

## ABSTRACT

JASTI, VAMSI KRISHNA. Electrostatic Charge Generation and Dissipation on Woven Fabrics Treated with Antistatic and Hydrophilic Surface Finishes. (Under the direction of Dr. William Oxenham and Dr. Abdel-Fattah M. Seyam).

The usage of synthetic fibers has been dramatically increased in the last seventy years. The majority of these materials are classified as insulating materials with a very high resistance of about  $10^{16}$  Ohms-cm, these materials generate static electricity during their processing when they contact and/or rub with other materials. Even after extensive research on static electricity for hundreds of years, there are several questions that still need to be answered regarding triboelectric charging and the dissipation mechanisms of textile materials. This is due to the fact that static electric charging is a surface phenomenon and it is very difficult to create a perfectly clean sample. In addition, such experiments are extremely difficult to reproduce and require extremely precise instruments.

The main objective of this research is to understand the frictional and contact charge generation and decay mechanism of textile materials. Woven fabrics made from cotton, polyester, nylon and polypropylene materials are investigated for contact and triboelectric charge measurements. In addition resistivity was measured to investigate the relation between the conductivity and charge decay. Experiments were done to compare the metal-polymer and polymer-polymer charge generation and dissipation mechanisms using the instrumentation developed by Seyam et al. For better understanding of the rubbing charge decay, an additional probe has been added to the existing setup to monitor the charge of an unrubbed selected area to find out whether static charge dissipates through the rubbed fabric sample. Commercial anti-static and commercial and experimental hydrophilic finishes developed were applied to examine how these topical surface finishes influence the static electric properties.

Polymer-polymer charging is higher than polymer-metal charging due to the backflow of the charge observed in the polymer-metal charge mechanism. More charge is generated on nylon than any other fibers because of the reactive CO-NH bonds which are responsible for the

charge generation. The charge generated on finish free cotton fabrics is also high when compared with other fabrics; however the charge on cotton fabric decays very quickly due to the higher conductivity of cotton. The charge decay on polyester, nylon and polypropylene is very slow compared to cotton. The charge decay observed on contact charged samples is slow when compared with the rubbed samples, and this is believed to be due to the different test conditions and availability of the atmospheric ions.

When anti-static finishes are applied on polyester fabrics, and tested for both contact and rubbing charge measurements, less charge is generated on these fabrics and the observed charge decays very quickly. When commercial and experimental hydrophilic finishes are applied on polyester a moderate charge is generated on the surface; however the generated charge is shown to migrate to the unrubbed parts of the fabrics and decays very quickly. When three different concentrations of the hydrophilic (Hydroperm® T) finish are applied on the polyester fabric, the charge decay pattern observed starts with a quick initial decay followed by a slower linear decay. The “Time decay coefficient” for the exponential decay depends on concentration of the surface finish applied.

Since nylon is highly reactive and very sensitive with respect to the surface, the charge generated on nylon is higher compared to other materials and also the polarity of the charge observed during contact and rubbing charging are different. Effect of antistatic finishes on the conductivity of polyester is more effective than nylon. Also antistatic finishes seems to be more effective on controlling charge generation and dissipation on polyester fabrics when compared to nylon fabrics.

Electrostatic Charge Generation and Dissipation on Woven Fabrics Treated with Antistatic  
and Hydrophilic Surface Finishes

by  
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## **DEDICATION**

Dedicated to my grandmother Sarojani Devi, grandfather Krishna Murthy Jasti (late) and my nephews Harshith and Nisanth.

## **BIOGRAPHY**

Vamsi Krishna Jasti, born in Guntur, India. Vamsi Krishna graduated with a bachelor's degree in Textile Technology from Bapuji Institute of Technology, Davangere, India. He did his Masters in Textile Technology and Management from Mönchengladbach, Germany. For his Master's thesis he worked at German Wool Research Institute at RWTH Aachen, Germany. After his Masters he was selected as one of the ten students by the International Wool Textile Organization and worked at Youngor Worsted Mills, Ningbo, China. He joined North Carolina State University in August, 2006 for his Ph.D in Fiber and Polymer Science.

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## TABLE OF CONTENTS

LIST OF TABLES .....	ix
LIST OF FIGURES .....	x
CHAPTER 1	
INTRODUCTION .....	2
CHAPTER 2	
LITERATURE REVIEW .....	6
2.1 SURFACE STATES .....	6
2.2 SURFACE PREPERATION .....	7
2.3 CONDUCTIVITY OF TEXTILES .....	7
2.4 CONTACT AND FRICTIONAL CHARGING .....	9
2.4.1 Triboelectric Series .....	9
2.4.2 Effect of Static Charge: Electrical Shocks and Sparks .....	11
2.5 MECHANISMS OF CONTACT ELECTRIFICATION .....	12
2.5.1 Electron Charge Transfer Mechanism .....	13
2.5.2 Ion Transfer Mechanism .....	14
2.6 CHARGE STORAGE IN POLYMERS - MACROSCOPIC VIEW .....	15
2.7 ELECROSTATIC MEASUREMENT TECHNIQUES .....	16
2.7.1 Direct Measurements .....	16
2.7.2 Indirect Methods .....	17
2.7.3 Simulation Measurements .....	18
2.8 ANTISTATIC FINISHES .....	18
2.8.1 Non-durable Finishes .....	19
2.8.2 Durable Antistatic Finishes .....	20
2.8.3 Evaluation of Antistatic Finishes .....	21
2.9 RESISTIVITY STANDARDS AND THEIR PROPENSITY TO TEXTILES .....	21
2.10 THEORY OF STATIC ELECTRIC CHARGING .....	22
2.11 CHARGE DISSIPATION ON INSULATING SURFACES .....	23
2.11.1 Time Constant for Charge Decay .....	23
2.11.2 Charge Decay Mechanism on Textile Surfaces .....	24
2.11.3 Effect of Moisture .....	25

2.11.4 Mechanisms of Charge Decay .....	27
2.11.4.1 Conduction.....	27
2.11.4.2 Dissipation Into Air.....	28
2.11.4.3 Absorption of Counter Ions .....	29
2.11.4.4 Other Factors.....	30
2.11.5 Crossover Phenomenon .....	31
REFERENCES .....	32
CHAPTER 3	
OBJECTIVES .....	38
3.1 RESEARCH GOALS .....	38
CHAPTER 4	
ELECTROSTATIC CHARGE GENERATION AND BUILDUP DURING CONTACT AND FRICTIONAL ELECTRIFICATION OF WOVEN FABRICS .....	41
4.1 INTRODUCTION .....	41
4.2 EXPERIMENTAL.....	43
4.2.1 Sample Preparation .....	43
4.2.2 Materials and Experimental Design.....	44
4.2.3 Equipment and Test Protocols .....	46
4.2.4 Signal Analysis .....	49
4.3 RESULTS AND DISCUSSION .....	51
4.3.1 Experimental Design - I.....	52
4.3.2 Experimental Design - II.....	61
4.3.3 Charge Decay Measurements.....	68
4.4 CONCLUSION.....	71
REFERENCES .....	72
CHAPTER 5	
FRICTIONAL ELECTRIFICATION AND CHARGE DECAY ON WOVEN TEXTILE FABRICS TREATED WITH IONIC ANTI-STATIC AND HYDROPHILIC FINISHES ...	75
5.1 INTRODUCTION .....	75
5.2 EXPERIMENTAL.....	77
5.2.1 Sample Preparation .....	77
5.2.2 Materials and Experimental Design.....	78

5.2.3 Equipment and Test Protocol.....	81
5.2.4 Resistivity Measurements .....	83
5.3 RESULTS AND DISCUSSION .....	83
5.3.1 Experimental Design - I.....	83
5.3.2 Experimental Design - II.....	87
5.3.3 Experimental Design - III .....	90
5.3.4 Surface Resistivity Measurements .....	93
5.4 ELECTROSTATIC CHARGE DECAY MECHANISM.....	94
5.5 CONCLUSION.....	97
REFERENCES .....	98
<b>CHAPTER 6</b>	
<b>EFFECT OF HYDROPHILIC FINISHES ON FRICTIONAL ELECTRIFICATION AND CHARGE DECAY OF WOVEN POLYESTER FABRICS .....</b>	<b>101</b>
6.1 INTRODUCTION .....	101
6.2 EXPERIMENTAL.....	102
6.2.1 Sample Preparation .....	102
6.2.2 Materials and Experimental design.....	103
6.2.3 Equipment and Test Protocol.....	103
6.3 RESULTS AND DISCUSSION .....	105
6.3.1 Experimental Design.....	105
6.3.2 Resistivity Measurements .....	115
6.4 CONCLUSION.....	117
REFERENCES .....	118
<b>CHAPTER 7</b>	
<b>EFFECT OF ANTI-STATIC AND HYDROPHILIC SURFACE FINISHES ON ELECTROSTATIC PROPERTIES OF NYLON WOVEN FABRICS .....</b>	<b>120</b>
7.1 INTRODUCTION .....	120
7.2 EXPERIMENTAL.....	120
7.2.1 Sample Preparation .....	120
7.2.2 Materials and Experimental Design.....	121
7.2.3 Signal Analysis .....	122
7.3 RESULTS AND DISCUSSION .....	122

7.3.1 Experimental Design - I.....	122
7.3.2 Experimental Design - II.....	125
7.3.3 Charge Decay Measurements.....	129
7.4 CONCLUSION.....	132
CHAPTER 8	
CONCLUSIONS.....	135
APPENDIX.....	137

## LIST OF TABLES

Table 2. 1 Contact potential series proposed by Gruner (Bartnikas, 1987) .....	11
Table 2.2 Surface resistivity and practical use of antistatic finished textiles (Schindler and Hauser 1998).....	22
Table 4.1 Triboelectric series published by several authors .....	43
Table 4.2 Fabric details .....	45
Table 4.3 Experimental design - I to investigate the static generation during the frictional charging of textile fabrics .....	45
Table 4.4 Experimental design - II used to investigate the contact charging of textile fabrics .....	46
Table 4.5 Comparing the Triboelectric series found in the literature and in this research when rubbed with steel and PTFE.....	61
Table 4.6 Comparing the Triboelectric series found in the literature and in this research when contacted with steel and PTFE.....	67
Table 4.7 Comparing resistivity and half life time .....	70
Table 5.1 Fabrics and surface finishes used in this research work .....	78
Table 5.2 Fabric details used in this work .....	79
Table 5.3 Experimental design - I used to study the charge decay mechanism on finish free cotton and polyester fabrics .....	80
Table 5.4 Experimental design - II to study the effect of static control finishes on the electrostatic decay properties of cotton and polyester fabrics .....	80
Table 5.5 Experimental design - III to study the charge decay at two places using two different probes .....	81
Table 6.1 Experimental design.....	103
Table 6.2 Time decay constants measured for the charge decay measurements .....	114
Table 7.1 Experimental design - I.....	121
Table 7.2 Experimental design - II.....	122

## LIST OF FIGURES

Figure 2.1 Conductivities of materials ( $\text{ohm}^{-1} \text{m}^{-1}$ ) (Blythe, 1979) .....	8
Figure 2.2 Triboelectric Series.....	10
Figure 2.3 Mechanism of electron charge transfer (Whitesides et al. 2007) .....	14
Figure 2.4 Ion charge transfer mechanism (Whitesides et al. 2007) .....	15
Figure 2.5 Phosphoric ester antistatic agents (Schindler and Hauser) .....	20
Figure 2.6 Quaternary ammonium agents and Non-ionic antistatic agents (Schindler and Hauser).....	20
Figure 2.7 Cross linking of polyamines to create durable antistatic agents (Schindler and Hauser, 1998).....	21
Figure 2.8 Exponential Decay of charge on a polymer surface with a time constant $\tau$ (Cross 1987) .....	24
Figure 2.9 Interface between charged surface and aqueous electrolyte solution (Whitesides et al. 2007) .....	27
Figure 2.10 Charge decay on corona charged polyethylene film (Ieda et al., 1968) .....	32
Figure 4.1 Rubbing Charge Equipment (Lu, 2010) .....	47
Figure 4.2 Contact charging tester (Lu, 2010) .....	48
Figure 4.3 Charge measurement and signal analysis during the during rubbing (Lu, 2010)..	49
Figure 4.4 Typical static charge data of repeated contact test .....	51
Figure 4.5 Surface potential measured after first cycle of rubbing on textile fabrics .....	53
Figure 4. 6(a) Charge generation and accumulation on cotton-I rubbed with steel (b) Charge generation and accumulation on cotton-I rubbed with PTFE .....	54
Figure 4.7(a) Charge generation and accumulation on cotton-II rubbed with steel (b) Charge generation and accumulation on cotton-II rubbed with PTFE.....	54
Figure 4.8(a) Charge generation and accumulation on filament polyester rubbed with steel (b) Charge generation and accumulation on filament polyester rubbed with PTFE .....	55
Figure 4.9(a) Charge generation and accumulation on spun polyester rubbed with steel (b) Charge generation and accumulation on spun polyester rubbed with PTFE .....	56
Figure 4.10(a) Charge generation and accumulation on filament nylon rubbed with steel (b) Charge generation and accumulation on filament nylon rubbed with PTFE .....	57
Figure 4.11(a) Charge generation and accumulation on spun nylon rubbed with steel (b) Charge generation and accumulation on spun nylon rubbed with PTFE.....	57
Figure 4.12(a) Charge generation and accumulation on spun polypropylene rubbed with steel (b) Charge generation and accumulation on spun polypropylene rubbed with PTFE.....	58
Figure 4.13 Surface potential accumulated after 50 rubbings on textile fabrics .....	60
Figure 4.14 Charge measured after first cycle of contact on textile fabrics .....	62
Figure 4.15(a) Charge generation and accumulation on cotton I contacted with steel (b) Charge generation and accumulation cotton I contacted with PTFE.....	63
Figure 4.16(a) Charge generation and accumulation on cotton II contacted with steel (b) Charge generation and accumulation cotton II contacted with PTFE .....	63
Figure 4.17(a) Charge generation and accumulation on filament nylon contacted with steel (b) Charge generation and accumulation filament nylon contacted with PTFE.....	64

Figure 4.18(a) Charge generation and accumulation on spun nylon contacted with steel (b) Charge generation and accumulation spun nylon contacted with PTFE .....	64
Figure 4.19(a) Charge generation and accumulation on filament polyester contacted with steel (b) Charge generation and accumulation filament polyester contacted with PTFE .....	64
Figure 4.20(a) Charge generation and accumulation on spun polyester contacted with steel (b) Charge generation and accumulation spun polyester contacted with PTFE .....	65
Figure 4.21(a) Charge generation and accumulation on spun polypropylene contacted with steel (b) Charge generation and accumulation spun polyester contacted with PTFE .....	65
Figure 4.22 Charge accumulated after 50 contacts on textile fabrics .....	66
Figure 4.23 Charge build up on PTFE contacted spun nylon fabric .....	68
Figure 4.24 Half-life time measured on textile fabrics after rubbing with steel and PTFE....	69
Figure 4.25 Half-life time decay measured on textile fabrics after contacted with PTFE.....	70
Figure 5.1 Sample with two probes measuring the surface charge (top view) .....	82
Figure 5.2 surface potential measured during rubbing with two voltmeter probes (front view) .....	83
Figure 5.3(a) Charge accumulation in 50 cycles and decay on cotton-1 (b) Charge accumulation in 50 cycles and decay on cotton-II .....	84
Figure 5.4(a) Charge accumulation in 50 cycles and decay on filament polyester (b) Charge accumulation in 50 cycles and decay spun polyester fabric .....	85
Figure 5.5(a) charge decay on cotton fabrics rubbing with steel (b) charge decay on cotton fabrics rubbing with PTFE .....	86
Figure 5.6(a) Charge decay on polyester rubbed with steel (b) Charge decay on polyester fabrics rubbed with PTFE .....	87
Figure 5.7(a) Charge accumulation in 50 cycles and decay on polyester fabric treated with 0.1% Larostat <sup>®</sup> 264A finish (b) Charge accumulation in 50 cycles and decay on polyester fabric treated with 0.1% phosphate finish.....	88
Figure 5.8(a) Charge accumulation in 50 cycles and decay on filament polyester fabric treated with 0.5% moisture management finish (b) Charge accumulation in 50 cycles and decay on spun polyester fabric treated with 0.5% moisture management finish .....	89
Figure 5.9(a) Charge accumulation in 50 cycles and decay on filament polyester fabric treated with 0.5% Hydroperm <sup>®</sup> T finish (b) Charge accumulation in 50 cycles and decay on spun polyester fabric treated with 0.5% Hydroperm <sup>®</sup> T finish.....	90
Figure 5.10 Charge accumulation in 50 cycles and decay of rubbing and unrubbing areas of filament polyester fabric .....	91
Figure 5.11 Charge accumulation in 50 cycles and decay of rubbing and unrubbing areas of spun polyester fabric .....	91
Figure 5.12 Charge accumulation in 50 cycles and decay of rubbing and unrubbing areas of filament polyester treated with 0.5% Hydroperm <sup>®</sup> T .....	93
Figure 5.13 Resistivity measured on cotton, polyester and polyester fabrics treated with various surface finishes .....	93
Figure 5.14 Charges stored in textile/polymers .....	94
Figure 5.15(a) Linear charge decay model (b) Linear charge decay on filament polyester fabric .....	95

Figure 5.16(a) Charge distribution on exponential charge decay fabric (b) Exponential charge decay on cotton fabric .....	96
Figure 5.17(a) Charge distribution on a double exponential decay fabric (b) Double exponential decay of charge on spun polyester .....	97
Figure 6.1 Charge measurement on fabric using two probes (top view) .....	104
Figure 6.2 Surface potential build up and decay on filament polyester fabric for 50 cycles of rubbing .....	105
Figure 6.3 Surface potential build up and decay on 0.5% Hydroperm <sup>®</sup> T applied filament polyester for 50 cycles of rubbing.....	106
Figure 6.4(a) Surface potential build up and decay on 0.25% Hydroperm <sup>®</sup> T applied polyester fabric (b) Surface potential buildup and decay on 0.1 Hydroperm <sup>®</sup> T applied polyester fabric.....	107
Figure 6.5(a) Surface potential accumulated on filament fabric against steel (b) Surface potential accumulated on filament fabric against PTFE .....	108
Figure 6.6 Comparing charge buildup on polyester fabric rubbing with steel and PTFE ....	109
Figure 6.7 Surface potential in unrubbed area as a % of surface potential in rubbed area ...	109
Figure 6.8 Half life time of the polyester samples .....	110
Figure 6.9 Surface potential decay on filament polyester samples rubbing head: steel .....	111
Figure 6.10 Surface potential decay on filament polyester samples rubbing head: PTFE ...	112
Figure 6.11a-d: Surface potential decay on steel rubbed untreated, 0.1%, 0.25%, 0.5% hydroperm applied polyester samples and the regression curves .....	113
Figure 6.12 Time for exponential decay ( $t_e$ ) on Hydroperm-T treated polyester samples ...	115
Figure 6.13 Surface resistivity measured on treated and untreated polyester fabrics.....	116
Figure 7.1 Charge measured after initial contact on filament nylon fabrics treated with surface finishes.....	122
Figure 7.2 Charge measured after fifty contacts on filament nylon fabrics treated with surface finishes .....	123
Figure 7.3 Charge measured after initial contact on spun nylon fabrics treated with surface finishes .....	124
Figure 7.4 Charge accumulated after fifty contacts on spun nylon fabrics treated with surface finishes .....	125
Figure 7.5 Charge generated after first rubbing cycle on filament nylon fabrics treated with surface finishes.....	126
Figure 7.6 Charge accumulated after fifty rubbing cycles on filament nylon fabrics treated with surface finishes.....	127
Figure 7.7 Charge measured after first rubbing cycle on spun nylon fabrics treated with surface finishes.....	128
Figure 7.8 Charge accumulated after fifty rubbing cycles on spun nylon fabrics treated with surface finishes.....	129
Figure 7.9 Charge decay measured on filament nylon fabrics treated with surface finishes and contacted with PTFE and Steel.....	130
Figure 7.10 Charge decay measured on spun nylon fabrics treated with surface finishes and contacted with PTFE and steel.....	130

Figure 7.11 Charge decay measured on filament nylon fabrics treated with surface finishes and rubbed with PTFE and steel ..... 131

Figure 7.12 Charge decay measured on spun nylon fabrics treated with surface finishes and rubbing with PTFE..... 132

**CHAPTER 1**  
**INTRODUCTION**

## INTRODUCTION

The world textile market is dominated by three classes of melt extruded synthetic fibers, namely polyester, polypropylene, nylon, all of which are based on low energy polymers. These three classes of materials are effective insulators, having inherent resistance values of  $> 10^{14}$  ohm-cm. When insulating polymeric materials are contacted or rubbed with any other material (conductor or insulator), a static electric charge is generated on the polymer surface. Because of the insulating properties of these polymers, the charge that is generated is fairly stable and only slowly dissipates. Textile materials, based on these polymers, will often accumulate charge during fiber or fabric processing and static control issues will often continue from the fiber's preparation stage right through into the fiber's or fabric's ultimate use form. Usually these charges are undesirable and they can lead to issues ranging from annoying performance phenomena to detrimental or serious hazard affects in either processing or ultimate use. In a few cases, this static charge is purposely generated and used as a critical performance aspect of the fiber in its processing or ultimate application. In some cases, long-term stable charge is generated below the surface of the polymeric materials to improve the fiber's effectiveness in a specific application, such as air filters and transducers. Polymers such as polypropylene, polyethylene terephthalate, polytetrafluoroethylene have been used in such applications.

Understanding the mechanism by which static charge is generated on or disappears from polymer surfaces has proven to be difficult. Questions remaining largely unanswered include:

- The chemical and physical origins of the tribo-electric series.
- The mechanism of contact and tribo- charging of polymer surfaces.
- The mechanism by which the charge disappears from the surface (dissipates) after generation.
- The mode by which materials applied to the polymer surface can substantially effect either the generation of static charge or the dissipation of the charge.

Significant research efforts have been committed to all of these questions without the development of either significant theoretical understanding or of practical rules that might provide guidance to those working in the area. Given the importance of static charge generation and control, in a wide range of technology applications and end-uses (including textiles), the development of a deeper understanding of the electrostatic charging mechanism and charge decay mechanism are very significant questions. Improved understanding or practical guidance in this area could generate improvements in both our ability to control or avoid the generation of undesired static electric charges or improve our ability to generate and store static electric charge in a range of applications where this is the desired outcome.

The literature relating to the most basic questions in this area is **still** struggling to develop an understanding of the fundamentals involved with static charge:

- On the mechanism of charging, some authors have explained that the charging of polymers is due to transfer of electrons (Lowell, 1977) while others argued that charging is due to transfer of ions (Whitesides, 2007).
- On the mechanism of charge dissipation, some authors see charge decay mechanisms as non-exponential (Sessler, 1987) while others explained the charge decay mechanism by exponential decay (Cross, 1987) or double exponential decay.

The major objectives of the research we propose are to develop deeper insights into the questions:

- What is the relationship between contact charging of a polymer surface and tribo-charging of the same surface?
- What mechanism or mechanisms are responsible for charge decay on the textile surfaces?
- How do topically applied finishes affect the electrostatic properties of polyester and nylon textile surfaces?

Success in this research work provides significant insights into the questions presented above. The research is carried out in the following specific areas:

- Studies of contact charging, tribo-charging, resistivity and charge decay made using four fabric substrates, cotton, nylon, polyethylene terephthalate (PET) and polypropylene (PP).
- Determination of the relationship between the resistance, contact charge (measured as coulombs), tribo-charge (measured as surface potential) and rates of decay.
- Studies of the impact of non-durable surface finishes (based on traditional antistatic materials) on the static electric properties of polyester and nylon synthetic fiber surfaces.
- Studies of the impact of durable, hydrophilic surface finishes (traditional and developmental materials) on the electrostatic properties of polyester and nylon synthetic fiber surfaces.

This data is then reviewed on the basis of the polymer substrate and the surface applied materials. The data was analyzed based on earlier electrostatic models. Based on these results, a deeper understanding of these complex electrostatic phenomena has been developed and advanced explanatory models have been proposed to provide insights and support the industry in its efforts to understand the origins of static charges. Furthermore, we hope to be able to suggest innovative approaches for the effective control of static charge generated under both contact and dynamic conditions.

In this dissertation the motivation of this research is introduced in chapter 1. Chapter 2 includes the critical review of the literature. Objectives and methods of research are discussed in chapter 3. Results are discussed in chapters 4, 5, 6 and 7 as journal articles to be published. Chapter 8 includes the summary of overall results.

**CHAPTER 2**  
**LITERATURE REVIEW**

## LITERATURE REVIEW

The purpose of this chapter is to present a brief overview of the current state of knowledge in the area of triboelectrification of textile surfaces and their charge decay properties. The textile fibers and fabrics used in this research consist of synthetic polymers. So while discussing the literature, often polymer surfaces are mentioned instead of textile surfaces.

### 2.1 SURFACE STATES

Triboelectrification is a surface phenomenon and not a bulk property. Most organic polymers are insulators with very high electrical resistance. For these polymers, the energy gap between the valance and conduction band is very large (about 4 to 8 eV). Because of weak molecular interactions, the valance and conduction bands are very narrow (Sessler, 1987, Mizutani 1976). Conductivity in such materials is low due to the restricted electron transport and slow movement. The surface of a polymer consists of few molecular layers and can be considered as a bulk exposed plane. In polymers, the crystalline symmetry that surrounds the atomic structure abruptly ends at the surface (Das Gupta, 2001; Moore, 1973; Lowell, 1977). Even at room temperature the polymer surface consists of very high segmental mobility. Because of this high segmental mobility, the polymer surface cannot be treated as a two dimensional plane. However the polymer surface can be defined as a region with some thickness. Therefore, when understanding the polymer surface one should see the polymer surface not only as a two dimensional plane, but should also consider material perpendicular to the surface plane. The presence of molecular imperfections, dislocations and adsorbed impurities cause these surface states. These impurities and imperfections are so high that they form separate energy bands. In semi-crystalline polymers, for e.g. polyester and nylon, amorphous regions introduce surface states in the band gap and extend into the bulk of the polymer. These surface states create an electrostatic field between the surface and the bulk which distort the band structure. These surface states also influence the electrical properties of the surface because these states may act as a source or sink of charge carriers and the chemical reactivity may be altered due to a change in the electron affinity of the surface. The bulk electrical properties of the polymer are likely to be different from the surface electrical

properties because of these surface states. However, the charging mechanism and the presence of a humid environment can cause the surface states to behave differently. In the present literature review, the contact electrification charging mechanism, charge storage mechanism, and charge decay mechanism are discussed keeping in mind that surface electrical properties are different from the bulk. While studying the static electrical properties, the surface should be dealt with very carefully.

## **2.2 SURFACE PREPERATION**

Preparing a surface means cleaning it from all the contaminations. Practically it is not possible to create a truly clean surface, free from any contamination. A very single thin layer of adsorbed gases is enough to create a significant impact on the static electrical properties by changing the work function of the surface. Adsorption is a surface mechanism which is completely different from absorption. These adsorbed layers are difficult to remove because they often react with the material and create bonds. (E.g. Oxygen forms oxides and hydrogen forms hydrides). However, adsorbed molecules are highly mobile and these monolayers can be compared with a two-dimensional gas or liquid. Most of the textile materials are treated with various finishes during their processing. Surface finishes remain on the surface and contribute to the static electrical properties of the textile materials (Moore, 1973). Difficulties in producing the clean surface is the reason for the inconsistencies found in the literature. Castle pointed out that Surface variability, experimental variability, nature of contact, charge flow back, charge species are the main reasons for the discrepancies found in the published data (Castle, 1997).

## **2.3 CONDUCTIVITY OF TEXTILES**

Polymers used as textile materials are often insulators. These fibers range from natural cellulosic fibers such as cotton with moderate conductivity in the range of  $10^{-10} \text{ ohms}^{-1} \text{ m}^{-1}$  to Synthetic fibers such as nylon and polyester with a very low conductivity in the order of  $10^{-18} \text{ ohms}^{-1} \text{ m}^{-1}$ . The conductivities of some of the textile fibers are shown in the Figure 2.1 (Blythe, 1979).

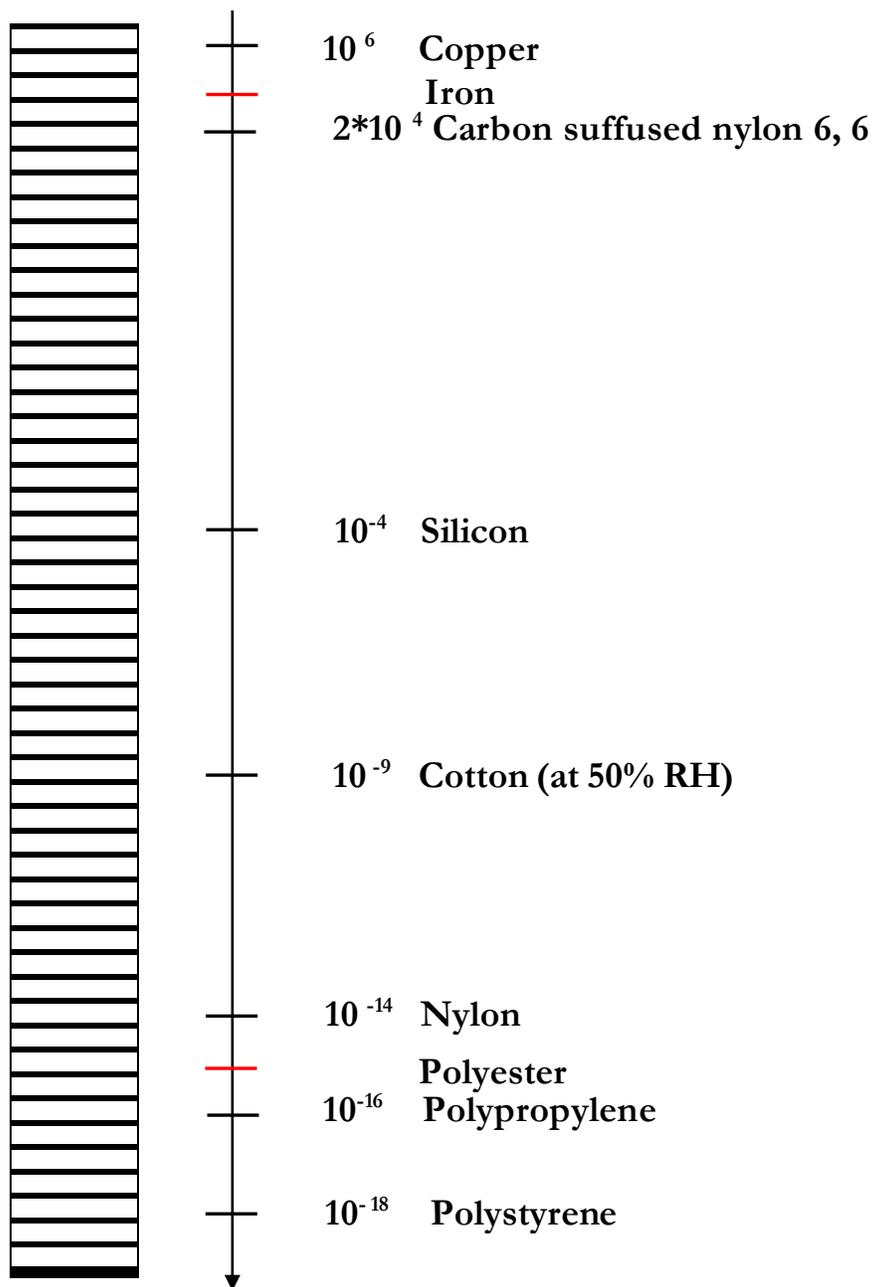


Figure 2.1 Conductivities of materials ( $\text{ohm}^{-1} \text{m}^{-1}$ ) (Blythe, 1979)

## 2.4 CONTACT AND FRICTIONAL CHARGING

When two insulating materials are rubbed together, the surfaces acquire a net electric charge, with one polymer surface becoming positive and the other becoming negative. In most cases, the frictionally charged surfaces contain both positively charged and negatively charged areas but one polarity predominates and determines the net charge on the surface. Even though frictional charging has gained the attention of researchers over the last thousand years, a complete understanding of the triboelectrification has not yet been made (Cross 1987).

### 2.4.1 *Triboelectric Series*

A triboelectric series is a list of materials empirically placed depending on their tendency to acquire a positive or negative charge upon contact. Materials placed near the top of the list become positive while contacting with materials lower in the list. Many researchers have published triboelectric series from over the last 150 years, and the ordering in these series generally agree with each other, despite inevitable differences in the composition of the materials, the preparation of the samples and the environment in the laboratory. A triboelectric series prepared by combining several different series from the literature is shown in the Figure 2.2 . This series consists of the placement of materials in the triboelectric series and shows some curious observations. Polar materials such as wool and nylon are placed on the positive side and non-polar polymers such as polypropylene and polytetrafluoroethylene are on the negative side.

Wilke published first triboelectric series in 1957, working with glass, amber, wool and silk. Since then, many authors have worked on various dielectric materials and several triboelectric series had been published (Bartnikas, 1987). Shashoua (1958) found most of the triboelectric series found to be identical and he constructed a triboelectric series with more widely used materials. However, there are several discrepancies also found in the literature. Nylon is placed in top of the triboseries expected to charge positive when rubbed with steel. Working with nylon filament yarns London (1966) found that rubbing with stainless steel

charged nylon negative. Gruner also pointed an important observation in the triboelectric series he constructed shown in Table 2.1. He rubbed series of materials with equal area of rubbing and found that steel and polyester are placed above nylon in the series. However, all the triboelectric series published are based on rubbing two materials. Triboelectric series developed based upon the contact charging is not published.

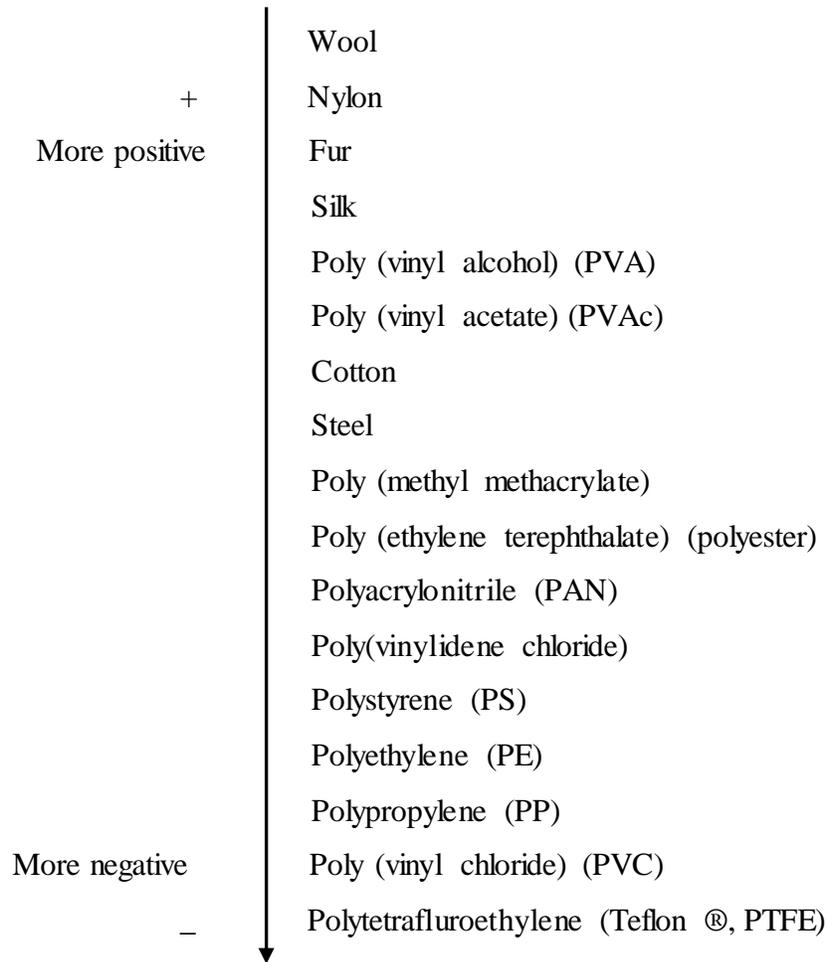


Figure 2.2 Triboelectric Series

Table 2. 1 Contact potential series proposed by Gruner (Bartnikas, 1987)

Material	Potential ( Volts)
Wool	+42
Perlon II	+20
Dacron (Polyester)	+14
Paper	+12
Glass, steel	+10
Nylon	+7
Cotton	+5
Brass	0
Orlon (Acrylic)	-4
Hard rubber	-14
Rubber	-20

Most of the published triboelectric series are based on the polarity of the charge generated on the surface of the polymer when rubbed with another. Semi quantitative triboelectric series is published by Diaz et al. (Diaz and Felix 2004). Welker et al. (2006) proposed that the magnitude of the charge generated on the surface also depends on the distance between the materials in the triboelectric series.

#### ***2.4.2 Effect of Static Charge: Electrical Shocks and Sparks***

Static electricity due to the contact between humans and the insulators creates detrimental effects. Due to the very low resistance of the materials used in shoes and the carpet, electric discharge (shocks) can be produced throughout the human body. Sometimes these low voltage discharges are high enough to ignite oil mixtures. However, these effects can be found only during the winter in environments of low humidity (Brundrett 1977, Kelly et. al., 1993).

The currents observed in these shocks are very low and about  $10^{-8}$  A (Brundett 1977). Under steady state conditions the maximum personal voltage that can be measured as

$$\text{Maximum personal voltage (volts)} = \text{Charging current (Amps)} \times \text{leakage resistance (ohms)}$$

The combination of leakage resistance with electrical capacitance of the person determines the time taken for the charge to leak away naturally. Even though the capacitance measurements of people reported by various authors are different, the average values lies between 95 Pico Faraday to 304 Pico Faraday. Factors which influence the personal sensitivity to shock are stored energy available and individual sensitivity of the subject. Energy stored in a person is a function of his capacitance and voltage (Brundrett 1977).

$$\text{Energy stored } E \text{ (Joules)} = 0.5 * \text{capacitance } C \text{ (Farads)} * (\text{voltage } V \text{ (Volts)})^2$$

The voltage at which people feel shock has been measured. All people detect a spark discharge through their hands when they are charged to a potential of 1-2.5 kV. Objectionable shocks have been observed between the voltages of 2 kV and 7 kV and most of these shocks cause severe discomfort. Energy stored in a person at a voltage of 2 kV is 0.4 millijoules. The minimum energy required for a vapor-air mixture to ignite is 0.2 millijoules. The charge on a person who is charged with a voltage of 2 kV could ignite the vapor-air mixture, which is hazardous. However, these effects of static electric charge also depend on the humidity. At 40% RH (Relative Humidity) a person walking on nylon carpet would create a voltage of 1.2 kV and at 30% RH walking on nylon would create a voltage of 3.0-3.6 kV. Nylon carpets can give electric shocks at up to 50% RH, but at 40% RH, shocks are avoided for most carpets.

Wilson observed that triboelectric charges generated on polyester and cotton fabrics at a magnitude of negative 0.1  $\mu\text{C}$ , could ignite the natural air/ gas mixtures (Wilson, 1985). A low charge of 0.02  $\mu\text{C}$  would be enough to ignite hydrogen/air mixtures. He also observed the sparks generated from negatively charged surfaces exists for a considerably shorter time but are greater in magnitude than those from positively charged surfaces (Brundrett 1977; Wilson, 1985).

## **2.5 MECHANISMS OF CONTACT ELECTRIFICATION**

Despite a lot of research on understanding the contact electrification mechanism, there is little consensus on how the charge has been transferred from one material to another upon

contact. Charge transfer was attributed to three different mechanisms by various authors (Seanor, 1972, Castle 1997).

1. Charge transfer due to electrons
2. Charge transfer due to ions
3. Charge transfer due to material transfer

In his famous book on static electrification, Harper (1967) reviewed the charging mechanism and proposed that contact charging of insulators involves ions not electrons. Another famous review on contact charging mechanisms by Lowell and Rose-Innes (1980) contradicted Harper's views and concluded that electron transfer is responsible for contact charging. In a very recent review, Whitesides et al. (2007) explained that charge transfer in polymers is due to transfer of ions, not because of electron transfer.

### ***2.5.1 Electron Charge Transfer Mechanism***

Contact electrification between metal and metal was found to be due to the transfer of electrons. (Davies, 1967) Some researchers assumed that the charge transfer between the polymers also involves the transfer of electrons. Significant amount of research has been done on polymer-metal contacts and concluded that charge transfer is due to electron transfer. Arridge (1967) measured the contact potential of nylon contacting different metals and found a linear relationship between the potential and the metal work function. These observations were supported by a few other authors (Davies 1967, Davis 1969, Fuhrmann 1977). The observation of a linear relationship between charge transfer and the metal work function implies that electrons are the major species transferred during contact electrification. However, Lowell (1977), and Bauser (1970) found that the charge transferred to polyethylene, polyester and PTFE are independent of the metal work function. This is because the most energetic electrons in an insulator do not have a single value of energy throughout the surface as they do in metal (Moore, 1973, Clark D.T. et al., 1978). Polymer work functions are measured by different researchers are not same. The electron charge transfer mechanism is shown in Figure 2.3.

However, experimental observations appear to contradict this view. Triboelectrification of polymers does not correlate with bulk electronic properties such as the dielectric constant, or atomic properties such as ionization energy and electron affinity. Whitesides et al. (2007) reviewed the triboelectric charging mechanism and argued that the electron charge transfer mechanism cannot be possible theoretically. When nylon and polyethylene polymers are contacted, according to the triboelectric series, nylon acquires positive charge, and polyethylene acquires negative charge. If the charge transfer is due to the electron transfer mechanism, one electron should be removed from nylon, separation of charge across the interface occurs, and an electron is added to polyethylene. The overall process exceeds about 5-10 eV; which is very much higher than the thermal energy at room temperature (0.026 eV). The transfer of an electron from a filled orbital of a polymer (insulating material) to an unfilled orbital of another polymer is on the order of several eV and this electron-transfer model is energetically plausible only for materials with no band gap (metals). Hearle (1997) also argued that the charge transfer is not due to transfer of electrons.

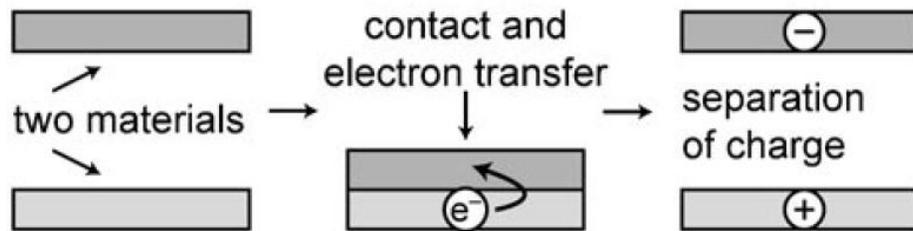


Figure 2.3 Mechanism of electron charge transfer (Whitesides et al. 2007)

### 2.5.2 Ion Transfer Mechanism

Diaz et al. (1993) proposed that proton transfer could explain the triboelectrification of a wide range of materials. The best evidence for the transfer of ions is observed in the polymers which contain covalently bound ions and mobile counter ions. The ion transfer mechanism of Diaz is shown in the Figure 2.4 (Diaz, 1993). Two kinds of ions can be seen in the Figure 2.4, cations which are covalently bound to the surface and counter ions which are mobile. Diaz et al. (1993) found that during the contact charging of ion containing polymers, the sign of the charge that these materials acquired is always the same as the covalently

bounded ion. They observed that as the concentration of the ions increases the amount of charge increased. Characterizing the polymer surface with X-ray photo electron spectroscopy, they found that only mobile ions have been transferred and not the covalently bonded ions.

