Study of the Effect of Rubbing Materials on the Tribo-electrification of Textile Materials

By

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STUDY OF THE EFFECT OF RUBBING MATERIALS ON THE

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Abstract

This research describes a study of the effect of rubbing materials on the electrostatic propensity of textile fibers. The fibers included were cellulose-based fibers, protein-based fibers, manufactured fibers, and blends. The three rubbing materials were poly-tetra-fluorethylene (PTFE), polyvinyl chloride (PVC) and nylon 6. Peak static charges were measured and monitored from tribo-charged fabric surfaces. Experiments were conducted in an environmental chamber at 20 °C and 30 % relative humidity.

In general, the pattern of results for this study was predictable on the basis of other studies and the theory of static electricity. It has been previously stated that the amount of static charges generated by tribo-charging depends on the inner properties of the materials involved, but it is also affected by environmental conditions, rubbing mode and surface characteristics.

Results showed that rubbing material had the greatest effect on the generated potential, but interaction effects with fiber content were also determined. Peak potentials were significantly different among fibers.

It has been previously reported that tests using tribo-charging mechanisms were notoriously unreliable and considerable effort might be needed to achieve consistent charging, and that little control could be expected over the level and polarity of charging. Unlike previously reported results of charge variation of three orders of magnitude among different samples, results from this study yielded a variation of less than 50%, which was perhaps due to the highly controlled conditions of the experiment. This

confirms what other researchers have reported before during controlled frictional charging.

It was found that peak potentials yielded using various rubbing materials were not only different in magnitude but also in their polarity. Their relative position on rankings sorted by potential magnitudes changed when analyzed by rubbing material, determining that there was no significant correlation among those rankings. In addition, no significant correlation was found between these rankings and known tribo-electric series.

Results from this study also suggest that surface characteristics may have a significant effect on the electrostatic properties of the fiber in addition to environmental conditions. Factors that may affect these surface properties include surface finish, dyeing, type of yarn (filament and spun yarn), and type of weave. Chemical processes such as bleaching or dyeing that alter the electrolyte content may alter their electrical resistance. It has been reported that the resistance of synthetic fibers is greatly affected by the application of surface finishes.

Electrostatic discharges from a charged object cannot be completely eliminated but their effects can be minimized and controlled based on better understanding of the phenomenon. Because static charges are affected by several factors, a comprehensive assessment incorporating these factors is highly recommended to decrease the hazards involving electrostatic discharges.

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CHAPTER 1. INTRODUCTION

Background

Static electricity forms part of our daily experience. Most people have experienced electric shocks when getting out of their car, or after walking across a carpet and, then, a spark can be generated after touching a metal door handle. The first understanding of the nature of electricity came from the study of the phenomena of static electricity in the eighteenth century, although the phenomena were observed as early as 600 B.C. (Morton & Hearle, 1993). Static has long been a problem in the industry. As early as the 1400s, European and Caribbean forts were using static control procedures and devices to prevent ignition of black powder stores caused by electrostatic discharges (The ESD Association, 1998). By the 1860s, paper mills throughout the US employed basic grounding, flame ionization techniques, and steam drums to dissipate static electricity from the paper web as it traveled through the drying process (The ESD Association, 1998). But after the discovery of alternate current electricity, however, the study of static electricity, with all its experimental difficulties, was neglected (Morton & Hearle, 1993).

It was comparatively recently, particularly during the first part of the 20th century that great concern was expressed and the importance of electrostatic effects recognized because of the widespread use of synthetic material, most of which are insulators. Modern synthetic fibers used in clothing, carpet and upholstery, with all the advantages of durability, reduced cost and weight, are also a main source of charge in our daily life. These materials easily become charged with static electricity upon making contact or rubbing with, and subsequent separation from other materials. This phenomenon is

known as "tribo-charging" or frictional charging, and it occurs often when insulative materials are in contact with other material and rub together. Due to the insulative property, they are able to keep the charge developed on their surface for a long period of time, especially in low humidity conditions. Once a charge is build up, the subsequent dissipation of the charge may occur during a long period of time.

The effect of static can be a minor inconvenience, but it can also be a more serious problem. Some of the unpleasant effects of the electrostatic charge on a fabric are well known. Examples are charged clothing clinging together or clinging to the skin, attracting dust from air, and causing nuisance shock experiences, as well. From an industrial point of view, static electricity and electrostatic discharges (ESD) affect production efficiency, manufacturing cost, product quality and reliability in every aspect of the high-tech industry. For example, charged warp filaments repel each other and make it difficult to handle them, and an electrostatic discharge from a charged clothed person may destroy or cause malfunction in an electronic device. But the most serious problem associated with electrostatic discharges is the ignition of flammable gases, vapors, or powders, which may be present in certain industrial environments, resulting in fires and explosions, and the possible loss of human life (Wilson, 1977/78). Industry experts have estimated that average product losses due to static range from 8 - 33% (The ESD Association, 1998).

Despite a number of investigations carried out during the last several decades, static electricity still remains an important issue in the industry.

Statement of Problem and Justification of the Study

There is a general concern about the electrostatic phenomenon in industrial settings because of the hazards involved with it. For example, with the trend of electrical devices becoming smaller and faster, even a small amount of static charge can destroy a sensitive electronic component, resulting in losses, reduced reliability and increased rework costs. This requires providing detailed specification of the electrostatic property of materials for specialized uses. Textile materials are not immune to this propensity, and there are documented hazards involving charged textiles used in clothing and other applications (Scott, 1981).

Static is all around us and always has been. We cannot eliminate either the static phenomenon or the potential damage caused by electrostatic discharges, but we can greatly reduce the risk by better controlling them. In many case, the selection of a material and its electrostatic properties is a key factor in controlling the generation and dissipation of static electricity. The electrical properties of textiles are determined by the fiber's chemical composition and polymer structure (Gonzalez, 2001), and also by external factors such as environmental and rubbing conditions (Hersh & Montgomery 1955). These factors include humidity, temperature, rubbing pressure, rubbing time and rubbing manner. External factors can greatly change the electrostatic propensity of textiles. For example, low humidity and intense rubbing can greatly increase the amount of charge accumulated on a textile surface, resulting on a high voltage discharge potential that greatly increases the destructive potential during an ESD event. Significant amount of work has been carried out on the electrostatic propensity of textiles, and the factors affecting this propensity. Some work has also focused on tribo-electrification and the

development of tribo-electric series (Ballou, 1954; Henniker, 1962; Hersh &
Montgomery, 1955). A tribo-electric series is a list of materials arranged by their relative
tribo-electric charging polarity. Hersh and Montgomery (1956) stated that a particular
order was created when two materials were rubbed together because of their unique
molecular structures and, therefore, their electron configuration. Some researchers have
proposed that when textile materials are ranked according to their tribo-electric behavior,
this ranking was a function of the rubbed material but not a function of the rubbing
material; rubbing materials changed the absolute value of charge generated, but did not
change this ranking (Gompf, Holdstock and Chubb, 1999).

All these studies give us a better understanding about the electrostatic
phenomena; therefore make us to better control the hazard associated with this
phenomena. There is a gap in our knowledge of the impact of rubbing material on the
electrostatic propensity of textiles. The present research is intended to address this gap in
our current knowledge and aimed to contribute to this body of knowledge. The study may
demonstrate that rubbing material is indeed a significant factor in industrial failures.
Productivity and hazard reduction can be positively impacted if this factor is taken into
account when production specifications and safety guidelines are developed.

Specific Objectives

The specific objectives of the study were to:

1. Measure surface peak potentials of fabrics from tribo-electrification at 30%
   relative humidity (RH) and room temperature, using different rubbing materials.

2. Rank peak potentials, and compare rankings from different rubbing materials.

3. Compare the obtained rankings with the electrostatic series.

Null Hypotheses

To meet objectives 1, 2, 3, the following null hypotheses were tested during the research:

1. There are no significant differences in the amount of charge generated by tribo-electrification among textile fibers rubbed by different materials;

2. There is no significant correlation among rankings from different rubbing materials.

3. There is no relationship between established rankings and known tribo-electric series.

Delimitations of the Study

The delimitations established for the research were as follows:

Fabrics were restricted to 100% content of fabrics made of cotton (included fire retardant cotton), wool, viscose rayon, lyocell, acetate, triacetate, polyester, nylon 6, acrylic, modacrylic, olefin, meta-aramid, glass, flax, silk and some blends, which included 60/40% cotton/lyocell, 70/30% polyester/cotton, 65/35% polyester/cotton, and 55/45% polyester/wool. The rubbing materials used were poly-tetra-fluorethylene (PTFE) felt (Teflon®), polyvinyl chloride (PVC) and nylon 6. PTFT and PVC are normally placed on the negative end of reported tribo-electric series and nylon 6 near the positive end in the series.

Definitions of Terms

For the purpose of the research, the following definitions applied:

Static Electricity

Electricity is often described as being either static or dynamic. Static electricity is a surface phenomenon and defined as an unmovable electrical charge caused by the deficiency or excess of electrons. This imbalance of electrons produces an electric filed that can be measured and influence other objects at a distance (The ESD Association, 1998). Static electricity can be generated by contact, friction or induction. It also connotes the phenomena of attraction and repulsion between electrically charged bodies (i.e., like charges repel each other and unlike charges attract themselves (Crugnola & Robinson, 1959).

Electrostatic Propensity

The capacity of a non-conducting material to acquire an electrical charge by induction or tribo-electric means (rubbing with another material) and to hold such charge.

Electrostatic Charge (q)

A static charge (positive or negative) is considered to be the amount or quantity of electricity generated on an object. It is caused by an imbalance of electrons on the surface of a material. When a neutral (or state of equilibrium) material acquires or loses electrons, it is negatively or positively charged, respectively. The unit of static charge is the coulomb (C), that corresponds to a charge of 6.25×10^{18} electrons. A charge produces an electric field that can influence other objects at a distance (e.g., it can induce a charge with opposite polarity on another nearby conductive object).

Electrostatic Discharge (ESD)

An ESD is a very fast transfer of electrostatic charges between bodies at different potentials caused by direct contact or induced by an electrostatic field (The ESD Association, 1998).

Charge Decay

Charge decay is a charge neutralization process that deals with the movement of charges under the action of electric fields spreading the charges or recombining opposite charges and making the original fields steadily decreasing (Jonassen, 2000).

Tribo-electrification

It is also referred as frictional electrification. It is the generation of static charges between two materials by rubbing them together. This is the most common charging mechanism.

Electrostatic field (E)

A stationary electric charge exerts an electric force around it. The electric field vector E at a point in space is defined as the electric force F acting on a positive test charge q placed at that point divided by its magnitude (Serway, 1990, p.634).

$$E = \frac{F}{q}$$

Potential (V)

Electric force exerted by a stationary electric charge is conservative. Thus it is possible to define a potential energy function associated with this force or this force can be represented as the gradient of a potential. Electrostatic potential V is defined as the potential energy U per unit charge (V=U/q). Potential difference between two point A and B equals the work per unit charge that an external agent must perform to move a test charge from A to B without a change in kinetic energy (Serway, 1990, p. 680). The SI unit of potential is the Volt (V) where 1 V = 1 Joule / Coulomb.

Capacitance (C)

Capacitance in electricity refers to the capability of a body, system, circuit or device for storing electric charge at a given potential difference. Capacitance is expressed as the ratio of stored charge in coulombs to the potential difference in volts (C=q/V) (Serway, 1990). The resulting unit of capacitance is the Farad (F).

Resistance (R) and Resistivity (ρ) and Surface Resistivity (ρ$_s$)

Resistance R and resistivity ρ are measurements of the extent to which the flow of electricity is hindered when passing through a material. Resistance is a measurement that depends not only on the material, but also on its geometry. The resistance of a material is defined as the ratio of the voltage applied to the electric current (I).

$$R = \frac{V}{I}$$

It can be also described in terms of its resistivity. Resistivity is an intrinsic property of a material describing how well that material inhibits current flow, which is independent of the geometrical factors.

When the "surface resistivity" ρ_s is referred to, the implication is that we are talking about a layer of ohmic material of intrinsic volume resistivity ρ that is very thin in one direction, e.g., in depth. And the surface resistivity defined as: $\rho_s = \rho/\tau$, where τ represents the thickness of the film. The unit for surface resistivity is ohms. It often described in ohms-per-square. The square term is a dimensionless unit that reminds us that the value is a surface resistivity measurement. The surface resistivity represents the volume resistivity of a unit thickness of a substance and it is an intrinsic material property (Horenstein, 2001).

Current (I)

Current is the rate at which a charge moves through a surface. It is defined by: $I = dq/dt$. The SI unit of current is the Ampere (A). One Ampere of current is equivalent to one Coulomb of charge passing through a surface in one second (Serway, 1990, p.742).

