The Types, Properties, and Applications of Conductive Textiles

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ABBREVIATIONS

ESD – electrostatic discharge

PPE – Personal protective equipment

EMSE – electromagnetic shielding effectiveness

EMR – electromagnetic radiation

RFR – radio frequency radiation

EMC – electromagnetic compatibility

RF – radio frequency

AC – alternating current

DC – direct current

SE – shielding efficiency

EMS – electromagnetic shielding

ICP – inherently conductive polymers

EMI – electromagnetic interference

ITS – intelligent textile system

MPD – modal power distribution

INTRODUCTION

The vertical resistance of humans as conductors is quite low, so electrostatic charges can accumulate on the garments of humans, who are insulated from the earth. Many electronic components can be damaged by electrostatic discharge or accumulated electrostatic charges can be transferred from the body to an electronic device by touching, thus damaging it. Electrostatic charges can be accumulated on the surface of the fabric due to tribo-phenomenon or due to induction charging. In both cases, the process of charge accumulation is not stable. The process depends on the intensity of the appropriate effect (rubbing or induction charging treatment), atmospheric (especially moisture) conditions and time factor.

Previous studies have shown that the electrostatic properties of each fibre are different and resistance values also depend on atmospheric conditions. The important characteristics of conductive fabrics are fibre content and the structure of the fabric.

Therefore, it is particularly necessary to control undesired static electric charge in those places, where a flammable or explosive medium might exist. In such cases, humans have to be grounded directly or through conductive footwear. Protective clothing is designed so as to prevent or reduce skin burn from incendiary discharge. According to the field of application, protective clothing must also fulfil specific requirements.

The application fields and forms of conductive textiles are very wide. Conductive materials can help to avoid charge accumulation on a device or humans, and also protect from incendiary discharge or electromagnetic waves at frequencies that are potential hazards to health. Conductive textiles are also utilized as sheet covers for equipment or to shield a space from electromagnetic fields. They are also used to ensure the closed current circuit needed for Smart or e-textiles.

Although conductive textiles are typically produced not only as shields against charge dissipation and EMI, they are also used in other specialist applications such as sensors, antennas, flexible heaters and specialized apparel. Electrically conductive woven or knitted fabrics with particular electrical properties offer an opportunity to achieve required EMI shielding effectiveness in various frequency ranges. Moreover, these thin shielding materials can provide the additional benefits of being user-friendly, and able to be used on surfaces of all shapes because of their structural order and ability to flex.

Various techniques are used to improve the conductivity of textiles: introduction of electrically conductive yarns (carbon fibres, metal fibre); metallization of fabrics or yarns (voltaic, vacuum vaporization); lamination or coating of conductive layers onto the fabric surface with metal particles, transparent organic metal oxides, carbon or intrinsically conductive polymers (ICPs).

The different chapters in this book provide basic knowledge about the principles, roles, types and evaluation methods of anti-static and conductive textile materials, which are used for protection against charge dissipation, incendiary discharge, intense electrostatic field and electromagnetic interference (EMI) at specific frequencies. The basic properties of different types of conductive fibres/filaments and the manufacturing processes of conductive textile products will also be discussed.

1. ELECTROSTATIC PHENOMENON

Humans face static electricity every day in various surroundings. Most people are mainly affected by an extremely low-frequency (50–60 Hz) electromagnetic field. Many electrical effects are harmless and imperceptible, but static electricity can also lead to very dangerous situations: ignition and explosion, electric shock, when there are other hazardous substances in the environment that can cause injury or death to a person (Nurmi et al., 2007; Kowalski and Wróblewska, 2006; Lerner, 1985; Lambrozo, 2001).

Static electricity is treated as a set of phenomena associated with the formation and accumulation of electrostatic charges on materials with low electrical conductivity and on conductive objects isolated from the ground. Electrostatic charges are created as excess electrical charges.

Many electronic components are damaged from electrostatic discharge (ESD). This discharge can be avoided if components are handled in an ESD-protected area (EPA). Electrostatic fields and sources of ESD are controlled in the EPA in order to keep ESD risks to an insignificant level. Static electricity also causes operational problems during the production and transportation of materials, e.g. by causing fabric pieces to adhere to each other or by attracting dust (Nurmi et al., 2007).

