1971).

Lord (1971) investigated the effect of conditions of laundering and service wear in a study on institutional bed sheets. Laundering has frequently been cited as the major cause of damage to bed linen. The study showed that the conditions of use and of laundering were more important to the life span of a sheet than the type of fabric it was made of. Sheets lost strength more rapidly when they were used and laundered than when they were laundered without use. The loss of strength of the sheets can be attributed to four causes:

- chemical damage in laundering produced by the agents used to promote cleansing;
- mechanical damage in laundering caused by the actions that occur during washing;
- chemical damage in use; and
- mechanical damage in use.

Tensile strength loss was chosen as criterion for comparing degradation in sheets. It was preferred above tearing strength because, unlike the latter, it is not affected by variations in lubrication that may result from finishing treatments. It was not possible to detect any important differences between the changes in strength in the warp and weft directions for any of the fabrics tested. Differences were found in the mean strengths of samples from different areas in the sheets, i.e. the middle and sometimes the tops of the sheets were much weaker than the bottoms. This suggests that the movement of arms and body perhaps contributes more to the wear of sheets than the movement of the feet.

Mohamed (1982a and 1982b) conducted service wear trials to evaluate the performance of white hospital uniforms made of durable press treated 65/35 and 50/50 polyester/cotton blends. Uniforms were worn and laundered with either phosphate or carbonate-built detergent. Although phosphate-built detergents showed significantly higher percentages of soil removal, improved durable press appearance ratings and increased strength retention, laundering was the major contributor to loss of strength. Scanning electron microscope (SEM) investigations indicated severe abrasion and deterioration due to fibrillation of cotton fibres with the use of carbonate-built detergent. Unlaundered samples showed fibres to be smooth and without deposits on the surface. Those laundered 25 times with phosphate-built detergent also had very few deposits, whereas samples laundered with carbonate-built detergent exhibited large amounts of calcium carbonate deposits which appeared to be firmly bound to the fibre surface.

Rollins *et al.* (1970) surveyed the breakdown of individual cotton fibres in durable press cotton fabrics by electron microscope photographs during selected laboratory abrasion and laundering tests. They found fibrillation and the stripping of fibre bundles in sheaths from the cotton fibre, resulting in thinner, weaker fibres. All the fabrics tested suffered greater deterioration in detergent solution laundering than in water alone. In general, a greater amount of deposition was observed on fabrics laundered with phosphate-built detergent in very hard water than with carbonate-built detergent. In untreated cotton, shredding and fibrillation of the fibre surface were commonly found.

Raheel and Lien (1985:102) studied durable press cotton fibres after 50 and 400 laundering cycles under the SEM and confirmed the above. Characteristics were similar at both levels of laundering (50 and 400 times), but were magnified at the 400 times level. This was confirmed by tensile strength tests using the Instron Tensile Strength Tester. It was also found that the degree of water hardness played a significant role in the retention of tensile strength in the experimental fabrics (Raheel, 1983a).

Raheel and Lien (1982) concluded that the general mechanism of laundry abrasion common to all experimental fabrics resulted from a combination of the swollen state of the wet cotton and the mechanical action encountered in the wash cycle. The mechanical action (agitation) in laundering causes stripping of the fibre surface and fibril separation of the abraded specimens in the wet condition. Separation of the fibrils is most likely to occur in swollen fibres when the hydrogen bonds between the cellulose chains are stretched to the limit, and the mechanical stress of agitation in laundering is sufficient to break the stretched hydrogen bonds, resulting in fibrillation. Further agitation may result in fibril separation.

2.4.4 Assessment of textile deterioration

Textile deterioration during laundering manifests itself in a number of ways. For the purpose of this study the focus was on possible changes in fabric tensile strength, print deterioration and degree of fraying during laundering.

Durability of textiles can be compared by measuring tensile strength (Smith & Block, 1982). **Tensile strength** is defined as the maximum resistance of a textile fabric to deformation in a tensile test carried to rupture; that is, the breaking load or force per unit cross-sectional area of the unstrained specimen (Merkel, 1991:, Booth, 1968). Hatch (1993) defines tensile strength as the ability of a textile to resist a longitudinal pulling force without rupturing. Breaking strength is the force required to break a fabric when it is pulled under tension and it can be used as a measure of the effect of different conditions on textiles (Tortora, 1978). Change in tensile behaviour of fibres appears to be the almost universal way to recognize deterioration (Slater, 1991). Any reduction in tensile strength could thus be an indication that a possible change in fabric structure, fibre content or finish had taken place (Taylor, 1990).

Tensile strength is determined by applying a load to a specimen in its axial direction, which develops tension in the specimen. This will cause the fabric to deform or strain and eventually break, at which point the load at break is measured. This load can be expressed in kilograms, pounds or Newton force and is commonly used as an expression of fabric strength (Booth, 1968, Merkel, 1991).

Improper cleaning and storage can result in severe damage to the fabric or an increased rate of wear over a period of time (Tortora, 1978). The ability of a textile article to function satisfactorily to a large extent depends on its ability to retain its strength (Slater 1993). Vaeck (1966) attributes deterioration in strength of cotton due to laundering to two factors, namely chemical degradation and mechanical abrasion.

Chemical damage to textile fibres can be measured successfully through fluidity tests which provide a very sensitive measure of the degree of chemical degradation of cellulose molecules. The cuprammonium fluidity test is a measure of the average molecular chain length of the cellulose in the cotton fibre. It is considered to be an accurate measurement of cotton deterioration, i.e. it is a useful measure of the tendering of cotton that can result from chemical processes such as bleaching or other chemical influences. The fluidity value indicates whether a fabric was chemically damaged during production or not (Mauersberger, 1948). Quite a number of investigations relating fluidity to loss of tensile strength have been reported in the literature (Lord, 1971, Trotman, 1987, Vaeck, 1966). Chemical damage to textile fibres during laundering is usually attributed to exposure to oxidation agents such as bleaches in detergents (Vaeck, 1966).

SEM can be used to evaluate degradation of textile fibres. Surface detail of fibres can be investigated at very high magnification and depth of focus and enables the researcher to identify the modified surface morphology of fibres due to patterns of fibre breakdown or incrustation (Raheel & Lien, 1985, Raheel, 1983b). Slater (1991) recommends the use of the SEM to examine damage to the primary and secondary fibre walls, caused by mechanical stress, bleaching or alkali treatment. De Villiers (1998) found SEM-inspection of fabric samples useful to supplement tensile strength results as an indication of fibre damage during laundering.

Mechanical agitation such as that which occurs during laundering can cause binding strength to deteriorate, which may cause colour loss and lead to a fabric getting a faded appearance (Kadolph & Langford, 1998, Smith & Block, 1982, Hall, 1978). For the purpose of this study this lightening or colour loss in fabric appearance, as a result of laundering, will be referred to as **print deterioration**. Print deterioration can be compared visually, but because of the slightness of some of the changes, reliable results would be difficult to achieve. With a colorimeter, however, even minute colour differences can be expressed numerically and colour changes reported objectively (refer discussion on assessment of colour change in paragraph 2.2.3).

Shiraiwa and Yamada (1993) used fraying of textile fabrics in the wash as a means of comparing the severity of different wash actions. Due to the fact that their reports are in Japanese, it is difficult to establish exactly how assessments were reached. For the purpose of this study, a method was developed by which fabric samples were rated on a five point scale to compare **degree of fraying** during laundering. This will be discussed in greater detail in Chapter 3.

In the literature study, research reports as well as technical information pointed out that textile fabric properties like tensile strength, print deterioration and the degree of fraying observed in textile fabrics after repeated laundering give an acceptable indication of damage that might have occurred as a result of laundering processes. It also indicates that fabric deterioration can be the result of chemical or mechanical damage. To measure possible mechanical damage as a result of, for example the mechanical wash action in a washing machine, the possibility of chemical damage due, for example, to chemical components in the wash solution, should be ruled out. This can be done by performing fluidity tests on washed cotton samples to confirm that no chemical damage had occurred during laundering. It should also be possible to confirm results obtained in the empirical study by studying the condition of fibres in the washed fabrics by means of a SEM.

2.5 Concluding remarks

This chapter constitutes a review of literature, with the objective of examining the main factors influencing mechanical damage to textile fabrics during repeated laundering. Factors that influence the efficiency with which the mechanical wash action of different washing machines affect soil removal are also discussed.

Washing machines are classified according to their mechanical wash actions and these actions are described in detail to assure that the reason for the difference in severity of these wash actions is explained. Literature relating to soil removal and the factors that influence soil removal was studied and is reported. As the aim of the study was to determine the effect of the mechanical wash actions of the different washing machines on fabric deterioration, textile durability and studies related to the effect of laundering processes on fabric deterioration are also discussed. The chapter also presents an overview of the assessment of textile deterioration, especially with regard to tensile strength, print deterioration, degree of fraying and soil removal efficiency.

CHAPTER 3

RESEARCH PROCEDURE

3.1 Overview of experimental design

Based on the introduction and problem statement given in Chapter 1, the aims of the study and the null hypotheses were formulated. In Chapter 2, a review of the literature study was given. The literature provided insight into concepts related to the problem, which proved valuable in the design of the research project. In this chapter, the empirical part of the study is described. An experimental study was designed. The variables that may influence the effect that repeated washing in a washing machine may have on the tensile strength, print deterioration and fraying of plain or printed cotton fabrics, as well as on effective soil removal from laboratory stained fabrics, were identified. The independent variables selected for this study were *washing machine, wash temperature, level of detergent* and *number of washes*. The effect of these on the *tensile strength, print deterioration* and *degree of fraying* of and *soil removal* from test fabrics (dependent variables) was measured under controlled conditions. A description of the materials and methods used in the study is also provided.

3.2 Rationale

The most obvious way to test serviceability is to conduct what might be called a service test or wear test, whereby examples of products are put into the hands of people who use the product in a normal way until it is ready for testing. In actual practice a number of questions are always raised about this approach. These questions are usually related to reliability, accuracy, cost (in terms of money and time), number of participants needed and whether participants are representative of the "typical" consumer (Merkel, 1991:11). Consumer studies on habits related to the use of washing machines (Lever Pond's, 1999, Lever Bros, 1995) indicate a wide variation in procedures associated with the cleaning of washing in household washing machines. Variables such as wash temperature, level of detergent and composition of the wash load, would be very difficult to control (Connor, 1981). Research such as this investigation, in which the main purpose is the comparison of washing machines with regard to their effect on the textile fabrics being washed, would be almost impossible to control through consumer trials. It would also be very costly and time consuming.

During laboratory testing, which may include accelerated testing, it is possible to speed up service testing to get quicker and reliable results. One can, for example, identify certain characteristics of a product that will predict serviceability and then measure those characteristics directly. Other characteristics and variables can be controlled to eliminate their effect on results. Kadolph and Langford (1998:77) defined laboratory testing as "...evaluating characteristics or performance of materials using standard procedures in a specialized facility...". This type of testing is used extensively in research because its approach is organized, systematic and carefully planned. These are criteria that have to be met for research studies to be credible and accepted by other researchers (Kadolph, 1998, Merkel, 1991). According to Leedy (1997) the basic idea behind experimental studies is to attempt to account for the influence of a factor or factors conditioning a given situation. Experimental studies attempt to control the entire research situation except for input variables that become suspect as a course of whatever change has taken place in the investigation. This makes laboratory testing ideal for this research project, as it is essential that the independent variables *(washing machine, temperature, level of detergent and number of washes)* should be kept constant.

An experimental study, in which the washing of the test fabrics, as well as the testing, is carried out under controlled conditions in a laboratory, was therefore decided on for this research project. During the planning, execution, testing and evaluation phases of the project, utmost care was taken to ensure that all actions would be carefully controlled, to make sure that valid and reliable data were obtained.

3.3 Selection of washing machines for the study

Domestic automatic washing machines can be classified into two main groups, namely horizontal drum machines (commonly referred to as front loaders, although some do open from the top for loading) and vertical drum machines (known as top loaders). The vertical drum machines can further be subdivided into those in which the wash action is produced by an *agitator* in the centre of the drum and those where an *impeller* (usually at the bottom of the drum) causes the movement of the wash load (Jakobi & Löhr, 1987, Lloyd & Adams, 1989). A very wide range of domestic automatic washing machines is currently available in South Africa and an attempt was made in this study to choose machines that are fairly representative of the market. Market data was obtained from leading suppliers[4] of washing machines and detergents and retailers[5] were questioned to determine which machines are commonly sold in South Africa and which are more popular.

In an extensive consumer study commissioned by Lever Pond's (1999) respondents' awareness of washing machine brand names was determined. Defy, AEG, Kelvinator, Whirlpool, Speedqueen, LG, Hoover and Hitachi were the brand names with the highest awareness ratings. A total of 97% of the respondents owned their own machines. Of the horizontal drum machine owners, 50% had a Defy in their home, 9% a Kelvinator, 8% an Indesit and 8% a Hoover. Speedqueen (38%) and Whirlpool (16%) were the most popular with vertical drum machine owners. When buyers were asked which washing machine they would buy in future, 39% of the horizontal drum machine users opted for Defy, 24% Speedqueen, 16% LG and 16% Whirlpool. Of the vertical drum machine users, 47% indicated that their next purchase would be a Speedqueen, 27% indicated Whirlpool, 19% LG and 13% Defy.

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[4] Sources of information prefer to remain anonymous
[5] Leading retailers in the Western Cape

Taking the above into consideration, seven washing machines (from the three categories identified in Chapter 1) were selected for this study. It was also attempted (especially with the horizontal drum machines) to choose machines from different price brackets, namely very expensive, fairly expensive and economy. Four horizontal drum machines were selected, three of which are imported. In the economy bracket, a locally manufactured and an imported machine were decided on. Sales data obtained from a leading washing machine manufacturer indicated that a total of 60 000 horizontal drum machines were sold in South Africa in 1999[6]. The machines selected for this study represent more than 80% of this figure. Regarding the vertical drum machines, two machines of the agitator type were selected and one of the impeller type. The selection represents 75% of the 80 000 vertical drum machines sold in South Africa in 1999. The two agitator type machines selected were the only two in this category mentioned on the list of best sellers for 1999[6]. When the selection was made, the impeller type machine chosen was the only one available with the same load capacity as the other two vertical drum machines. Load capacity had to be kept constant to be able to compare the results from the vertical drum machines. This resulted in other, smaller capacity impeller type machines not being included in the study.

To identify the washing machines used for the investigation, a coding system was developed (Table 3.1). This allowed for washing machines to be identified only by the codes allocated to them, and not by brand name or model numbers. The reason for the washing machines to be unidentified, was that the suppliers of at least four of the washing machines gave permission for their products being used in this study, but under condition that the brand names were not published. Another reason for not exposing brand names was that only one model of the brand was used in each case, and the technical features of that specific machine were analysed and used for comparison with the others. It would thus again be unfair to generalize.

[6] Source (a leading washing machine manufacturer in South Africa) prefers to remain anonymous

TABLE 3.1: CODING OF SELECTED WASHING MACHINES

WASHING MACHINE CATEGORY	CODES ALLOCATED TO MACHINES
Horizontal drum machines	*H1, H2, H3, H4*
Vertical drum agitator type machines	*V(A)1, V(A)2*
Vertical drum impeller type machines	*V(I)1*

3.3.1 Description of horizontal drum machines (front loaders) selected for the study

The four front loading machines used in this study will be referred to as *H1* (imported, price range >R5000), *H2* (imported, price range between R3000 and R5000), *H3* (locally manufactured, price range <R3000) and *H4* (imported, price range <R3000). All the machines are meant for household use and have a maximum capacity of 5 kg dry washing. They have internal heating facilities and take in cold water only. The wash temperature can be selected separately. The laundering programmes recommended for "*regularly soiled, colourfast fabrics*" were chosen to be used in all the wash tests. The programmes of the specific machines used in this study were monitored and analysed and are described below. The individual programmes are illustrated in a Figures 3.1, 3.2, 3.3 and 3.4 and the technical measurements describing the different machines are summarised in Tables 3.2, 3.3, 3.4 and 3.5.

3.3.1.1 Machine *H1*: Description of washing machine and programme used in the study

The machine has a wash cycle of approximately 45 minutes, which includes approximately ten minutes of heating (drum action 10/5[7]) and 35 minutes of washing at the required temperature (drum action 12/4[7]). This is followed by a three-minute spin (type A) and three rinses (drum action 10/5[7]) of respectively four, five and seven minutes each. Rinse time includes draining while motion

[7] Note: drum action indicated as X/Y: where X indicates drum rotation and Y a rest period (duration in seconds)

continues until the drum is empty. After each rinse follows a three minute spin (type A) and after the last three minute spin the machine moves into a type B spin which continues for five minutes. The type A spin is quite unique. The drum speed starts at 54 revolutions per minute (rpm), accelerates to 557rpm and includes short periods (approximately three seconds each) at 876rpm. When the laundering programme is completed, the drum continues to move slowly for another five minutes. The total duration of the wash programme (including water intake and draining) is approximately 95 minutes (excluding the slow turning period).

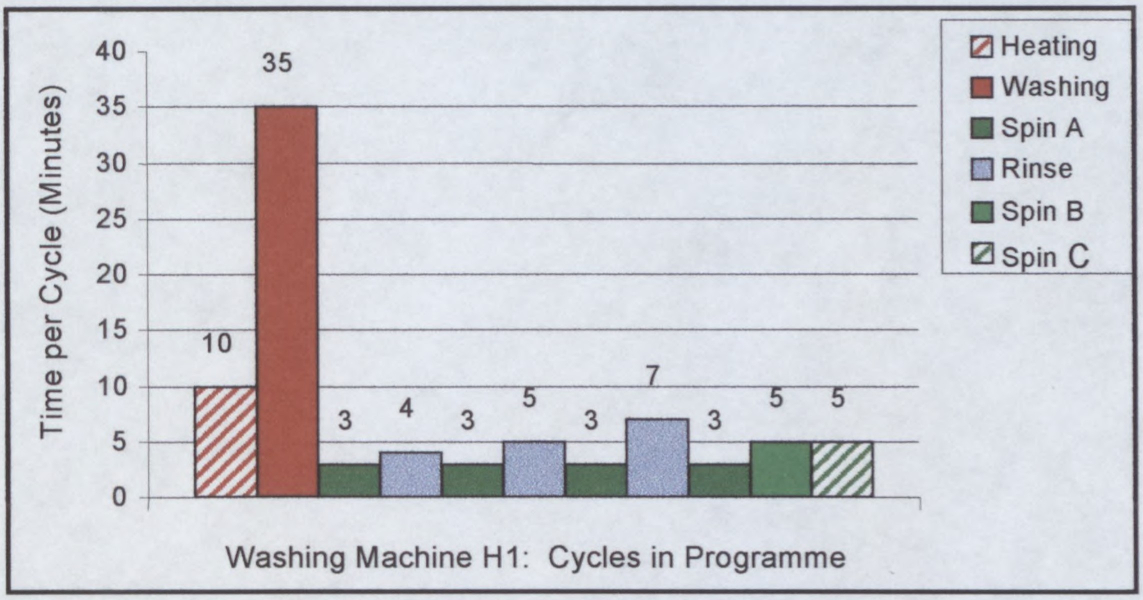

FIGURE 3.1: MACHINE *H1*: VISUAL PRESENTATION OF WASH PROGRAMME USED IN STUDY

TABLE 3.2: TECHNICAL MEASUREMENTS: MACHINE *H1*

Drum speed	54,3rpm (revolutions per minute)
Spin speed A	54 - 557rpm
Spin speed B	896rpm (*manufacturer indicates 900rpm*)
Maximum temperature measured in drum during wash cycle	Machine setting 40°C: 38°C Machine setting 60 °C : 58°C
Water consumption (wash cycle)	10ℓ
Drum dimensions	48X31cm (drum volume = 56,1ℓ)
Free fall distance in drum	39cm

3.3.1.2 Machine *H2*: Description of washing machine and programme used in the study

This machine has a washing cycle of approximately 30 minutes, during which the water is heated for ten minutes (drum action 12/12[7]) and the fabric washed for another 20 minutes (drum action 12/12[7]). More water is then added and the wash load is washed for another three minutes (drum action 7/7[7]). This is followed by three rinses (drum action 12/12[7]) with a spin after the second and third rinse. Rinse time includes draining while the motion continues until the drum is empty. The final spin of six minutes starts with two minutes at slow speed and then an acceleration to top speed (804rpm) for the next four minutes. The total duration of the wash programme (including water intake and draining) is about 67 minutes.

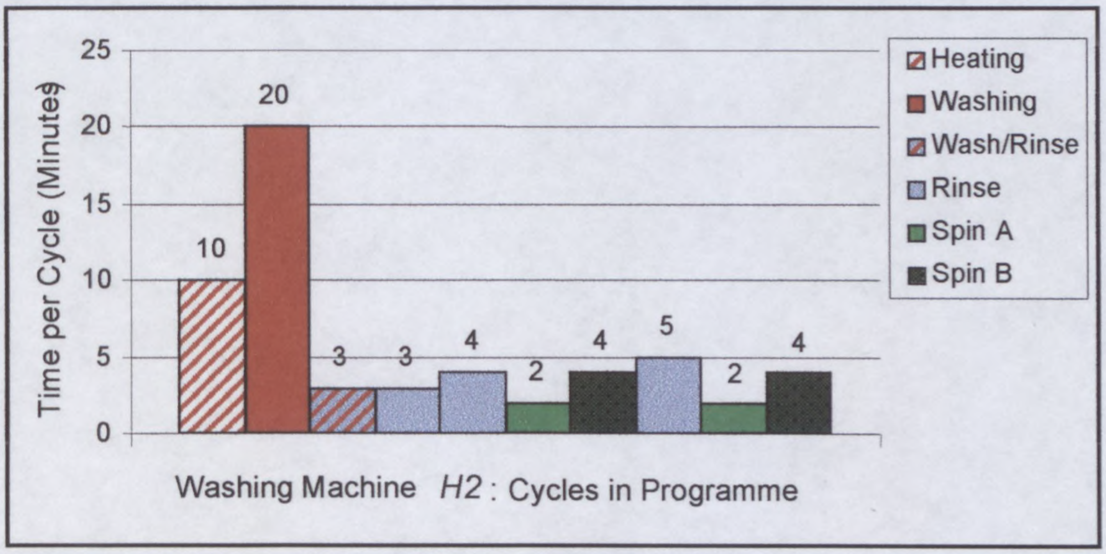

FIGURE 3.2: MACHINE *H2*: VISUAL PRESENTATION OF WASH PROGRAMME USED IN STUDY

TABLE 3.3: TECHNICAL MEASUREMENTS: MACHINE *H2*

Drum speed	63,5rpm (revolutions per minute)
Spin speed A	134 - 309rpm
Spin speed B	804rpm *(manufacturer indicates 900rpm)*
Maximum temperature measured in drum during wash cycle	Machine setting 40 °C : 38 °C Machine setting 60 °C : 57 °C
Water consumption (wash cycle)	11ℓ
Drum dimensions	47 X 27cm (drum volume = 46,9ℓ)
Free fall distance for washing in drum	36cm

3.3.1.3 Machine *H3*: Description of washing machine and programme used in the study

The programme starts with a wash cycle of approximately 45 minutes during which the water is heated for the first two thirds of the time, with the drum rotating (drum action 4/11[7]) until the required temperature is reached, and then washed for the last 15 minutes (drum action 11/4[7]). This is followed by four rinses (drum action 11/4[7]) of approximately four minutes each. Rinse time includes draining as motion continues until the drum is empty. There is a two minute spin after the second rinse and a six minute spin after the fourth. The total duration of the wash programme (including water intake and draining) is approximately 82 minutes.

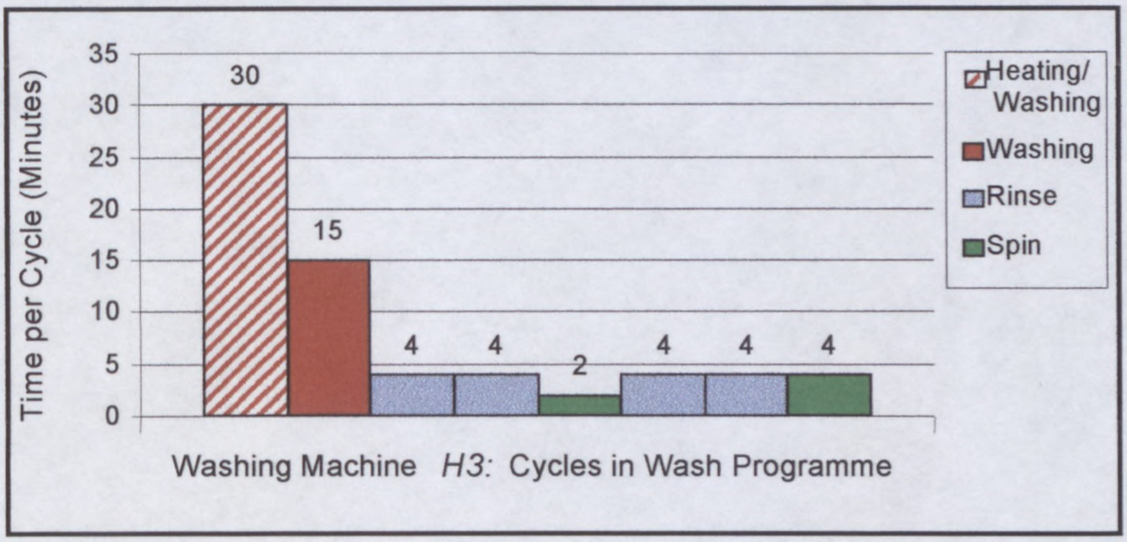

FIGURE 3.3: MACHINE *H3*: VISUAL PRESENTATION OF WASH PROGRAMME USED IN STUDY

TABLE 3.4: TECHNICAL MEASUREMENTS: MACHINE *H3*

Drum speed	66rpm (revolutions per minute)
Spin speed	519rpm
Maximum temperature measured in drum during wash cycle	Machine setting 40°C: 38 °C Machine setting 60 °C : 55 °C
Water consumption (wash cycle)	16ℓ
Drum dimensions	47 X 25cm (drum volume = 43,4ℓ)
Free fall distance for washing in drum	36cm

3.3.1.4 Machine *H4:* Description of washing machine and programme used in the study

This machine has the longest laundering programme. It starts with 30 minutes of heating and then 30 minutes of washing (drum action 5/17 for 2,5 minutes alternating with 10/5 for 2,5 minutes[7]) at the required temperature, giving a total wash cycle of 60 minutes. There are four rinses (drum action 5/17 for 2,5 minutes alternating with 10/5 for 2,5 min[7]) of approximately four minutes each. After every rinse, the water is slowly pumped out while the drum continues turning. The total duration of the wash programme (including water intake and draining) is approximately 115 minutes.

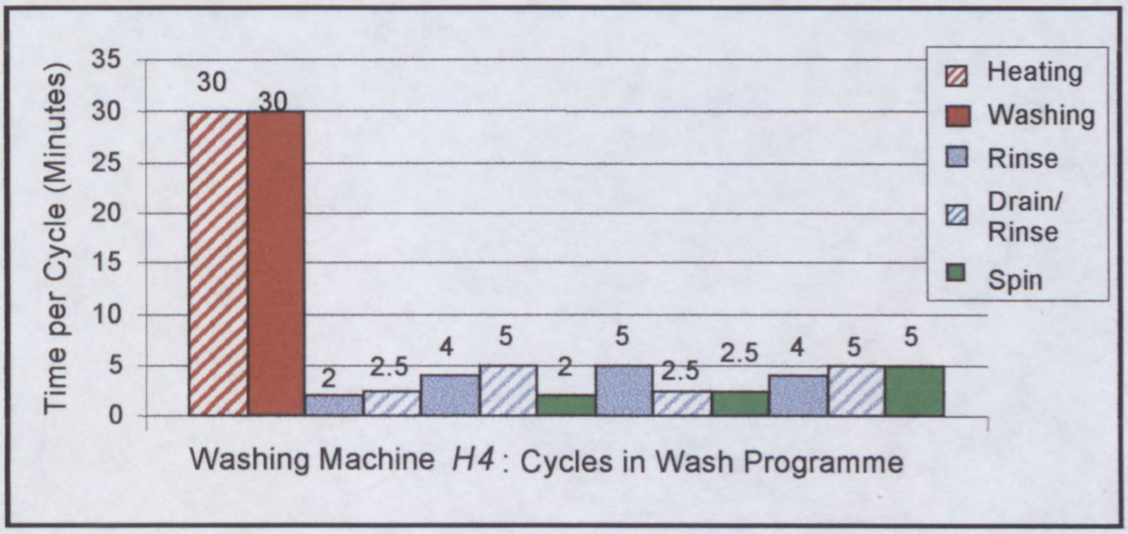

FIGURE 3.4: MACHINE *H4*: VISUAL PRESENTATION OF WASH PROGRAMME USED IN STUDY

TABLE 3.5: TECHNICAL MEASUREMENTS: MACHINE *H4*

Drum speed	56rpm (revolutions per minute)
Spin speed	545rpm
Maximum temperature measured in drum during wash cycle	Machine setting 40°C: 38 °C Machine setting 60°C : 53 °C
Water consumption (wash cycle)	17ℓ
Drum dimensions	45 X 26cm (drum volume = 41,4ℓ)
Free fall distance for washing in drum	33cm

3.3.1.5 Comparison of horizontal drum machines

The data obtained by technical measurements and observations, that describe the four horizontal drum machines that were used for the washing procedures in this study, and their individual mechanical wash actions and wash programmes, are summarized in Table 3.6(a).

TABLE 3.6(a): TECHNICAL DETAILS DESCRIBING THE HORIZONTAL DRUM WASHING MACHINES AND THEIR MECHANICAL WASH ACTIONS AND WASH PROGRAMMES

WASHING MACHINE		*H1*	*H2*	*H3*	*H4*
DRUM MEASUREMENTS	cm	48 x 31	47 x 27	47 x 25	45 x 26
DRUM VOLUME	litre	56,1	46,9	43,4	41,4
WATER CONSUMPTION PER WASH CYCLE	litre	10	11	16	17
FREE FALL DISTANCE	cm	39	36	36	33
DRUM TURN ROUTINE	sec.	12/12* or 10/5**	12/12	11/4	5/17 and 10/5***
DRUM SPEED DURING WASH CYCLE	rpm	54,3	63,5	66	56
DURATION OF WASH CYCLE	min.	45	30	45	60
NUMBER OF TURNS PER WASH CYCLE	spin excluded	1724	953	990	683
NUMBER OF TURNS PER TOTAL WASH		2205	1429	1766	2086
DURATION OF TOTAL PROGRAMME	min.	95	67	82	115
SPIN TIME	min.	14	12	8	9,5
MAXIMUM SPIN SPEED	rpm	896	804	519	545

** heating and rinsing* ***wash cycle* ****alternating*

In Table 3.6(a), the measurements that ranked highest in each case are printed in red and those that ranked lowest, in blue.

The above measurements were taken on the actual machines that were used in this study. Drum measurements as well as water consumption were measured manually with suitable measuring equipment. Water consumption per wash cycle was determined by measuring the volume of water pumped out after the wash cycle when washed with a wash load, as the water consumption with and without a wash load tended to vary for some machines. The free fall distance is an indication of the distance from the top of the drum to the water level. The values shown were measured with the drum filled with the amount of water measured as "water consumption per wash" in the drum, but without a wash load. The reason for this was to make sure that the level of water was constant, and not affected by the water absorption of the textiles in the wash load. Drum speed was measured in revolutions per minute (rpm) with a tachometer.

To make a better comparison of the stress that the fabrics in the wash were submitted to during washing, rinsing and spinning, the centrifugal force (CF) that developed in the drum during drum movement, was calculated. The following formula was used: $CF = m.\omega^2.r$

m = weight of wet wash load (kg) (dry weight X 150%)

ω = (drum speed (rpm) $\div$ 60) X 2π

r = drum radius (Results are depicted in Table 3.6(b))

TABLE 3.6(b): CENTRIFUGAL FORCE DEVELOPED IN DRUMS OF HORIZONTAL DRUM WASHING MACHINES DURING DRUM MOVEMENT

WASHING MACHINE		*H1*	*H2*	*H3*	*H4*
FORCE DEVELOPED DURING WASHING AND RINSING	N	29,1	39,0	42,1	28,8
FORCE DEVELOPED DURING SPINNING	N	7923,0	6246,6	2602,9	2723,7

It was assumed that the values obtained for the centrifugal force developed in the drum during washing and rinsing, would be of lesser importance in its effect on fabric deterioration than those obtained during spinning. The reason for this is that the drum movement during washing and rinsing is aimed at lifting and dropping the fabric pieces in the wash load, to create mechanical agitation. This is in contrast to the spinning cycle, where the aim is to create a centrifugal force to remove excess water from wet fabrics. To compare the amount of mechanical agitation in the different machines during washing and rinsing, the number of times that the drum turns on its axis during these cycles would be a better indicator. During spinning, a centrifugal force is developed in the drum, causing the fabrics to press against one another and against the sides of the drum. Although this cannot be described as mechanical agitation, a force is applied to the fabrics which could potentially cause damage to the fabric structure and should be kept in mind.

Machine *H1* has the highest drum volume, longest free fall distance, highest number of turns per wash cycle and wash programme, the highest spin speed and second longest total wash programme. The centrifugal force that develops during spinning, however, is the highest of the four horizontal drum washing machines. From the above it can be concluded that the mechanical wash action of machine *H1* is the most severe of the four horizontal drum machines.

By far the shortest wash programme and the lowest number of turns per wash programme was measured in machine *H2*. In this machine, the washing is thus submitted to the wash liquid and mechanical wash action for a much shorter period than in the other machines. The spin speed and spin time, however, are almost as high as that of machine *H1* and the centrifugal force during spinning is the second highest of the four horizontal drum machines.

Another observation from Table 3.6(a) is that machine *H3* differs from the others only with respect to its spin speed and spin time (lowest) and its higher drum speed during the wash cycle. This might prove to be important in the mechanical damage to textile fabrics, as the wash cycle consists of 11 seconds turning for every four-second rest period, causing the highest number of drum turns per unit of time. The centrifugal force during spinning is the lowest of the four horizontal drum machines and the spin cycle duration the shortest.

Machine *H4* has the smallest drum, but uses the most water during the wash cycle, leading to the shortest free fall distance. According to this, it can be assumed that the washing will be submerged in water (or water plus detergent) to a greater extent than in the other washing machines. As this machine also exhibits the longest wash cycle and total wash time, the washing is also exposed to the wash liquid for a longer period. During the relatively long wash cycle, the machine exhibits the lowest number of drum turns per wash cycle of the four horizontal drum machines. The centrifugal force in the drum during washing, rinsing and spinning is the lowest of the four horizontal drum machines. All the above indicate that machine *H4* creates the least amount of mechanical action during its wash programme.