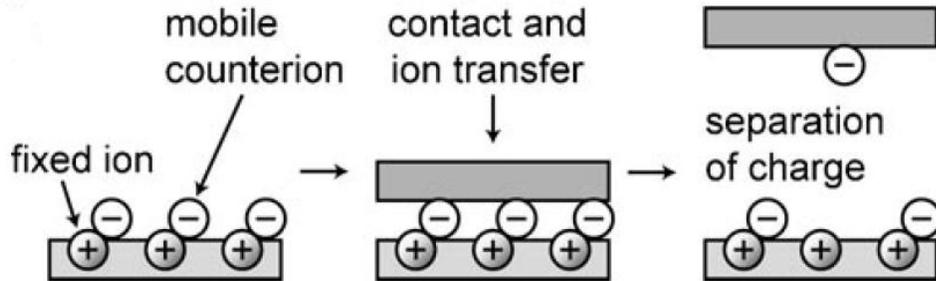


Figure 2.4 Ion charge transfer mechanism (Whitesides et al. 2007)

## 2.6 CHARGE STORAGE IN POLYMERS - MACROSCOPIC VIEW

Most polymers used to make textile fibers are semi-crystalline polymers which have a very high resistance, of the order of  $10^{14}$  ohms-cm<sup>3</sup>. These insulators have very low ion/electron mobility. Polypropylene is composed of (CH<sub>2</sub>CH (CH<sub>3</sub>)) units, and is chemically inert. All the lower electron shells of the C's are full, and their energies lie well below their Fermi energy level; polypropylene is a poor conductor. So, the charge is unlikely to reside on the polypropylene repeat unit. Charge storage in polymers is attributed to the presence of traps. In polypropylene, little is known about the nature of the surface traps, although chemical impurities could be the reason for charge traps, specific surface defects caused by oxidation products, broken chains, absorbed molecules or differences in short range order or surface also could be responsible for trapping charges in certain cases (Sessler, 1987).

Among all polymers which can be made into textile fibers, polypropylene has the ability to store the charge for the longest time. Nonwoven fabrics made from melt blown polypropylene store the electrostatic charge for a longer time and widely used as air filters. It can be anticipated that charges must remain on larger entities, i.e. trapped polymer chain segments or chain ends that are well removed from the surface. There is also a chance that charges can be trapped on additives or impurities (Behrendt et al. 2006). If charge resides on

the surface of a polymer, e.g. by adding chemical groups to another polymer which can completely cover the surface, the static electric properties of the first polymer would vary. A very thin layer of surface coating could be changing its static electrical properties such as surface charge density and charge dissipation (Brennen et al.1995).

## **2.7 ELEECROSTATIC MEASUREMENT TECHNIQUES**

The electrostatic methods measuring textile materials are divided into three different classes.

- The first is direct measurement of charge on the surface
- The second method indirect measurements related to the tendency of developing the electrical charge, such as measuring resistance or conductance
- The third class of testing the static electric properties can be evaluated by testing the end use properties such as cling tests, stroll tests and filtration efficiency (Holme et al. 1998).

### ***2.7.1 Direct Measurements***

Direct measurements include measuring the charge or surface potential on the textile fabrics by charging them triboelectrically or with a corona. The charge can be measured directly using a Faraday pail and electroscope/electrometer and surface potential (which is proportional to charge) also can be measured.

A Faraday pail or Faraday cage is an instrument which consists of an uncharged metal container into which the charged sample is placed. The metal outer container is connected to the ground, and prevents the external electrical charges so that they influence the measurement. The inner wall of the metal container is connected to the electrometer so that the charge inside the metal container can be measured. When a charged object is placed inside the metal container, an equal and opposite charge is induced on the inner wall. This charge leaves behind an equal and opposite charge on the capacitor of the electrometer which is equal to the charge inside the metal container. The other way to measure the charge is measuring its field or surface potential. The electric field (in kV/m) can be measured using a field meter and the potential in volts can be measured using a voltmeter.

### 2.7.2 Indirect Methods

Indirect methods of measuring the charge on a polymer surface include the measurement of resistance. However, some authors found that there is no correlation between the measurement of resistance and the surface charge on the textile fabrics. Resistance R is the property of material which resists the flow of current (which is measured in ohms). Its SI unit is  $\text{kg m}^2 \text{S}^{-3} \text{A}^{-2}$ . Volume resistivity  $\rho$  of a material is the resistance between the opposite faces of a 1m cube. For textile fibers the resistivity can be measured as mass specific resistance, which is the resistance between the ends of a specimen 1m long and of mass 1 kg. Most commonly measured on fabrics is square resistance, (the resistance between the two points of the fabric) which is measured by applying a voltage between the parallel electrodes. The spacing between the electrodes and length of the electrodes remains the same. Units to express the surface resistivity are ohms per square ( $\Omega/\text{sq}$ ) (Seaver A.E, 2005).

Measuring resistivity is relatively easy and highly reproducible. Hence, in this research work surface resistivities of the fabrics have been measured following the AATCC test standard method 76-1995, Electrical Resistivity of Fabrics. This resistance is measured by measuring the current passing through a fabric under known voltage and the electrode dimensions. The resistivity is calculated as follows:

$$R_s = \rho_s \times D/W$$

where  $R_s$  = Surface Resistance ( $\Omega$ )

$\rho_s$  = Surface Resistivity ( $\Omega/\text{sq}$ .)

D = Distance between Electrodes (m)

W = Width of Specimen (m)

Surface resistivity that can be measured using the concentric ring electrode is

$$\rho_s = 2\pi R_s \ln (r_2/r_1)$$

where  $r_2$  = radius of the outer electrode

$r_1$  = radius of inner electrode

The surface resistivity measured using the concentric ring electrodes is expressed in ohms/square and has the same value as measured using the square parallel electrodes.

### ***2.7.3 Simulation Measurements***

The two kinds of tests which are used to test the antistatic properties by simulation are cling tests and simulated walking tests. The most reproducible method of testing is suggested by the AATCC Test method 115-1995. A strip of fabric is clamped at one end and placed horizontally on a steel plate which is not grounded. The test fabric is placed on the steel plate and rubbed with a standard fabric material which is wrapped around a wooden block. The steel plate with the test fabric is inclined to an angle of 70°, after the rubbing as the fabric clings to the metal plate. The time needed for the fabric to be free from the cling and fall to the ground on its own weight is calculated. Stroll tests are used to measure the charge on carpets. However, these results depend upon the carpet materials, shoe sole material etc.

## **2.8 ANTISTATIC FINISHES**

Antistatic agents are the chemicals that are applied to the surface of the yarn or fabric to control the accumulation of the static electric charges. The principle mechanism involved in the working of antistatic agents is that they increase the conductivity of the fiber surface and reduce the frictional forces through lubrication (Schindler and Hauser 1998). The presences of mobile ions are important for the functioning of antistatic agents. These agents increase the conductivity by creating an intermediate layer on the surface. The created layer is hygroscopic so that it can increase the moisture content on the surface and hence the conductivity. The effect of these hygroscopic finishes depends on the humidity of the surrounding air (Schindler and Hauser 1998).

Antistatic agents are applied during the manmade fiber spinning process in the form of spin finish to prevent the generation of static charges. Antistatic finishes are added during the processing of polymers and making them into yarns, woven fabrics and nonwovens. However, most of them are removed during or after the fabric preparation. The antistatic agents can be nondurable or durable antistatic agents. Non-durable antistatic agents are applied to fabrics that never need to be washed or shampooed such as conveyer belts, transport bands, and driving cords. Although application of antistatic agents is necessary for hydrophobic fibers such as nylon and polyester, fabrics made from cotton, wool and rayon

also need to be treated with antistatic agents depending on the end use. In general, to avoid detrimental problems during the usage of textiles, antistatic finish of 0.1% on weight of the fiber/fabric is used. However, the concentration may vary based upon the effectiveness of the antistat material, diameter of the fiber/yarn, fabric structure, relative humidity, temperature and degree of protection desired (Slade, 1998)

### ***2.8.1 Non-durable Finishes***

These finishes are preferably used for fiber and yarn processing, since they need to be removed. Non-durable finishes are hygroscopic materials include surfactants, organic salts, glycols, polyethylene glycols, polyelectrolyte, quaternary ammonium salts with fatty alkyl chains, polyethylene oxide compounds and esters of salts of alkylphosphonium acids.

Esters of phosphoric acid, quaternary ammonium compounds and non-ionic compounds belong to the non-durable finishes. Esters of phosphoric acid are shown in the Figure 2.5. The most known quaternary ammonium finishes are ditallowdimethylammonium chloride and dihydrogentaed tallowdimethylammonium chloride. Long chain quaternary compounds on manmade fibers provide some durability to wash and moderate antistatic properties can be found even after washing. The chemical structure of quaternary ammonium antistatic finishes is shown in the Figure 2.6. Compounds such as ethoxylated fatty esters, alcohols and alkylamines belong to the non-ionic antistatic agents. Alkylamine non-ionic finishes are shown in the Figure 2.7. These non-ionic finishes absorb more moisture; which gives better antistatic properties. Cationic finishes applied to cotton and polyester fabrics were found to be removed after one wash (Holme et al. 1998). However most of these antistatic agents lie on their surface. Grafting chemically these surface finishes would change their static electric properties significantly (Duke et al. 1976, Brennen et al. 1995).

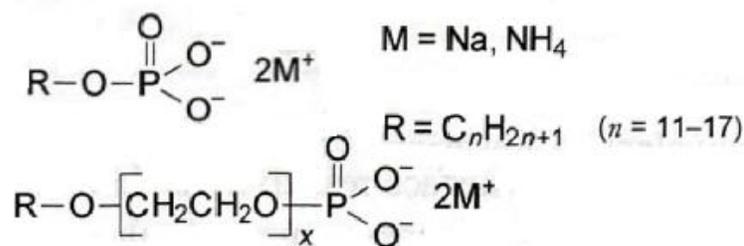


Figure 2.5 Phosphoric ester antistatic agents (Schindler and Hauser)

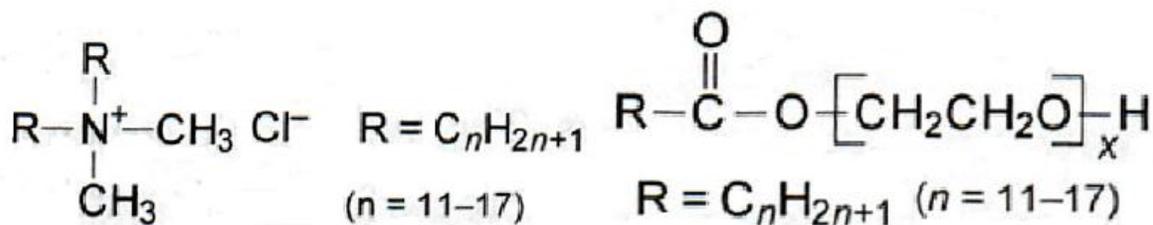


Figure 2.6 Quaternary ammonium agents and Non-ionic antistatic agents (Schindler and Hauser)

### 2.8.2 Durable Antistatic Finishes

It is not easy to obtain an antistatic coating which can endure to several washings on a fabric with a single finish application. The main principle involved in this finish is to form a cross linked polymer network containing hydrophilic groups. These cross linked polymer network groups can be formed by reacting polyamines with polyglycols. The concentration of the hydrophilic groups in the final polymer can be customized. As the larger portion of the hydrophilic groups are added, more moisture can be absorbed, which greatly improves the antistatic effect. Crosslinking of polyelectrolyte is shown in Figure 2.7. At higher levels of absorbed moisture, the polymer layer formed on the surface could be softened and is more easily removed by abrasion during laundering. Even higher levels of cross linking are not good for the antistatic properties. The amount of moisture absorbed will be reduced at higher degrees of cross linking, and is more easily washed away due to abrasion during laundering. Due to the difficulties involved in optimizing the desired properties by using durable antistatic coatings, the usage of durable antistatic finishes are limited.

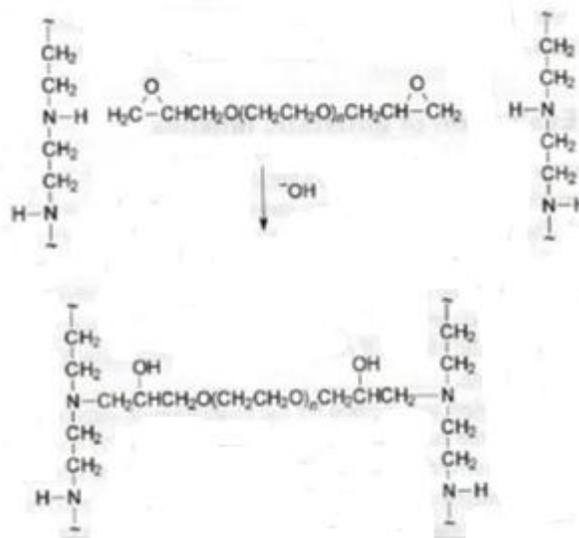


Figure 2.7 Cross linking of polyamines to create durable antistatic agents (Schindler and Hauser, 1998)

### 2.8.3 Evaluation of Antistatic Finishes

There are several ways to evaluate the antistatic coating on textile materials. The measurement of surface resistivity is the easiest way to measure the resistivity. AATCC method 76, measurement of electrical resistivity of the fabrics is commonly used to measure the resistivity of the fabrics. Other measurements can include measuring the triboelectric charge by contacting with metals, rubbing with a cotton fabric and measuring the surface potential, measuring electrostatic potential half-life, surface electrical resistance and wicking of water measurements (Schindler and Hauser, 1998).

## 2.9 RESISTIVITY STANDARDS AND THEIR PROPENSITY TO TEXTILES

There are certain standards which have been set to define the antistatic properties of textile materials. A material with a surface resistivity of  $10^{11}$  ohm/ square is considered to be a fabric with negligible static propensity. Hauser and Schindler (1998) provided the surface resistivity values for the practical use of antistatic finished fabrics at 65% RH as shown in Table 2.2.

Table 2.2 Surface resistivity and practical use of antistatic finished textiles (Schindler and Hauser 1998)

Surface Resistivity range $\Omega/\text{square}$	Assessment
$1 \times 10^6 - 1 \times 10^8$	Very good
$1 \times 10^8 - 1 \times 10^9$	Good
$1 \times 10^9 - 1 \times 10^{10}$	Satisfactory
$1 \times 10^{10} - 5 \times 10^{10}$	Limit of Sufficiency
$> 5 \times 10^{10}$	Insufficient

## 2.10 THEORY OF STATIC ELECTRIC CHARGING

Electrostatic force is one of the four important forces in the universe which binds atoms and molecules together. However, it is so small in a macroscopic world, only light weight particles are to be charged when two materials contact each other. According to Gauss' law, around a uniform density of charge if an imaginary area of surface S has been drawn, the component of the electric field is proportional to the total electric field.

$$E = \frac{\sum q}{S \epsilon_r \epsilon_0}$$

$\sum q$  = total sum of the charges enclosed in a surface

$\epsilon_0$  = relative permittivity of free space

$\epsilon_r$  = relative permittivity of the medium

At one atmospheric pressure, dry air ionizes at an electric field of  $3 \times 10^6$  V/m. The total charge enclosed in a surface is the surface density of the charge Q is multiplied by the surface area S i.e.

$$\sum q = Q_s S$$

From Gauss's law,  $E = \frac{(Q_s * S)}{(S * \epsilon_0)} = \frac{Q_s}{\epsilon_0}$

The maximum charge that can be built up on any solid surface is limited by the breakdown strength of the air. When the dielectric strength of air gets broken down, the charge on the

surface gets dissipated. The maximum electric field (V) on any material before the dielectric strength of air gets breakdown is  $3 \times 10^6 \text{ V m}^{-1}$  a capacitance (C) of  $8.8 \times 10^{12} \text{ F/m}$  then the maximum charge density that can be sustained on any insulator surface is

$$\begin{aligned} Q_{\max} &= 8.8 \times 10^{12} \text{ F m}^{-1} * 3 * 10^6 \text{ V/m} \\ &= 26.4 * 10^{-6} \text{ C m}^{-2} \end{aligned}$$

The primary charge on one electron is  $1.6 * 10^{-19} \text{ C}$ . At maximum charge density there are approximately  $1.7 * 10^{14}$  electrons per square meter can be found on a negatively charged surface. On any solid surface the number of atoms present is of the order of  $2 * 10^{19}$  atoms per square meter. This shows that on a monolayer of surface only about 8 atoms per million are charged, which means that only one atom out of 125,000 is charged. For that reason the surface charges are found to be so sensitive and even at a very low level contamination of a few parts per million will have a significant effect on the static electrical properties of the polymer surfaces (Cross, 1987).

For any polymer surface that is charged with maximum charge, if we assume that these charges are equally distributed, there can be only 163 traps/ $\text{mm}^2$ , which corresponds to one charge stored in a square 78 nm/side. For polymers typical interatomic distances are in the range of 0.1-0.2 nm, thus the charge concentration is of the order of 0.5 -1.5 parts per million even in the most optimistic case. Similar observations were observed by experimental research by Mellinger (2005).

## **2.11 CHARGE DISSIPATION ON INSULATING SURFACES**

### ***2.11.1 Time Constant for Charge Decay***

It is very important to calculate the time for the charge to dissipate away from the charged textile surface. The charge decay depends on the size of the capacitance on which the charge is stored and resistance through which it can flow to earth. In the case of conductors the capacitance and the resistance values are constants, however for insulators the capacitance and the resistivities are more complicated. The rate at which a charge flows through

resistance is proportional to the voltage on the capacitor. The voltage is proportional to the charge remaining on the surface. Mathematically the charge decay can be expressed as

$$q = q_0 \exp(-t/\tau)$$

where  $q$  = charge at time  $t$

$q_0$  = initial charge

$\tau$  = time constant =  $RC = \epsilon_\rho \epsilon_0 \rho$

where  $\rho$  = resistivity

$R$  = resistance

$C$  = capacitance

$\tau$  is called the time constant for exponential decay which is equal to the time to reach approximately 37% of the initial potential decay. Exponential decay on an insulator surface is shown in Figure 2.9. Another parameter that can be used to measure the charge decay is half decay time, the time to reach the 50% of initial charge, which is also called as half life time.

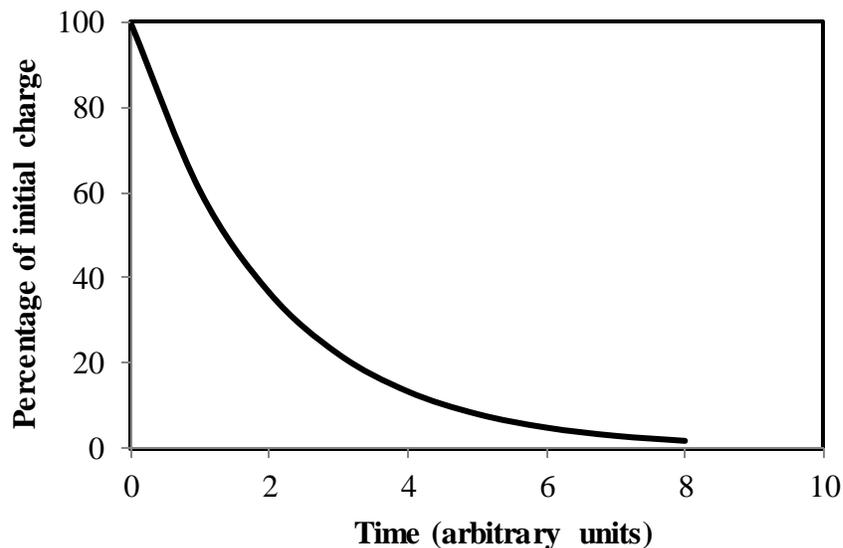


Figure 2.8 Exponential Decay of charge on a polymer surface with a time constant  $\tau$  (Cross 1987)

### ***2.11.2 Charge Decay Mechanism on Textile Surfaces***

Experimental studies by several researchers have shown that long-term charge decay in most charged polymer materials is characterized by relatively fast initial decay, followed by slow

final decay (Sessler 1987). Based on kinetic equations, and considering aspects such as capture and release of traps, creation of carrier pairs, recombination, stochastic hopping, etc., several models have been proposed to explain charge decay. However most of these models have been proposed based upon charge decay measurements on the corona charged polymer films or fabrics.

### ***2.11.3 Effect of Moisture***

The most important factor that is responsible for significant electrostatic charge effects is humidity. Water has a high dielectric constant which reduces the strength of all electrostatic interactions by that factor. Water can play a role in charge decay acting on both surface (for hydrophobic polymers) and bulk (for hydrophilic polymers). Among organic polymers, polymers with no polar groups with certain structural features such as polypropylene and PTFE are found to have very low charge decay properties. These nonpolar polymers have hydrophobic surfaces. Even these hydrophobic polymer surfaces adsorb some water from air. This water is probably localized in islands and does not form a continuous film. The presence of moisture affects surface conductivity. Water can dissociate into H<sup>+</sup> and OH<sup>-</sup> ions, which can be an important source of ionic charge carriers and increases the surface conductivity. For example the presence of 18 ppm of water by weight in pure n-hexane polymer reduced resistivity from  $10^{19}$  to  $10^{14}$  ohm-cm, and hence charge could be dissipated very easily. A schematic representation of the interface between the charged polymer surface and an aqueous solution is shown in Figure 2.9. This interface is called the electrical double layer, and is often divided into more than two layers. In the Figure 2.9 it was assumed that the solid has a positive electrostatic charge arising from its surface. Some of the counter-ions (anions) are accumulated as an immobile layer near the surface of the solid. The remaining anions along with other electrolyte ions form a diffuse “ion atmosphere” called the Gouy-Chapman layer which is extended into the electrolyte solution. The thickness of a single layer of water is about 0.3 nm. The total interfacial region (surface with cations and counter anions and electrolyte ions) is electrically neutral. The effect of this double layer is found to have significant effect in contact charging.

Charge on corona treated nonpolar polymers, such as polyethylene and polypropylene, are found to be stable at room temperature even at high humidity (98%). But charges on these polymers are not stable at temperatures higher than the crystalline dispersion temperatures ( $T_a$  not  $T_g$  glass transition temperature) as observed by Mishra (1982).  $T_a$  is the temperature at which motion of crystal domains is possible, which is much higher than  $T_g$ . Polar polymers such as nylon and polyester have functional groups such as amide bonds and carboxyl groups in their molecular chain configuration. These groups absorb water and increase electrical conductivity by ionic transport, thus the dielectric constant of the polymer will increase. Because of interaction between water, polymer molecules, and charged particles, charge will be transported in the polymer, and can be neutralized easily.

According to Mishra (1982), the interaction between water and polymer molecules could cause the following effects on the electrostatic properties of polymers. Water absorption increases the dielectric constant and creates various charge carriers including mobile electrons/ions. The following equation is derived between conductivity and moisture absorbed in polar polymers

$$\text{Log } S = Cm + D$$

Where  $S$ = electrical conductivity

$m$ = amount of moisture absorbed by polymer

$C$  and  $D$  are constants.

Water absorption creates a plasticizing effect on some polar polymers by decreasing their glass transition temperature. Water molecules themselves can break into  $H^+$  ( $H_3O^+$ ) and  $OH^-$  ions and provide charge carriers. This could improve the conductivity of the polymers, particularly at lower humidity.

Mishra (1982) found that for polar polymers, moisture absorption and charge decay rate are directly related. As the amount of moisture absorption increases, the charge decay rate increases. Das-Gupta et al. (1990) also agreed with these findings and concluded that absorption of moisture, a common contributor for charge decay, acts both on the surface and the bulk of the sample.

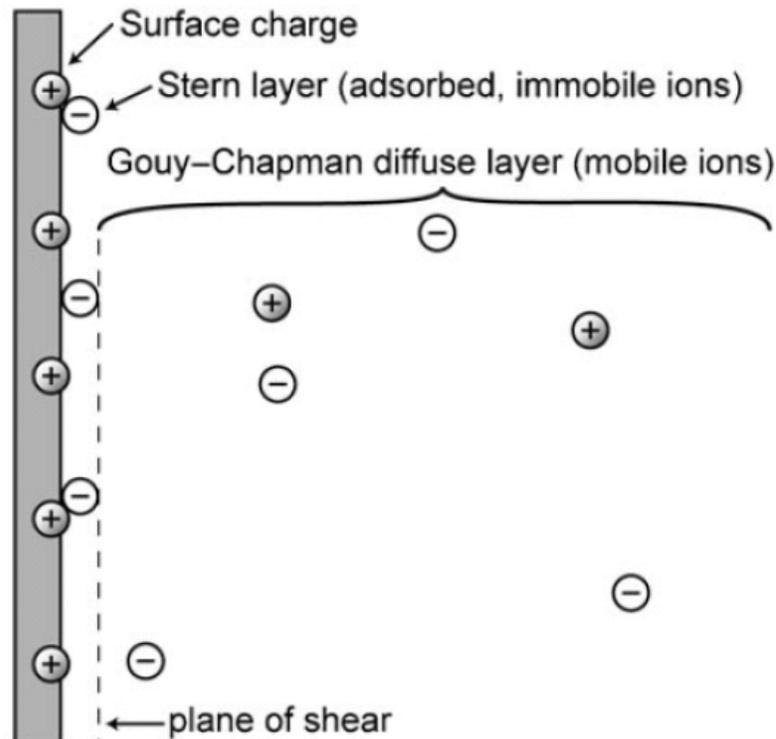


Figure 2.9 Interface between charged surface and aqueous electrolyte solution (Whitesides et al. 2007)

Shashoua (1958) investigated the relation between the chemical structure and charge decay properties of polymers. He proposed that polymers contains the chemical groups such as  $-Cl$ ,  $-CN$ , or  $-COOCH_3$  generate less static charge compared to the polymers with functional groups such as  $-COONa$ ,  $-SO_3Na$  or  $-CH_2CH_2O-$ .

#### ***2.11.4 Mechanisms of Charge Decay***

Charge decay on triboelectrically charged polymer surfaces can be attributed to the following factors.

##### ***2.11.4.1 Conduction***

Charge dissipation on a triboelectrically charged surface was expected to be explained by the mechanism of conduction, by means of free electron diffusion in to ground (Sessler, 1987). However, various workers proposed that dissipation by conduction is not the only

mechanism responsible for the charge decay on textile surfaces. Onogi et al. (1996) measured charge decay on triboelectric charged textile surfaces. They examined two different cases of charge decay when the charged textile fabrics are in earthed and unearthed (insulated) situations. For the earthed fabrics they found that the charge dissipation is linear with time on a log scale. The charge dissipation is due to the free diffusion of electrical charges into the ground. These observations were supported by several other authors. The internal phenomenon of charge decay in polymers is due to ohmic conduction or drift or diffusion of excess charges. Ohmic conduction is due to intrinsic carriers (which can be positive or negative) available in the valence and conduction band of some materials, particularly at higher temperatures. These carriers are responsible for the fields that persist in these polymers. Excess charges created due to charging are subjected to drifts caused by their own fields (Rychkov 1992, Frese 2007). Ohmic conduction and drift currents are responsible for most of the internal decay. Random motion of excess charges with the effect of diminishing concentration gradients is called diffusion. The role of diffusion in charge decay is predicted by Sessler (1987) to be minor.

#### ***2.11.4.2 Dissipation Into Air***

Onogi et al. (1996) examined charge decay on various textile fabrics under highly insulating conditions. They proposed that three different mechanisms are responsible for the charge dissipation on textile fabrics: conduction to earth, which is the primary mechanism, adsorption of counter ions, and dissipation into the air. When placing the charged surface on a thicker insulated plate, the charge decay was slower, compared to the charge decay on a surface placed on a thinner insulated plate. They examined the rate charge dissipation into air on triboelectrically charged samples of wool, cotton, nylon, and polyester at a range of humid conditions from 45% to 75%. They observed that the dissipation rate constant depends on the water content of the textile fabrics. A linear relationship between the rate constant and the amount of water level above a critical level has been observed.

Onogi et al. (1996) explained the charge decay mechanism by explaining that the fibers contain two different states of absorbed water found in polymer solids. Water molecules

which are bound to polymer molecules very firmly are not involved in charge dissipation. Other type of water molecules that are loosely bound are called free water, which present above the critical concentration and are responsible for the charge dissipation.

Onogi et al. (1997) also observed the effect of temperature on charge decay into air at a range of 15- 30°C and 45-85 % RH. It was found that the critical water content on these fibers was reduced as the temperatures rose. At 20°C, the amount of free water which is responsible for charge dissipation is more than the critical water content. It was observed that the rate constants for charge decay have a linear relationship with the amount of free water. However at other temperatures, there is no relationship found between the rate constant and the amount of free water (Onogi, 1996).

#### ***2.11.4.3 Absorption of Counter Ions***

When the charged polymer is stored in unshielded conditions and open to large area of ions, the charge decay due to the ion deposition can be very large. When corona charged Teflon<sup>®</sup> FEP films were stored in open air, the charge decay was very rapid, and because compensation charges in the form of atmospheric ions neutralized the charge at a faster rate (Sessler, 1987). Charge decay on identical 47 polymer films stored in an aluminum box, polystyrene box, or cardboard box were found to be very slow. In a large room, due to the convection process, a large reservoir of new ions is available in the proximity of the polymer and the charge decay was found to be quick. However, the same kind of experiments performed on other nonpolar polymer polypropylene shows that airflow has a very minor effect on charge decay. These contradictory results could be because polypropylene is less sensitive to atmospheric ions than Teflon<sup>®</sup> FEP, which could be unlikely, or the experimental conditions could be different from each other. When the charged polymer is stored in a small storage volume, the external decay can be diminished to the point where only internal phenomena determine charge storage. However, Haenen (1975) contradicted that the decay of charge is due to ions, because the effect of these ions from the air is not significant if the observed time is less than 1000 hours. He proposed that the ion concentration in air is small.

However, charge decay does not need to be single exponential decay. Ramer et al. (1968) investigated the charge decay on triboelectrically charged textile surfaces and found that the charge decay is made up of two exponential components. They expressed the equation from the voltage/ time curve

$$V = A e^{-t/\tau_1} + B e^{-t/\tau_2}$$

where A and B are ordinate intercepts of the curves of the two components and  $\tau_1$  and  $\tau_2$  are the time constants.

#### ***2.11.4.4 Other Factors***

Pressure also plays a role in charge decay (Mekishev et al. 2005). Mekishev (2005) charged polypropylene and stored it at various pressures between 20-300 Torr and concluded that at low pressures, charge decays faster. As pressure decreases, desorption of ions from the polypropylene surface is possible, which leads to decrease in the surface potential of these polymers.

Mishra (1982) found other contributors for charge stability in polyolefins. She proposed that the high volume resistance and development of crystal structures inside the polymer are responsible for the charge stability in polyolefins. Long side chain polyolefins such as poly (1-butene) and poly (1-hexadecene) were found to have poor charge storage properties. Long term charge storage is due to the charges being stored in molecular chains, functional groups and between the crystalline and amorphous regions. But, at higher temperatures, one reaches the onset of thermally activated motion of these trapped sites, and thus the trapped charges would be dislodged. Thus only polymers with high transition ( $T\alpha$ ) temperature would be stable at higher temperatures. However, impurities in polar polymers are responsible for the moisture absorption and the charge decay.

However, charge decay properties also depend upon the structure. Tsai et al. (1998) compared corona charged melt blown nonwovens and spun bond nonwovens charged at various temperatures ranging from 60° C to 130° C, and found that melt blown nonwovens exhibit longer charge retention. According to his study, slower charge decay on meltblown

nonwovens is due to the electrical properties of the material such as conductivity and the dielectric constant of the polymers. The charging technique did not show any difference (Tsai 1999) in the charge decay properties. In another article, Tsai et al. (2002) also concluded that finer fiber polypropylene nonwovens have lower charge decay rates compared to coarser fiber webs. They also stated that heavier basis weight webs have longer charge retention than the lighter ones. These observations were also confirmed by Motyl et al. Some authors found that the charge decay on polypropylene is a first order exponential decay. However, their experimental approach was not clear and they did not describe how the materials have been charged.

### ***2.11.5 Crossover Phenomenon***

A different charge decay mechanism was observed on polyethylene by several researchers. Charge decay on corona charged polyethylene at higher initial charge levels is much faster than at lower levels, as observed by Ieda et al. (1967). These observations are shown in Figure 2.11. Corresponding decay curves cross each other, which is called the crossover-phenomena. Researchers predicted that at higher charge densities, complete charge injection occurs into the bulk and partial injection (i.e. to surface) occurs at lower charge densities. Since bulk charges are subject to faster decay than the surface charges, the potential on the samples with high initial charge density is expected to fall below charge density of the samples charged with low initial charge density. However, the crossover phenomenon is limited to polyethylene with certain additives. However, research by several other authors on other polymers did not observe the crossover mechanism. Some other researchers observed charge decay on the polyethylene crossover phenomenon (Herous et al., 2009, Neagu et al. 1997). Recently Chen et al. (2010) observed the cross over charge decay mechanism on low density polyethylene films and explained that the cross over mechanism is due to bipolar charge injection from the corona, which is beyond the interest of this project.

Various charge transfer mechanisms such as an ionic charge transfer mechanism and electronic charge mechanism are also proposed by various authors. The surfaces of these polymers are too sensitive; a very little contamination on its surface or a very thin layer of

surface finish added to its surface would influence its charge generation and charge decay properties. Application of surface finishes by applying a very thin layer of known coating on the surface of the textile material would be useful to determine the static electrical properties. However, the surface of the polymer should be covered completely in order to find any significant influence on charge generation and charge decay properties due to the surface modification.

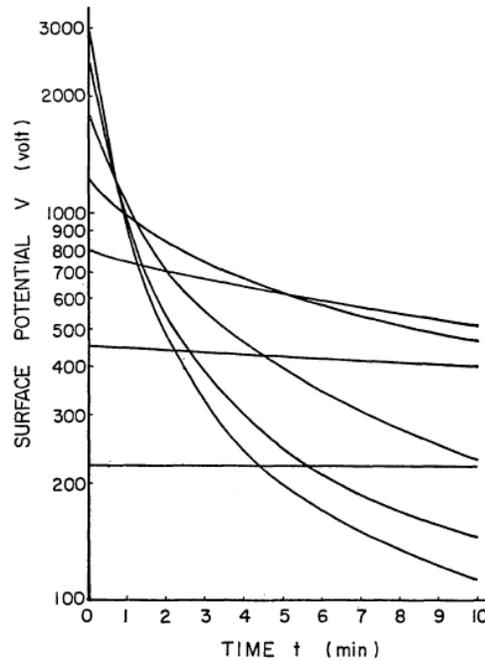


Figure 2.10 Charge decay on corona charged polyethylene film (Ieda et al., 1968)

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**CHAPTER 3**  
**OBJECTIVES**

## **OBJECTIVES**

The literature review indicates that considerable amount of research has been done to understand the static electric properties of the textile surfaces in order to avoid the detrimental effects of the unwanted static charges developed on these textile surfaces and also to make effective air filters. However, even after so much research, complete understanding of the static properties of these materials has not been made and also consensus between various research findings needs to be made. However in order to understand the charge generation and charge decay mechanism it is important to design a system. In this research work an experimental system is designed to obtain reproducible results, so that meaningful observations can be made. The Literature review also indicates that there are several discrepancies found in the published literature.

For example in some triboelectric series, cotton is placed above steel and in others it's vice versa. Also nylon, which is placed on top in the triboelectric series, is supposed to get charged positive; however the charge on nylon was negative when rubbed with stainless as observed by London (London, 1966). The surface of the textiles needs to be cleaned as observed by many authors. However, Mishra (1982) found that the surface impurities has no effect

### **3.1 RESEARCH GOALS**

The goal of this research is to study the static electric properties such as resistivity and the triboelectric and contact static charge generation and charge dissipation mechanism on woven textile surfaces. These findings would be useful to understand and control the static charge generation and dissipation.

Specific objectives are including but not limited to

- Investigating the differences in contact and frictional charging mechanism between polymer-polymer and polymer-metal contacts.
- Investigating charge decay mechanism and proposing a model for charge decay on textile surfaces applying antistatic and hydrophilic finishes on polyester fabrics

- Studying the relationship between static electrical properties, surface resistivity, charge generation and charge decay measurements on polyester fabrics applying different concentrations of hydrophilic finishes during frictional charging measurements.
- Investigating the effect of durable and non-durable antistatic surface finishes on static electric properties of polyester and nylon woven fabrics.

The overall goal of this research work is to gain a better understanding of the electrostatic charge generation and dissipation mechanism of the textile materials. Different parameters varied are various polymers, various surface finishes and various charging methods. This research is expected to provide some insights about the charge generation and dissipation models. This research could provide knowledge that allow the control of static charge generation and dissipation and could be utilized to reduce the detrimental effects of static charge during use of consumer products and processing of textile fibers, yarns, and fabrics.

The results are presented here as a collection of journal articles. Chapters 4, 5, 6 and 7 are articles being prepared to be submitted to peer-reviewed journals. Instruments, materials and methods are explained separately in each chapter. Each of the chapter is dedicated to answer the each objective listed above. The reader may found some redundancy of some introductory and experimental information because of the reason these publications are intended to be independent from each other. Chapter 4 provides insight to the differences in the contact and dynamic charging of polymer-polymer and polymer-metal charging. Chapter 5 discusses the charge decay mechanism on cotton and polyester fabrics and polyester fabrics treated with topical finishes. Effect of concentration of the hydrophilic finish on the charge decay is explained in chapter 6. Studies on nylon fabrics is discussed in chapter 7

**CHAPTER 4**  
**ELECTROSTATIC CHARGE GENERATION AND BUILDUP DURING**  
**CONTACT AND FRICTIONAL ELECTRIFICATION OF WOVEN**  
**TEXTILE FABRICS**

# **ELECTROSTATIC CHARGE GENERATION AND BUILDUP DURING CONTACT AND FRICTIONAL ELECTRIFICATION OF WOVEN FABRICS**

## **4.1 INTRODUCTION**

When any two neutrally charged materials are contact and separated, it is generally observed that one material acquires positive charge and the other negative charge. If these materials are conductors such as metals, the generated charge quickly dissipates through the conductive matrix. If the materials are insulators, the generated charge accumulates on the surface. Polymers with relatively polar surfaces and relatively low resistance (i.e. cotton and rayon) are able to spread the charge throughout the structure and a rapid decay of the charge is observed. Synthetic textile fibers, such as polyester and polypropylene are insulators with high resistance (generally  $>1 \times 10^{16}$  ohms-cm volume resistance) and any charge that is generated is retained on the surface and dissipates only slowly. Thus, in the processing of fibers, synthetic fibers generally have significant issues with static generation and control while high surface energy fibers, like cotton, have relatively few issues. In order to understand and reduce the detrimental effects of static charge generation on such textile materials, it is important to understand the charge generation and dissipation mechanism(s). Significant research has been done and several careful reviews have been published explaining the electrostatic charging mechanism on textile materials (Harper, 1957; Rose-Innes 1980; Holme et al. 1998, Whitesides et al. 2007), however a thorough understanding of mechanisms in this area continues to elude the research community. This work will focus on two specific questions in this area:

What if any, of the differences between contact and rubbing charge generation mechanism(s)?

What are the differences between polymer-insulator and insulator-insulator charging mechanism(s)?

The generation of static electric charge is an interfacial phenomenon and it is found that the charge lies about few nanometers from the surface (Arridge, 1967). The surface of polymeric

materials is different from the bulk with surface thickness limited to a few nanometers. Maximum surface charge that can be generated on any solid insulated surface is  $26.4 \mu\text{C}/\text{sq.m}$ , due to discharge of the materials to the ground through air. Even at this maximum charge level, only eight out of a million atoms are charged. Surface charges involving a few parts per million could significantly influence the electrostatic properties of the textile materials.

A series of materials, called the triboelectric series, in which materials are listed in an order according to the sign of the static charge generated on its surface when it is rubbed with another material has been established by several authors. In this series, materials which are placed near the top are charged positive when rubbed with materials placed on the bottom of the table. The first triboelectric series was established back in 1757 by Wilcke (Hersh and Montgomery, 1955). Later research on the static electrification of the textile materials has resulted in several modified triboelectric series. However, the order of materials in the triboelectric series is still subject to minor differences with several researchers having published several different triboelectric series. A triboelectric series established by two different authors is shown in the Table 4.1. The difference in the relative placement of cotton and steel may be due to small differences in the source or impurities in either material. Since the static properties of textile materials can be very sensitive to surface differences based on processing/chemical treatments or the structural characteristics of fabrics, differences of this type are surprising. Most of the published triboelectric series are based on the polarity of the charge generated on the surface of the polymer when rubbed with another. However, Welker et al (2006) proposed that the magnitude of the charge generated on the surface also depends on the distance between the materials in the triboelectric series.

Explaining the source of the triboelectric charging on polymers (insulators) is an unanswered question (Castle, 1997). Adding to this the complexities associated with materials, fiber structure and surfaces along with fabric structure and treatments, renders research on textile materials a challenge. Electrostatic charging of metals and semiconductors is explained clearly in the literature, whereas the same phenomena on polymer surfaces and textiles are

not completely understood and explanatory theories remain elusive. Considerable research has been done on textile fibers, yarns, films, polymer plates and fabrics to understand the electrostatic charge generation. In this research work, most widely used woven textile fabrics such as cotton, polyester, nylon and polypropylene, have been tested to understand the differences in contact and frictional charging. All these fabrics were tested with PTFE for insulator-insulator charging and steel for insulator-conductor charging. A triboelectric series has been established based on the sign and characteristics of the charge generated with tribocharging (contact rubbing), quantified and compared with the triboelectric series in the literature.

Table 4.1 Triboelectric series published by several authors

Triboelectric Series (Adams 1987)	Triboelectric series (Tsuji et al.1985)
Nylon	Nylon
Cotton	Steel
Steel	Cotton
Polyester	Polyester
Polypropylene	Polypropylene
PTFE	PTFE

## 4.2 EXPERIMENTAL

### 4.2.1 Sample Preparation

Woven fabrics of cotton, polyester, nylon and polypropylene (purchased from Testfabrics Inc.) were cut into rectangles of 110 X 80 mm for the rubbing electrification tests and circles of 6 mm diameter for contact charging tests. Rubbing and contact heads of steel and Polytetrafluoroethylene (PTFE) of 10 mm X 20 mm X 3 mm (for rubbing) and a circular sample of 6 mm diameter (contact) size were used to study the polymer-metal and polymer-polymer rubbing effects. The edges of the rubbing head were polished in order to avoid any abrasive damage to the fabric specimens during the rubbing.

Two types of cleaning procedure were adopted for these fabrics. For cotton, polyester and polypropylene fabrics a simple cleaning procedure was followed as adopted by previous workers (Lu, 2010). These samples were cleaned with deionized water at 60° C for 20 minutes. These samples were cleaned with Isopropyl Alcohol ((CH<sub>3</sub>)<sub>2</sub>CHOH, FW = 60, Sigma-Aldrich) at room temperature for 20 minutes (Seyam, Cai, and Oxenham, 2009; Lu, 2010). The samples were then dried in the oven at 120° C. The fabrics were then conditioned in the environmental room at 21° C and 43% Relative Humidity (RH) for 24 hours before testing. The surface of nylon fabric was very sensitive and more thorough cleaning was required for these fabrics. For nylon fabrics, 1g/l Alkon MRV and 1 g/l TSPP was added to water and heated to 70° C and then nylon fabric is added and treated for 20 minutes. Then these fabrics were again cleaned with the procedure adopted for cotton and polyester fabrics. All of these experiments were conducted at a temperature of 21° C and 43% RH as suggested by AATCC standards (AATCC test method 76). Before each test, the initial surface potential of the fabric was measured and any residual charges were removed by using an ionized air gun. The contact/ rubbing heads were also cleaned with 2-propanol (Sigma-Aldrich) and deionizer gas before each experiment.