Conductor, Semiconductor, Insulator, and Static Dissipative Material

A Conductor is a material that conducts electrical current very well. Electrons are fairly free to move through its surface or through the bulk of the material; it has low electrical resistance and can be grounded[*] at one single point.

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[*] The term ground means intentionally connected to earth through a directly grounded connection or connections of sufficiently low impedance and having sufficient current-carrying capacity to prevent the buildup of voltages which may result in undue hazard to connected equipment or to person.

A Semi-conductor is an electrical non-conductor in its pure state or at low temperature and becomes a conductor when impure or at high temperature.

An insulator is a material where electrons are more bound to the atom that prevents or limits the flow of electrons across its surface or through its volume. An insulator has a high electrical resistance and is difficult to ground. Static charges remain in place on these materials for a long time.

Static dissipative materials have electrical resistance between insulative and conductive materials. There can be electron flow across or through the dissipative material, but it is controlled by the surface resistance or volume resistance of the material. It allows the transfer of charge to ground or other conductive objects and charge transfers from static dissipative materials are significantly faster than from insulators, and slower than from conductors (The ESD Association, 1998).

CHAPTER 2. REVIEW OF LITERATURE

This literature review addresses the basic principles of static electricity that relate to the tribo-electrification or frictional electrification of textiles, which include charge generation and charge dissipation and the factors that affect this phenomenon. Methods of measuring these properties are also included.

Basic Theory of Static Electricity

Electricity is often described as being either static or dynamic. Since all electrons are alike, these words do not actually describe two different types of electricity; rather, they distinguish between electrons at rest and those in motion. Static electricity is defined as an electrical charge caused by an imbalance of electrons on the surface of a material (The ESD Association, 1998) and refers to the deficiency or to the excess of electrons. The term "electrostatic" or "static electricity" also refers to the phenomenon associated with the build up of electrical charges generated.

Charge Generation

Roth (1990) stated that the primary sources of charge generation were usually tribo-electric and induction methods or mechanisms.

Tribo-electrification

Mechanism of the contact or frictional charging.

The static charges are invariably produced at the interface between two dissimilar

materials when they are brought into firm contact with each other and separated. This

phenomenon has been referred to as contact, frictional, or tribo-electric charging.

Usually, but by no means exclusively, contact charging is used to describe simple

contacts between surfaces, while frictional or tribo-electrification means the charging

process in which contact is make while rubbing force and relative movement of the

contacting surfaces are involved (Gonzalez, 1999). Charges transfer from one surface to

another, in order to bring the contacting material into thermodynamic equilibrium,

balancing the molecular configuration in the case of relatively non-conductive materials

(Sello and Stevens, 1983). This transfer of charge may occur via electrons, ions, or

charged particles or any combination of these (N. Wilson, 1987; Harper, 1967).

Materials vary in their propensity and the degree to lose and gain charges when in

contact with another material (Crow, 1991). The direction of transfer of the electrons

depends upon the relative position of the energy levels of the surface electrons i.e. the

work functions of the two contacting materials. The work function is defined as the

energy required to cause the removal of an electron from a material (N. Wilson, 1987).

When two solids come into contact, the electrons flow from the material with low work

function to the one with high work function, resulting in the former being positively

charged and the latter negatively charged.

The state of electrons determines the electrical conductivity of a material. A

material is considered to be a good conductor if its electrons are fairly free to move

through its surface or through the bulk of the material (Serway, 1990). An insulator is a material in which electrons are more bound to the atom and prevents or limits the flow of electrons along their surface or through their volume (Serway, 1990). Usually there are three interfaces during the contact charging: metal /metal, metal/insulator and insulator/insulator.

It is well established that contact charging between two metals is caused by the transfer of electrons from one metal to the other (N. Wilson, 1987). When two metals of different work function are placed in contact, the Fermi levels of the two metals will coincide and this will result in a potential difference being established between the adjacent faces of the two samples and this potential will cause electrons flow from the metal of lower work function to the metal of higher work function (Greason, 1999). For metal/ metal interface, almost a complete backflow of the charge takes place during the separation process yielding very small charge accumulation on the contacting partners. This charge flow back across the interface is due to either electron tunneling or air breakdown (Greason, 1999; Lowell, 1975) or the tunneling phenomenon stops when the separation distance exceeds a certain distance (Greason, 1999). Due to the near zero charge accumulation, the electrostatic charges on metal/metal interface can be negligible.

Most textile products and polymers are considered insulators. The insulator-charging phenomenon is very complex (N. Wilson, 1987). In practice, the surfaces of textiles are usually contaminated with additives, finishes, dirt and moisture in all of which resides an abundance of ions. This suggests that for textiles, charge transfer across the interface is caused not only by the electron behavior, but also by ions. Ions and electrons may take part in the charging process when two materials are brought into

contact. Even if all the electrons of the insulator are bonded and cannot move, there may be a charged layer at the surface of an insulator and this layer is due to various finishes applied to the fabric before and after processing (Osei-Ntiri, 1992). When the insulator partner is separated, the charge flow happens, but the degree is much less than in the case of the interface of metal/metal due to the insulators properties, resulting amount of charge remains on the insulator. An insulator is difficult to ground, once the charge is generated on its surface, a static charge will remain there for a very long time.

So far the explanation given for the charging mechanism describes electrification due to simple contact and separation. In practice, however, charges are often produced by frictional charging which involve rubbing pressure and relative movement between two materials and it is probable the major mechanism for the generation of electrostatic charge in textile materials (Harper, 1967; Wilson and Cavanaugh, 1972; Chubb, 1988; Taylor and Secker, 1994).

Although rubbing is not necessary for charge generation, it usually increases the amount of charge produced. Previous experiments have shown that rubbing an insulator can increase charge transfer several orders of magnitude greater than in a simple touching contact. The manner of rubbing, the rubbing pressure, the characteristic of the material and the environment conditions affect the amount of charge transferred (Hersh & Montgomery, 1955).

Tribo-electric Series.

Tribo-electrification is defined as a contact electrification involving some types of frictional force and sliding between two contacting surfaces and is the term used to

describe the electrification of textile as to be responsible for most practical static problems. The characterization of the charging behavior of a material can be determined by observing the polarity of the charges on pairs of different materials after rubbing them together in a controlled manner (N. Wilson, 1987). This results in the establishment of the tribo-electric series, which is a list of materials that arranges the materials by their relative tribo-electric charging characteristics. Any material in the list rubbed against another positioned at the bottom of the list becomes positively charged and vice-versa. Justification for a tribo-electric series is given by Hersh and Montgomery (1956). They stated that a particular order was created because of the unique molecular structure of a material. Such list is useful to predict tribo-charging behavior, in terms of polarity, of two materials when rubbed together (Hayek & Chromey, 1951).

Factors affecting the tribo-electrification.

There are several factors that influence the charge generation by tribo-electrification.

1) Surface characteristics and rubbing force. Haenan (1976) showed that charge transfer increased as surface roughness decreased. This can be explained by the fact that the actual contacting area increases as surface becomes smoother. Rubbing pressure also helps to increase the intimacy between contacting surfaces and, therefore, charge transfer increases with rubbing pressure (N. Wilson, 1987). The surfaces of fabrics are quite uneven and the really contacting area is less than the apparent area (Hersh & Montgomery, 1955). The factors that affect the actual contact area for textile products

include: type of yarns (filament or spun yarn), type of fabric, structure and surface state after rubbing (D. Wilson, 1963).

2) Rubbing velocity. Rubbing velocity affects the amount of charge generated (Hersh & Montgomery, 1955). Its effects include two sides when increasing the rubbing velocity: one is to decrease the time period for electrons to tunnel or flow back, and the other is to increase the temperature at the point of contact (Hersh & Montgomery, 1956). For insulators, the first effect means charges will build up since they have less time to leak away (Hersh & Montgomery, 1955; Chubb, 1988). The fast repeated rubbing introduces another charging mechanism: thermoelectric charging. The temperature gradients appearing across the contact surface in asymmetrical rubbing result in the enhanced diffusion of electrons from the hotter to the cooler surface (Taylor and Secker, 1994). This may be related with some instances where the charging goes through a maximum value (Zimmer, 1970; Ohara, 1979).

Induced Charging

Unlike contact charging, which occurs on all materials, Induction charging only occurs with conductors. Charging by induction is a process that produces a net electric charge on an object without touching it. For example, when a negatively charged object is near a neutral conductor, the electrons in the conductor will be affected by the electric field established by the nearby charge, this results in a separation of the charges within the neutral conductor. The side nearest the charge will be positive while the other side far from the charge is negative due to the fact that unlike charges attract each other and like charges repel each other. If the conductor is grounded this time, the electrons will flow to

the ground. When the conductor is isolated from the earth again, it will be then positively charged. Induction charging plays an important role in the hazard of electrostatic discharges related to clothing and textiles. Since the human body is the nearest conductor in this situation, the discharge often occurs from the body and not from the charges on the clothing. Discharge from a conductor represents a higher risk than from an insulator.

Charge Dissipation

Once the charge is generated on the surface of a material, the subsequent dissipation or neutralization process may happen. Under the action of electric fields established by the charges to be neutralized, they spread or recombine with opposite changes, making the field decay or at least decrease. This process occurs whenever the charge area comes into contact with a medium containing charge carriers of the opposite polarity (Jonassen, 1991). Charge can dissipate through various ways. That charges dissipate themselves through some sort of conducing path, usually from charged area to the ground is usually thought to be the main mechanism of charge decay (Hearle, 1953; D. Wilson, 1963). Onogi, Sugiura and Nakaoda (1996) state that dissipation by conduction is only the one of the three main mechanisms involved in the decay of surface charges. The charges on fabric can be dissipated into the air by the evaporation process of water that is absorbed by the fiber. The charge can also decay through a charge absorption process in which charge is absorbed by a substance having opposite charge. Polar groups existing on a polymer can absorb opposite charges built up on it and make charge decay.

Jonassen (1991) distinguishes the charge neutralization process by two terms: charge decay and discharge. Both terms are used to describe the process involving a reduction in total charge or local charge density. Charge decay refers to the process of charge reduction in which the conductivity of the conducting medium remains the same. Charge is neutralized by opposite charge carriers originally presenting in the conducting path. Discharge, however, is reserved for processes involving breakdown and ionization, where the conductivity of the conducting medium changes. In the discharge process new charge carriers are created by the process of breakdown and ionization.

Charge Decay

According to Ohm's law, charge decay is usually described as an exponential function with time. Depending on the material on which charge is generated, the decay scheme can be described by three different types (Jonassen, 1991): 1) Charge decay of a capacitive system (i.e., charge decay from an isolated conductor); 2) Charge decay of a no-conducting system, where the charge is located on an insulating material; and 3) Charge decay through the air. The time constant of decay depends on the system's capacitance and resistance, or permittivity and resistivity. For the charge decay from an isolated conductor, a special consideration needs to be introduced. If the charged conductor is suddenly connected to ground through a low resistance, the charge will decay as a fast current pulse, which may be destructive if it happens to pass through a electrostatic sensitive component. Charge decay through the air usually takes a long time because of the high resistivity of the air.

Electrostatic Discharge

Discharge unlike the decay process that occurs at any level of field strength can only happen when the electronic field exceeds a certain degree. Any insulating material will break down when the electric field strength reaches to a critical value resulting in the insulating characteristics failure and the discharge process.

Here we limit the discharge process only to the case of discharge through the air, of which spark discharge is a typical case. When the electrical field produced by the charge reaches a certain degree, the airborne charged particles move and collide together. This may cause the electron separation from the molecules and atoms of the air, leaving behind positive ions. This electron will also accelerate and may repeat the process several times making more positive and negative particles. These positive and negative charges then gain energy by accelerating in the field and by colliding with other molecules causing more electron separation and finally an electron avalanche. By this way, charge on the surface of material was neutralized quickly by these charge carriers to the earth (N. Wilson 1987). Usually this process is accompanied with a spark. Spark discharge occurs when the electrical field strength exceeds the air breakdown value of 3×10^6 V/m at atmospheric pressure (between plane electrodes) (Gibson and Lloyd, 1965). This means that the maximum charge that can exist on a plane surface is about $\pm$ 30 $\mu C/m^2$.