3.3.2 Description of vertical drum machines (top loaders) selected for the study

Two agitator type automatic vertical drum machines, *V(A)1* and *V(A)2*, were selected for this study. Both machines function by means of an agitator that turns to move the washing, but the agitators differ in design and the manufacturers claim that they do not have the same effect on a wash load. Both machines have a total wash load capacity of 8,5kg dry washing. Although the semi-automatic twin tub impeller type washing machines are well known, the automatic vertical drum impeller type machines are relatively new to the South African market. *V(I)1* falls into this category and has the same wash load capacity as *V(A)1* and *V(A)2*.

Compared to the horizontal drum machines (front loaders), the vertical drum types (top loaders) show little variation in their washing programmes. The machines do not heat the wash water internally but take in heated water directly from a geyser. The volume of hot and cold water is regulated to reach the desired end temperature (desirably 60°C for a "hot" and 40°C for a "medium" wash). The thermostat of the geyser in the laboratory (to which the machines were connected) was set at a temperature that would ensure that the water in the drums of the vertical drum machines would reach 60±2°C and 40±2°C, depending on the wash temperature selected. One of the major differences between horizontal and vertical drum machines is that the latter uses significantly more water. In the horizontal drum machines, only about a third of an average wash load is immersed in water at any time, whereas, in the vertical drum machines, the wash load is fully immersed and able to move freely in the wash liquid.

As in the case of horizontal drum washing machines, the laundering programmes suitable for "regularly soiled, colourfast fabrics" were selected for all the wash tests. The programmes for the specific vertical drum machines were monitored and analysed and are described below. The individual programmes are illustrated in Figures 3.5, 3.6 and 3.7 and the technical measurements describing the different machines are summarised in Tables 3.7, 3.8 and 3.9.

3.3.2.1 Machine *V(A)1*: Description of washing machine and programme used in the study

After water intake, the wash cycle starts. This entails the agitator turning 360° in one direction, followed by a 360° turn in the opposite direction, for about 9,5±1 minutes. The drum itself does not turn. After draining, the drum spins slowly for about two minutes, accelerating to a full spin for another two minutes. The rinse, during which the agitator follows the same motion as described above, lasts approximately three minutes. The programme ends with a final spin of seven minutes. The total duration of the wash programme (including water intake and draining) is about 60 minutes.

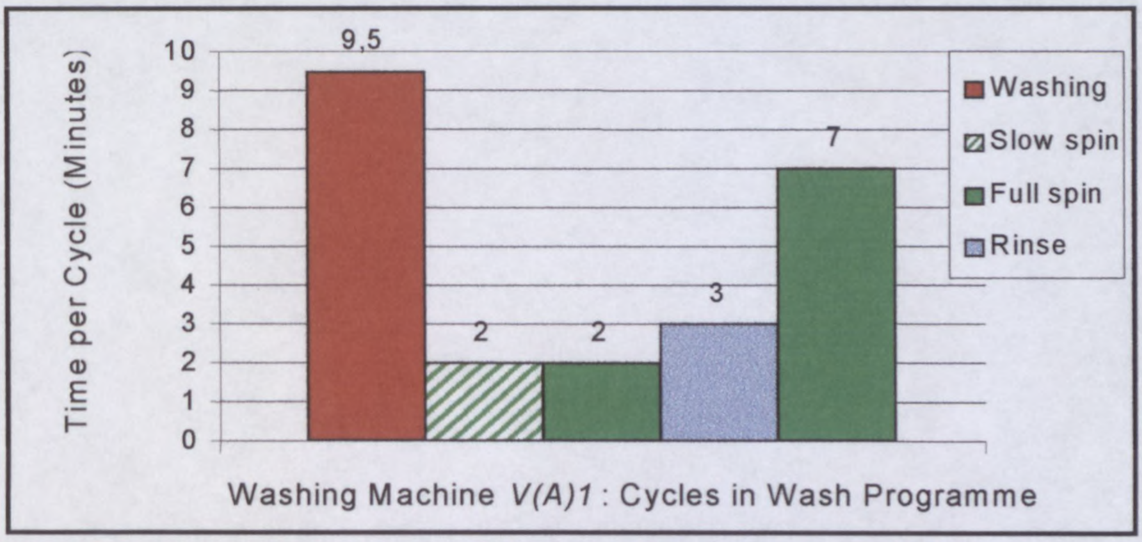

FIGURE 3.5: MACHINE *V(A)1*: VISUAL PRESENTATION OF WASH PROGRAMME USED IN STUDY

TABLE 3.7: TECHNICAL MEASUREMENTS: MACHINE *V(A)1*

Drum speed	Stationary during wash cycle
Agitator speed	68 forward and reverse turns per minute
Spin speed	666rpm
Maximum temperature measured in drum during wash cycle	Machine setting 40°C: 40 °C Machine setting 60°C : 60 °C
Water consumption (wash cycle)	65 - 70ℓ
Drum dimensions	52 X 38cm
Centrifugal force developed during spinning	6639,2N

3.3.2.2 Machine *V(A)2:* Description of washing machine and programme used in the study

After water intake the wash cycle starts, during which the agitator turns continuously (in one direction only) for 10±1 minutes. After draining the drum spins for three minutes. The rinse, during which the agitator follows the same motion as described above, lasts about two minutes. The programme ends with a final spin of ten minutes. The total duration of the wash programme (including water intake and draining) is approximately 55 minutes.

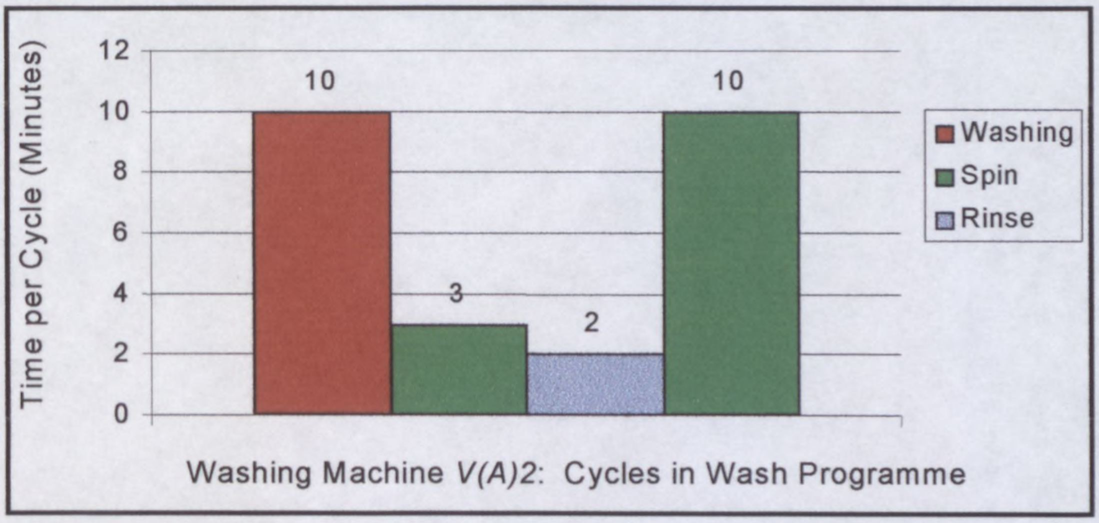

FIGURE 3.6: MACHINE *V(A)2*: VISUAL PRESENTATION OF WASH PROGRAMME USED IN STUDY

TABLE 3.8: TECHNICAL MEASUREMENTS: MACHINE *V(A)2*

Drum speed	Stationary during wash cycle
Agitator speed	119rpm
Spin speed	644rpm
Maximum temperature measured in drum during wash cycle	Machine setting 40°C: 40 °C Machine setting 60°C : 60 °C
Water consumption (wash cycle)	65 - 70ℓ
Drum dimensions	53 X 41cm
Centrifugal force developed during spinning	6327,2N

3.3.2.3 Machine *V(I)1*: Description of washing machine and programme used in the study

After water intake, the wash cycle starts, during which the impeller movement, together with the drum turning backwards and forwards, swirls the water and wash load around for about nine minutes. During draining, the drum turns, accelerating to a spin, for about 2,5 minutes. The first rinse, during which the drum turns only 45° backwards and forwards, lasts about two minutes. This is followed by a second spin (4,5 minutes) and rinse (three minutes). The programme ends with a final spin of seven minutes. The total duration of the wash programme is about 60 minutes.

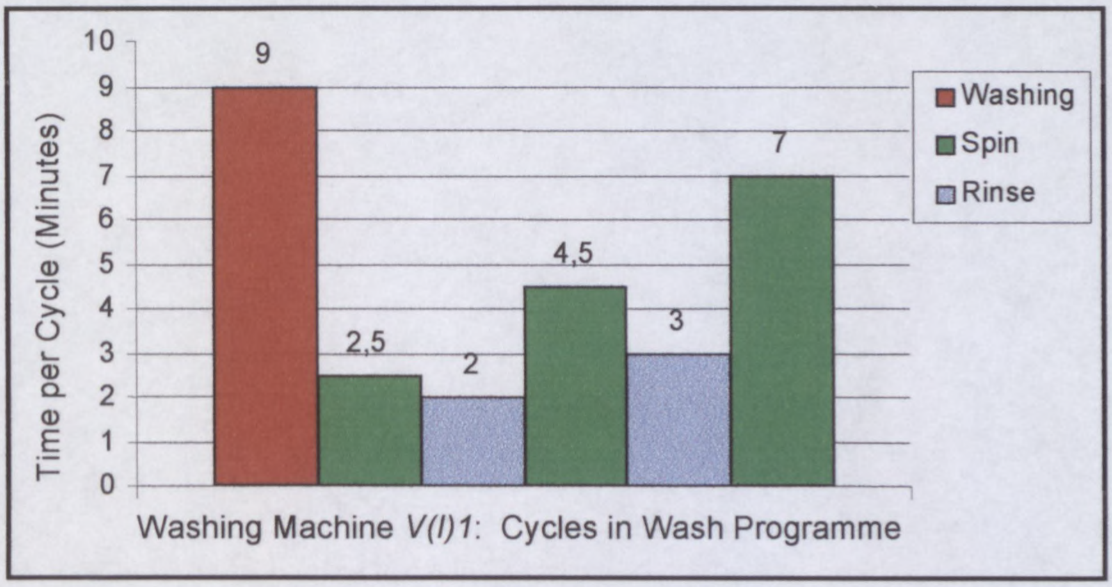

FIGURE 3.7: MACHINE *V(I)1*: VISUAL PRESENTATION OF WASH PROGRAMME USED IN STUDY

TABLE 3.9: TECHNICAL MEASUREMENTS: MACHINE *V(I)1*

Drum speed	Stationary during wash cycle
Impeller wings speed	130rpm
Spin speed	723rpm
Maximum temperature measured in drum during wash cycle	Machine setting 40°C: 40 °C Machine setting 60°C : 60 °C
Water consumption (wash cycle)	55 - 60ℓ
Drum dimensions	47 X 37cm
Centrifugal force developed during spinning	7071,9N

3.4 Choice of wash temperatures

To reflect consumer practice of home laundering, fabrics were washed at 40°C as well as 60°C (Kadolph, 2000, Kadolph & Langford, 1998, Lever Pond's, 1999). Consumer research shows a trend towards washing at lower temperatures. At present, washing powders are developed for optimum functioning at 40°C (Plumbley, 1999). The temperatures 40°C and 60°C are also the two temperatures recommended most often in wash programmes in the instruction manuals of the automatic washing machines used in this study. "Cold water" (also referred to as "tap water") is also sometimes recommended, but the recommendation does not specify a temperature, as the temperature of cold water varies according to geographical area or season. An extreme temperature of 90°C is usually only recommended in special circumstances and is seldom used for a normal wash load (Lever Bros, 1995). According to Kadolph and Langford (1998), higher washing temperatures are more likely to cause damage to textiles. Washing instructions on garment care lables usualy indicate temperatures of 40 °C, 50 °C or 60 °C (SABS, 1990).

3.5 Composition and size of the wash load

A wash load consisting of the test fabrics and ballast cloths was standardised (AATCC, 1996) to resemble a normal consumer's wash load as closely as possible. Suppliers of horizontal drum machines recommend that the best way to determine the optimum load is to fill the machine with dry fabric until a human hand turned on its side can still fit easily between the fabric and the top of the drum. This was done and the weight of a standard load for the horizontal drum machines was set as 2,5 kg. This is almost similar to the wash load of 2,8 kg indicated by Lever Bros (1995) as average. Four loads were then made up of test fabrics and ballast cloths of polyester and cotton (individual weight per ballast cloth: ±100g) to resemble a normal household wash load as closely as possible. Consumer research indicates a tendency towards a normal load consisting of approximately 40% synthetic and 60 % cotton fabrics (Lever Pond's, 1999).

In a study done by Lever Bros (1995) on consumer habits when using vertical drum type machines, it was reported that a mean load size of 3,54 kg was observed. Consumers appear to make infrequent use of the large capacity of the machines only requiring it for occasional washing of large items such as curtains (Lever Bros, 1995). The standard loads for the three vertical drum machines were made up to 3,5kg in the same way as described for horizontal drum machines.

All fabric samples removed from the wash load for testing during the wash cycles were replaced by other fabrics of the same weight and composition, to keep the load unchanged throughout the experiment.

3.6 Level of detergent in the wash

Serious discrepancies were found in the literature regarding the effect of detergents in the wash solution on mechanical degradation of textiles during laundering. Ulrich and Mohamed (1982) reported more severe abrasion and loss of breaking strength, characterised by abrupt fractures of fibres, occurring on fabrics laundered with water only, when compared to fabrics laundered with two types of detergents. Raheel and Lien (1985) reported the opposite. They tested cotton fabrics with four different finishes and found that they all suffered more deterioration in detergent solution laundering than in water alone. It was thus decided to test this contradiction by carrying out the laundering cycles without detergent and repeating it with detergent.

For the horizontal drum machines, Plumbley (1999) recommended the use of a commercial detergent for automatic horizontal drum machines with a foam reducer (commonly referred to as antifoam) as ingredient. A similar product, but without antifoam, was recommended for the vertical drum machines. The detergent powder[8] (a popular household brand without bleach) to be used in this study was prepared by Lever Pond's. They supplied 50kg of detergent with antifoam as an ingredient for use in the horizontal drum machines and 50kg of the same batch without antifoam for use in the vertical drum machines. This would be used in all the washing machines to ensure continuity. A concentration of ±4,5g detergent per litre of water was recommended for the horizontal drum type machines (Plumbley, 1999). Measuring indicated that the horizontal drum machines in this study used an average of 14,5 litres per wash cycle. The detergent dosage for the horizontal drum machines was thus standardized as 65g per wash load of 2,5kg dry washing. For the vertical drum machines the recommendation was that the amount of detergent should be adapted pro rata in relation to the weight of a standard wash load (Plumbley, 1999). The dosage for the vertical drum machines was standardised as 91g detergent per wash load of 3,5kg dry washing.

3.7 Test Methods

Based on the objectives and hypotheses of the study, different test methods were selected for data gathering. Before testing, fabrics were washed as described in 3.9.

The **tensile strength** of fabrics was tested according to SABS method 93 (Refer Addendum C) on an Instron Tensile Strength Tester.

The **fabric count** of washed and unwashed fabrics was determined by counting

[8] Composition confidential

the number of yarns per unit area in the fabrics with the use of a linen counter or magnifying glass.

The Cuprammonium Fluidity Tests on washed and unwashed fabrics were done at the CSIR. (Refer Addendum D for full report).

> *The Cuprammonium Fluidity Test is a measure of the average molecular chain length of the cellulose in a cotton fibre. It is considered to be an accurate measurement of cotton degradation, i.e. it is an useful measure of the tendering of cotton that can result from chemical processes such as bleaching or other chemical influences. The results will indicate whether the fabric tested was chemically damaged during production (*Mauersberger, 1948*).*

To investigate and compare the severity of mechanical wash actions, the textile fabric properties **print deterioration** and **degree of fraying** were selected to be used as further indication of fabric deterioration during washing. The purpose of the tests was to compare the severity of the different mechanical wash actions of the different machines. With this information, one would be able to predict in which machine(s) garments would retain their appearance longer. Because of the specialised application, special test methods were developed for this study.

To assess **print deterioration**, the colour of the fabric surface was measured with a colorimeter and the lightness (L*) readings reported. Care was taken to make sure that the readings taken before washing and after every ten wash cycles were always taken on the same designated area of the test fabric. Readings were repeated five times.

> *Colorimeter (tristimulus) readings on printed fabrics showed that control readings, even when taken in the plain coloured areas of the print, marked as described above, were spread unevenly for measurements a* (red/green value) and b* (blue/yellow value). These variations could be the result of small differences in the plain background colour of the printed fabric, which were not visually detected. The values for lightness (L*) were more consistent and showed results comparable with visual observations of the extent of*

print deterioration in the laundered fabrics. Only the lightness results were thus used as indication of print deterioration during the comparison of the fabrics.

To assess **degree of fraying** in fabrics after washing, an ordinal scale was developed, showing images of five frayed cuts (Addendum E). The cuts were rated 1 (severely frayed) to 5 (slightly frayed). Washed fabrics were rated in a light cabinet at standard lighting according to the scale.

A **scanning electron microscope** was used to view magnified images of washed fabrics to aid in the interpretation of data on fabric deterioration.

Soil removal efficiency was assessed on fabrics that was washed once as described in 3.9. The colour of the soiled test fabrics was measured with a colorimeter and values for a*, b* and L* reported. To compare the soil removal efficiency of the seven washing machines, the colours of the washed fabrics were compared with a control (average for unwashed fabrics) to calculate the colour change (ΔE).

3.8 Test fabrics

3.8.1 Selection of experimental fabrics

To select a suitable fabric for measuring possible change in **tensile strength**, a pilot study was undertaken in a Hoovermatic impeller-type semi-automatic (twin tub) washing machine. This machine has an impeller mounted on the side of the drum and the model that was used is commonly known to have a quite severe wash action. A lightweight plain weave 100% cotton Voile ($75g/m^2$), a plain weave 100% viscose ($135g/m^2$) and a plain weave 100% cotton fabric ($115g/m^2$) were compared for loss in tensile strength. Fabrics were removed after one, two and three hours and the tensile strength determined and compared with that of an unwashed fabric. The purpose was to find a fabric which would deteriorate enough during laundering to show a significant difference in tensile strength, but still produce consistent tensile strength results when tested on an Instron Tensile Strength Tester. The instructions on the control panel of the Hoovermatic machine suggest that a "normal" wash cycle should last two to three minutes. One hour could thus be considered equivalent to about 20 washes. (Results of pilot study reported in Addendum B).

The fabric that showed the most consistent reduction in tensile strength is a quality L2 bleached 100% cotton plain weave fabric from Berg River Textiles[9] which can be technically described as follows:

Mass per unit area:	115/116g/m^2
Fabric count:	32 X 23
Cuprammonium Fluidity	42,6 (Pa.s)$^{-1}$

To select test fabrics to be used for assessment of print deterioration and degree of fraying, a technical manager at Berg River Textiles recommended a pigment printed cotton plain weave fabric (175g/m^2) produced by them. Fabric samples were washed in the Hoovermatic twin tub washing machine during pilot tests and showed slight, but noticeable print deterioration after repeated washing. On this account, five metres from one piece were bought to be used to assess **print deterioration**. The fabric did not show any visible structural deterioration like yarn slippage or distortion after washing, which made it acceptable for the test method designed for this study to determine **degree of fraying.**

To assess the **soil removal efficiency** of each of the seven washing machines, a laboratory-soiled test fabric was used. A product, AS-1, from the Centre for Test Fabrics was selected. AS-1 is recommended as suitable for testing of washing machines and washing programmes, due to its sensitivity to mechanical action. The fabric was soiled with a mixture of soot and mineral oils, not aged at elevated temperature and had a high pigment (soot) content. It was described as "difficult to clean". The soiling on the test fabric can thus be categorised as "simple coatings or mechanically entrapped particles" (Lloyd & Adams, 1989) or

[9]Berg River Textiles, Driebergen Street, Daljosafat, Paarl

"particulate soil" (Hatch, 1993). These soils are sensitive to mechanical action during the washing process for their removal. This is the reason why fabric AS-1 was chosen to compare the soil removal efficiency of the mechanical wash actions of the different washing machines. (Refer Addendum F)

3.8.2 Sample preparation

The fabrics that would be washed repeatedly for eventual testing of **tensile strength**, were prepared as follows. Samples sized 600 X 750 mm were cut from the fabric described in 3.8.1 and overlocked with an industrial overlocker to prevent fraying. At least six test samples per machine per experimental procedure were prepared, giving a total of 168. Samples were numbered randomly after preparation, with the numbers corresponding to the treatment and machine it would be submitted to. All samples were conditioned[10] prior to washing.

After the wash cycles were completed, the fabrics were conditioned again for at least 24 hours in the laboratory. From each washed fabric, ten samples of 60 X 300mm each were cut and prepared for tensile strength testing. The samples were all cut with the longer side running in the warp direction (Taylor, 1990, Vaeck, 1966). No samples were taken from within 50mm from the selvage. They were then frayed down to a finished width of 50±0,5mm and conditioned for at least another 24 hours prior to testing on the Instron Tensile Strength Tester.

Test fabrics for the **print deterioration** tests (size 500 X 500mm) were cut and overlocked and conditioned for at least 24 hours prior to testing.

To assess **fraying,** fabric samples of 500 X 500mm were cut and overlocked. Three 50 mm cuts were made at a 45^0 angle, with the fabric folded double in the warp direction, on each of the samples. The method of cutting and the finished appearance of the cuts are illustrated in figure 3.8.

[10] All conditioning was done in the laboratory at the Department of Consumer Science, University of Stellenbosch, at standard atmospheric conditions (65±2% relative humidity and 21±1°C). (Refer Addendum A)

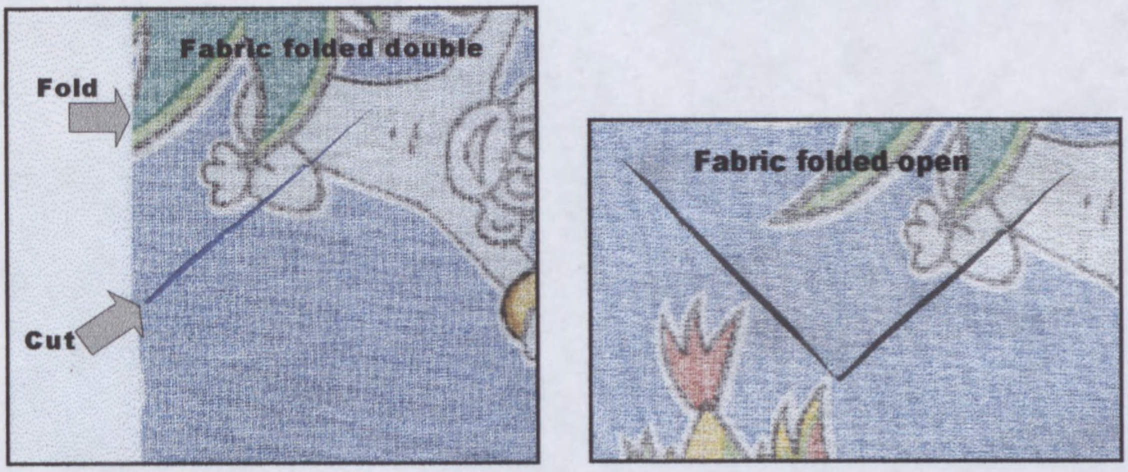

FIGURE 3.8: PREPARATION OF FABRICS FOR ASSESSMENT OF DEGREE OF FRAYING

To measure **soil removal efficiency**, the laboratory-stained test fabrics (quality AS-1) were cut into 75 X 75mm samples and attached to ballast cloths. They would then be removed after one wash, flat dried and conditioned for at least 24 hours before both sides of the sample would be assessed for colour change.

3.9 Experimental procedure and assessment of results

In the experimental phase of the project, fabrics (prepared as described in 3.8.2) were washed in the various automatic washing machines for the number of times required for the testing of each dependent variable. Fabrics were not dried in between washes, to ensure that any effect that the drying procedure could have on fabric deterioration was avoided. In all the machines, the wash cycle for regularly soiled, colourfast fabrics was selected, which, in each case, included a wash cycle, rinse cycle(s) and spin cycle(s). The details of the individual programmes of the different machines compared in this study are described in 3.3.1 and 3.3.2. The wash temperature was selected as either 40°C or 60°C (in the horizontal drum machines) and medium or hot (in the vertical drum machines). The geyser supplying water to the vertical drum machine was set at a temperature which allowed the water in the drum to reach either 40°C (for medium) of 60°C (for hot). Detergent, when required by the test, was added through the detergent dispenser for the horizontal drum machines and directly into the drum for the vertical drum machines.

Fabrics for **tensile strength** testing were withdrawn after 10, 20, 30, 40 and 50 washes and flat dried in the laboratory after washing. After conditioning, the fabrics were cut and test strips (60 X 300 mm) prepared as described in 3.8.2. Tensile strength was measured on an Instron Tensile Strength Tester in the temperature and humidity controlled textile laboratory at the Department of Consumer Science, University of Stellenbosch. The unwashed (control) fabrics were tested at the same time as the washed fabrics. (Test methods discussed in 3.7)

Fabrics (500 X 500mm) for determination of **print deterioration** were washed 10 and 20 times at 40°C without detergent. The use of detergent was avoided to rule out the effect of optical brighteners or bleaches. All fabrics were conditioned for at least 24 hours before evaluation. On each fabric sample five areas were marked with water-resistant ink. The lightness value (L*) of the colour in these areas on each fabric was measured with the colorimeter and recorded before washing. This procedure was repeated in the same marked areas after 10 and after 20 washes. With the placement of the colorimeter on the fabric, care was taken to avoid lighter coloured lines that appeared in these areas due to folds in the fabric.

The **degree of fraying** was assessed on fabrics that were washed once, three and five times. Fabrics were allowed to dry on drying racks in the laboratory under standard atmospheric conditions. The dried fabrics were then cut into equally sized squares (each square hosting one cut), marked and ironed lightly to flatten the frayed edges to be evaluated by means of a 5 point ordinal scale (Addendum E). The evaluation was done by the researcher, together with an assistant to compare the amount of fraying that had taken place in the wash.

Soil removal efficiency was measured by adding one prepared soiled cloth to a wash load and submitting it to one laundering cycle, after which it was dried flat and conditioned. This procedure was repeated ten times in each washing machine at each temperature, with and without detergent.

The colour of the washed and unwashed soiled test fabric (AS-1) was measured with the colorimeter (tristimulus) and results reported as red/green values (a*), blue/yellow values (b*) and lightness values (L*). The difference between the values obtained from the unwashed fabrics and that of the washed fabrics represent the total colour change in the test fabric which is representative of how a stain would become lighter during washing. This was calculated as Δa*, Δb* and ΔL*. The soil removal efficiency of the different washing machines can be compared by comparing the ΔE[11] values of the washed fabrics. ΔE is calculated according to the following formula:

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

A higher ΔE value indicates a "cleaner" fabric.

3.10 Statistical analyses of data

The experimental design was a completely randomised design, including 141 treatments with 10 replicates of each. The treatment designs comprised a 7 x 2 x 2 x 5 factorial with the following factors: seven washing machines (*H1, H2, H3, H4, V(A)1, V(A)2* and *V(I)1*), two wash temperatures (40°C and 60°C), two levels of detergent (with detergent and without detergent) and five levels of washing repeats (10 washes, 20 washes, 30 washes, 40 washes and 50 washes). The factors used in the experimental design and the levels used to examine these factors are summarised in Table 3.10.

[11] "Δ" indicates difference - pronounced "delta" - as discussed in Chapter 2.

TABLE 3.10: FACTORS AND LEVELS USED IN EXPERIMENTAL DESIGN

PROPERTY	FACTOR	LEVEL	VALUES
TENSILE STRENGTH	Washing machine	7	*H1, H2, H3, H4, V(A)1, V(A)2, V(I)1*
	Level of detergent	2	With detergent Without detergent
	Temperature (°C)	2	40 60
	Number of wash cycles	5	10, 20, 30, 40, 50
PRINT DETERIORATION	Washing machine	7	*H1, H2, H3, H4, V(A)1, V(A)2, V(I)1*
	Level of detergent	1	Without detergent
	Temperature (°C)	1	40
	Number of wash cycles	2	10, 20
DEGREE OF FRAYING	Washing machine	7	*H1, H2, H3, H4, V(A)1, V(A)2, V(I)1*
	Level of detergent	1	Without detergent
	Temperature (°C)	1	40
	Number of wash cycles	3	1, 3, 5
SOIL REMOVAL EFFICIENCY	Washing machine	7	*H1, H2, H3, H4, V(A)1, V(A)2, V(I)1*
	Level of detergent	2	With detergent Without detergent
	Temperature (°C)	2	40 60
	Number of wash cycles	1	1

A standard factorial analyses of variance (ANOVA) was performed on all the data to determine the effects of the individual factors comprising washing machine, number of washes, temperature and level of detergent and their simultaneous interaction upon tensile strength, print deterioration, degree of fraying and soil removal efficiency. The Shapiro-Wilk test was carried out to test for non-normality and a Student's t(LSD) calculated to compare treatment means and determine whether differences and interactions were statistically significant. The results for degree of fraying were subjected to rank before an ANOVA was performed. Tukey's studentized range was calculated to compare results in this case.

In the following chapter, the results are discussed. Tables and figures are used to present data and to illustrate significant differences between the effect of the different washing machines and categories of washing machines on the tensile strength, print deterioration and degree of fraying of tested fabrics. Differences in soil removal efficiency will also be compared. Scanning electron microscope photographs will be used to illustrate fibre deterioration where applicable.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The broad aim of this exploratory study was firstly, to assess the effect of repeated washing in different domestic automatic washing machines (seven machines, divided into three categories) on the mechanical damage to textile fabrics and, secondly, to compare the soil removal efficiency of the mechanical wash actions of the different machines. Apart from the *different mechanical wash actions of the individual machines*, the effect of the variables *wash temperature*, *level of detergent* and *number of wash cycles*, was also investigated. This was done by measuring tensile strength, print deterioration and fraying on fabrics laundered repeatedly at 40°C or 60°C, with different levels of detergent in the washing liquid, and comparing the colour change measured on laboratory-soiled test fabrics after washing.

In this chapter, a short overview is given of the experimental design, the statistical analyses of the data is described in detail and the major findings obtained in the empirical study (described in Chapter 3), are reported. The results are discussed in terms of the specific objectives of the study. Based on the above, the null hypotheses laid down in Chapter 1 will be accepted or rejected.

4.2 Overview of experimental design

In the literature review in Chapter 2, the variables or factors that may influence the effect that repeated washing in an automatic domestic washing machine may have on the tensile strength, print deterioration and degree of fraying of plain or printed cotton fabrics, as well as on effective soil removal from laboratory-soiled fabrics, were identified and discussed in depth. The factors considered for this study were *washing machine*, *wash temperature, level of detergent* and *number of wash cycles*. These were the independent variables. The effect of these on the *tensile strength, print deterioration, degree of fraying of* and *efficiency of soil removal from* the test fabrics (dependent variables) was measured under atmospherically controlled laboratory conditions. The factors included in the experimental design and the levels used to examine these factors, are summarised in Table 3.10 (Chapter 3). The response measurements are summarised in Table 4.1.

TABLE 4.1: RESPONSE AND OUTCOME MEASUREMENTS USED IN EXPERIMENTAL DESIGN

RESPONSE	MEASUREMENT
Tensile strength	Load at break (Newton) on Instron Tensile Strength Tester
Print deterioration	Lightness-value measured with colorimeter
Degree of fraying	Visual assessment of fabrics on a five-point ordinal scale
Soil removal efficiency	ΔE (Delta-E) value calculated from measurements for lightness, red/green and blue/yellow values measured with colorimeter

The results of the empirical study will be discussed with reference to the aims that were expressed in Chapter 1.

4.3 Effect of repeated washing on tensile strength

As explained in Chapter 3, samples for tensile strength testing were withdrawn from the wash loads after 10, 20, 30, 40 and 50 washes in each of the washing machines, at a wash temperature of either 40°C or 60°C, and in each case either with or without detergent. All samples were conditioned in the laboratory at standard atmospheric conditions for at least 24 hours. This was done after washing and before preparation of the ten tensile strength test strips for each variable. A total of 1400 test strips were prepared from the washed fabrics.

Samples were tested on an Instron Tensile Strength Tester in the laboratory under standard atmospheric conditions.

During exposure to wash liquid during washing, the tensions between fibres and yarns are released, which can cause consolidation of the fabric and a change in dimensions and fabric count, referred to as relaxation shrinkage. Most of this occurs during the first care cycle (Kadolph & Langford, 1998, Taylor, 1978). Fabric count was determined on a random test sample to detect whether change in the number of threads per cm had taken place during washing as a result of consolidation due to relaxation of fibres and yarns in the washing liquid.

It was found that the mean number of warp yarns per 50mm had increased from 152 in the unwashed fabric to 156,2 in the fabric washed 50 times. (Tensile strength tests were conducted on 50 mm strips of fabric cut in the warp direction). The means for fabrics washed 10, 20 and 50 times were 157,2, 157,0 and 156,2, respectively, indicating that relaxation shrinkage had taken place. A factorial analysis of variance (ANOVA) was used to determine the effect of individual factors, *number of wash cycles* (W), *type of washing machine* (M), *level of detergent used* (D) and *wash temperature* (T), and their simultaneous interactions (WM, WD and MD) on fabric count (Table 4.2).

TABLE 4.2: ANOVA FOR FABRIC COUNT

SOURCE OF VARIATION	FABRIC COUNT		
	DEGREES FREEDOM	MEAN SQUARE	PROBABILITY LEVEL (P)
W (*number of washes*)	3	74,0	<0,01**
M (*washing machine*)	6	10,7	0,13
D (*level of detergent*)	1	26,2	0,04*
T (*temperature*)	1	0,1	0,93
WM	11	17,5	0,01*
WD	2	15,0	0,10
MD	6	7,4	0,32
Error	52	6,18	
Corrected total	88		

** Term highly significant at P<0,01 * Term significant at P<0,05

Table 4.2 indicates a highly significant difference between washed and unwashed fabrics (P<0,01). To compare the significance of differences between fabrics washed 10, 20 and 50 times, Student's t-LSD[12] (P=0,05) was calculated. The results are shown in Table 4.3.

TABLE 4.3: STUDENT'S t-LSD FOR FABRIC COUNT (WARP THREADS PER 50mm) ACCORDING TO NUMBER OF WASHES (P=0,05)

t-GROUPING*		MEAN (THREADS PER 50mm)	SAMPLE SIZE	NUMBER OF WASHES
A		157,2	31	10
A		157,0	19	20
A		156,2	29	50
	B	152,0	10	0

*Means with the same letter are not significantly different (LSD=2,2)

No significant differences were found among the fabrics that were submitted to more than 10 wash cycles, but a highly significant difference was again indicated between washed and unwashed fabrics. Tensile strength test results were thus adjusted to 96.9% of their original values (according to Table 4.3) to allow for the fact that there was a mean of 156,7 threads per 50mm in the washed fabric, as opposed to the 152 threads per 50mm in the unwashed fabric. Tensile strength was measured in Newton (N) per 50mm test strip.