### ***Sampling***

In this research the samples are chosen randomly from the fabric. The selvages are avoided while selecting the samples. The samples are selected randomly that no sample was chosen that made from same type of warp yarns and same type of weft yarns. Sampling procedure were followed the radom sampling procedure suggested by Saville (Saville B.P. 1999)

### ***4.2.2 Materials and Experimental Design***

Finish free fabrics of cotton, polyester, nylon and polypropylene were used in this work. Basic fabric specifications are given in Table 4.2

Table 4.2 Fabric details

<b>Fabric</b>	<b>Density</b>	<b>Cover Factor</b>
Cotton I	1.52	22.94
Cotton II	1.52	15.81
Filament PET	1.14	20.19
Spun PET	1.14	20.62
Filament Nylon	1.38	17.36
Spun Nylon	1.38	19.20
Spun Polypropylene	0.90	16.48

***Experimental design - I***

In order to study the effect of rubbing on the electrostatic properties of textile fabrics, experimental design I was used. Table 4.3 gives the parameters and levels used in experimental design.

Table 4.3 Experimental design - I to investigate the static generation during the frictional charging of textile fabrics

<b>Parameters</b>	<b>Levels</b>
Fabrics	Cotton I, Cotton II Filament Polyester, Spun polyester Filament Nylon, Spun Nylon, Spun Polypropylene
Frictional charging heads	Steel, PTFE
Charge measurements	Charge after first rubbing, Charge after 50 rubbings
Total number of measurements	$7 \times 2 \times 2 \times 3 = 84$

### ***Experimental design - II***

In order to study of the effect of contact and separation on the charge generation on textile fabrics, experimental design II was used. Table 4.4 shows the parameters and levels used during the rubbing charging.

Table 4.4 Experimental design - II used to investigate the contact charging of textile fabrics

<b>Parameters</b>	<b>Levels</b>
Fabrics	Cotton I, Cotton II Filament Polyester, Spun Polyester Filament Nylon, Spun Nylon, Spun Polypropylene
Contact charging heads	Steel, PTFE
Charge measurements	Charge after first rubbing, Charge after 50 rubbings
Total number of measurements	7 x 2 x 2 x 3=84

### ***4.2.3 Equipment and Test Protocols***

#### ***Rubbing Charging Equipment***

To investigate the effect of rubbing on static charge generation as a part of experimental design-I customized rubbing charge measurement equipment was built in a controlled environment by previous workers (Seyam et al. 2009). Rubbing apparatus consists of a movable rubbing head with an insulated stationary platform to place the fabric sample. A probe is placed at a constant distance (21mm) next to the moving rubbing head. When the rubbing head is moving along the fabric, the charge generated on the fabric is monitored by the probe continuously. The following parameters were maintained constant for the rubbing test measurements rubbing force: 1N; rubbing frequency: 25 cycles/ min; rubbing speed: 47mm/sec; acceleration/deceleration: 400 mm/ s<sup>2</sup>; rubbing stroke length: 52 mm (46.48 mm at constant speed; + 2.76 mm acceleration; + 2.76 mm deceleration); number of rubbings: 50; data collection rate: 100 points/sec; The responses measured for the rubbing are surface

potential after the first cycle of rubbing, after 50 cycles of rubbing and half life time day in seconds. Typical rubbing charge data after every rubbing is shown in Figure 4.3.

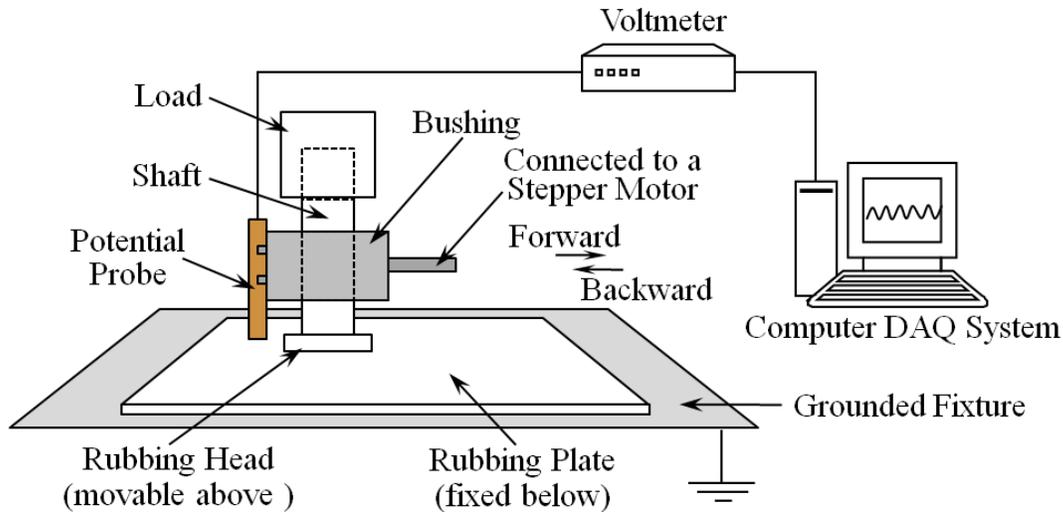


Figure 4.1 Rubbing Charge Equipment (Lu, 2010)

### ***Contact Charging Equipment***

To investigate the effect of contact and separation on the electrostatic charge generation of the textile fabrics as a part of experimental design-II contact charge equipment if build by previous works is shown in Figure 4.2 (Seyam et al, 2008). For the contact charging measurements, fabric sample of 6 mm diameter was placed on a contact head using a double sided tape, and the fabric sample has been in contact and separation with stainless steel/ PTFE surface. After every contact, the fabric sample was moved inside a faraday cage and the charge was detected and the data was recorded. The following test conditions were unchanged for all the contact tests. Parameters used in this work are contact force of 16 N, contact frequency 50 contacts/ min, number of contacts for the test 50 and data collection rate 300 points/minute. The responses measured for this research are charge after the first contact, charge accumulated after 50 contacts and half life time in seconds. Typical static charge data after every contact is shown in the Figure 4.4.

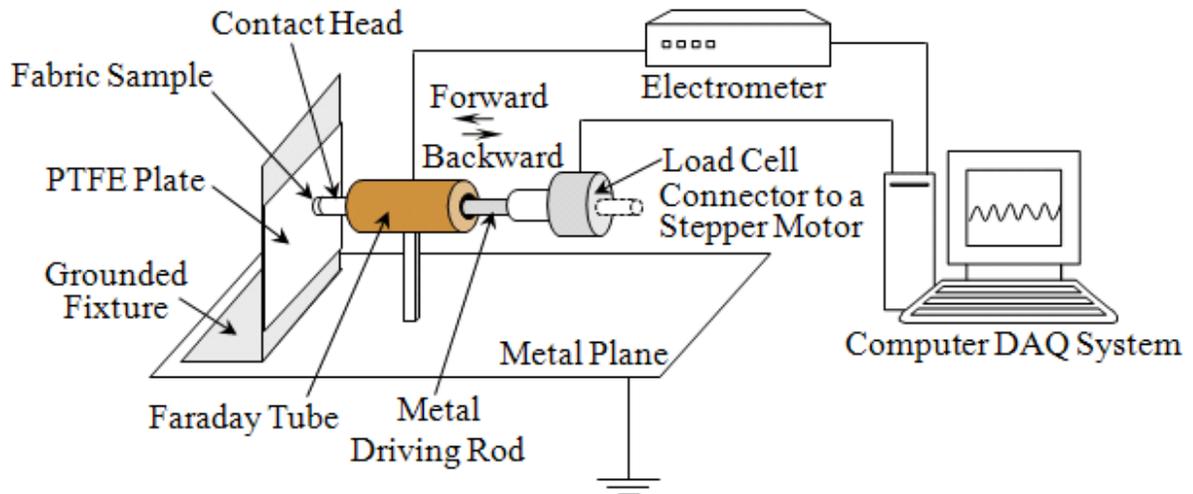


Figure 4.2 Contact charging tester (Lu, 2010)

### ***Resistivity Measurements***

Surface resistivity of the fabrics was measured using the AATCC method 76-2005 and ASTM standard D 257-99. The resistivity measurements were made using the Trek Model 152 model surface resistivity meter and the Trek model 152P-CR concentric ring probe. The accuracy of the measurement is about 5% when the resistivity is around  $10^4 - 10^{14}$  ohms/square.

Electrode assembly with two concentric rings shown in the figure is used to measure the resistivity. The diameter of the inner ring is  $30.48 \pm 0.64$  mm and the outer electrode is  $57.15 \pm 0.64$  mm. The thickness of the each ring is  $3.18 \pm 0.2549$  mm. The total weight of the electrode assembly is  $2.27 \pm 0.056$  kgs. This instrumentation includes an ammeter and a power supply (10-100 volts). For materials with a low resistance of below  $10^6$  ohms, voltage of 100 volts will be used and for materials with a resistance of higher than  $10^{12}$  ohms.

The test specimen of 30 cm X 30 cm is placed on a grounded insulator. The test specimen is contacted with the electrode and the current passed through the supply is measured by supplying a voltage to the electrodes. The resistivity has been measured at nine different places on the fabrics. Resistivity meter is placed on the sample for at least one minute. Resistivity of the specimens is calculated from the equation

$$\rho_s = 2\pi R \log (r_2/r_1)$$

Where  $r_2$  = radius of the outer electrode

$r_1$  = radius of inner electrode

R= resistance measured in ohms.

#### 4.2.4 Signal Analysis

##### *Rubbing Electrification*

Surface potential measured during several repeats of rubbing testing is shown in the Figure 4.3. Before the test specimen has been rubbed, the surface potential measured on the specimen is near about zero. As shown in the Figure 4.3, rubbing has been started at when the probe is point A and the rubbing cycle has been ended when the probe is at point E.

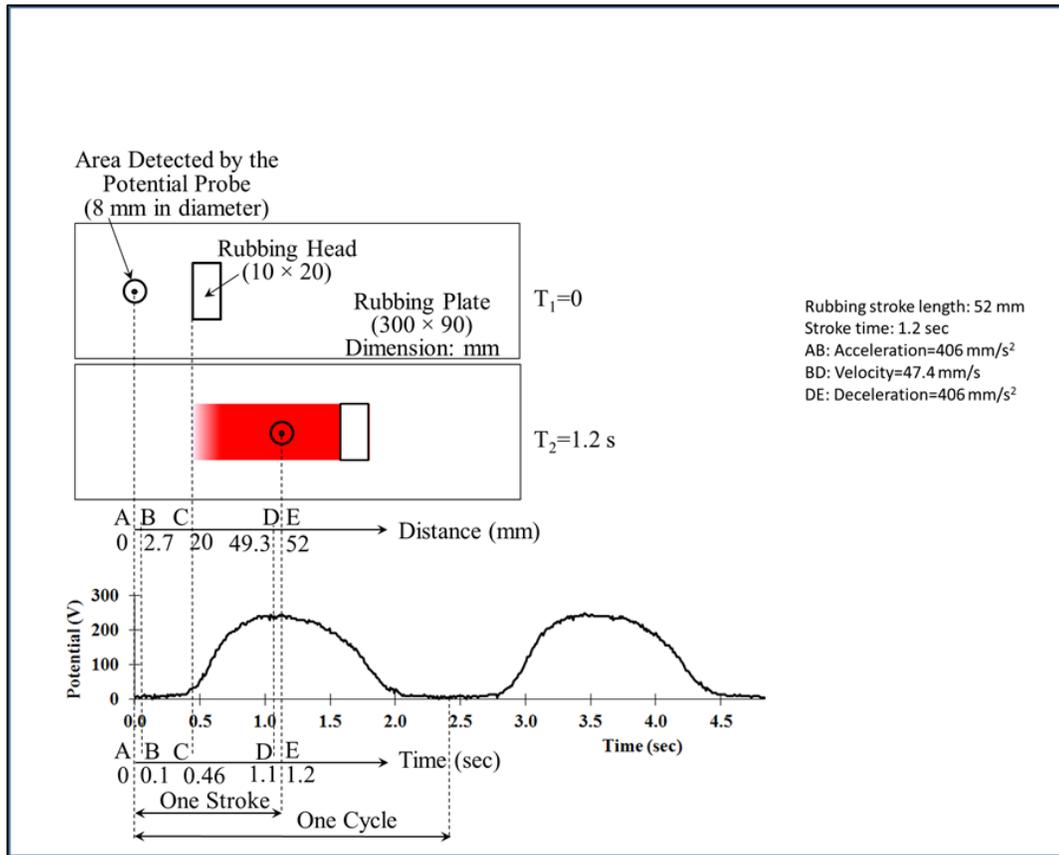


Figure 4.3 Charge measurement and signal analysis during the during rubbing (Lu, 2010)

In Figure 4.3 the whole rubbing measurement cycle has been portrayed. The rubbing equipment consists of a surface potential probe, and a rubbing head which rubs the fabric specimen placed on a rubbing plate. The rubbing head and the probe are fixed parallel to each other horizontally at a distance of 21 mm. The rubbing head and probe are placed vertically above 3 mm from the test specimen. Voltmeter probe has a resolution of 8 mm in both x,y and z directions. The dimensions of rubbing head is 10X20 mm and the rubbing plate is 300X 90 mm. Dimensions of rubbing head, rubbing plate and the probe are shown in Figure 2. Total length covered during the rubbing (one stroke) is 52 mm and time required for one stroke is 1.2 seconds.

At a point A probe is placed and the from point A to point B in the Figure 4.3, the stepper motor moves with acceleration for a time period of 0.1 seconds. At point B the stepper motor reaches the constant speed, with this constant speed the motor moves till position D for a time period of 1 second and then decelerates for 0.1 seconds and stops at position E. However, the rubbed area lies in points between C and E. Since, the probe is placed distantly from the rubbing head, the area that is rubbed and measured the surface potential is from C to E which is about 32 mm. at point E, the stepper motor stops its forward position and moves back and this cycle is repeated until the probe reaches the position A. The surface potential measured is shown in the curve. As shown, from point A to C, the surface potential is measured on an unrubbed area, which is nearing about zero. From point C to E the surface potential is increasing as rubbing has been taken place. At point E, the rubbing stroke is finished and the rubbing head moves backwards.

### ***Contact Electrification***

The device developed to establish the contact electrification is described elsewhere (Seyam et al. 2008). Typical signal measured during contact electrification is shown in the Figure 4.4. At point B<sub>1</sub> fabric specimen is entered the faraday cage and at point D<sub>1</sub> the fabric is completely inside the faraday cage and the charge is measured after the first contact. Similarly at point F<sub>1</sub> fabric specimen completely is out of the faraday cage and at point D<sub>2</sub>

the specimen is placed inside the faraday cage and charge measured after second contact. Similarly charge is measured for 50 contacts during the contact charge measurements.

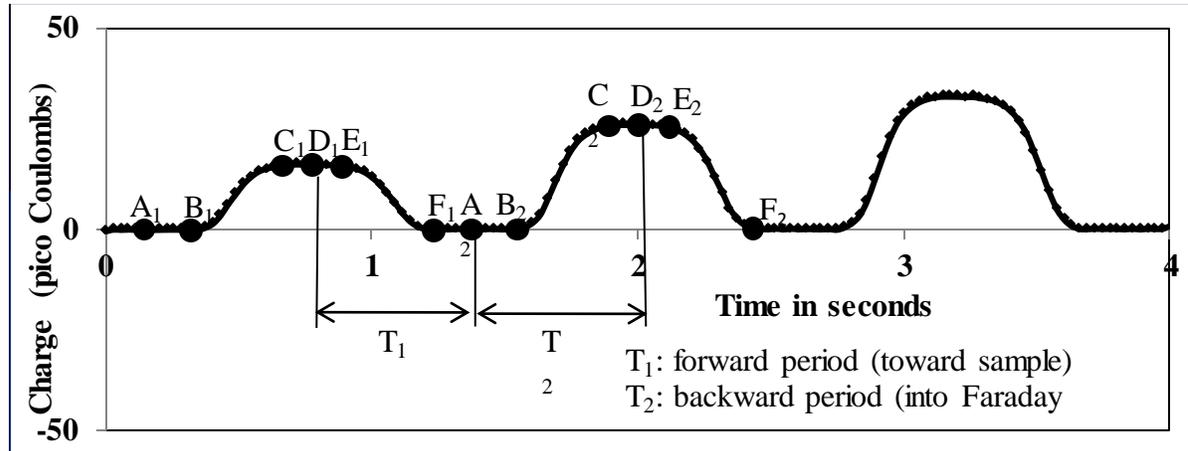


Figure 4.4 Typical static charge data of repeated contact test

### 4.3 RESULTS AND DISCUSSION

#### *Statistical Analysis*

In this research seven different fabrics made from four different polymers namely cotton, polyester, polypropylene and nylon were investigated with two different contact materials (stainless steel and Teflon®). Measured responses include charge measured after initial contact/rubbing and charge measured after 50 contacts/rubbings. If only two populations means need to be compared, the two sample T test is used. However, if there are more than two population means to be compared, Analysis of Variance (ANOVA) is adopted to compare the different means (Ott, 2001). Although this testing gives the information of whether the means of the populations are different from each other or not, we don't know which means are different from each other. To answer these questions multiple comparison procedures and contrasts are used.

In this research Tukey's Honest Significant Difference (HSD) test is adopted to compare the effects of rubbing material (steel or PTFE), number of rubbings and fabric type. When

multiple comparisons are made, the probability of making a type-I error increases. However Tukey's test corrects this experiment-wise error rate. Due to the random sampling procedure that we adopted in this research, it is reasonable to assume that our observations are independent.

Assumptions for the Tukey's HSD test are

1. All the observations tested in this research are independent
2. The variation across the observations are equal

All of the statistical analysis was made using SAS 9.1 software

#### ***4.3.1 Experimental Design - I***

##### ***Rubbing Charge Generation***

Figure 4.3 illustrates the charge (surface potential in Volts) measured after an initial cycle of rubbing with steel and PTFE. The data represents an average of three specimens. Rubbing with steel generated less initial charge in all samples tested.

The triboelectric series (from the literature – Figure 2.2 and Table 4.1) places steel in the middle of the list and PTFE at the bottom of list. This supports the observation that all materials should charge positive when contacted with PTFE. When rubbed with steel, nylon expected to charge positive, polyester and polypropylene expected to charge negative. Cotton is in a region of the list where it might charge negative or positive against steel. The quantity of charge measured on the fabrics is believed to be related to the nature of the surfaces being contacted and will have nothing to do with their placement in the triboelectric series. Also the charge generated on all of these samples after rubbing with steel and PTFE are statistically different ( $P$  value  $< 0.01$ ) as shown in the Table A3 in the appendix. Complete details are listed in the appendix.

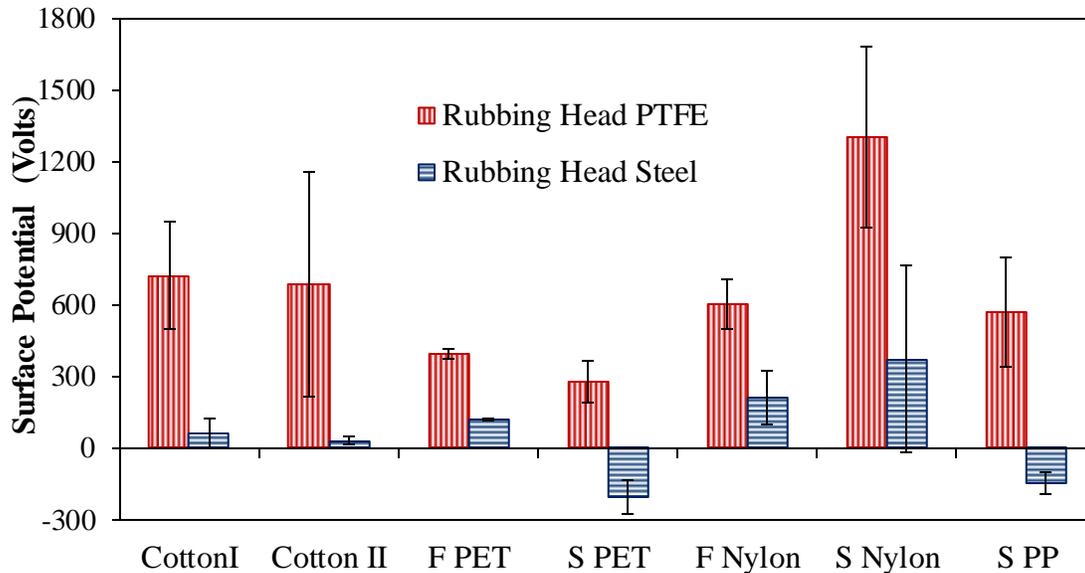


Figure 4.5 Surface potential measured after first cycle of rubbing on textile fabrics

Polypropylene and spun polyester fabrics were charged negatively when rubbed with steel as expected. From the triboelectric series shown in Table 4.1, it can be understood that when rubbed with steel, nylon would charge positive, polyester and polypropylene charged negative and cotton could charge either positive or negative. In the experiments reported here, these observations were found to be true, except in the case of filament polyester. Filament polyester was supposed to charge negative when rubbed with steel, but charged positively. This charge reversal could be due to a residual finish applied to the fibers or fabric during processing or could be related to the structure of the fabric. Even a very small contamination could influence the static electric properties of the textile and polymeric materials.

### ***Rubbing Charge Buildup***

The charge measured after 50 cycles of rubbing on cotton, polyester, nylon and polypropylene fabrics are shown in the Figures 4.6 to 4.10. The amount of charge generated on these fabric samples and time to reach the saturation (maximum) value depends upon the nature of the polymer, the structure of the yarn/fabric and the rubbing head. The surface potential developed on cotton-I and cotton-II samples rubbed with steel and PTFE are shown

in Figure 4.6 and 4.7. Similar to the other fabrics used in this research, the charge generated after contact with steel is significantly less than that generated when rubbed with PTFE (P value < 0.001, as shown in appendix Table A3). Cotton is characterized by the charge reaching its maximum value after first few cycles (about 5 cycles of rubbing) and then relatively stable through the remaining cycles, followed by rapid exponential decay. Higher charge generated during rubbing with PTFE than steel can be attributed to the placement of these materials in the triboelectric series and insulator-insulator charging effects.

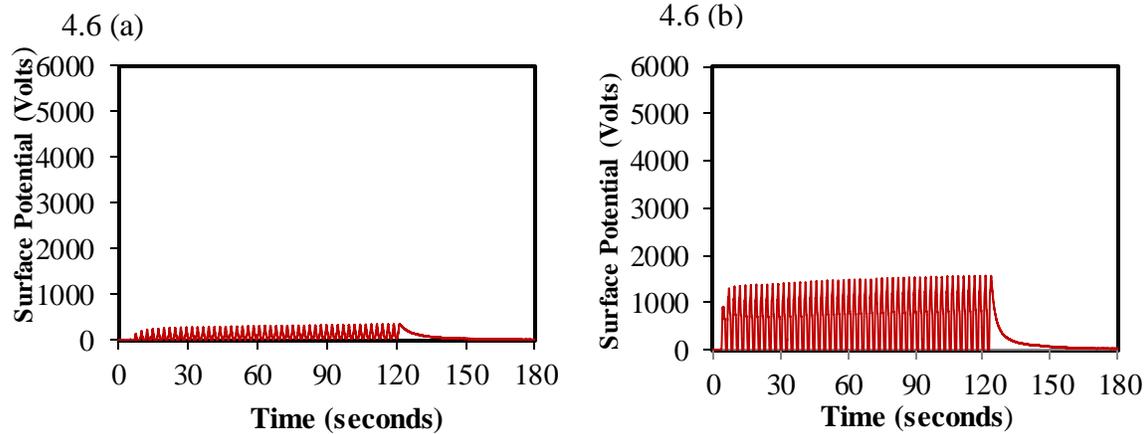


Figure 4. 6(a) Charge generation and accumulation on cotton-I rubbed with steel (b) Charge generation and accumulation on cotton-I rubbed with PTFE

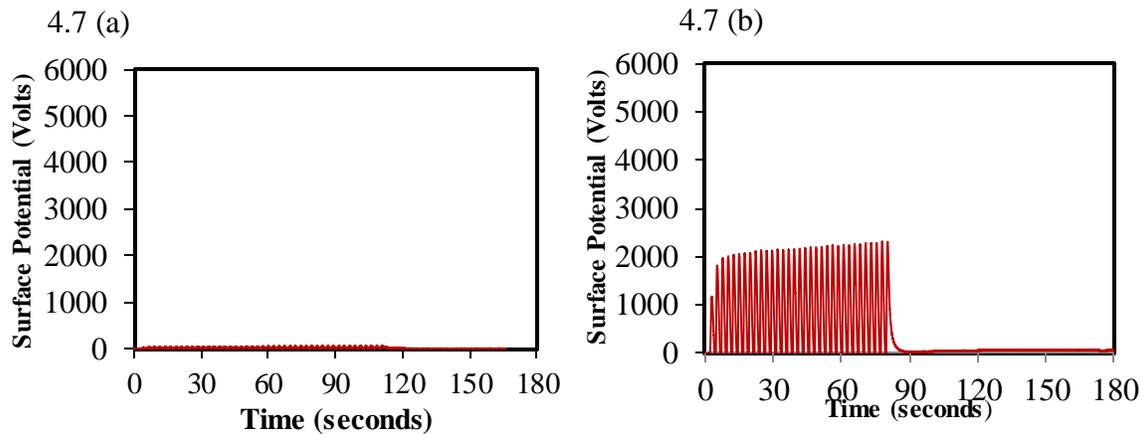


Figure 4.7(a) Charge generation and accumulation on cotton-II rubbed with steel (b) Charge generation and accumulation on cotton-II rubbed with PTFE

For all the cotton samples, the charge generated decays very quickly to zero, regardless of the amount of charge generated. On cotton-I, the charge decay times are same (reaches to zero

within 15-20 seconds), independent of the amount of charge generated during the rubbing cycles. Cotton II charged with higher surface potential (about 1500- 2300 Volts) the charge decays to zero more rapidly. The measured resistivity of these cotton fabrics is in the range of  $12 \times 10^{10}$  ohms/square (cotton I) and  $300 \times 10^{10}$  ohms/square (cotton II), and according to textile conductive standards (Schindler and Hauser, 2004) cotton is a highly conductive material. This is undoubtedly related to the rapid dissipation of the charge, but given that the fabrics are mounted on a PTFE sheet, and there is no direct contact with ground, it is still unclear as to where the charge dissipates to.

The surface potential accumulated on the filament and spun polyester is shown in Figure 4.8 and 4.9. Similar to the observations found on cotton, rubbing with PTFE generated more charge on both spun and filament polyester. For steel rubbed samples, for first few rubbings the charge increased rapidly and then charge increases very slowly when rubbed further (for remaining rubbing cycles). For PTFE rubbed samples, the charge increases as the number of rubbing cycles increased and even after 50 cycles of rubbing the surface potential measured is still increasing.

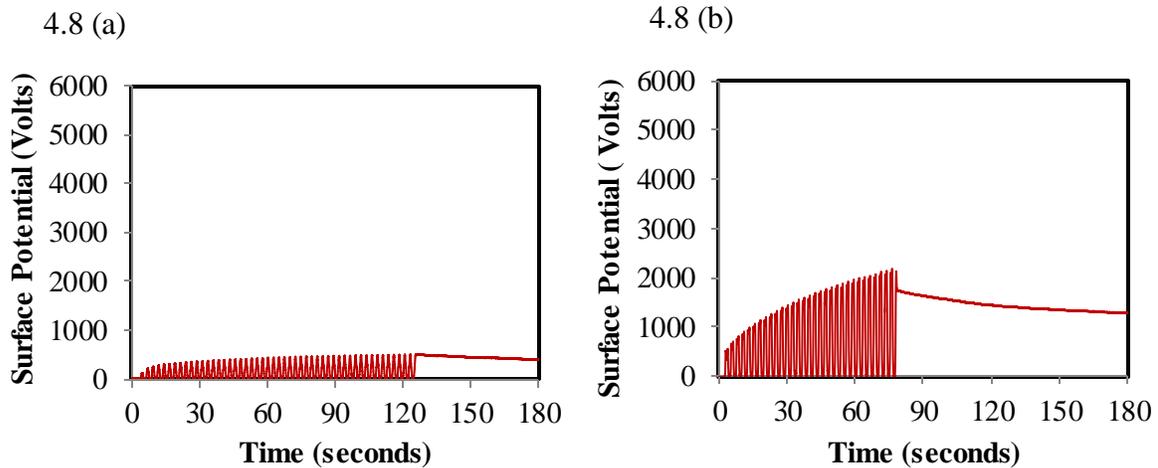


Figure 4.8(a) Charge generation and accumulation on filament polyester rubbed with steel (b) Charge generation and accumulation on filament polyester rubbed with PTFE

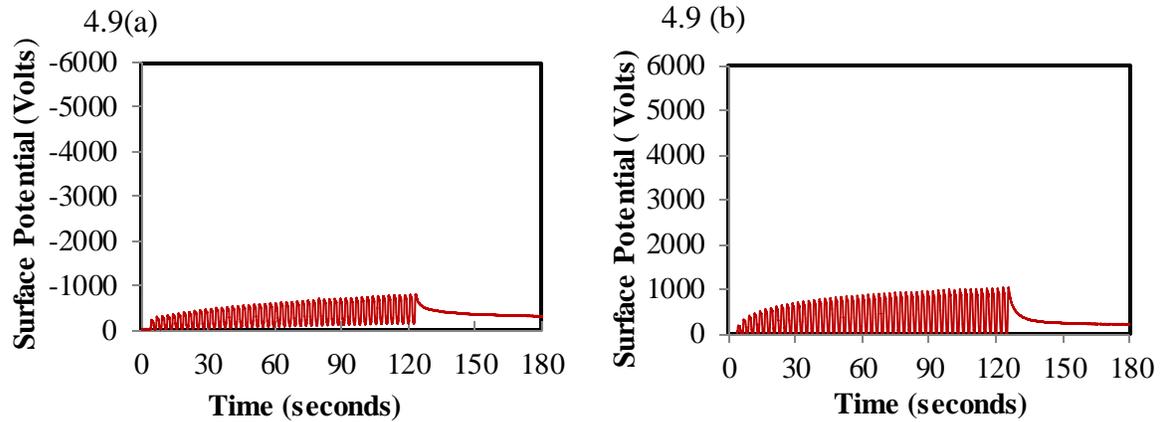


Figure 4.9(a) Charge generation and accumulation on spun polyester rubbed with steel (b) Charge generation and accumulation on spun polyester rubbed with PTFE

The charge decay on filament polyester is very slow, and even after 60 seconds the amount of charge loss is about 10% of its accumulated charge. For spun polyester samples the charge decays quickly for the first few seconds, followed by a slower decay. Charge decay behavior on spun polyester fabric is an intermediate form between those observed for cotton and filament polyester.

Charge accumulated on filament and spun nylon fabrics are shown in Figures 4.10 and 4.11. Compared to cotton and polyester the amount of charge generated on nylon fabrics is much higher (as high as 6000 Volts). Again, we see patterns of charge build that are hard to understand. After the first cycle of rubbing spun nylon with steel, charge reached the maximum value and further no increase in charge was observed as the number of rubbing cycles increased. For filament nylon fabrics when rubbed with steel, charge increased gradually with number of rubbing cycles. When rubbed with PTFE, for both nylons the charge increased gradually with number of rubbings and reached about 6000 Volts for spun nylon and 4500 Volts for filament nylon. We believe that the different levels of charge and the shapes of the charging curves is the result of differences in the fabric structure and trace materials remaining on the surface after spinning and weaving. For all the nylon fabrics charge dissipation is relatively slow, but there seems to be on regular patters associated with this phenomena either.

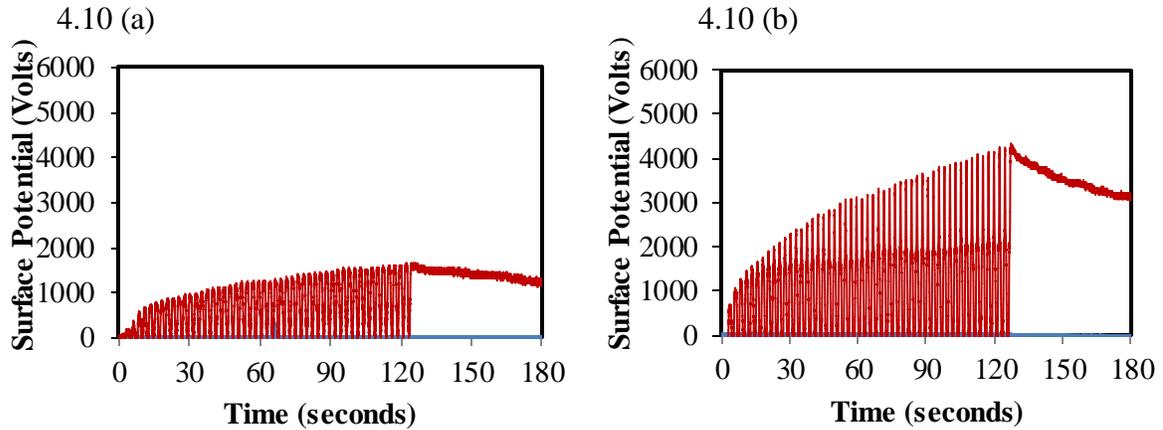


Figure 4.10(a) Charge generation and accumulation on filament nylon rubbed with steel (b) Charge generation and accumulation on filament nylon rubbed with PTFE

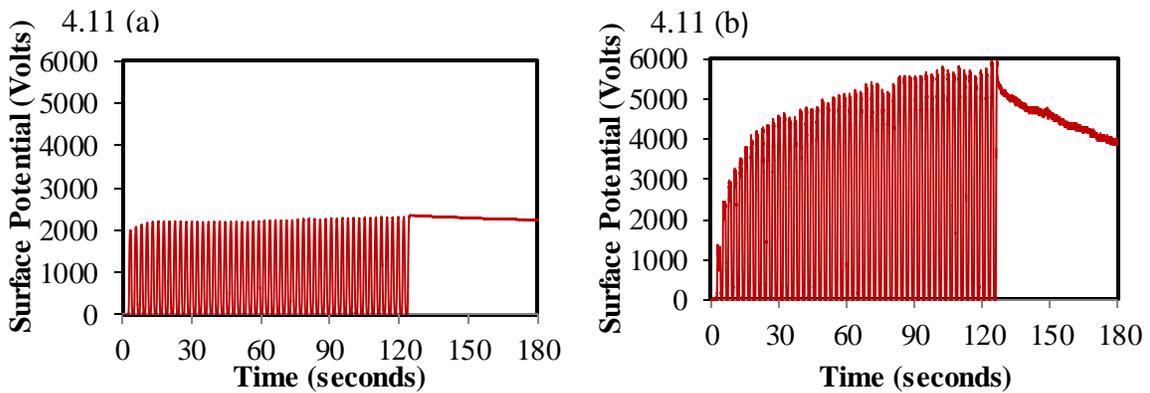


Figure 4.11(a) Charge generation and accumulation on spun nylon rubbed with steel (b) Charge generation and accumulation on spun nylon rubbed with PTFE

Charge accumulation on polypropylene fabrics is shown in the Figure 4.12. Similar to cotton, polyester and nylon, less charge is accumulated on samples rubbed with steel, when compared with PTFE. Charge accumulation reaches its maximum value within few cycles (about 5) of rubbing when rubbed with steel but rubbing with PTFE generates a slower, steady increase in the charge observed. Charge dissipation on polypropylene is very slow regardless of the amount of the charge on its surface.

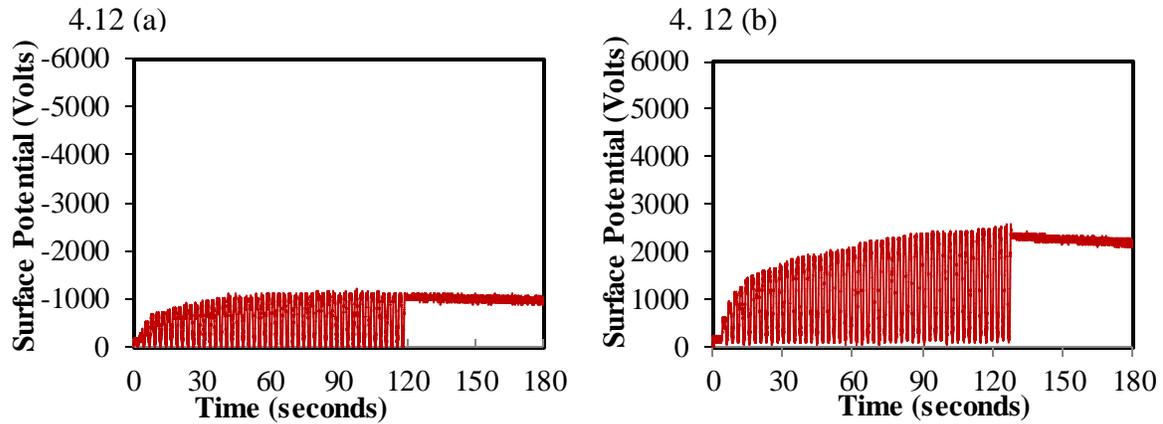


Figure 4.12(a) Charge generation and accumulation on spun polypropylene rubbed with steel  
 (b) Charge generation and accumulation on spun polypropylene rubbed with PTFE

The important observations found from the charge buildup measurements are

- Cotton is placed next to steel (Welker 2006, Adams 1987, Tsuji and Okada 1985) in the triboelectric series, suggesting that the charge generated on cotton is less when contacted/rubbed with steel when compared with other materials. Most of the triboelectric series that are published only based upon the sign of the charge developed on the rubbed surface; Welker et al. (Welker 2006) proposed that the magnitude of the charge depends on the distance between the materials in the triboelectric series.
- The charge generated after first rubbing and the charge accumulated after 50 rubbings are statistically different for all the samples ( $P$  value  $< 0.01$ ). Repeated rubbings increase the amount of charge generated on the fabric surface due to the increase in the real contact area during rubbing due to the reorientation of the fabric surface and destroying the asperities on the surface. This phenomenon is more evident for the PTFE rubbed samples. For steel rubbed samples, the saturation potential is reached quickly because steel is a conductive material, and there is a possibility that charge can back flow to steel.
- Duke and Fabish (Duke and Fabish 1977) proposed that in metal-insulator charge transfer, electrons tunnel between the metal and electron states in the insulator which are within a narrow range of energy near the metal Fermi level. The same mechanism applies to

insulator-insulator electrification; however, the range of energy is much wider, because for insulators, the strong energy dependence of the density of the states counter balances the strong energy dependence of the tunneling matrix element.

- The charge dissipates quickly on cotton, because cotton is a low resistant material (resistivity  $10^9$  ohms/ square) compared to other synthetic fibers (polyester, nylon and polypropylene) which are highly resistant (more than  $10^{14}$  ohms/ square).

### ***Rubbing Charge Accumulation***

Figure 4.13 shows the charge accumulated after 50 rubbings on the tested textile fabrics. Similar to the charge measured after the initial contact, the charge measured after 50 rubbings is very high for nylon compared with other samples. Also higher charge is generated on spun nylon fabric when compared with filament nylon. It appears that there is a common trend for fabrics based on spun fibers to accumulate higher surface potential when compared with filament fabrics. This may be related to the fact that these fabrics are made from smaller fibers with higher surface area. Filament nylon/ fabrics are made from longer continuous filament fibers which have less surface area than the fabrics which are made from smaller spun staple fibers. ANOVA results shows (in Table A3 in appendix) that the charge accumulated on the Steel and PTFE rubbed samples are statistically different (P value < 0.01). Also the charge accumulated depends on the polymer type because the charge accumulated on these samples is statistically different from each other (P value <0.01) and Tukey's test results shows that the charge accumulated on spun and filament nylon fabric are statistically different from the other fabric samples.

Rubbing with PTFE generated higher charge when compared to rubbing with steel, due to the general observation that insulator-insulator rubbing generates higher charge compared to insulator-conductor charging (Duke and Fabish, 1977). As expected from the triboelectric series, rubbing with PTFE generated positive charge on all the fabrics. Similarly, rubbing with steel should generate a positive charge on nylon and cotton and a negative charge on polyester and polypropylene. When compared with the triboelectric series, these trends were

true for all the fabrics, except in the case of filament polyester. The exact cause of this charge reversal observed on the filament polyester fabric is unclear, but may be related to trace materials left on the surface from the processing of the fiber to generate fabric. The triboelectric series of the materials from the literature and the observed triboelectric series when rubbed with steel and PTFE are showed in the Table 4.5. These materials arranged as triboelectric series, and compared based on the polarity and the magnitude of the charge that is generated when two materials are rubbed.

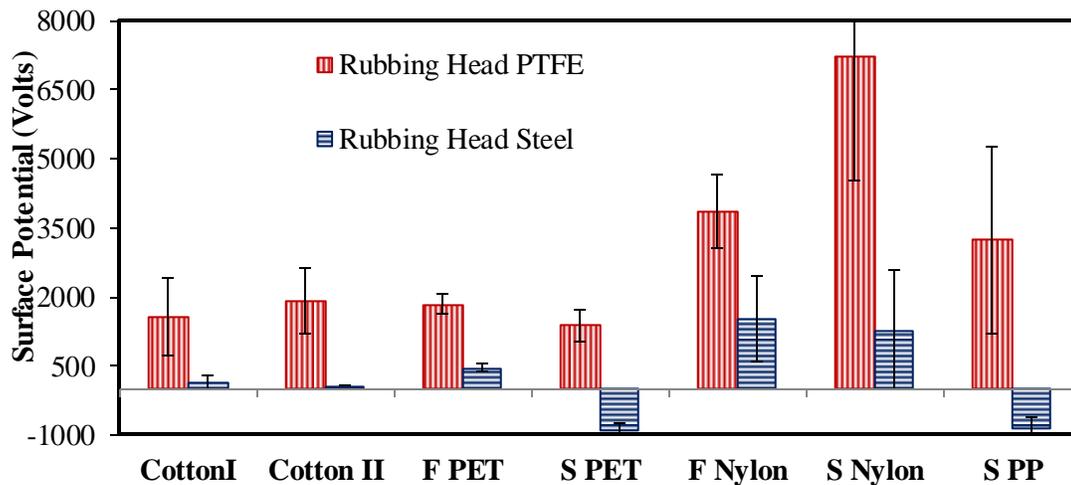


Figure 4.13 Surface potential accumulated after 50 rubbings on textile fabrics

For the steel rubbed samples the observed triboelectric series was perfectly matched with the triboelectric series published in the literature in terms of charge magnitude and charge polarity (except for filament polyester). For the samples which are rubbed with PTFE, the observed series matches the triboelectric series found in the literature in terms of polarity; however there is slight mismatch in terms of magnitude. In this work, polypropylene fabric charged with a higher charge than the cotton and the polyester fabrics. The observed charge on cotton could be less than the generated charge because some of the charge generated already might have dissipated because of the higher conductivity of the cotton fabrics.