This is very important to know that the discharge behavior of an ungrounded conductor is quite different from that of an insulator (Jonassen 1991). There are three kinds of discharge forms from a conductor. They are Corona discharge, spark discharge and brush discharge. Corona discharge will stop once enough charge has been neutralized for the voltage to drop to such a value that the breakdown field strength is no longer

exceeded anywhere. The charge remained uniformly distributed on conductor. Spark discharge can instantly release most energy stored on the conductor in a narrow channel between two conductors in a form of a spark. Because the discharge channel is very narrow and short and the discharge as a whole very fast, the energy density of a spark discharge can be very high, making the spark discharge the most incendiary of all types of discharges (Jonassen, 1991). Spark discharge is most experienced by the body. Brush discharge takes place between an electrode, which has a radius of curvature in the order of millimeters, and the ground. The energy released by brush discharge is somehow between the energy released by corona discharge and spark discharge (Jonassen, 1991).

For the insulator, because their high surface and volume resistivity impede the flow of charge to the point of discharge, only a fraction of the total charge on the surface is released in the discharge. The different discharge behavior of an insulator from a conductor lies in the fact that charged insulator surface is not of the equi-potential nature (Lobel, 1987). The character of a discharge from an insulator may be described in terms of the total charge transferred in the discharge and its distribution with space and time.

Resistance, Resistivity and Surface Resistivity

Resistance R and resistivity ρ are measurements of the extent to which the flow of electricity is hindered when passing through a substance.

The resistance of a material is defined as the ratio of the voltage applied to the electric current, which can also be described in terms of its resistivity. The surface resistivity characterizes the intrinsic volume resistivity ρ of ohmic material, which is very

thin in one direction e.g., in depth. The surface resistivity ρ_s is defined as: $\rho_s = \rho/\tau$. Here τ represent the thickness of the film.

According to Ohm's low, resistivity is a factor that affects the time variable of the dissipation process. This can imply that a fabric having a high resistivity has a low conductivity therefore its charge decays slowly. Hearle (1953) claimed that the electrical resistance of a material is the most important factor in determining whether it will build up large static charges or not. D. Wilson (1963) concluded that the resistance may be used as an index of the electrostatic propensity of a textile fabric. But the resistivity is only an index for describing the charge dissipating process based on the conduction mechanism (Ramer & Richards, 1968). Using resistivity measurements to evaluate materials might be appropriate where a conductor is involved (Gompf, Holdstock and Chubb, 1999). But when considering textiles, some researchers have expressed some limitations in using resistivity measurements, as follows:

1. Charge migration often varies with the remaining electrical stress in the material i.e. the material does not obey the Ohms law which follows the first order decay kinetics. It is often found that the resistivity increases with decreasing field strength (Chubb, 1988). Nevertheless, resistivities are usually determined at one field strength (one voltage difference between a set of electrodes on the sample) and there is no way to determine whether this particular field strength is typical for the physical conditions during a practical decay process (Jonassen, 2000). So, for a material that does not obey the Ohm's law, the resistivity is not an appropriate way to evaluate the charge decay process.

2. Heterogeneous materials, such as composite materials, may have conductivity provided by localized high conductivity with features within a relatively insulating matrix (for example, conducting fibers in fabrics or fabrics containing anti-static finishes). For these materials, resistance is only measured from the conductive part, whose resistance is much lower than that of the bulk part (Chubb, 1988; Crow, 1991; Scott, 1981), thus may not truly reflect the real resistance of the material when the static charge dissipates through them. Measuring resistance only considers charge dissipation based on direct conduction. Anti-static agents may dissipate charge primarily through a different method of charge leakage, other than conduction.

3. Another limitation about resistivity is that the rate of charge decay depends not only on the resistivity, but also on the system permittivity to the ground. Only under very ideal conditions, it is possible to calculate the rate of charge decay reasonably accurately from material parameters (resistivity and permittivity). There is usually no way to know the system permittivity of practical situations which are affected not only by the properties of the region where the decay takes place such as the initial charge distribution, but also by the properties outside the region of decay, such as the geometry of surrounding environments (Jonassen, 2000).

4. Conductive decay is not the only way of charge decay for textile. Other factors affect this process, such as charge decay into the air by water evaporation or charge absorbed by opposite polar groups in a material.

Considering the mechanism of conduction of electricity, it is usually accepted that for textile materials current is carried mainly by ions, but conduction can also be electronic in nature (Morton & Hearle, 1993). For hygroscopic fibers, it seems that volume conduction is the dominant effect (i.e., the current flows through the bulk of the material and surface conduction is negligible in comparison). For synthetic fibers with higher resistance and negligible moisture absorption, the surface conduction is likely to be more significant and considered as a main mechanism (Morton & Hearle, 1993). When conducting surface finishes are applied, the current will be conducted almost entirely through the surface.

Environmental Factors Affecting Electrical Characteristics of Textiles

The electrostatic propensity of textiles refers to the capacity of a given textile material to acquire and hold on electrical charge by induction (via corona discharge) or by tribo-electric means (rubbing with another material) (ASTM D4238-90, p. 399). This propensity depends on the properties and structure of the textile material itself, but environmental conditions have also great influence on it, mainly on the charge migration processes, such as on the resistivity or resistance of textiles.

Humidity

Water is a good conductor that has very low resistivity. Thus, the moisture content of a textile fiber will affect the resistivity or resistance of textile materials. Many textiles become good electrical conductors at high humidity level, because of the moisture absorbed from the air (Crow, 1991). Morton and Hearle (1993) reported that

moisture content is the most important factor in determining the resistance of textile materials and every 13% increase in relatively humidity causes a tenfold decrease in resistance. In fact, because the difference of sorption properties of textiles, the effect of humidity varies across a wide range for different textile fibers. The moisture regain characteristics depend on the nature of a fiber, thickness and density of material and environmental conditions.

Another important factor that has significant effect on the electrostatic propensity of textiles is the hysteresis effect, which means "lag of effect", or a delay before an action. Most textile fibers absorb moisture (water vapor) from the air. As the relative humidity (RH) of the air increases, the amount of moisture absorbed generally increases. The amount of moisture the fiber contains when placed in an environment at a certain temperature and relative humidity is called its moisture regain. When regain plots with relatively humidity, the absorption isotherm which is a plot of equilibrium regains at successively higher humidity of a specimen initially bone-dry, different from the desorption isotherm which is a plot for a specimen initially wet at successively lower humidity. This phenomenon of which wetting profile and drying profile are different is called hysteresis. Because of its effect, water regain of a fiber will change in a range even for the same relative humidity depending on the history of condition (Morton & Hearle, 1993).

Sereda and Feldman (1964) reported the influence of humidity on both charge generation and charge dissipation. They studied the phenomenon between metals and polymers, and stated that the mechanism of electrification at zero RH was caused by the transfer of electrons from the metal to the insulator where they were trapped. With the

rising of humidity, the electrostatic potential increased between the two surfaces; at certain critical RH, this potential reaches a maximum value. They explained that the absorbed water on the surface of fabrics increased the electrostatic potential by allowing more effective transfer of electrons from the metal. Water increased the practical contact area between the metal and fiber. Because of its dipole nature, absorbed water may change the characteristics of the surface in a way to make more sites available for the trapping of electrons. This effect may explain the increase in charge generation at the conditions of relative humidity below a critical point. This critical point is commonly known as the critical water content and a monomolecular layer of water is present on the surface of the fiber. With a further increase in RH, water on the surface of the fiber will form a continuous thin film. Acting as a conductive path, water greatly increases the conductivity of the fiber, and charge dissipation increases and limits the value of the maximum charge that retains on the surface.

Temperature

Temperature affects the Fermi level of a material (Hersh and Montgomery, 1956), therefore affects the amount of charge transferred and the direction across the surface during contacting or tribo-electrification charging. Because most textiles are used at room temperature, where this effect is negligible, humidity plays a more important role in determining the electrostatic properties (Sello & Stevens, 1983).

Electrostatic Hazards in Textiles

Human Body Model

Static electricity mainly manifests its destructive nature through electrostatic discharges (ESD). One problem associated with the charge building up on a textile material is that the field from the charge makes a nearby conductor, the human body, inductively charged. The damage associated with clothing or textiles is often described with a human body model (HBM). Charging process of human body involves both tribo-electrification and induction processes (Roth, 1990). A person can be electrostatic-charged by rubbing his or her clothing with the sounding environment, such as the seat of chair, walking on the carpet, and removing his clothing. Because the human body is a good conductor of static electricity, due to the high water and ionic salt contents and is usually insulated from earth by footwear, the charge built up on the clothing or the shoe sole cause the body to be inductively charged. This effect is similar to that of charging an electrical capacitor (N. Wilson, 1987). Because the capacitance of the body is very small, a little charge can cause human body potential to rise to very high level. This charging process makes the person ready to dissipate the charge in the form of spark by touching or near an earthed conductor or large conductor. That is why the electrostatic discharge often presents from the body, not from the charged area on the clothing. If the nearest conductor is an ESD sensitive equipment or an assemble, damage may be caused. In some working sittings, where flammable gas or explosive materials are present, they may be an ignition hazard. Studies have showed that a person in a manufacturing environment frequently develops 5000 volts or more just by walking on the carpet (Matisoff, 1986; Sclater, 1990).

Incendivity of ESD

The damage of electrostatic range from small nuisance such as shock people, make clothing cling to the skin or absorb airborne dust soiling the garment to threats to the life of electronics and particular semiconductors, a real problem for the high tech industry. The most serious consequence of a spark discharge is the possibility of incendiary sparks in the presence of flammable atmospheres or explosive materials.

Damage to an ESD sensitive device by an ESD event is determined by the device's ability to dissipate the energy of the discharge or withstand the current or voltage level involved (ESD Association, 1998). Today's electrical components become more sensitive to the ESD, some printed circuits or assemble may be damaged under 100 volts. Some semiconductor devices are damaged by as little as 20-30 volts.

Usually there are two approaches to assess the ignition risk from an electrostatically charged body. One is by comparison of the igniting power of any discharge from the body with the minimum ignition energy (MIE) of the flammable atmosphere (Glor, 1988; Owens, 1984), which is the lowest energy required to cause the ignition of a material. Another way is to measure the electric field intensity (kV/cm) at the surface of the charged fabric (Owens, 1984), because electrostatic field exists in the region surrounding an electrically charged object.

Different MIEs have been reported for various gas/air mixtures at different conditions (N. Wilson, 1977/78; Tolson, 1980). For example, the MIE to ignite methane and air in a closed chamber by a spark between a finger and an earthed electrode has been evaluated between 0.5 and 18.6 mJ. The actual spark energy requirement to ignite sensitive flammable vapor is much higher than published minimum value of ignition

energy (Scott, 1981; Crow, 1991). Wilson (1987) summarized that the higher energy is due to the discharge from the body, which is not released all at once, but rather fragmented into discrete sparks and some of the energy is absorbed as heat because of the resistance of the body. It seems unlikely that the electrostatic hazard could be underestimated in the case of human-body results because laboratory experiments are conducted under the maximum controlled conditions. However several variables influence the amount of charge generated and subsequently discharge process. There is always the possibility that a very unexpected low discharge could ignite a gas/air mixture. Study has shown that the capacitance of the body varies according to the size, the insulation situation, stance and the environment.

Antistatic Solutions

We cannot eliminate static charges, but we can greatly reduce the risk associated with the static electricity by appropriate control. Charge generation is unavoidable, however if there is an electrically conductive path that can dissipate the charge away, there will not be charge build up. The more the charge is accumulated, the more dangerous the discharge spark might be produced. It is important to avoid the dangerous spark by reducing static build to safe levels. Grounding is an effective method for conductors, but for textiles it does not eliminate the charge, because most textile products are insulators. A better way is to improve conductivity by modification of the fiber or surface finish. Three basic methods are as follows:

1. To increase the material conductivity by blending metal fiber or composite fibers containing metal or carbon. The problem of this method is when these tiny metal fibers wear out of the fabric with the usage; the effect of anti static is lost.

2. To finish or to modify the polymer in order to increase the material's ability to absorb water, such as incorporating cationic polyelectrolyte components containing polyethylene oxide segments into the fiber structure before extrusion. Therefore, it decreases the electric resistance or increases conductivity. However this effect depends on the environment humidity and does not work well under cold and dry conditions. (Gonzalez, 1994).

3. To use highly conductive materials. Current ESD-control apparel can knit a grid pattern of carbon-suffused monofilament nylon into the fabric. The pattern depends upon the protection needed. The conductive carbon fiber controls the static charge and helps it drain from the user. Carbon content can range from 1% to 15% of the fabric weight (Mayer, 2001).

Measurement of Static Electricity in Textiles

Human Body Experiment

Because the electrostatic hazard associated with clothing and textiles is often present in the form of discharge spark from the human body (human body mode), some studies use the human body as a study subject. In this experiment, the amount of charge generated on the clothing, the body capacitance as well as discharge potential and the energy from the body are measured after a person performs common activities such as sliding off a chair, walking on a carpet, or removing clothing (Wilson, 1977/78; Osei-

Ntiri, 1992). These studies intend to investigate the charge generation characteristics of clothing and to establish a safe criterion for clothing wearing in dangerous flammable environment.