A mean tensile strength of 499N was calculated for fabrics prepared from unwashed fabric. Washed fabrics showed a mean tensile strength of 527N (after the adjustment). Tensile strength means per number of washes are illustrated in Figure 4.1. (Addendum G contains the raw data for tensile strength)

[12] (LSD = Least significant difference)

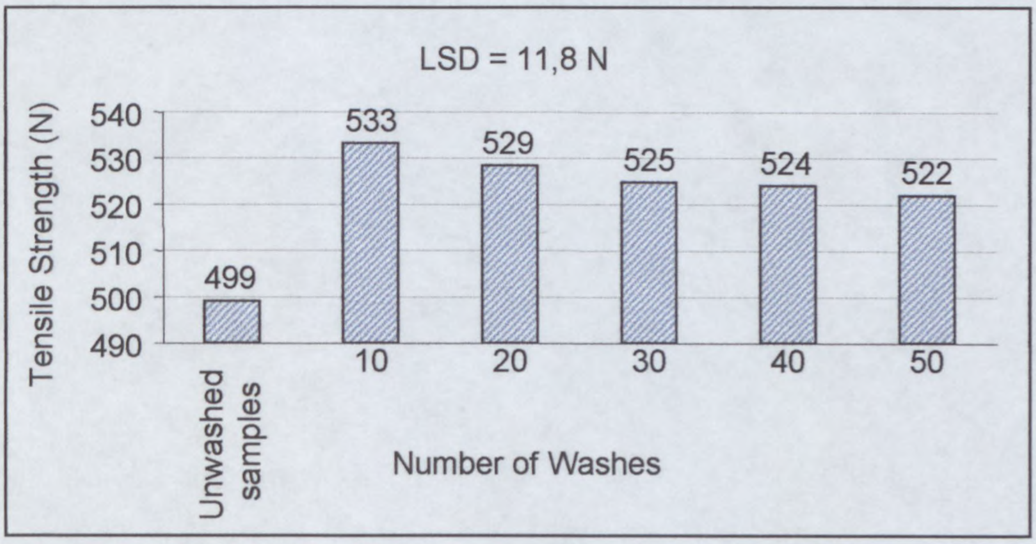

FIGURE 4.1: TENSILE STRENGTH ACCORDING TO NUMBER OF WASHES

As can be seen in Figure 4.1, the tensile strength of the washed fabric differs drastically from that of the unwashed fabrics. Consolidation of yarns in the fabric after washing due to relaxation shrinkage, as reported above, could be the cause of the increase in tensile strength observed in the results. The highly significant difference between the tensile strength of the unwashed and washed fabrics is therefore acknowledged by the researcher. The purpose of this study was the comparison of the effect of the different washing machines on the textile fabric, therefore the rest of the statistical analysis of the tensile strength results will exclude results obtained from the unwashed fabric.

Unwashed and washed fabrics were tested for cuprammonium fluidity. The values obtained were 42,6$(Pa.s)^{-1}$ for the unwashed and 43,9$(Pa.s)^{-1}$ for the fabric washed 50 times. The values were, as is normally expected for scoured and bleached cotton (Refer Addendum D), indicating that no chemical degradation occurred in the fabrics. Any deterioration in the fabric as a result of repeated washing (as might be depicted in loss of tensile strength) could thus be ascribed to mechanical damage.

A factorial analysis of variance (ANOVA) was used to determine the effects of the individual factors *washing machine* (M), *number of wash cycles* (W), *level of* *detergent* (D) and *wash temperature* (T), and their simultaneous interactions upon tensile strength (Table 4.4).

TABLE 4.4: ANOVA FOR TENSILE STRENGTH

SOURCE OF VARIATION	TENSILE STRENGTH (N)		
	DEGREES FREEDOM	MEAN SQUARE	PROBABILITY LEVEL (P)
M (*washing machine*)	6	15615	<0,01**
W (*number of washes*)	4	5020	<0,05*
D (*level of detergent*)	1	39479	<0,01**
T (*temperature*)	1	3344	0,15
MT	6	5280	<0,01**
MD	6	9822	<0,01**
MW	24	3580	<0,01**
TD	1	2334	0,23
TW	4	6800	<0,01**
DW	4	10883	<0,01**
MTD	6	3578	<0,05*
MDW	24	2307	0,07
MTW	24	2488	<0,05*
TDW	4	3101	0,10
MTDW	23	1502	0,53
Error	1239	1589,2	
Corrected total	1377		
Shapiro Wilk	0,1		

** Term highly significant at P < 0,01 * Term highly significant at P < 0,05

The factors *washing machine* (M) and *detergent* (D), as well as the interactions MT, MD and MW, had highly significant effects on tensile strength (P<0,01). *Number of washes* (W) and the interaction MTD showed effects at a significant level (P<0,05). Although significant interactions between TW, DW and MTW were indicated, they could be considered as of no practical importance for the purposes of this study, as T, W and D are controlled variables. No significant difference was indicated for the variable temperature (T), although (as mentioned above) significant interactions were found between TW, MT and MTW. These effects and interactions will be discussed in the following order:

4.3.1 effect of *number of washes*

4.3.2 effect of *washing machine*

4.3.3 effect of *category of washing machine*

4.3.4 effect of *wash temperature* and

4.3.5 effect of *level of detergent* on tensile strength.

4.3.1 Effect of *number of washes* on tensile strength

Figure 4.1 indicates that, after the initial increase in tensile strength from nil to ten washes, fabrics showed a tendency to decrease in tensile strength after every ten wash cycles completed. This could be due to deterioration of textile fibres resulting from the mechanical wash actions that the fabrics were exposed to. Student's t-LSD (P=0,05) was calculated to determine which of these differences in tensile strength are significant. A summary can be seen in Table 4.5.

TABLE 4.5: STUDENT'S t-LSD FOR TENSILE STRENGTH ACCORDING TO NUMBER OF WASHES (P=0,05)

t-GROUPING*		MEAN TENSILE STRENGTH (N)	SAMPLE SIZE	NUMBER OF WASHES
A		533,1	282	10
A	B	528,5	277	20
	B	524,9	279	30
	B	524,2	263	40
	B	522,2	277	50

*Means with the same letter are not significantly different (LSD=6,7N)

Table 4.5 shows that significant differences were only found between the means of all the fabrics laundered 10 times (with and without detergent, at both temperatures) and those laundered more than 20 times. No significant differences were found between the means of fabrics washed 20, 30, 40 and 50 times.

The tensile strength results were analysed further per washing machine, as the purpose of this study was to compare the effect of the wash actions of the various washing machines (and not the effect of washing only). The significant interaction between the variables *washing machine* and *number of washes* (indicated in the ANOVA) also contributed to this decision. The breakdown of tensile strength results per washing machine and number of washes is reported in Table 4.6 and illustrated in Figure 4.2 below.

TABLE 4.6: TENSILE STRENGTH ACCORDING TO WASHING MACHINE AND NUMBER OF WASHES

WASHING MACHINES	TENSILE STRENGTH (N)				
	10 washes	**20 washes**	**30 washes**	**40 washes**	**50 washes**
H1	545	542	523	521	516
H2	539	540	532	537	550
H3	525	519	533	530	540
H4	546	530	531	531	528
Mean *H*	538,8	532,8	529,8	529,8	533,5
V(A)1	515	531	516	514	501
V(A)2	535	522	519	508	499
Mean *V(A)*	525,0	526,5	517,5	511,0	500,0
V(I)1	525	517	520	529	520
Mean *V(I)*	525	517	520	529	520

(LSD = 17,5)

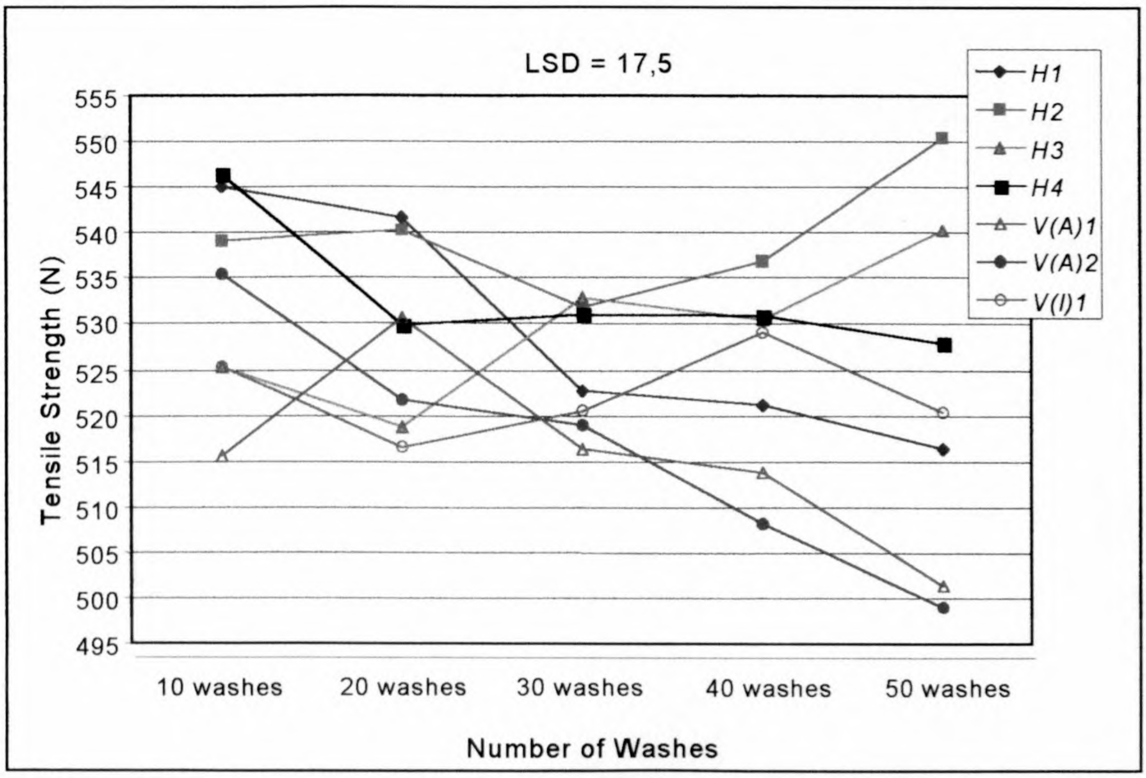

FIGURE 4.2: TENSILE STRENGTH ACCORDING TO WASHING MACHINE AND NUMBER OF WASHES

Figure 4.2 shows clearly that it is only after 30 washes that results from categories of machines begin to group together in tensile strength per *washing machine* per *number of washes*. The spreading of results also becomes more obvious with an increased number of washes, and is best illustrated in the results obtained after 50 washes, where differences in the effect of the different washing machines become most obvious. The effect of the variable *washing machine* on the tensile strength of fabrics after 50 washes will be discussed in paragraph 4.3.2. Differences in the effect of category of washing machine are also indicated. This was investigated and will be discussed in paragraph 4.3.3.

4.3.2 Effect of *washing machine* on tensile strength

Durablility of textiles can be compared by measuring tensile strength (Smith & Block, 1982). Any drop in tensile strength signals a possible change in fabric structure, fibre content or finish (Taylor, 1990). A change in tensile strength after repeated washing could thus be an indication of fabric and/or fibre detrioration due to the mechanical wash action of the washing machine.

In the discussion on the effect of the variable *number of washes* on tensile strength (4.3.1), it was concluded that the tensile strength values after 50 washes gave the best indication of the effect of the variable *washing machine* on washed fabrics. These results are shown in Table 4.7.

TABLE 4.7: MEAN TENSILE STRENGTH VALUES AFTER 50 WASHES ACCORDING TO WASHING MACHINE AND CATEGORY OF WASHING MACHINE

WASHING MACHINE*	MEAN TENSILE STRENGTH (N)	WASHING MACHINE CATEGORY**	MEAN TENSILE STRENGTH PER CATEGORY (N)
H1	516	*H*	533,8
H2	550	*H*	
H3	540	*H*	
H4	528	*H*	
V(A)1	501	*V(A)*	500,2
V(A)2	499	*V(A)*	
V(I)	520	*V(I)*	520,4

*LSD = 17,5 **LSD = 28,4

Table 4.7 indicates apparent differences among the effects of washing in the different washing machines on tensile strength. To determine whether the differences between the mean tensile strength values from the different washing machines are significant, Student's t-LSD (P=0,05) was calculated. The results are shown in Table 4.8.

TABLE 4.8: STUDENT'S t-LSD FOR TENSILE STRENGTH (FABRICS WASHED 50 TIMES) ACCORDING TO WASHING MACHINE (P=0,05)

t-GROUPING*				MEAN TENSILE STRENGTH (N)	SAMPLE SIZE	WASHING MACHINE
A				550	40	*H2*
A	B			540	39	*H3*
	B	C		528	39	*H4*
		C		516	39	*H1*
		C		520	40	*V(I)1*
			D	501	40	*V(A)1*
			D	499	40	*V(A)2*

*Means with the same letter are not significantly different (LSD = 17,5N)

Table 4.8 shows that there are no significant differences between the tensile strength of fabrics washed 50 times in washing machines *H2* and *H3*, neither between fabrics from machines *H3* and *H4,* and also not between fabrics from machines *H1* and *H4*.. Fabrics from machine *H1* and *H4* did also not differ significantly from those washed in machines *V(I)1*. Among fabrics washed in the horizontal drum machines the tensile strength values from machine *H2* were significantly higher than those from machines *H1* and *H4*. The horizontal drum machines can thus be arranged in the following order: *H2, H3, H4, H1*. *H2* produced the highest and *H1* the lowest mean tensile strength of the four. Although all these differences are not significant, they are considered relevant for the purpose of this discussion.

No significant difference was found between the fabrics from machines *V(A)1* and *V(A)2*. The tensile strength results from fabrics washed in the two machines differed significantly from the rest. The findings discussed above are depicted in Figure 4.3.

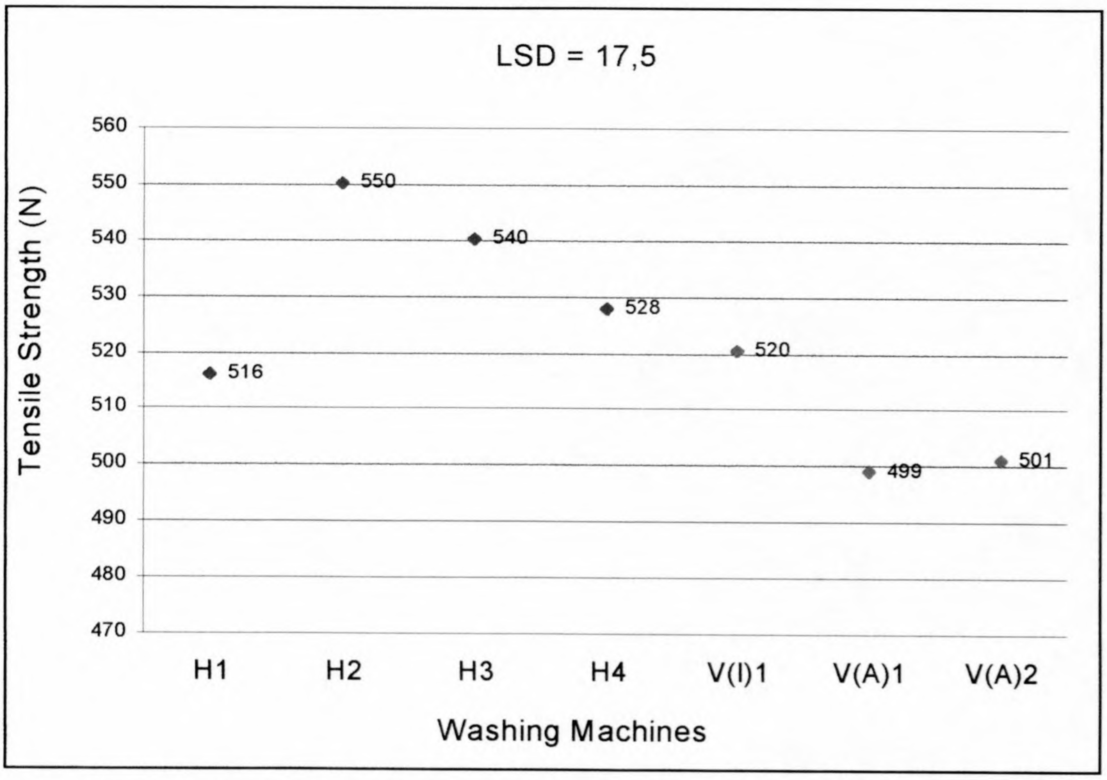

FIGURE 4.3: MEAN TENSILE STRENGTH VALUES AFTER 50 WASHES ACCORDING TO WASHING MACHINE

From Figure 4.3, the differences in the effect of the variable *washing machine,* and also *category of washing machine,* are clear. This will be discussed in paragraphs 4.3.2.1, 4.3.2.2 and 4.3.3.1.

4.3.2.1 Effect of washing in horizontal drum machines on tensile strength

The mean tensile strength results of the fabrics washed 50 times in the horizontal drum machines did not differ significantly from the mean for this category of machines, neither from the mean obtained after 10 washes. However, differences among the mean values after 50 washes obtained from the different machines are clearly visible in Figure 4.3 and can be arranged in the following order with regard to tensile strength after 50 washes: *H2* (highest), *H3, H4, H1*(lowest).

From Table 4.8 and the discussion that followed, it is clear that among the horizontal drum machines, the following individual differences between machines are significant: Between machine *H1* and *H2, H1* and *H3,* and *H2* and *H4.* In the following paragraphs, an attempt will be made to establish whether these differences can be explained with regard to the technical features of the individual horizontal drum machines (as explained in Chapter 3).

Although the mechanical wash actions of the four horizontal drum machines are basically the same, the wash programmes of the machines differ noticeably with regard to time as well as drum speed, drum turning sequence and drum size of the machines. According to Penney (1999) the distance that the washing falls into the wash liquid is one of the most important factors that influence soil removal efficiency. As this has an influence on the severity of the wash action, the assumption could be made that it would also have an influence on fabric deterioration. The technical details describing the horizontal drum machines and their mechanical wash actions and wash programmes are summarised in Table 3.6(a) and (b), in Chapter 3. Some of the features that directly affect the amount of agitation and stress in the drum during washing, and consequently the severity of the wash action, are ranked (ranking 1=highest and 4=lowest of the four machines) and compared visually in Figure 4.4.

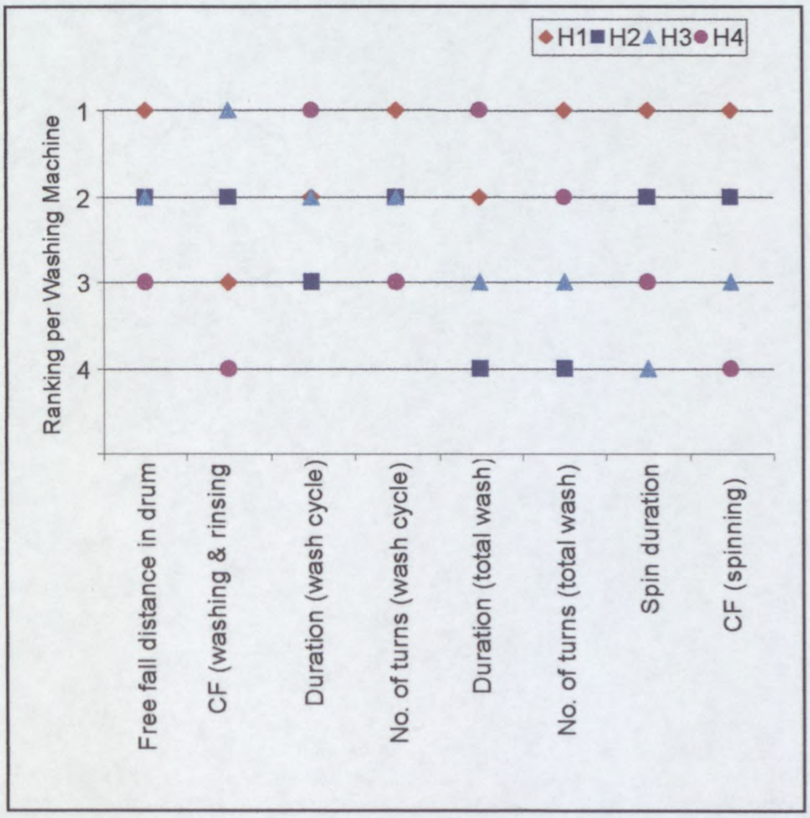

FIGURE 4.4: RANKING OF WASHING MACHINE PROGRAMMES ACCORDING TO TECHNICAL FEATURES (Refer Table 3.6(a) and (b), Chapter 3)

Figure 4.4 and Table 3.6(a) show that machine *H1*, from which washed fabrics exhibited the lowest tensile strength, also has the largest drum volume, lowest water consumption, highest free fall distance, highest number of turns per wash cycle, highest spin speed and second longest total wash programme. The highest centrifugal force during spinning is also developed in this drum and it has the longest spin duration. All the above indicate that this machine has the most severe wash action of the four horizontal drum machines, which probably caused the fabrics washed in this machine to exhibit the lowest tensile strength after 50 washes.

Machine *H2* yielded fabrics with the highest tensile strength after washing. This machine has the shortest wash programme and the lowest number of turns per wash in relation to the other machines. The washing is thus submitted to the wash liquid and mechanical movement for a much shorter period than in the other machines. The fact that the centrifugal force developed in this machine during spinning was the second highest of the horizontal drum machines, does not seem to have had a marked influence on tensile strength.

The tensile strength of the fabrics obtained from machine *H3* was slightly lower, but did not differ significantly from those washed in machine *H2*. It is important to note that the fabrics washed in machines *H2* and *H3* had a significantly higher mean tensile strength than fabrics washed in *H1* and *H4*. Figure 4.4 show that the mutual difference between the first two machines and the latter two is again a shorter wash duration and smaller number of drum turns per wash.

Fabrics washed in machine *H3* showed a significantly lower reduction in tensile strength than fabrics washed in machine *H1*. When the wash programmes of these two machines are compared, there is a wash duration difference of only 13 minutes, but machine *H1* seems to have a more severe wash action with regard to free fall distance, spin speed, centrifugal force in the drum during spinning and number of turns per wash cycle. The combination of these factors, together with the longer total wash duration, caused fabrics in machine *H1* to deteriorate more during repeated washing.

Machine *H4* is depicted in Figure 4.4 as the machine in which the lowest amount of mechanical agitation is created in the drum during washing (lowest free fall distance, lowest CF during washing and spinning, lowest number of turns per wash cycle). However, when compared with the other washing machines, machine *H4* did not cause significantly less reduction in tensile strength during washing. Fabrics from this machine did in fact have a lower mean tensile strength than those from machine *H2* and no significant difference was found between the results from *H1* and *H4*. The only factors in the wash programmes that correlate directly with these findings are the wash cycle duration and total wash duration (and consequently also the number of turns of the drum per wash). *H4* has a less severe wash action, but significantly longer wash programme than machine *H2* and caused significantly more fabric deterioration. Furthermore, it can be said that machines *H1* and *H4*, the two machines with the longest wash programmes, produced fabrics with the lowest mean tensile strength after 50 washes.

4.3.2.2 Effect of washing in vertical drum machines on tensile strength

When the effect of washing in the two categories of vertical drum machines, is compared with regard to tensile strength, the following is noted:

Fabrics washed in the impeller type machine did not show a significant decrease in tensile strength from 10 to 50 washes. A significant difference, however, can be seen between the mean tensile strengths of the fabrics washed in the impeller type machine and the mean of the fabrics washed in the agitator type machines. The agitator type machines (mean 500N after 50 washes) caused more deterioration to the test fabrics than the impeller type machines (mean 520N after 50 washes). In the agitator type machines, the wash action is caused by an agitator that physically produces the movement of the washing, while in the impeller type machines, the wash load is swirled around inside the machine by the action of the impeller in the base of the drum. The difference in the severity of the two actions is obvious in the effect on tensile strength of fabrics washed 50 times (Refer Figure 4.3).

As mentioned above, the tensile strengths of fabrics washed in the agitator type machines show almost no difference, indicating that the different shapes of the agitators of the two machines do not have an influence on deterioration in tensile strength.

Based on the above results, it seems imperative to focus on the category of washing machine as a variable that could influence tensile strength. The effect of the variable *category of washing machine* was further investigated and will be discussed in 4.3.3.

4.3.3 Effect of *category of washing machine* on tensile strength

Table 4.7 shows clearly that differences exist not only among the the tensile strength of fabrics washed in the different washing machines as separate entities, but also among the categories into which these washing machines can be classified. An ANOVA was performed on the results, using *category of washing machine* as source of variation instead of *washing machines*. The purpose was to determine the effect of category of washing machine as individual factor, as well as possible simultaneous interactions with other factors, on tensile strength of washed fabrics (Table 4.9).

TABLE 4.9: ANOVA FOR TENSILE STRENGTH *(CATEGORY OF WASHING MACHINE* AS SOURCE OF VARIATION)

SOURCE OF VARIATION	TENSILE STRENGTH (N)		
	DEGREES FREEDOM	MEAN SQUARE	PROBABILITY LEVEL (P)
C (category of *washing machine*)	2	39881	<0,01**
W (*number of wash cycles*)	4	5106	<0,05
D (*level of detergent*)	1	39373	<0,01**
T (*temperature*)	1	3344	0,15
CT	2	10341	<0,01**
CD	2	13009	<0,01**
CW	8	40230	<0,01**
TD	1	2387	0,22
TW	4	6794	<0,01**
DW	4	10883	<0,01**
CTD	2	1999	0,28
CDW	4	3143	0,09
CTW	8	1471	0,49
TDW	4	3143	0,10
CTDW	7	1394	0,54
ERROR	1239	1589,2	
Corrected Total	1377		
Shapiro Wilk	0,15		

** Term highly significant at P < 0,01

The factor *washing machine category* (C) and interactions CT and CD had highly significant effects on tensile strength (P<0,01). Highly significant effects on tensile strength were indicated for the factor level of detergent (D) as well as for the interactions TW, CW and DW. This will be discussed in 4.3.4 and 4.3.5 or are not of practical importance to this study.

The effect of the factor *category of washing machine* on the mean tensile strength of fabrics washed 10, 20, 30, 40 and 50 times is illustrated in Figure 4.5. It is clear that differences exist among the results from the three categories of machines.

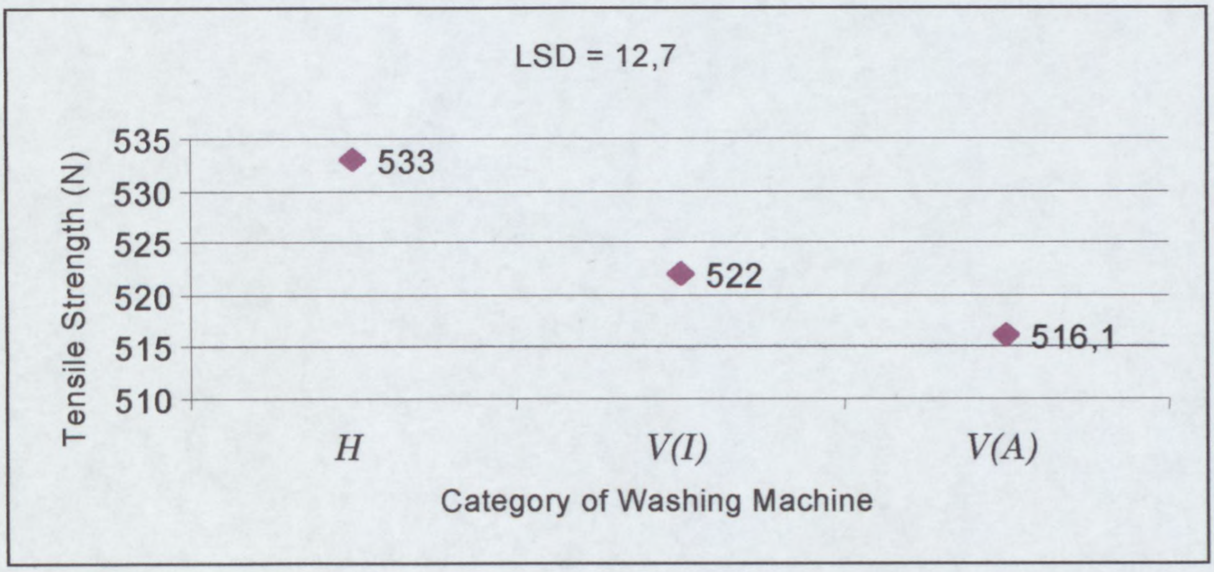

FIGURE 4.5: MEAN TENSILE STRENGTH VALUES AFTER 10, 20, 30, 40 AND 50 WASHES ACCORDING TO CATEGORY OF WASHING MACHINE

Student's t-LSD (P=0,05) was calculated to establish how significant the differences among the mean tensile strength of fabrics from the different washing machine categories are. Results are shown in Table 4.10.

TABLE 4.10: STUDENT'S t-LSD FOR TENSILE STRENGTH ACCORDING TO CATEGORY OF WASHING MACHINE (P=0,05)

t-GROUPING*		MEAN TENSILE STRENGTH (N)	SAMPLE SIZE	CATEGORY OF WASHING MACHINE
A		533,0	793	*H*
A	B	522,0	189	*V(A)*
	B	516,1	396	*V(I)*

*Means with the same letter are not significantly different (LSD = 12,7N)

As was described in paragraph 4.3.1 and 4.3.2, results per category of washing machine were further analysed according to number of washes. The mean tensile strength after 50 washes is depicted per *washing machine category* in Figure 4.6.

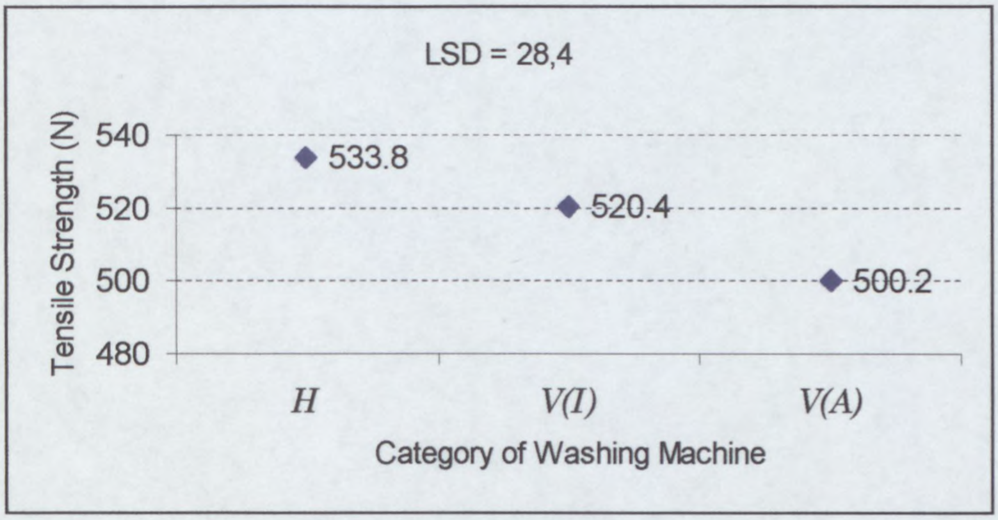

FIGURE 4.6: MEAN TENSILE STRENGTH VALUES AFTER 50 WASHES ACCORDING TO CATEGORY OF WASHING MACHINE

Student's t-LSD (P=0,05) was calculated to establish if the differences in mean tensile strength of fabrics washed 50 times are also significant for the factor *washing machine category*. Results are shown in Table 4.11.

TABLE 4.11: STUDENT'S t-LSD FOR TENSILE STRENGTH (AFTER 50 WASHES) ACCORDING TO CATEGORY OF WASHING MACHINE (P=0,05)

t-GROUPING*		MEAN TENSILE STRENGTH (N))	SAMPLE SIZE	WASHING MACHINE CATEGORY
A		533,8	157	*H*
A	B	520,4	40	*V(I)*
	B	500,2	80	*V(A)*

*Means with the same letter are not significantly different (LSD = 28,4N)

Both Tables 4.10 and 4.11 show clearly that the tensile strength of fabrics washed in washing machines from category *H* (horizontal drum type) differed significantly (P=0,05) from fabrics washed in the machines from category *V(A)* (agitator type). The mean tensile strength of the fabrics washed in the washing machine from category *V(I)* (impeller type) was lower than that of the fabrics from the horizontal drum machines and higher than that of the agitator type machines. Although these differences are clearly noticeable in Figures 4.5 and 4.6, they are not significant at the 95% confidence level (P=0,05).

4.3.3.1 Tensile strength results according to category of washing machine

When the tensile strength means of fabrics washed in the different categories of washing machines (horizontal drum, vertical drum impeller type and vertical drum agitator type) are compared, significant differences can be observed. Although the mean tensile strength of fabrics washed in the horizontal drum machines did not differ significantly from that of fabrics washed in the vertical drum impeller type machine, the results from both the vertical drum impeller type and horizontal drum type machines differed significantly from those from the vertical drum agitator type machines. This indicates that the mechanical wash action caused by the horizontal drum type, turning on a horizontal axis (where the washing gets lifted by the rolling action of the drum and dropped to fall free into the wash liquid) is much less severe than that of the vertical drum agitator type machines (where the washing is moved around physically by the agitator). The effect of the mechanical wash action of the vertical drum impeller type machine on tensile strength of textile fabrics, compares well with that of the horizontal drum machines (no significant difference found between the tensile strength means). In the impeller type machines, washing is swirled around in the vertical drum by the actions of the impeller and moving drum, but is not physically manipulated by a device such as an agitator. The effect is less severe with regard to possible fibre or fabric deterioration.

When it is taken into account, however, that the mean tensile strength for fabrics washed 10 times in the horizontal drum machines is 533N (Table 4.6), it can be emphasised that the fabrics washed in the horizontal drum machines (tensile strength after 50 washes: 533N) do not show a significant decrease in tensile strength from 10 to 50 washes. The same observation can be made regarding the vertical drum impeller type machine (tensile strength after 50 washes: 520N). Fabrics washed in the vertical drum agitator type machines did show a significant decrease in tensile strength (tensile strength after 50 washes: 500N), indicating possible fibre or fabric deterioration. This confirms that the mechanical wash action of the agitators in these machines is more severe than that of the machines in the other two categories. The tensile strength of fabrics washed in the different vertical drum agitator type machines shows almost no difference, indicating that the different shapes of the agitators of the two machines do not have an influence on fabric deterioration.

4.3.4 Effect of *wash temperature* on tensile strength

To reflect consumer practice in home laundering, fabrics were washed at 40°C as well as 60°C (Kadolph, 2000, Kadolph & Langford, 1998, Lever Pond's, 1999). As discussed in Chapters 2 and 3, it was expected that the higher temperature wash water would further fabric deterioration. The results, however, indicate that fabrics washed at 60°C showed no significant difference in tensile strength from those washed at 40°C (P=0,15). The results are depicted in Table 4.12.