Table 4.5 Comparing the Triboelectric series found in the literature and in this research when rubbed with steel and PTFE

From literature (Adams,1987)	Observed series Steel	From literature- (Adams,1987)	Observed series
<b>Rubbing head: Steel</b>		<b>Rubbing head: PTFE</b>	
Nylon +	Nylon +	Nylon +	Nylon +
PP -	Polypropylene -	Cotton +	Polypropylene +
PET -	Filament PET + Spun PET -	PET +	Cotton +
Cotton +	Cotton +	Polypropylene +	Filament PET + Spun PET +

#### 4.3.2 Experimental Design - II

##### Contact Charge Generation

Charge measured on the surface of the fabric after first contact with steel and PTFE are shown in Figure 4.14. The charge is measured inside a faraday cage and is shown in micro Coulombs/square meters. All the samples when contacted with PTFE charged positively and the fabrics which are contacted with steel are charged negatively. Contacting with PTFE generated a higher positive charge on these fabrics, in the range of 1.2 to 2.9  $\mu\text{C}/\text{m}^2$ , contacting with steel generated a lower negative charge in the range of - 0.07 to -1.2  $\mu\text{C}/\text{m}^2$ . According to published triboelectric series, when contacted with steel, nylon should be charged positively, polypropylene, polyester should be charged negatively and cotton's charge will be dependent on where it is placed in the series. The contact charge generation results showed that there is statistically significant influence of the contacting material during testing. The charge generated on materials that are contacted with steel are statistically different ( $P$  value  $< 0.01$ ) from the samples contacted with PTFE as shown in the Table B3 in appendix. Rubbing with steel generated positive charge on nylon, whereas contacting with steel on nylon generated negative charge.

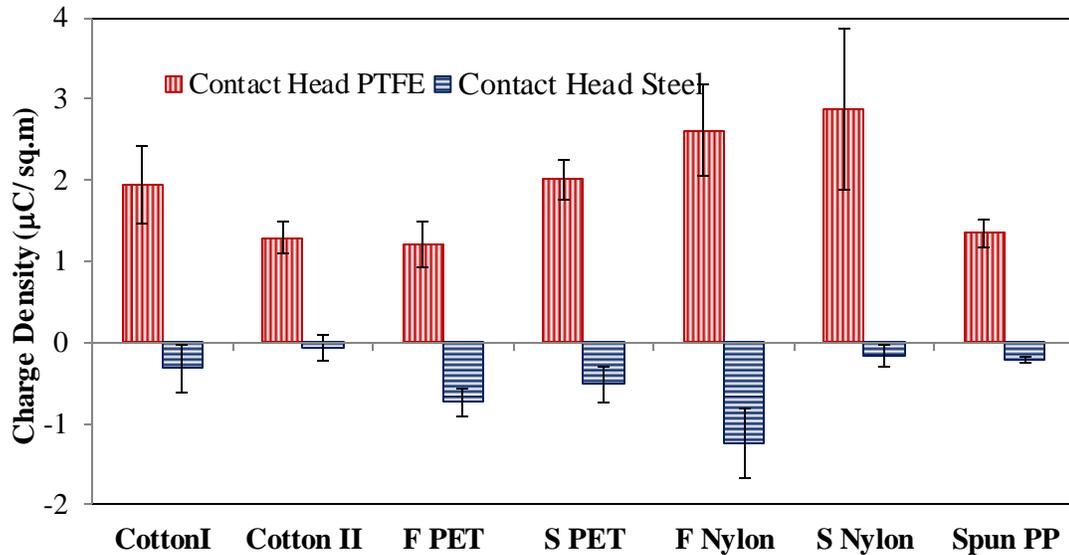


Figure 4.14 Charge measured after first cycle of contact on textile fabrics

### ***Contact Charge Buildup***

The surface charge buildup on textile fabrics cotton, polyester, nylon and polypropylene, when contacted with steel and PTFE (50 contacts) is shown in Figures 4.15-4.21 respectively. With all samples, we again see several general patterns:

- The level of charge buildup with PTFE is always much greater than that generated from steel (at least 5 times as much charge).
- The charge accumulated on the fabrics contacting with steel builds quickly (first 5 cycles or less) and then levels off.
- The charge accumulated on fabrics contacting with PTFE keeps building through the 50 contact cycles
- The charge once generated dissipates very slowly, even on cotton.

This last observation, that even on cotton, the charge is stable has a substantial impact for our understanding of how charge dissipates from contact charged samples.

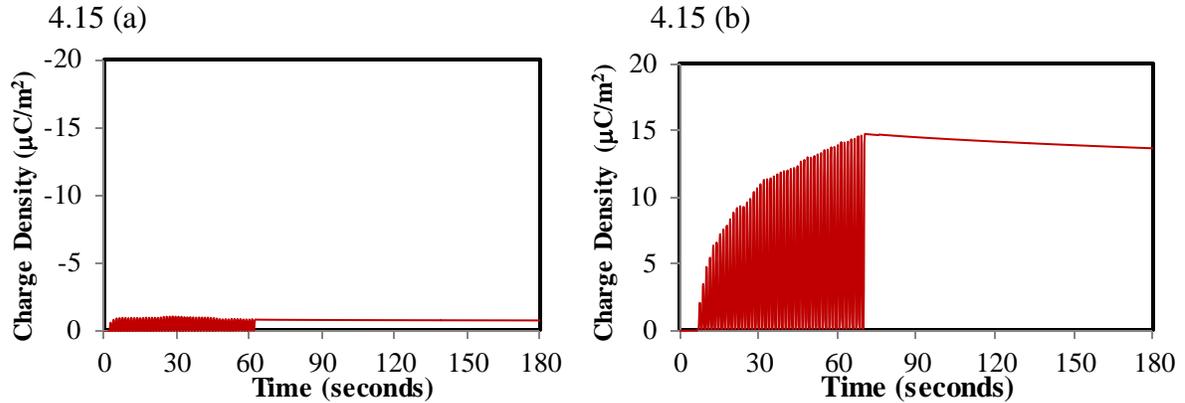


Figure 4.15(a) Charge generation and accumulation on cotton I contacted with steel (b) Charge generation and accumulation cotton I contacted with PTFE

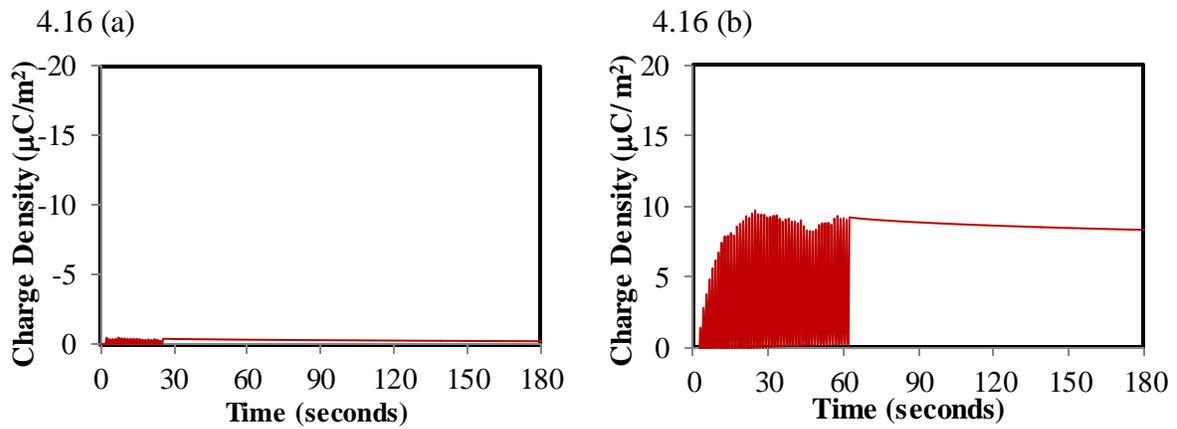


Figure 4.16(a) Charge generation and accumulation on cotton II contacted with steel (b) Charge generation and accumulation cotton II contacted with PTFE

The charge buildup observed on nylon samples is observed on Figure 4.17 and 4.18. For steel contacted samples, the charge accumulated is very slow and limited to  $-3.0 \mu\text{C}/\text{sq.m}$  for filament nylon and  $0.1 \mu\text{C}/\text{sq.m}$  for spun nylon. Charge generated and increased gradually after every contact and reached about  $14 \mu\text{C}/\text{sq.m}$  for PTFE contacted samples, for filament nylon the buildup was gradually increased and for spun nylon it has been increased to about  $15 \mu\text{C}/\text{sq.m}$  and then a slow increase was observed. Slower charge decay was observed for the contact charge nylon samples when compared with rubbed samples.

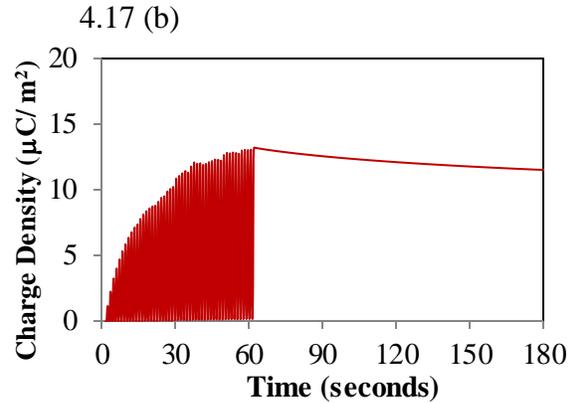
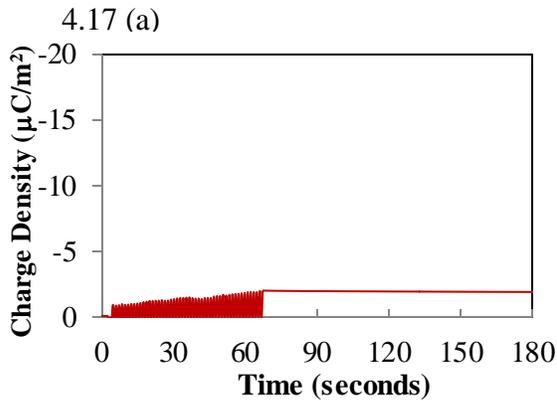


Figure 4.17(a) Charge generation and accumulation on filament nylon contacted with steel  
 (b) Charge generation and accumulation filament nylon contacted with PTFE

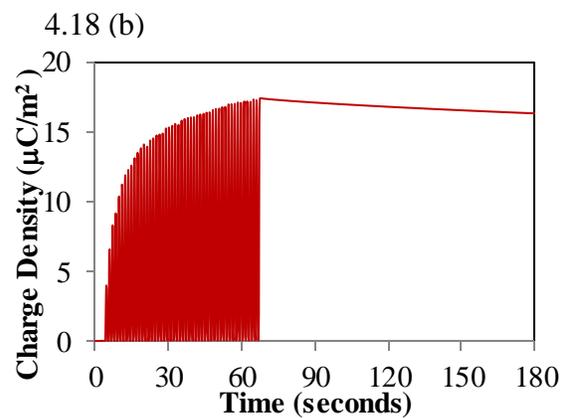
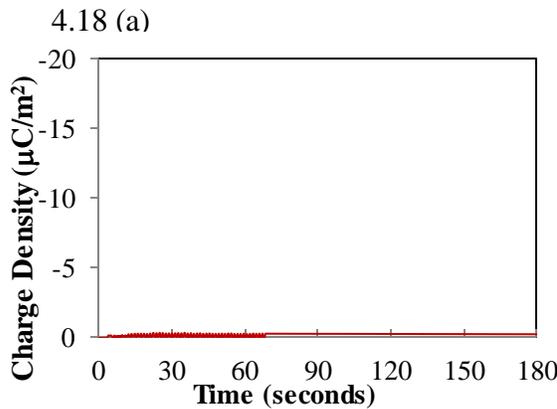


Figure 4.18(a) Charge generation and accumulation on spun nylon contacted with steel (b)  
 Charge generation and accumulation spun nylon contacted with PTFE

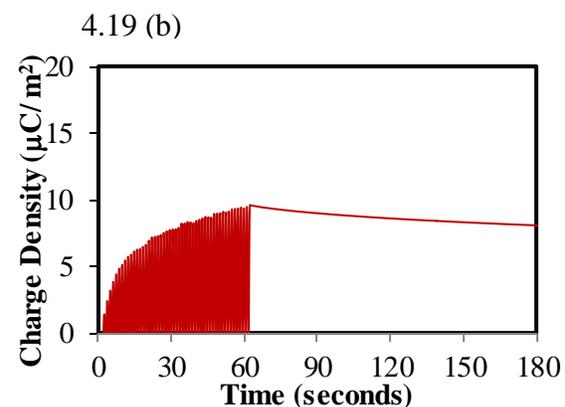
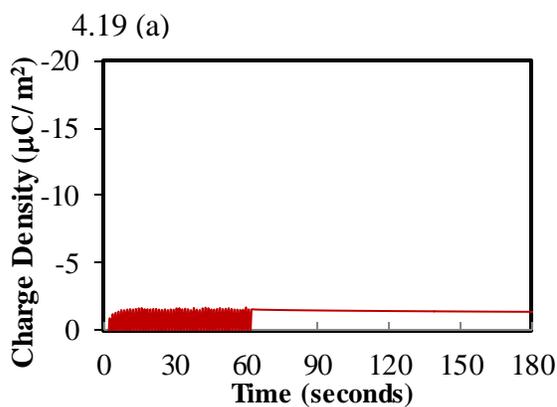


Figure 4.19(a) Charge generation and accumulation on filament polyester contacted with steel (b) Charge generation and accumulation filament polyester contacted with PTFE

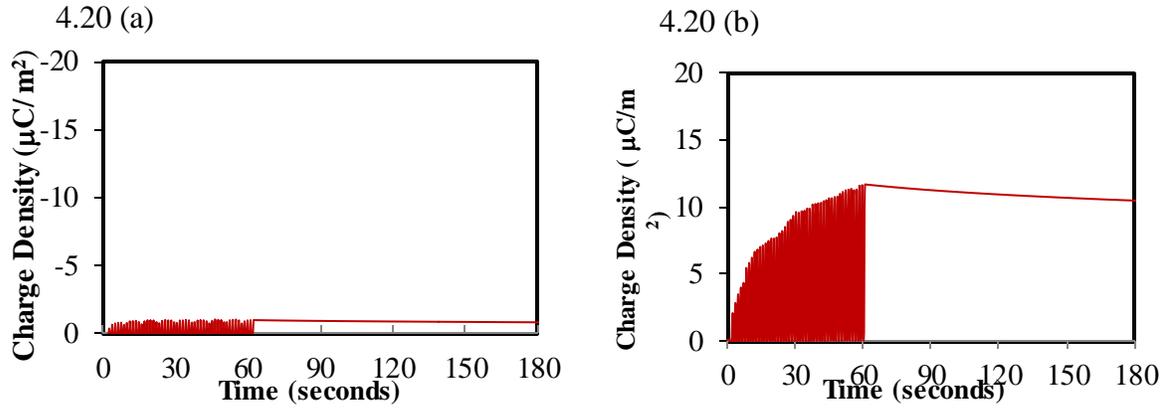


Figure 4.20(a) Charge generation and accumulation on spun polyester contacted with steel b) Charge generation and accumulation spun polyester contacted with PTFE

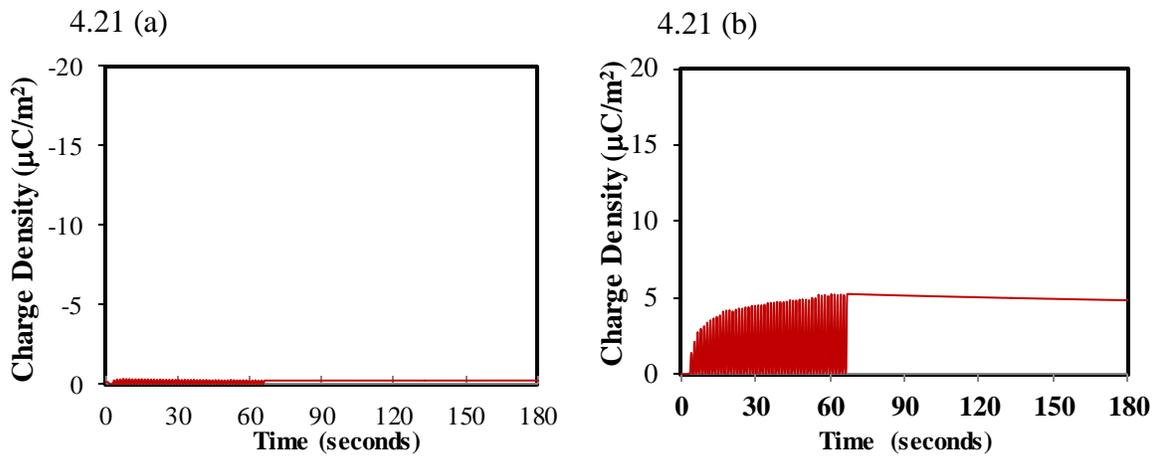


Figure 4.21(a) Charge generation and accumulation on spun polypropylene contacted with steel (b) Charge generation and accumulation spun polyester contacted with PTFE

**Contact Charge Accumulation**

Charge accumulated on various textile fabrics after 50 contact cycles with PTFE and steel are shown in Figure 4.22. Similar to the previous rubbing charge results, contact with PTFE generated more charge than contact with steel. After 50 contacts samples contacted with steel are charged with a negative charge, and samples contacted with PTFE are charged with positive charge.

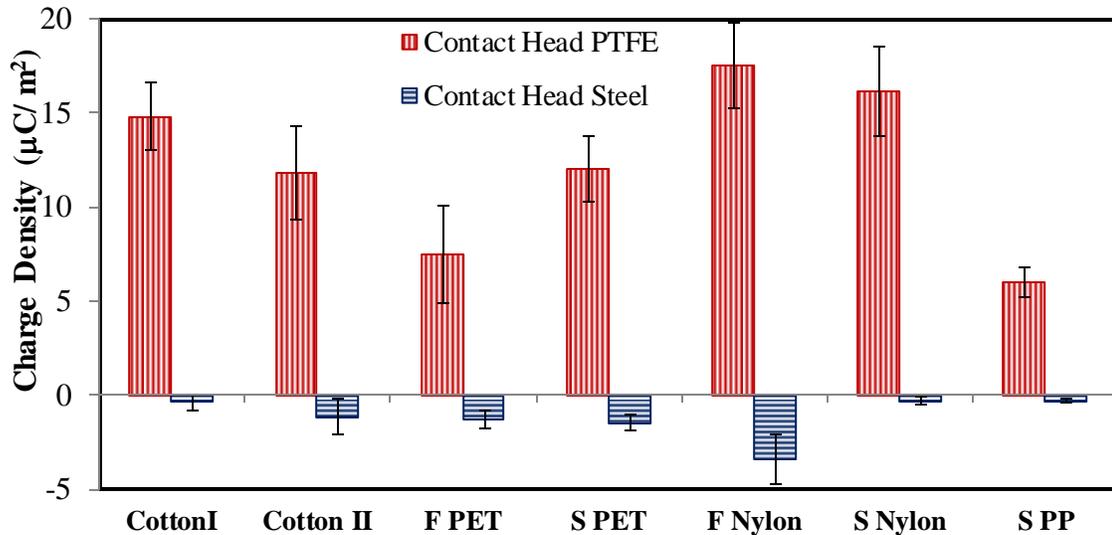


Figure 4.22 Charge accumulated after 50 contacts on textile fabrics

Samples which are contacted with PTFE follow the triboelectric series found in the literature with respect to both magnitude and polarity of the charge measured. Measured triboelectric series in this research is compared with the published triboelectric series is shown in Table 4.6. For PTFE contacted samples, the observed and published series are in a perfect match in terms of magnitude and the polarity of the charge accumulated. Nylon is placed on the top with a very higher generated charge (spun nylon 16.13 and filament nylon 17.54  $\mu\text{C}/\text{m}^2$ ) and polypropylene is on the bottom with a very lower charge (6.01  $\mu\text{C}/\text{m}^2$ ). Nylon fabric is able to charge with a very higher charge close to the maximum saturated charge which is 26.4  $\mu\text{C}/\text{m}^2$ . Interestingly, some discrepancies are found even in this research when compared with the triboelectric series. Nylon and cotton which are placed above steel in the published triboelectric series were charged with negative charge when they contacted with steel. However for both cotton samples and spun nylon samples when contacted with steel even after 50 contacts the generated charge is very low ( -1.46  $\mu\text{C}/\text{m}^2$ ), but for filament nylon higher charge (-3.42  $\mu\text{C}/\text{m}^2$ ) is generated. However, these samples are charged with positive when rubbed with steel. Contact material has statistically significant influence on the charge accumulated on the fabric (P value <0.01 as shown in Table B3 in appendix). Also number of contacts has statistically greater influence on PTFE charged samples (P value <0.01 as shown

in Table B3 in appendix). The different observations on the nylon and polyester contact charging from rubbing shows that the contact and rubbing charging mechanism are very different from each other.

Table 4.6 Comparing the Triboelectric series found in the literature and in this research when contacted with steel and PTFE

From literature (Adams,1987)	Observed series Steel	From literature- (Adams,1987)	Observed series
Contact head: Steel		Contact head: PTFE	
Nylon +	Nylon -	Nylon +	Nylon +
Polypropylene -	Polypropylene -	Cotton +	Cotton +
Polyester -	Filament PET - Spun PET -	Polyester +	Polyester +
Cotton +	Cotton -	Polypropylene +	Polypropylene +

### ***Contact Charge Break Down***

Charge break down occurs when materials that are charged with substantial static electric charge, according to Gauss's law, creates an electric field. If the electric field created is huge in a smaller area, then the charge will be discharged due to the dielectric breakdown of the air molecules. Theoretically the maximum charge that can be generated on any solid surface at normal atmospheric conditions is  $26.4 \mu\text{C}/\text{m}^2$  (Cross J.A, 1987). The charge buildup measured on the nylon fabric is shown in the Figure 4.23. As the number of contacts increases, the charge accumulated on the sample increased and reached the saturation level. Once the charge has been reached the maximum value or saturation it breaks down and sparks will be produced. As seen in the Figure 4.23, after 20 contacts charge has been increased to  $18.14 \mu\text{C}/\text{m}^2$  and some charge has been decayed due to air break down. The air breaks down the charge on nylon at a smaller charge than the theoretical breakdown limits. From these measurements it can be found that breakdown charge of the insulating surfaces can be vary. This could be attributed to surface anomalies of these structures such as non-uniform surface, impurities on the surface etc.

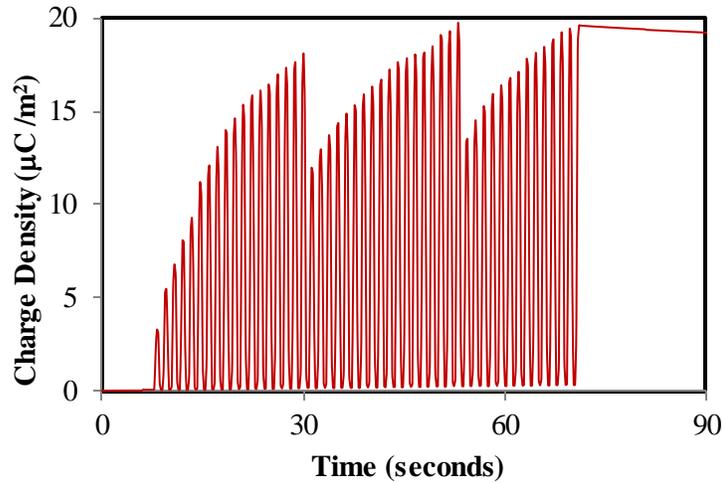


Figure 4.23 Charge build up on PTFE contacted spun nylon fabric

### 4.3.3 Charge Decay Measurements

Charge decay measurements done on various textile fabrics are shown in Figure 4.24 and 4.25. In Figure 4.25 the half life time decay is measured after these fabrics are rubbed with PTFE and Steel for 50 cycles. The charge decay is independent of rubbing material and for both steel and PTFE the rubbed material's half life time appears to be similar. Samples which are rubbed with PTFE were charged for higher charges compared with steel rubbed samples, but their charge decay times are same. This means that the charge decay is independent of the magnitude of the charge measured on the samples. The cross over mechanism as observed by Ieda et al. (Ieda et al. 1972) explains that materials which are charged with a higher charge decays quicker when compared with fabrics charged with a lower charge.

Spun fabrics appear to decay slightly quicker when compared with filament samples. This could be because the shorter fibers on the spun fabrics have a higher surface area that has a greater potential to interact with air, which helps the charge to decay quickly.

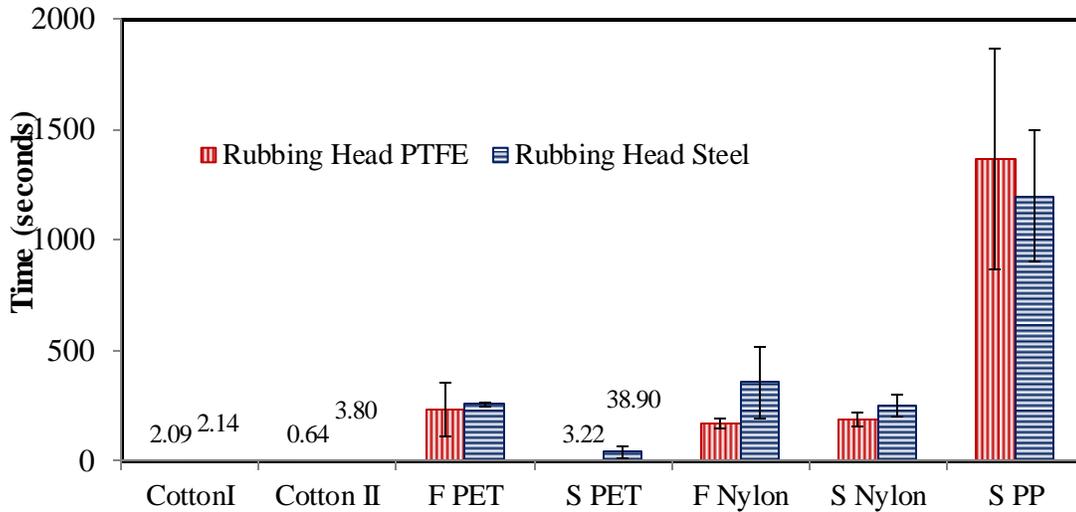


Figure 4.24 Half-life time measured on textile fabrics after rubbing with steel and PTFE

Charge decay measurements on the rubbing charged samples, indicate that the charge decay is independent of the rubbing material and also the amount of charge generated on their surface. It appears to be completely a surface characteristic of the materials. In the Table 4.7, the volume resistivity measured on the textile fabrics (Blythe, A.R. 1979) and the half-life time measured on these textile fabrics were compared. From the table it can be understood that on cotton which has a much lower resistivity, the charge decayed very quickly (0.6-3.8 seconds) irrespective of the charge generated on its surface. In the case of polyester, for which the resistivity is more than cotton, the half-life time is more. Similarly for nylon and polypropylene which are highly resistive materials, the charge decayed slowly. Half-life decay time is similar to their resistivity measured. The charge decay on the rubbed samples is mainly attributed to emission into the atmosphere, breakdown of the voltage (charge), surface and volume conductivity of the material and ion desorption. Using the Tukey's test results, it is shown that the polypropylene rubbed samples are statistically different from the other samples (see Appendix Table C2).

Table 4.7 Comparing resistivity and half life time

Fiber	Resistivity ohm m (Blythe, A.R. 1979)	Half-life time (seconds)	
		Rubbing Head:Steel	Rubbing Head:PTFE
Cotton	$10^9$	$2.09 \pm 0.61$	$2.14 \pm 2.09$
		$0.64 \pm 0.24$	$3.8 \pm 2.09$
Filament polyester	$10^{14}$	$230 \pm 120$	$258 \pm 8$
Spun polyester		$3.2 \pm 0.1$	$39 \pm 30$
Filament nylon	$10^{15}$	$169 \pm 23$	$356 \pm 162$
Spun nylon		$187 \pm 30$	$250 \pm 46$
Polypropylene	$10^{16}$	$1366 \pm 503$	$1200 \pm 300$

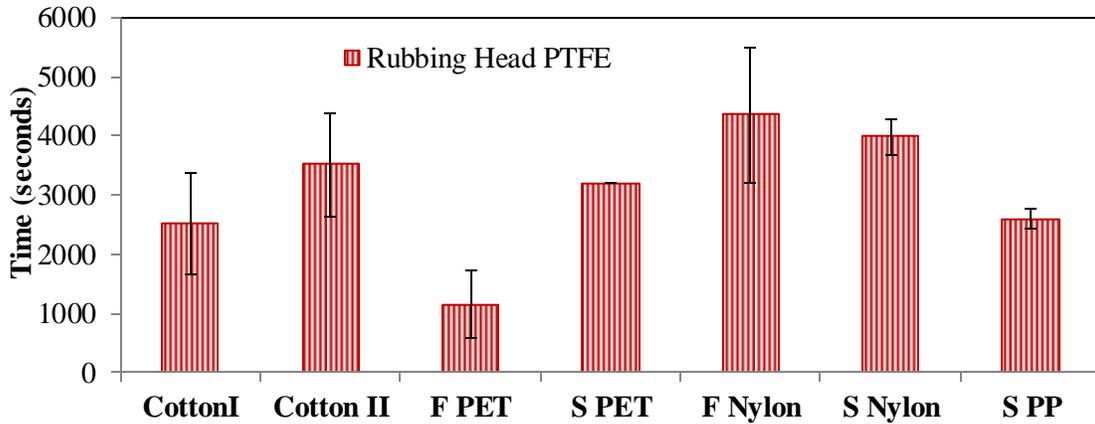


Figure 4.25 Half-life time decay measured on textile fabrics after contacted with PTFE

Charge decay measured on the contact charged samples with PTFE is shown in Figure 4.25. Since charge measured when contacted with steel is low, and all these measurements were done inside the faraday cage, the charge decay measurements on steel are not discussed here. Significant difference between the half-life decay times on the contact charged samples is observed (P value 0.002) as shown in the Table C5 in Appendix. Charge decays on filament polyester Quicker compared to other materials and categorized differently in tukey's grouping (See Appendix Table C6). The charge decay times of cotton (which have higher

conductivity) and polypropylene (which has lower conductivity) are not statistically different. Also the charge decay times of the rubbed samples are different from the contact charged samples. The differences observed on the charge decay times of contact and rubbed samples is probably due to the reason the contact charge material is placed inside the faraday cage which shields the charges on the sample from the external effects such as ions etc.

#### **4.4 CONCLUSION**

Woven textile fabrics are charged with steel and PTFE for contact and frictional electrification to study the static electric properties of cotton, polyester, nylon and polypropylene fabrics. Compared with the other insulator and solid materials, the surface of the textile and polymer materials is more sensitive, because of their semi-crystalline structure. Rubbing and contact charging cotton with steel generated very less charge on cotton and similarly testing with PTFE generated much higher charge on cotton. The mechanism of metal-polymer charge is different from polymer - polymer charging. Also the charge generation mechanism involved in contact and frictional electrification is different. Since cotton is placed next to steel in the triboelectric series, this implicates that charge transfer between cotton and steel will be less.

After every cycle of rubbing/contact charging the charge builds gradually and the charge measured after 50 cycles is higher. Repeated rubbings/ contacts increase the charge on the fabric surface because increase in contact area due to deformation of the surface and destroying the asperities on the surface after every cycle of rubbing/contact. When compared, the polarity and amount of charge generated on the samples followed the triboelectric series except

- Filament polyester charged positive when rubbed with steel as it was supposed to charge negative. However, filament polyester has been charged negative when contacted with steel. Spun polyester charged negative when rubbed /contacted with steel.
- Nylon and cotton are supposed to charge positive when contacted with steel however they charged negative.

- From these observations it can be found that there is a difference between contact and frictional charging mechanisms. Contact charging mechanisms are very simple when compared with frictional charging mechanisms. The contact charge series we observed is different from the triboelectric series we found in the literature.

During contact charging, higher charge is accumulated on nylon at a much higher charge density in the range  $20 \mu\text{C}/\text{sq.m}$ . Theoretically, charge breakdown occurs at a charge density of  $26 \mu\text{C}/\text{sq.m}$ . In the case of nylon, the breakdown occurs even at  $18.1 \mu\text{C}/\text{sq.m}$ .

The charge decay measurements during contact and rubbing charging show completely different observations. Rubbing charged samples decayed quickly compared with contact charged samples. This could be due to the fact that during rubbing charging these samples were exposed to air, whereas during contact charging the samples were placed in a shielded faraday cage. These observations indicate that the air in the atmosphere and the ions in the air play a major role in charge decay properties. Also the charge decay properties of the rubbed samples are related to the conductivity of the fabrics. For cotton a conductive material, compared to other fabrics, the charge disappears very quickly; in contrast polypropylene a more insulating material, the charge stays on its surface for a longer time.

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**CHAPTER 5**  
**FRictional ELECTRIFICATION AND CHARGE DECAY ON**  
**WOVEN TEXTILE FABRICS TREATED WITH IONIC ANTI-STATIC**  
**AND HYDROPHILIC FINISHES**

# **FRictionAL ELECTrIFICATION AND CHARGE DECAY ON WOVEN TEXTILE FABRICS TREATED WITH IONIC ANTI-STATIC AND HYDROPHILIC FINISHES**

## **5.1 INTRODUCTION**

When two materials are separated after contacting and/or rubbing, static charges are readily produced on their surface. If both of these materials are conductors such as metals, these charges dissipate quickly. The electrostatic charging mechanism on metals is well explained in the literature (Cross J.A, 1987). Despite a large number of both theoretical and experimental studies (Harper, 1960), the static electrification of insulating materials, such as polymeric and textile materials, is still not clearly understood. The study of static charging remains important, because of the detrimental effects it creates such as fabric cling, dry soiling, and spark discharges to human body or other grounded surfaces and difficulty in processing various materials. It is also studied because of its wide range of beneficial applications such as electrostatic spraying, copying and various forms of printing, flocking and in the manufacturing of air filters (Hearle 2008). High efficient air filters are made from fine textile fibers, produced as a melt blown nonwoven, and charged corona (static electricity) or other mechanism. The charge created on these materials is stable for long periods of time, even for several years, and seems to improve the products filtration (Sessler 1987, Cross 1987).

Static electrification can be divided into two different aspects: charge generation and charge dissipation. Much research has been done on polymeric materials to understand mechanism of static charging. Various theories, such as ion transfer mechanism (Harper 1960, Whitesides et al., 2007) and electron charge transfer mechanism (Lowell et al., 1980), have been proposed to explain the charge generation process on textiles and other non-conducting materials. Polarity and magnitude of the charges generated during the frictional electrification appear to be influenced by surface property of the polymer material, atomic groups within the polymeric material and the conditions of rubbing etc. (Ohara et al., 2001).

Understanding, the charge dissipation mechanism is also difficult and research has not been able to identify a single mechanism that can directly explain the charge decay properties of these materials. Several experimental studies have been made on the charge dissipation of these polymeric materials, and results obtained have been variable. This, in turn, led to different explanations for charge dissipation, but these could be influenced by the data, which was obtained under various experimental conditions for significantly different samples. A significant body of research has been dedicated to studying polymer films that are charged using corona and their subsequent charge decay (Ieda 1967, Chen G 2010, Tsai et al., 1998). These polymer films are homogeneous and the corona charging mechanism is uniform. Triboelectric charge decay on textile materials, such as fibers, yarns woven fabrics and nonwovens, involve much more complex surfaces with higher level irregularities and directional characteristics. Additionally all these polymer systems, have much high surface area than films and it has long been recognized that the surface properties play an important part in the tribo charging process (Das-Gupta, 1990).

Charge decay on textile materials could be significantly impacted by a range of material factors. These could include a number of fiber structural parameters and surface characteristics, geometrical features of yarns and fabrics and orientation of fiber surfaces within the structure and along with typical external factors such as the temperature, humidity, charged ions present in the air (Onogi et al., 1997, Ramer 1967). While the decay properties can be attributed to any one of the above mentioned factors or combination of several factors, the electro static decay properties of textile and polymer materials vary greatly across the range of structures materials that are available. Natural materials such as cotton and wool are considered to be practically static free materials because of their higher conductivity and higher moisture regain. Synthetic materials, such as polyester, nylon and polypropylene, with their much lower conductivity and lower moisture regain, are considered candidates for special treatment to control static generation and improved dissipation during both their manufacture and use.

The principle charge decay mechanism for grounded samples is considered to be free diffusion of the charges to the ground. However, when the samples are not grounded, the charges on the fabric surface can be neutralized by the absorption of the air born counter ions or charge can dissipate into the air (Onogi et. al, 1995, Onogi et. al, 1996). In this case, the charge decay function is reported to be exponential with time and mathematically expressed as

$$Q_t = Q_o * \exp(-t/\tau)$$

$Q_t$  = Charge at time  $t$

$Q_o$  = initial charge

$\tau$  = time constant (the time to decay to 1/e of the initial charge) (Cross J.A, 1987)

However, Ramer et al. investigated the charge decay mechanism on triboelectrically charged surfaces and suggested that the charge decay mechanism is made up of two exponential components (Ramer. 1967). In the textile industry people often consider the half-life (the time required for the charge to fall half of its initial value) as a basis to compare the static decay properties of various textile materials and surface treatments.

The present research was aimed at explaining the charge decay mechanism on textile fabrics. A significant body of research has been carried out on static phenomenon of textile yarns, polymer films and nonwoven fabrics (Lu, 2010); however, limited work has been done on woven fabrics. Since, many inconsistencies are evident in the literature in this area, it was very important to design a system to yield consistent results. This research is continuation of the research conducted by previous workers (Seyam et al. 2009, Lu 2010) to explain the charge decay mechanism on textile materials.

## **5.2 EXPERIMENTAL**

### ***5.2.1 Sample Preparation***

Woven fabrics of polyester and cotton were purchased from Test Fabrics Inc. and cut into the required size (typically 11 X 8 cm) for rubbing electrification tests. Rubbing heads of steel and Polytetrafluoroethylene (PTFE) of 10 mm X 20 mm X 3 mm size were used to study the

polymer- metal and polymer – polymer rubbing effects. The edges of the rubbing heads were polished in order to avoid any scratching damage to the fabric specimens during the rubbing process. Prior to the evaluation the fabrics were cleaned through a deionized water bath at 60° C for 20 minutes. Then the samples were cleaned with Isopropyl Alcohol ((CH<sub>3</sub>)<sub>2</sub>CHOH, FW = 60, Sigma-Aldrich) at room temperature for 20 minutes (Seyam et al. 2009, Lu, 2010). The samples were then dried in the oven for 20 minutes at 120°C (or until the fabric dried completely). The fabrics were then conditioned in the environmental room at 21 ° C and 43% RH for 24 hours before testing. All of these experiments were conducted at a temperature of 21 °C and 43% RH. The RH level is lower than the usual standard atmosphere 65%, but 43% is the suggested value to use (AATCC standard method) when assessing static phenomenon in textile materials. Before each test the initial surface potential on the fabric was measured and residual charges were removed by using ionized air gun. Anti-static finish has been applied to treat the surface of the polyester fabric. Complete explanation can be found elsewhere (Lu, 2010).

### 5.2.2 Materials and Experimental Design

Finish free filament polyester fabric (style no 700-3), spun polyester fabric (777), and two different cotton fabrics (style 418 and 441) are purchased from Test fabrics Inc. Also two different anti-static finishes and two different hydrophilic finishes were used to study the impact of finish materials on the static generation and dissipation properties of the polyester fabrics. Details about the fabrics and the static control finishes are given here in the Table 5.1

Table 5.1 Fabrics and surface finishes used in this research work

Parameters	Levels
Fabrics	Cotton-1, Cotton-II , Filament polyester, Spun polyester
Ionic antistatic agents	0.1% C12Phosphate, K+Neutralized (Leomin <sup>®</sup> PN) 0.1% Dimethyl Oleyl Amine Diethyl Sulfate Quaternary Finishes (Larostat <sup>®</sup> 264A)
Hydrophilic finishes	0.5% Hydroperm <sup>®</sup> T 0.5% Hydrophillic Finish (Experimental Moisture Management)

Table 5.2 Fabric details used in this work

S.no	Style no	Fiber blend	yarn count		yarn type		Fabric thickness (cms)	Cover factor
			warp (tex)	weft (tex)	warp	weft		
1	418	cotton	14.4	13.6	ringspun	ringspun	0.0174	22.92
2	441	cotton	14.0	15.8	ringspun	ringspun	0.0180	15.80
3	700-3	polyester	9.5	9.6	filament	filament	0.0120	20.19
4	777	polyester	39.5	21.1	ringspun	ringspun /double	0.0231	20.62

The specifications used in this research are given in Table 5.2. Three sets of experiments were conducted to evaluate the charge decay behavior of the textile fabrics, and Tables 5.3, 5.4 and 5.5 depict the parameters and their levels. The first set of experiments were conducted to study the effect of rubbing between fabric and steel (polymer- metal) and fabric and PTFE (polymer - insulator), charge buildup and the charge decay properties has been measured. The fixed parameters maintained in this research were including the rubbing speed of 47mm/second, rubbing stroke length of 52 mm, number of rubbing cycles was 50 and the rubbing force was 1N. After 50 th cycle, the rubbing head has been stopped after the forward moment. At this point, the charge measured was the charge buildup is at its maximum and the charge decay has been observed for a period of 60 seconds.

In the second set of experiments, both spun and filament polyester fabrics were treated with two “ionic anti-static agents” and two “hydrophilic surface treatments” and rubbed with steel (polymer-metal) and PTFE (polymer-polymer) rubbing charge measurements. Ionic anti-static agents are ammonium quaternary salt Larostat<sup>®</sup> 264A (produced by BASF) and a C12 alkylalcohol phosphate ester, potassium salt, Leomin<sup>®</sup> PN (produced by Clariant). Two hydrophilic finishes used are composed of PET-polyoxyethylene glycol block copolymers, Hydroperm<sup>®</sup> T (from Clariant) and an experimental moisture management polymer. The

experimental moisture management finish is a higher molecular weight polymer consists of higher polyoxyethylene glycol content. As explained above, the rubbing charge buildup was been observed followed assessment of the decay properties.

Third set of experiments were designed to study the charge decay properties of the fabric at two different places. One probe (probe I) is fixed as in the previous experimental designs on the rubbing area of the fabric and the new probe (probe II) is placed parallel to the probe I at a distance of 36 mm from probe-I in the unrubbed area. Surface potential is measured in both the rubbed and unrubbed areas at the same time. Both the probes are attached to a metal plate which is connected to the motion controller, so, that both the probes will have same lateral moment during rubbing.

Table 5.3 Experimental design - I used to study the charge decay mechanism on finish free cotton and polyester fabrics

<b>Parameters</b>	<b>Levels</b>
Fabrics	Cotton-I, Cotton-II, Filament polyester, Spun polyester
Rubbing Material	PTFE (Teflon <sup>®</sup> ), Polytetrafluoroethylene), Steel

Table 5.4 Experimental design - II to study the effect of static control finishes on the electrostatic decay properties of cotton and polyester fabrics

<b>Parameters</b>	<b>Levels</b>
Fabrics	Filament polyester, Spun polyester
Rubbing Material	PTFE, Steel
Ionic antistatic finishes	0.1% C12 Phosphate, K+ Neutralized (Leomin <sup>®</sup> PN) 0.1% Dimethyl Oleyl Amine Diethyl Sulfate Quaternary Finishes (Larostat <sup>®</sup> 264 A)
Hydrophilic finishes	0.5% Hydroperm <sup>®</sup> T 0.5% Experimental Moisture Management Finish

In the second set of experiments, both spun and filament polyester fabrics were treated with the two “ionic anti-static agents” and the two “hydrophilic surface treatments” and rubbed with steel (polymer-metal) and PTFE (polymer-polymer) rubbing charge measurements. As explained above, the rubbing charge buildup was been observed followed assessment of the decay properties

Third set of experiments were designed to study the charge decay properties of the fabric at two different places. One probe (probe I) is fixed as in the previous experimental designs on the rubbing area of the fabric and the new probe (probe II) is placed parallel to the probe I at a distance of 36 mm from probe-I in the unrubbed area. Surface potential is measured in both the rubbed and unrubbed areas at the same time. Both the probes are attached to a metal plate which is connected to the motion controller, so, that both the probes will have same lateral moment during rubbing.