Small-Scale Tests

Many small-scale test methods have been developed to predict the electrostatic propensity of textile material.

Resistivity Measurement

Traditionally, the electrostatic propensity of textile has been assessed by surface resistivity, because the resistance of the flow of electric charge determines a material's ability of charge dissipation. Examples of those test methods are: AATCC Test method 84-1987: Electrical resistivity of yarns and AATCC Test Method 76-1987: Electrical resistivity of fabrics.

Charge Decay Measurement

Because the limitations of the resistivity as an index to assess the propensity of textile (previously discussed), measure of charge decay time directly is a more appropriate alternative (Jonassen, 2000). The decay rate is usually estimated by the time required for the charge to fall to half of its original value or observe the charge decay after certain time. The methods that focus on charge decay measurement include: ASTM D 4238-90: Standard Test Method for electrostatic propensity of textiles; Federal Test Method Standard 191A method 5931: Determination of electrostatic decay of fabrics.

Federal Test Method Standard No. 101B method 4046: Electrostatic properties of materials; EOS/ESD Standard No. 2: Standard for protection of electrostatic discharge susceptible items: personnel garments (Draft August 1987); AATCC method 115-1986: Electrostatic clinging of fabrics: fabric-to-metal test; AATCC Test method 134-1986: Electrostatic propensity of carpets; ASTM F2350.05: Standard test method for evaluating tribo-electric (static) charge generation on protective clothing (draft January 1994).

Typical test measures the charge decay at certain time or half decay time by non-contact measurement while the test surface is located on a ground metal plate. Usually there are three methods for charging the test surface: tribo-charging, high voltage corona discharge and simple contact charging. Corona charging presents a simple reliable way to allow choice of charge level and charge polarity (Chubb, 1988). But this is not responsible for the daily encountered electrification related with textiles and charge species generated on the textiles by this method maybe different from the one produced by tribo-charging and therefore the subsequent charge dissipation process maybe vary from the actual process. Small test should predict the electrostatic propensity of textile materials in real-life conditions, from this perspective, tribo-charging in principle should be a preferred method for charging test surface.

The problem of this method is that it may not appraise the hazard under the actual use conditions. But just as Researcher Stull (cited by Gonzalez, 1999) reported that " .... Although this method may not appraise the hazard under actual use conditions, it does permit the ranking of material performance and identification of potential material problems for a given set of conditions."

Discharge Measurement from a Capacitor

In order to simulate a clothed human body which rubs an insulated surface and touches a grounded object generating a spark, a method has been developed to measure potentials and energies from the discharge of a capacitor which has been previously charged from the tribo-electrification of a fabric system (Gonzalez, Rizvi, & Crown, 2000). The capacitor acts as a human body in which the charge generated by the rubbing clothing is stored. The resulting discharge from the body, which occurs when the person touching a conductor, is simulated by discharging the capacitor through turning on a switch. The discharge potential of the resulting spark is measured and monitored by a digital oscilloscope. By this method, the electrostatic propensity of clothing can be assessed and standards can be established according to the known minimum ignition energy of incentive sparks for different gas mixtures.

Summary

Hazards associated with clothing and textiles are present in our everyday life, especially with the wide use of new materials, such as man-made fibers. The generation, accumulation and polarity of static charges produced by rubbing have been studied intensively, with many reports on the tribo-electric series (Ballou, 1954; Henniker, 1962). The past work has enable investigators to understand the concept of electrostatics, but the subject of electrostatic charging is still complex and misunderstood.

Current problems in productivity and quality, as well as hazards ranging from equipment damage to explosions, suggest that the static problem has not been adequately

resolved. Therefore, further inquiry in static electrification is important for the proper assessment of the electrostatic propensity of textiles.

Significant benefits cold arise from a greater improvement in the techniques of controlling static electricity, which are based on a better understanding of the phenomenon.

CHAPTER 3. METHODS AND MATERIALS

Research Design

This research was conducted as an experimental study. The purpose of this study was to study the effect of three different rubbing materials on the electrostatic propensity of 24 textile fibers. The three rubbing materials were: polytetrafluoroethylene (PTFE) felt, polyvinyl chloride (PVC) and nylon 6. Table 1 shows the characteristics of the fabrics tested. All fabrics were characterized in terms of fabric mass, count, and thickness following CAN/CGSB-4.2 No. 5.1, Unit mass of fabrics, CAN.CGSB-4.2 No. 6, Determination of threads per unit length, and CAN/CGSB-4.2 No. 37, Thickness of fabrics, respectively.

The tested samples fell into four groups according to their fiber content, as follows: Natural fibers, natural-based manufactured fibers, synthetic manufactured fiber and blends. Each group included variations in fabric structure with same fiber content for studying the effect of fabric structure. The selection of rubbing material was based on the fact that PTFE is the rubbing material recommended in a standard test method for evaluation of the electrostatic propensity of textile materials (NFPA 1991, par 9-29, Material Static Charge Accumulation Resistance Test), and PVC is a common textile material used in upholstery. Considering that both PTEF and PVC are normally placed near the negative end of known electric series, a third rubbing material nylon 6 was included because it is normally placed near the positive end in previously reported tribo-electric series.

The independent variables of the study were fiber content and rubbing material. The dependent variable (measured value) of the study was peak potential.

Procedures

Fabric Sampling

Ten specimens were prepared from each fabric. The size of each specimen was

150 mm×100 mm. The specimens were cut following standard sampling procedures

(Appendix A).

Pretreatment of Specimen and Conditioning

In order to avoid the influence of impurities, all specimens were prepared

following CAN/CGSB-4.2 No. 15, Non-fibrous materials on textiles, par 6.2 to remove

water-soluble materials, and according to par 6.3 to remove oils, fat, waxes, etc.

After pretreatment, all specimens were dried out in an oven at 105°C following

CAN/CGSB-4.2 No.3, Determination of moisture in textiles. For olefin fiber, the dry

temperature was 70°C because of its low melting point. The objective of drying out the

specimens was to let them start conditioning from a dry state avoiding any hysteresis

effect.

Then, specimens were conditioned inside an environmental chamber at 30 ±2 %

RH and room temperature 20° C at the Human Performance and Activity Research Lab in

the Max Bell building, University of Manitoba, and following CAN/CGSB-4.2 No. 2

M88, Conditioning Textile Materials for Testing. Although temperature and moisture

equilibrium is established relatively rapidly, ionic equilibrium requires more time (ASTM

D4238-83). As a result, specimens were conditioned for five days.

Table 1. *Fabrics Used in Experiment*

Fiber Code	Fiber	Count (W×F) (yarns/2cm)	Mass (g/m^2)	Thickness (mm)
	Natural Fibers			
01	Cotton A	47×43	294	0.7375
02	Cotton B	60×66	111	0.3277
03	Cotton C	53×41	149	0.5080
04	FR cotton	68×40	334	0.7366
05	Wool	78×48	257	0.7620
24	Linen	34×26	220	0.5080
25	Silk	124×74	75	0.2311
	Natural-Based Manufactured Fibers			
06	Viscose Rayon	59×44	142	0.3886
07	Lyocell	52×42	154	0.4572
08	Di-Acetate	33×25	164	0.3200
09	Tri-Acetate	78×49	102	0.1778
	Synthetic Manufactured Fibers			
10	Polyester A	52×43	131	0.4166
11	Polyester B	38×34	169	0.5461
13	Nylon 6, 6	38×44	89	0.3048
14	Acrylic A	31×26	177	0.5080
15	Acrylic B	40×32	168	0.6223
16	Modacrylic	34×25	175	0.5588
17	Olefin	35×26	168	0.6096
18	Meta-Aramid	39×37	160	0.5461
19	Glass	34×25	207	0.2540
	Blends			
20	60/40% Cotton/Lyocell	53×41	147	0.4572
21	70/30% PET/Cotton	65×36	90	0.2921
22	65/35% PET/Cotton	82×66	93	0.2870
23	55/45% PET/Wool	54×46	126	0.4826

Test System and Measurement of Dependent Variables

To conduct the study, a modified UA ESD Test System (Gonzalez, Rizvi, Crown & Smy, 1996) was used to measure peak potentials from the charged surface of fabric. The frame diagram of the instrument was shown in Figure 1. It had the following components: a specimen holder, a rubbing element, lap counter, a conducting plate, a digital oscilloscope, a voltmeter and a plotter.

A Simco model A300 static eliminator was used for eliminating any initial charge on the specimen surface. The discharge potential was measured and recorded by a Tektronix Model 2430A digital oscilloscope. Details of the testing procedure are given in Appendix B.

Data Collection

Data and measurements were recorded on a specific form for each fabric (Appendix C). Voltage waveforms acquired by the oscilloscope were saved in spreadsheet format for subsequent analysis.

Statistical Analysis: Hypotheses Testing

Using commercial available software, SPSS® version 10, the statistical analyses that were performed to process all the data collected were as follows:

1. Descriptive statistics and box plots. These analyses were used to characterize each fiber and rubbing materials with respect to the independent variables.

Figure 1. Diagram of the ESD Test System.

Electrostatic Generator with
Rubbing Element

Sensor Head

Rubbing
Element

Specimen

Digital
Oscilloscope

Conducting
Plate

To Ground
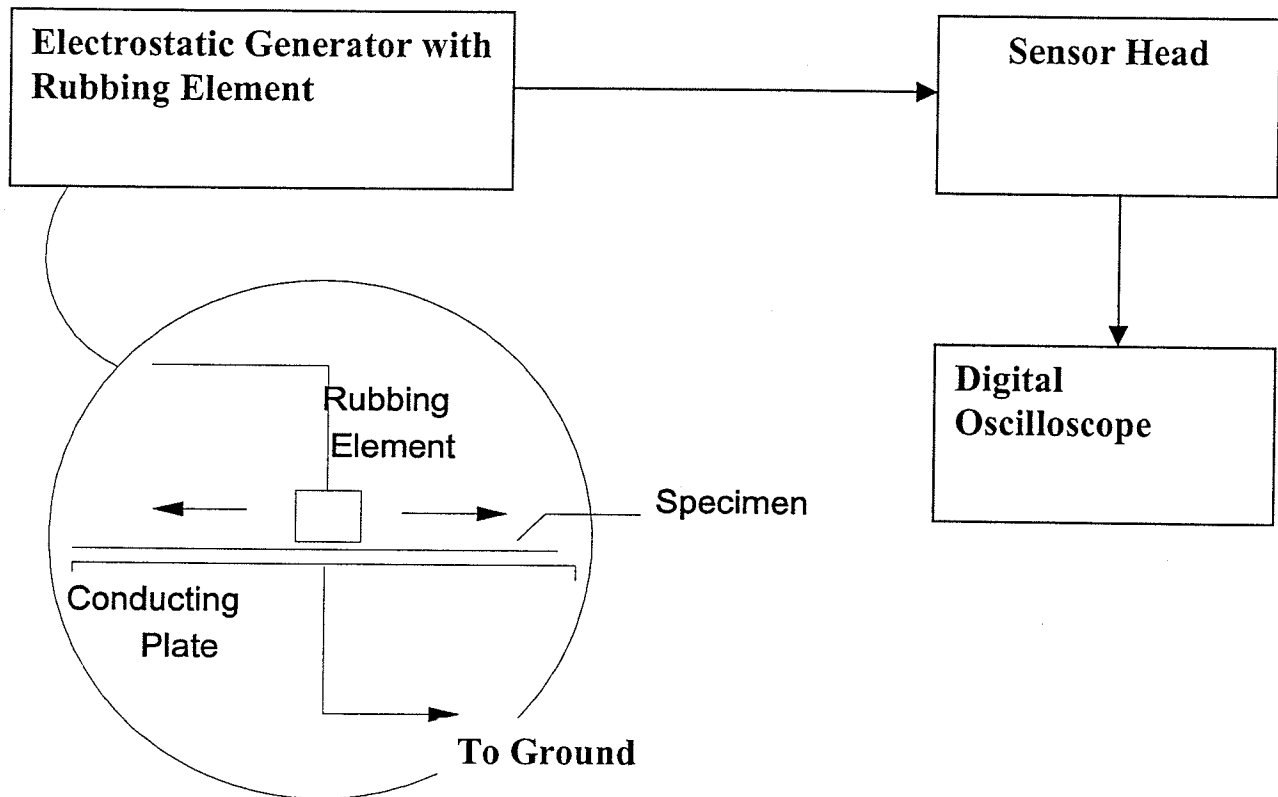
2. Multivariate ANOVA (analysis of variance) to test the null hypothesis that there were no significant differences among tested fibers and rubbing materials in the amount of charge generated by tribo-electrification.