TABLE 4.12: MEAN TENSILE STRENGTH FOR FABRICS WASHED AT 40°C AND 60°C

NUMBER OF TIMES WASHED	MEAN TENSILE STRENGTH (N)		
	Wash temp.: 40°C	Wash temp.: 60°C	Comparison of tensile strength of samples washed at 40°C and 60°C
All washed fabrics*	525	528	No significant difference
10 washes**	537	530	No significant difference
20 washes**	531	526	No significant difference
30 washes**	524	526	No significant difference
40 washes**	517	532	No significant difference
50 washes**	516	528	No significant difference

*LSD = 4,21 **LSD = 9,4

4.3.5 Effect of *level of detergent* on tensile strength

The mean tensile strength of fabrics washed without detergent was significantly lower than those washed with detergent. The results are illustrated in Figure 4.7.

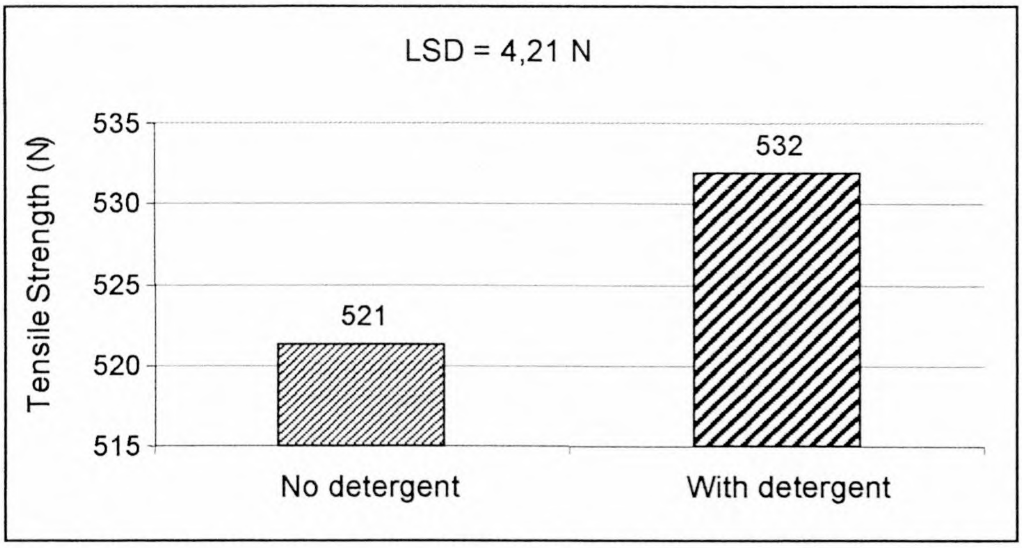

FIGURE 4.7: TENSILE STRENGTH ACCORDING TO LEVEL OF DETERGENT

The above confirms results reported by Ulrich and Mohamed (1982) who found more severe deterioration in textile fibres occurring in fabrics washed in water only, compared to fabrics washed in water containing detergent. According to Taylor (1978) the detergent in the washing liquid acts as lubricator. A high incidence of suds in the wash liquid, however, can also lead to a "cushioning" effect, which could prevent fibre damage to a certain extent (Plumbley, 1999). The absence of this lubricating or "cushioning" effect could lead to the wash action being more severe and might be the reason why the fabrics that were washed without detergent, showed decreased tensile strength after washing.

Apart from the fact that the total mean tensile strength of fabrics washed with and without detergent differed significantly, the ANOVA for tensile strength (Table 4.4) also showed a highly significant interaction between the factors, *level of detergent* (D) and *washing machine* (W). Results for the mean tensile strength analysed per washing machine for fabrics washed with and without detergent are shown in Table 4.13.

TABLE 4.13: MEAN TENSILE STRENGTH PER WASHING MACHINE FOR FABRICS WASHED WITH AND WITHOUT DETERGENT

WASHING MACHINE	TENSILE STRENGTH AFTER WASHING WITH NO DETERGENT (N)	TENSILE STRENGTH AFTER WASHING WITH DETERGENT (N)
H1	531	528
H2	528	551*
H3	514	545*
H4	527	540*
MEAN: *H*	525,1	540,8*
V(A)1	517	514
V(A)2	518	515
MEAN: *V(A)*	517,6	514,7
V(I)	517	531*
MEAN: *V(I)*	517,0	531,0*

* Indicates a significant difference (p<0,05) between fabrics washed with detergent and without detergent (LSD=11,1)

From Table 4.13 it is clear that there are significant differences (P<0,05) with regard to the horizontal drum machines, between the tensile strength of fabrics washed with detergent and those washed without detergent in the three washing machines *H2*, *H3* and *H4*. No significant difference could be found between fabrics washed with or without detergent in washing machine *H1*. In the case of the vertical drum machines, a significant difference was found between fabrics washed with or without detergent in washing machine *V(I)* (Category V(I)). Fabrics washed in machines *V(A)1* and *V(A)2* (Category V(A)) did not differ significantly in tensile strength. These results are depicted in Figure 4.8.

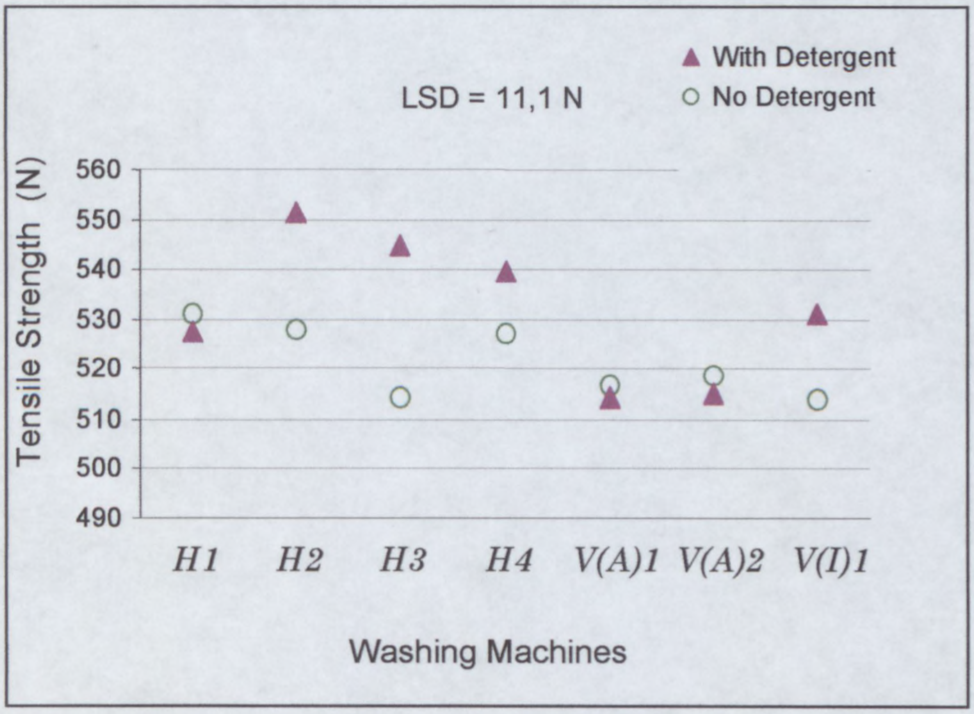

FIGURE 4.8: TENSILE STRENGTH ACCORDING TO WASHING MACHINE AND LEVEL OF DETERGENT

The mean tensile strengths (per category of washing machine) for fabrics washed with or without detergent, were also calculated from Table 4.13. The results are illustrated in Figure 4.9.

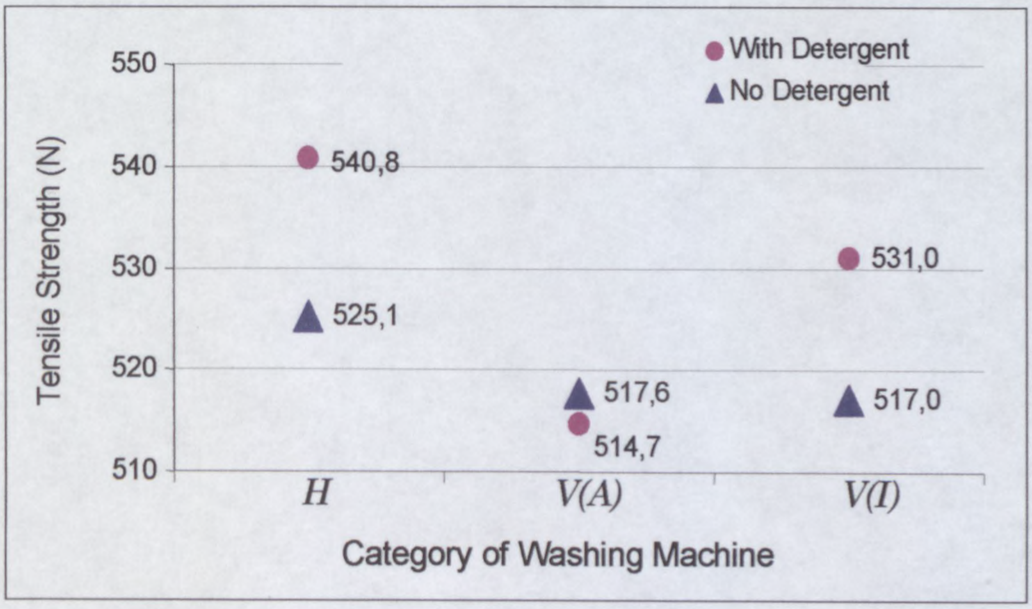

FIGURE 4.9: TENSILE STRENGTH ACCORDING TO CATEGORY OF WASHING MACHINE AND LEVEL OF DETERGENT

In most of the horizontal drum machines, as well as the vertical drum impeller type machine, the tensile strength of fabrics washed with detergent was higher than that of those washed with no detergent in the wash solution. Table 4.7 shows that these machines are also the ones that caused less fabric deterioration, from which the assumption was made that they have a less severe mechanical wash action. In the vertical drum agitator type machines, no significant difference was found in the effect of washing with or without detergent (Figure 4.9). From this it was concluded that the cushioning effect described by Penney (1999) is inhibited when the wash action is more severe.

When the effect of the variable *number of washes* on tensile strength was investigated (4.3.1), results showed that no significant differences existed among fabrics washed 20, 30, 40 and 50 times (Table 4.5). Results also showed that the differences in the effect of washing in the different washing machines were most obvious in the tensile strength results of fabrics washed 50 times (Figure 4.2). The mean tensile strength of fabrics washed 10 times differed significantly from fabrics washed 50 times.

The mean tensile strength of fabrics per washing machine per level of detergent was therefore compared for fabrics washed 10 times and 50 times. Results are shown in Table 4.14.

TABLE 4.14: MEAN TENSILE STRENGTH VALUES FOR FABRICS WASHED 10 TIMES AND 50 TIMES WITH AND WITHOUT DETERGENT PER WASHING MACHINE AND WASHING MACHINE CATEGORY

WASHING MACHINE	TENSILE STRENGTH (N) OF FABRICS WASHED 10 TIMES		TENSILE STRENGTH (N) OF FABRICS WASHED 50 TIMES	
	No detergent	With detergent	No detergent	With detergent
H1	544	546	512	520
H2	512	566*	558	542
H3	509	544*	529	550
H4	536	557	539	517
Mean:*H1*	**525**	**554***	**535**	**533**
V(I)	495	556*	514	527
Mean: *V(I)*	**495**	**556***	**514**	**527**
V(A)1	506	525	507	496
V(A)2	532	539	515	482*
Mean: *V(A)*	**519**	**532**	**511**	**489**

*Indicates significant difference(P<0,05) (LSD = 24,7)

After 50 washes, the difference between fabrics washed with and without detergent was not significant for any of the washing machines or categories of washing machines. It is important to note, however, that after 10 washes a significant difference existed between the fabrics washed with and those washed without detergent in some of the horizontal drum and vertical drum impeller type machines. No significant difference was found between fabrics washed with and without detergent in the vertical drum agitator type machines. From this it can be deduced that it was the difference in tensile strength of fabrics after 10 washes that caused the total means (reported in Table 4.13) for fabrics washed in the horizontal drum and impeller type machines to differ significantly.

It seems that, in the early stages, after only a few washes, the fibres of the fabrics which were washed in the horizontal drum and vertical drum impeller type machines might have been lubricated to such an extent by the detergent present in the wash solution, that the consolidation of fibres during the relaxation shrinkage process was enhanced. This, in turn, could have caused the tensile strength of these fabrics to increase more than that of those fabrics washed without detergent. With the progression of the washing cycles, this effect was probably cancelled, and the fabrics from both categories ended up with more or less the same tensile strength. In the vertical drum machines, where the mechanical wash action has been shown to be more severe and where the water level is higher, the effect was not noticed. The continuous rolling motion of the wash load in horizontal drum machines, together with the longer wash times, result in a higher degree of foam formation in the machine than is found in vertical drum machines. More foam in the wash liquid could cause the wash action to be less severe, as described in 4.3.5 (Plumbley, 1999).

4.4 Effect of repeated washing on the print deterioration of a textile fabric

Whenever printed textile fabrics are subjected to washing, some colour loss takes place during the earlier wash cycles. Merkel (1991) defines this change in colour, caused by localised abrasive wear, as "frosting". The mechanical agitation which occurs during laundering, causes the binding strength of the pigment print attached to the fibres to deteriorate, which may lead to colour loss and a faded appearance (Kadolph, 1998, Smith & Block, 1982, Hall, 1978). For the purpose of this study, this is referred to as print deterioration. The extent of the deterioration is influenced by washing temperature, type and level of detergent, quality or fastness of the printing, severity of the washing action and various other factors not related to this investigation.

To establish whether the individual wash actions of the washing machines compared in this study affect print deterioration differently, printed fabrics were washed at 40°C without detergent. The variables, *temperature* and *level of detergent*, were thus kept constant to assure that only the effect of the mechanical wash action was measured. Fabric samples were subjected to 10 and 20 wash cycles, conditioned for 24 hours and then evaluated for print *deterioration* by means of colour measurement with a colorimeter. Five measurements per fabric were taken. All measurements were taken on the plain background colour of the print. (Raw data given in Addendum H).

Colorimeter readings showed that control measurements were spread unevenly for measurements of red/green values (a*) and blue/yellow values (b*). These variations could be the result of small differences in the plain background colour of the printed fabric, which were not detected visually. The values for lightness (L*) were more consistent and showed results comparable with visual observations of the extent of print deterioration in the laundered fabrics. Only the lightness results were thus used as an indication of print deterioration during the comparison of the fabrics.

A factorial analysis of variance was used to determine the effect of the variables *washing machine* and *number of wash cycles* on print deterioration (lightness values). Table 4.15 represents a summary of the effects of these factors according to the analysis of variance (ANOVA).

TABLE 4.15: ANOVA FOR PRINT DETERIORATION

SOURCE OF VARIATION	LIGHTNESS VALUE (L*)		
	DEGREES FREEDOM	MEAN SQUARE	PROBABILITY LEVEL (P)
M (*washing machine*)	6	7,8	<0,01**
W (*number of wash cycles*)	2	19,2	<0,01**
MW	12	2,0	<0,01**
Error	84	0,126	
Corrected total	104		
Shapiro Wilk	0,05		

** Term highly significant at $P < 0,01$

Both the factors *washing machine* and *number of wash cycles*, had a highly significant effect on print deterioration and an interaction was found between *washing machine* and *number of wash cycles* ($P<0,01$). Student's t-LSD ($P=0,05$) was calculated to determine the significance of differences between results obtained from the different washing machines (Table 4.16).

TABLE 4.16: STUDENT'S t-LSD FOR PRINT DETERIORATION (LIGHTNESS VALUES) ACCORDING TO *WASHING MACHINE* (P=0,05)

t-GROUPING*					LIGHTNESS VALUE (L*)	SAMPLE SIZE	WASHING MACHINES
A					39,0	15	*V(A)2*
	B				38,6	15	*V(A)1*
		C			37,9	15	*H4*
		C			37,8	15	*H3*
		C			37,7	15	*H1*
			D		37,3	15	*H2*
				E	36,9	15	*V(I)*

*Means with the same letter are not significantly different (LSD = 0,25)

Table 4.16 shows no significant differences among the results from machines *H4*, *H3* and *H1*. A significant difference was found between *H2* and the rest of the horizontal drum machines, which raises the question whether reduced print deterioration resulting form *H2* could be the result of the shorter wash programme and thus shorter exposure time to the wash liquid (Refer comparison of technical features of horizontal drum machines in Chapter 3). A significant difference was also indicated between the results from two vertical drum agitator type machines (*V(A)1* and *V(A)2*). The different actions of the agitators in these machines are explained in Chapter 3. It seems that the continuous motion in one direction of the agitator in machine *V(A)2* has a more severe effect on the print deterioration of a fabric than the forward and reverse turn action of the agitator in machine *V(A)1*. The mechanical wash action of the impeller type vertical drum machine seems to have the least effect on textile print deterioration, as machine *V(I)1* differed significantly from all the other machines, showing much less print deterioration. The print deterioration results are shown in Figure 4.10.

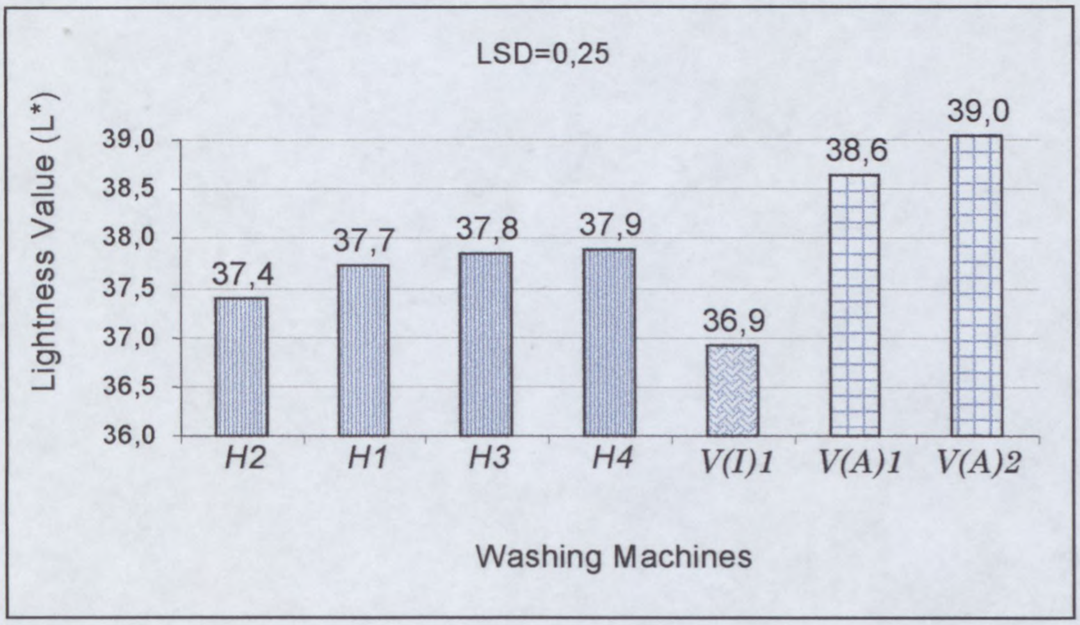

FIGURE 4.10: PRINT DETERIORATION ACCORDING TO WASHING MACHINE (P<0,05)

When the machines are compared per category, a significant distinction can be made between the three categories, as is clearly depicted in Figure 4.10. To confirm this assumption, an analysis of variance was performed on the data to test the effect of the factor, *category of washing machine* (C), instead of individual *washing machines* (M), on print deterioration. The ANOVA is shown in Table 4.17

TABLE 4.17: ANOVA FOR PRINT DETERIORATION (*CATEGORY OF WASHING MACHINE* AS SOURCE OF VARIATION)

SOURCE OF VARIATION	LIGHTNESS VALUE (L*)		
	DEGREES FREEDOM	MEAN SQUARE	PROBABILITY LEVEL (P)
C (category of washing machine)	2	21,8	<0,01**
W (number of wash cycles)	2	19,2	<0,01**
MW	4	25.5	<0,01**
ERROR	92	0,142	
Corrected total	104		

** Term highly significant at P < 0,01

The above confirms the assumption that *category of washing machine* (C) as a factor also has a highly significant effect on print deterioration. The Student's t-LSD (P=0,05) was calculated as shown in Table 4.18. The ANOVA also indicated a highly significant effect of the factor, *number of washes* (W), and an interaction between factors C and W. This will be discussed later.

TABLE 4.18: STUDENT'S t-LSD FOR PRINT DETERIORATION (LIGHTNESS VALUES) ACCORDING TO *CATEGORY OF WASHING MACHINE* (P=0,05)

t-GROUPING*			(L*) LIGHTNESS VALUE	SAMPLE SIZE	CATEGORY OF WASHING MACHINES
A			38,8	30	*V(A)*
	B		37,7	60	*H*
		C	36,9	15	*V(I)*

*Means with the same letter are not significantly different (LSD = 0,25)

The vertical drum impeller type machine caused the least print deterioration and the vertical drum agitator drum machines the most. The horizontal drum machines can be categorised in between the two vertical drum types. Student's t-LSD, as calculated in Table 4.18, confirms that these differences are all significant at a 95% confidence level (P=0,05).

As mentioned, the ANOVA indicated a significant interaction between the effect of the factors C (category of washing machine) and W (number of washes) on print deterioration. To investigate, print deterioration results (L*) were analysed according to these factors. The results are illustrated in Figure 4.11.

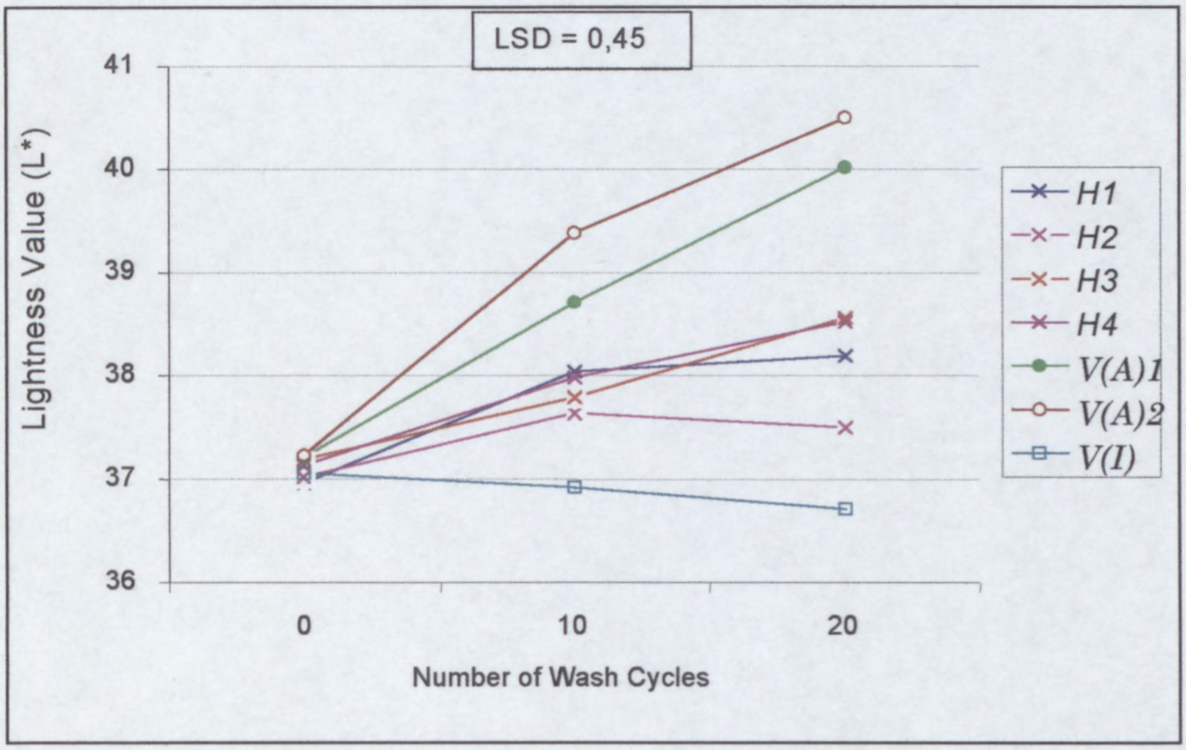

FIGURE 4.11: PRINT DETERIORATION ACCORDING TO WASHING MACHINE AND NUMBER OF WASH CYCLES (P<0,05)

Figure 4.11 shows that the vertical drum impeller type machine caused the least print deterioration and the two vertical drum agitator type machines the most. The graph also indicates that significant differences in lightness values already existed among fabrics washed ten times in the horizontal drum machines, when compared to the vertical drum agitator types and the vertical drum impeller type machines. The speed with which the prints deteriorated seems to differ for the different mechanical wash actions.

Figure 4.12 shows a histogram in which the effects of the first 10 washes and that of the next 10 washes are illustrated more clearly. This shows that the colour of the fabrics washed in the vertical drum agitator type machines continued to deteriorate after 10 washes, whereas the fabrics washed in the horizontal drum machines deteriorated at a slower pace and those washed in the vertical drum impeller type machines did not deteriorate further.

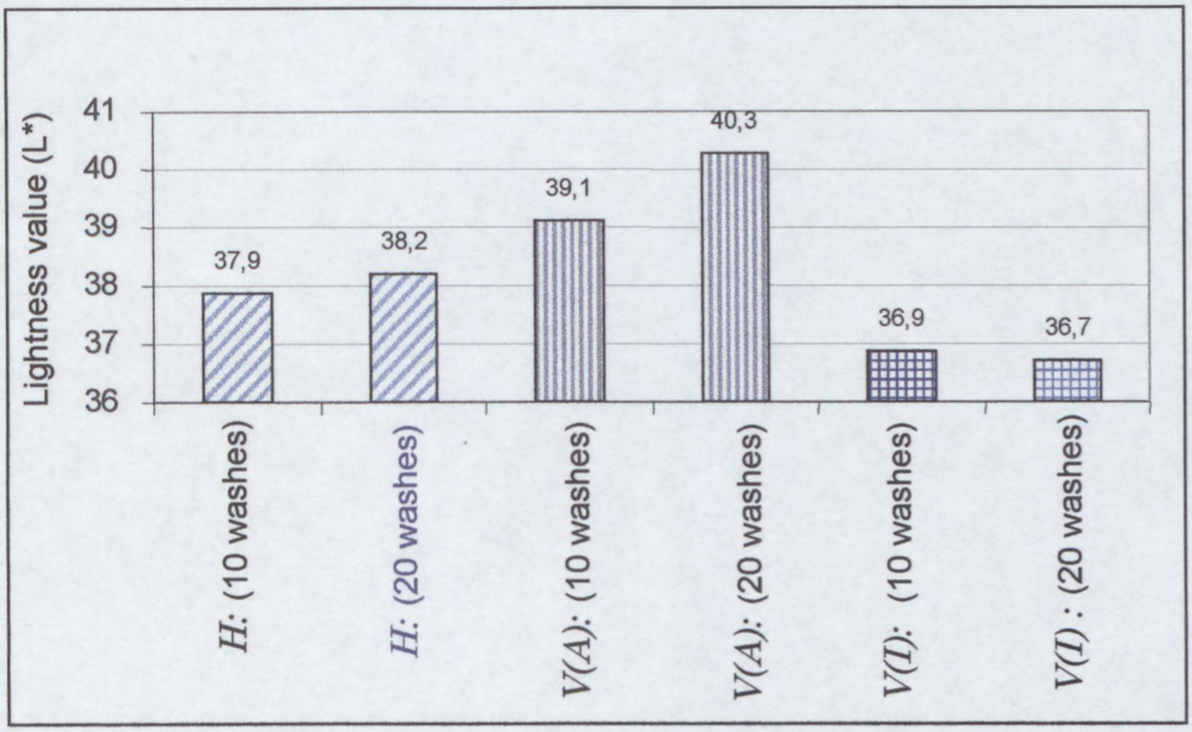

FIGURE 4.12: PRINT DETERIORATION ACCORDING TO CATEGORY OF WASHING MACHINE AND NUMBER OF WASHES

It can be concluded that fabrics washed in the vertical drum agitator type machines will show visible signs of deterioration in visual appearance much sooner, and the print will also continue to deteriorate at a faster pace, than those washed in washing machines from the other two categories.

4.5 Effect of repeated washing on the degree of fraying of a textile fabric

Taylor (1990) defined fraying as the loss of threads from a raw edge cut parallel to the threads. The severity of the wash action will determine the extent of the deterioration that will be caused in fabrics during the wash process. The test for fraying during washing was thus implemented in this study to compare the severity of the wash actions of the different washing machines.

Three cuts (as described in 3.7 and illustrated in Figure 3.8) were made in each test fabric and the test fabrics laundered once, three and five times in each washing machine at 40°C without detergent. The variables, *wash temperature* and *level of detergent*, were thus kept constant to make sure that only the effect of the variable *washing machines* is determined. Because of the fact that the fabrics already showed a marked difference in degree of fraying after one wash, fabrics were only submitted to one, three and five washes, and not more than ten as was done in the other tests.

After washing, fabrics were dried, lightly ironed to flatten the area around the cut, and assessed on a five point ordinal scale. A rating of 5 represented the best appearance with the least fraying and 1 the worst appearance, showing excessive fraying. Ratings of 4/5, 3/4 and 2/3 were given to fabrics that were classified between the five points. The results are shown in a frequency table in Addendum I.

Values for *degree of fraying* were ranked statistically before an analysis of variance was performed on the data. A high rank mean (*rank means*) represents a high rating and a low rank mean represents a low rating (e.g. 1). The ANOVA was performed on the rank mean and will be discussed in terms of the variable *washing machine* (M), *number of washes* (W) and possible interactions. The ANOVA is shown in Table 4.19.

TABLE 4.19: ANOVA FOR DEGREE OF FRAYING

SOURCE OF VARIATION	RANK MEANS		
	DEGREES FREEDOM	MEAN SQUARE	PROBABILITY LEVEL (P)
M (*washing machine*)	6	1678,6	<0,01**
W (*number of wash cycles*)	2	3063,6	<0,01**
MW	12	79,7	0,06
Error	42	41,1	
Corrected total	62		

** Term highly significant at P < 0,01

As can be seen in Table 4.19, the variables *washing machine and number of washes,* both had a highly significant effect on the fraying that took place on the washed fabrics (P<0,01). No significant effect was found regarding the interaction of the two variables. To establish whether the differences between the results from the different washing machines are significant, Tukey's studentized range (HSD) were calculated. Results are shown in Table 4.20.

TABLE 4.20: TUKEY GROUPING ACCORDING TO WASHING MACHINE

TUKEY GROUPING*				RANK MEANS**	SAMPLE SIZE	WASHING MACHINE
A				49,7	9	*H2*
A	B			41,1	9	*V(I)*
	B	C		37,3	9	*H4*
	B	C		36,6	9	*H3*
		C		31,4	9	*H1*
			D	17,2	9	*V(A)1*
			D	10,7	9	*V(A)2*

* Means with the same letter are not significantly different

***Rank means* represents the ranked mean per sample

From Table 4.20 it can be seen that there is a significant difference between *H2* and the other three horizontal drum machines. A significant difference was also found between the vertical drum agitator type machines and all the other machines. The results from the vertical drum agitator type machines thus indicate that significantly more severe fraying took place in the washed fabrics. The results also indicate that the two categories of vertical drum machines differ significantly in the severity of their mechanical wash actions. Although there was a substantial difference between the fabrics washed in the two vertical drum agitator type machines, it was not statistically significant at $P<0,05$. (LSD for rank means = 9,4). It is, however, important to note that the above analysis was done on mean ratings for the fabrics washed once, three and five times.

The differences in the effect of the different washing machines on the fraying of the fabrics are shown in Figures 4.13 and 4.14. To illustrate the results better, the means after one wash and the means after five washes were depicted separately in two graphs.

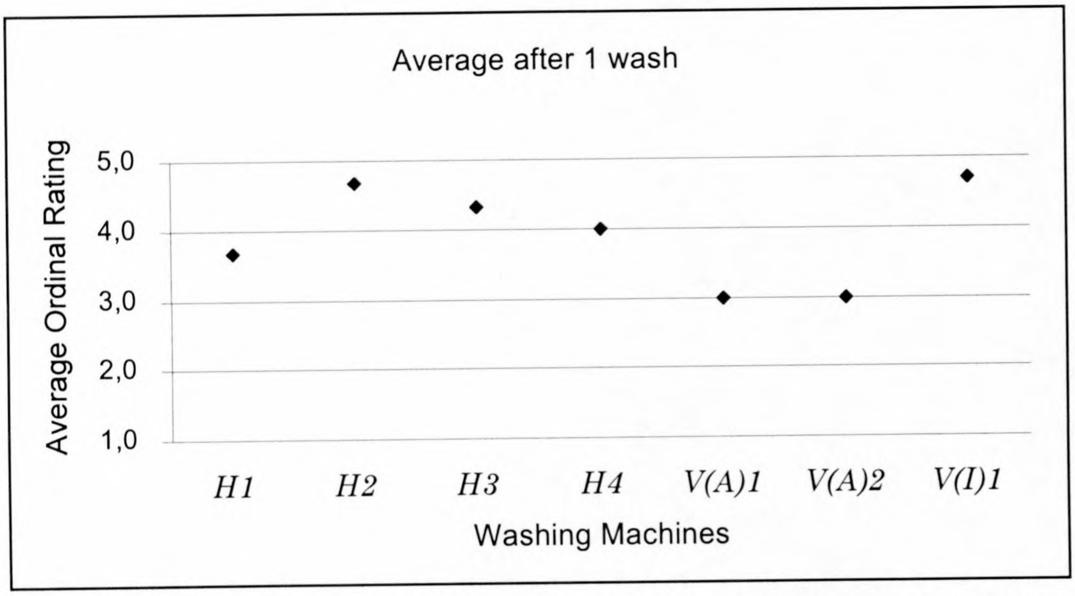

FIGURE 4.13: MEAN RATING FOR DEGREE OF FRAYING ACCORDING TO WASHING MACHINE (AFTER ONE WASH)

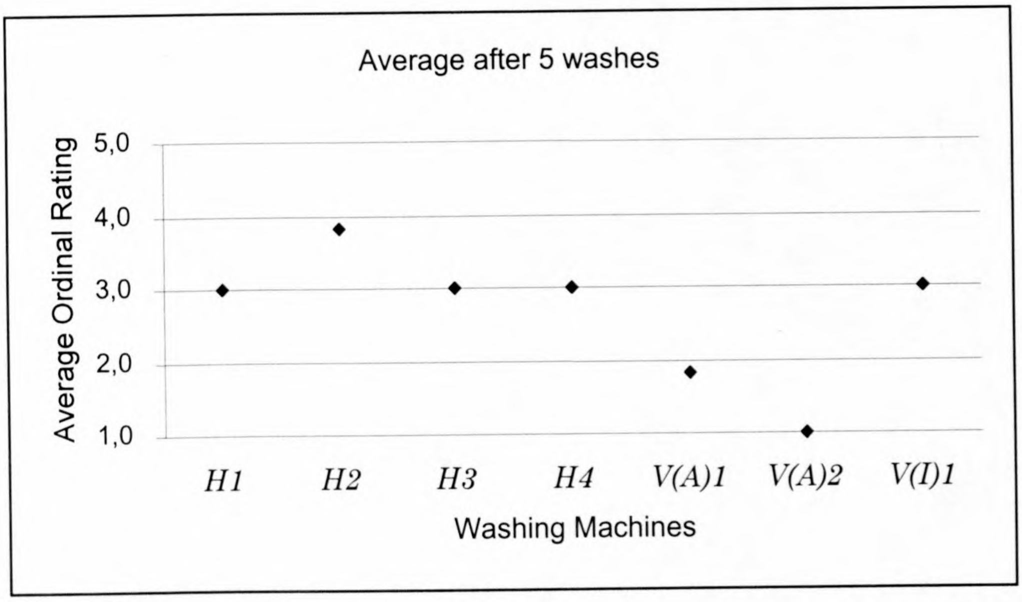

FIGURE 4.14: MEAN RATING FOR DEGREE OF FRAYING ACCORDING TO WASHING MACHINE (AFTER FIVE WASHES)

Both of the figures show that more excessive fraying was observed in fabrics washed in the vertical drum agitator type machines. It is also clear that, after five washes, machine *V(A)2* showed more severe fraying than *V(A)1*. Fabrics washed in the horizontal drum machines showed results similar to those washed in the vertical drum impeller type machine. To test these observations, an ANOVA was done on the results, testing the effect of C (*category of washing machine*) as variable on the degree of fraying observed in washed fabrics (Table 4.21).