Table 5.5 Experimental design - III to study the charge decay at two places using two different probes

Parameters	Levels
Fabrics	Filament polyester, Spun polyester
Rubbing Material	PTFE, Steel
Static control finishes applied	0.5% Hydroperm <sup>®</sup> T

### ***5.2.3 Equipment and Test Protocol***

The device developed for assessing frictionally charging (rubbing) using one probe in the rubbed area is schematically shown in the Figure 4.1 and signal analysis is shown in the Figure 4.3 and explained in the previous chapter (section 4.2.4). The top view of the fabric rubbed and measured with two probes is shown in Figure 5.1 and side view is shown in Figure 5.2. Fabric is placed on an insulated polymer plate using double sided tape. The stepper motor is connected to a motion controller which is used to drive the rubbing head. A surface potential Volt meter probe (Probe I) is attached to the rubbing unit, so that it senses the potential on the rubbed area of the fabric, 21 mm away from the rubbing head. For the experiments to measure the surface potential on the unrubbed area of the fabric in order to

verify the surface charge leakage additional volt meter probe (Probe II) is connected to the bush parallel to the first probe, and at a distance of 23 mm from the rubbed area and as the rubbing head moves, both of the probes will move. The rubbing movement can be precisely controlled by the preprogrammed user interface.

When the rubbing head moves in the “forward direction” the probes trail the rubbing head and measure the newly generated surface potential on the fabric surface. During the backward motion the probes are lead the rubbing head and Probe I monitors the charge retained on the surface. Probe II always measures the surface potential on the unrubbed area about 22 mm away from the rubbed area. Using the instrumental setup surface potential in the area of 8mm diameter on the rubbing plate surface can be detected at 99% resolution (Monroe Electronics Inc, 1991). A complete description about the signal analysis is mentioned in the section 4.2.

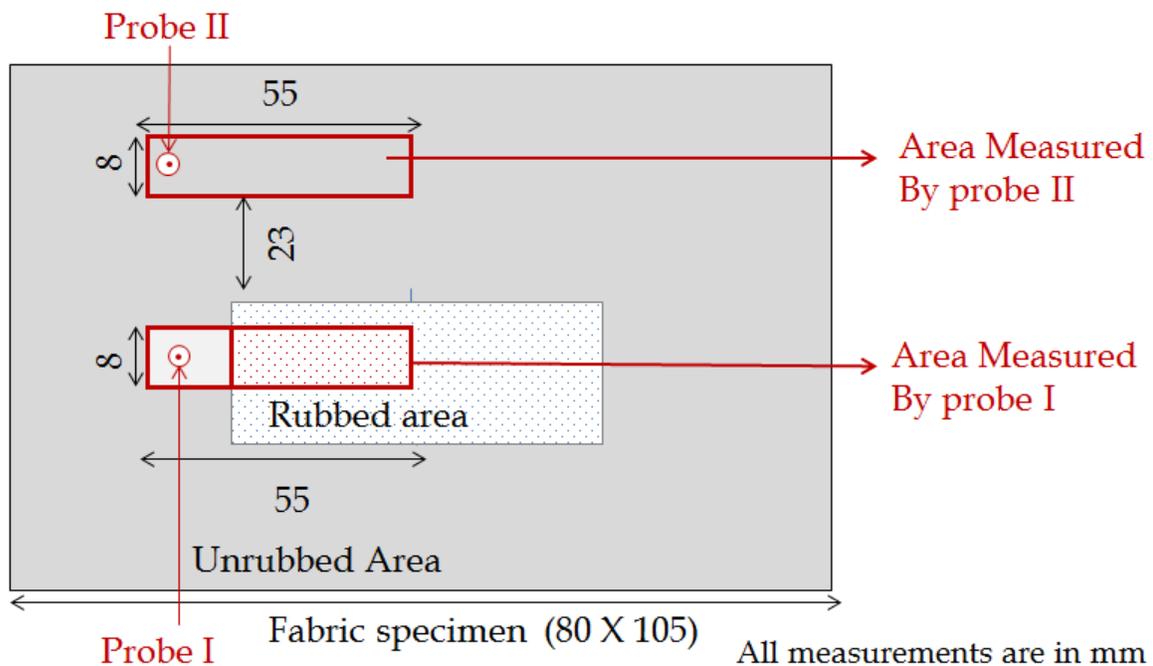


Figure 5.1 Sample with two probes measuring the surface charge (top view)

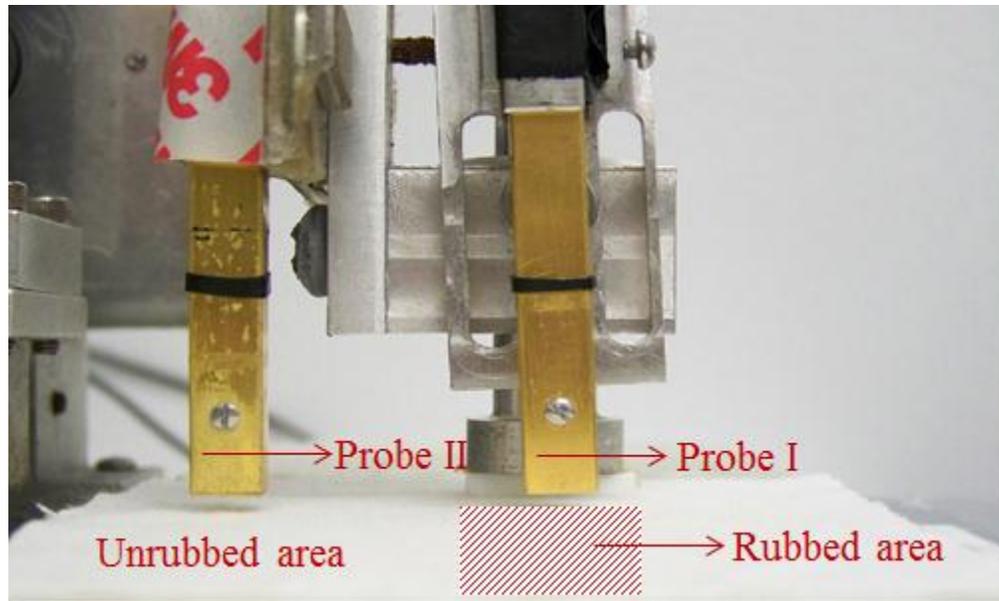


Figure 5.2 surface potential measured during rubbing with two voltmeter probes (front view)

#### **5.2.4 Resistivity Measurements**

Surface resistivity of the fabrics was measured using the AATCC method 76-2005 and ASTM standard D 257-99. The resistivity measurements were made using the Trek Model 152 model surface resistivity meter and the Trek model 152P-CR concentric ring probe. The accuracy of the measurement is about 5% when the resistivity is around  $10^4 - 10^{14}$  ohms/square. Electrode assembly with two concentric rings is used to measure the resistivity. This instrumentation includes an ammeter and a power supply (10-100 volts). For materials with a low resistance of below  $10^6$  ohms, voltage of 100 volts will be used and for materials with a resistance of higher than  $10^{12}$  ohms.

### **5.3 RESULTS AND DISCUSSION**

#### **5.3.1 Experimental Design - I**

When any insulating materials, such as textile fabrics, are repeatedly contacted or rubbed with another material (metal or insulator), after every rubbing cycle, charge is generated on the fabric surface and is accumulated as the number of rubbing cycles increases. The charge reaches a maximum (saturation) level after a certain number of rubbing cycles. The number of rubbing cycles required to reach the saturation level depends upon a range of properties

related to the composition and construction of the fabrics. A fuller description about measuring the effect of rubbing cycles or accumulated charge is given elsewhere (Lu, 2010).

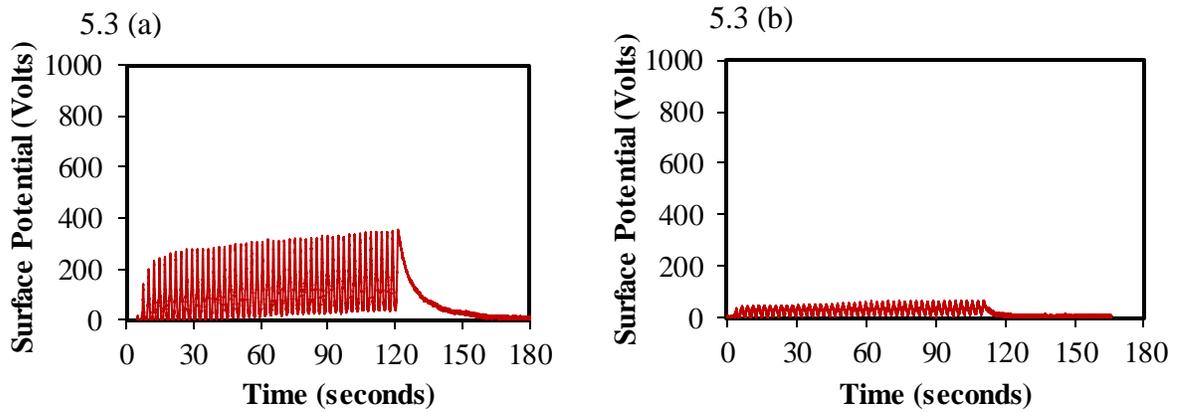


Figure 5.3(a) Charge accumulation in 50 cycles and decay on cotton-I (b) Charge accumulation in 50 cycles and decay on cotton-II

In Figure 5.3, the buildup and decay of surface potential on the cotton-I and cotton-II fabrics when rubbed with steel is shown. Rubbing with steel charged the cotton fabric to a positive surface potential. After the first cycle of rubbing, the surface potential measured on cotton I was in the range of 80 volts, and after 50 rubbing cycles, accumulated surface potential was measured at approximately 300 volts. The surface potential was observed to decay very quickly and was reduced to almost zero within next 30 seconds. The surface potential decay observed could be expressed as a single exponential decay. Cotton II fabric produced significantly less charge generation (39 Volts after first rubbing) and charge buildup (68 Volts after 50 cycles). Here again we see very rapid and exponential charge decay (losing >90% of the initial charge in 30 seconds). Charging the samples against a PTFE surface resulted in higher positive charge build up on the fabrics, but similar simple exponential charge decay was observed.

Figure 5.4 shows the surface potential generated when filament and polyester fabrics are rubbed with steel contact surface. The surface potential after the initial rubbing cycle is about 100 volts and with the number of rubbing cycles increasing, the surface potential has been accumulated and after 50 cycles, it reached about 490 volts. The charge dissipation is very slow compared with the previous cotton sample (which lost 95% of charge after 30 seconds)

and retains more than 80% of its charge even after 60 seconds. Surface potential measured on spun polyester when rubbed with steel is shown in Figure 4b. The surface potential generated after first rubbing is about -230 volts and the surface potential has been increased after every rubbing cycle and reached to -725 Volts after 50 cycles. The charge decay measured is completely different from both the cotton and polyester filament samples. The charge decays quickly (exponentially and similar to the cotton samples) initially for first 10 seconds from -725 Volts to -460 Volts and then the remaining charge decays linearly, similar to filament polyester samples.

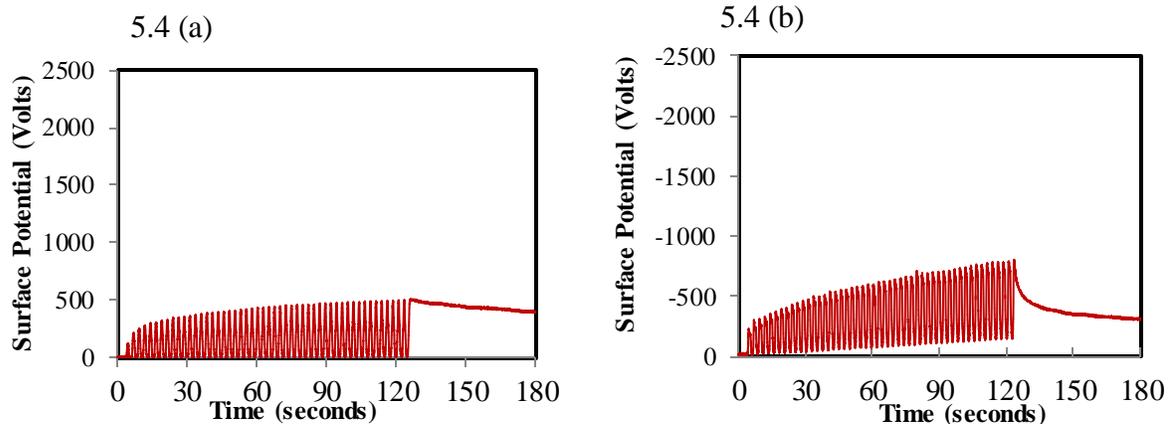


Figure 5.4(a) Charge accumulation in 50 cycles and decay on filament polyester (b) Charge accumulation in 50 cycles and decay spun polyester fabric

The charge decay properties of the cotton fabrics after being rubbed with steel and PTFE are shown in the Figure 5.5 (a) and 5.5(b). Charge decay curves shown here are the averages calculated on three different samples. Surface potential measured after 50 rubbing cycles and the surface potential decay measured over 60 seconds is shown in the Figure 5.5. Cotton fabrics rubbed with metal (steel) are charged with lower surface potential (about 70-150 Volts); whereas rubbing with polymer (PTFE) generated much higher surface potential (1600-1900 Volts). However, for all the samples the surface charge decays both rapidly and exponentially. Regardless of the amount of the charge generated on the surface, half life time is about 1 second for all the cotton samples. The amount of charge doesn't influence the decay properties of the cotton fabrics contradicted to the fact found by Ieda et al. (Ieda et al.1979).

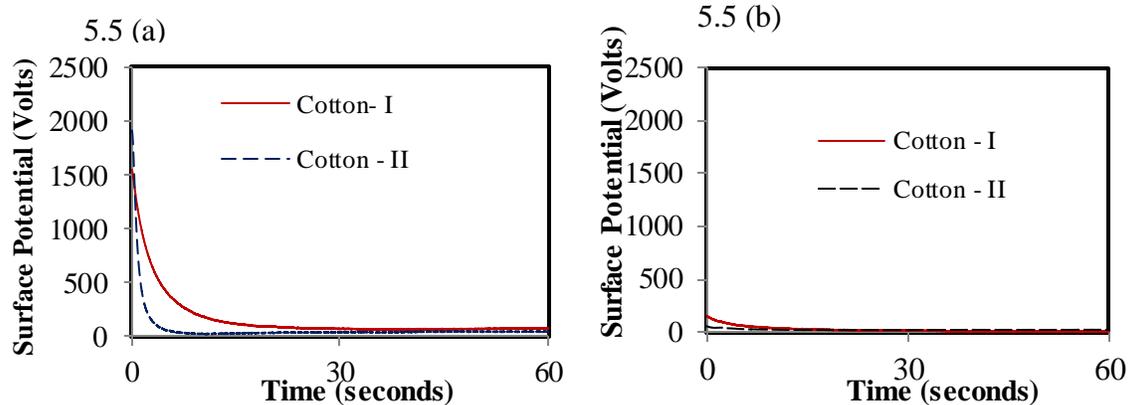


Figure 5.5(a) charge decay on cotton fabrics rubbing with steel (b) charge decay on cotton fabrics rubbing with PTFE

Under similar experimental conditions, the charge decay properties of polyester fabrics were observed to be very different from those of cotton. Charge dissipation measured on filament polyester and spun polyester are shown in the Figure 5.6a and 5.6b. Surface potentials measured on spun polyester is shown as absolute surface potential in Figure 5.6b, as spun polyester is charged negative when rubbed with steel. Similar to cotton, higher surface potential was measured on both filament and spun polyester fabrics when rubbed with PTFE than steel. Spun polyester was charged negative and filament polyester was charged positive when rubbed with steel. However, the charge decay properties of cotton fabrics are very different from filament and spun polyester fabrics. The charge decay of the filament polyester fabric is slow and linear with time while the charge decay on cotton is rapid and exponential. For the spun polyester the charge decay is neither a simple exponential or simple linear decay. It is a combination of both. It is double exponential decay curve fit with initial exponential decay; followed by slower nearly linear decay. The reason for this behavior is not clear. It may be due to the fact that spun polyester is made spun staples yarns (similar to the cotton fabrics) or it may be due to a surface modification of the polyester that is associated with the staple production and spinning process. For both polyester samples, similar charge decay properties were observed, independent of the type of rubbing head or the amount of charge generated on the materials. When different samples are tested under identical conditions, the charge decay process is clearly dependent on the structural

properties of the fabric and surface properties of the polymeric material. To study the impact of the surface properties on the charge generation and decay properties of the polyester fabrics, we investigated the impact of applying anti-static and hydrophilic surface finishes on the static charge behavior.

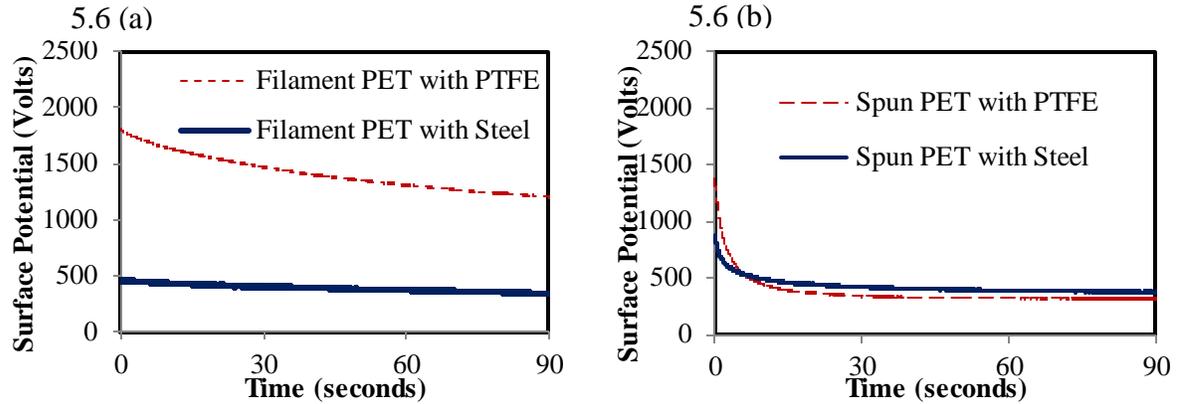


Figure 5.6(a) Charge decay on polyester rubbed with steel (b) Charge decay on polyester fabrics rubbed with PTFE

### 5.3.2 Experimental Design - II

Antistatic finishes are used to control the detrimental static electric effects on textile materials during processing. Ionic antistatic finishes are applied to increase the surface conductivity of the fiber/fabric and to reduce the accumulation of static charge by providing a conductive path to ground (Schindler and Hauser 1998). Hydrophilic surface finishes are applied primarily to improve the wicking and processing characteristics of textile fabrics, but can also reduce charge accumulation by providing a surface that absorbs water and provides a moderate level of surface conductivity. In this research work, two kinds of ionic antistatic finishes and two kinds of hydrophilic finishes were studied to determine their impact on the electrostatic properties of polyester textile fabrics.

Charge buildup and decay of 0.1% Larostat<sup>®</sup> 264 A and 0.1% phosphate finish applied to the filament polyester fabrics and contacted with steel are shown in Figures 5.7a and 5.7b. Ionic antistatic finish on the surface of the polyester fabric shows no charge generation. In the phosphate finish case, a low surface potential of about 30 volts is observed, but it shows no

signs of either building with increasing cycles or decaying, it is assumed to be a testing anomaly.

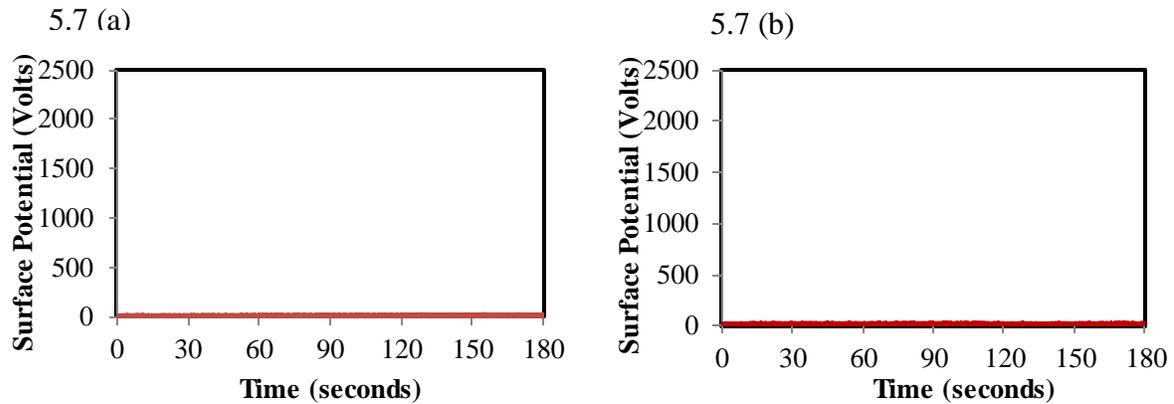


Figure 5.7(a) Charge accumulation in 50 cycles and decay on polyester fabric treated with 0.1% Larostat<sup>®</sup> 264A finish (b) Charge accumulation in 50 cycles and decay on polyester fabric treated with 0.1% phosphate finish

Similar results were obtained with anti-static agent treated spun polyester, rubbed with steel, and with both treated polyester fabrics rubbed with PTFE. These results indicate that these ionic antistatic finishes are strong antistatic finishes and effective in their control the static charge. Two possible mechanisms could be responsible for the static charge control. These finishes either modify in some way the interacting surfaces such that no static charge is generated on the fabric or they provide a level of conductivity to ground such that any static charge generated decays so quickly that it cannot be measured give the time scale of the experiment. With this experimental setup, it cannot be determined which of these mechanisms is responsible for the observed results. As previously reported by Hearle (Hearle, 2008) measurement of charge generation can be very difficult due to the fact that charge decay usually limits the charge generation measured. One can also expect that the original charge generation is often more than the observed the charge, in that by the time it is quantified, some of the charge will already have been subject to decay.

Polyester fabrics treated with 0.5% hydrophilic moisture management finish (TensTech Inc.) were rubbed with steel surface and the results are given in the Figure 5.8. Compared to the surfaces treated with ionic antistatic agents, these samples show the development of a modest level surface potential (~100 volts on filament polyester and ~150 volts on spun polyester)

and the charge is fairly stable through the 50 rubbing cycles. At the end of the rubbing cycles, the charge clearly decays very quickly ( $< 5$  seconds) and it appears to be an exponential decay.

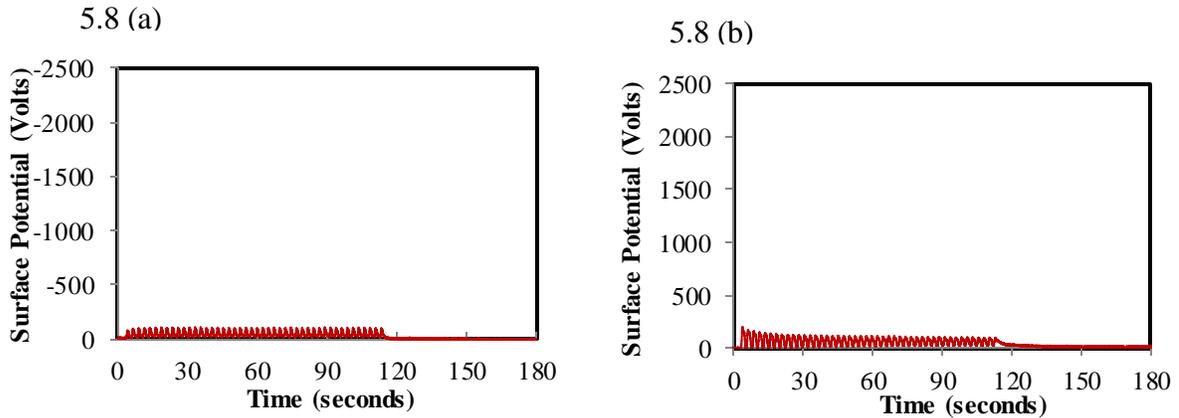


Figure 5.8(a) Charge accumulation in 50 cycles and decay on filament polyester fabric treated with 0.5% moisture management finish (b) Charge accumulation in 50 cycles and decay on spun polyester fabric treated with 0.5% moisture management finish

The Hydroperm<sup>®</sup> T finish (Clariant) was also applied to filament and spun polyester at the 0.5% level and rubbed with steel (Figure 5.9). In this case, the two fabrics behave very differently. The filament based fabric built charge through 50 rubbing cycles, reaching a maximum of 750 Volts, and then decayed with a complex decay curve [ $\sim 80\%$  of the charge decays in  $< 5$  seconds (exponential decay) with the residual charge decaying slowly (a near linear decay)] Also, a shift in the base line of the was observed during the rubbing of the Hydroperm<sup>®</sup> T treated filament fabric sample. More detailed discussion about this will be found in the next section.

The Hydroperm<sup>®</sup> T treated spun polyester samples, on the other hand, behaved like the samples treated with ionic antistatic agents, showing no detectable charge generation. Filament polyester samples showed a different behavior. It is clear that the applications of a hydrophilic polyester surface treatment to these fabrics generated a significant change in their static generation properties as well as the mechanism by which static dissipation occurs. However, most important question to answer is where the charge is going? Is it dissipating

towards the ground? Is it dissipating into the air? Is it a polymer property or surface property or external factors have the major influence?

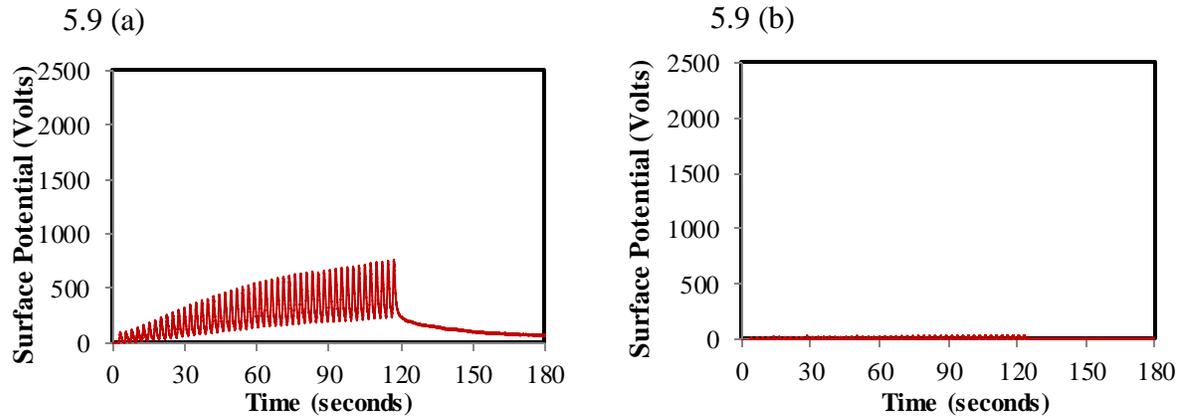


Figure 5.9(a) Charge accumulation in 50 cycles and decay on filament polyester fabric treated with 0.5% Hydroperm<sup>®</sup> T finish (b) Charge accumulation in 50 cycles and decay on spun polyester fabric treated with 0.5% Hydroperm<sup>®</sup> T finish

### 5.3.3 Experimental Design - III

To explore the questions raised by the unstable base line in the previous study, the equipment was modified to measure the surface potential at two different places on the fabric. One probe, to measure the charge in the rubbed area, was maintained in its original position and the other, to monitor the charge in the unrubbed areas, was placed parallel to the first probe at a distance of 36 mm from the first probe and 22 mm away from the rubbing head. A new probe measured the charge on unrubbed fabric, in a pattern parallel to the original probe. Filament polyester which has a very slower decay and other samples which showed more rapid decay (cotton, spun polyester and filament polyester finished with Hydroperm<sup>®</sup> T) were studied using this instrumental configuration.

Surface potential measured at two different places using two different probes on a filament polyester fabric, rubbing with steel, is shown in the Figure 5.10. Surface potential measured in the rubbed area using probe-I has been increased with the increase in number of rubbing cycles. After every rubbing cycle the probe-I measures the surface potential in small unrubbed area, as explained in Figure 5.2, curve reaches to zero at the end of the cycle, which indicates that the probe-I has measured the surface potential in an unrubbed area

which is zero volts. In the unrubbed area, using probe -II the surface potential measured was much lower and there was no change in the value as the number of rubbing cycles increased, which indicates that the charge stays on the areas where it is generated and does not migrate in to the unrubbed areas. It is characteristic of samples with no charge migration that their decay is slow and that the decay curve is nearly linear.

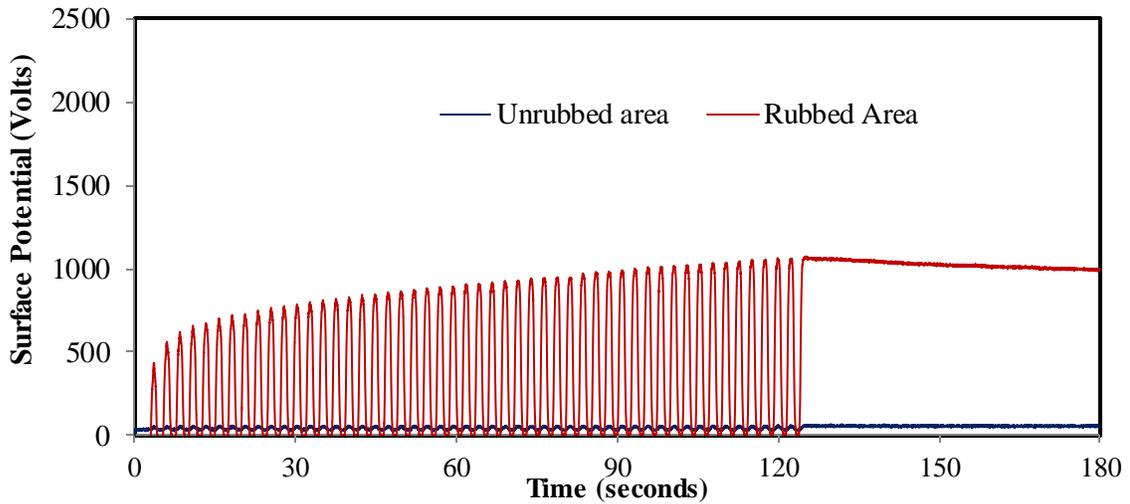


Figure 5.10 Charge accumulation in 50 cycles and decay of rubbing and unrubbing areas of filament polyester fabric

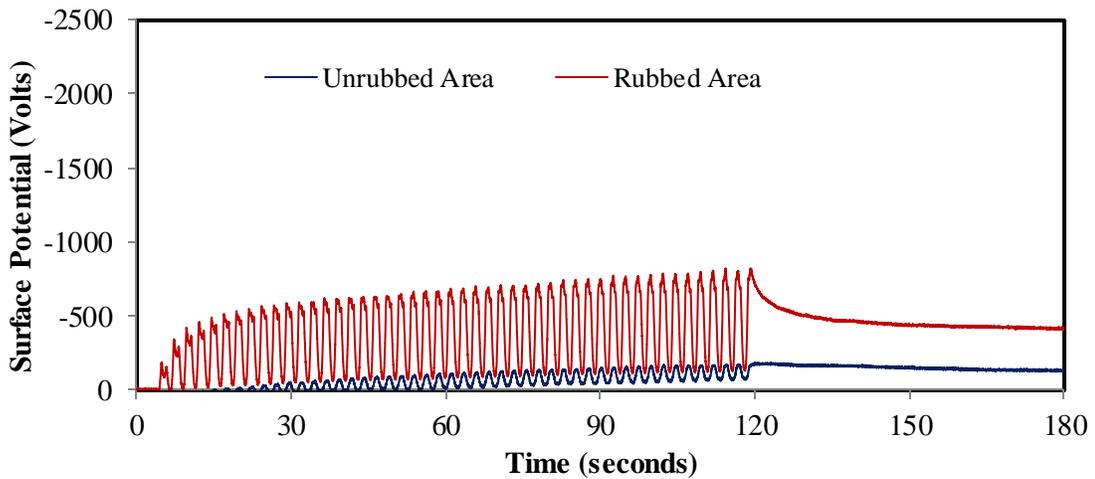


Figure 5.11 Charge accumulation in 50 cycles and decay of rubbing and unrubbing areas of spun polyester fabric

Surface potential measured on the spun polyester fabric, rubbed with steel, and is shown in the Figure 5.11. Surface potential measured using probe-I in the rubbing area shows a steady increasing in charge through the 50 rubbing cycles. Also, one can observe a slight shift in the base line as probe-I measured the surface potential in the un-rubbed area. The fact that the charge is this increase with the number of cycles indicates that the charge is migrating into the unrubbed area. This can also be seen in the surface potential measured by probe-II (the unrubbed area parallel to the rubbed area) also increases with the increasing number of rubbing cycles. This movement of the surface potential in the unrubbed areas indicates that charge is migrating from the rubbed area towards the unrubbed area and the whole fabric is taking on charge. There is also now a clear change in the nature of the charge decay curve in the rubbed area. The charge on spun polyester initially decays very quickly in an exponential decay and then shifts to a much slower, nearly linear decay. The charge decay on the unrubbed areas of the spun polyester is a slow, linear decay that parallels that of the second linear decay in the rubbed area. Charge migration from rubbed areas to unrubbed area and the appearance of the rapid exponential decay appear together and must in some way be related to one another.

Surface potential measured using two probes on filament polyester treated with 0.5% Hydroperm<sup>®</sup> T is shown in the Figure 5.12. As observed in the previous spun polyester fabric, surface potential has been increased and this is observed in both rubbed and unrubbed areas. This samples shows that the charge is rapidly migrating over the surface of the fabric that at the start of each cycle, the charge in the rubbed area and the unrubbed area are essentially identical. The lack of structure in the unrubbed area is again indicative of the rapid equilibration of charge across the entire fabric sample. Again, this rapid equilibration leads to a rapid very rapid exponential decay of the charge on the sample and within a second of the end of the last cycle, both curves are identical.

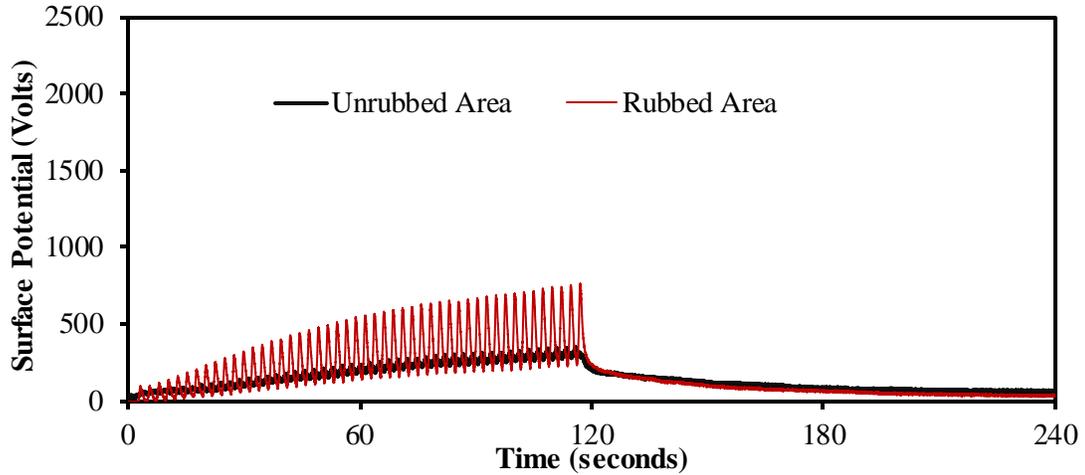


Figure 5.12 Charge accumulation in 50 cycles and decay of rubbing and unrubbing areas of filament polyester treated with 0.5% Hydroperm® T

### 5.3.4 Surface Resistivity Measurements

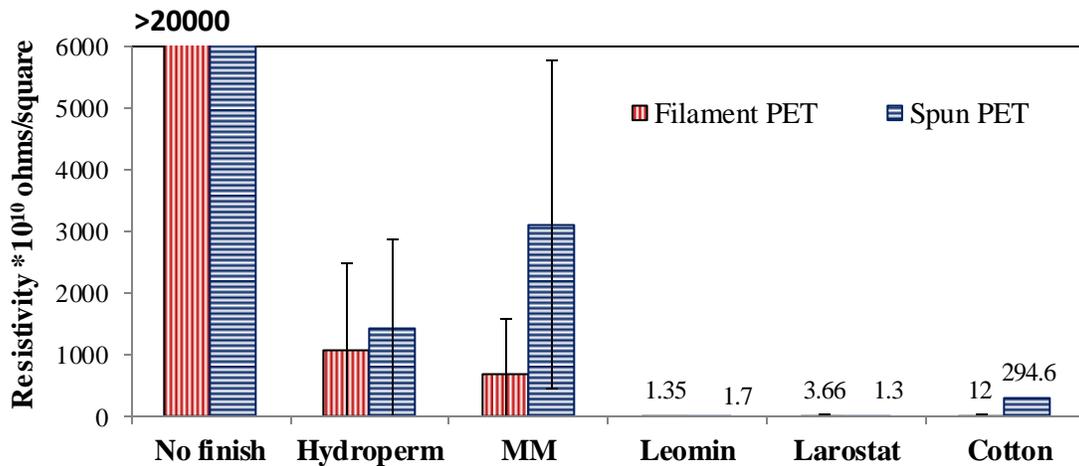


Figure 5.13 Resistivity measured on cotton, polyester and polyester fabrics treated with various surface finishes

Resistivity measured on the cotton, polyester and polyester fabrics treated with different surface finishes are shown in the Figure 5.13. Polyester fabrics with no finishes have very high resistance of greater than  $2 \times 10^{14}$  Ohms/ square. Cotton fabrics have lower resistance of about  $12-300 \times 10^{10}$  Ohms/square. Also the polyester fabrics treated with ionic antistatic finishes were found to have the expected low surface resistance ( $1.3-3.6 \times 10^{10}$  Ohms/square).

Fabrics treated with hydrophilic finishes are found to have intermediate resistance values of about 700 to  $3000 \times 10^{10}$  Ohms/ Square. It is clear that resistance values in this latter range allow sufficient surface conduction that the surface charge can rapidly equilibrate itself across the whole fiber sample and this result in the bulk of the charge being dissipated by a rapid exponential process rather than the much slower, nearly linear process.

#### 5.4 ELECTROSTATIC CHARGE DECAY MECHANISM

Electrostatic charge in textile (polymeric) materials can be stored as surface charges or space charges which are stored a few nanometers near the surface and stabilized there by true polarization (dipoles) or with a combination of both (Sessler 1987). The static charges stored in a textile material when rubbed with another material are shown in Figure 5.14 below. The material shown has been divided in to rubbed area and unrubbed area. During rubbing all the charges are stored in the area which is rubbed. The surface charges lies on the surface or within few nanometers of the surface which space charges lie deeper below the polymer surface (also called as bulk charges). These space charges can set up polarized dipoles within the solid and this helps to stabilize the charge. The balance of surface and space charges in triboelectric charged textiles is a matter of controversy in the literature.

These textile materials can be differentiated in to three types of materials such as perfect insulator, moderate insulator and conductor as described by Hearle (Hearle 2008). Three different charge decay mechanisms were observed on these materials and are shown in Figure 5.15, 5.16 and 5.17. The observed charge decay mechanisms are linear charge decay, exponential decay and double exponential decay which is a combination of the exponential and linear charge decay mechanism.

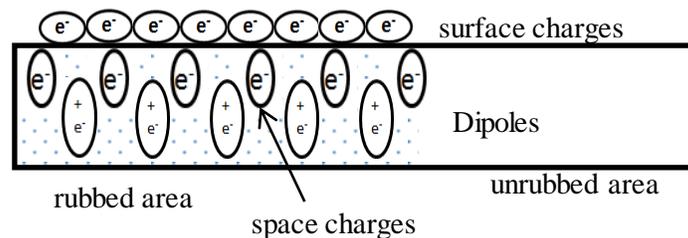


Figure 5.14 Charges stored in textile/polymers

The linear charge decay model and mechanism observed on a perfect insulator as shown in Figure 5.15(a). When all the charges has no mobility on the fabric surface, the charge, whether surface charge or sub-surface charge, tends to stay where it is generated and decays very slowly, probably by neutralization of the charge with ions from the air. For insulating materials with surface resistivity of  $10^{14}$  Ohms/ square or higher, this slower and liner decay charge pattern is observed. The generated charge remains on the surface for an extended period of time, there is no apparent path to ground and the observed decay is nearly linear. This decay mechanism is observed on filament polyester fabric as shown in Figure 5.15(b).

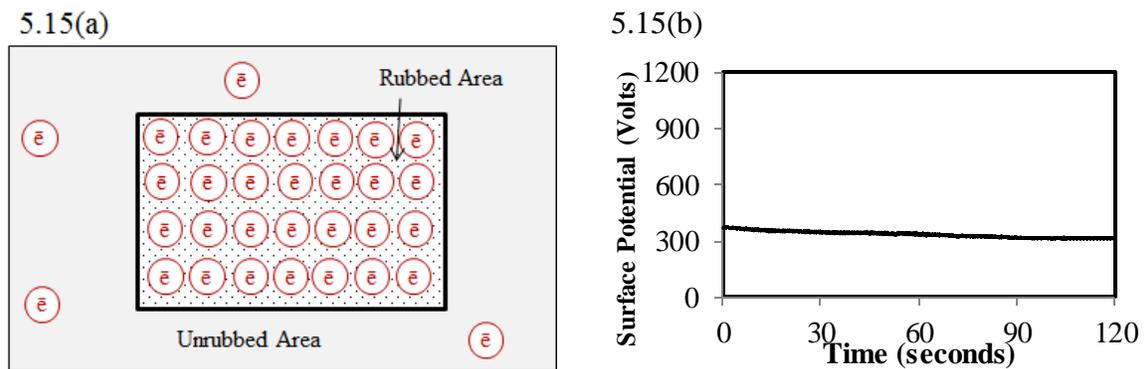


Figure 5.15(a) Linear charge decay model (b) Linear charge decay on filament polyester fabric

Exponential decay of static charge observed on a conductor is shown in Figure 5.16(a). This can be explained as the charge decay observed when there is lower surface resistivity ( $<10^{11}$  Ohms/square) and the charge can move on fabric surface and be released to ground. The charge decay is rapid and exponential, with the rate of the exponential decay being highly dependent on the surface resistance of the fabric. This charge decay is observed in materials with surface resistance values as low as  $10^9$  ohms/square. Since these fabrics are more conductive, the surface charges moves from the area where they are generated to the unrubbed parts of the fabric and space charges, those located near the surface, can move to the surface and dissipate. This kind of charge decay mechanism is observed on cotton fabrics as shown in the Figure 5.16(b) as well as other fabrics with high surface conductivity such as polyester treated with certain antistatic agents.