3. One-way AVOVA and Duncan's multiple range tests to determine which fibers group together. In the same group, fibers were not significantly different from each other, while between groups, there were significant differences.

4. Pearson's correlation analysis to test the null hypnosis that there was no significant correlation between rankings using the three different rubbing materials.

5. Spearman's correlation analysis to test that there was no significant correlation between the obtained ranking and tribo-electric series.

CHAPTER 4. RESULTS AND DISCUSSION

Development of the Tribo-Electric Series

To achieve the third Objective of this study (see page 9), a tribo-electric series was initially established including all tested fibers. For the comparative study, some fibers have more than one specimen. In the case there were more than one sample of the same fiber content, the one with most typical fabric structure was selected, example, among the four cotton samples, Cotton A (code 1) was included. For the two polyester samples, polyester A (code 10) was included. For the two acrylic samples, acrylic A (code 14) was included. For the PET/Cotton blend group, 70/30% PET/Cotton (code 21) was included. Totally, 18 samples and two rubbing materials PVC (vinyl) and PTFE (Teflon®) were included in the series. Nylon was included as a rubbing material, because it was also a sample.

To develop the tribo-electric series, the first step is to create a matrix including all samples, then rub the first sample against the rest of the sample until all pairs formed have been tested. An electrostatic voltmeter (ESD model 105) and a digital oscilloscope were used to monitor the polarity of charge on each specimen. This process repeats until the last pair is rubbed. This process ensures that all the different test materials are rubbed in pairs. According to the polarity signs, a list was developed and arranged according to whether a specimen developed a positive or negative charge when rubbed against other fiber. The tribo-electric series obtained is shown in Appendix D.

Results

This chapter has been divided into three sections according to the established null

hypotheses.

H_{01}:   "There will be no significant differences in the amount of charge

generated by tribo-electrification among textile fibers rubbed by different

materials."

Two-way analysis of variance (ANOVA) indicated significant main effects of

fabric and rubbing material as well as interaction effect on peak potential, indicating that

there were significant differences in the magnitude of peak potential among rubbing

materials, but this effect varied somewhat by the different fibers (Appendix E). Thus, it

can be expected that different rubbing material may yield different peak discharge

potential for the same fiber. In addition, the statistics F value suggest that rubbing

material has greater effect than fibers. Thus, the null hypothesis one was rejected.

Mean peak potentials and the standard deviation were plotted by fiber and rubbing

material in Figures 2 to 4. Generally, nature fiber cotton, wool and linen and natural

based manufactured fibers have a little bigger standard deviation than the manufactured

fibers. Because nature fibers such cotton got relatively low mean peak potential, the

standard deviation comparing their individual mean peak potentials is relatively large,

especially the cases when the nylon was rubbing material. Some observations were

extreme, namely the standard deviations of wool (code 5) and nylon (code 13), which are

almost the same value as their mean peak potential when nylon was the rubbing material.

It can be seen from Figure 2 that all fibers with the exception of polyester B (code

11) were positively charged when rubbed by PTFE (Teflon®). Peak potentials varied

between 618 V and -322.4 V, which were the value of wool (code 5) and polyester B (code 11) respectively. The absolute average peak potential for 24 kinds of fibers was 316.63 V. A different pattern was observed from Figure 3 when PVC (vinyl) was used as the rubbing material because more than half of fibers were positively charged and rest negatively charged. The peak potentials varied from 440.4V to –682V with olefin (code 17) yielding 440.4V and polyester B (code 11) generating -682V. The absolute average peak potential for all 24 fibers was 260V. In the case of nylon 6 as the rubbing material shown in Figure 4, all fibers were negatively charged except for glass (code 19). Peak potentials varied from 41.3V to –214V, with glass fiber (code 19) generated a positive potential of 41.3V and di-acetete (code 8) generating lowest negative potential of -214 V. The absolute average peak potential for 24 fibers was 113.80V. For three rubbing materials, nylon 6 generated the lowest average peak potential and PTFE yielded the highest value of peak potential.

One-way ANOVA and Duncan's multiple range test were used to determine which fabrics differed significantly from each other for the same rubbing material (Table 2). Results generally suggested that for peak potential, most fabrics differed significantly (at $P<0.05$) from each other, but some homogeneous subsets could be formed in three rubbing materials (see Figure 2, 3 and 4).

Further analyses the results were performed by fiber type. For cotton group, when the rubbing material was PTFE, cotton A (code 1) and cotton B (code 2) yielded similar values while dyed cotton C (code 3) and FR cotton (code 4) had much greater peak potential than those. Similar trend was observed with the other two rubbing materials PVC and nylon 6.

Linen (code 24), a cellulose-based fiber, yielded higher potentials than undyed cotton for all three rubbing materials. Viscose rayon (code 6), which is a cellulose-based manufactured fiber, generated higher potentials than undyed cottons.

Lyocell (code 7) a solvent-spun cellulose-based manufactured fiber developed higher potentials than viscose rayon. In addition, lyocell generated higher potentials than cotton C (both fabrics were chambray type and dyed) with the exception of PTFE as rubbing material; and higher potentials than the other undyed cottons.

Di-acetate (code 8) had higher potentials than Tri-acetate (code 9) in all three cases.

For the polyester group, it can be seen that polyester A (code 10) and polyester B (code 11) present quite different behaviors. When the rubbing material was PTFE, they developed opposite polarity. When the rubbing material was PVC, polyester A and polyester B both developed negative potential, but polyester B developed much higher potential than polyester A. In the case of nylon 6 as rubbing material, they developed similar potentials.

For the acrylic group, acrylic A (code 14) acrylic B (code 15) and modacrylic (code 16) yielded similar potentials with all three rubbing materials.

In the case of blends, results showed a trend of potential with magnitudes between values of those fibers in fabrics of single content. For example, cotton/lyocell (code 20) generated potentials between cotton C (code 3) and lyocell (code 7) for all rubbing materials.

Figure 2. **Peak potentials and their variation by ± one standard deviation by fiber and by rubbing material PTFE (Teflon®).**
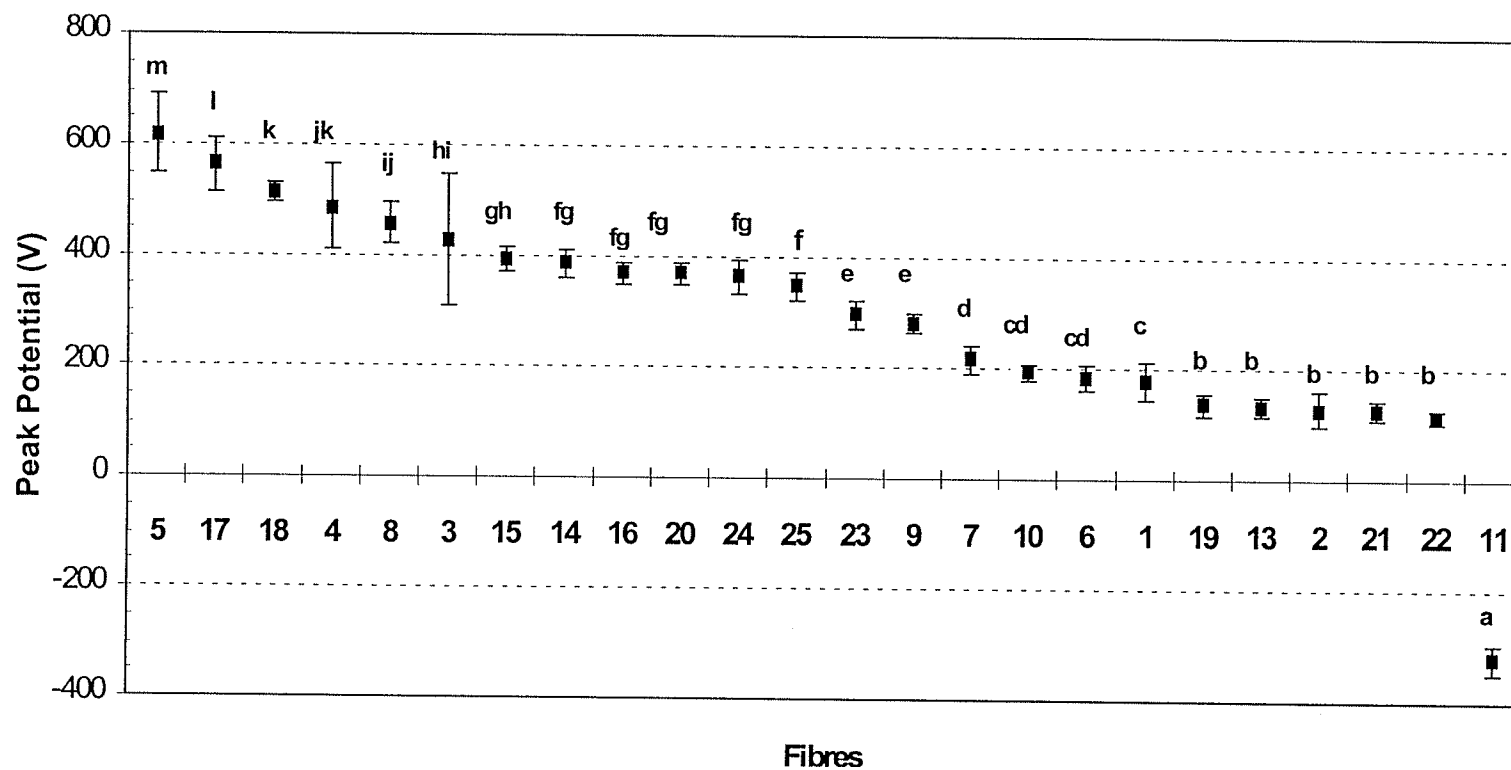
Means with the same letter indicate homogeneous subsets (highest and lowest means are not significantly different) when subjected to Duncan's multiple range test (p<0.05).

Figure 3. **Peak potentials and their variation by ± one standard deviation by fiber and by rubbing material PVC (vinyl).**
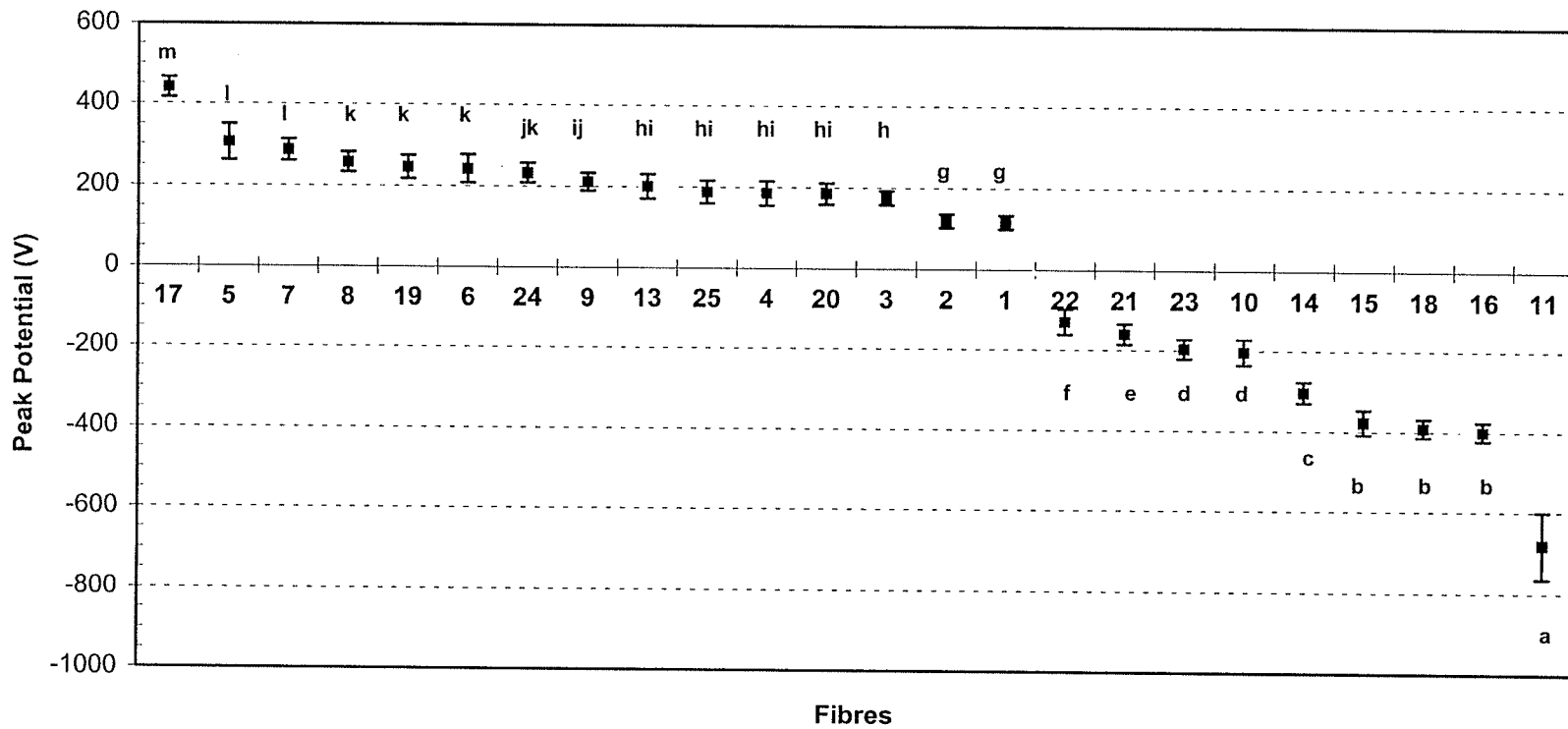
Means with the same letter indicate homogeneous subsets (highest and lowest means are not significantly different) when subjected to Duncan's multiple range test (p<0.05).