An operating device can be damaged by the transfer of an accumulated electrostatic charge from the human body to the electronic device; the device does not have to actually touched. The presence of a charged human body near a functioning device may be sufficient to create a voltage potential that can damage the device. It has been found that a person does not feel ESD when the voltage potential is up to 3000–4000 V and over 5000 V ESD can cause malfunctions in semi-conductor devices (Lerner, 1985; Sweet et al., 1986).

There are three main sources of electric charge that can lead to damaging effects of the ESD (Lerner, 1985):

1. An electrified person touches the device and transfers the accumulated charge to/through the device to the ground.

2. The device is a solid capacitor plane that can accumulate an electric charge, i.e. to charge triboelectrically. The ESD pulse can cause a malfunction when in contact with the ground.
3. The device is located in an electrostatic field that is generated by an electrostatically charged object that can cause potential charge through the device and damage the device.

All electrostatic effects are caused by forces between the electric charges (Nurmi et al., 2007).

2. ELECTROSTATIC CHARGE GENERATION AND CHARGING OF TEXTILES

The effects of static charges are familiar to most people because we can feel, hear and even see the sparks as excess charges are neutralized when brought close to a grounded conductor, or a region with excess charges of the opposite polarity. The familiar phenomenon of a static "shock" is caused by the neutralization of charges. However, in the real world, there are actually many mechanisms that can lead to the formation of static charges, and some of the more common ones are listed below. Any one of these mechanisms can lead to static charging on textile materials, but in many cases, more than one mechanism may work together to generate static charges (Zhang, 2011).

2.1. Contact charging mechanism and the Triboelectric Series

The main source of electrostatic charge is the electrification of particles during contact, i.e. the electric charge is generated by rubbing two closed fabrics against each other and then separating them (triboelectric charging) (Nurmi et al., 2007; Lerner, 1985). Electrons can be exchanged between textile materials on contact: materials with sparsely filled outer orbital shells tend to gain excess electrons, while materials with weakly bound electrons tend to lose them. This can cause one material to be negatively charged and the other—positively charged (Zhang, 2011). If in the system of contacting materials, one of them is a grounded conductor, then the charge remains on the non-conductive material only. Due to the limited mobility of this type of charge, it is referred to as an "electrostatic" charge (Nurmi et al., 2007; Kowalski and Wróblewska, 2006; Lerner, 1985).

In addition to electrons, other elements or ions can also be exchanged between materials, e.g. in textiles made of acidic or basic polymers, or polymers with space charge layers, ions can be exchanged at the interface of two textile materials that are in contact. In this case, charges redistribute according to Boltzmann statics, i.e. charges move between the two contact materials in numbers (n) that depend on the activation energy ΔG (Zhang, 2011):

$$n = n_0 \exp\left(\frac{-\Delta G}{kT}\right) \quad (1)$$

where: n_0– the pre-exponential constant, k– the Boltzmann's constant, T– the absolute temperature.

The size and the sign of the resulting electrostatic charge on textiles depends on such factors as the chemical composition, the physical state and structure of the material, the type and amount of admixtures of foreign substances in the electrifying bodies and the electrical conductivity of the material (Nurmi et al., 2007; Kowalski and Wróblewska, 2006; Lerner, 1985).

In the contact-induced charge separation mechanism, the polarity of static charges generated on the materials depends on their relative positions in the triboelectric series. The triboelectric series is an empirically compiled list where materials are arranged from top to bottom depending on their relative ability to lose or gain electrons, beginning with the most positively charged material and ending with the material carrying the most negative charge (see Table 2.1.1) (Welsher et al., 1990).

According to the triboelectric series shown in Table 2.1.1 the polarity of static charge generated on a material can be predicted, e.g. when wool fibres contact with cotton fibres, wool acquires a positive charge and cotton acquires a negative charge because cotton has a better ability to gain electrons than wool. In contrast, the same cotton fibres acquire a positive charge when in contact with polyethylene fibres because cotton has a greater tendency to lose electrons compared to polyethylene (Zhang, 2011).