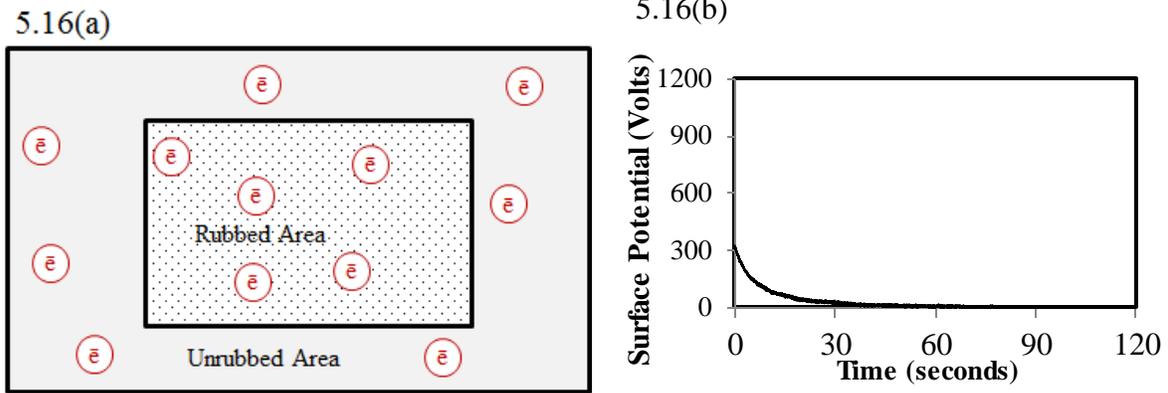


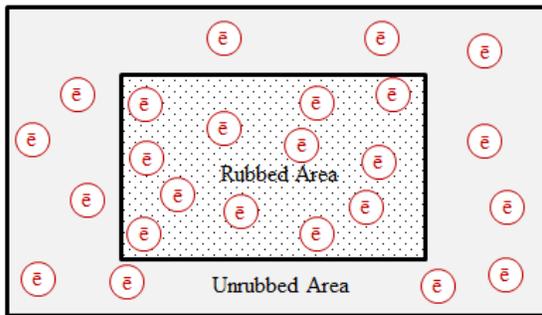
Figure 5.16(a) Charge distribution on exponential charge decay fabric (b) Exponential charge decay on cotton fabric

The third type of charge decay mechanism observed on moderate insulators is a double exponential decay process. The charge decays initially exponential decay followed by a linear decay once the exponential decay is complete. In this case, part or all of the charges on the surface can spread across the surface. Again, the rate at which the charge spreads (exponential decay) seems to be related to the surface resistance of the fabric. At these intermediate resistances (about  $10^{11}$  to  $10^{14}$  ohms/square), the spreading charge seems to occupy both surface charge sites and space charge sites. At the end of the rubbing cycle, one can observe this in the unrubbed areas. Once the rubbing has been stopped generation and accumulation of the charge will be stopped followed by the stoppage of the charge spreading. Then the charge on the rubbed and unrubbed areas starts decaying. This charge also follows a double exponential decay process. This kind of charge decay mechanism is observed on the spun polyester fabrics and on fabrics that are treated with hydrophilic surface treatments. The charge that generated on the surface is either spread over the fabric due to its surface conductivity and finds its way to ground or is held in sub-surface space charge sites and decays by a different mechanism that gives the observed slow, nearly linear decay.

However, there still remains one significant question: Where does the charge “decay to” in the two different mechanisms? The literature suggests that the slow linear decay is caused by leakage of the charge into air or by neutralization of the charge by ions in the air. While the exponential decay is clearly related to the ability of the charge to spread across the fabric

surface, this provides no indication as to where the charge is discharged. The fabrics are on a PTFE surface and not ground once the rubbing surface is raised (steel surface) and not ground at all when the surfaces are rubbed with a PTFE surface. Further, grounding the edge of the fabric makes no difference in the decay pattern. Clearly some or all of the charge is finding its way to ground when the surface has conductivity, but exact path for this discharging process is yet to be determined.

5.17(a)



5.17(b)

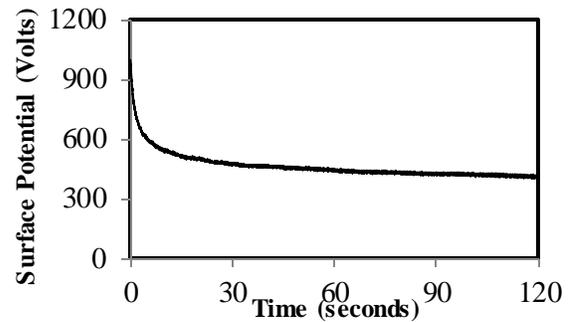


Figure 5.17(a) Charge distribution on a double exponential decay fabric (b) Double exponential decay of charge on spun polyester

## 5.5 CONCLUSION

Two types of cotton and two polyester fabrics have been rubbed with steel and PTFE to study the charge decay mechanism of these fabrics. Surface potential increased as the number of rubbing cycles increased. After fifty cycles of rubbing, the charge decay has been measured and the results analyzed and an attempt to understand the electrostatic charge generation-dissipation process has been made. Three general modes of charge decay were observed:

- A slow linear decay and we observed no sequence of spreading of charge on the test sample.
- An exponential decay and associated with this mechanism, the spreading of charge on the test sample was observed.
- A combination of linear and exponential decay mechanism and with that a clear indication that there were two types of charge on the fabric surface

To further try to understand the static charge generation and dissipation process the ionic antistatic agents and hydrophilic surface treatments:

- With the ionic antistatic agents were applied to the fabric samples, there was little or no charge was observed during the rubbing tests. It cannot be determined whether there applied finishes modify the surface and reduce the charge generated or if they provide a high level of surface conductivity that makes the charge unobservable on the time scale of the experiment. As previously reported by Hearle (Hearle, 2008) measurement of charge generation is very difficult to the fact that charge decay usually limits the charge generation measured.
- The application of hydrophilic surface treatments to the polyester fabric samples produced fabrics with complex patterns of both exponential and linear decay.

The patterns of decay in these various fabrics have been analyzed and explained based on a model that postulates two distinct types of charge on the surface and that the decay pattern of both types of charge is highly dependent on the surface resistance of the fabric.

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**CHAPTER 6**  
**EFFECT OF HYDROPHILIC FINISHES ON FRICTIONAL**  
**ELECTRIFICATION AND CHARGE DECAY OF WOVEN**  
**POLYESTER FABRICS**

# **EFFECT OF HYDROPHILIC FINISHES ON FRICTIONAL ELECTRIFICATION AND CHARGE DECAY OF WOVEN POLYESTER FABRICS**

## **6.1 INTRODUCTION**

Textiles are processed at high speeds and during their processing they experience contact and triboelectric charging due to the material interactions and frictional interactions with various contact materials. Materials with inherently low resistance, such as cotton and rayon, rarely have significant static related processing issues, whereas high resistive materials such as polyester and nylon often experience processing problems associated with static charging. This process of contact and triboelectric charging can create problems ranging from mere nuisance issues to the shutting down of equipment and major spinning/weaving defects during the processing and handling of synthetic textile materials. Major problems created by contact and triboelectric charging include ballooning of yarns, damage to electronic equipment and shocks to personnel. Most of these static problems can be controlled by processing at higher humidity conditions and by using static control finishes; however some of the problems cannot be eliminated completely. It is very important to understand the process of triboelectric charge generation and dissipation in order to provide directions in our attempts to control the static problems (Schindler and Hauser 1998). This research is dedicated to understand the charge decay process on textile fabrics that have been subjected to triboelectric charging, by using different concentrations of the hydrophilic surface treatments influence

Finishes designed to control static charge through rapid dissipation are often used to minimize the impact of static charge during the processing of textile materials. In these finishes, the “anti-static agents are generally ionic and are non-durable (they are removed with the finish at some point in textile processing). Several reviews have been published in the literature to explain different static finishes and their approach to control the static charge generation and dissipation (Slade 1998, Holme et al., 1998; Kowalski & Wroblecka 2006). This research is dedicated to study the impact of hydrophilic treatments for polyester fabrics on the static generation and dissipation properties of those fabrics. These finishes are

classified as durable treatments and are designed to increase the surface energy of the polyester fiber and enhance the wicking properties of the fabric (provide moisture management properties). These materials are hydrophilic block copolymers based on polyester and polyoxyethylene glycol. The hydrophobic portion of the polymer provides durability through affinity interactions with the polyester fiber surface and the hydrophilic blocks provide increased hydrophilicity, and moisture absorption. It is expected that these characteristics will lead to increases in both the conductivity and the rate of charge decay of the fabric.

The objective of this work is to determine the impact of such hydrophilic fabric treatments on both tribocharging process and the charge dissipation process. Based on the analysis of these results, we will develop models that expand our understanding of the mechanism by static charges decay on polyester textile fabrics. In the previous chapter (chapter 5), it was observed that when hydrophilic finish of this type is applied to polyester fabrics, it results in an increase in the rate of static charge decay. In another work Lu observed that with increasing concentration of traditional ionic and nonionic antistatic agents, the charge generated on the plates decays more quickly (Lu, 2010). In this work, three different levels of the hydrophilic treatment were applied to two types of polyester fabric and tribo-charged with two contact surfaces (steel and PTFE). It is the data from this series of tests that will provide the bases for our model of the charge decay mechanism.

## **6.2 EXPERIMENTAL**

### ***6.2.1 Sample Preparation***

Finish free filament polyester fabrics (style no 700-3 are purchased from Test Fabrics Inc.) were initially cleaned with deionized water at 70 °C for 20 minutes and then washed with 2-propanol at room temperature for 20 minutes to remove any surface contaminants. Then the fabrics were dried at 80°C for 40 minutes. The stainless steel/ PTFE rubbing surface was also cleaned with 2-propanol. Before each test, any residual charge that stays on the sample was removed by the deionizer gas. The Hydroperm<sup>®</sup> T is a commercial hydrophilic surface treatment for polyester fiber and was supplied by Clariant Inc.

These cleaned fabric surfaces were the treated with Hydroperm<sup>®</sup> T antistatic finish using three different concentrations. Hydroperm<sup>®</sup> T finish was mixed with deionized water to make solutions of three different concentrations (weight percentage of agent to solution). These solutions were sprayed on the fabric surface using an airbrush following the procedure recommended by Lu (Lu, 2010). After the application of the surface treatment, the fabric was dried in an oven, at 80°C for 45 minutes. The samples were subsequently moved to the environmental room for conditioning for 48 hours at testing conditions about 21°C and 43 % RH.

### ***6.2.2 Materials and Experimental design***

Table 6.1 Experimental design

Parameters	Levels
Fabrics	Filament Polyester
Rubbing materials	Steel, PTFE
Hydrophilic finishes applied	No finish, 0.1% Hydroperm <sup>®</sup> T, 0.25% Hydroperm <sup>®</sup> T, 0.5% Hydroperm <sup>®</sup> T

During the frictional electrification experiments, the sample was fixed on to an insulated plate using double sided tape. Flat rubbing heads made of stainless steel and PTFE were used to rub the surface of the fabric. A full description of the experimental procedure has been given elsewhere (Lu, 2010).

### ***6.2.3 Equipment and Test Protocol***

#### ***Rubbing Charge generation/Dissipation measurement device***

The device developed for assessing frictionally charging (rubbing) using one probe in the rubbed area is schematically shown in the Figure 4.1 and signal analysis is shown in the Figure 4.3 and explained in the chapters 4.2 and 5.2. The top view of the fabric rubbed and measured with two probes is shown in Figure 6.1. Fabric is placed on an insulated polymer plate using double sided tape. The stepper motor is connected to a motion controller which is

used to drive the rubbing head. A surface potential Volt meter probe (Probe I) is attached to the rubbing unit, so that it senses the potential on the rubbed area of the fabric, 21 mm away from the rubbing head. For the experiments to measure the surface potential on the unrubbed area of the fabric in order to verify the surface charge leakage additional volt meter probe (Probe II) is connected to the bush parallel to the first probe, and at a distance of 23 mm from the rubbed area and as the rubbing head moves, both of the probes will move. The rubbing movement can be precisely controlled by the preprogrammed user interface.

When the rubbing head moves in the “forward direction” the probes trail the rubbing head and measure the newly generated surface potential on the fabric surface. During the backward motion the probes are lead the rubbing head and Probe I monitors the charge retained on the surface. Probe II always measures the surface potential on the unrubbed area about 22 mm away from the rubbed area. Using the instrumental setup surface potential in the area of 8mm diameter on the rubbing plate surface can be detected at 99% resolution (Monroe Electronics Inc, 1991). A complete description about the signal analysis is mentioned in the section 4.2.

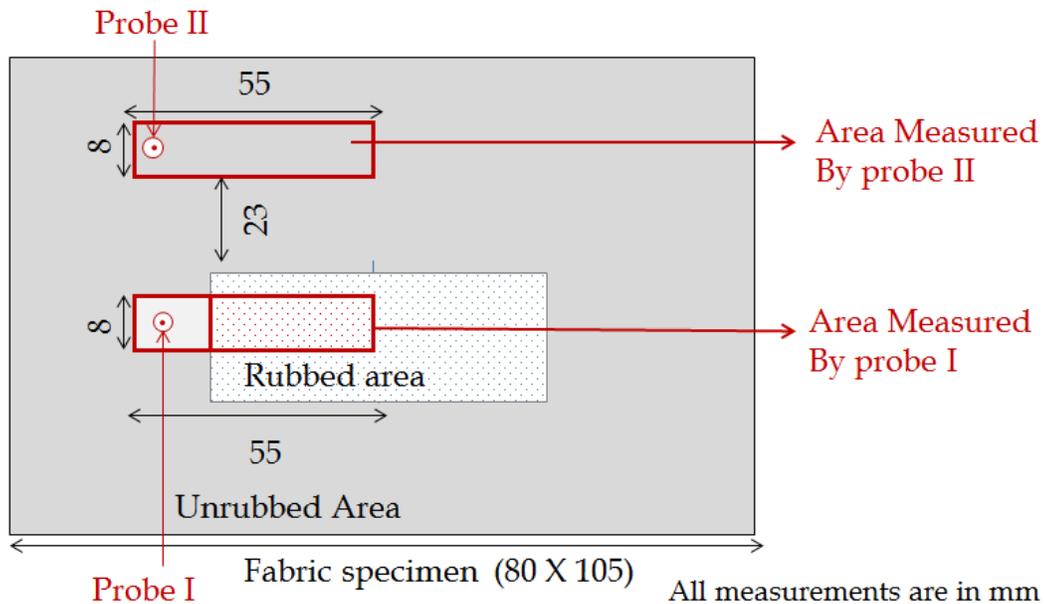


Figure 6.1 Charge measurement on fabric using two probes (top view)

## 6.3 RESULTS AND DISCUSSION

### 6.3.1 Experimental Design

Figure 6.2 shows the charge measured on the cleaned and untreated “controlled” sample of filament polyester fabric, contacted by steel rubbing head. Surface potentials are measured in both the rubbed area and in unrubbed areas, (21 cm away from the rubbed area). The surface potential buildup is measured during 50 rubbing cycles, then the tribo-charging process is stopped and the charge decay is measured for 120 seconds (Figure 6.2). After initial rubbing cycle, the surface potential measured on untreated polyester fabric is about 126 Volts and the charge builds up gradually after each rubbing cycle, reaching about 341 Volts after 10 rubbings and then the charge build up increases at a slower rate, reaching about 500 Volts after 50 cycles. The surface potential on polyester then decays very slowly and after 60 seconds, it retained about 80% of the charge accumulated (about 400 Volts). The charge measured in the unrubbed area is small compared to the surface potential measured at rubbed area (about 50 volts), and does not significantly change during the tribo-charging process.

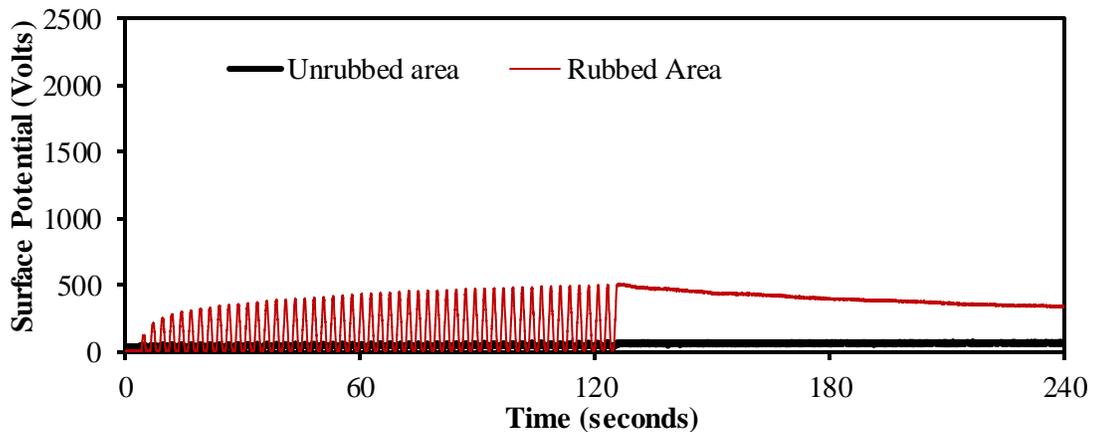


Figure 6.2 Surface potential build up and decay on filament polyester fabric for 50 cycles of rubbing

Figure 6.3 shows the surface potential measurements for filament polyester fabric treated with 0.5% Hydroperm<sup>®</sup> T and contacted with steel rubbing head. As observed in the case of untreated polyester fabric, the surface potential on the Hydroperm<sup>®</sup> T treated fabric increased slowly in the rubbing area as the number of rubbing cycles increased. After the first rubbing

cycle, the surface potential measured was about 100 Volts and after fifty cycles the surface potential increased to about 700 Volts. Interestingly, a similar is observed in unrubbed area (21 mm away from the rubbed area). The surface potential after the initial rubbing cycle was about 30 volts and increased to about 250 Volts after fifty rubbing cycles. It is also clear from a comparison of the trends in Figure 6.2 and Figure 6.3 that the charge dissipates much more rapidly on the fabric which has been treated. This clearly indicates that the generated charge on the treated fabric due to rubbing is not just constrained to the rubbed area of the fabric; but it rapidly migrates towards the unrubbed area and then dissipates by an as of yet undetermined mechanism. Similar observations were found when the Hydroperm<sup>®</sup> T treated fabric is rubbed with the PTFE rubbing head. To understand the charge spreading mechanism, three different surface concentrations of Hydroperm<sup>®</sup> T, along with an untreated filament polyester fabric, were tested for frictional electrification by rubbing with both steel and PTFE rubbing heads.

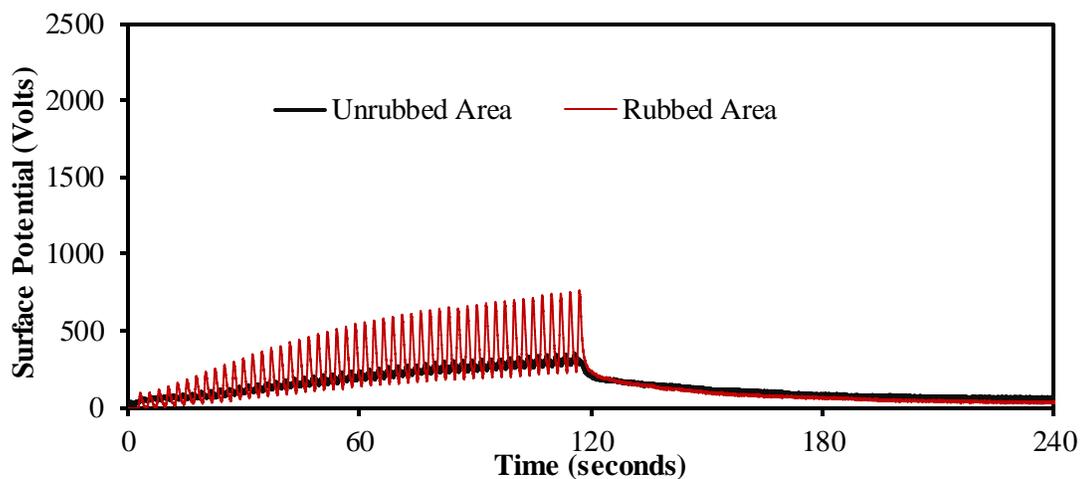


Figure 6.3 Surface potential build up and decay on 0.5% Hydroperm<sup>®</sup> T applied filament polyester for 50 cycles of rubbing

The surface potential measured on filament polyester fabrics treated with 0.25% and 0.1% are shown in Figure 6.4a and 6.4b. In the rubbed areas, the amount of charge generated and the pattern of charge buildup is significantly different in all 4 samples and there seems to be no regular correlation of either property with the level of Hydroperm<sup>®</sup> T applied to the fabric

sample. In the unrubbed area, the charge shows a steady pattern of build in all the Hydroperm<sup>®</sup> T treated samples. Charge decay in both the rubbed and unrubbed areas is double exponential decay, with a rapid initial decay followed by a slow linear decay. Charge spreading has been observed and it has been determined that for all these samples, within a few seconds, the change in the rubbed and unrubbed areas are very similar or identical. The rate at which the charge becomes uniform and the rate of initial exponential decay was found to depend on the level of Hydroperm<sup>®</sup> T applied. A more detailed analysis of these properties follows.

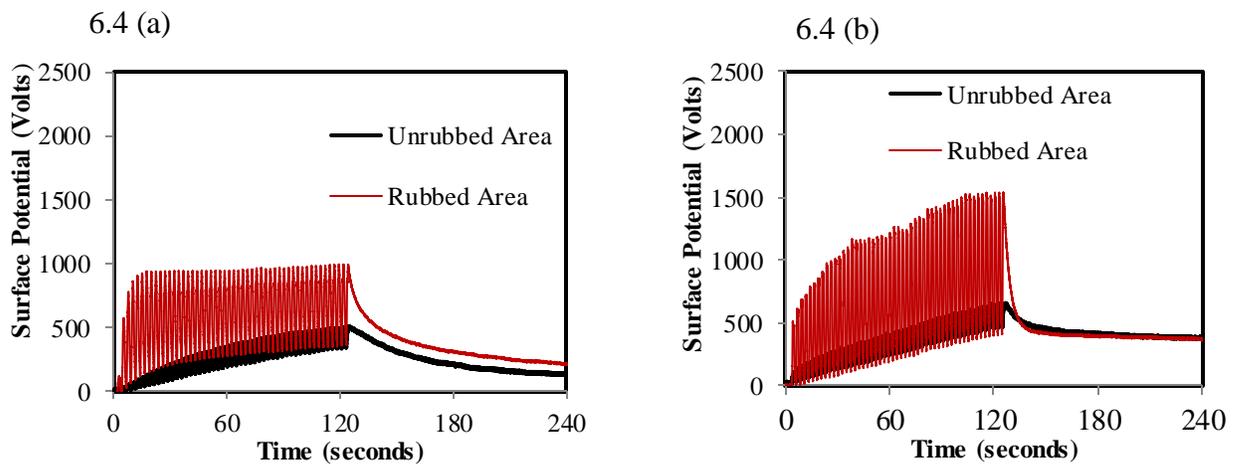


Figure 6.4(a) Surface potential build up and decay on 0.25% Hydroperm<sup>®</sup> T applied polyester fabric (b) Surface potential buildup and decay on 0.1 Hydroperm<sup>®</sup> T applied polyester fabric

Surface potentials measured on Hydroperm<sup>®</sup> T treated and untreated polyester fabrics contacted with the rubbed steel and PTFE rubbing heads are shown in the Figure 6.5(a) and 6.5(b). Both untreated and treated Hydroperm<sup>®</sup> T treated fabrics were charged positively when rubbed with both steel and PTFE. Similar to steel rubbed samples, no clear trend has been observed for the charge build up on these samples. No clear trend has been observed between the surface concentration of the hydrophilic treatment and the surface potential buildup. When rubbed with steel, 0.1% Hydroperm<sup>®</sup> T treated fabric accumulated the highest surface potential when compared with the other fabrics. For the PTFE rubbed samples, the untreated and the 0.25% treated fabrics showed the maximum charge. The charge measured

on the unrubbed area on the untreated polyester is very low (about 50 Volts) and this was attributed to background charging. On the Hydroperm<sup>®</sup> T treated fabrics; the charge measured on unrubbed areas is substantial, reaching 350 to 1000 Volts. This indicates that when a hydrophilic surface finish such as Hydroperm<sup>®</sup> T is applied onto the surface of the polyester fabric, the charge generated on the rubbed area of the surface can rapidly redistribute itself into the unrubbed areas. We would suggest that this spreading is the cause of the exponential decay which is present in all the treated samples and is not present in the untreated sample.

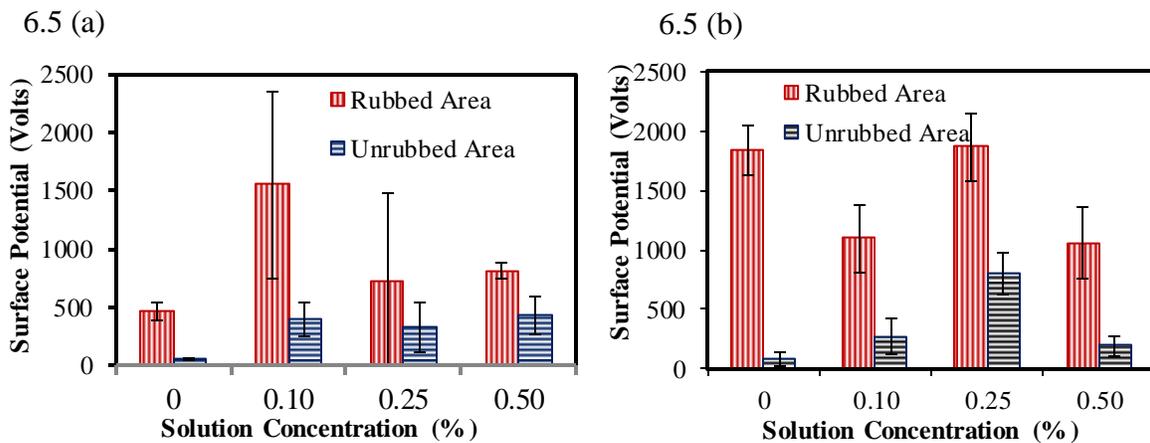


Figure 6.5(a) Surface potential accumulated on filament fabric against steel (b) Surface potential accumulated on filament fabric against PTFE

Charge accumulated on finish free and Hydroperm<sup>®</sup> T treated polyester fabrics due to rubbing for 50 cycles with steel and PTFE are compared in the Figure 6.6. All the samples were charged positively. Finish free sample generated higher charge when it is rubbed with PTFE than when it is rubbed with steel. No specific trend has been observed for the Hydroperm<sup>®</sup> T applied samples.

The surface potential measured in the unrubbed area expressed as percentage of the surface potential in the rubbed area is shown in Figure 6.7. It is clearly evident that for untreated polyester, the surface potential in unrubbed areas is low, only about 5-12% of the surface potential measured in the rubbed area, and does not increase during the rubbing cycle,

indicating that it is likely this is background charge. In case of Hydroperm-T applied samples, the surface potential measured in the unrubbed areas is higher, about 25 to 70% of the surface potential measured in the rubbed areas. Interestingly for all the samples, the percentage of charge that spreads when rubbed with steel is more than for the samples which are rubbed with PTFE.

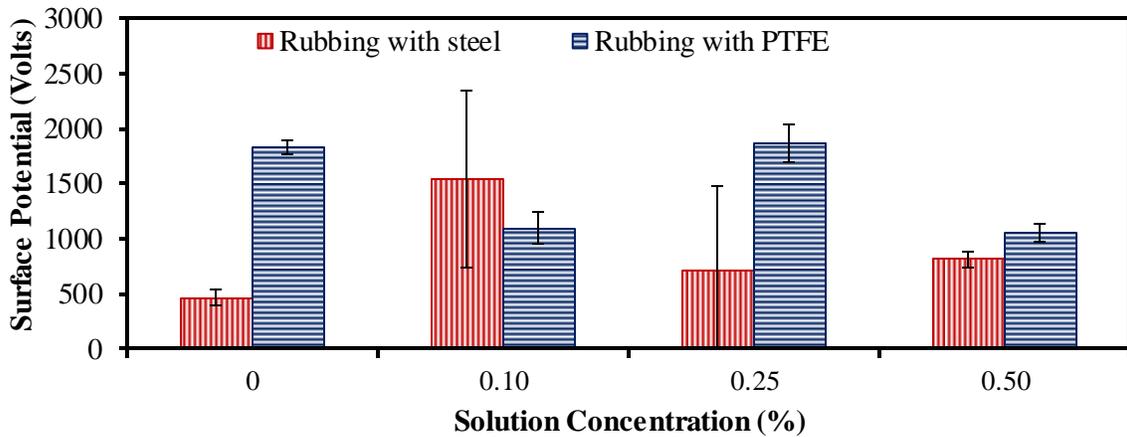


Figure 6.6 Comparing charge buildup on polyester fabric rubbing with steel and PTFE

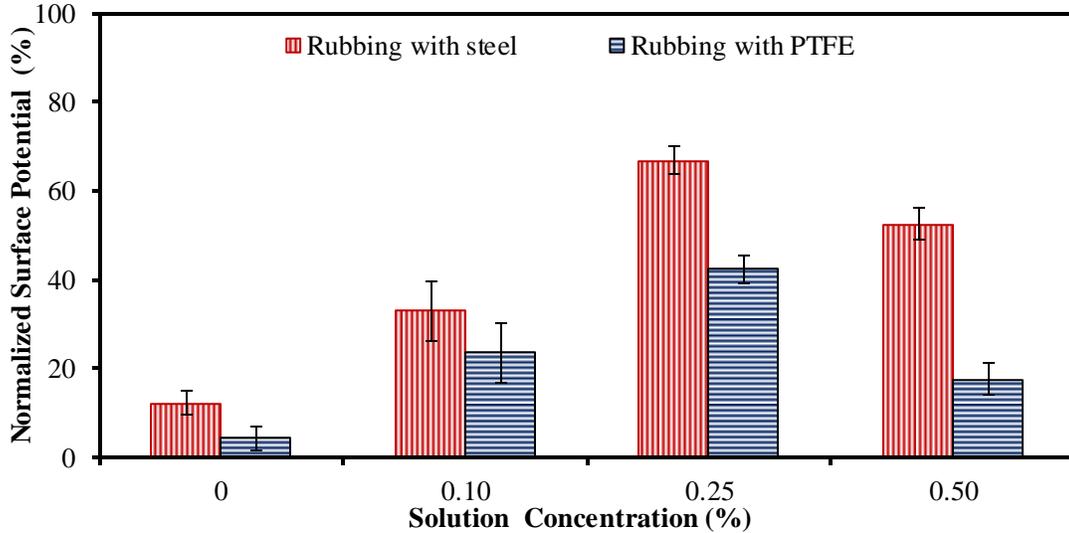


Figure 6.7 Surface potential in unrubbed area as a % of surface potential in rubbed area

The average half life time (which was the time for the potential measured on the sample after fifty rubbings to decay to 50% value) is shown in the Figure 6.8. As the concentration of the

Hydroperm<sup>®</sup> T solution increases, the surface potential decays quickly. Untreated sample has the highest half-life (160-270 seconds). The presence of even the lowest level of Hydroperm<sup>®</sup> T on the fabric surface leads to radical change in the decay process. The initial half-life is reduced by greater than a factor of 10 and as we noted earlier, we see a shift from linear decay to exponential decay. As the level of Hydroperm<sup>®</sup> T increases, we see further reductions in the initial half-life, with the highest solution concentration (0.5%) decaying to half of its original value in with 0.45 to 1.8 seconds. Clearly the presence of the hydrophilic Hydroperm<sup>®</sup> T finish on the surface has generated a change in the mechanism of charge decay.

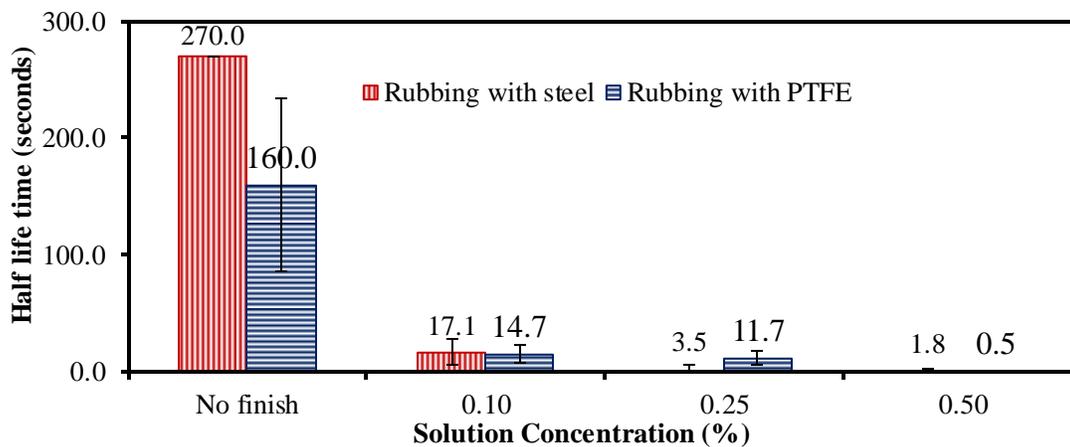


Figure 6.8 Half life time of the polyester samples

Figure 6.9 shows the trends for charge decay curves for the untreated and Hydroperm<sup>®</sup> T treated polyester samples rubbed with the steel rubbing surface. The charge decay on untreated polyester fabric is different from the other Hydroperm<sup>®</sup> T treated samples. On untreated polyester fabric the charge is relatively stable; decaying only slowly, with a decay curve is nearly linear. On the Hydroperm<sup>®</sup> T treated samples, the surface potential decays very quickly and loses about 90% of its charge in first 90 seconds. These charge decay curves for the Hydroperm<sup>®</sup> T treated samples are dual in nature, being composed of an exponential decay curve followed by a much slower, nearly linear decay. On 0.5% Hydroperm<sup>®</sup> T treated sample, the charge decays exponentially for the first 7 seconds (termed as  $t_e$ ) and then reverts to a very slowly, almost linear decay ( $t_l$ ). Similar trends were

observed on the other Hydroperm<sup>®</sup> T treated samples, the rate of the rapid exponential decay (termed as  $t_e$ ) is highly dependent on the concentration of the Hydroperm<sup>®</sup> T applied on to the fabric.

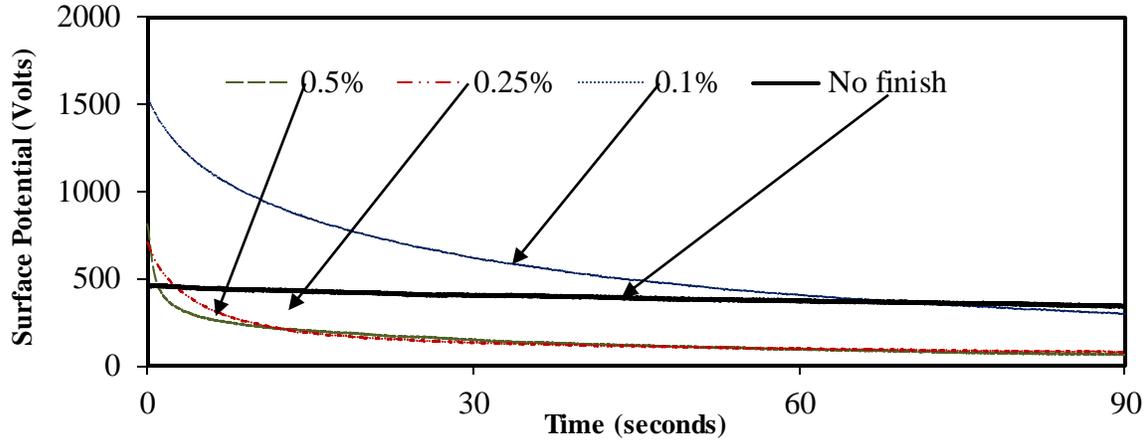


Figure 6.9 Surface potential decay on filament polyester samples rubbing head: steel

Figure 6.10 shows the charge decay measured on the polyester samples rubbed with PTFE. Similar to the steel rubbed samples, the charge decay on the untreated samples is slow and closer to linear while the treated samples show a rapid initial exponential initial decay. The Hydroperm<sup>®</sup> T treated samples show a double exponential decay, a quick initial decay ( $t_e$ ) followed by the slower decay ( $t_l$ ). From the graph it can be observed that the time for its initial exponential decay ( $t_e$ ) depends upon the concentration of the surface finish. Further studies were done to understand the exact nature of the curves.

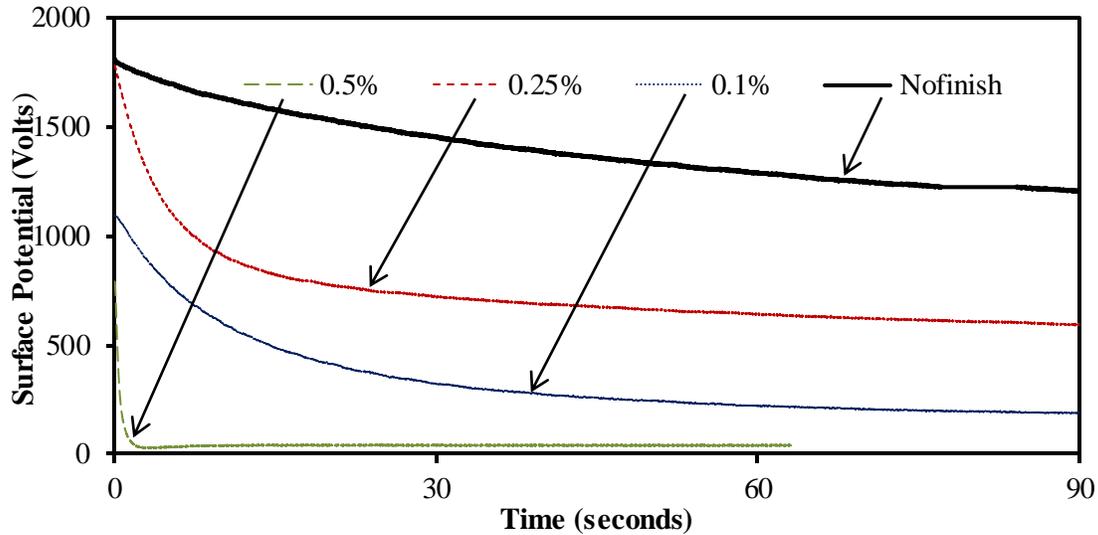


Figure 6.10 Surface potential decay on filament polyester samples rubbing head: PTFE

Curves were fitted to the surface potential decay for the various polyester samples rubbed with steel and the curve fitting are shown in Figures 6.11a to 6.11d.

$$V_{\text{untreated}} = -1.11 t + 443.3 \quad (1)$$

$$V_{0.50\%} = 474 \times e^{-0.7t_e} + 264 \times e^{-0.017 t_l} \quad (2)$$

$$V_{0.25\%} = 717 \times e^{-0.2t_e} + 116 \times e^{-0.017 t_l} \quad (3)$$

$$V_{0.01\%} = 745 \times e^{-0.073t_e} + 687 \times e^{-0.009 t_l} \quad (4)$$

Each curve was divided into sum of the two exponential components. The double exponential decay of charge on the textile fabrics was observed earlier by Ramer (Ramer, 1968). For the untreated polyester, since there is no hydrophilic surface finish was applied, the charge decay is slow and linear. For the other samples, which are treated with Hydroperm<sup>®</sup> T, the curves have been divided into two parts. In the divided curves, initial curve shows a rapid exponential decay of the charge ( $t_e$ ) and then reverts to a slower, almost linear decay ( $t_l$ ).

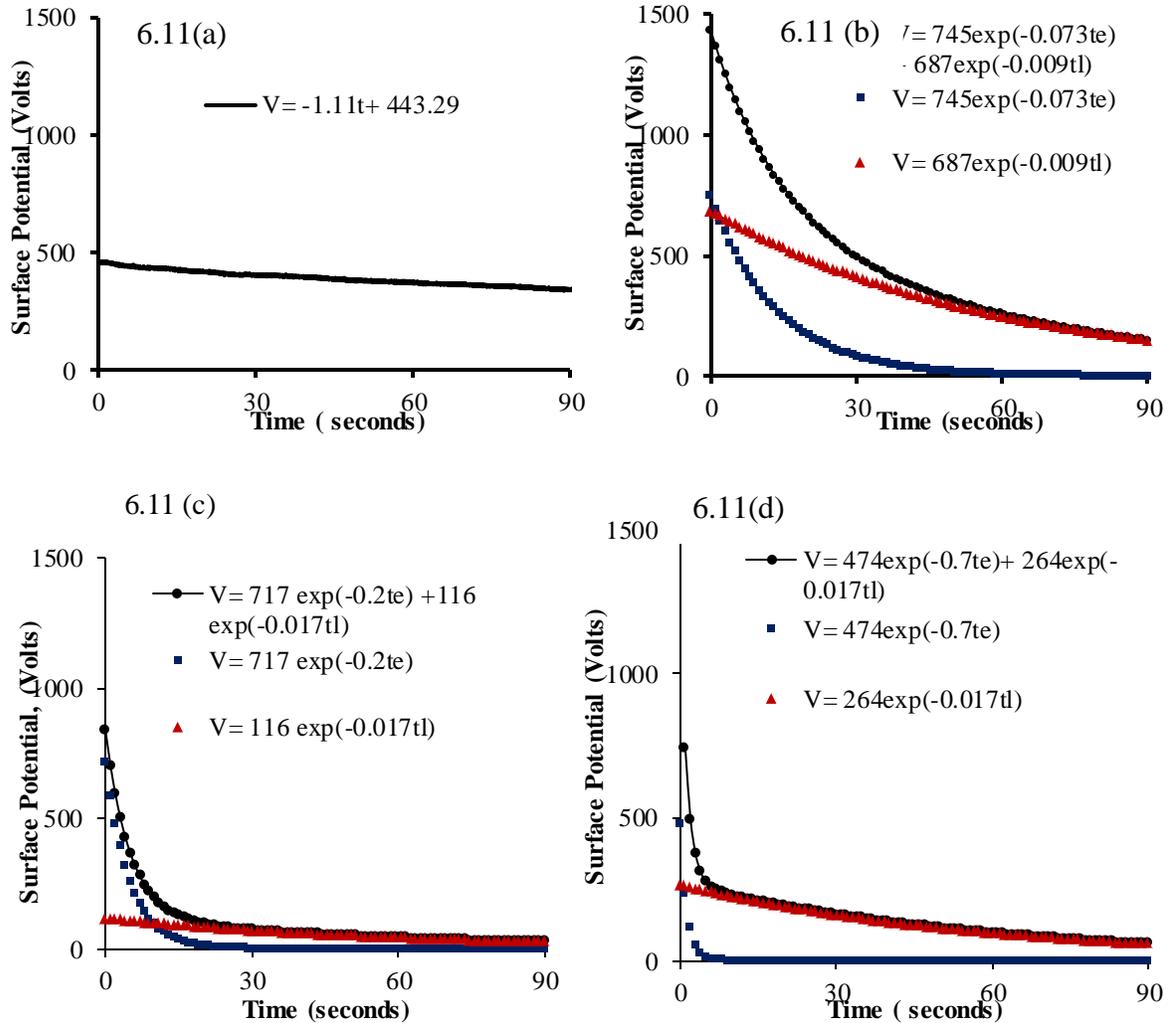


Figure 6.11a-d: Surface potential decay on steel rubbed untreated, 0.1%, 0.25%, 0.5% hydroperm applied polyester samples and the regression curves

From these curve fittings it can be observed that even though the generated charge (surface potential) after rubbing does not directly correlate to the surface finish, the charge decay is directly dependent on the surface finish concentration (Figure 6.8). The data suggests that there are two kinds of mechanisms responsible for the charge decay on the Hydroperm<sup>®</sup> T treated samples, whereas only one mechanism is responsible for the charge decay on untreated samples. Initially the Hydroperm<sup>®</sup> T surface finish allows the charge to decay exponentially and after this initial decay, the surface potential that remains on the sample dissipates by a much slowed, nearly linear mechanism. For all of these Hydroperm<sup>®</sup> T treated

samples initial charge decay takes 7 to 60 seconds (depending upon the concentration of the Hydroperm<sup>®</sup> T solution) and they lose about 80% of the surface potential during this period.