Figure4. **Peak potentials and their variation by ± one standard deviation by fiber and by rubbing material Nylon 6.**

Means with the same letter indicate homogeneous subsets (highest and lowest means are not significantly different) when subjected to Duncan's multiple range test (p<0.05).

Table 2. *Analysis of Variance: Peak potentials of different fabrics at three rubbing materials.*

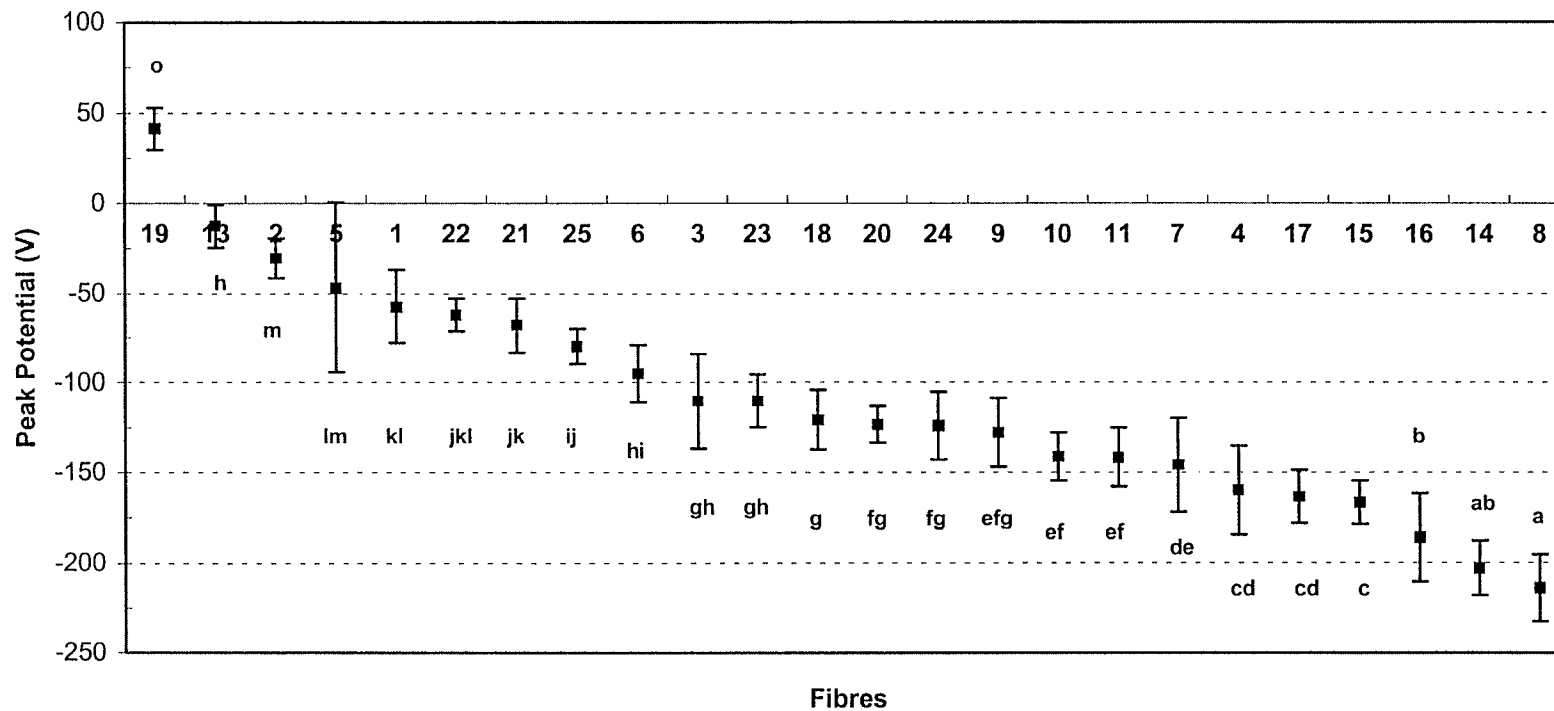| Code	Fibre	Rubbing Material					
		PTEF (Teflon®)		PVC (Vinyl)		Nylon 6	
		Peak Pot.	St. Dev.	Peak Pot.	St. Dev.	Peak Pot.	St. Dev.
01	Cotton A	176.40^c	33.96	116.80^g	17.36	-57.40^{kl}	20.57
02	Cotton B	128.00^b	29.93	120.00^g	16.97	-30.00^m	10.74
03	Cotton C	428.00^{hi}	119.70	175.60^h	17.12	-110.20^{gh}	26.44
04	FR cotton	488.00^{jk}	76.13	185.60^{hi}	29.95	-160.00^{cd}	24.44
05	Wool	618.00^m	72.08	305.60^l	43.54	-46.70^{lm}	47.26
06	Viscose Rayon	181.20^{cd}	23.40	242.40^k	34.32	-94.95^{hi}	15.93
07	Lyocell	215.60^d	27.22	286.80^l	26.20	-146.00^{de}	26.08
08	Di-Acetate	460.00^{ij}	36.51	257.20^k	23.93	-214.00^a	18.60
09	Tri-Acetate	279.20^e	17.87	211.60^{ij}	21.70	-127.80^{efg}	19.31
10	Polyester A	191.80^c	15.42	-204.00^d	32.04	-141.40^{ef}	13.50
11	Polyester B	-322.40^a	27.78	-682.00^a	81.89	-141.60^{ef}	16.41
13	Nylon 6,6	131.20^b	19.12	201.00^{hi}	30.35	-12.70^n	11.93
14	Acrylic A	387.20^{fg}	25.02	-303.40^c	26.32	-202.80^{ab}	14.82
15	Acrylic B	393.00^{gh}	23.59	-377.20^b	30.60	-166.80^c	12.08
16	Modacrylic	370.00^{fg}	20.55	-400.00^b	23.09	-186.00^b	24.46
17	Olefin	564.00^l	48.81	440.00^m	25.24	-163.60^{cd}	14.69
18	Meta-Aramid	514.00^k	18.97	-391.60^b	22.43	-120.60^g	16.68
19	Glass	136.00^b	20.13	246.00^k	27.97	41.30^o	11.63
20	60/40% Cotton/Lyocell	369.00^{fg}	21.32	185.40^{hi}	26.26	-123.40^{fg}	10.46
21	70/30% PET/Cotton	128.00^b	16.87	-160.00^e	26.25	-68.00^{jk}	15.26
22	65/35% PET/Cotton	112.00^b	11.35	-129.40^f	31.61	-62.00^{jkl}	9.24
23	55/45% PET/Wool	295.00^e	24.61	-196.80^d	24.93	-110.20^{gh}	14.59
24	Linen	363.00^{fg}	31.29	233.00^{jk}	23.59	-124.00^{fg}	18.86
25	Silk	348.00^f	25.73	188.40^{hi}	27.61	-79.70^{ij}	9.87

a.b.etc: In each column, means with the same letter indicate homogeneous subsets (highest and lowest means are not significantly different) when subjected to Duncan's multiple range test ($p < 0.05$).

For the polyester blend group, it can be seen that 70/30 polyester/cotton (code 21) and 65/35 polyester/cotton (code 22) showed similar behavior with all three rubbing materials. Those potentials were between cotton A (code 1) and polyester A (code 10) with the exception of PTFE as rubbing material. For all the three rubbing materials, 70/30% polyester/cotton blend developed higher potential than 65/35% polyester/cotton blend. Polyester/wool blend (code 23) developed the potentials between wool (code 5) and polyester (code 10). In addition, the polyester/wool blend developed higher potential than polyester/cotton blends in all the three rubbing material cases.

Wool (code 5) developed higher potentials than silk even though both are protein-based fibers, but with different polymer structure.

H_{02}:   "There is no significant correlation between rankings from different rubbing materials".

Pearson's correlation analysis was used to test this null hypothesis, which measures the strength of the relationship of peak potential among three rubbing materials. The results were shown in Table 3. It can be seen that at the 0.01 significant level, all correlation coefficients were significant. The three coefficients were respectively 0.373, -0.310 and 0.274. Because the values for three correlation coefficients were relatively far from 1, the relationship between three peak potentials was not strong. So we failed to reject the hypothesis 2. If we use the ranking of peak potential to give the explanation for this conclusion, which means the three rubbing materials will yield different ranking orders for the tested fibers.

Although the null hypothesis was rejected, it can be seen that all the three correlation coefficients were significant at 0.01 significant level. It means that the possibility of getting 0.375, -0.310 and 0.274 correlation coefficients of peak potential between different rubbing materials were very large. Although the value of 0.373 and -0.310 for the correlation coefficient are not sufficiently near the value of ±1 for us to reject the hypothesis, it can be said that there are some degree of relationship between these two peak potentials when Teflon® and vinyl are the rubbing materials and when Teflon® and nylon are the rubbing materials. The negative value of the correlation coefficient indicate that two peak potentials has opposite association.

Table 3. *Correlation coefficient of peak potential between different rubbing materials.*

	Peak Potential by Vinyl		Peak Potential by Nylon 6	
	Correlation coefficient	P value (2- tailed)	Correlation coefficient	P value (2- tailed)
Peak Potential by Teflon	0.373	0.000	-0.310	0.000
Peak Potential by Vinyl			0.274	0.000

H_{03}: "There are no significant correlation between established rankings and the tribo-electric series."

The tribo-electric series containing 24 tested fibers is shown in Appendix D. Because for the tribo-electric series we only have the ranking information, Spearman's ranking correlation analysis was performed to test null hypothesis 3. This analysis measures the strength of the relationship among rankings, and the relationship does not need to be linear (Neter, Kutner, Nachtsheim, & Wasserman, 1996). The results are shown in Table 4.

Table 4. *Correlation coefficient among different rankings.*

	Ranking By Vinyl		Ranking by Nylon 6		Ranking by Tribo-electric series	
	Correlation coefficient	P value (2-tailed)	Correlation coefficient	P value (2-tailed)	Correlation coefficient	P value (2-tailed)
Ranking by Teflon	-0.129	0.610	-0.218	0.385	0.271	0.276
Ranking by Vinyl			0.137	0.587	-0.007	0.977
Ranking by Nylon 6					0.397	0.10

From the Table 4, it could be seen that at 0.05 significant level, all coefficients were not significant. The three coefficients were respectively 0.271, -0.007, and 0.397. None of them was strong, so we failed to reject the hypothesis 3. That means for the three rubbing materials, the ranking orders were different from those of the tribo-electric series. Although we failed to reject the hypnosis 3, it can be seen that rankings between nylon and tribo-electric have some degree of relationship.

Discussion

This study was part of a larger project to investigate the electrostatic propensity of textile materials at low humidity levels. Based on previous studies, objectives of this research were to study the effect of rubbing materials on the electrostatic propensity of textile fibers.

Objective 1

The first objective was to measure surface peak potentials of fabrics generated by tribo-electrification using different rubbing materials at 30% relative humidity (RH) and

room temperature 20°C. This objective was accomplished for all fibers tested with three rubbing materials. The fabrics included natural and manufactured fibers, and blends. The three rubbing materials were PTFE (Teflon®) felt, PVC (vinyl) composite and nylon 6 fabric.