TABLE 4.21: ANOVA FOR DEGREE OF FRAYING (*CATEGORY OF WASHING MACHINE* AS SOURCE OF VARIATION)

SOURCE OF VARIATION	*RANK MEANS*		
	DEGREES FREEDOM	MEAN SQUARE	PROBABILITY LEVEL (P)
C (*category of washing machine*)	2	4126,5	<0,01**
W(*number of wash cycles*)	2	3063,6	<0,01**
CW	4	91,2	0,08
Error	42	41,1	
Corrected total	62		

** Term highly significant at P < 0,01

Table 4.21 shows that both the variables C and W had a highly significant effect on degree of fraying (P<0,01). The effect of the variable number of washes was expected, as an increased number of washes will increase the degree of fraying under most circumstances. To establish whether the differences between the results from the different categories of washing machines are significant, Tukey's studentized range (HSD) was calculated. Results are shown in Table 4.22.

TABLE 4.22: TUKEY GROUPING ACCORDING TO *CATEGORY OF WASHING MACHINE*

TUKEY GROUPING*		MEAN *RANK MEANS***	SAMPLE SIZE	WASHING MACHINE
A		41,1	9	*H*
A		38,8	36	*V(I)*
	B	13,9	18	*V(A)*

* Means with the same letter are not significantly different

***Rank means* represents the ranked mean per sample

The Tukey grouping indicates that the degree of fraying caused by the horizontal drum and vertical drum impeller type machines were the least and that there is no significant difference between the results from these two categories of washing machines. It also indicates a significant difference between the horizontal drum and vertical drum impeller type machines, on the one hand, and the vertical drum agitator type machines, on the other hand. Once again the results indicate that the agitator type machines have a more severe wash action, causing a significantly higher degree of fraying in the washed fabrics.

4.6 Effect of washing machine on fabric deterioration as viewed in a scanning electron microscope

Magnified images of fabrics were viewed in a scanning electron microscope to aid in the interpretation of tensile strength data. Surface detail of fibres was investigated at 1000X magnification on unwashed fabrics and fabrics washed 50 times in the different washing machines. On all fabrics photo-micrographs were taken at specified coordinates to avoid subjectivity (Refer Addendum K for photomicrographs).

When the photomicrographs are compared, significant differences are noticeable between the unwashed fabrics and the washed fabrics. All washed fabrics showed deterioration of fibre surfaces in the form of fibrillation and fibril separation from the cotton fibres of the test fabrics. The mechanical agitation encountered during laundering resulted in mashing and pulling of fibril bundles from the fibre to form an entangled mass. Fibre fractures were also observed, but seemed to be few. This confirms findings by Raheel and Lien (1985). Hurren *et al* (1985) identified the short fibrous debris with which some fibres are covered as small fibre wedges that had been cut from the fibres during laundering. It is difficult to identify marked differences among the effects of the different washing machines in categories *V(A)* and *H* with regard to fibre surface deterioration. Photomicrographs of fabrics washed in the category *V(I)* washing machine did, however, show less fibre surface deterioration. This does not confirm findings with regard to reduction in tensile strength, as reported in 4.3.2, but is in agreement with print deterioration results as reported in 4.4.

4.7 Effect of washing machine on soil removal efficiency

The efficiency with which soil is removed from fabrics depends not only on the composition and temperature of the wash solution but also on the mechanical wash action to which the washing is submitted. This includes different wash times and degrees of agitation (Kadolph & Langford, 1998). The focus of this study was to compare the different mechanical wash actions of the washing machines. This was the only aspect of soil removal efficiency that was investigated. Data on consumer habits prove that consumers wash their washing at various wash temperatures (Lever Pond's, 1999). To compare the soil removal efficiency of the different machines, soiled fabrics were washed at 40°C and 60°C, with and without detergent. By comparing the soil removal efficiency of the different machines under these varying conditions, an attempt was made to take all the factors that could affect the cleaning actions of the washing machines into account.

The soil removal efficiency of the mechanical wash action of each individual machine was measured by adding a laboratory soiled test fabric (described in Chapter 3) to the wash load and submitting it to one wash cycle, after which it was flat dried and conditioned before assessment. This was repeated ten times in each machine at 40°C with detergent, at 40°C without detergent, at 60°C with detergent and at 60°C without detergent. A total of 40 fabric samples were prepared for evaluation.

Colour changes in the test fabric were measured with a colorimeter. Both sides of a fabric were evaluated and the mean of the two sides reported as red/green (a*), blue/yellow (b*) and lightness (L*) values. From this, $\triangle$E* (delta-E) was calculated to represent the total colour change in the test fabric, which was indicative of how the effect of soiling would become lighter during washing. $\triangle$E* indicates the total colour change, based on measurements of unwashed soiled fabrics and washed soiled fabrics. $\triangle$a*, $\triangle$b* and $\triangle$L* refer respectively to changes in a*, b* and L* from the unwashed to the washed laboratory-soiled test fabric. $\triangle$E* was calculated using the following formula (AATCC no152, 1978): $\Delta E = \sqrt{\Delta a^{*2} + \Delta b^{*2} + \Delta L^{*2}}$ (Colour values given in Addendum J).

A factorial analysis of variance was used to determine the effects of the individual factors *washing machine* (W), *level of detergent* (D) and *wash temperature* (T) and their simultaneous interactions on the colour change of the laboratory-soiled test fabric (in this study referred to as soil removal efficiency and reported as $\triangle$E*). This is shown in Table 4.23. The factors M (*washing machine*) and D (*level of detergent*), as well as the interactions MD and MTD, had highly significant effects on △E* (P<0,01). The interaction TD was also highly significant, but is not of practical importance in this discussion.

TABLE 4.23: ANOVA FOR SOIL REMOVAL EFFICIENCY

SOURCE OF VARIATION	Delta-E (△ E*)		
	DEGREES FREEDOM	MEAN SQUARE	PROBABILITY LEVEL (P)
M (*washing machine*)	7	57,33	<0,01**
T (*wash temperature*)	1	2,76	0,14
D (*level of detergent*)	1	583,7	<0,01**
MT	6	2,36	0,07
MD	6	13,9	<0,01**
TD	1	64,2	<0,01**
MTD	6	3,92	<0,01**
Error	244	1,18	
Corrected total	271		

** Term highly significant at P < 0,01

To assess whether the differences in the results were significant, a Student's t-LSD was calculated and the result can be seen in Table 4.24.

TABLE 4.24 STUDENT'S t-LSD FOR SOIL REMOVAL EFFICIENCY (△ E*) ACCORDING TO WASHING MACHINE

t-GROUPING*					△ E*	SAMPLE SIZE	WASHING MACHINE
A					8,02	40	*H1*
A	B				7,58	38	*V(A)1*
	B	C			7,47	38	*V(A)2*
	B	C	D		7,05	39	*H2*
			D		6,95	40	*H4*
			D		6,68	40	*H3*
				E	4,24	37	*V(I)*

*Means with the same letter are not significantly different (LSD=0.5)

The results show that the highest △E*-values were measured on fabrics washed in washing machines *H1* and *V(A)1* (indicating the most efficient soil removal). They were closely followed by machines *V(A)2, H2,* *H4* and *H3*. Results obtained from fabrics washed in the vertical drum impeller type machine, *V(I)1* indicated the least efficient soil removal. Table 4.24 indicates a significant difference (P=0,05) between the fabrics washed in *V(I)1* and the rest. It did not indicate any significant differences between *H1* and *V(A)1*, among *V(A)1*, *V(A)2* and *H2*, between *V(A)2* and *H2*, or among *H2*, *H4* and *H3*. It did indicate, though, that *H1* and *V(A)1* cleaned the soiled test fabric more efficiently than *H3* and *H4*.

Among the front loader machines the soil removal efficiency of *H1* differed significantly from the other three. No significant difference could be seen between the results from the two top loader agitator type machines, *V(A)1* and *V(A)2*. A highly significant difference was found between agitator and impeller type top loaders. The effect of the variable *washing machine* on soil removal efficiency is shown in Figure 4.15.

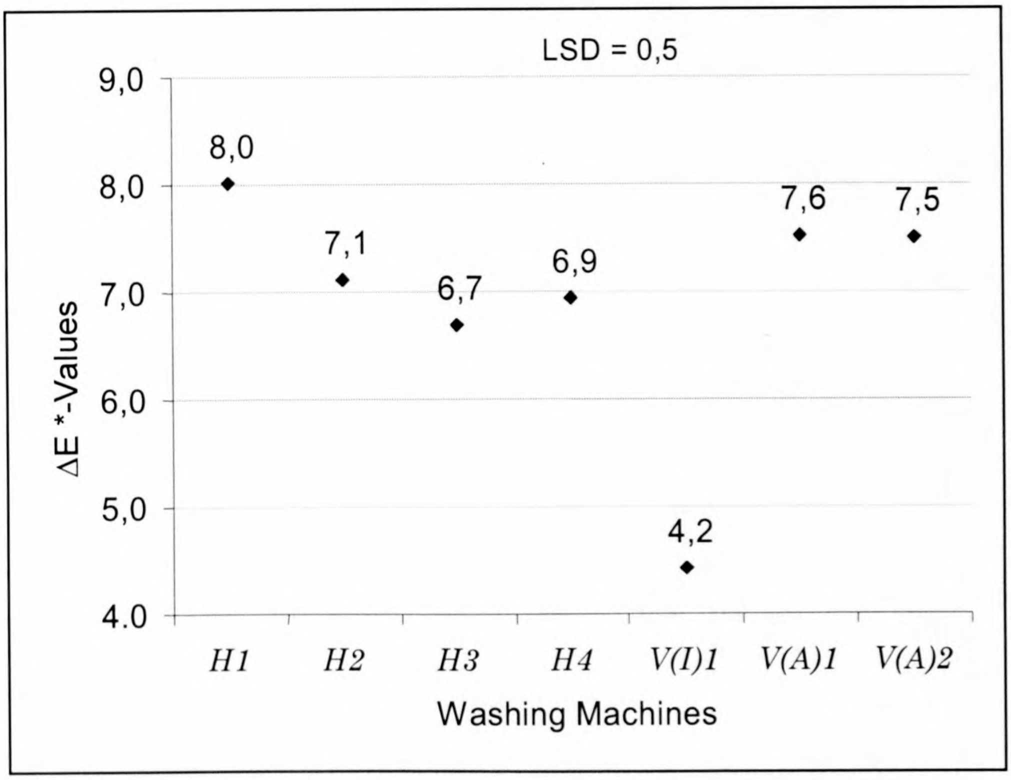

FIGURE 4.15 EFFECT OF THE VARIABLE *WASHING MACHINE* ON SOIL REMOVAL EFFICIENCY (△E*)

To determine whether the variable *category of washing machine* has a significant effect on soil removal, an ANOVA (Table 4.25) was carried out on the results, using C (*category of washing machine*), in stead of M (*washing machine*) as source of variation. Highly significant effects were indicated for the factors C (*category of washing machine*) and D (*level of detergent*), as well as for the interaction CD. No significant effect was found regarding the effect of the factor T *(wash temperature*). The interactions CT, TD and CTD were also significant, but are not of practical importance to this discussion.

TABLE 4.25: ANOVA FOR SOIL REMOVAL EFFICIENCY (*CATEGORY OF WASHING MACHINE* AS SOURCE OF VARIATION)

SOURCE OF VARIATION	ΔE*		
	DEGREES FREEDOM	MEAN SQUARE	PROBABILITY LEVEL (P)
C (category of washing machine)	2	151,5	<0,01**
T (wash temperature)	1	2,8	0,14
D (level of detergent)	1	583,7	<0,01**
CT	2	4,0	0,04*
CD	2	24,9	<0,01**
TD	1	62,9	<0,01**
CTD	2	11,3	<0,01**
ERROR	256	1,29	
Corrected total	271		

** Term highly significant at P < 0,01 * Term highly significant at P< 0,05

A Student's t-LSD was calculated and confirmed significant differences in the soil removal efficiency of washing machines according to the categories under which they are classified (horizontal drum machines, vertical drum agitator type machines and vertical drum impeller type machines). The test showed that the soil removal efficiency of the horizontal drum and vertical drum agitator type machines was significantly superior to that of the impeller type machine. The Student's t-LSD is shown in Table 4.26.

TABLE 4.26: STUDENT'S t-LSD FOR SOIL REMOVAL EFFICIENCY (ΔE*) ACCORDING TO *CATEGORY OF WASHING MACHINE*

t-GROUPING*		WASHING MACHINE	SAMPLE SIZE	ΔE*
A		*V(A)*	76	7,52
A		*H*	159	7,17
	B	*V(I)*	37	4,24

*Means with the same letter are not significantly different (LSD=0,05)

The mean $\triangle E^*$ values, indicating soil removal efficiency, are depicted graphically in Figure 4.16.

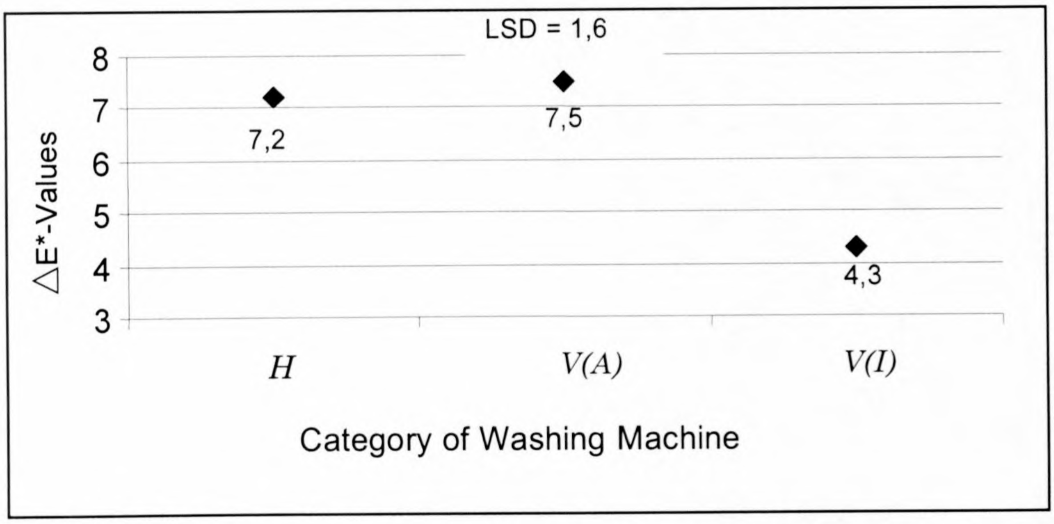

FIGURE 4.16 EFFECT OF THE VARIABLE *CATEGORY OF WASHING MACHINE* ON SOIL REMOVAL EFFICIENCY

Figure 4.16 indicates clearly that the soil removal efficiency of the horizontal drum- and agitator type washing machines does not differ significantly, but the impeller type machines showed very poor results.

Literature discussed in Chapter 2 shows that the efficiency of the soil removal process is dependent on factors such as detergent, mechanical wash action and temperature of the wash solution. Keeping the aim of this study in mind, results will be analysed separately for fabrics washed with and without detergent (per category of washing machine, at two different temperatures). This should give an indication of the effectiveness of the mechanical wash actions without the effect of a detergent in the wash water. A comparison of the soil removal efficiency of the different categories of washing machines for fabrics washed without detergent is depicted in Figure 4.17.

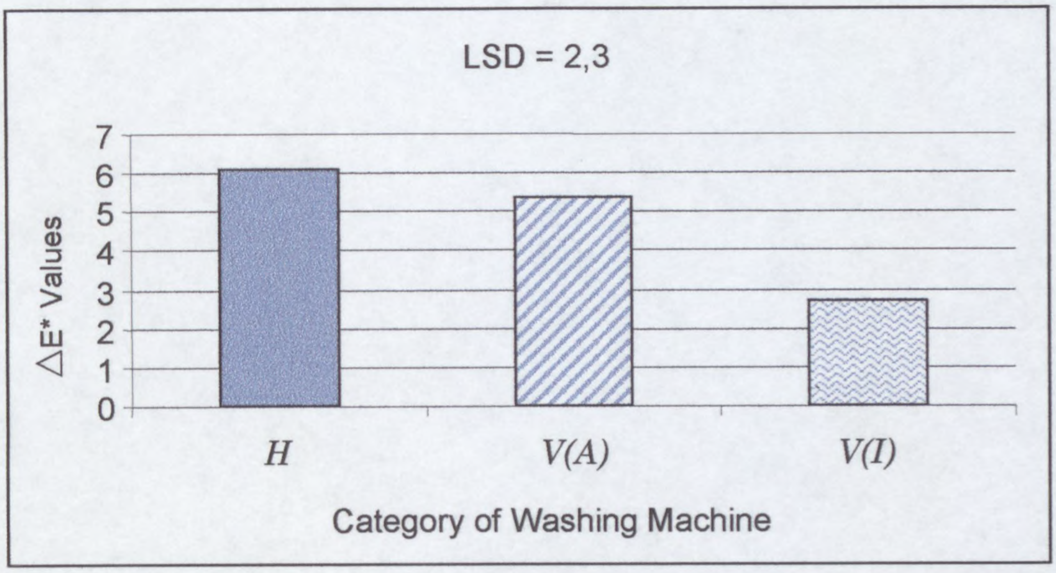

FIGURE 4.17: SOIL REMOVAL EFFICIENCY ACCORDING TO *CATEGORY OF WASHING MACHINE* FOR FABRICS WASHED *WITHOUT* DETERGENT

Virtually all consumers use some kind of detergent or washing powder in their washing machines (Lever Pond's, 1999). To be realistic, it was therefore necessary to compare the soil removal efficiency of washing machines for fabrics washed with detergent as well. Results are shown in Figure 4.18.

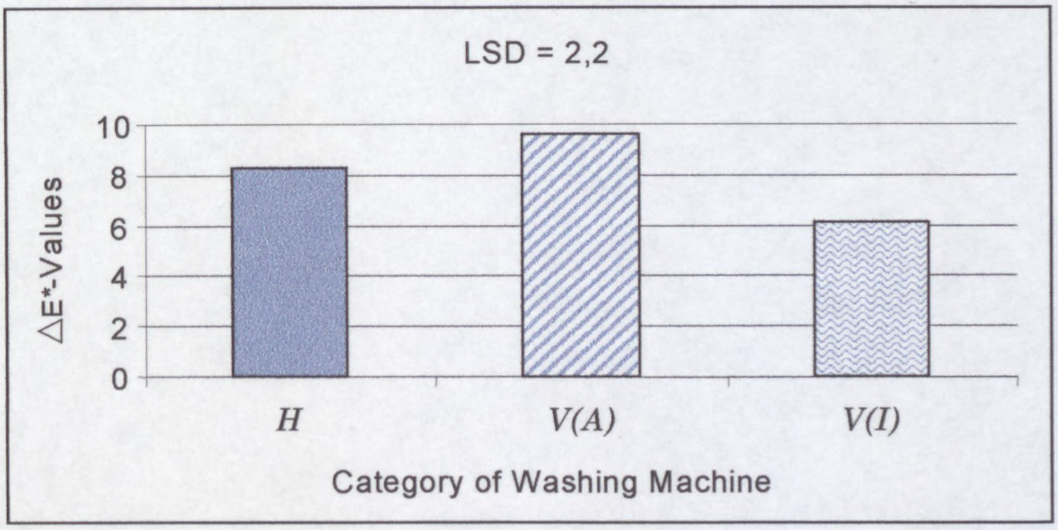

FIGURE 4.18: SOIL REMOVAL EFFICIENCY ACCORDING *TO CATEGORY OF WASHING MACHINE* FOR FABRICS WASHED *WITH* DETERGENT

Figures 4.17 and 4.18 show that no significant difference in soil removal efficiency was found between samples washed in the horizontal drum machines and those washed in the vertical drum agitator type machines, with or without detergent. The difference between the soil removal efficiency of the vertical drum impeller type machine and the other two types was smaller for fabrics washed with detergent than for those washed without detergent.

Because the ANOVA for soil removal efficiency did not show a significant effect for the variable *wash temperature*, results were not analysed according the temperature of the washing liquid.

4.8 Null hypotheses

To conclude this chapter and to, once again, link the results with the objectives of the study, the hypotheses will be discussed. Ten null hypotheses were formulated in Chapter 1:

> $H1_0$ There will be no difference in the effect of the variable, *washing machine*, on the *tensile strength* of fabrics of a 100% cotton fabric washed respectively 10, 20, 30, 40 and 50 times in the seven different washing machines.

$H1_0$ is rejected, as results show clearly that there are significant differences in the tensile strengths of fabrics washed in the different machines. When the mean values for tensile strength after washing were compared, the results from machine *H2* were significantly higher than those from machines *H1* and *H4*. The tensile strength values of fabrics washed in the horizontal drum machines can therefore be arranged in the following order: *H2, H3, H4, H1*. (*H2* produced the highest and *H1* the lowest mean tensile strength of the four.) The results from the fabrics washed in *V(I)1* did not differ significantly from those washed in *H1* and *H4*. No significant difference with regard to tensile strength was found between the fabrics from machines *V(A)1* and *V(A)2*, but the tensile strength results from the two machines differed significantly from the rest.

$H2_0$ There will be no difference in the effect of the variable, *category of washing machine*, on the *tensile strength* of fabrics of a 100% cotton fabric washed 10, 20, 30, 40 and 50 times in the seven different washing machines.

$H2_0$ is rejected. Results show clearly that the tensile strength of fabrics washed in washing machines from category *H* (horizontal drum type) differed significantly from fabrics washed in the machine from category *V(A)* (vertical drum agitator type). The mean tensile strength of the fabrics washed in the washing machine from category *V(I)* (vertical drum impeller type) was lower than that of the fabrics from the horizontal drum machines and higher than that of the agitator type machines. Although these differences are clearly noticeable in the data, they are not significant at a 95% confidence level. Mean tensile strength values from all the washed fabrics, including those measured after 50 washes, showed that the wash action of the vertical drum agitator type machines caused the most pronounced deterioration in tensile strength.

$H3_0$ There will be no difference in the effect of the variable, *washing machine*, on the *print deterioration* measured on fabrics of a pigment printed 100% cotton fabric washed 10 and 20 times without detergent at 40°C in the seven different washing machines.

$H3_0$ is rejected. Although no significant differences were found among the results from machines *H4, H3* and *H1,* a significant difference was found between *H2* and the rest of the horizontal drum machines It was also identified that the print deterioration of fabrics washed in *V(A)2* was worse than that found on fabrics from *V(A)1*, which indicates a difference in the effect of the differing agitators of the two machines. The mechanical wash action of the impeller type vertical drum machine seems to have the least effect on textile print deterioration, as machine *V(I)1* differed significantly from all the other machines, showing much less print deterioration.

> $H4_0$ There will be no difference in the effect of the variable, *category of washing machine,* on the *print deterioration* measured on fabrics of a pigment printed 100% cotton fabric washed 10 and 20 times without detergent at 40°C in the seven different washing machines.

$H4_0$ is rejected. The three categories of washing machines differed significantly from one another. The vertical drum impeller type washing machine caused the least print deterioration, whereas the vertical drum agitator type machines caused the most, indicating a more severe mechanical wash action in these machines.

> $H5_0$ There will be no difference in the effect of the variable, *washing machine*, on the *degree of fraying* assessed on fabrics of a pigment printed 100% cotton fabric washed one, three and five times without detergent at 40°C in the seven different washing machines.

$H5_0$ is rejected. The results show that a significant difference exists between *H2* and the other front loaders. A significant difference was also identified between the two vertical drum agitator type machines (*V(A)1* and *V(A)2*) and the other machines, indicating that significantly more severe fraying took place in these machines. Of the vertical drum agitator type machines, *V(A)2* caused a significantly higher degree of fraying after five washes. Machine *V(I)1* (a vertical drum impeller type machine) produced results very similar to those from the horizontal drum machines, but caused significantly less fraying than the vertical drum agitator type machines.

> $H6_0$ There will be no difference in the effect of the variable, *category of washing machine,* on the *degree of fraying* assessed on fabrics of a pigment printed 100% cotton fabric washed one, three and five times without detergent at 40°C in the seven different washing machines.

$H6_0$ is rejected. The degree of fraying caused by the horizontal drum and impeller type machines was the least and there are no significant differences between the results from these two categories of washing machines. The results also indicate a significant difference between the above two categories, on the one hand, and the agitator type machines, on the other hand. This confirms previous findings that the agitator type machines have a more severe wash action, which causes a significantly higher degree of fraying.

> $H7_0$ There will be no difference in the effect of the variable, *wash temperature*, on the *tensile strength* of 100% cotton fabric washed 10, 20, 30, 40 and 50 times in the seven different washing machines.

$H7_0$ is accepted. Results showed that fabrics washed at 60°C showed no significant difference in tensile strength from those washed at 40°C.

> $H8_0$ There will be no difference in the effect of the variable, *level of detergent*, on the *tensile strength* of 100% cotton fabric washed 10, 20, 30, 40 and 50 times in the seven different washing machines.

$H8_0$ is rejected. The mean tensile strength of fabrics washed without detergent was significantly lower than those washed with detergent. Further analyses, however, show an interaction in the effect of *washing machine category, number of washes* and *level of detergent used.*

> $H9_0$ There will be no difference in the *soil removal efficiency* of the seven different *washing machines.*

$H9_0$ is rejected. Washing machines *H1* and *V(A)1* showed the most efficient soil removal. They were closely followed by machines *V(A)2, H2, H4* and *H3*. The poorest soil removal efficiency results were obtained from fabrics washed in the vertical drum impeller type machine, *V(I)1*

$H10_0$ There will be no difference in the *soil removal efficiency* of the three *categories of washing machines*

$H10_0$ is rejected. The soil removal efficiency of the horizontal drum and vertical drum agitator type machines does differ significantly, but both these categories of washing machines cleaned soiled fabrics better than the vertical drum impeller type machine did.

In Chapter 5 the conclusions drawn from the results and based on the literature review in Chapter 2, will be discussed.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Overview

The complexity of the consumer decision making process when buying a domestic washing machine is increasing nationally and internationally as consumers get confronted by the widening range of models and categories of washing machines on the market. Amongst models, but especially among categories of machines, the wash actions employed in the washing machines for cleaning textiles differ drastically. These wash actions vary from a less severe action in the horizontal drum machines, where the washing is lifted by fins in the sides of a revolving drum to let it fall back into the washing solution, or the swirling action of the vertical drum impeller type machine, to a more severe wash action in the vertical drum agitator type machines. In the latter the washing is physically agitated in the wash liquid by the action of an agitator in the centre of the drum. The wash programmes of the different machine types also vary in action sequence and duration, as well as total programme duration. For the purpose of this investigation, the three categories of washing machines tested were referred to as *H* (horizontal drum machines), *V(A)* (vertical drum agitator type machines) and *V(I)* (vertical drum impeller type machines).

The differences in the mechanical wash actions described above gave rise to the main objective of this study being to compare the different **mechanical wash actions** of domestic automatic washing machines with regard to the effect they have on possible **fabric deterioration**. Regarding the effect of the mechanical wash action on fabric deterioration, very little information was available in literature. Research focused mainly on the effect of factors like detergent composition, water hardness, type of soiling, etc., in the wash process.

Fabric deterioration manifests itself in a variety of ways. For the purpose of this exploratory study, it was decided that comparing the *tensile strength, print deterioration* and *degree of fraying* of cotton fabrics washed in different washing machines could give an indication of the deterioration that had taken place in the fabrics during the wash process. The main variables in the wash process studied, were identified *as washing machine, wash temperature, level of detergent* and *number of washes*. The effect of *category of washing machine* as a source of variance was also investigated.

As the main purpose of the wash action of a washing machine is to remove soil, the study would not be complete without a comparison of the **soil removal efficiency** of the different machines. This would also indicate possible differences in the effect of the different mechanical wash actions on soil removal efficiency. The soil removal efficiency was determined by measuring colour change (ΔE) on laboratory-soiled fabrics after washing.

Laboratory testing was employed to determine the effect of different wash actions on fabric deterioration and to compare soil removal efficiency. Detail on the empirical work is described in Chapter 3 and the results are discussed in Chapter 4. This chapter constitutes the conclusions drawn from Chapter 4, as well as the researcher's views with regard to the limitations of the study. Recommendations for future research and implications for the consumer are highlighted in 5.3 and 5.4.

5.2 Conclusions

Initial analysis of the mechanical wash actions of the seven washing machines compared in this study indicated conspicuous differences among machines. This led to the empirical study being planned with the seven *washing machines* as individual variables. Results indicated that the seven machines could also be compared according to *category of washing machine*, as fabrics washed in different machines from the same category tended to produce similar results. The conclusions drawn from the study will thus also be discussed according to *category of washing machine*.

5.2.1 Horizontal drum type machines

In this category, four washing machines (*H1, H2, H3* and *H4*) were selected for the investigation. They employ the same basic mechanical action for agitating the wash load and wash solution, but the wash actions differ in severity. This is the result of varying wash durations, individual differences in the amount of drum movement during the wash process (leading to variations in the total number of times the drum turns on its axis to lift the washing and let it fall back into the wash), the distance of the free fall of the washing in the drum during the wash process, as well as the severity and duration of the spin cycles. Unfortunately the wash programmes of the different washing machines are fixed with regard to these factors. Consequently it was impossible to keep selected factors constant during testing and thereby obtain individual measurements of the effect of any one on the other factors on fabric deterioration during washing, or soil removal efficiency. General observations only will be made in this regard.

The tensile strength results indicate that the fabrics washed in the horizontal drum machines exhibit the highest tensile strength values with regard to the three categories of washing machines after 50 washes. The results also show that the mean tensile strength of fabrics washed 50 times in the horizontal drum machines does not differ significantly from the mean tensile strength of fabrics washed ten times in the same machines, indicating that most of the fabrics do not exhibit loss of tensile strength from 10 to 50 washes as a result of the mechanical wash action that it was exposed to.

Comparison of results from the four horizontal drum machines show that fabrics washed in machine *H1* had the lowest, and fabrics from *H2,* the highest tensile strength after 50 washes. This difference is significant (P=0,05). When the wash programmes of the two machines are compared, the analysis shows that the main difference between the two is the much shorter wash programme of machine *H2,* which involves a lower number of turns of the drum per wash. In general, the textile fabrics in the wash load are exposed to the mechanical wash action for a much shorter time, resulting in less exposure of the fabric to degradative factors.

The same conclusion can be drawn regarding the significant differences between the tensile strength of fabrics from machines *H2* and *H4*. Again, the difference in wash programme duration seems to be the predominant variant. Fabrics from machine *H2,* which has the shorter wash, exhibited the highest tensile strength after 50 washes.

Fabrics washed in machine *H1* have a significantly lower mean tensile strength than those from machine *H3*. When the programmes of these two machines are compared, it is noticeable that the wash cycles of the two machines have the same duration, but machine *H1* has a significantly higher number of drum turns per wash cycle. Machine *H1* also has a longer total wash programme and a generally more severe wash action than machine *H3*. The combination of a more severe mechanical wash action and longer exposure to this action could therefore be responsible for the more significant reduction in tensile strength of fabrics washed in machine *H1*.

To summarise, it is clear that the severity of the wash action and the duration of the wash programme have a definite influence on the tensile strength of fabrics during repeated washing in horizontal drum washing machines.

The print deterioration of fabrics that were repeatedly washed in the different horizontal drum washing machines was determined by measuring colour loss in the fabrics with a colorimeter. This method of objective measuring indicated that no significant differences were found between machines *H1*, *H3* and *H4* on the print deterioration of fabrics. However, significantly less print deterioration was measured on fabrics washed in machine *H2*. As with tensile strength, this can be ascribed to machine *H2* having a much shorter wash programme, resulting in exposure to the mechanical wash action being shorter than in the other machines. As the fabrics were washed in water without detergent, the possible effect of detergent ingredients on fabric colour deterioration was eliminated. The measured print deterioration can thus be ascribed to mechanical action alone.

Measurements to test for degree of fraying confirmed the results found for print deterioration. For fabrics washed in horizontal drum type washing machines, the duration of the wash programme seems to be the predominant factor in determining the degree of fraying of fabrics during washing. This is the main source of variation in the programmes of machines *H1, H3* and *H4*, on the one hand, and machine *H2* on the other.

From the above, it can be concluded that longer exposure to the wash action in the case of the horizontal drum machines, caused more extensive print deterioration and a higher degree of fraying, in spite of the severity of the wash action.

With regard to soil removal efficiency, the aim of this investigation was to compare the efficiency with which the different mechanical actions of the washing machines remove soil. For this reason, a laboratory-soiled test fabric, covered with soil that can be classified as "mechanically entrapped particles", was used to investigate soil removal efficiency. This type of soil is recommended as suitable for investigating the ease of soil removal by means of mechanical wash action.

When the soil removal efficiency of the horizontal drum machines was compared, machine *H1* performed much better than the other three horizontal drum machines. As mentioned above, machine *H1* has the longest free fall distance, the second longest wash programme and the highest number of drum turns per wash. These combined factors are responsible for a more vigorous wash action. This is concurrent with the results for tensile strength, print deterioration and degree of fraying. Machine *H2,* with the shortest wash cycle, did not produce results that differ significantly from those from machines *H3* and *H4*. Both have longer wash cycles than machine *H2*. This proves that the duration of the wash cycle is not the most important factor in soil removal efficiency resulting from mechanical wash action. However, this conclusion does not take into account the possible interaction between wash duration and the influence of detergent.