All the charge decay curves are expressed in double exponential decay and the time decay constants for the treated samples rubbed with steel and PTFE are shown in the Table 6.2. The exponential time decay constant for Hydroperm<sup>®</sup> T treated sample indicate that the charge decay for these samples is strongly related to the level of surface treatment. The exponential time decay constant for 0.5 % treated samples is 10 factors more than for the samples treated with 0.1 % concentration. The linear time decay constants appear to be similar for all the treated samples and closely related to that observed for the untreated samples.

Table 6.2 Time decay constants measured for the charge decay measurements

<b>Finish Concentration</b>	<b>Rubbing Head</b>	<b>a</b>	<b>b (t<sub>e</sub>)</b>	<b>c</b>	<b>d(t<sub>l</sub>)</b>
Untreated	Steel	193.5	1.26*10 <sup>-11</sup>	255.7	4.34*10 <sup>-4</sup>
0.1 %	Steel	745.63	0.07	687.87	0.009
0.25 %	Steel	717.92	0.20	116.72	0.017
0.5 %	Steel	474.28	0.70	264.56	0.017
Untreated	PTFE	1002	4.08*10 <sup>-12</sup>	744.5	0.014
0.1 %	PTFE	802.89	0.07	255.83	0.003
0.25 %	PTFE	1010.06	0.19	787.50	0.003
0.5%	PTFE	836.25	1.90	39.48	1.3*10 <sup>-11</sup>

The time taken for the initial exponential surface potential decay for the Hydroperm<sup>®</sup> T applied samples (t<sub>e</sub>), and the amount of charge lost due to exponential decay are shown in Figure 6.12. It can be seen that there is a strong correlation between the exponential decay times and the solution concentration and related surface concentration of the hydrophilic surface treatment. For the 0.5% treated samples, the time for the exponential decay (t<sub>e</sub>) is about 7 seconds and during this time the sample lost about 72% of its accumulated surface potential. Similarly for the 0.25% Hydroperm<sup>®</sup> T applied samples t<sub>e</sub> is 18 seconds and it lost

90% of its generated charge and for 0.1% Hydroperm<sup>®</sup> T applied samples decay  $t_e$  was 52.5 seconds and the sample lost 80% of its surface potential.

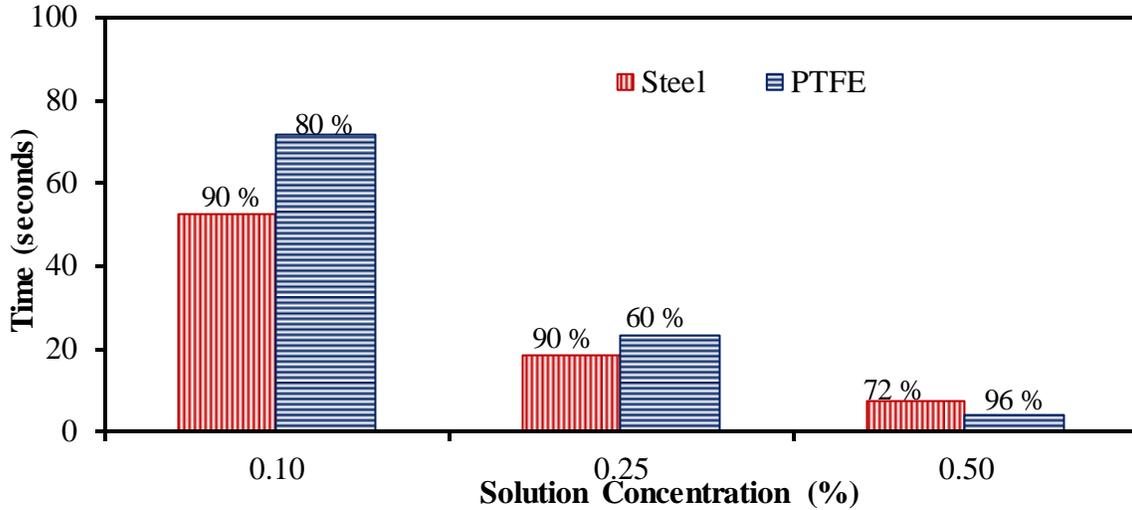


Figure 6.12 Time for exponential decay ( $t_e$ ) on Hydroperm-T treated polyester samples

### 6.3.2 Resistivity Measurements

Figure 6.13 shows the resistivity values measured on the polyester fabrics. Untreated polyester fabric has the highest resistivity (more than  $20000 \times 10^{10}$  ohms/square which is the maximum capacity of the resistivity meter), whereas the Hydroperm<sup>®</sup> T treated samples have the lower resistivity ranging about  $105 \times 10^{10}$  ohms/ square to  $16636 \times 10^{10}$  ohms/ square. Resistivity results indicate that treating with Hydroperm<sup>®</sup> T increases the surface conductivity, which is undoubtedly related to both the charge spreading and the initial exponential charge observed on the fabrics; however, while there is a general correlation of higher concentration with reducing resistivity, it also appears that once one reaches the region of  $10^{12}$  to  $10^{13}$  ohms, the resistivity stabilizes and becomes more complex.

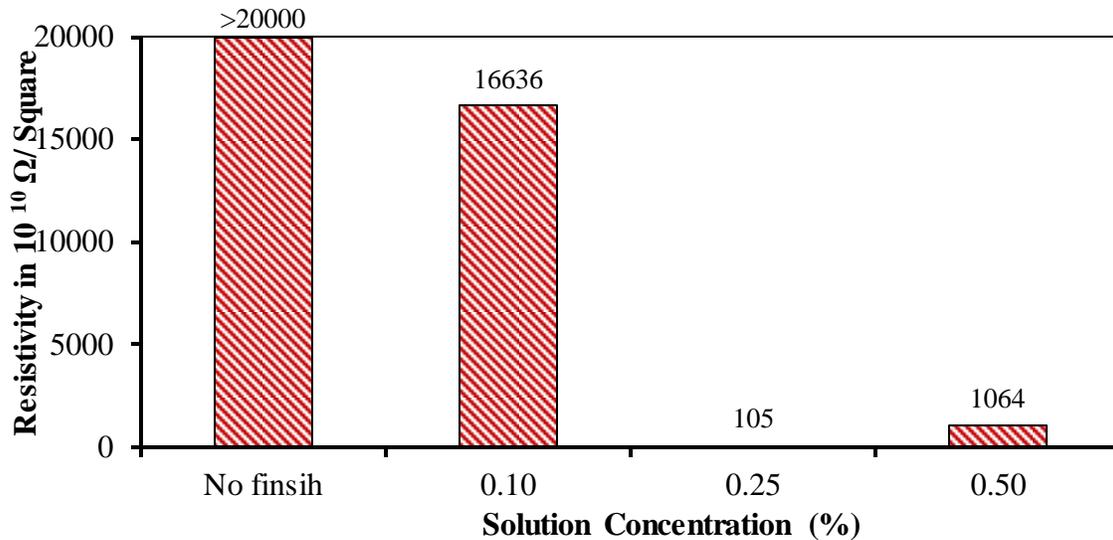


Figure 6.13 Surface resistivity measured on treated and untreated polyester fabrics

The decay of the change in the unrubbed areas shows that even after redistribution of the generated charge from rubbed areas to unrubbed areas the charge decay pattern is linear and appears to be same for all over the fabric. The question that we had hope to shed light on and which still remains is where to the charge go when it dissipates. The main reasons for the charge decay on textile materials is due to leakage inside the material, Leakage into the air, neutralizing by the oppositely charged particles/ions in the air. If these materials are moderately conductive or conductive materials the charge on the surface can be moved throughout the material surface and can be penetrated into the bulk and leaked into ground. When these materials are highly insulating materials the only mechanism that is responsible for charge decay is leakage of the charges in to air. The opposite charges or ions in the air neutralize the charges on the surface and responsible for the charge decay. These charges can also conduct through the air and can reach the neighboring conducting materials around the surface and can be decayed. If the materials are conductors the water in the air can be absorbed by material and can be responsible for the charge decay by conducting through the material. At higher or moderate humid conditions the moisture in the atmospheric air also creates a surface layer even on the insulating materials and responsible for the charge decay. However exact reasons where the charge is going is yet to be answered.

## 6.4 CONCLUSION

Untreated filament polyester fabric and fabrics treated with Hydroperm<sup>®</sup> T with three different concentrations of Hydroperm<sup>®</sup> T (0.1%, 0.25% and 0.5%) were tested for frictional electrification by rubbing with steel and PTFE rubbing heads. These samples were investigated for charge generation after 50 rubbings and charge decay for 120 seconds. There was no clear relationship between the different samples and the charge accumulation observed on treated and untreated fabrics; however, their charge decay behavior were completely different and directly related to the level of hydrophilic material applied to the fabric surface. On the untreated polyester fabric charge decays very slowly and is almost linear. For the Hydroperm<sup>®</sup> T treated fabrics the charge decay is a double exponential mechanism: initially the charge decays rapidly and exponentially ( $t_e$ ) and is then followed by slower decay ( $t_l$ ). The exponentially decayed charge on the treated samples spreads rapidly to the entire surface of the fabric samples. At the end of the rubbing cycles, the final decay of the charge in both the rubbed and unrubbed areas clearly parallels each other. This charge migration and apparent decay based on a larger surface area is clearly related to the rapid initial decay of the treated samples. For untreated fabrics the charge remains on the rubbed area and does not migrate towards the unrubbed area.

When fabrics treated with various concentrations of Hydroperm<sup>®</sup> T, we were able to directly relate the rate of initial charge decay to the level of hydrophilic treatment applied to the fabric. To understand character of the decay process, we analyzed in detail the shapes associated with each cure. All curves showed a double exponential decay process that was associated with the charge decay (loss of charge from the fabric surface). These double exponential decay curves could be divided into an initial rapid charge decay stage and slower, nearly linear decay stage. The duration of the initial rapid decay ( $t_e$ ) is highly dependent on the concentration of the Hydroperm<sup>®</sup> T applied to the fabric.

When these samples were tested for resistivity measurements, the untreated polyester samples showed the expected very higher resistance and the treated samples much lower resistance. While there is a general pattern of resistance reduction in the treated samples, the

resistance reduction seems to maximize at intermediate concentrations after which the behavior seems to become more complex.

We are proposing a two phase decay mechanism to explain these observations. The initial decay is rapid and exponential and directly related to the surface conductivity of the fabric and the ability of the charge to spread over the entire surface of the fabric. The secondary decay is much slower and linear and while the level of this type of charge seems to be greatly reduced by the hydrophilic treatment, the rate at which it dissipates does not seem to be directly related to the level of hydrophilic surface treatment. The secondary decay is due to the decay of the charges into the air. The secondary decay is due to the neutralization of surface charges by the ions in the air or can be leakage of charges towards the neighboring conductors through air.

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## **CHAPTER 7**

### **EFFECT OF ANTI-STATIC AND HYDROPHILIC SURFACE FINISHES ON ELECTROSTATIC PROPERTIES OF POLYESTER AND NYLON WOVEN TEXTILE FABRICS**

# **EFFECT OF ANTI-STATIC AND HYDROPHILIC SURFACE FINISHES ON ELECTROSTATIC PROPERTIES OF NYLON WOVEN FABRICS**

## **7.1 INTRODUCTION**

Static electricity is a very old phenomenon observed by researchers in ancient times (600 B.C.). When two materials are rubbed or/and contacted with each other static electricity is generated. Textile materials, especially synthetic fibers are highly insulated materials with a volume conductivity of about  $10^{16}$  ohms-cm. These generated static charges create many problems during the processing of textile materials. The problems created include ballooning of yarns, damage to electronic equipment and shocks to the people. However there are several applications based on the static electric charge generated during rubbing/contact. The main applications of static electric charge are air filters, transducers etc.

The detrimental effects of surface charges can be avoided by increasing the conductivity of the textile materials by humidity and by adding static electric finishes to the fabrics. The static electric finishes used are either durable or non-durable. Nondurable antistatic finishes include cationic anti static quaternary ammonium salts, nonionic anti-static finishes and phosphate esters. These anti-static finishes increase the surface conductivity of the fabrics by reducing the frictional forces through lubrication. By increasing the surface conductivity, lower surface charge is generated and accumulated and also helps the charge to dissipate quickly. The increase in the lubrication also reduces the charge generation.

## **7.2 EXPERIMENTAL**

### ***7.2.1 Sample Preparation***

Finish free filament and spun nylon fabrics were initially cleaned with deionized water at 70°C for 20 minutes and then washed with 2-propanol at room temperature for 20 minutes to remove any surface contaminants. Then the fabrics were dried at 80° C for 40 minutes. The stainless steel/ PTFE rubbing surface was also cleaned with 2-propanol. Before each test, any residual charge that stayed on the sample was removed by the deionizer gas. A complete description of the sample preparation is explained Section 4.1.

These solutions were sprayed on the fabric surface using an airbrush following the procedure recommended by Lu (2010). After the application of the surface treatment, the fabric was dried at the room temperature for 45 minutes. The samples were subsequently moved to the environmental room for conditioning for 48 hours at testing conditions of about 21°C and 43 % RH. Application of surface finishes is explained in the section 5.2.2

### ***7.2.2 Materials and Experimental Design***

#### ***Experimental Design I***

Two kinds of surface finishes were used to investigate the charge generation and decay on nylon fabrics. Commercially available antistatic finishes, Leomin<sup>®</sup>PN (C12Phosphate, K+Neutralized made by Hoechst AG) and Larostat<sup>®</sup>264 A (Dimethyl Oleyl Amine Diethyl Sulfate Quaternary Finish made by BASF), and a hydrophilic finish (Aquatex uno 21% made by Mount Vernon chemicals) as well as an experimental moisture management finish (made by Tenstech Inc.) are applied on the nylon surfaces. After the finish has been applied heat treatments were not applied, as suggested by Slade (1998).

Table 7.1 Experimental design - I

<b>Parameters</b>	<b>Levels</b>
Fabrics	Filament Nylon, Spun Nylon
Contact charging heads	Steel and PTFE
Anti-static finishes	Larostat <sup>®</sup> 264 A , Leomin <sup>®</sup> PN
Hydrophilic Finishes	Aquatex Uno 21%, Sryde 100b

Responses measured are charge measured after first rubbing, charge accumulated after fifty rubbings and half life time decay.

#### ***Experimental Design II***

Rubbing measurements were done on the nylon fabrics treated with the various anti-static and hydrophilic finishes.

Table 7.2 Experimental design - II

Parameters	Levels
Fabrics	Filament Nylon, Spun Nylon
Rubbing charge heads	Steel and PTFE
Anti-static finishes	Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN
Hydrophilic Finishes	Aquatex Uno 21%, Sryde 100b

### 7.2.3 Signal Analysis

Rubbing and contact charging instruments and signal analysis are explained in chapter 5.2.

## 7.3 RESULTS AND DISCUSSION

### 7.3.1 Experimental Design - I

Charge density measured on filament nylon after initial contact is shown in Figure 7.1. Contacting with PTFE charged higher charge than contacting with steel, as previously observed on unfinished samples (Section 4.4). Steel contacted and PTFE contacted samples are compared separately using Tukey's HSD method. On filament nylon fabrics, contact charged with steel and PTFE, hydrophilic finish treated (Aquatex Uno and Sryde 100b) samples are statistically different from other untreated and antistatic finish treated samples (P value 0.027 from Appendix Table D3).

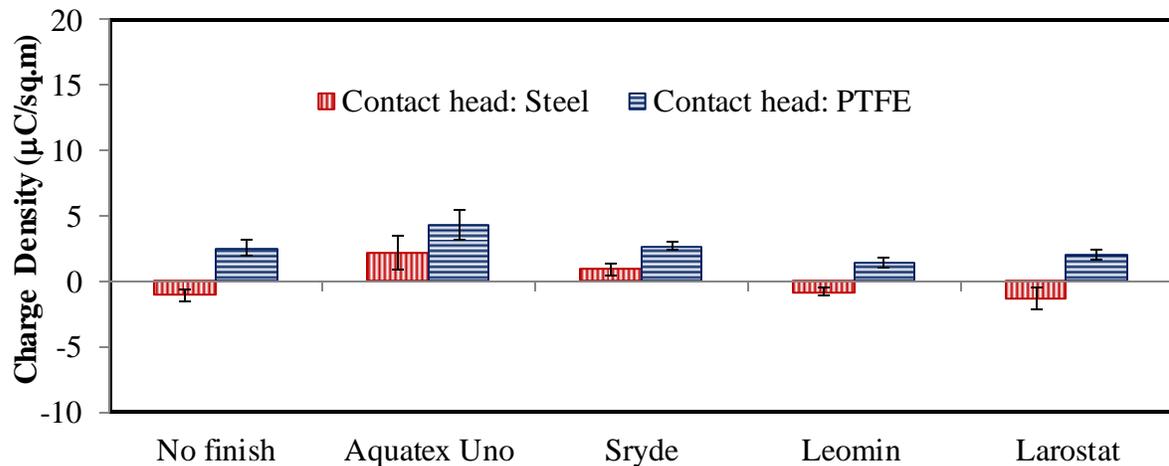


Figure 7.1 Charge measured after initial contact on filament nylon fabrics treated with surface finishes

Charge measured on untreated and antistatic finish treated samples is not statistically different (these materials are classified into same group as shown in Appendix Tables D3 and D6). PTFE contacted samples (all the samples) are charged positive, when contacted with steel, untreated and antistatic finish treated samples charged negative, whereas hydrophilic treatments caused the charge reversal (from negative to positive). Treating with hydrophilic finishes reverses the charge polarity, generates higher charge than the untreated samples. Compared with hydrophilic finishes, antistatic treatments showed better performance in reducing the static charge generation

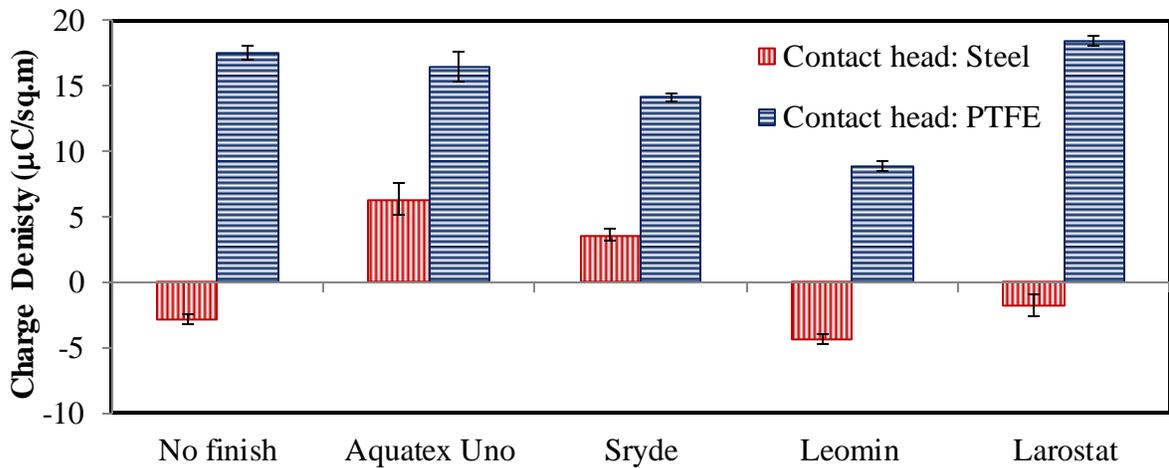


Figure 7.2 Charge measured after fifty contacts on filament nylon fabrics treated with surface finishes

Charge accumulated on filament nylon samples after 50 contacts with steel and PTFE are shown in Figure 7.2. PTFE contacted samples accumulated higher charge, when compared with steel. Polymer-polymer contact always generated a much higher charge than the charge generated by polymer-metal contacts as discussed in chapter 4. This could be attributed to the charge loss observed by the polymer-metal contacts. Effect of surface treatments on samples contacted with steel and PTFE are statistically compared using Tukey’s HSD test method in the appendix (see tables D7-D12). Steel contacted samples are statistically different (P value 0.005) from each other and categorized into three groups. Hydrophilic treated samples charged positive are grouped A, Leomin<sup>®</sup> PN treated samples are grouped C (higher negative

charge compared to untreated samples) and untreated and larostat treated samples are grouped B. However, PTFE contacted samples are categorized into two groups. Treatment with Leomin<sup>®</sup> PN reduces the charge generation on filament nylon and grouped separately, whereas no significant difference has not found on other fabrics and belonged to the same group.

Charge density measured on spun nylon samples after their first contact and fifty contacts are shown in Figure 7.3 and 7.4 respectively. Tukey's HSD tests are made and statistical analysis is shown in the appendix (Tables D13- D24). Important observations are

- PTFE contacted samples are charged higher compared with steel contacted samples.
- For the all the contact charge measurements with steel and PTFE, significant difference has been found between Aquatex Uno treated samples and other samples (P value <0.0001). Similar observations were found on filament nylon fabrics as discussed previously.
- Hydrophilic finish Aquatex Uno is responsible for higher charge generation on filament and spun nylon fabrics.

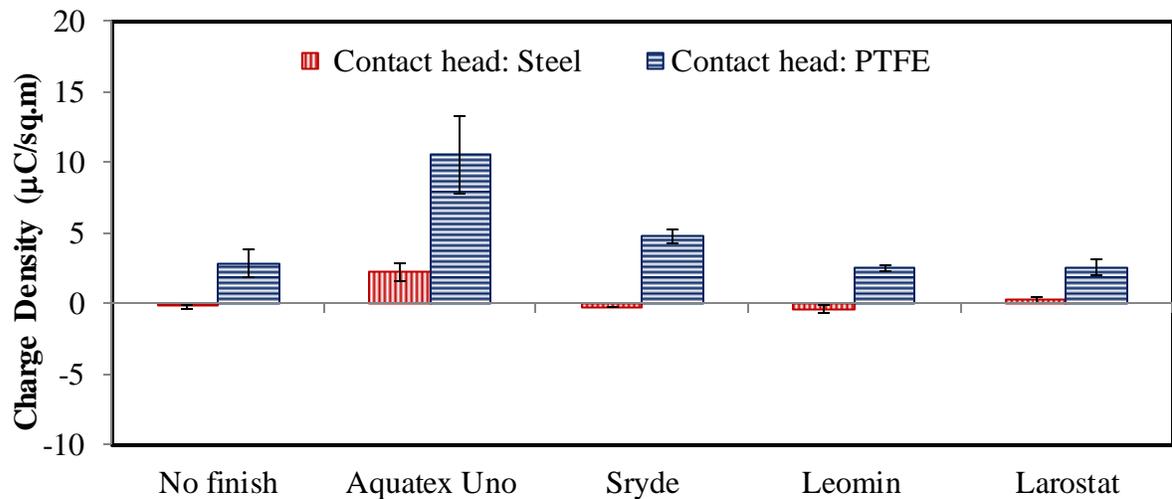


Figure 7.3 Charge measured after initial contact on spun nylon fabrics treated with surface finishes

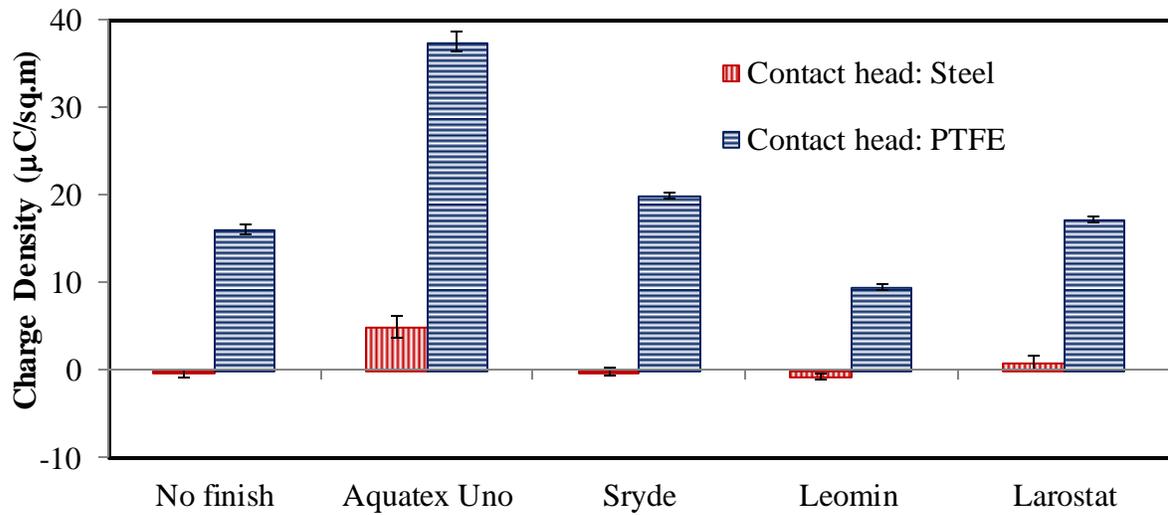


Figure 7.4 Charge accumulated after fifty contacts on spun nylon fabrics treated with surface finishes

### 7.3.2 Experimental Design - II

Charges generated on filament nylon samples after first rubbing and after fifty rubbing are shown in Figure 7.5 and 7.6 respectively. Compared to the contact charging samples, untreated filament nylon samples are charged with positive when they rubbed with steel. In the triboelectric series, nylon is on the top of the table and is supposed to be charged positive when it is contacted/ rubbed with steel. However, the same nylon fabric has a positive charge when rubbed with steel and a negative charge due to contact charging. The observed reversal in polarity could be due to the differences in charging mechanism in contact and rubbing charging, which was discussed in the chapter 4. The exact mechanism which is responsible for the differences in change in polarity is not found. The charge measured after the first cycle of rubbing and charge accumulated after fifty rubbing are studied for statistical analysis using Tukey's HSD method and results are shown in the appendix (Tables E1- E12). Important observations made are

- No significant difference was found on the untreated filament nylon samples and samples treated with anti-stat finishes and hydrophilic finishes (P value 0.1063 for initial charge

measurements from table and P value 0.55 for charge measured after 50 rubbings from tables E2 and E8 in Appendix) and rubbed with steel.

- When contacted with steel, hydrophilic treated filament nylon samples charged negative and during rubbing change in the polarity has been observed. Though exact differences for the change in polarity are hard to explain, we can expect that charging mechanisms of contact and frictional electrification are different. Similarly Larostat<sup>®</sup>264A samples charged positive during contact charging with steel and while rubbing negative charge was generated.
- Effect of hydrophilic finishes has significant influence (P value 0.009 from Table E5 Appendix) on the charge generated after the initial rubbing with PTFE on filament nylon fabrics. Due to the lower charge generated Tukey's HSD test group's untreated nylon and Leomin treated nylon into group B and hydrophilic treated nylon samples into different group (group A).
- For PTFE rubbed samples, Topical finishes has no significant effect, on the charge accumulated after fifty rubbings (P value 0.1540 from Table E 11 Appendix).

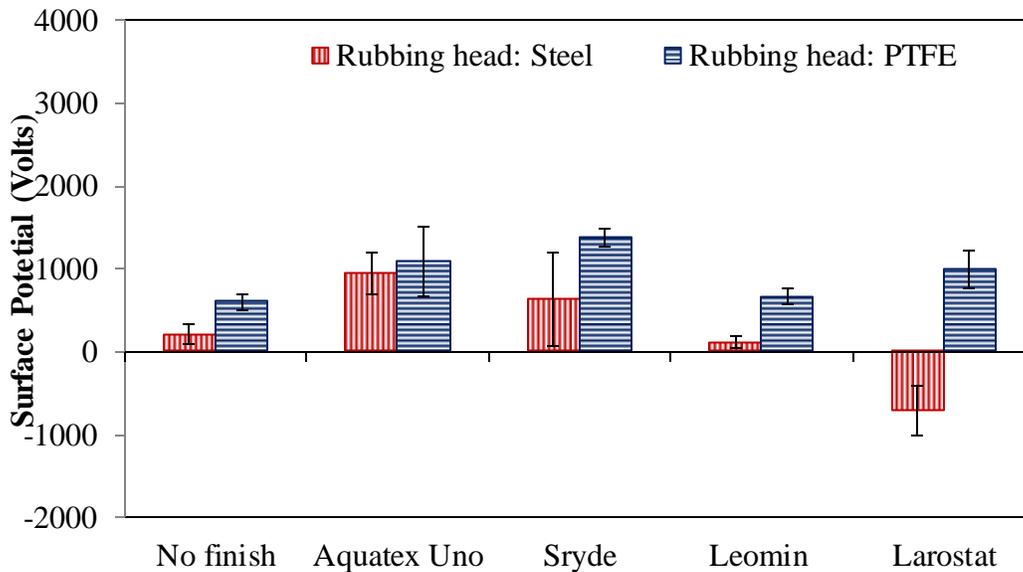


Figure 7.5 Charge generated after first rubbing cycle on filament nylon fabrics treated with surface finishes

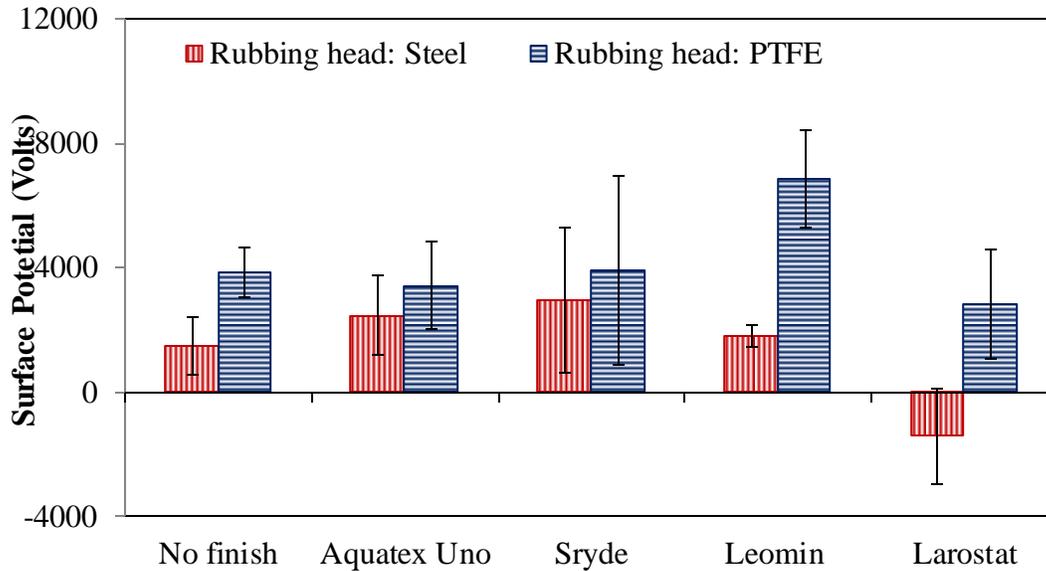


Figure 7.6 Charge accumulated after fifty rubbing cycles on filament nylon fabrics treated with surface finishes

Charge generated after an initial cycle of rubbing and charge accumulated after 50 cycles of rubbing on spun nylon fabrics are shown in Figures 7.7 and 7.8 respectively. Statistical analysis was made using Tukey's HSD test to find the significant differences on charge measured due to effect of applied surface finishes (see Tables E13- E24 in the Appendix). Significant observations made are

- No significant difference was found on the untreated spun nylon and samples treated with anti-stat finishes and hydrophilic finish and rubbed with steel. (P value 0.059 for charge measured after 50 rubbings from tables E20 in Appendix)
- Untreated and Sryde treated samples generated positive charge when rubbed with steel, whereas the samples charged negative. Effect of these topical finishes found to be different for filament and spun nylon fabrics.
- For PTFE rubbed samples, the charge accumulated after initial rubbing and after fifty rubbings is statistically different (P value < 0.0001 and 0.0013 from tables E 16 and E 23 in the Appendix respectively). Antistatic finishes (Leomin<sup>®</sup> PN and Larostat<sup>®</sup> 264A) found to be effective in reducing the charge generation and accumulation. Tukey's HSD

test categorizes the anti-static finish treated spun nylon fabrics different from the other spun nylon fabrics.

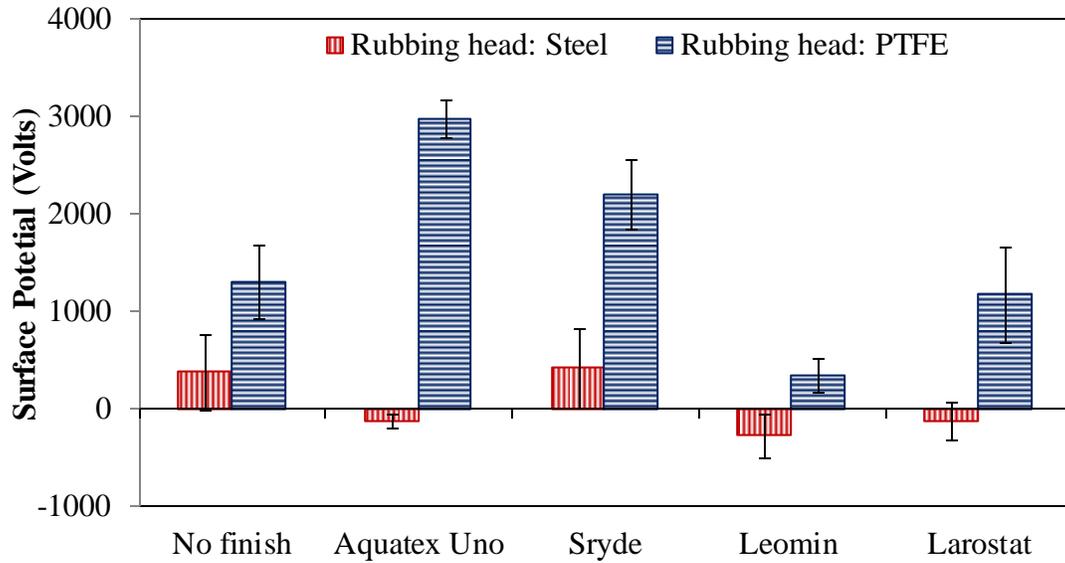


Figure 7.7 Charge measured after first rubbing cycle on spun nylon fabrics treated with surface finishes

The effect of antistatic and hydrophilic finishes proved to be different for spun and filament nylon fabrics. Antistatic finishes are found to be more effective in reducing the charge generation than the hydrophilic treatments on spun nylon fabrics. These observations were more profound when these samples are rubbed with PTFE. Similar observations were found on polyester fabrics (chapter 5). Anti-static finishes are effective on reducing the charge generation and accumulation. Hydrophilic finishes are not effective on charge generation, however they found to be effective in charge decay properties of the polyester fabrics. Hence, the charge decay properties (half-life decay time) are discussed in the next section.

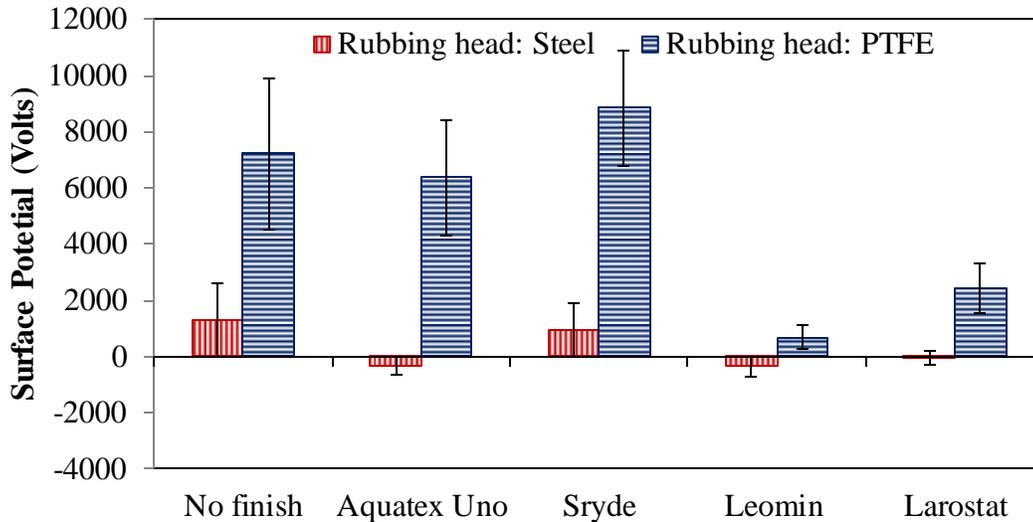


Figure 7.8 Charge accumulated after fifty rubbing cycles on spun nylon fabrics treated with surface finishes

### 7.3.3 Charge Decay Measurements

#### *Contact charge decay*

Charge decay measurements on filaments nylon treated with various topical finishes are shown in the Figure 7.9. These samples are contacted with 50 contact cycles and then measured for the half-life charge decay time inside the faraday cage. To understand the influence of the surface finishes on the charge decay time, statistical analysis has been done and reported in the appendix. Tukey's HSD test is used and these materials are grouped as shown in Tables F2-F4 in the Appendix. Charge decay on Anti-stat treated samples is statistically different from the other samples (P value 0.0019 from Table F3 in Appendix). Hydrophilic treatments have not significant influence on the charge decay properties of the filament nylon fabrics.

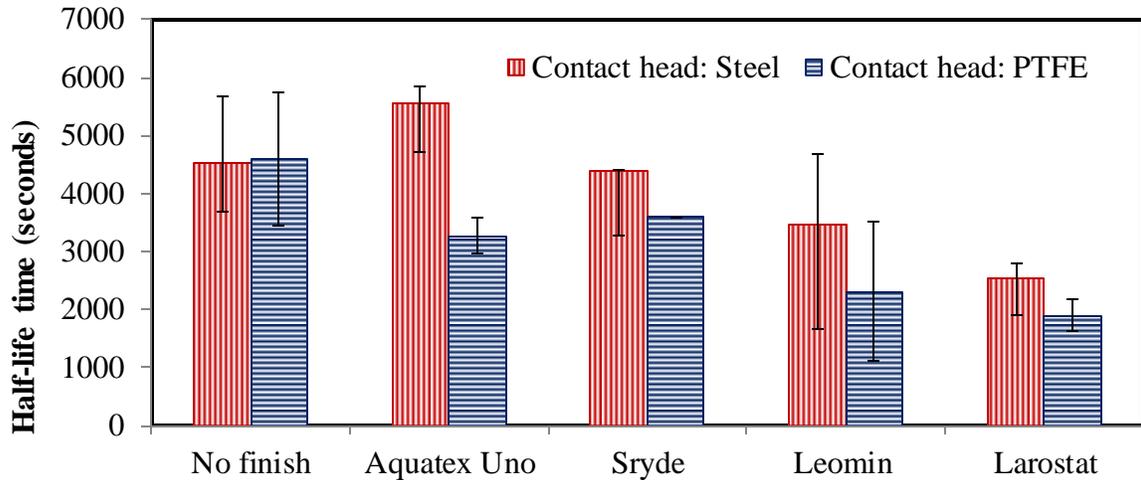


Figure 7.9 Charge decay measured on filament nylon fabrics treated with surface finishes and contacted with PTFE and Steel

Half-life time decay measured on fabrics made from spun nylon that undergoes for contact charging is shown in Figure 7.10. Statistical analysis shows that the topical finishes have significant influence (P value 0.0003 from Table F6 in Appendix) on the charge decay properties of filament nylon fabrics. Tukey's HSD test categorizes the materials into two groups. Aquatex Uno applied samples are grouped A and Sryde applied samples are grouped into B. Untreated and antistatic finish applied samples are grouped both A and B.

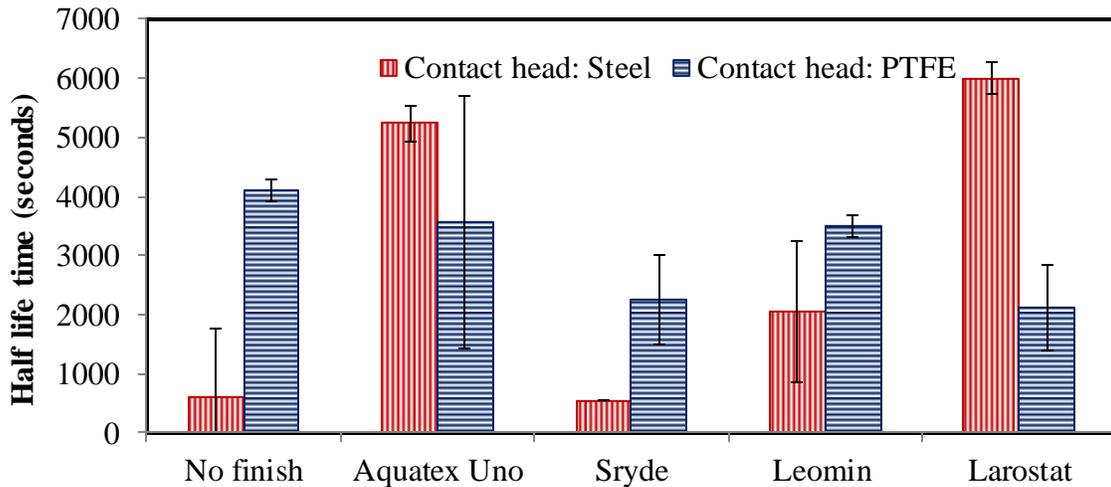


Figure 7.10 Charge decay measured on spun nylon fabrics treated with surface finishes and contacted with PTFE and steel

### ***Rubbing charge decay***

Half life time decay, measured on filament nylon fabrics undergone rubbing charging measurements are shown in the Figure 7.11. Statistical analysis to study the effect of topical finishes on charge decay was done using Tukey's HSD test. The topical finishes applied on the filament nylon have significant influence (P value 0.0008 from Table F10 in Appendix) on the charge decay properties. When the materials are classified, untreated samples are grouped A (slower charge decay) compared to anti-stat and hydrophilic treated filament nylon fabrics (grouped B). Compared to the contact charged samples (half-life time of about 1400-4400 seconds) charge decay on rubbing charged samples is much quicker (33-267 seconds). Hydrophilic finishes are more effective in controlling the charge decay on the filament nylon fabrics. Charge decay on antistatic finish treated nylon is quick, when compared with the unfinished nylon fabrics however, slower compared to hydrophilic finish treated samples. Nylon contain OH groups, when the hydrophilic finish is applied, these OH groups would attract more water molecules from the which helps the conductivity increases and helps the charge to decay very quickly.