Chubb (1988) stated that tribo-charging was notoriously unreliable and considerable effort might be needed to achieve consistent charging, and that little control could be expected over the level and polarity of charging. The results obtained from this study are relatively consistent in magnitude and polarity, although some standard deviations for some fiber types are relatively large compared with their individual mean peak potential. This confirms the report that with controlled frictional charging, a consistent result would be obtained (Gompf, 1984; Gonzalez, Rizvi, Crown, & Smy, 1996). The nature fibers cotton, wool and linen show a little larger standard deviation than manufactured fibers, maybe because those nature fibers have less degree of uniformity in their properties compared to manufactured fibers in nature. The scale structure of wool fiber affects the rubbing degree, therefore their position and direction will affect the value of peak potential. This may explain why wool has a relatively larger standard deviation than the others. Because nature based manufactured fibers have very quick charge decay rate due to their high moisture regain, how fast the measure of peak potential was taken after the rubbing process, will great affect the value measured. This maybe the reason why they show a little larger standard deviation than other manufactured fibers. Specimen nylon has a very large standard deviation compared with its peak potential when nylon is the rubbing material because the value of the peak

potential is too small, due to the very similar properties between fiber and rubbing material.

Our common knowledge is that manufactured fibers usually develop higher electrostatic charges than cellulose-based fibers such as cotton. The explanation for this phenomenon usually is based on the moisture regain between the fiber types. The moisture absorbed by the fiber provides a conductive path to the static charges during the dissipation process. Therefore, hydrophilic fibers usually decay faster than hydrophobic fibers at relatively high humidity levels (above 45% RH). At low humidity conditions, both hydrophilic and hydrophobic fiber the actual moisture content in the fibers drops significantly, and may develop enough static charge with the subsequent potential hazard if the charge is generated in an explosive environment. The existence of polar groups (e.g., hydroxyl groups) in cotton fibers makes them absorb more moisture than most manufactured fibers, which helps in providing water ions to cancel out any static charge; this study confirms this. At 30% RH and room temperature 20°C, for the three rubbing materials, cotton (code 1 and code 2) had lower absolute peak potentials than all manufactured fibers excepting nylon (code 13), which developed lower peak potential than cotton when the rubbing material was nylon 6 (see Figure 2, 3 and 4). But, for the three rubbing materials, dyed cotton C (code 3) and FR cotton (code 4) had much higher potentials than the plain cottons A and B. This could mean that dyeing and surface finishes may have significant effect on the electrostatic properties of fiber. Any wet process, such as bleaching or dyeing, that alters the electrolyte content may alter their electrical resistance and the resistance of the synthetic fibers is much affected by the presence of surface finishes (Morton & Hearle, 1993). In fact, finishes is an effective

methods used in industry to decrease static build-up, the resistance of fiber can be reduced 1000 times by treatment with a suitable anti-static agent (Hayek and Chromey, 1951).

Linen is also a cellulose-based fiber, but linen generated higher charge potential than cotton with all three rubbing materials. This could be explained by the polymer structure of linen, which has higher degree of crystallization and orientation than cotton, giving linen a hard surface. In addition, the fabric made of linen had a coarse surface, which increased the friction force during rubbing.

Viscose rayon (code 6) is a manufactured regenerated cellulose fiber, and wood pulp is the major source to produce it. Rayon polymers have normally low degree of crystallization and polymerization. The degree of polymerization is only about 400 to 700, compared to 6000 to 10000 for cotton (Hatch, 1993). The molecules are also less ordered, the crystalline areas are smaller in size, and the fiber has a higher amount of amorphous material. Compare with cotton, it has higher moisture regain. At the testing condition of 30% RH, the moisture regain of viscose rayon was 7.38 %, while cotton A and cotton B were 4.55% and 3.23% (Gonzalez, 2001). It could be predicted that rayon may develop lower absolute value of peak potential than cotton, but it was not. Viscose rayon developed much higher charge potential than plain cotton A and B (see figure 2, 3 and 4). This phenomenon of moisture effect on the electrostatic property has been previously documented by other researchers (Sereda & Feldman, 1964; Onogi, Sugiura & Nakaoka, 1996; and Onogi, Sugiura & Matsuda, 1997). Sereda and Feldman (1964) stated that sorbed water on the surface of the fabrics contributed to a higher electrostatic potential either by contributing more ions such as hydrogen irons or by allowing a more

effective transfer electrons or ions from one surface to another generated by tribo-electrification. Because only a part of the surface area actually makes contact during the tribo-electrification procedure, sorbed water on the surface may act as a medium for distributing the electrons or ions, having the effect as if a greater area of the surface contacted. They stated that because of the dipole nature, sorbed water may modify the character of the fabric surface in a way to make available more sites for the trapping of electrons. In fact, any tribo-electrification procedure involves two processes: charge generation and charge dissipation. The charge observed at any instant in the charging procedure is the net charge. Electrostatic charge generation appears to reach a maximum value at a relative humidity corresponding to that of a monomolecular layer of water existing on the surface of the material (Sereda & Feldman, 1964). This water content is called *critical water content* (Onogi, Sugiura & Matsuda, 1997). The water molecules in this layer are tightly bound to the fiber molecules and as such, do not participate in charge dissipation as is traditionally thought to occur at higher humidity levels, where the charge dissipation or leakage process predominates. Whether the testing conditions meet the requirement of critical moisture content of rayon tent to present an argument against the explanation of rayon developed higher charge potential. But moisture in the fiber providing more ions could be a reasonable explanation to this phenomenon. In addition, by observing the voltage waveforms acquired by the oscilloscope, it can be seen that rayon indeed had fast charge decay than cotton A and B. if we observe the charge potential after peak potential about 30 seconds, rayon had low charge potential than cotton A and B.

Lyocell (code 7) is another type of rayon, produced by a process known as solvent spinning. A solvent is mixed with the wood pulp to make lyocell fiber. In the producing process, there is no degradation of the polymer as is necessary in the viscose rayon process (Hatch, 1993). Viscose rayon usually has slightly higher moisture regain than lyocell. Lyocell developed higher charges than viscose rayon. A possible explanation is that the fabric made of lyocell was dyed, and the change in the polymer because of the presence of big dye molecules may have an effect of their tribo-charging propensity. Results from this study were consistent with this statement, as potentials from Lyocell fabrics were higher than viscose rayon with all three rubbing materials.

Di-acetate (code 8) and tri-acetate (code 9) are also manufactured cellulose-based fibers. From its polymer structure, di-acetate has very low crystallinity and fiber orientation, while triacetate are heat-treated which has a higher order of crystallinity and orientation than acetate. At 30%RH, di-acetate and tri-acetate had moisture regain of 2.72 and 2.36 %, respectively (Gonzalez, 2001). Whereas due to the different yarn type and fabric structure, di-acetate and tri-acetate had great difference in the surface properties. It has been previously reported that the magnitude and polarity of charge generated by tribo-charging depend on the inner properties of the materials but also greatly affected by the surface characters (Hersh & Montagomery, 1956). The type of yarn and weave may affect the contact area between two fabric surfaces, therefore affect the amount of charge generated (Wilson, 1963). Di-acetate fabric was made of spun yarns and plain weave, and tri-acetate fabric was made of filament yarns and satin weave. Di-acetate developed higher potentials despite its higher moisture regain. A possible explanation for this phenomenon could be that with its fabric construction, more yarns were exposed to

rubbing, and its spun yarns were harsher than those filaments in triacetate. In summary, di-acetate may have more actual contact and rougher area to rubbing than triacetate.

It can be seen from Figures 2, 3 and 4 that same type of fiber tends to have similar range of charge developed although there were some exceptions. For example, plain cotton A and B had similar values with all three rubbing materials; acrylic fibers (codes14, 15, and16) yielded also similar potentials for the three rubbing materials. But polyester A (code 10) and polyester B (code 11) showed different trend. With PTFE, they developed opposite charges, and with vinyl they generated different peak potentials. Polyester A had a moisture regain of 0.65% while polyester B has 0.38% at 30% RH. For hydrophobic fibers, small change of moisture may greatly change the conductive ability of the fiber and this maybe give the explanation why polyester B developed higher charge potential than polyester A regardless the polarity. Polyester B developed negative charge while rubbing with PTFE was erratic behavior. Hersh and Montgomery (1955) observed abnormal behavior during their experiments with textile fibers which were eliminated upon washing and they suggested that such erratic behavior may related with the contamination of fibers which result in an increase or decrease in the charge generation, including changes in polarity in some cases. Impurities have great effect on the electrostatic properties of fibers that even can reverse change polarities (Morton & Hearle, 1993). Because it was noticed that there was some white dust accumulated on the monitor screen from the air circulation system in the testing chamber, the specimens were re-treated with water and solvent treatment following CAN/CGSB-4.2 No. 15 to remove any impurity from the specimen. In addition, the PTFE used was a felt, which left tiny pieces of fibers on the rubbed surface of the specimens, and they were hard to remove

after a test was performed. This may give an explanation why polyester B developed negative charge when rubbing with PTFE. Further analysis of this case is required to determine the actual cause of the negative polarity of polyester B.

It is natural to expect that blend fabrics should present the properties between the two materials involved in the blend. This study confirmed this trend in most of the cases. Lyocell/cotton blend (code 20) yielded peak potentials between cotton C (code 3) and lyocell (code 7). All three referred samples were dyed (type chambray). PET and cotton blends (code 21 and code 22) had similar values for all three rubbing materials, even though the 70/30% polyester/cotton blend developed higher potentials than the 65/35% polyester/cotton blend. This could be explained by the higher content of polyester of the former blend, and that polyester developed higher charge than cotton. The average value of cotton A and cotton B as the value of cotton and the average value of polyester A and polyester B as the value of polyester were selected for comparison purposes. It can be seen that polyester/cotton blends (codes 21 and 22) had values between polyester and cotton. Also fabrics of PET and wool blend (code 23) had potentials between polyester and wool (code 5). Because wool had higher potential than polyester, it could be expected that a 55/45% PET/wool blend would develop higher absolute potential than 65/35% polyester/cotton blend and 70/30% polyester/cotton blend, which was the case with all three rubbing materials.

The magnitude and polarity of charge generated by wool and silk can be explained by their position in a tribo-electric series. The amount of static electricity generated by tribo-charging depends on the atomic makeup of the materials involved (Hardwick, 2002). Objects made of materials that are far apart in the tribo-electric series

will tribo-charge more than materials that are close together in the series, as the structures are different. In the developed tribo-electric series (Appendix D), wool is closer to the positive end than silk, so when rubbing with PTFE and vinyl, wool would developed more positive charge than silk. When rubbing with nylon, which is near the positive end in the series, silk would develop more negative charge than wool.

Natural protein-based wool has relative higher moisture regain than cotton fiber, but it developed much higher charge potential than cotton. It may be explained by the special scaly structure of wool fiber. The scale increases the roughness of the surface, therefore increasing the degree of rubbing. On the other hand, most moisture absorbed by wool fibers are beneath the scale layer, which is hardly involved during the charge dissipation process as moisture does with other hydrophilic fibers.

Polyester and acrylic are both manufactured fibers. In the production of manufactured fibers, many qualities can be built into the fiber, for this reason, it is difficult to generalize about each type of them, since each manufacturer may produce them differ somewhat. At testing conditions, Acrylic A, B and modacrylic had moisture regain of 0.57%, 0.67% and 0.55% respectively. Polyester A had moisture regain of 0.65% (Gonzalez, 2001). It can be seen that the average peak potential for acrylic was higher than polyester A.

Among all 24 samples, olefin (code 17) had the lowest moisture regain, which was 0.19%. For all three rubbing materials, olefin developed relatively high potential (Figure 2, 3 and 4). Glass had low moisture regain, which was 0.34% at 30% RH, while it did not develop high charge potentials. One possible reason may be due to a very smooth surface of glass, which greatly decreases the degree of rubbing.

Objectives 2 and 3

The second Objective was to study if there was any relationship between peak potential when using different rubbing material. Pearson's correlation analysis was applied and results shown that there were no strong relationships between these peak potentials.

The generation, accumulation and polarity of static charges produced by rubbing have been studied intensively. Tribo-electric series is one of the results of these studies. It reflects the tendency of material to lose or gain electrons. Hersh and Montgomery (1956) justified a tribo-electric series by stating that a particular order was created because of the unique molecular structure of a material. They speculated that there would be no change in the order of a tribo-electric series when only changing the rubbing material. There would be, however, a change in magnitude of charge generation. The result of this study does not support this statement. Although we failed to reject the hypothesis that there was no significant correlation between peak potential when using different rubbing materials, we can see that the degree of correlation between peak potentials when Teflon and vinyl are rubbing material was larger than the degree of correlation between Teflon and nylon as rubbing materials and between Vinyl and nylon as rubbing materials. This is maybe because both Teflon and vinyl are located near the negative end in the tribo-electric series while nylon is located near the positive end in the series.