5.2.2 Vertical drum agitator type machines

Two machines in this category of washing machines were compared. The main differences between the two are the shapes and the mechanical actions of the agitators that cause the mechanical wash action. The tensile strength results from the two machines did not differ significantly with regard to the effect of repeated washing. Neither was there a difference in the effect on degree of fraying. The print deterioration caused by machine *V(A)2* was, however, significantly more than that found on the fabrics washed in machine *V(A)1* (P=0,05). This indicates that the turning in one direction only of the agitator in machine *V(A)2* caused a more severe result, with reference to print deterioration, than the reverse turning of the agitator in machine *V(A)1*. The soil removal efficiency of the two machines did not differ significantly.

5.2.3 Vertical drum impeller type machines

Only one vertical drum impeller type machine was used in this investigation. An impeller in the base of this type of washing machine swirls the water and wash load around for the duration of the wash cycle. This action is enhanced by the drum turning backwards and forwards.

The tensile strength in fabrics washed 50 times in this machine was higher than that of fabrics washed in the vertical drum agitator type machines, but lower than those from the horizontal drum machines. Although these differences are not significant at a 95% confidence level, they are clearly visible when illustrated graphically. The print deterioration resulting from washing in machine *V(I)1* was significantly less than that found in any other machine, but the machine caused the same degree of fraying as the horizontal drum machines. The degree of fraying, however, was significantly less than what was caused by machines *V(A)1* and *V(A)2*. From the results of this investigation, it can be concluded that the mechanical wash action of this machine has a much less severe effect with regard to deterioration of textile fabrics than that of all six other washing machines investigated for comparison in this study.

With regard to soil removal efficiency the vertical drum impeller type machine performed poorly and produced results that are poorer than those from machines from the other two categories. The same wash action that is favourable with regard to retention of appearance (implicated in this study by print deterioration and degree of fraying measurements), unfortunately does not produce sufficient mechanical action to remove mechanically entrapped soil.

5.2.4 Categories of washing machines

When the three categories of washing machines (*V(A), V(I)* and *H*) are compared with regard to the effect of their respective mechanical wash actions on tensile strength, the effect of the agitators in category *V(A)* is responsible for the greatest deterioration. Fabrics washed in these machines exhibited significantly lower tensile strength than those washed in machines from the other two categories. Fabrics washed in the category *V(A)* machines showed a significant reduction in tensile strength from ten to 50 washes, as opposed to the mean tensile strength of fabrics from the category *H* machines.

The tensile strength results obtained from fabrics washed in category *V(I)* washing machines fell in between the means from categories *H* and *V(A),* but did not differ significantly from any of the two. It is interesting to note that, although the difference in tensile strength is not significant, this machine caused slightly more fabric deterioration than the horizontal drum machines. This does not quite correspond to the print deterioration results.

Category *V(A)* machines caused by far the greatest print deterioration and the highest degree of fraying, which demonstrate the severity of the wash action of these machines. The more delicate wash action of category *V(I)* was responsible for the finding that fabrics washed in this machine showed the lowest degree of print deterioration. With regard to degree of fraying, the results from categories *V(I)* and *H* did not differ significantly. In these two categories (both exhibiting less severe wash actions), the duration of the wash seemed to be the predominant factor in determining the degree of fraying.

From the above, it can be concluded that the mechanical wash action in the category *V(A)* machines is the most severe, and causes the highest reduction in tensile strength, the greatest print deterioration and the highest degree of fraying. These machines did not, however, exhibit greater soil removal efficiency than the other two categories of washing machines. This finding makes an important contribution to the consumer decision making process, which will be discussed in 5.4. Category *V(I)* machines seem to have the most delicate wash action and will probably cause the slightest fabric deterioration over the long term, but unfortunately produces poor cleaning efficiency results.

5.2.5 Effect of temperature and level of detergent

It is commonly accepted and confirmed in the literature that higher wash temperatures are conducive to better cleaning efficiency and that, in most cases, a wash temperature of 60°C will produce better soil removal results than washing at 40°C. Another consumer belief is that a higher wash temperature might cause greater fabric deterioration. One of the aims of this study was to investigate the latter. Results proved that, with regard to the cotton fabric used for testing, washing in the different washing machines at 60°C did not cause a significantly higher decrease in tensile strength than washing at 40°C. Further investigations might aim at proving whether this is also true with regard to the appearance retention of textile fabrics after repeated washing.

As shown in past investigations, this study confirmed that washing fabrics in water alone causes more deterioration of tensile strength in fabrics than washing with detergent in the wash solution. Reference was made to the "cushioning" effect of suds in the wash solution, which has a less severe wash action. This cushioning effect was more pronounced in fabrics washed in the horizontal drum and vertical drum impeller type machines, whereas no significant difference was found between fabrics washed with detergent or with water only in the vertical drum agitator type machines. An explanation for this could be that the more severe wash action of the agitator in these machines overrides the cushioning effect of the suds in the wash solution.

5.3 Limitations of the study and recommendations for further research

Due to the limited scope and exploratory nature of this study, certain aspects of automatic washing machine processes could not be tested empirically. These aspects will be discussed below.

One of the limitations of this study was the fact that commercially available washing machines with set wash programmes had to be used. This posed the problem that the variables in the wash programme that could have an effect on the severity of the wash action, could not be controlled individually. Variables could consequently not be kept constant to measure the effect of one factor exclusively...This resulted in conclusions with regard to individual differences between the results from especially the horizontal drum machines having to be generalised.

In accordance with the aim of the study, the soil removal efficiency of the different machines was only compared with regard to the effect of the specific mechanical wash actions on soil removal. For this reason, laboratory-soiled fabrics developed specifically for the purpose of comparing soil removal through mechanical wash action were used. Further research could be aimed at exploring and comparing possible interactions among factors, such as type of soiling, detergent action, duration of exposure to detergent and severity of wash action on soil removal efficiency. The more severe wash action of the agitator type vertical drum machines seems to override the cushioning effect of the suds in the wash solution. This issue could also be further investigated. The above could be of value to both the detergent manufacturers and washing machine industries, as well as to consumers.

Another recommendation for further research is to compare the different ways in which fabric deterioration during washing can be assessed. Tensile strength measurements are commonly regarded by researchers as reliable, but changes in tensile strength during washing are sometimes very small. The strip test method was used in this investigation, but no information has been found on how the grab test method would compare to the latter. SEM photographs were valuable in confirming the tensile strength results, but a method should be developed to prevent subjectivity in the interpretation of results.

Methods to compare the effect of other factors that influence potential changes in surface appearance during washing, like pilling or greying of fabric colour, could also be investigated or developed.

5.4 Implications for the consumer

The main purpose of a washing machine is to clean soiled textiles. Soil removal efficiency, as mentioned in Chapters 1 and 2, should therefore be one of the main factors that play a role in the consumer's final choice when buying a washing machine. Other factors like appearance retention and deterioration of textile fabrics in the wash load are usually also considered by consumers, but with differing degrees of importance. From the technical measurements made on the washing machines used in this study, it can be noted that the machines from the three categories differ in certain aspects that might be of varying importance to individual consumers. Machines from category *V(A)* and *V(I)* for example, use substantially more water per wash, but have the advantage of a much higher load capacity and a shorter wash programme than the machines from category *H*. The machines from category *H* uses considerably less water and heat the water internally, eliminating the necessity of a geyser or hot water supply. They have, however, a longer wash programme duration. They also have a larger variety of wash programmes to choose from, including special programmes for more delicate washing.

This study has confirmed that the washing machines from category *V(A)* undoubtedly have a more severe effect on textile fabric deterioration than machines from categories *H* and *V(I)*. It can also be concluded that the soil removal efficiency of the washing machines from categories *V(A)* and *H* does not differ significantly. It must be noted, however, that the conclusion with regard to soil removal efficiency is based on a comparison of soil removal efficiency of the mechanical wash actions only. Whether the results on cleaning efficiency obtained in this study are also applicable to soil removal efficiency when the effect of other variables in components of the wash process are taken into account, has not been established. Findings have also revealed that the soil removal efficiency of the category *V(I)* machine was significantly lower that that of the other machines. It was also found, however, that this category of machines caused significantly less print deterioration than the other machines. For the consumer who uses a washing machine mainly for refreshing worn clothes which are not severely soiled, such a washing machine could be a good choice.

If future research can confirm the findings related to soil removal for all conditions, it means that consumers will not have to be concerned about cleaning efficiency when making a choice between horizontal drum and vertical drum agitator type machines. They can then prioritise other features of the washing machines, as mentioned above, when making a choice. This would contribute to optimal decision making and consumer satisfaction.

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ADDENDUM A

(a)

SABS METHOD 70: CONDITIONING OF TEXTILES AND STANDARD TEMPERATURE AND ATMOSPHERE FOR DETERMINING THEIR PHYSICAL AND MECHANICAL PROPERTIES

(b)

HYGROMETER CHART FROM DEPARTMENT OF CONSUMER SCIENCE (UNIVERSITY OF STELLENBOSCH) TEXTILE TESTING LABORATORY

STANDARD METHOD SUMMARY

SABS METHOD 70

Conditioning of textiles and standard temperature and atmosphere for determining their physical and mechanical properties

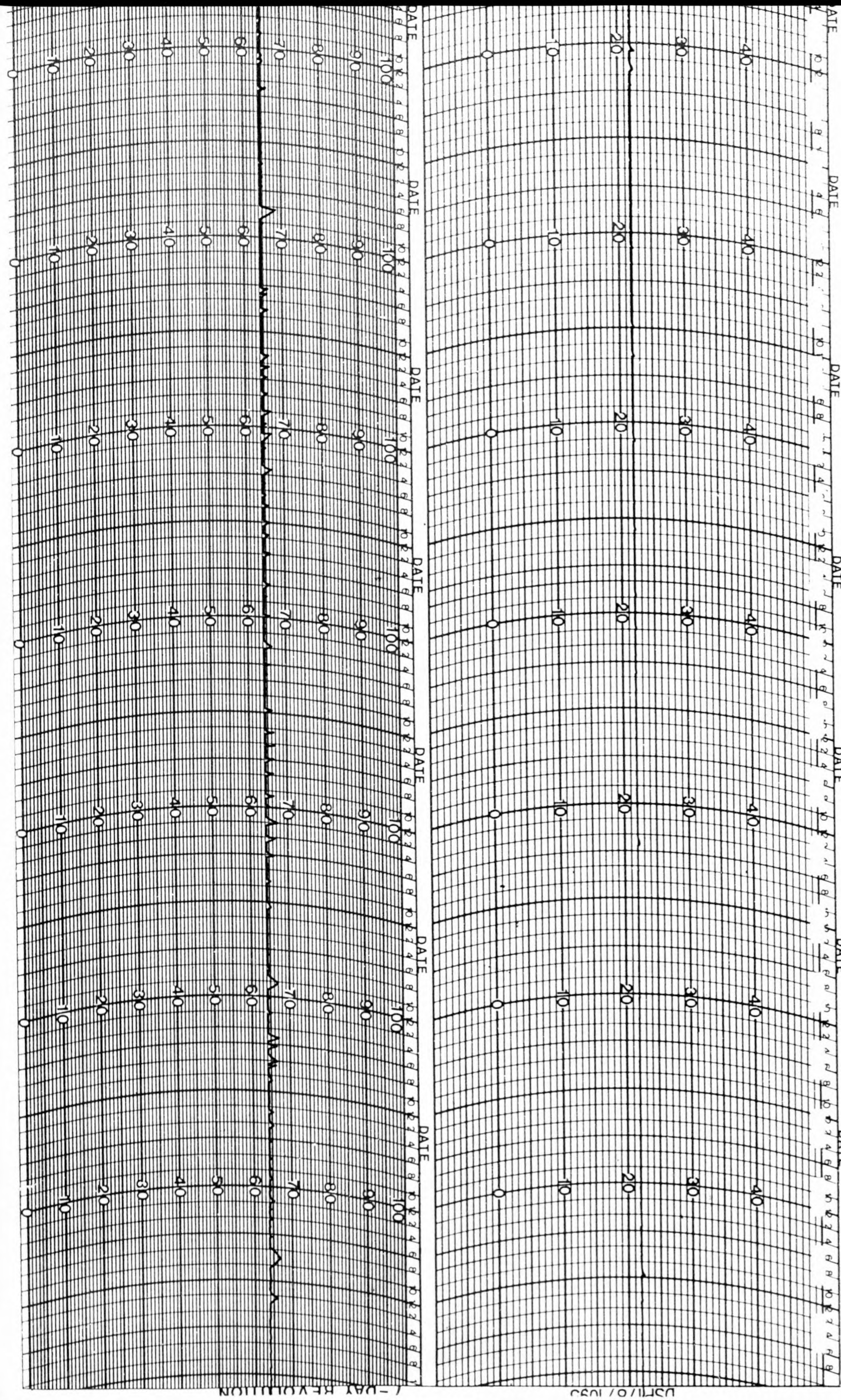
STANDARD TEMPERATURE AND ATMOSPHERE FOR TESTING

An atmosphere having a relative humidity of 65 +/- 2% and a temperature of 20 +/- 2°C at the prevailing barometric pressure.

CONDITIONING

Before a textile is tested in order to establish a physical or mechanical property, condition it in the standard atmosphere for testing. A textile is conditioned when (after having been pre-conditioned if necessary) it has reached equilibruim with the standard atmosphere for testing.

Provided that there has been a free flow of conditioned air through the textile throughout the entire period of conditioning, consider a textile to be in equilibrium with the atmosphere if the change in mass between successive weighings, carried out at intervals of at least 2 hours, is less than 0,25%.



ADDENDUM B

PILOT STUDY FOR SELECTION OF FABRICS SUITABLE TO BE USED FOR TESTING IN THIS INVESTIGATION

REPORT ON PILOT STUDY

Aims and selection criteria

A pilot study was performed to select textile fabrics that would be suitable to use as sample fabrics for this investigation. The criteria used in the selection were as follows:

- To assess fabric degradation with regard to tensile strength during repeated laundering. The fabrics tested should show a consistent decrease in tensile strength consistent with the number of times laundered.
- To assess print deterioration. The fabrics tested should show a visible lightening of surface appearance after washing.
- To assess degree of fraying. The fabric should have a stable woven structure that does not disintegrate or lose shape during washing, but show a tendency to ravel consistently at a cut edge.

Fabrics tested:

The fabrics selected for testing in the pilot study are described in Table B1.

TABLE B1: DESCRIPTION OF SAMPLES COMPARED IN PILOT STUDY.

FABRIC REFERENCE	FABRIC CONSTRUCTION	FIBRE COMPOSITION	FABRIC WEIGHT
P1	plain weave (Voile)	100% cotton	75 g/m^2
P2	plain weave	100% cotton	115g/m^2
P3	plain weave printed	100% viscose rayon	135g/m^2
P4	plain weave printed	100% cotton	175g/m^2

The motive behind the selection of the four fabrics used in the pilot study were to find fabrics that show a marked reduction in the mentioned properties (tensile strength, print deterioration and degree of fraying) after washing. The fabric should, however, also withstand the test conditions fairly well and not, for example, disintegrate during washing or testing. P1 was chosen because of its light construction, although it was expected that the washed fabric might be weakened to such a degree that the samples would not withstand tensile strength testing. Literature show that viscose rayon is weakened during the wash process, and it was hoped that the fabric might show a more substantial reduction in tensile strength than the cotton fabrics. Fabric P2 and P4 was recommended by the supplier as suitable for respectively tensile strength and print deterioration assessment. It was expected that P4 would also be suitable for the assessment of degree of fraying..

Test procedure

The four fabrics were washed in a Hoovermatic twin tub washing machine (at the Woolworths Laboratory, Cape Town). This type of washing machine is recommended by Woolworths for print deterioration assessment because of its severe wash action. The instruction manual recommends a wash cycle of two to three minutes as "normal" for regular washing. Exposure of samples for one hour to this wash action could thus be regarded as equivalent to about 20 washes in a domestic automatic washing machine.

Fabrics were washed without detergent, at 60°C in the twin tub machine. Samples were withdrawn after one, two and three hours for tensile strength testing according to SABS method 93 (Addendum C). To select the most suitable fabric for print deterioration, samples were withdrawn after 30 and 60 minutes and visually inspected. Fabrics prepared for assessment of print deterioration and degree of fraying (as described in Chapter 3, paragraphs 3.8.2) were also included in the wash load and fabrics were withdrawn and inspected after ten and twenty minutes.

Results and discussion

Sample fabrics P1, P2 and P3 were tested for tensile strength after being washed one, two and three hours in the twin tub washing machine. The results of the tensile strength tests are summarised in Table B2.

TABLE B2: TENSILE STRENGTH VALUES OF SAMPLES AFTER WASHING IN THE TWIN TUB WASHING MACHINE

FABRIC REFERENCE	SAMPLE NUMBER	TENSILE STRENGTH (N)			
		UNWASHED FABRIC	FABRIC WASHED 1 HOUR	FABRIC WASHED 2 HOURS	FABRIC WASHED 3 HOURS
P1	1	113	81	84	98
P1	2	94	131	107	72
P1	3	109	107	125	79
P1	4	107	76	110	93
P1	5	-	68	101	74
P1	6	-	137	94	-
AVERAGE (P1)		105,8	150,7	140,3	83,2
P2	1	541	450	429	450
P2	2	524	509	451	432
P2	3	488	457	410	434
P2	4	471	455	450	424
P2	5	554	481	463	447
P2	6	422	515	410	399
AVERAGE (P2)		500,1	477,3	435,5	430,8
P3	1	74	47	161	233
P3	2	244	160	133	156
P3	3	138	78	229	261
P3	4	186	204	231	131
P3	5	158	292	167	138
P3	6	189	75	192	205
AVERAGE (P3)		165,1	142,7	185,5	187,3

Fabric P2 decreased in tensile strength after respectively one, two and three hours washing and the variation among individual test samples were the smallest of the three fabrics. Samples from fabric P1 (cotton Voile) were so weak after washing that the breaks that occurred on the Instron Tensile Strength Tester were unacceptable. Some samples tended to pull apart in stead of breaking when tested. Fabric P3 (viscose rayon) would also not be suitable for the investigation, as the results were very inconsistent. This could be attributed to relaxation and progressive shrinkage in the washed samples. **Fabric P2** was consequently selected as suitable for the **tensile strength** tests in this investigation. **Fabric P4** conformed to the criteria for the selection of a suitable sample fabric for the assessment of **print deterioration** and **degree of fraying**.

ADDENDUM C

SABS METHOD 93: BREAKING STRENGTH AND ELONGATION AT BREAK

STANDARD METHOD SUMMARY

SABS Method 93-1989

Second Revision

Breaking strength (Strip method)

Section 1. Applicability

1.1 This method is applicable to woven fabrics, non-woven fabrics and certain types of warp-knitted fabrics. It is not applicable to weft-knitted fabrics or fabric that are coated with rubber or plastics to such an extent that the base fabric cannot be distinguished. The method can be expected to give repeatable results. The method is similar to ISO 5081 except for the determination of the rate of extension.

1.2 The results obtained can indicate wether the fabric is correct quality when compared with experience or commodity specification requirements (or both). When the likely performance in use of a fabric is being assessed the results of other strength tests, e.g. seam strength, slippage, tearing strength or bursting strength, may be more useful.

Section 2. Apparatus

Testing was done on the Instron Tensile Tester in the laboratory at the Department of Consumer Science, University of Stellenbosch.

Section 3: Conditioning

Samples were conditioned in accordance with SABS Method 70 and the preparation and testing on the samples were done in the same standard atmosphere.

Section 4. Preparation of test specimens

4.1 From each conditioned test sample that has no crease and no visible fault, cut at least 12 specimens so that in 6 of the specimens the longitudinal yarns are warp and in the other 6 weft. Use one specimen in each direction for the preliminary test. So cut the two sets of specimens that their longitudinal yarns all represent different portions of the warp and weft (length and width) of the fabric, respectively, and do not cut any warp (length) direction specimen from nearer either selvedge than one-tenth of the width of the test sample.

4.2 So cut each specimen (that is to be unravelled) that its width exceeds 50 mm (allowing for fringed of suitable width) and its length is approximately 350 mm (allowing for an initial distance of 200 mm, the depth of the jaws, and an additional length for supporting the specimen while it is clamped).

4.3 The fringes are of such a width that during the process of testing, no longitudinal thread can escape from the fringes. For the majority of fabrics a fringe of width approximately 5 mm on each side will be sufficient. On fabrics that have very open weaves, a fringe of 10 mm and more may be required. For very closely woven fabrics, a narrow fringe may be satisfactory.

4.4 By removing an approximately equal number of yarns from each edge, unravel each specimen to a width of 50 mm. Take care not to damage the middle 200 mm length of the specimen.

4.5 Cut fabrics and non-wovens that cannot be unravelled in this manner, along lines 50 mm apart and parallel to the appropriate (thread) direction.

SECTION 5: Procedure

5.1 Preliminary test. First use an additional specimen in each direction and estimate the pre-tension and the working range.

5.2 Choose the working range on the machine that will give the greatest accuracy and avoid using results from the first 10% and the last 10% part of the scale.

5.3 So mount a specimen centrally in the jaws that after pre-tensioning, the longitudinal axis of the specimen is at right angles to the edges of the jaws.

5.4 Pre-tensioning. Unless otherwise required, take the pre-tension of the specimen as 1 ± 0,25% of the probable breaking strength.

5.5 Set the moving clamp in motion and when the specimen has broken record the following:

a) The maximum load required, N

b) the elongation at break, mm

5.6 Return the moving clamp to the initial distance, remove the broken parts of the specimen and repeat the procedure until the required number of specimens have been tested.

5.7 Where the break of a fabric takes place in two or more stages (as can be the case with double weaves and more complex weave structures) record the maximum load indicated in the course of breaking the first set of thread as the breaking strength of the fabric unless otherwise agreed upon between the parties concerned.

5.8 Jaw breaks. When a test specimen slips in the jaws, breaks at the jaw or, for any other reason attributable too faulty operation, shows a result markedly below the average for the set of specimens, discard the results and, where possible, carry out a duplicate test on another specimen that is cut from the same set of longitudinal yarns. Include the value so obtained in the average for the set of test specimens. If a duplicate test cannot be made use the results of the valid test, provided that these number at least five.

SECTION 6: Calculation

6.1 Breaking strength: Calculate the arithmetic mean of the breaking strength for each set of test specimens separately and record it as the warp/weft breaking strength, expressed in Newton.

SECTION 7: Report

7.1 Recording: Report that the test was carried out in accordance with SABS Method 93.

7.2 State the type of machine used (CRE or CRT) and report the mean of the specimens tested in each direction and the individual values, if so required.

7.3 Report any deviation from the specified test procedure.

ADDENDUM D

CSIR TEST REPORT: FLUIDITY TESTS

CSIR

M & MTEK CFTC

CONFIDENTIAL TEST REPORT

WET PROCESSING LABORATORY

Date: 13 July 2001

Our Ref: 10525

Client: University of Stellenbosch

4. RESULTS:

The results obtained are given in the following table:

Table 1: Results showing Fluidity and Degree of Polymerization results

Sample	Fluidity value $(Pa.s)^{-1}$	DP value
Washed	43,9	2024
Unwashed	42,6	2049

COMMENTS:

- The Cuprammonium Fluidity test is a measure of the average molecular chain length of the cellulose. It is considered to be an accurate measurement of cotton degradation, i.e. it is a useful measure of the tendering of cotton, that can result from chemical processes such as bleaching or, when in use, the cotton being submitted to chemical influences.

- Cellulose molecules do not contain the same number of glucose units but exhibit "polymolecularity". Hence, an average number of glucose units per molecule is usually determined – the degree of polymerization (DP) value. The degree of polymerization is related to the strength of the fibre.

CSIR

M & MTEK CFTC

CONFIDENTIAL TEST REPORT

WET PROCESSING LABORATORY

Date: 13 July 2001

Our Ref: 10525

Client: University of Stellenbosch

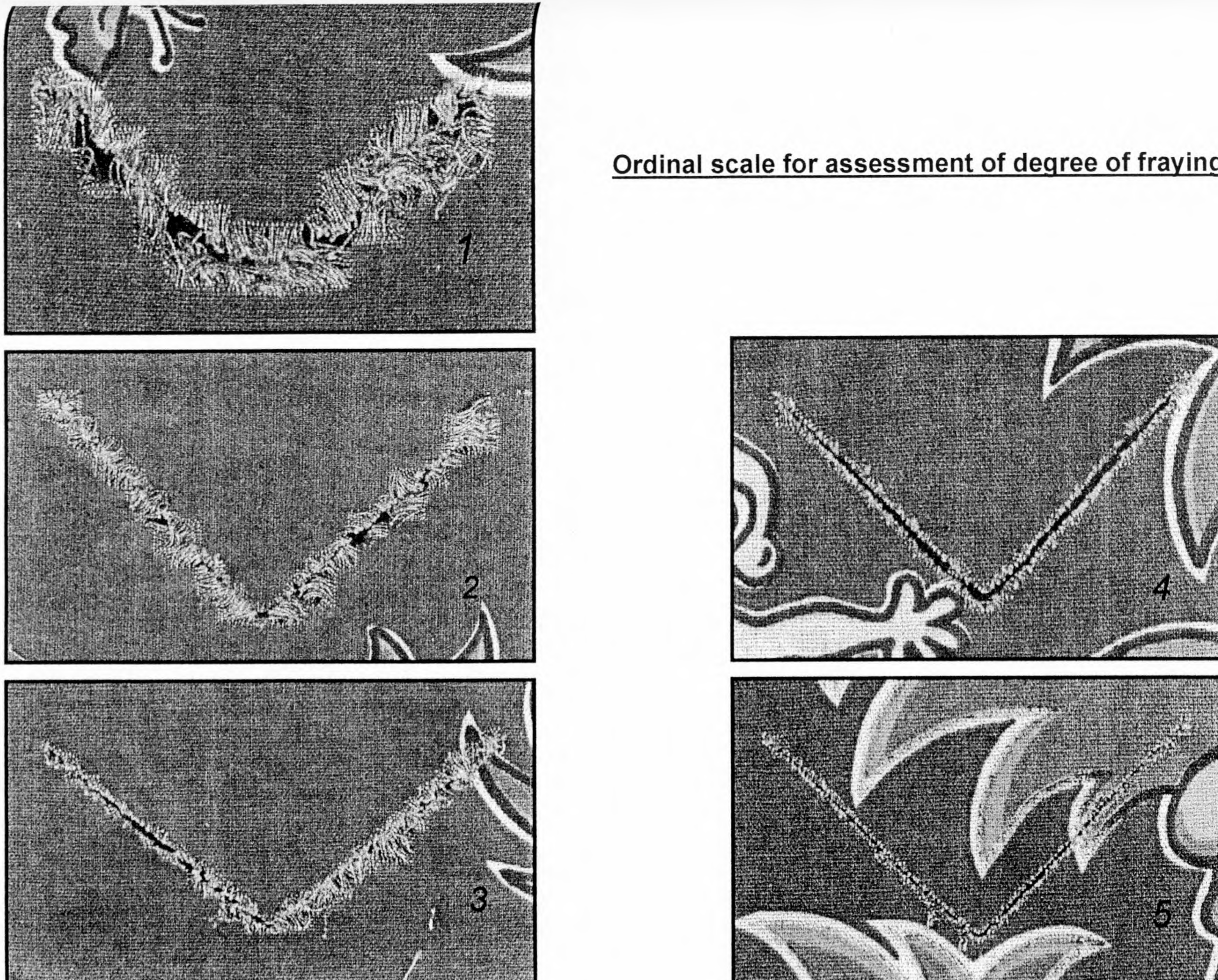
Table 2: The interpretation of the significance of the values obtained:

Fluidity Value (poise)	Comments:
1 to 5	Very mildly scoured and bleached cottons
5 to 10	Normally scoured and bleached cottons
10 to 20	Strongly bleached cotton e.g. surgical cotton wool. Textile cottons rather strongly treated in chemical processing. Fluidity value of 10 noted as the beginning of chemical tendering. Fluidity values of 15 – 20 represent definite chemical tendering.
20 to 30	Badly over-bleached cottons which show serious loss in strength.
30 to 40	Serious chemically damaged cottons which are beginning to show loss of fibrous structure and have serious loss in strength. This range is unsuitable for normal use.
40 or above	Highly degraded cotton, converted largely into either hydrocellulose or oxycellulose.
DP Value: 2300 – 3000	Natural Fibres: cotton, flax, ramie
DPValue: 1800 – 2000	Acceptable Bleached Cotton
DP Value: 1000 – 1200	Regenerated cellulose : polynosic
DP Value: 250 – 400	Regenerated cellulose : viscose

ADDENDUM E

ORDINAL SCALE FOR EVALUATING DEGREE OF FRAYING

Ordinal scale for assessment of degree of fraying



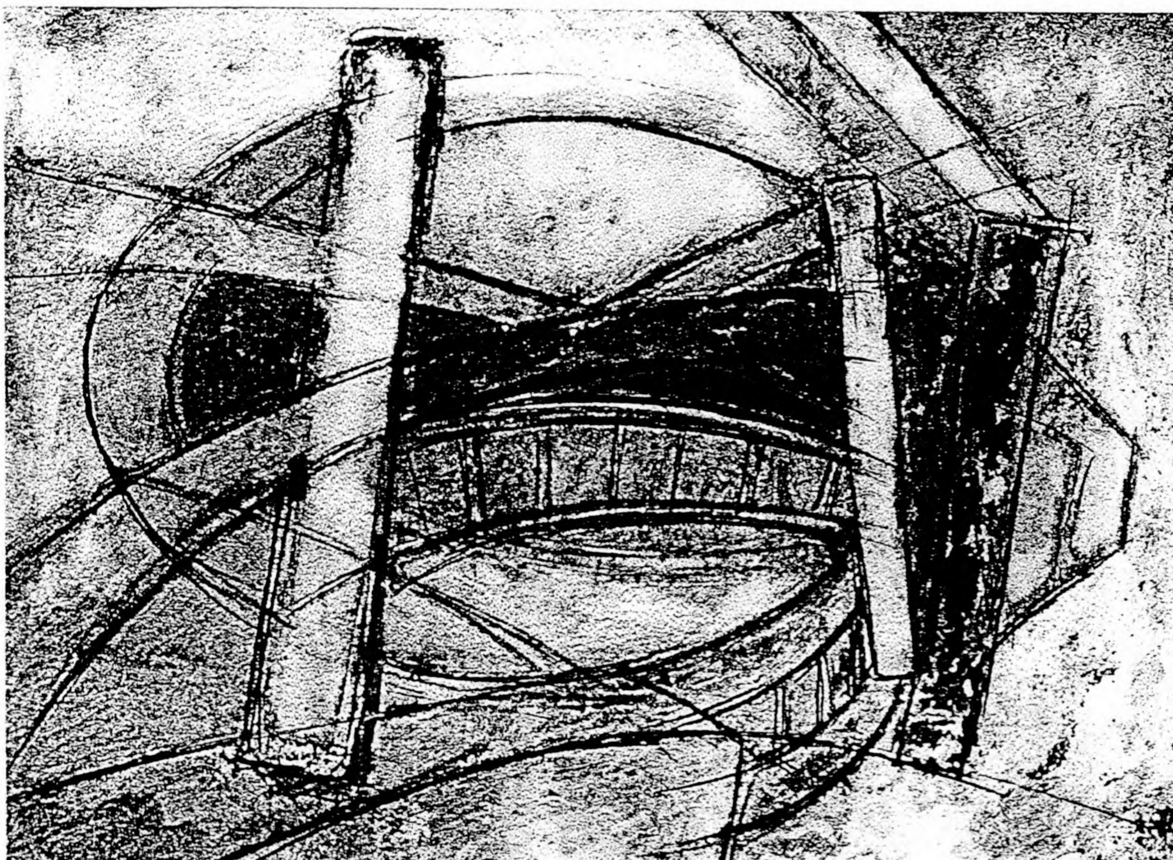
ADDENDUM F

CENTRE FOR TEST MATERIALS PRODUCT INFORMATION. VOLUME 1: SOILED AND CLEAN TEST FABRICS RELATED PRODUCTS AND SERVICES

Product Information

C.F.T. B.V.

Volume 1: SOILED AND CLEAN TESTFABRICS Related products and services



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ISO 9001

DUTEST AGENCIES
P.O. Box 84
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1. INTRODUCTION

C.F.T. – producer of soiled test cloths for evaluating the performance of washing machines and detergents – was founded in 1989, and produces now one of the most extensive ranges of soiled materials in the world.

Since July, 1998, the C.F.T. organisation is certified under ISO 9001:1994.

The C.F.T. organisation consists of:

- C.F.T. Holding B.V.
- C.F.T. B.V., the production and sales unit.
- I.T.L. B.V., a test facility for the evaluation of detergent products and washing.

2. CFT BV TEST CLOTHS SOILED BY IMMERSION

1. GENERAL

Test cloths refer here to both soiled and clean fabrics and they are used to monitor fabric washing performance.

Artificially soiled cloths are produced at CFT BV according to standardised receipts. They are a convenient means of monitoring the cleaning performance of fabric detergent products and the efficiency of washing machines.

2. OBJECTIVES

The major objective of using test cloths is to measure a certain property, mostly the reflectance before and after washing of the soiled test cloths. Thereby a quantitative indication of the degree of detergent (washing machine) performance can be obtained by comparison. This performance is normally related to characteristic reactions of the test fabric to major ingredients entering in the formulation of detergents such as active builders (pCa), bleaches and enzymes.

3. SCOPE

3.1 Properties of C.F.T. test cloths

- uniform soiling (low within-batch variability);
- good reproducibility (low batch-to-batch variability);

- specific product or ingredient effects can be demonstrated and measured;
- cost-effective, since few (expensive) repeat washes are needed to obtain reliable results;
- stable during storage, C.F.T. test fabrics, unless indicated otherwise, are aged by prolonged heating at 75 °C, resulting in an unmatched long-term stability in performance.

3.2 Limitations of soiled test cloths

- most soiled test fabrics are only suitable for studying single-wash effects;
- most test fabrics respond to more than one product ingredient. Therefore, the results obtained should be interpreted with care;
- at selection, the ingredient response characteristics of test fabrics should be taken into account.

4. USE OF TEST CLOTHS

4.1 Storage

Unless specified otherwise on the package, all artificially soiled standard test fabrics should be stored in the dark, at room temperature or below, and the relative humidity should not exceed 60%. Under these conditions, our (aged) regular test fabrics can be stored for more than one year, without significant changes in response taking place. From January 1997 on all our soiled test cloths, as well those supplied by the metre as ready-to-use swatches, are supplied vacuum-packed together with Ageless, an oxygen absorbent. The latter is used to further increase its shelf life. Test fabrics that are not extensively aged have to be stored in a refrigerator. This is mentioned on the product label. However, in the case of any doubt, always store the test fabric vacuum sealed in the refrigerator or ask us.

4.2 Guide-lines for use

Our artificial soil mixtures contain natural components, which makes it impossible to eliminate differences between batches completely. In addition, extra variability will be introduced by using natural fabrics as cotton and wool. Therefore care should be taken that fabrics of the same batch are used for a given set of experiments.