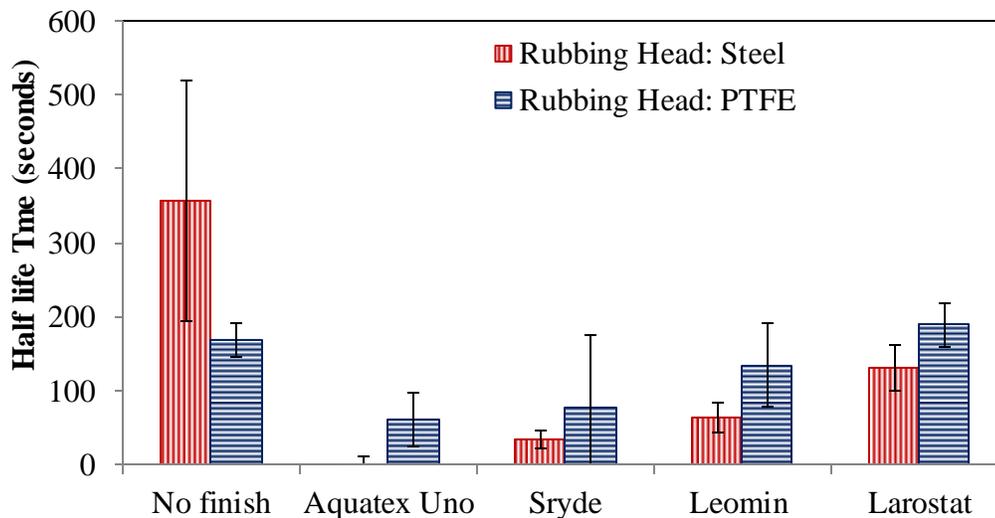


Figure 7.11 Charge decay measured on filament nylon fabrics treated with surface finishes and rubbed with PTFE and steel

Half life time decay measured on spun nylon fabrics treated with PTFE is shown in Figure 7.12. Charge accumulated on spun nylon rubbing with steel is smaller; hence the half-life decay time could not be measured. Statistical analysis to study the effect of topical finishes is shown in the Table F14 in the Appendix. The applied finishes has significant effect on the charge decay times of the nylon fabrics (P value <0.0001). When these materials are grouped based on the half-life decay time observed, sryde applied and untreated nylon are grouped A with slower charge decay time compared to other surface treated samples in group B.

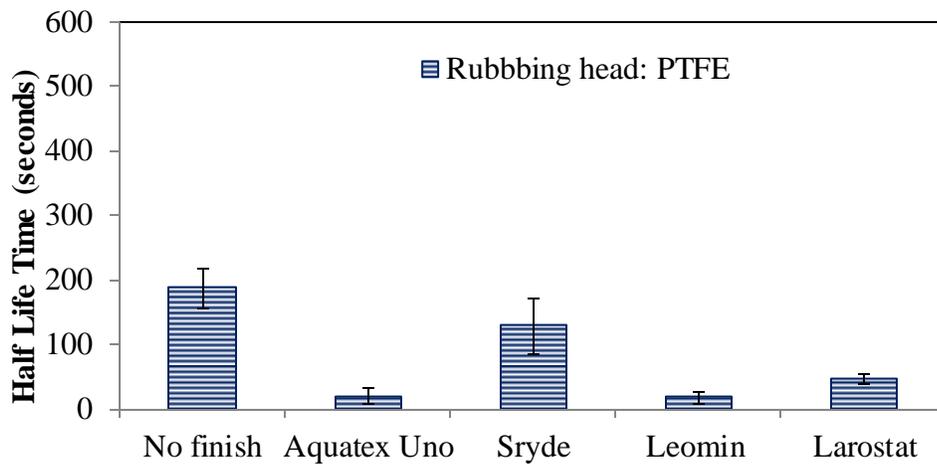


Figure 7.12 Charge decay measured on spun nylon fabrics treated with surface finishes and rubbing with PTFE

#### 7.4 CONCLUSION

Fabrics made from filament and spun nylon fibers are treated with commercially available antistatic finishes and hydrophilic finishes and tested for static electrification measurements. Based on the contact and frictional charge measurements on the fabrics treated with same surface finishes, it is found that charge generation mechanism for contact and frictional charging are different. Surface finishes applied has not significant influence on the charge generation and accumulation properties. However, these finishes have greater influence on the charge decay properties of the nylon. Effect of Hydrophilic and antistatic finishes applied

on spun and filament nylon fabrics are not the same. Greater differences between contact and rubbing charge measurements in the charge accumulation and charge decay properties also been observed. Charge decay during contact charging is slower ( $>2000$  seconds), whereas the rubbing charge decay time observed to be quicker ( $<270$  seconds). This could be due to the reason the fabric is shielding inside a faraday cage. Higher charge is accumulated on spun nylon fabrics than the filament nylon fabrics; this could be due to the higher surface area of the spun nylon fabrics when compared with the filament nylon fabrics.

**CHAPTER 8**  
**CONCLUSIONS**

## CONCLUSIONS

This research is focused to answer some of the questions which are needed to be answered to understand the electrostatic charge generation and dissipation mechanism on textile materials. The experiments are divided into four categories

1. Frictional and contact charging measurements on finish free fabrics
2. Frictional electrification and charge decay on cotton and polyester fabrics
3. The effect of hydrophilic finish with three different concentrations on polyester woven fabrics
4. The effect of anti-static and hydrophilic finishes on polyester and nylon fabrics

Conclusions for each chapter were given at the end of the chapter. Here is the summary of the important observations.

Working with clean finish free textile fabrics made from different polymers indicates that polymer-polymer charging is always higher than polymer-metal charging. This could be attributed to the rubbed insulator surface and charge back flow during frictional electrification with metal. No relation has been found between the charge generation and the surface resistivity of the textile materials. However, resistivity has an influence on charge dissipation mechanism/properties of these textile materials. Nylon, which is placed on top of the triboelectric series, generates more charge than the other materials tested in this work. The surface of nylon is very sensitive and the amide bonds are responsible for greater charge generation on the nylon surface. The polarity of the charge generated during contact and rubbing charging of nylon-steel are found to be different, which indicates the charge mechanism for contact and rubbing charging could be different. Hence the contact and triboelectric series expected to be different from each other.

Antistatic finishes are found to be highly effective on reducing the charge generation on spun and filament polyester fabrics. Moderate charge is generated on cotton and polyester fabrics treated with hydrophilic finishes, but this charge dissipates very quickly. On a large fabric when only part of the fabric is rubbed, it was observed that the generated charge on these fabrics has been moves to the unrubbed areas of the fabric. The charge decays very quickly

until it reaches same level on rubbed and unrubbed areas and then decays slowly. However, where the decayed charge goes is the question which needs to be answered. Ions in the air could be one of the major factors which influence the charge decay. This was observed on the contact charged samples which are stored inside a faraday cage against the ions in the air; the observed charge decay is slow when compared with the rubbing charged samples.

The charge decay on polyester, nylon and polypropylene is linear and slow. Commercial antistatic finishes are highly effective on polyester fabrics, polyester fabrics treated with these finishes; contacted/rubbed with PTFE much less charge is generated. The charge decay on Hydrophilic finish applied polyester is double exponential decay; the charge dissipation starts with an exponential and follows a linear decay. When hydrophilic finishes of different concentrations are applied on polyester fabric, the exponential decay component of the charge decay is depends on the solution concentration applied on the fabric. The charge generated is not influenced by the solution concentration but the charge decay is influenced by the hydrophilic finish applied. Nylon has more sensitive surface, hence more thorough cleaning is required to obtain a clean nylon surface. Also, these commercially available anti-static finishes have less effect on nylon than polyester in reducing the electrostatic charge generation.

## APPENDIX

### Statistical Analysis

In this research seven different fabrics made from four different polymers such as cotton, polyester, polypropylene and nylon were investigated with two different contact heads. We measured responses including charge measured after initial contact/rubbing and charge measured after 50 contacts/ rubbings. If there are only two population means to be compared, a two sample T test is used. The difference in the sample means is evaluated by calculating the test statistic “t” and comparing with the critical t value obtained from the students “t” distribution table at significance level  $\alpha=0.05$ . However if there are more than two population means needs to be compared, Analysis of Variance (ANOVA) is adopted to compare the different means. The test static “F” is calculated to determine the variability between the samples is larger than the variability within the samples. If the computed value “F” is larger than the critical value obtained from the F distribution table, the alternative hypothesis is true that at least one of the t population means is different from the others. Although this testing gives the information of whether or not the means of the populations are different from each other, we don’t know which means are different. To answer these questions multiple comparison procedures have been developed (Ott, 2001).

In this research Tukey’s Honest Significant Difference (HSD) test is adopted to compare the effects of rubbing material (steel or PTFE), number of rubbings and fabric type. Tukey’s test is similar to t-test but, when multiple comparisons are made, the probability of making a type-I error increases. Tukey’s test corrects this experiment-wise error rate. All of the statistical analysis was made using SAS 9.1 software and the results are described below.

The assumptions to do this test are

1. All the observations tested in this research are independent
2. The variance across the populations are equal

**A. Rubbing Charge Measurements on untreated samples Chapter 4 (section 4.3.2)**

Table A1 Experimental design: Rubbing charge measurements - Finish free fabrics

Class	Levels	Values
Blend	7	Cotton I, Cotton II, Filament Nylon, Spun Nylon, Filament Polyester, Spun Polyester, Spun Polypropylene
Rubbing material	2	Steel and PTFE
Number of rubbing cycles	2	Fifty rubbing Cycles, First rubbing Cycle
Total runs	$7 \times 2 \times 2 = 28$	

Each run was replicated for 3 times and a total of 84 observations were made

Table A2: Overall ANOVA for Rubbing charge measurements – Finish free fabrics

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Due to rubbing	8	137968457.9	17246057.2	12.07	<.0001
Error	75	107197892.5	1429305.2		
Corrected total	83	245166350.5			

R-Square    Coeff. Var.    Root MSE    Charge Mean  
 0.562754    120.5175    1195.536    992.0019

Table A3: Type I ANOVA for rubbing charge measurements: finish free samples

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Blend	6	45972456.10	7662076.02	5.36	0.0001
Rubbing material	1	58230911.66	58230911.66	40.74	<.0001
Number of rubbings	1	33765090.16	33765090.16	23.62	<.0001

Table A4 Tukey's grouping of finish free rubbed samples

Tukey's grouping	Mean	N	Blend
A	2543.1	12	Spun Nylon
B A	1546.4	12	Filament Nylon
B	707.7	12	Polypropylene
B	704.7	12	Filament Polyester
B	674.2	12	Cotton II
B	622.6	12	Cotton I
B	145.3	12	Spun Polyester

Means with the same letter are not significantly different.

**Analysis:**

- The effect of polymer blend of the fabric has significant influence on the amount of charge generated (P value 0.0001) during rubbing.
- Tukey's HSD test groups the fabrics used in the research into two categories. Nylon fabrics accumulated higher charge and are categorized in group A, whereas the other fabrics are placed in group B. However, some fabrics rubbed with steel are charged negative and the samples rubbed with PTFE are charged positive, hence it would be meaningful to compare the samples charged with steel and PTFE separately.
- The charge generated due by rubbing with steel is statistically different (P value < 0.0001), and much lower than the charge generated after rubbing with PTFE.
- Influence of the charge generated after first contact and 50 contacts are statistically different (P value < 0.0001). As the number of rubbing cycles increases the charge accumulated increases.

Further samples "rubbed with Steel and PTFE" are compared separately to find is there any statistically significant difference on the charge accumulated after 50 rubbing cycles.

Table A5 Experimental design: Rubbing charge measurements: finish free fabrics with *PTFE*

Class	Levels	Values
Blend	7	Cotton I, Cotton II, Filament Nylon, Spun Nylon, Filament Polyester, Spun polyester, Spun polypropylene
Rubbing material	1	PTFE
Number of rubbing cycles	1	Fifty rubbing Cycles
Total number of runs	7x1x1= 7	

Each run was replicated for 3 times and a total of 21 observations were made

Table A6: Overall ANOVA for Rubbing charge measurements –Finish free fabrics with PTFE

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Due to PTFE	6	77341988.0	12890331.3	6.79	0.0016
Error	14	6596916.8	1899779.8		
Corrected total	20	103938904.7			

R-Square    Coeff. Var.    Root MSE    Charge Mean  
 0.744110    45.98016    1378.325    2997.651

Table A7: Tukey's grouping for finish free fabrics rubbed with *PTFE*

Tukey's Grouping	Mean	N	Blend
A	7210	3	Spun Nylon
B A	3858	3	Filament Nylon
B	3236	3	Polypropylene
B	1914	3	Cotton II
B	1838	3	Filament Polyester
B	1550	3	Cotton I
B	1379	3	Spun Polyester

Means with the same letter are not significantly different.

**Analysis:**

- PTFE rubbed samples are grouped into two categories. Spun and filament nylon are charged higher and belongs to group A, whereas all other samples belong to group B.

Table A8: Experimental design: Rubbing charge measurements: finish free fabrics with *Steel*

Class	No.of levels	Levels
Blend	7	Cotton I, Cotton II, Filament Nylon, Spun Nylon, Filament Polyester, Spun polyester, Spun propylene
Rubbing material	1	Steel
Number of rubbing cycles	1	Fifty rubbing Cycles
Total number of runs	7x1x1= 7	

Each run was replicated for 3 times and a total of 21 observations were made

Table A9: Overall ANOVA for Rubbing charge measurements –Finish free fabrics with Steel

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Due to steel	6	15567095.32	2594515.89	6.89	0.0015
Error	14	5275053.67	376789.55		
Corrected Total	20	20842148.99			

R-Square    Coeff Var    Root MSE    Charge Mean  
0.746905    241.3173    613.8319    254.3671

Table A10: Tukey's grouping for finish free fabrics rubbed with *steel*

Tukey's Grouping	Mean	N	Blend
A	1513.7	3	Filament Nylon
A	1285.8	3	Spun Nylon
B A	465.5	3	Filament Polyester
B A	153.0	3	Cotton II
B A	66.7	3	Filament Polyester
B	-830.1	3	Cotton I
B	-874.0	3	Spun Polyester

Means with the same letter are not significantly different.

**Analysis:**

PTFE rubbed samples are grouped into two categories. Spun and filament nylon are charged higher and belongs to group A, where are all other samples belong to group B

**B. Contact Charging Measurements on untreated samples Chapter 4 (section 4.3.2)**

Table B1 Experimental design: Contact charge measurements on finish free fabrics

Class	Levels	Values
Blend	7	Cotton I, Cotton II, Filament Nylon, Spun Nylon, Filament Polyester, Spun polyester, Spun propylene
Contact Material	2	PTFE, Steel
Number of Contacts	2	Single contact, Fifty Contacts,
Total number of runs	7x2x2= 28	

Each run was replicated for 3 times and a total of 84 observations were made

Table B2 Overall ANOVA for contact charge measurements –Finish free fabrics

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Due to charging	8	1934.122012	241.765251	18.43	<.0001
Error	75	984.032030	12.120427		
Corrected Total	83	2918.154042			

R-Square	Coeff. Var	Root MSE	Charge Mean
0.662790	123.6602	3.622213	2.929167

Table B3 Type I ANOVA for contact charge measurements –Finish free fabrics

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Blend	6	145.709200	24.284867	1.85	<b>0.1006</b>
Contact Material	1	1383.567001	1383.567001	105.45	<.0001
Number of contacts	1	404.845811	404.845811	30.86	<.0001

**Analysis:**

- The effect of the polymer blend of the fabric has not significantly influenced the amount of charge generated (from the P value 0.1006 in Table B3). Some of the materials contacted with steel are charged negatively, hence it would be important to compare the samples charged steel and PTFE separately.
- The charge generated after contacting with steel is statistically different (P value < 0.0001) from the charge generated after contacting with PTFE
- The influence of the charge generated after first contact and 50 contacts are statistically different (P value < 0.0001).

To find the effect of polymer blend on the charge generated, steel contacted and PTFE contacted materials are analyzed statistically using Tukey's method. In this section below steel contacted fabrics are compared to study the effect of polymer blend on charge accumulated after 50 contacts.

Table B4 Experimental design : Contact charge measurements on finish free fabrics with PTFE

Class	Levels	Values
Blend	7	Cotton I, Cotton II, Filament Nylon, Spun Nylon, Filament Polyester, Spun polyester, Spun Polypropylene
Contact Material	1	PTFE
Number of Contacts	1	Fifty Contacts
Total number of runs	7x1x1 =7	

Each run was replicated for 3 times and a total of 21 observations were made

Table B5 Overall ANOVA for contact charge measurements –Finish free fabrics with *PTFE*

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Due to PTFE	6	298.6996667	49.7832778	11.77	<.0001
Error	14	59.2402000	4.2314429		
Corrected Total	20	357.9398667			
	R-Square	Coeff. Var	Root MSE	Charge Mean	
	0.834497	17.06149	2.057047	12.05667	

Table B6: Tukey’s grouping for finish free fabrics contacted with *PTFE*

Tukey’s Grouping	Mean	N	Blend
A	16.983	3	Filament Nylon
A	15.263	3	Spun Nylon
A	14.817	3	Cotton I
B A	12.003	3	Spun Polyester
B A	11.820	3	Cotton II
B C	7.503	3	Filament Polyester
B C	6.007	3	Spun Polypropylene

Means with the same letter are not significantly different.

**Analysis:**

- Tukey’s test results show that the polymer blend has significant influence on the charge accumulated when it is contact charged with PTFE.
- The materials are grouped into three different categories A, B and C. Some materials belonged to three groups A, B and C, however, Cotton II and spun polyester belongs to both the groups A and B, whereas filament polyester and spun polypropylene belongs to groups B and C.

Table B7 Experimental design Contact charge measurements on finish free fabrics with Steel

Class	Levels	Values
Blend	7	Cotton I, Cotton II, Filament Nylon, Spun Nylon, Filament Polyester, Spun polyester, Spun Polypropylene
Contact material	1	<b>Steel</b>
Number of contacts	1	Fifty contacts
Total number of runs	7x1x1 =7	

Each run was replicated for 3 times and a total of 21 observations were made

Table B8 Overall ANOVA for contact charge measurements –Finish free fabrics with *Steel*

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Due to Steel	6	52.18664762	241.765251	18.43	<.0001
Error	14	10.27213333	0.73372381		
Corrected Total	20	62.4587095			

R- Square	Coeff. Var	Root MSE	Charge Mean
0.835537	-47.38702	0.856577	-1.807619

Table B9 Tukey's grouping for finish free fabrics contacting with steel

Tukey grouping	Mean	N	Blend
A	-0.3033	3	Spun Nylon
A	-0.4467	3	Cotton I
B A	-1.1433	3	Cotton II
B A	-1.2767	3	Filament Polyester
B A	-1.4633	3	Spun Polyester
B C	-2.8400	3	Filament Nylon
C	-5.1800	3	Spun Polypropylene

**Analysis:**

- Tukey's test results show that the polymer blend has significant influence on the charge accumulated when it is contact charged with steel.
- The materials are grouped into three different categories A, B and C. Spun nylon and cotton are belonged to group A and Cotton II, Filament polyester and spun polyester belongs to both the groups A and B, whereas filament nylon belongs to groups B and C and spun polypropylene is categorized into group C.

### C. Charge Decay Measurements on untreated samples (Section 4.3.3)

Table C1 Experimental design: Half life time measurements finish free fabrics with rubbing charging

Class	Levels	Values
Blend	7	Cotton I, Cotton II, Filament Nylon, Spun Nylon, Filament Polyester, Spun polyester, Spun Polypropylene
Contact material	2	Steel, PTFE
Total number of runs	7x2 =14	

Each run was replicated for 3 times and a total of 42 observations were made

Table C2 Overall ANOVA for Rubbing charge decay on finish free fabrics

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	6813412.15	973344.59	32.92	<.0001
Error	34	1005177.68	29564.05		
Corrected Total	41	7818689.83			

R- Square	Coeff. Var	Root MSE	Charge Mean
0.871437	60.63	171.94	283.56

Table C3 Tukey's grouping for rubbing charge decay on finish free fabrics

Tukey's grouping	Mean	N	Blend
A	1233.33	6	Spun Polypropylene
B	263.00	6	Filament Nylon
B	244.26	6	Filament Polyester
B	218.93	6	Spun Nylon
B	21.06	6	Spun Polyester
B	2.22	6	Cotton I
B	2.11	6	Cotton II

**Analysis:**

- Tukey’s test results show that the polymer blend has significant influence on the half life time decay during rubbing charge measurements.
- The materials are grouped into three different categories A, and B. Spun polypropylene is categorized into group A, charge decay is very slower. All the other materials are grouped into B.

Table C4 Experimental design: Half life time measurements finished free fabrics with contact charging

Class	Levels	Values
Blend	7	Cotton I, Cotton II, Filament Nylon, Spun Nylon, Filament Polyester, Spun polyester, Spun Polypropylene
Contact material	1	PTFE
Total number of runs	7x1 =7	

Each run was replicated for 3 times and a total of 21 observations were made

Table C5 Overall ANOVA for contact charge decay on finish free fabrics

Source	DF	Sum of Squares	Mean Square	F value	Pr>1
Model	6	21281648.95	3546941.49	6.40	0.0021
Error	14	7757814.0	55412.9.57		
Corrected Total	20	29039462.95			

R- Square	Coeff. Var	Root MSE	Time Mean
0.732853	24.35	744.39	3056.04

Table C6 Tukey's grouping for rubbing charge decay on finish free fabrics

Tukey's grouping	Mean	N	Blend
A	4400.0	3	Filament Nylon
A	4013.3	3	Spun Nylon
A	3516.3	3	Cotton II
B A	3205.7		Spun Polyester
B A	2600	3	Spun Polypropylene
B A	2505	3	Cotton I
B	1152.0	3	Filament Polyester

**Analysis :**

The materials are categorized in to two groups. Charge decayed on Filament polyester Very quickly is grouped B. All the other materials are grouped in to A and charge decay on those materials is slower. Spun polyester, spun polypropylene and Cotton are grouped into Both A and B.

**D. Contact Charging Measurements nylon samples Chapter 7 (section 7.3.1)**

Table D1 Experimental design: Filament nylon samples charged with steel (initial charge)

Parameters	Levels	Values
Fabrics	1	Filament Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN, Aquatex Uno 21%, Sryde 100b
Contact charge head	1	Steel
Number of contacts	1	Single contact
Total number of runs	5 x1x1 =5	

Each run was replicated for 3 times and a total of 15 observations were made

Table D2 Overall ANOVA for filament nylon contact charge with steel

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	25.88	6.47	8.73	0.0027
Error	10	7.41	0.7411		
Corrected Total	14	33.30			

R- Square	Coeff Var	Root MSE	Charge mean
0.7773	-652.32	0.86	-0.132

Table D3 Tukey's grouping for Filament nylon samples for initial charge contacting with steel

Tukey's Grouping	Mean	N	Blend
A	2.2067	3	Aquatex Uno
B A	0.3867	3	Sryde 100b
B	-0.8067	3	Leomin <sup>®</sup> PN
B	-1.0600	3	Nofinish
B	-1.3867	3	Larostat <sup>®</sup> 264 A

Table D4 Experimental design: Filament nylon samples contacted with PTFE (initial charge)

Parameters	Levels	Values
Fabrics	1	Filament Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN ,Aquatex Uno 21%, Sryde 100b
Contact charge head	1	PTFE
Number of contacts	1	Single contact
Total number of runs	5 x 1x1 =5	

Each run was replicated for 3 times and a total of 15 observations were made

Table D5 Overall ANOVA for filament nylon contact charge with PTFE

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	13.86	3.46	8.28	0.0033
Error	10	4.18	0.41		
Corrected Total	14	18.05			

R- Square	Coeff. Var.	Root MSE	Charge mean
0.7680	-24.90	0.647	2.59

Table D6 Tukey's grouping for Filament nylon samples for initial charge contacting with *PTFE*

Tukey Grouping	Mean	N	Blend
A	4.3200	3	Aquatex Uno
B A	2.6800	3	Sryde 100b
B	2.5300	3	No finish
B	1.9933	3	Larostat <sup>®</sup> 264 A
B	1.4667	3	Leomin <sup>®</sup> PN

Table D7 Experimental design: Filament nylon samples charged with steel (50 contacts)

Parameters	Levels	Values
Fabrics	1	Filament Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN ,Aquatex Uno 21%, Sryde 100b
Contact charge head	1	Steel
Number of contacts	1	fifty contacts
Total number of runs	5 x 1x1 =5	

Each run was replicated for 3 times and a total of 15 observations were made

Table D8 Overall ANOVA for filament nylon contact charge with Steel (for 50 contacts)

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	250.95	62.73	7.19	0.0054
Error	10	87.29	8.72		
Corrected Total	14	338.25			

R- Square	Coeff Var	Root MSE	Charge mean
0.7419	1617.47	2.95	0.182

Table D9 Tukey's grouping for Filament nylon samples for fifty contacted with *steel*

Tukey's grouping	Mean	N	Blend
A	6.34	3	Aquatex Uno
B A	3.60	3	Sryde 100b
B C	-1.79	3	Larostat <sup>®</sup> 264 A
B C	-2.86	3	Nofinish
C	-4.38	3	Leomin <sup>®</sup> PN

Table D10 Experimental design: Filament nylon samples contacted with PTFE (fifty contacts)

Parameters	Levels	Values
Fabrics	1	Filament Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN ,Aquatex Uno 21%, Sryde 100b
Contact charge head	1	PTFE
Number of contacts	1	Single contact
Total number of runs	5 x 1x1 =5	

Each run was replicated for 3 times and a total of 15 observations were made

Table D11 Overall ANOVA for filament nylon contact charge with PTFE (for 50 contacts)

Source	DF	Sum of Squares	Mean Square	F value	Pr >F
Model	4	166.70	41.67	5.67	0.012
Error	10	73.47	7.34		
Corrected Total	14	240.17			

R- Square	Coeff . Var	Root MSE	Charge mean
0.6940	18.07	2.71	14.99

Table D12 Tukey's grouping for Filament nylon samples for fifty contacts with *PTFE*

Tukey's grouping	Mean	N	Blend
A	18.47	3	Larostat <sup>®</sup> 264 A
A	16.98	3	No finish
A	16.44	3	Aquatex Uno
B A	14.12	3	Sryde 100b
B	8.94	3	Leomin <sup>®</sup> PN

Table D13 Experimental design: Spun nylon samples contacted with steel (initial charge)

Parameters	Levels	Values
Fabrics	1	Spun Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN ,Aquatex Uno 21%, Sryde 100b
Contact charge head	1	Steel
Number of contacts	1	Single contact
Total number of runs	5 x 1x1 =5	

Each run was replicated for 3 times and a total of 15 observations were made

Table D14 Overall ANOVA for spun nylon contact charge with steel (for initial contact)

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	14.30	3.57	34.80	<0.0001
Error	10	1.02	0.102		
Corrected Total	14	15.33			

R- Square	Coeff Var	Root MSE	Charge mean
0.9329	93.55	0.32	0.34

Table D15 Tukey's grouping for spun nylon samples for initial charge contacting with *steel*

Tukey's Grouping	Mean	N	Blend
A	2.2533	3	Aquatex Uno
B	0.2367	3	Larostat <sup>®</sup> 264 A
B	-0.1633	3	Nofinish
B	-0.2467	3	Sryde 100b
B	-0.3667	3	Leomin <sup>®</sup> PN

Table D16 Experimental design: Spun nylon samples contacted with PTFE (initial charge)

Parameters	Levels	Values
Fabrics	1	Spun Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN ,Aquatex Uno 21%, Sryde 100b
Contact charge head	1	PTFE
Number of contacts	1	Single contact
Total number of runs	5 x 1x1 =5	

Each run was replicated for 3 times and a total of 15 observations were made

Table D17 Overall ANOVA for spun nylon contact charge with PTFE (for initial contact)

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	137.27	34.31	20.49	<0.0001
Error	10	16.74	1.67		
Corrected Total	14	154.01			

R- Square	Coeff Var	Root MSE	Charge mean
0.8912	27.30	1.29	4.74

Table D18 Tukey's grouping for spun nylon samples for initial charge contacting with *PTFE*

Tukey's Grouping	Mean	N	Blend
A	10.57	3	Aquatex Uno
B	4.75	3	Sryde 100b A
B	3.30	3	Nofinish
B	2.54	3	Larostat <sup>®</sup> 264
B	2.53	3	Leomin <sup>®</sup> PN

Table D19 Experimental design: Spun nylon samples contacted with steel (fifty contacts)

Parameters	Levels	Values
Fabrics	1	Spun Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN ,Aquatex Uno 21%, Sryde 100b
Contact charge head	1	Steel
Number of contacts	1	Fifty contacts
Total number of runs	5 x 1x1 =5	

Each run was replicated for 3 times and a total of 15 observations were made

Table D20 Overall ANOVA for spun nylon contact charge with steel (for 50 contacts)

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	64.41	16.10	52.79	<0.0001
Error	10	3.05	0.30		
Corrected Total	14	67.46			

R- Square	Coeff Var	Root MSE	Charge mean
0.9329	93.55	0.32	0.34

Table D 21 Tukey's grouping for spun nylon samples for fifty contacts with *steel*

Tukey's grouping	Mean	N	Blend
A	4.88	3	Aquatex Uno
B	0.2367	3	Larostat <sup>®</sup> 264 A
B	-0.2267	3	Sryde 100b
B	-0.3033	3	Nofinish
B	-0.6967	3	Leomin <sup>®</sup> PN

Table D22 Experimental design: Spun nylon samples contacted with PTFE (Fifty contacts)

Parameters	Levels	Values
Fabrics	1	Spun Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN ,Aquatex Uno 21%, Sryde 100b
Contact charge head	1	PTFE
Number of contacts	1	Fifty Contacts
Total number of runs	5 x 1x1 =5	

Each run was replicated for 3 times and a total of 15 observations were made

Table D23 Overall ANOVA for spun nylon contact charge with PTFE (for 50 contacts)

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	1341.96	335.49	46.27	<0.0001
Error	10	72.49	7.24		
Corrected Total	14	1414.46			

R- Square	Coeff Var	Root MSE	Charge mean
0.9487	13.52	2.69	19.91

Table D 24 Tukey's grouping for spun nylon samples for fifty contacts with *PTFE*

Tukey's Grouping	Mean	N	Blend
A	10.57	3	Aquatex Uno
B	4.75	3	Sryde 100b A
B	3.30	3	Nofinish
B	2.54	3	Larostat <sup>®</sup> 264
B	2.53	3	Leomin <sup>®</sup> PN

**E. Rubbing Charging Measurements nylon samples Chapter 7 (section 7.3.2)**

Table E1 Experimental design: Filament nylon samples rubbed with steel (initial charge)

Parameters	Levels	Values
Fabrics	1	Filament Nylon
Surface treatments	5	No finish, Larostat®264 A, Leomin® PN ,Aquatex Uno 21%, Sryde 100b
Rubbing head	1	Steel
Number of Rubbings	1	Initial rubbing
Total number of runs	5 x 1x1 =5	

Each run was replicated for three times and a total of 15 observations were made

Table E2 Overall ANOVA for filament nylon rubbed with steel (initial charge)

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	5329402	1332350	2.54	0.1053
Error	10	5236170	523617		
Corrected Total	14	10565572			

R- Square	Coeff Var	Root MSE	Charge mean
0.504412	270.74	723.61	267.26

Table E3: Tukey's grouping for filament nylon rubbed with steel (initial charge)

Tukey's grouping	Mean	N	Blend
A	1082.2	3	Aquatex Uno
A	634.8	3	Sryde 100b
A	211.8	3	Nofinish
A	115.6	3	Leomin® PN
A	-708.0	3	Larostat®264 A

Table E4: Experimental design: Filament nylon samples rubbed with PTFE (initial charge)

Parameters	Levels	Values
Fabrics	1	Filament Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN ,Aquatex Uno 21%, Sryde 100b
Rubbing head	1	PTFE
Number of Rubbings	1	Initial rubbing
Total number of runs	5 x 1x1 =5	

Each run was replicated for three times and a total of 15 observations were made

Table E5 Overall ANOVA for filament nylon rubbed with PTFE (initial charge)

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	1230859.37	307714.84	6.17	0.0091
Error	10	499091.43	49909.14		
Corrected Total	14	1729950.806			

R- Square	Coeff Var	Root MSE	Charge mean
0.711500	23.58	223.40	947.26

Table E6: Tukey's grouping for Filament nylon samples for initial charge rubbing with *PTFE*

Tukey's grouping	Mean	N	Blend
A	1383.5	3	Sryde 100b
B A	1090.5	3	Aquatex Uno
B A	992.8	3	Larostat <sup>®</sup> 264 A
B	667.3	3	Leomin <sup>®</sup> PN
B	602.2	3	Nofinish

Table E7: Experimental design: Filament nylon samples Rubbed with steel (fifty rubbings)

Parameters	Levels	Values
Fabrics	1	Filament Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN, Aquatex Uno 21%, Sryde 100b
Rubbing head	1	Steel
Number of Rubbings	1	Fifty rubbings
Total number of runs	5 x1x1 =5	

Each run was replicated for three times and a total of 15 observations were made

Table E8 Overall ANOVA for filament nylon rubbed with steel (fifty rubbings)

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	5354679.58	1338669.89	0.79	0.55
Error	10	16975291.00	1697529.10		
Corrected Total	14	22329970.58			

R- Square	Coeff Var	Root MSE	Charge mean
0.239798	63.92	1302.89	2038.08

Table E9 Tukey's grouping for filament nylon rubbed with steel (fifty rubbings)

Tukey's grouping	Mean	N	Blend
A	2979	3	Sryde 100b
A	2471	3	Aquatex Uno
A	1812	3	Leomin <sup>®</sup> PN
A	1514	3	Nofinish
A	1416	3	Larostat <sup>®</sup> 264 A

Table E10 Experimental design: Filament nylon samples Rubbed with PTFE (fifty rubbings)

Parameters	Levels	Values
Fabrics	1	Filament Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN, Aquatex Uno 21%, Sryde 100b
Rubbing head	1	PTFE
Number of Rubbings	1	Fifty Rubbings
Total number of runs	5 x 1x1 =5	

Each run was replicated for three times and a total of 15 observations were made

Table E11 Overall ANOVA for filament nylon rubbed with PTFE (fifty rubbings)

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	29525753.83	7381438.46	2.11	0.1540
Error	10	34950261.16	3495026.12		
Corrected Total	14	64476014.99			

R- Square	Coeff Var	Root MSE	Charge mean
0.457934	44.69	1869.49	4182.49

Table E12 Tukey's grouping for filament nylon rubbed with PTFE (fifty rubbings)

Tukey's grouping	Mean	N	Blend
A	6880	3	Leomin <sup>®</sup>
A	3909	3	PN Sryde 100b
A	3857	3	Nofinish
A	3434	3	Aquatex Uno
A	2832	3	Larostat <sup>®</sup> 264 A

Table E13 Experimental design: Spun nylon samples rubbed with steel (initial charge)

Parameters	Levels	Values
Fabrics	1	Filament Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN, Aquatex Uno 21%, Sryde 100b
Rubbing head	1	Steel
Number of Rubbings	1	Initial rubbing
Total number of runs	5 x 1x1 =5	

Each run was replicated for three times and a total of 15 observations were made

Table E14 Overall ANOVA for Spun nylon samples rubbed with steel (initial charge)

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	1221549.71	305387.42	3.89	0.0372
Error	10	785705.20	78570.52		
Corrected Total	14	2007254.91			

R- Square	Coeff Var	Root MSE	Charge mean
0.711500	23.58	223.40	947.26

Table E15 Tukey's grouping for spun nylon samples for initial charge rubbing with *Steel*

Tukey's grouping	Mean	N	Blend
A	415.0	3	Sryde 100b
A	374.3	3	No finish
A	- 122.1	3	Larostat <sup>®</sup> 264 A
A	- 130.1	3	Aquatex Uno
A	- 276.7	3	Leomin <sup>®</sup> PN

Table E16: Experimental design: Spun nylon samples rubbed with PTFE (initial charge)

Parameters	Levels	Values
Fabrics	1	Filament Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN, Aquatex Uno 21%, Sryde 100b
Rubbing head	1	PTFE
Number of Rubbings	1	Initial rubbing
Total number of runs	5 x 1x1 =5	

Each run was replicated for three times and a total of 15 observations were made

Table E17 Overall ANOVA for spun nylon samples rubbed with PTFE (initial charge)

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	12336431.14	3084107.79	26.47	<0.0001
Error	10	1165074.04	116507.40		
Corrected Total	14	13501505.18			

R- Square	Coeff Var	Root MSE	Charge mean
0.913708	21.35	341.33	1598.30

Table E18 Tukey's grouping for spun nylon samples rubbed with PTFE (initial charge)

Tukey's grouping	Mean	N	Blend
A	2978.5	3	Aquatex Uno
B A	2197.3	3	Sryde 100b
B C	1302.1	3	Nofinish
B C	1171.9	3	Larostat <sup>®</sup> 264 A
B C	341.8	3	Leomin <sup>®</sup> PN

Table E19: Experimental design: Spun nylon samples rubbed with steel (fifty rubbings)

Parameters	Levels	Values
Fabrics	1	Filament Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN ,Aquatex Uno 21%, Sryde 100b
Rubbing head	1	Steel
Number of Rubbings	1	Fifty Rubbings
Total number of runs	5 x 1x1 =5	

Each run was replicated for three times and a total of 15 observations were made

Table E20 Overall ANOVA for spun nylon rubbed with steel (fifty rubbings)

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	7343304.89	1835826.22	3.24	0.059
Error	10	5664257.12	566425.71		
Corrected Total	14	13007562.02			

R- Square	Coeff Var	Root MSE	Charge mean
0.564541	272.95	752.61	275.72

Table E21: Tukey's grouping for spun nylon rubbed with steel (fifty rubbings)

Tukey's grouping	Mean	N	Blend
A	1285.8	3	Nofinish
A	953.7	3	Sryde 100b
A	-177.4	3	Larostat <sup>®</sup> 264 A
A	-341.7	3	Aquatex Uno
A	- 341.8	3	Leomin <sup>®</sup> PN

Table E22: Experimental design: Spun nylon samples rubbed with PTFE (fifty rubbings)

Parameters	Levels	Values
Fabrics	1	Spun Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN ,Aquatex Uno 21%, Sryde 100b
Rubbing head	1	PTFE
Number of Rubbings	1	Fifty rubbings
Total number of runs	5 x 1x1 =5	

Each run was replicated for three times and a total of 15 observations were made

Table E23 Overall ANOVA for spun nylon rubbed with PTFE (fifty rubbings)

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	140532482.6	35133120.6	10.64	0.0013
Error	10	33008167.1	3300816.7		
Corrected Total	14	173540649.7			

R- Square	Coeff . Var	Root MSE	Charge mean
0.809796	35.54	1816.81	5110.72

Table E24: Tukey's grouping for spun nylon rubbed with PTFE (fifty rubbings)

Tukey's grouping	Mean	N	Blend
A	8854	3	Sryde 100b
B A	7210	3	No Finish
B A	6380	3	Aquatex Uno
B C	2425	3	Larostat <sup>®</sup> 264 A
C	684	3	Leomin <sup>®</sup> PN

**F. Charge decay Measurements nylon samples Chapter 7 (section 7.3.3)**

Table F1 Experimental design: Filament nylon samples contact charge decay

Parameters	Levels	Values
Fabrics	1	Filament Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN ,Aquatex Uno 21%, Sryde 100b
Contact Charge head	2	Steel, PTFE
Charge decay	1	Half life time
Total number of runs	5 x 2x1 =10	

Each run was replicated for three times and a total of 30 observations were made

Table F2 Overall ANOVA for charge decay on filament nylon contact charged samples

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	5	31282297.73	6256459.55	6.18	0.0008
Error	24	24280618.13	1011692.42		
Corrected Total	29	55562915.87			

R- Square	Coeff Var	Root MSE	Charge decay mean
0.563007	27.94	1005.82	3599.26

Table F3 Type I ANOVA for charge decay on filament nylon contact charged samples

Source	DF	Type I SS	Mean Square	F value	Pr>F
Blend	4	23768291.20	5942072.80	5.87	0.0019
Contactmaterial	1	7514006.53	7514006.53	7.43	0.0118

Table F4 Tukey's grouping for contact charged filament nylon samples for charge decay

Tukey's grouping	Mean	N	Blend
A	4466.7	6	Nofinish
A	4410.7	6	Aquatex Uno
A	4000.0	6	Sryde 100b
B A	2897.0	6	Leomin <sup>®</sup> PN
B	2222.0	6	Larostat <sup>®</sup> 264 A

Table F5 Experimental design: Spun nylon samples contact charge decay

Parameters	Levels	Values
Fabrics	1	Spun Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN ,Aquatex Uno 21%, Sryde 100b
Contact Charge head	2	Steel, PTFE
Charge decay	1	Half life time
Total number of runs	5 x 2x1 =10	

Each run was replicated for three times and a total of 30 observations were made

Table F6 Overall ANOVA for charge decay on spun nylon contacted samples

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	5	37703219.5	7540643.9	2.71	0.0442
Error	24	66676656.7	2778194.0		
Corrected Total	29	104379876.2			

R- Square	Coeff Var	Root MSE	Charge decay mean
0.361212	55.92	1666.79	2980.16

Table F7 Type I ANOVA for charge decay on spun nylon contact charged samples

Source	DF	Type I SS	Mean Square	F value	Pr>F
Blend	4	37444678.67	9361169.67	3.37	0.0253
Contactmaterial	1	258540.83	1011692.42	0.09	0.7630

Table F8 Tukey's grouping for charge decay on contact charged spun nylon samples

Tukey's grouping	Mean	N	Blend
A	4400	6	Aquatex Uno
B A	4064	6	Larostat <sup>®</sup> 264 A
B A	2773	6	Leomin <sup>®</sup> PN
B A	2261	6	Nofinish
B	1401	6	Sryde 100b

Table F9: Experimental design: Filament nylon samples rubbing charge decay

Parameters	Levels	Values
Fabrics	1	Filament Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN ,Aquatex Uno 21%, Sryde 100b
Rubbing Charge head	2	Steel, PTFE
Charge decay	1	Half life time
Total number of runs	5 x 2x1 =10	

Each run was replicated for three times and a total of 30 observations were made

Table F10 Overall ANOVA for charge decay on filament nylon rubbed samples

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	5	205230.73	41046.14	6.20	0.0008
Error	24	158772.63	6615.52		
Corrected Total	29	364003.36			

R- Square	Coeff Var	Root MSE	Charge decay mean
0.563815	66.48	81.33	122.34

Table F11 Type I ANOVA for charge decay on filament nylon rubbed samples

Source	DF	Type I SS	Mean Square	F value	Pr>F
Blend	4	204743.10	51185.77	77.4	0.0004
Contactmaterial	1	487.63	487.63	0.07	0.7883

Table F12 Tukey's grouping for charge decay on rubbed filament nylon samples

Tukey's grouping	Mean	N	Blend
A	263.0	6	Nofinish
B A	160.39	6	Larostat <sup>®</sup> 264 A
B	99.32	6	Leomin <sup>®</sup> PN
B	55.55	6	Sryde 100b
B	33.46	6	Aquatex Uno

Table F13 Experimental design: Spun nylon samples rubbed and charge decay

Parameters	Levels	Values
Fabrics	1	Spun Nylon
Surface treatments	5	No finish, Larostat <sup>®</sup> 264 A, Leomin <sup>®</sup> PN ,Aquatex Uno 21%, Sryde 100b
Rubbing Charge head	2	PTFE
Charge decay	1	Half life time
Total number of runs	5 x 2x1 =10	

Each run was replicated for three times and a total of 30 observations were made

Table F14 Overall ANOVA for charge decay on spun nylon rubbed samples

Source	DF	Sum of Squares	Mean Square	F value	Pr>F
Model	4	67856.27	16964.06	27.46	<0.0001
Error	10	6177.08	617.70		
Corrected Total	14	74033.36			

R- Square	Coeff Var	Root MSE	Charge decay mean
0.916563	30.98	24.85	80.21

Table F15: Tukey's grouping for charge decay on rubbed spun nylon samples

Tukey's grouping	Mean	N	Blend
A	187.87	6	No finish
A	128.85	6	Sryde 100b A
B	46.69	6	Larostat <sup>®</sup> 264
B	20.09	6	Aquatex Uno
B	17.56	6	Leomin <sup>®</sup> PN