The third Objective was to rank peak potential for the three rubbing materials and to study whether these rankings had any relationship with developed tribo-electric series. In fact, we failed to reject hypotheses 3, which implies that these rankings of peak potential for the three rubbing materials has no significant correlation with the order of

tribo-electric series. The spearman's ranking correlation analysis supports this. Although the correlation coefficient between the ranking of nylon and tribo-electric series was as large as 0.397, that means there is some degree of relationship between them, the p-value was larger enough implying that correlations were not significant.

Some researchers have placed the PTFE at the negative end of reported tribo-electric series, this means that all the tested fiber should be charged to the positive sign. In this study, when PTFE was used as a rubbing material, all tested fibers developed positive charges with the exception of Polyester B (code 11). Nylon has been reported to the positive end in known tribo-electric series, and below glass fibers. This study confirmed with this previous knowledge.

In fact, different researchers had developed different tribo-electric series (Fowler, 1988) and the common explanation for this variation is that the tribo-charging are affected by many factors. Shinohara, Yamamoto, Anzai and Endo (1976) reported that the magnitude and sign of electrostatic charges of polymers were determined by internal conditions such as the chemical structure, orientation, crystallinity, surface state of materials and impurities, as well as by external conditions such as relative humidity, contact area and force. The ordering of the tribo-electric series is different when surfaces are rubbed rather than simply touched. The order also changes when surfaces of different roughness are rubbed together. Even, identical substances can generate a charge-imbalance if they have different surface properties (William, 1995). This was the case when nylon (code 13) was rubbed with nylon 6, and yielded negative charges, although very small (Figure 4). One explanation for the change of the order in the tribo-electric series was given by Lowell (1976). He stated that rubbing disturbs the structure of the

molecules, bringing to the surface molecular groups from inside the material no deeper than 50 °A; these molecules may participate in the acceptance or donation of additional electrons, resulting in an increase or decrease of charge generation, including changes in polarity. This may explain the exceptional case observed during this study.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Peak discharge potentials from the surface of 24 different fabrics were measured using three rubbing materials. The magnitude of the discharge potential was affected by such factors as rubbing material, fiber content, and surface characteristics. In general, the pattern of results for this study was predictable on the basis of other studies and the theory of static electricity. Some conclusions reached on the basis of this study or confirmed by this investigation can be stated as follows:

1) Peak discharge potentials vary among different fibers. Cellulose-based fibers generated charge potentials, which were smaller in magnitude than manufactured fibers, while protein-based fiber, silk and wool, yielded similar peak potentials as manufactured fibers.

2) Rubbing material had a great effect on the electrostatic properties of the fiber, and interaction effects were also determined between rubbing material and fiber content.

3) Surface characteristics may have a significant effect on the electrostatic properties of a textile material. The factors affecting surface properties may include surface finishes, dyeing, type of yarn (filament or spun yarn) and type of weave.

4) Different rubbing materials may yield variation in both the magnitude of generated charges and the placing on ranking lists of fabrics with different fiber content.

5) At low humidity, moisture absorbed by a fiber may not solely contribute to the charge dissipation process as reported in previous studies. When the moisture content is below its critical value, water ions may contribute to tribo-electrification, but may no

contribute to establishing a conducting path during the dissipation process, or facilitate the cancellation of those charges by existing ions in the surrounding air.

Recommendations

Recommendation for the industry

Electrostatic discharges from a charged object cannot be completely eliminated but their effects can be minimized and controlled. Correct assessment and material selection are often the key to preventing or decreasing the damage. The recommendations that follow are made on the basis of this study only and must be considered in light of other factors, not included in the present research, in the development of any safety code or industry specification.

Peak potential was affected by several factors, such as humidity, fiber, rubbing material and mode, and surface characteristics. Therefore when considering what kind of materials can be selected to ensure safe electrostatic levels, a comprehensive approach that incorporates all factors together is recommended for optimum results. Because interacting effect exists between rubbing materials and fibers, it is highly recommended to carry out pre-tests, which simulates real conditions before making a final decision.

Under low humidity conditions, using solely moisture regain as an index to predict electrostatic properties of the fiber may mislead, and may result in incorrect usage of the material.

Recommendations for Further Research

The following are suggestions for further research work in this area:

1) It seems that 30% RH approximates the critical moisture content. In order to further clarify the effect of moisture on the electrostatic properties of the fiber, research should be replicated at different humidities. Special attention should be placed on measurements taken at those RH levels near 30%, for example 20 - 25%, in order to confirm the results of this study. In addition, it should be repeated under two other conditions, one which is higher than 30% RH, and another at 0 % RH, to better understand the complex effect of moisture content in textile materials and environmental conditions on their electrostatic propensity.

2) Because rubbing material has a significant effect on peak potential, more rubbing materials should be tested to confirm the results reported in this study. Special consideration should be given to materials located near the positive end of the tribo-electric series as well as located at the middle of the series.

3) This study has shown that surface characteristics may have a significant influence on the electrostatic properties of textiles. Therefore, a new research may include samples of fabrics with different structures and/or surface finishes. For example, these could include a comparison study of the effect of filament and spun yarns, and the effect of different weaves.

4) Previous studies and this study have shown that different rubbing conditions (such as rubbing materials, rubbing speed and rubbing pressure) have significant effect on tribo-charging textile surfaces, but they usually do not influence their dissipative properties. It is suggested that a study including charge decay properties of surface tribo-charged fabrics be carried out as well.

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APPENDICES

APPENDIX A. SAMPLING DIAGRAM

Specimens A and specimens B will be used for two different rubbing materials.
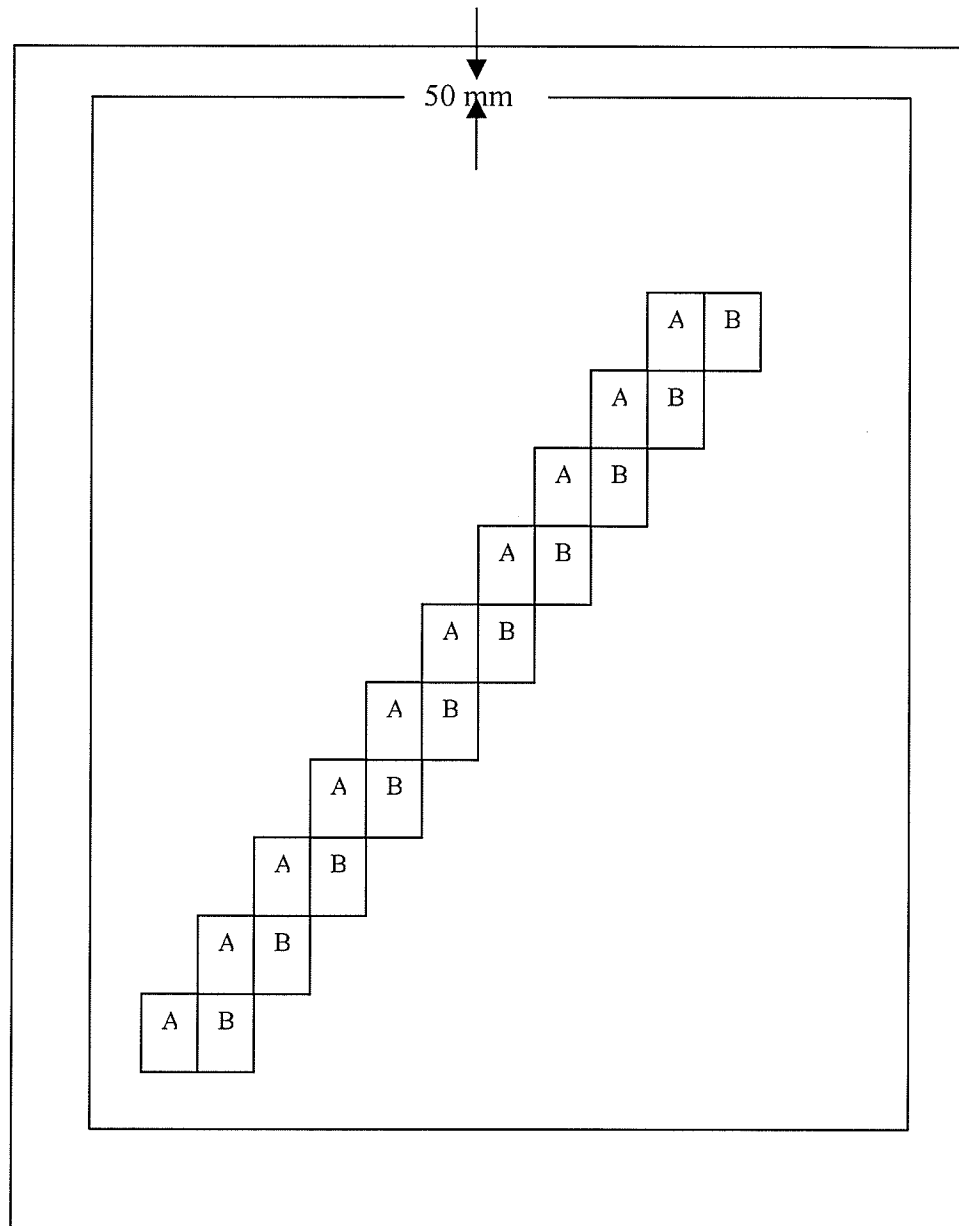
Note:
Drawing is not at scale. Specimens will be cut at least 50 mm away from fabric edges.

APPENDIX B. TESTING PROCEDURE

The testing procedure is as follows:

1. Operator must be grounded using a wrist ground.

2. Set-up oscilloscope to pre-determined settings according to fabric to be tested.

3. Place the specimen on the specimen holder and then place the specimen on the conducting plate and secure it with the clamp. Wear gloves while handling specimens.

4. Ground specimen.

5. Adjust voltmeter to zero.

6. Make sure the gap between the sensor head and the specimen is according to the manufacturer's specifications (50.8 mm).

7. Apply ionized airflow to the specimen at least for 30 seconds to cancel any initial charge on the surface of the fabric as well as the surface of the rubbing element.

8. Rub the specimen 20 times in approximately 10 seconds.

9. Place the sensor head over the specimen and turn the sensor button on in electrostatic voltmeter.

10. Turn off the voltmeter when the voltmeter pointer returns to zero or after 100 seconds. Save the waveform acquired by oscilloscope in spreadsheet format.

11. Record the data on the data collection form, which includes: atmosphere conditions, peak discharge potential on the oscilloscope, voltmeter range, fiber code, disk number, spreadsheet file number and specimen number.

12. Repeat the steps 3 to 12 for a new specimen.

APPENDIX C. DATA COLLECTION FORM

University of Manitoba   Date:_____
Department of Clothing and Textiles
ESD project

Temperature:_____   Humidity:_____
Rubbing material:_____   Voltage meter range:_____
Fibre code:_____   Disk No.:_____

Results

Specimen No.	Peak Volt (mV)	File No.
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Observations:

_____
_____
_____
_____
_____

APPENDIX D. TRIBOELECTRIC SERIES

FABRIC	CHARGE
Glass	+ ve
Nylon	|
Wool	|
Cotton	|
Viscose Rayon	|
Lyocell	|
Cotton/Lyocell	|
Flax	|
Acetate	|
Silk	|
Triacetate	|
Olefin	|
PVC	|
Aramid	|
Pet/Wool	|
Pet	|
Pet/Cotton	|
Acrylic	|
Modacrylic	|
PTFE (Teflon)	- ve

APPENDIX E. ANALYSIS OF VARIANCE

Tests of Between-Subjects Effects
Dependent Variable: Peak Potential (V)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	49711307.166(a)	71	700159.256	698.254	.000	.987
Intercept	3275979.059	1	3275979.059	3267.065	.000	.834
RUBMAT	19924802.484	2	9962401.242	9935.293	.000	.968
FIBER	13528856.883	23	588211.169	586.611	.000	.954
RUBMAT * FIBER	16257647.799	46	353427.126	352.465	.000	.962
Error	649768.025	648	1002.728			
Total	53637054.250	720				
Corrected Total	50361075.191	719				

a R Squared = .987 (Adjusted R Squared = .986)

Levene's Test of Equality of Error Variances(a)
Dependent Variable: Peak Potential (V)

F	df1	df2	Sig.
9.630	71	648	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a Design: Intercept+RUBMAT+FIBER+RUBMAT * FIBER

Lack of Fit Tests
Dependent Variable: Peak Potential (V)

Source	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Lack of Fit	.000	0	.	.	.	.000
Pure Error	649768.025	648	1002.728			