ADDENDUM G

RAW DATA: TENSILE STRENGTH

AVERAGE TENSILE STRENGTH RESULTS PER SAMPLE AS MEASURED ON THE INSTRON TENSILE STRENGTH TESTER					
SAMPLE REFERENCE	WASHING MACHINE	WASH TEMPERATURE	LEVEL OF DETERGENT	NUMBER OF WASHES	AVERAGE CORRECTED TENSILE STRENGHT PER SAMPLE (Newton)
1	*V(A)1*	60°C	no detergent	10	495.2
2	*V(A)1*	60°C	no detergent	20	535.2
3	*V(A)1*	60°C	no detergent	30	517.8
4	*V(A)1*	60°C	no detergent	40	512.7
5	*V(A)1*	60°C	no detergent	50	505.9
7	*V(A)2*	60°C	no detergent	10	510.2
8	*V(A)2*	60°C	no detergent	20	511.6
9	*V(A)2*	60°C	no detergent	30	500.5
10	*V(A)2*	60°C	no detergent	40	519.3
11	*V(A)2*	60°C	no detergent	50	512.8
13	*V(I)1*	60°C	no detergent	10	495.9
14	*V(I)1*	60°C	no detergent	20	503.3
15	*V(I)1*	60°C	no detergent	30	534.4
16	*V(I)1*	60°C	no detergent	40	557.0
17	*V(I)1*	60°C	no detergent	50	525.4
19	*H1*	60°C	no detergent	10	531.1
20	*H1*	60°C	no detergent	20	542.1
21	*H1*	60°C	no detergent	30	537.8
22	*H1*	60°C	no detergent	40	536.4
23	*H1*	60°C	no detergent	50	492.9
25	*H2*	60°C	no detergent	10	517.6
26	*H2*	60°C	no detergent	20	528.2
27	*H2*	60°C	no detergent	30	523.3
28	*H2*	60°C	no detergent	40	518.0
29	*H2*	60°C	no detergent	50	563.5
31	*H4*	60°C	no detergent	10	541.4
32	*H4*	60°C	no detergent	20	516.6
33	*H4*	60°C	no detergent	30	538.9
34	*H4*	60°C	no detergent	40	533.3
35	*H4*	60°C	no detergent	50	540.3
37	*H3*	60°C	no detergent	10	536.7
38	*H3*	60°C	no detergent	20	508.5
39	*H3*	60°C	no detergent	30	531.1
40	*H3*	60°C	no detergent	40	529.8
41	*H3*	60°C	no detergent	50	546.0
43	*V(A)1*	40°C	no detergent	10	517.4
44	*V(A)1*	40°C	no detergent	20	523.2

45	*V(A)1*	40°C	no detergent	30	538.2
46	*V(A)1*	40°C	no detergent	40	514.4
47	*V(A)1*	40°C	no detergent	50	507.9
49	*V(A)2*	40°C	no detergent	10	554.2
50	*V(A)2*	40°C	no detergent	20	538.7
51	*V(A)2*	40°C	no detergent	30	511.8
52	*V(A)2*	40°C	no detergent	40	500.9
53	*V(A)2*	40°C	no detergent	50	518.7
55	*V(I)1*	40°C	no detergent	10	493.1
56	*V(I)1*	40°C	no detergent	20	516.9
57	*V(I)1*	40°C	no detergent	30	501.6
58	*V(I)1*	40°C	no detergent	40	508.0
59	*V(I)1*	40°C	no detergent	50	502.5
61	*H1*	40°C	no detergent	10	556.1
62	*H1*	40°C	no detergent	20	544.1
63	*H1*	40°C	no detergent	30	520.4
64	*H1*	40°C	no detergent	40	519.1
65	*H1*	40°C	no detergent	50	532.8
67	*H2*	40°C	no detergent	10	505.9
68	*H2*	40°C	no detergent	20	522.2
69	*H2*	40°C	no detergent	30	526.4
70	*H2*	40°C	no detergent	40	520.8
71	*H2*	40°C	no detergent	50	553.0
73	*H4*	40°C	no detergent	10	532.8
74	*H4*	40°C	no detergent	20	525.7
75	*H4*	40°C	no detergent	30	498.2
76	*H4*	40°C	no detergent	40	503.6
77	*H4*	40°C	no detergent	50	538.9
79	*H3*	40°C	no detergent	10	467.1
80	*H3*	40°C	no detergent	20	486.0
81	*H3*	40°C	no detergent	30	509.0
82	*H3*	40°C	no detergent	40	503.4
83	*H3*	40°C	no detergent	50	527.5
85	*V(A)1*	40°C	with detergent	10	522.6
86	*V(A)1*	40°C	with detergent	20	525.7
87	*V(A)1*	40°C	with detergent	30	514.8
88	*V(A)1*	40°C	with detergent	40	520.1
89	*V(A)1*	40°C	with detergent	50	477.6
91	*V(A)2*	40°C	with detergent	10	565.2
92	*V(A)2*	40°C	with detergent	20	542.4
93	*V(A)2*	40°C	with detergent	30	544.4
94	*V(A)2*	40°C	with detergent	40	500.2
95	*V(A)2*	40°C	with detergent	50	465.1

97	*V(I)1*	40°C	with detergent	10	556.9
98	*V(I)1*	40°C	with detergent	20	513.9
99	*V(I)1*	40°C	with detergent	30	514.5
100	*V(I)1*	40°C	with detergent	40	522.3
101	*V(I)1*	40°C	with detergent	50	523.5
103	*H1*	40°C	with detergent	10	559.4
104	*H1*	40°C	with detergent	20	540.6
105	*H1*	40°C	with detergent	30	510.3
106	*H1*	40°C	with detergent	40	496.2
107	*H1*	40°C	with detergent	50	513.6
109	*H2*	40°C	with detergent	10	563.3
110	*H2*	40°C	with detergent	20	563.5
111	*H2*	40°C	with detergent	30	542.5
112	*H2*	40°C	with detergent	40	544.3
113	*H2*	40°C	with detergent	50	546.9
115	*H3*	40°C	with detergent	10	543.2
116	*H3*	40°C	with detergent	20	560.8
117	*H3*	40°C	with detergent	30	546.8
118	*H3*	40°C	with detergent	40	542.0
119	*H3*	40°C	with detergent	50	542.0
121	*H4*	40°C	with detergent	10	560.5
122	*H4*	40°C	with detergent	20	527.1
123	*H4*	40°C	with detergent	30	558.8
124	*H4*	40°C	with detergent	40	543.8
125	*H4*	40°C	with detergent	50	496.3
127	*V(A)1*	60°C	with detergent	10	526.5
128	*V(A)1*	60°C	with detergent	20	538.6
129	*V(A)1*	60°C	with detergent	30	494.8
130	*V(A)1*	60°C	with detergent	40	507.5
131	*V(A)1*	60°C	with detergent	50	514.4
133	*V(A)2*	60°C	with detergent	10	511.8
134	*V(A)2*	60°C	with detergent	20	496.6
135	*V(A)2*	60°C	with detergent	30	518.6
136	*V(A)2*	60°C	with detergent	40	509.9
137	*V(A)2*	60°C	with detergent	50	499.7
139	*V(I)1*	60°C	with detergent	10	555.0
140	*V(I)1*	60°C	with detergent	20	532.1
141	*V(I)1*	60°C	with detergent	30	530.9
143	*V(I)1*	60°C	with detergent	50	530.3
145	*H1*	60°C	with detergent	10	533.3
146	*H1*	60°C	with detergent	20	539.4
147	*H1*	60°C	with detergent	30	524.2
148	*H1*	60°C	with detergent	40	532.9

149	*H1*	60°C	with detergent	50	527.2
151	*H2*	60°C	with detergent	10	569.3
152	*H2*	60°C	with detergent	20	547.2
153	*H2*	60°C	with detergent	30	535.0
154	*H2*	60°C	with detergent	40	562.3
155	*H2*	60°C	with detergent	50	537.9
157	*H4*	60°C	with detergent	10	554.2
158	*H4*	60°C	with detergent	20	548.1
159	*H4*	60°C	with detergent	30	528.8
160	*H4*	60°C	with detergent	40	540.9
161	*H4*	60°C	with detergent	50	537.9
163	*H3*	60°C	with detergent	10	559.7
164	*H3*	60°C	with detergent	20	520.1
165	*H3*	60°C	with detergent	30	542.5
166	*H3*	60°C	with detergent	40	544.4
167	*H3*	60°C	with detergent	50	558.7
	CTRL	.	.	0	499.2

ADDENDUM H

RAW DATA: PRINT DETERIORATION

COLORIMETER MEASUREMENTS FOR PRINT DETERIORATION				
WASHING MACHINE	NUMBER OF WASHES	REPEAT	VALUE FOR LIGHTNESS*	AVERAGE VALUE FOR LIGHTNESS*
V(A)1	0	1	-41.9	
V(A)1	0	2	-41.3	
V(A)1	0	3	-41.6	
V(A)1	0	4	-41.6	
V(A)1	0	5	-41.5	-41.6
V(A)2	0	1	-42.0	
V(A)2	0	2	-42.0	
V(A)2	0	3	-42.0	
V(A)2	0	4	-41.8	
V(A)2	0	5	-41.2	-41.8
V(I)1	0	1	-40.9	
V(I)1	0	2	-41.9	
V(I)1	0	3	-41.8	
V(I)1	0	4	-41.4	
V(I)1	0	5	-41.6	-41.5
H1	0	1	-41.5	
H1	0	2	-41.6	
H1	0	3	-41.1	
H1	0	4	-41.3	
H1	0	5	-41.7	-41.4
H2	0	1	-41.5	
H2	0	2	-41.5	
H2	0	3	-41.3	
H2	0	4	-41.8	
H2	0	5	-41.8	-41.6
H4	0	1	-42.2	
H4	0	2	-41.1	
H4	0	3	-40.9	
H4	0	4	-42.0	
H4	0	5	-42.0	-41.6
H3	0	1	-40.0	
H3	0	2	-39.3	
H3	0	3	-40.1	
H3	0	4	-39.3	
H3	0	5	-39.9	-39.7
V(A)1	10	1	-41.5	
V(A)1	10	2	-39.1	
V(A)1	10	3	-40.6	
V(A)1	10	4	-40.9	

V(A)1	10	5	-40.5	-40.5
V(A)1	20	1	-35.7	
V(A)1	20	2	-35.9	
V(A)1	20	3	-35.9	
V(A)1	20	4	-35.9	
V(A)1	20	5	-36.0	-35.9
V(A)2	10	1	-38.7	
V(A)2	10	2	-38.4	
V(A)2	10	3	-39.7	
V(A)2	10	4	-38.6	
V(A)2	10	5	-39.2	-38.9
V(A)2	20	1	-36.7	
V(A)2	20	2	-37.0	
V(A)2	20	3	-37.0	
V(A)2	20	4	-37.0	
V(A)2	20	5	-37.3	-37.0
V(I)1	10	1	-41.7	
V(I)1	10	2	-41.1	
V(I)1	10	3	-41.2	
V(I)1	10	4	-41.5	
V(I)1	10	5	-41.5	-41.4
V(I)1	20	1	-39.2	
V(I)1	20	2	-39.6	
V(I)1	20	3	-39.1	
V(I)1	20	4	-39.4	
V(I)1	20	5	-39.4	-39.3
H1	10	1	-39.5	
H1	10	2	-39.4	
H1	10	3	-40.5	
H1	10	4	-39.5	
H1	10	5	-39.5	-39.7
H1	20	1	-38.6	
H1	20	2	-37.3	
H1	20	3	-38.7	
H1	20	4	-38.0	
H1	20	5	-38.5	-38.2
H2	10	1	-41.5	
H2	10	2	-41.5	
H2	10	3	-41.3	
H2	10	4	-41.8	
H2	10	5	-41.8	-41.6
H2	20	1	-40.4	
H2	20	2	-39.9	
H2	20	3	-40.2	

H2	20	4	-39.4	
H2	20	5	-39.9	-39.9
H4	10	1	-39.5	
H4	10	2	-39.4	
H4	10	3	-39.7	
H4	10	4	-40.3	
H4	10	5	-39.5	-39.7
H4	20	1	-38.4	
H4	20	2	-38.2	
H4	20	3	-38.0	
H4	20	4	-38.3	
H4	20	5	-38.4	-38.3
H3	10	1	-38.8	
H3	10	2	-39.3	
H3	10	3	-39.8	
H3	10	4	-39.3	
H3	10	5	-39.1	-39.3
H3	20	1	-37.9	
H3	20	2	-37.7	
H3	20	3	-38.3	
H3	20	4	-37.0	
H3	20	5	-37.4	-37.6

ADDENDUM I

RAW DATA: DEGREE OF FRAYING

FREQUENCY TABLE FRAYING RATINGS PER WASHING MACHINE

(Including all ratings for samples washed one, two and three times)

WASHING MACHINE **RATING**

Frequency	1	1.5	2	2.5	3	3.5	4	4.5	5	**Total**
H1	0	0	0	0	6	2	1	0	0	9
H2	0	0	0	0	1	2	2	3	1	9
H3	0	0	0	0	5	1	2	0	1	9
H4	0	0	0	0	4	2	3	0	0	9
V(A)1	0	1	3	0	5	0	0	0	0	9
V(A)2	3	3	0	0	3	0	0	0	0	9
V(I)1	0	0	0	0	4	1	1	2	1	9
Total	3	4	3	0	28	8	9	5	3	63

ADDENDUM J

RAW DATA: SOIL REMOVAL EFFICIENCY

COLORIMETER RESULTS FOR SOIL REMOVAL EFFICIENCY								
WASHING MACHINE	WASH TEMPERATURE	LEVEL OF DETERGENT	REPEAT	Δa*	Δb*	ΔL*	ΔE*	AVERAGE - ΔE*
H2	40°C	NO DETERGENT	1	0.21	0.66	-6.00	6.0	
H2	40°C	NO DETERGENT	2	0.34	0.99	-5.87	6.0	
H2	40°C	NO DETERGENT	3	0.47	0.73	-5.46	5.5	
H2	40°C	NO DETERGENT	4	0.12	0.85	-5.15	5.2	
H2	40°C	NO DETERGENT	5	0.30	0.76	-7.03	7.1	
H2	40°C	NO DETERGENT	6	-0.01	1.17	-5.84	6.0	
H2	40°C	NO DETERGENT	7	0.48	0.83	-6.95	7.0	
H2	40°C	NO DETERGENT	8	0.18	0.97	-7.71	7.8	
H2	40°C	NO DETERGENT	9	0.42	0.73	-7.28	7.3	
H2	40°C	NO DETERGENT	10	0.34	0.90	-6.44	6.5	6.4
H2	40°C	WITH DETERGENT	1	0.17	0.44	-6.62	6.6	
H2	40°C	WITH DETERGENT	2	0.13	0.23	-6.61	6.6	
H2	40°C	WITH DETERGENT	3	0.14	0.41	-7.72	7.7	
H2	40°C	WITH DETERGENT	4	-0.03	0.85	-8.85	8.9	
H2	40°C	WITH DETERGENT	5	0.02	0.53	-6.24	6.3	
H2	40°C	WITH DETERGENT	6	0.45	0.10	-7.70	7.7	
H2	40°C	WITH DETERGENT	7	0.10	0.73	-7.92	8.0	
H2	40°C	WITH DETERGENT	8	0.16	0.67	-7.39	7.4	
H2	40°C	WITH DETERGENT	9	0.00	0.33	-6.71	6.7	
H2	40°C	WITH DETERGENT	10	0.01	0.47	-7.61	7.6	7.4
H2	60°C	NO DETERGENT	1	0.43	0.84	-5.55	5.6	
H2	60°C	NO DETERGENT	2	0.49	0.92	-5.64	5.7	
H2	60°C	NO DETERGENT	3	0.43	1.04	-5.14	5.3	
H2	60°C	NO DETERGENT	4	0.45	0.92	-5.76	5.8	
H2	60°C	NO DETERGENT	5	0.45	0.55	-4.42	4.5	
H2	60°C	NO DETERGENT	6	0.32	0.80	-4.77	4.9	
H2	60°C	NO DETERGENT	7	0.31	1.18	-5.84	6.0	
H2	60°C	NO DETERGENT	8	0.22	0.75	-3.97	4.0	
H2	60°C	NO DETERGENT	9	0.27	1.29	-5.99	6.1	
H2	60°C	NO DETERGENT	10	0.60	0.72	-5.44	5.5	5.3
H2	60°C	WITH DETERGENT	1	0.32	0.57	-8.90	8.9	
H2	60°C	WITH DETERGENT	2	0.11	0.87	-9.45	9.5	
H2	60°C	WITH DETERGENT	3	0.55	0.55	-10.20	10.2	
H2	60°C	WITH DETERGENT	4	0.22	0.86	-9.40	9.4	
H2	60°C	WITH DETERGENT	5	0.21	0.65	-8.87	8.9	
H2	60°C	WITH DETERGENT	6	0.14	0.44	-7.37	7.4	
H2	60°C	WITH DETERGENT	7	0.51	0.60	-10.47	10.5	
H2	60°C	WITH DETERGENT	8	0.07	0.68	-8.85	8.9	
H2	60°C	WITH DETERGENT	9	0.45	0.60	-9.73	9.8	
H2	60°C	WITH DETERGENT	10	.	.	.	.	9.3
H1	40°C	NO DETERGENT	1	0.49	0.86	-9.62	9.7	
H1	40°C	NO DETERGENT	2	0.45	0.77	-6.28	6.3	
H1	40°C	NO DETERGENT	3	0.09	0.88	-8.16	8.2	

H1	40°C	NO DETERGENT	2	0.45	0.77	-6.28	6.3	
H1	40°C	NO DETERGENT	3	0.09	0.88	-8.16	8.2	
H1	40°C	NO DETERGENT	4	0.46	0.91	-8.10	8.2	
H1	40°C	NO DETERGENT	5	0.44	0.65	-7.19	7.2	
H1	40°C	NO DETERGENT	6	-0.05	1.22	-6.42	6.5	
H1	40°C	NO DETERGENT	7	0.31	0.81	-7.86	7.9	
H1	40°C	NO DETERGENT	8	0.27	1.15	-7.65	7.7	
H1	40°C	NO DETERGENT	9	0.24	0.86	-9.72	9.8	
H1	40°C	NO DETERGENT	10	0.06	0.63	-7.88	7.9	*7.9*
H1	40°C	WITH DETERGENT	1	0.10	0.39	-8.25	8.3	
H1	40°C	WITH DETERGENT	2	0.32	0.60	-8.67	8.7	
H1	40°C	WITH DETERGENT	3	0.48	0.19	-8.16	8.2	
H1	40°C	WITH DETERGENT	4	0.21	0.70	-9.12	9.1	
H1	40°C	WITH DETERGENT	5	0.21	0.51	-8.65	8.7	
H1	40°C	WITH DETERGENT	6	0.23	0.42	-8.42	8.4	
H1	40°C	WITH DETERGENT	7	-0.01	1.12	-9.31	9.4	
H1	40°C	WITH DETERGENT	8	0.01	0.65	-6.13	6.2	
H1	40°C	WITH DETERGENT	9	-0.23	0.75	-7.47	7.5	
H1	40°C	WITH DETERGENT	10	0.04	0.46	-7.01	7.0	*8.1*
H1	60°C	NO DETERGENT	1	0.28	1.28	-6.46	6.6	
H1	60°C	NO DETERGENT	2	0.41	1.19	-5.85	6.0	
H1	60°C	NO DETERGENT	3	0.69	0.95	-7.79	7.9	
H1	60°C	NO DETERGENT	4	0.70	0.90	-6.67	6.8	
H1	60°C	NO DETERGENT	5	0.22	1.14	-6.06	6.2	
H1	60°C	NO DETERGENT	6	0.67	0.77	-7.33	7.4	
H1	60°C	NO DETERGENT	7	0.12	1.34	-5.61	5.8	
H1	60°C	NO DETERGENT	8	0.37	1.14	-5.79	5.9	
H1	60°C	NO DETERGENT	9	0.34	1.21	-5.65	5.8	
H1	60°C	NO DETERGENT	10	0.37	1.12	-6.54	6.6	*6.5*
H1	60°C	WITH DETERGENT	1	0.14	0.55	-8.76	8.8	
H1	60°C	WITH DETERGENT	2	0.13	0.81	-8.08	8.1	
H1	60°C	WITH DETERGENT	3	0.36	0.64	-10.13	10.2	
H1	60°C	WITH DETERGENT	4	0.16	0.82	-10.46	10.5	
H1	60°C	WITH DETERGENT	5	0.09	0.74	-7.92	8.0	
H1	60°C	WITH DETERGENT	6	0.21	0.91	-9.94	10.0	
H1	60°C	WITH DETERGENT	7	0.35	0.94	-10.96	11.0	
H1	60°C	WITH DETERGENT	8	0.01	0.73	-9.08	9.1	
H1	60°C	WITH DETERGENT	9	0.00	0.78	-8.64	8.7	
H1	60°C	WITH DETERGENT	10	0.43	0.71	-10.54	10.6	*9.5*
H3	40°C	NO DETERGENT	1	0.28	0.84	-6.90	7.0	
H3	40°C	NO DETERGENT	2	0.29	0.88	-6.32	6.4	
H3	40°C	NO DETERGENT	3	0.36	0.47	-4.08	4.1	
H3	40°C	NO DETERGENT	4	0.36	0.82	-5.95	6.0	
H3	40°C	NO DETERGENT	5	0.31	0.98	-6.86	6.9	

H3	40°C	NO DETERGENT	6	0.34	0.44	-5.15	5.2	
H3	40°C	NO DETERGENT	7	0.27	0.97	-4.64	4.7	
H3	40°C	NO DETERGENT	8	0.43	0.85	-7.45	7.5	
H3	40°C	NO DETERGENT	9	0.08	0.87	-5.67	5.7	
H3	40°C	NO DETERGENT	10	0.10	0.92	-4.70	4.8	*5.8*
H3	40°C	WITH DETERGENT	1	-0.06	0.47	-7.74	7.8	
H3	40°C	WITH DETERGENT	2	0.30	-0.12	-5.79	5.8	
H3	40°C	WITH DETERGENT	3	0.13	0.29	-6.30	6.3	
H3	40°C	WITH DETERGENT	4	0.18	0.50	-6.61	6.6	
H3	40°C	WITH DETERGENT	5	0.15	0.26	-6.97	7.0	
H3	40°C	WITH DETERGENT	6	0.37	0.19	-6.92	6.9	
H3	40°C	WITH DETERGENT	7	0.20	0.33	-6.30	6.3	
H3	40°C	WITH DETERGENT	8	0.25	0.69	-6.86	6.9	
H3	40°C	WITH DETERGENT	9	0.31	0.45	-8.24	8.3	
H3	40°C	WITH DETERGENT	10	0.16	0.30	-4.66	4.7	*6.7*
H3	60°C	NO DETERGENT	1	0.54	0.85	-7.12	7.2	
H3	60°C	NO DETERGENT	2	0.32	0.76	-3.55	3.6	
H3	60°C	NO DETERGENT	3	0.47	1.02	-6.63	6.7	
H3	60°C	NO DETERGENT	4	0.23	0.68	-5.19	5.2	
H3	60°C	NO DETERGENT	5	0.64	0.85	-5.46	5.6	
H3	60°C	NO DETERGENT	6	0.51	0.79	-4.91	5.0	
H3	60°C	NO DETERGENT	7	0.43	0.64	-3.89	4.0	
H3	60°C	NO DETERGENT	8	0.65	0.65	-4.72	4.8	
H3	60°C	NO DETERGENT	9	0.56	1.03	-4.96	5.1	
H3	60°C	NO DETERGENT	10	0.54	0.62	-3.77	3.9	*5.1*
H3	60°C	WITH DETERGENT	1	0.32	0.88	-10.22	10.3	
H3	60°C	WITH DETERGENT	2	0.13	0.87	-9.51	9.5	
H3	60°C	WITH DETERGENT	3	0.25	0.49	-8.23	8.2	
H3	60°C	WITH DETERGENT	4	0.16	0.86	-9.79	9.8	
H3	60°C	WITH DETERGENT	5	0.11	0.57	-8.94	9.0	
H3	60°C	WITH DETERGENT	6	0.08	0.44	-7.99	8.0	
H3	60°C	WITH DETERGENT	7	0.29	0.65	-9.20	9.2	
H3	60°C	WITH DETERGENT	8	0.29	0.64	-9.27	9.3	
H3	60°C	WITH DETERGENT	9	0.42	0.62	-9.35	9.4	
H3	60°C	WITH DETERGENT	10	0.58	0.14	-8.47	8.5	*9.1*
H4	40°C	NO DETERGENT	1	0.48	0.61	-5.67	5.7	
H4	40°C	NO DETERGENT	2	0.49	0.90	-6.88	7.0	
H4	40°C	NO DETERGENT	3	0.43	1.06	-7.66	7.7	
H4	40°C	NO DETERGENT	4	-0.01	0.70	-2.83	2.9	
H4	40°C	NO DETERGENT	5	0.46	0.88	-7.33	7.4	
H4	40°C	NO DETERGENT	6	0.29	1.01	-5.67	5.8	
H4	40°C	NO DETERGENT	7	0.48	0.79	-5.68	5.8	
H4	40°C	NO DETERGENT	8	0.23	0.86	-4.95	5.0	
H4	40°C	NO DETERGENT	9	0.20	0.83	-4.87	4.9	

H4	40°C	NO DETERGENT	10	0.52	0.91	-6.18	6.3	*5.9*
H4	40°C	WITH DETERGENT	1	0.40	-0.15	-6.21	6.2	
H4	40°C	WITH DETERGENT	2	0.19	0.38	-6.14	6.2	
H4	40°C	WITH DETERGENT	3	0.07	0.27	-6.57	6.6	
H4	40°C	WITH DETERGENT	4	0.13	0.53	-7.49	7.5	
H4	40°C	WITH DETERGENT	5	0.10	0.56	-7.75	7.8	
H4	40°C	WITH DETERGENT	6	0.51	0.13	-8.70	8.7	
H4	40°C	WITH DETERGENT	7	0.28	0.38	-7.04	7.1	
H4	40°C	WITH DETERGENT	8	0.29	0.61	-8.29	8.3	
H4	40°C	WITH DETERGENT	9	0.43	0.35	-8.18	8.2	
H4	40°C	WITH DETERGENT	10	0.39	0.02	-6.63	6.6	*7.3*
H4	60°C	NO DETERGENT	1	0.17	1.12	-4.81	4.9	
H4	60°C	NO DETERGENT	2	0.56	0.75	-6.57	6.6	
H4	60°C	NO DETERGENT	3	0.53	1.10	-5.62	5.8	
H4	60°C	NO DETERGENT	4	0.57	0.81	-5.09	5.2	
H4	60°C	NO DETERGENT	5	0.46	1.02	-5.57	5.7	
H4	60°C	NO DETERGENT	6	0.64	0.51	-6.62	6.7	
H4	60°C	NO DETERGENT	7	0.23	1.03	-4.73	4.9	
H4	60°C	NO DETERGENT	8	0.49	1.19	-6.12	6.3	
H4	60°C	NO DETERGENT	9	0.52	0.31	-3.92	4.0	
H4	60°C	NO DETERGENT	10	0.38	0.79	-4.95	5.0	*5.5*
H4	60°C	WITH DETERGENT	1	0.14	0.93	-10.00	10.0	
H4	60°C	WITH DETERGENT	2	0.00	1.14	-8.64	8.7	
H4	60°C	WITH DETERGENT	3	0.07	0.68	-8.74	8.8	
H4	60°C	WITH DETERGENT	4	0.45	0.55	-10.27	10.3	
H4	60°C	WITH DETERGENT	5	0.46	0.22	-8.67	8.7	
H4	60°C	WITH DETERGENT	6	0.13	0.61	-10.73	10.8	
H4	60°C	WITH DETERGENT	7	0.49	0.32	-7.79	7.8	
H4	60°C	WITH DETERGENT	8	0.35	0.54	-8.65	8.7	
H4	60°C	WITH DETERGENT	9	0.17	0.64	-9.45	9.5	
H4	60°C	WITH DETERGENT	10	0.05	0.82	-7.99	8.0	*9.1*
V(I)1	40°C	NO DETERGENT	1	0.19	0.97	-3.52	3.7	
V(I)1	40°C	NO DETERGENT	2	0.26	0.44	-2.67	2.7	
V(I)1	40°C	NO DETERGENT	3	0.14	0.89	-4.88	5.0	
V(I)1	40°C	NO DETERGENT	4	0.17	0.92	-2.69	2.8	
V(I)1	40°C	NO DETERGENT	5	0.04	0.88	-3.23	3.3	
V(I)1	40°C	NO DETERGENT	6	0.04	0.96	-2.53	2.7	
V(I)1	40°C	NO DETERGENT	7	0.18	0.70	-2.59	2.7	
V(I)1	40°C	NO DETERGENT	8	0.10	0.89	-2.68	2.8	
V(I)1	40°C	NO DETERGENT	9	0.25	0.69	-2.17	2.3	
V(I)1	40°C	NO DETERGENT	10	0.50	0.61	-3.73	3.8	*3.2*
V(I)1	40°C	WITH DETERGENT	1	0.23	0.54	-7.22	7.2	
V(I)1	40°C	WITH DETERGENT	2	0.17	0.41	-7.29	7.3	
V(I)1	40°C	WITH DETERGENT	3	0.34	0.76	-7.70	7.7	

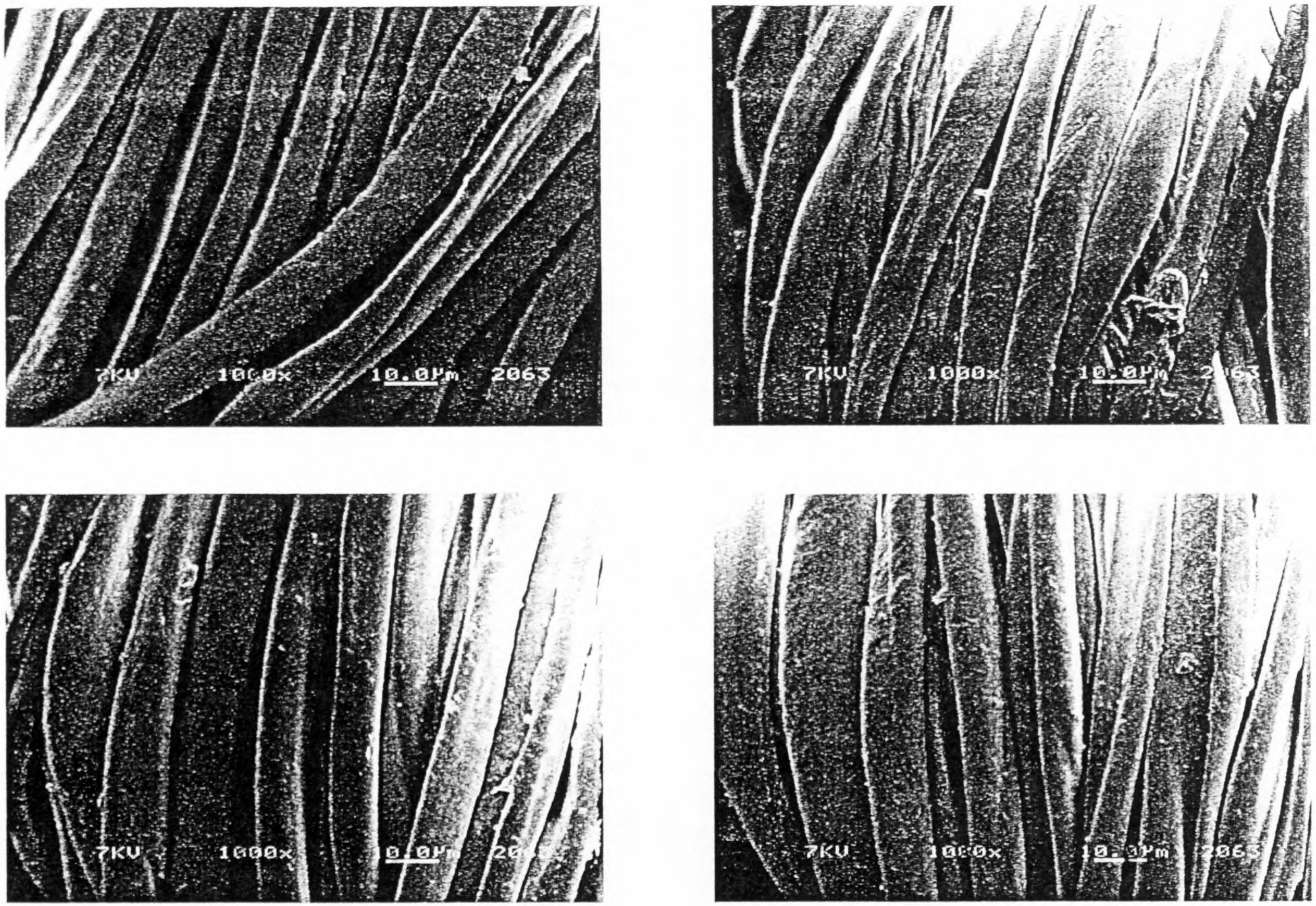
V(I)1	40°C	WITH DETERGENT	4	0.35	0.53	-5.96	6.0	
V(I)1	40°C	WITH DETERGENT	5	0.12	0.70	-6.05	6.1	
V(I)1	40°C	WITH DETERGENT	6	0.19	-0.07	-3.13	3.1	
V(I)1	40°C	WITH DETERGENT	7	0.00	0.60	-4.89	4.9	
V(I)1	40°C	WITH DETERGENT	8	0.09	0.30	-6.13	6.1	
V(I)1	40°C	WITH DETERGENT	9	0.43	-0.08	-4.81	4.8	
V(I)1	40°C	WITH DETERGENT	10	0.25	0.33	-4.08	4.1	*5.8*
V(I)1	60°C	NO DETERGENT	1	0.18	0.80	-1.19	1.4	
V(I)1	60°C	NO DETERGENT	2	0.06	0.73	-1.73	1.9	
V(I)1	60°C	NO DETERGENT	3	0.20	0.63	-2.42	2.5	
V(I)1	60°C	NO DETERGENT	4	0.48	0.04	-3.10	3.1	
V(I)1	60°C	NO DETERGENT	5	0.28	0.65	-2.72	2.8	
V(I)1	60°C	NO DETERGENT	6	0.09	0.61	-2.58	2.7	
V(I)1	60°C	NO DETERGENT	7	0.22	0.70	-1.28	1.5	
V(I)1	60°C	NO DETERGENT	8	0.19	0.49	-2.26	2.3	
V(I)1	60°C	NO DETERGENT	9	0.49	0.11	-1.37	1.5	
V(I)1	60°C	NO DETERGENT	10	0.62	0.22	-1.50	1.6	*2.1*
V(I)1	60°C	WITH DETERGENT	1	0.01	0.59	-3.59	3.6	
V(I)1	60°C	WITH DETERGENT	2	0.17	0.73	-6.66	6.7	
V(I)1	60°C	WITH DETERGENT	3	0.25	0.26	-3.38	3.4	
V(I)1	60°C	WITH DETERGENT	4	0.23	0.59	-5.11	5.1	
V(I)1	60°C	WITH DETERGENT	5	0.21	1.11	-9.90	10.0	
V(I)1	60°C	WITH DETERGENT	6	.	.	.	.	
V(I)1	60°C	WITH DETERGENT	7	0.23	0.76	-7.28	7.3	
T4	60°C	WITH DETERGENT	8	.	.	.	.	
V(I)1	60°C	WITH DETERGENT	9	0.13	0.91	-9.93	10.0	
V(I)1	60°C	WITH DETERGENT	10	.	.	.	.	*6.6*
V(A)1	40°C	NO DETERGENT	1	0.22	0.96	-4.91	5.0	
V(A)1	40°C	NO DETERGENT	2	0.32	0.78	-3.95	4.0	
V(A)1	40°C	NO DETERGENT	3	0.16	0.80	-3.07	3.2	
V(A)1	40°C	NO DETERGENT	4	0.26	1.02	-4.41	4.5	
V(A)1	40°C	NO DETERGENT	5	0.12	0.71	-4.96	5.0	
V(A)1	40°C	NO DETERGENT	6	0.50	0.68	-4.75	4.8	
V(A)1	40°C	NO DETERGENT	7	0.23	0.91	-5.22	5.3	
V(A)1	40°C	NO DETERGENT	8	0.15	0.82	-5.01	5.1	
V(A)1	40°C	NO DETERGENT	9	0.11	1.00	-4.67	4.8	
V(A)1	40°C	NO DETERGENT	10	0.19	0.95	-5.83	5.9	*4.8*
V(A)1	40°C	WITH DETERGENT	1	0.45	0.42	-10.52	10.5	
V(A)1	40°C	WITH DETERGENT	2	0.29	0.62	-9.98	10.0	
V(A)1	40°C	WITH DETERGENT	3	0.38	0.77	-10.56	10.6	
V(A)1	40°C	WITH DETERGENT	4	0.21	0.51	-10.20	10.2	
V(A)1	40°C	WITH DETERGENT	5	0.36	0.45	-9.67	9.7	
V(A)1	40°C	WITH DETERGENT	6	0.44	0.52	-10.45	10.5	
V(A)1	40°C	WITH DETERGENT	7	0.30	0.69	-10.20	10.2	

V(A)1	40°C	WITH DETERGENT	8	0.20	0.94	-10.90	10.9	
V(A)1	40°C	WITH DETERGENT	9	0.37	0.51	-9.81	9.8	
V(A)1	40°C	WITH DETERGENT	10	0.42	0.41	-9.38	9.4	*10.2*
V(A)1	60°C	NO DETERGENT	1	0.38	1.13	-4.32	4.5	
V(A)1	60°C	NO DETERGENT	2	0.27	1.01	-5.30	5.4	
V(A)1	60°C	NO DETERGENT	3	0.16	1.07	-4.90	5.0	
V(A)1	60°C	NO DETERGENT	4	0.16	0.78	-5.37	5.4	
V(A)1	60°C	NO DETERGENT	5	0.40	0.84	-3.22	3.4	
V(A)1	60°C	NO DETERGENT	6	0.29	1.16	-5.94	6.1	
V(A)1	60°C	NO DETERGENT	7	0.45	1.03	-5.75	5.9	
V(A)1	60°C	NO DETERGENT	8	0.34	0.99	-5.38	5.5	
V(A)1	60°C	NO DETERGENT	9	0.16	0.88	-4.14	4.2	
V(A)1	60°C	NO DETERGENT	10	.	.	.	.	*5.0*
V(A)1	60°C	WITH DETERGENT	1	0.63	0.40	-10.17	10.2	
V(A)1	60°C	WITH DETERGENT	2	0.52	0.22	-10.99	11.0	
V(A)1	60°C	WITH DETERGENT	4	0.40	0.39	-10.53	10.5	
V(A)1	60°C	WITH DETERGENT	5	0.32	0.87	-11.06	11.1	
V(A)1	60°C	WITH DETERGENT	6	0.18	1.15	-11.00	11.1	
V(A)1	60°C	WITH DETERGENT	7	0.30	0.90	-10.56	10.6	
V(A)1	60°C	WITH DETERGENT	8	0.38	0.85	-9.40	9.5	
V(A)1	60°C	WITH DETERGENT	9	0.53	0.59	-8.70	8.7	
V(A)1	60°C	WITH DETERGENT	10	0.24	1.05	-10.25	10.3	*9.3*
V(A)2	40°C	NO DETERGENT	1	0.12	0.67	-7.55	7.6	
V(A)2	40°C	NO DETERGENT	2	0.10	0.39	-4.16	4.2	
V(A)2	40°C	NO DETERGENT	3	-0.02	0.82	-5.91	6.0	
V(A)2	40°C	NO DETERGENT	4	0.08	0.66	-7.65	7.7	
V(A)2	40°C	NO DETERGENT	5	0.26	0.97	-5.71	5.8	
V(A)2	40°C	NO DETERGENT	6	-0.03	0.98	-4.74	4.8	
V(A)2	40°C	NO DETERGENT	7	0.07	1.09	-5.64	5.7	
V(A)2	40°C	NO DETERGENT	8	0.22	1.08	-4.81	4.9	
V(A)2	40°C	NO DETERGENT	9	0.32	1.02	-6.11	6.2	
V(A)2	40°C	NO DETERGENT	10	0.13	0.78	-10.04	10.1	*6.3*
V(A)2	40°C	WITH DETERGENT	1	0.27	0.57	-9.37	9.4	
V(A)2	40°C	WITH DETERGENT	2	0.36	0.56	-8.16	8.2	
V(A)2	40°C	WITH DETERGENT	3	0.44	0.45	-9.70	9.7	
V(A)2	40°C	WITH DETERGENT	4	0.16	0.57	-9.45	9.5	
V(A)2	40°C	WITH DETERGENT	5	0.41	0.34	-8.98	9.0	
V(A)2	40°C	WITH DETERGENT	6	0.09	0.77	-8.07	8.1	
V(A)2	40°C	WITH DETERGENT	7	0.02	0.64	-7.06	7.1	
V(A)2	40°C	WITH DETERGENT	8	0.41	0.44	-10.17	10.2	
V(A)2	40°C	WITH DETERGENT	9	0.06	0.80	-9.69	9.7	
V(A)2	40°C	WITH DETERGENT	10	.	.	.	.	*9.0*
V(A)2	60°C	NO DETERGENT	1	0.29	0.57	-7.28	7.3	
V(A)2	60°C	NO DETERGENT	2	0.09	1.36	-6.26	6.4	

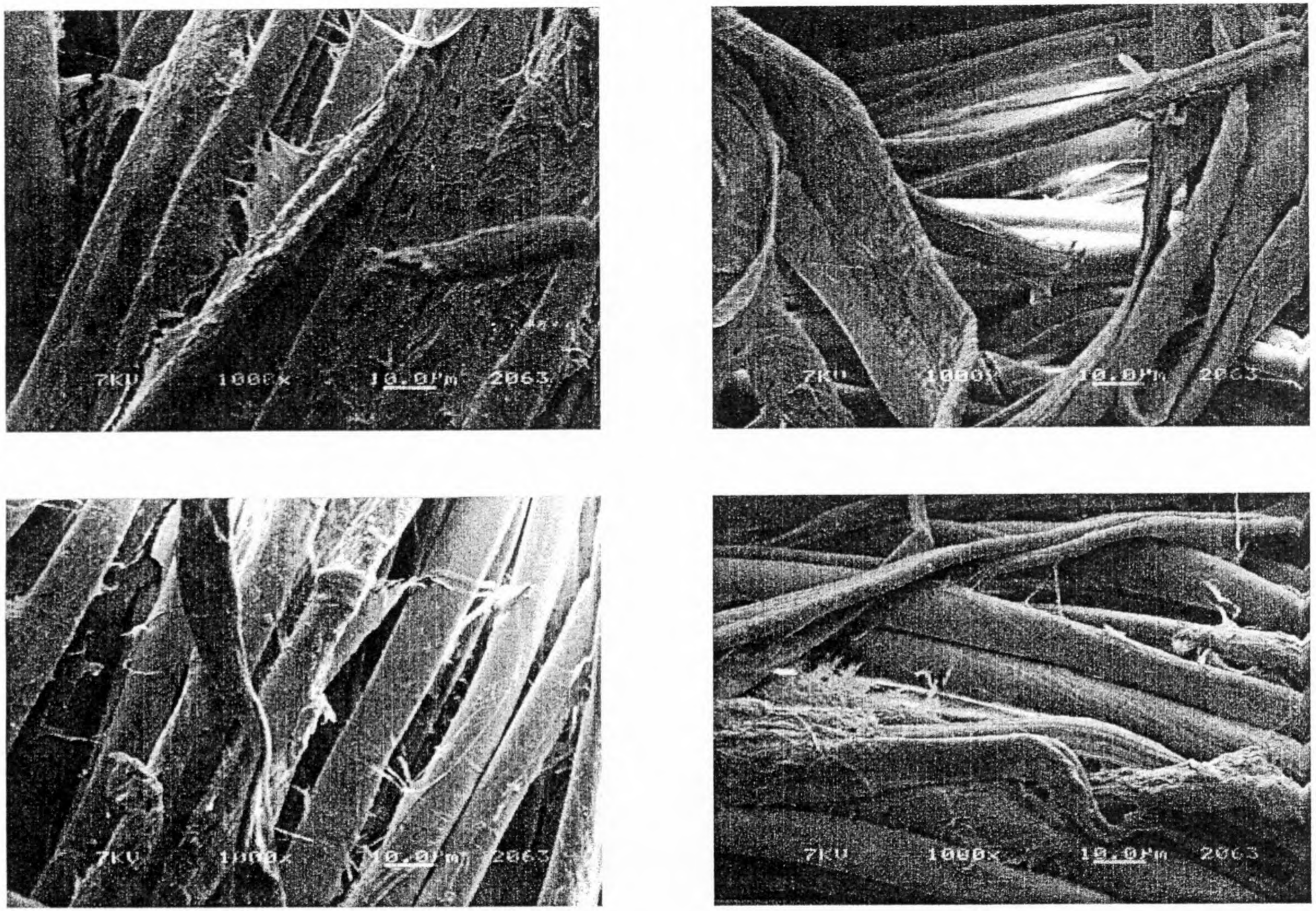
V(A)2	60°C	NO DETERGENT	3	0.45	0.81	-4.74	4.8	
V(A)2	60°C	NO DETERGENT	4	0.47	0.74	-4.92	5.0	
V(A)2	60°C	NO DETERGENT	5	0.39	1.16	-5.44	5.6	
V(A)2	60°C	NO DETERGENT	6	0.23	1.17	-6.05	6.2	
V(A)2	60°C	NO DETERGENT	7	0.24	0.86	-4.91	5.0	
V(A)2	60°C	NO DETERGENT	8	0.40	0.97	-5.16	5.3	
V(A)2	60°C	NO DETERGENT	9	0.38	1.18	-5.27	5.4	
V(A)2	60°C	NO DETERGENT	10	.	.	.	.	*5.7*
V(A)2	60°C	WITH DETERGENT	1	0.55	0.59	-10.06	10.1	
V(A)2	60°C	WITH DETERGENT	2	0.35	1.04	-11.35	11.4	
V(A)2	60°C	WITH DETERGENT	3	0.14	1.22	-9.75	9.8	
V(A)2	60°C	WITH DETERGENT	4	0.41	1.09	-10.48	10.5	
V(A)2	60°C	WITH DETERGENT	5	0.23	1.32	-6.56	6.7	
V(A)2	60°C	WITH DETERGENT	6	0.55	0.89	-7.50	7.6	
V(A)2	60°C	WITH DETERGENT	7	0.27	0.81	-9.07	9.1	
V(A)2	60°C	WITH DETERGENT	8	0.35	1.33	-7.71	7.8	
V(A)2	60°C	WITH DETERGENT	9	0.26	1.24	-7.60	7.7	
V(A)2	60°C	WITH DETERGENT	10	0.17	1.50	-7.93	8.1	*8.9*

ADDENDUM K

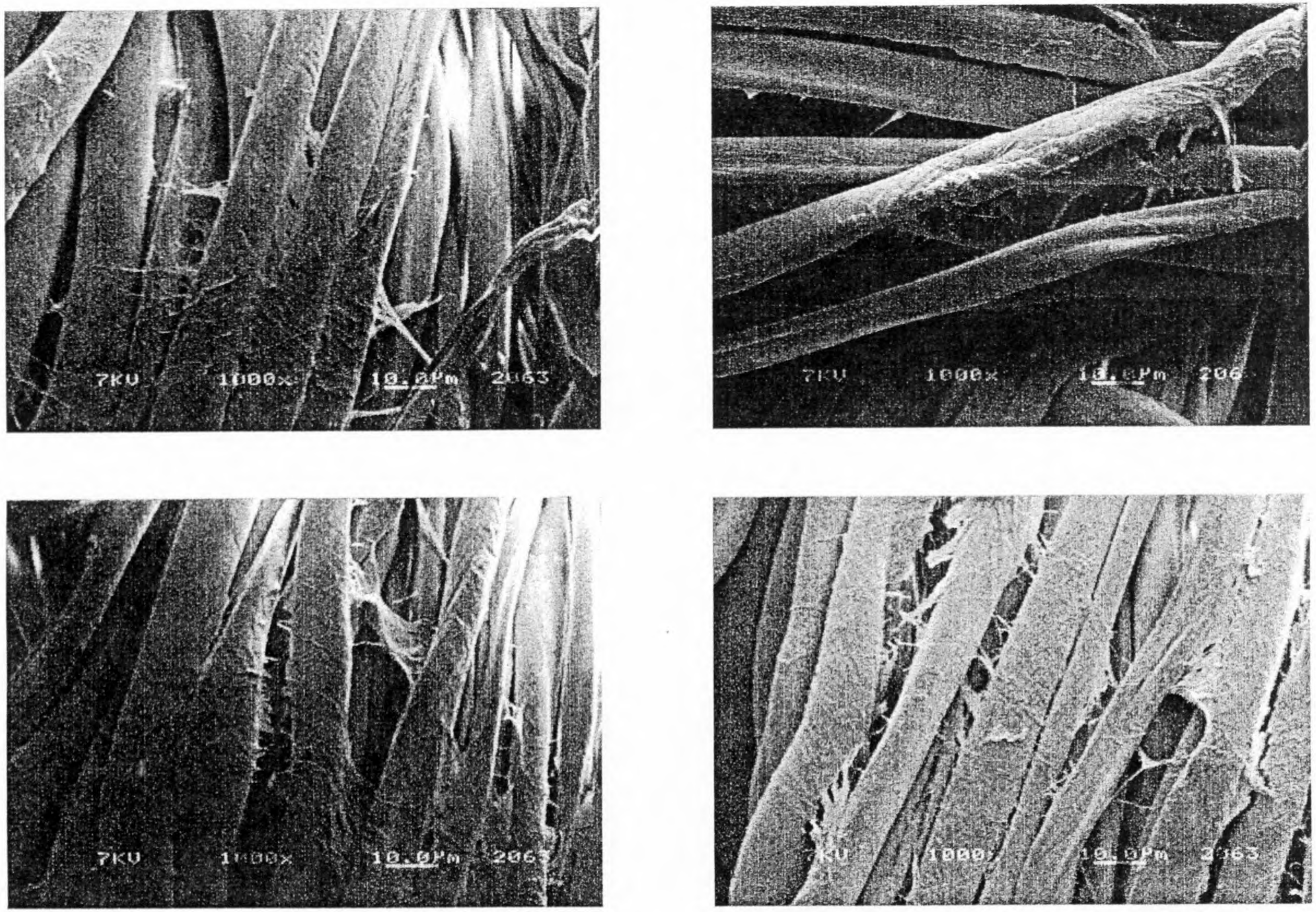
SEM PHOTOMICROGRAPHS



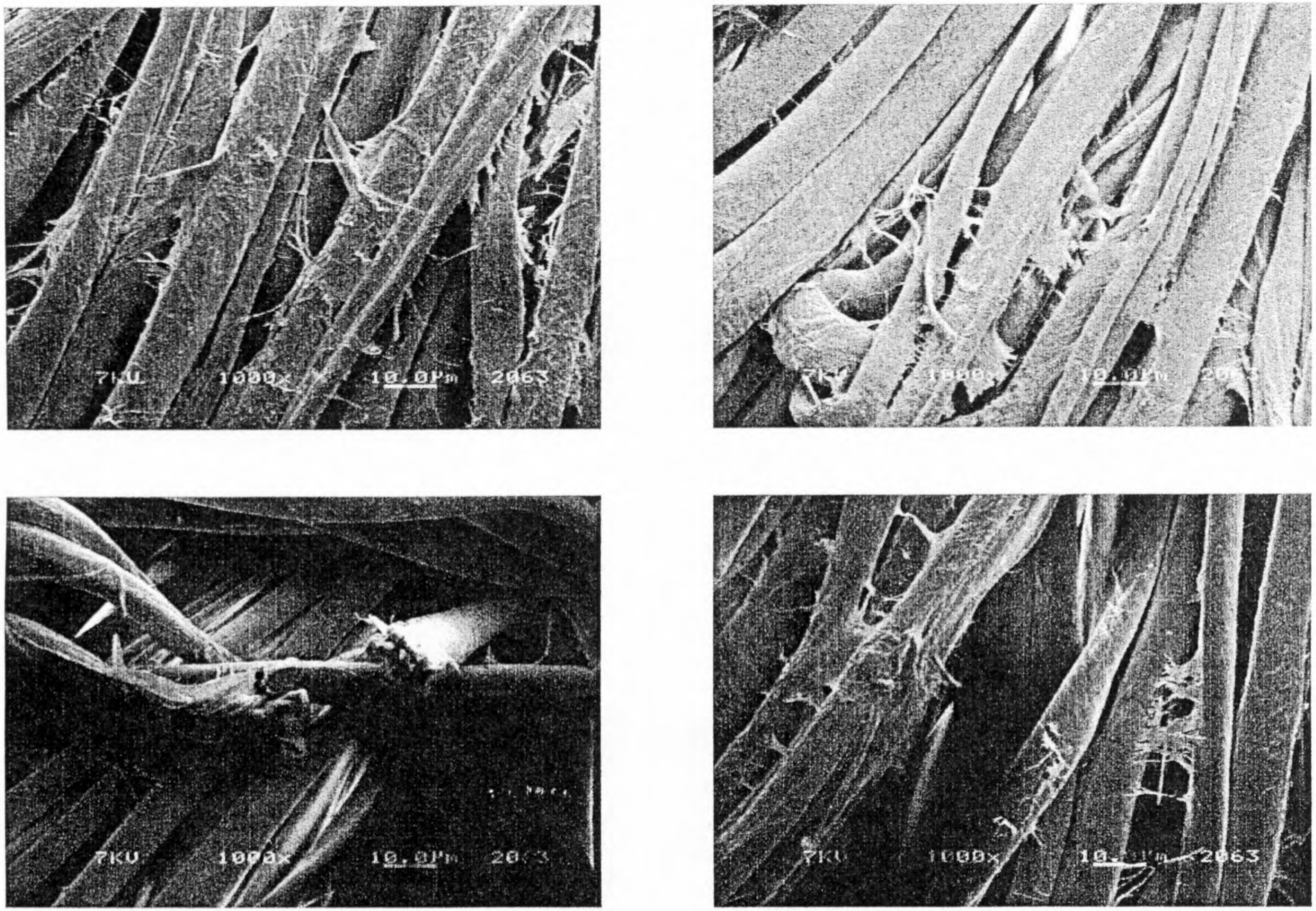
CONTROL (Unwashed) - 1000X Magnification



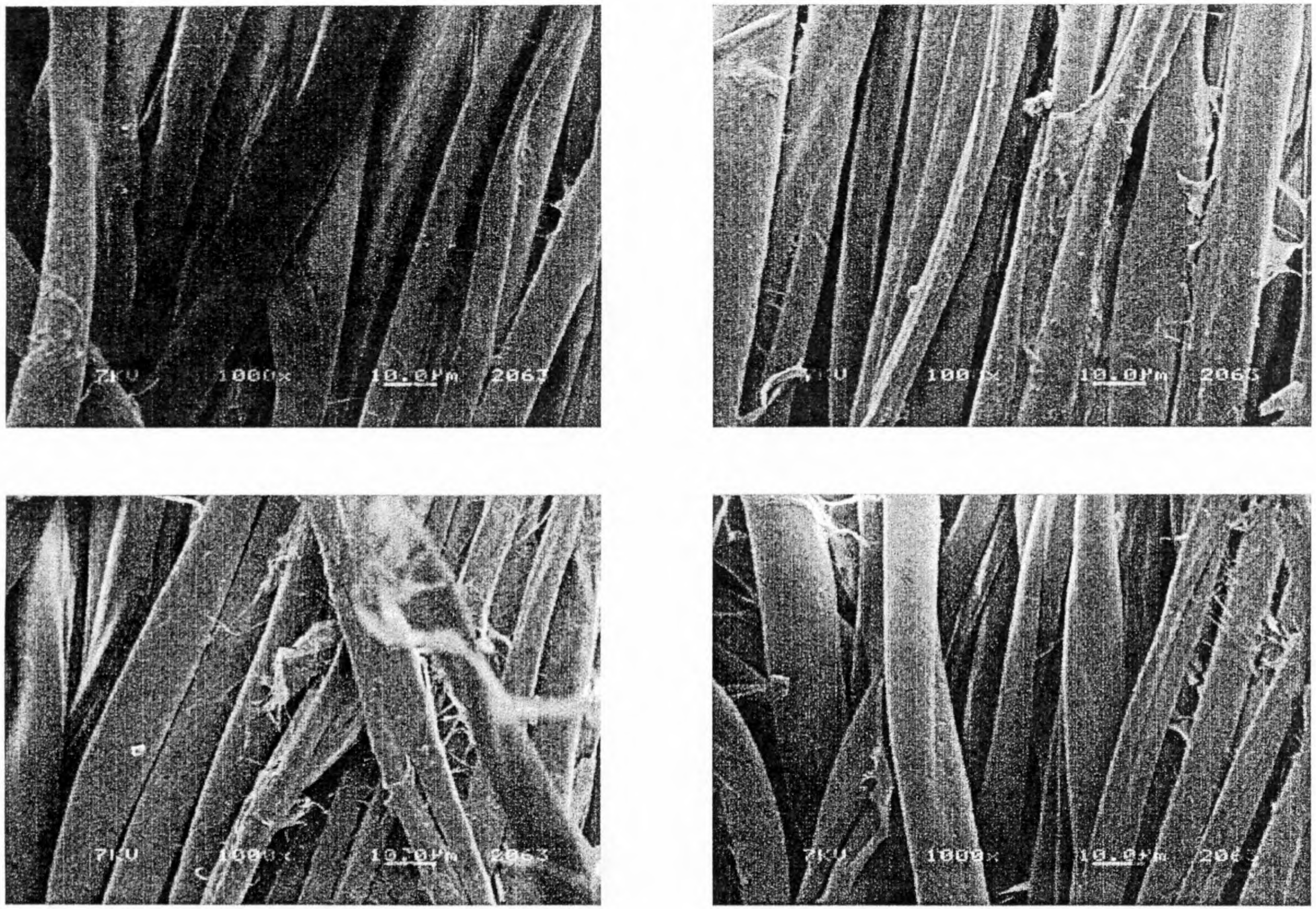
Machine *H1* - 1000X Magnification



Machine *H2* - 1000X Magnification



Machine *H3* - 1000X Magnification



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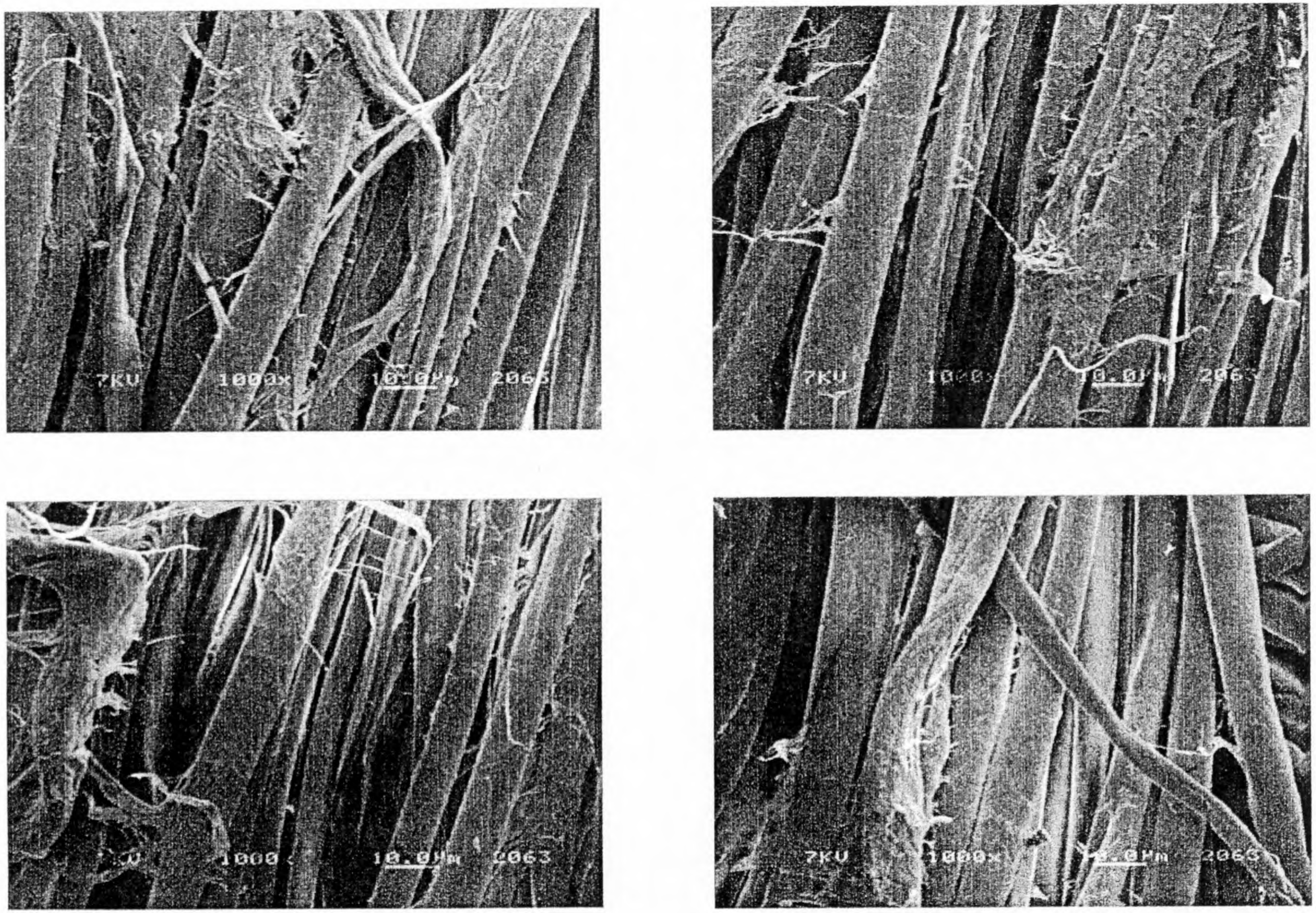
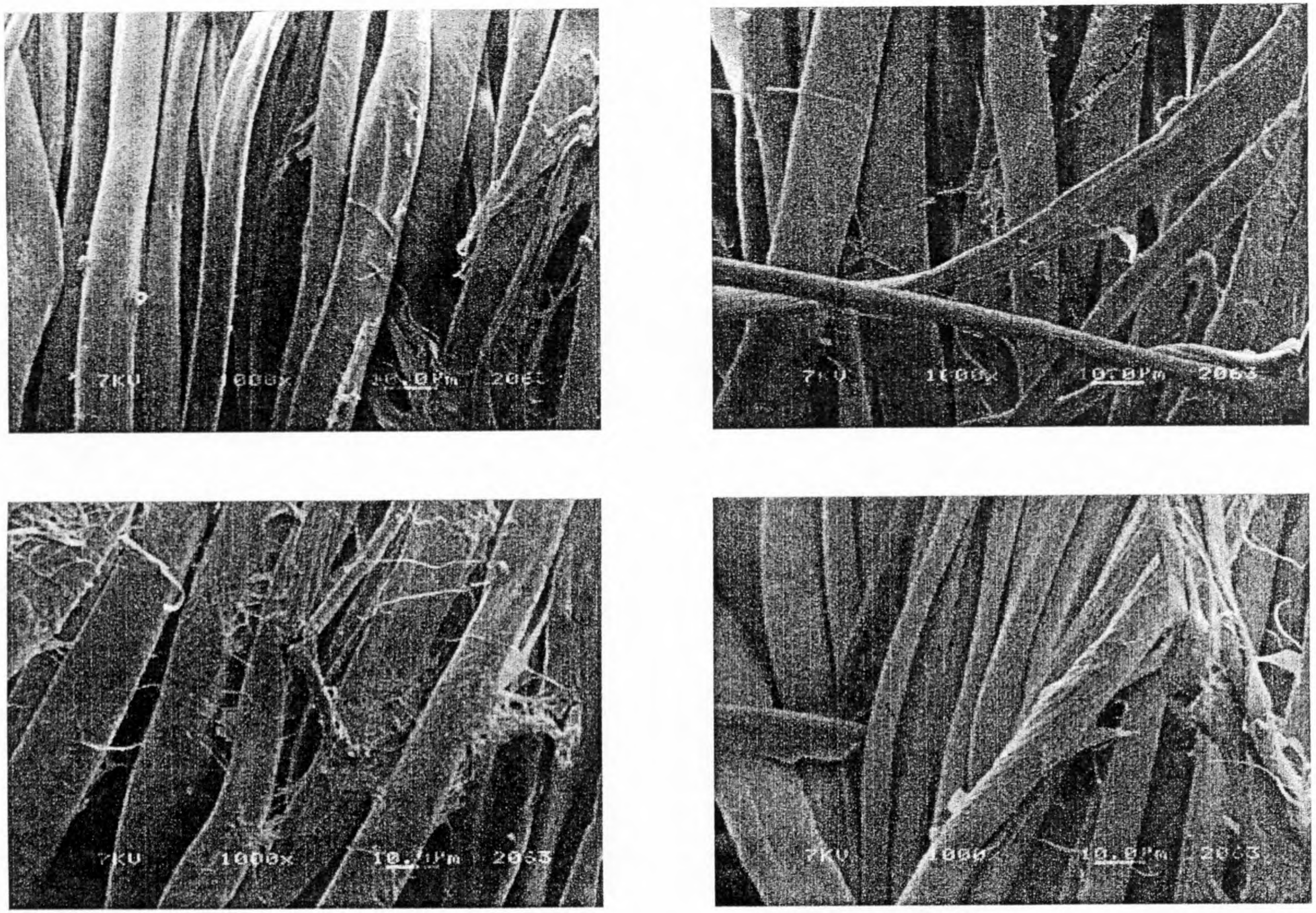
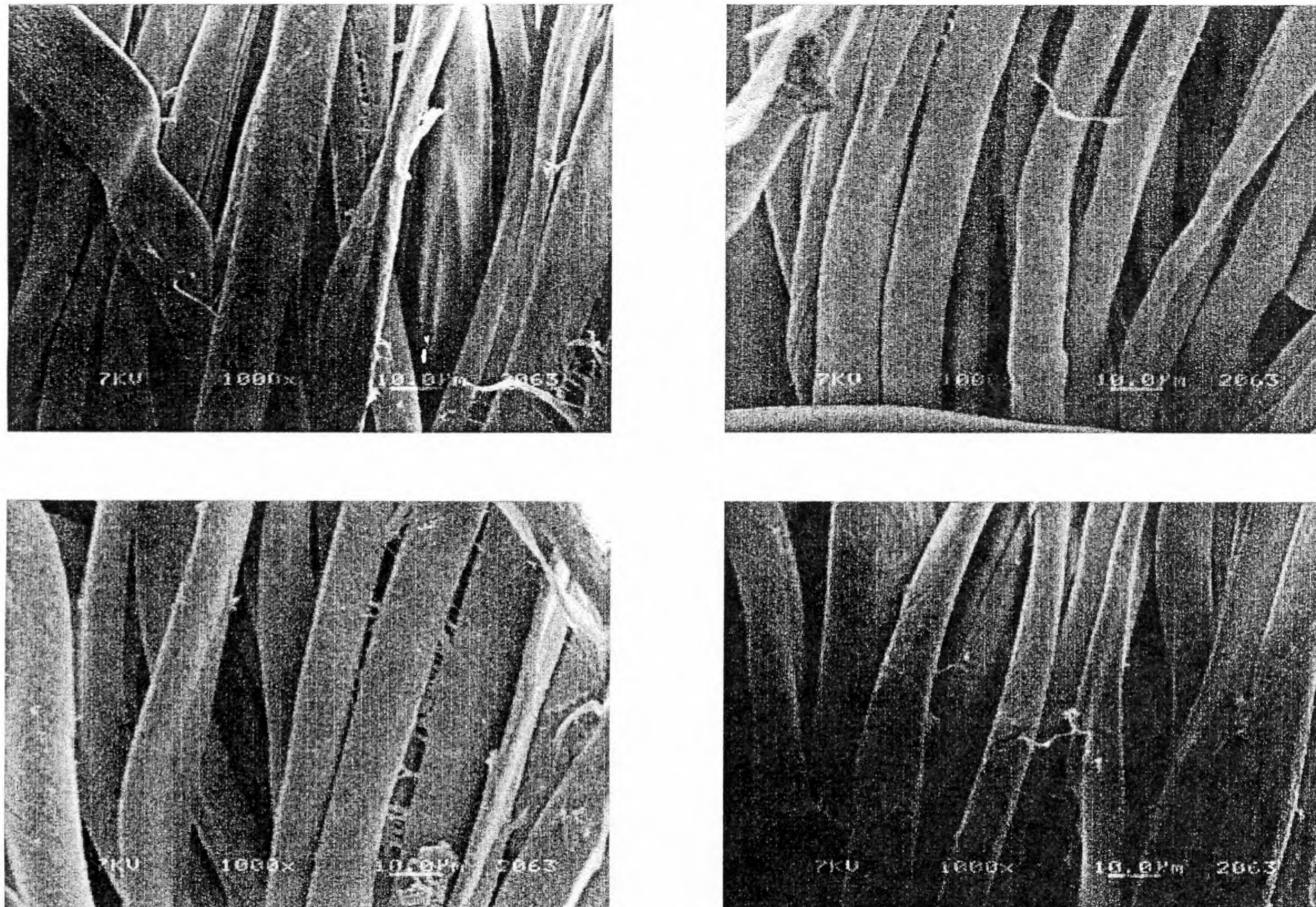


Machine *V(A)1* - 1000X Magnification



Machine *V(A)*2 - 1000X Magnification



Machine *V(I)1* - 1000X Magnification