In many cases, rubbing two textile materials produces temperature gradients, and charges can move from a hot spot to a cold surrounding area due to the thermoelectric effect. Heating can also generate a separation of charge in the atoms or molecules of certain materials. This is so-called heat-induced charge separation (i.e. pyroelectric effect). The atomic or molecular properties of warmth and pressure response are closely connected. All pyroelectric materials are also piezoelectrics (Zhang, 2011).

Table 2.1.1. Triboelectric series of textile fibres

Material	Polarity
Asbestos	
Acetate	
Glass	+
Human hair	
Nylon	
Wool	
Fur	
Lead	
Silk	
Aluminum	
Paper	
Polyurethane	
Cotton	
Wood	
Steel	
Sealing wax	
Hard rubber	
Acetate fiber	
Mylar† film	
Epoxy glass	
Nickel, copper, silver	
UV resist	
Brass, stainless steel	
Synthetic rubber	
Acrylic	
Polystyrene foam	
Polyurethane foam	
Saran† film	
Polyester	
Polyethylene	
Polypropylene	
PVC (vinyl)	−
Teflon§ coating	
Silicone rubber	

Other static charge generation mechanisms, such as pressure-induced charge separation (i.e. piezoelectric effect), also play important roles. It is determined by the ability of textile materials to generate static charges in response to applied mechanical stress or strain. The nature of the pressure-induced charge separation is closely related to the formation of electric dipole moments in materials. Such separation is often observed in natural fibres, such as wool and silk (Zhang, 2011).

2.2. Induction charging mechanism

Charge-induced charge separation (i.e. electrostatic induction) is another mechanism for static charge generation (Zhang, 2011). During induction charging, an uncharged isolator is placed in the electrical field of the object (positively charged isolator), where the voltage of the uncharged insulator changes due to the nearby electrically charged insulator and its generated electric field (Nurmi et al., 2007). The induced charge is opposite in sign from the inducing charge (Holme et al., 1998). In non-conductive textile materials, although the electrons are bound to atoms and are not free to flow between atoms, they can move within the atoms (Zhang, 2011). Charge induction is not usually considered to be of major importance as a means of charging textiles, but it is important as a means of transferring charge from textiles to relatively conducting surfaces, such as the human body or charge-dissipating fibres (Holme et al., 1998; Jonassen, 2013).

The integrated study of Stankute et al. on electrostatic charge accumulation and kinetics on the surface of five fibre-forming polymers influenced by friction and induction charging has shown that the most significant parameters of tribocharge were determined during the contact of investigated objects with plexiglass pads. However, the values of the dynamic friction coefficient obtained using these pads were the lowest. The authors concluded that according to the results of electrostatic charge alteration (charge decay time) applying the induction charge method, all objects of investigation might be grouped into several groups: polylactide, soybean protein, cotton–Tencel–bamboo (Stankute et al., 2010).

2.3. Charging by ion or electro-bombardment mechanism

This method of charging is usually affected by creating a corona discharge, which results from raising fine points or fine wires of a conductive material, usually metallic, to a high enough electric potential to cause an electric breakdown of the local atmosphere. The lower the radius of curvature of the point or wire, the lower the potential needed for electrical breakdown to occur. If the discharging electrode is positively charged, positive ions are repelled and negative ions and electrons are attached, and vice versa. Consequently, a textile brought into the vicinity of the discharging electrode accumulates charge of the same sign as the electrode (Holme et al., 1998; Jonassen, 2013).

2.4. The surface electrode charging mechanism

Electrostatic charge can be produced on a sample by direct contact with a highly charged conductive electrode. This principle is used both as a means of charging a sample in a region directly in contact with the electrode whose charge acceptance and decay rate will be measured, and also as a means of charging a sample in a neighbouring region, not directly in contact with the electrode, to which the charge diffusion rate and/or from which the charge decay rate will be measured (Holme et al., 1998).

2.5. Electrokinetic or Zeta Potential mechanism

At a solid-liquid interface, an electrical double layer consisting of positive and negative charges is formed; one set of charges is associated with the solid phase and is fixed, the other is associated with the liquid and is mobile. As a result, there is a difference in potential between the locus of separation between the fixed charge and the mobile charge on the one hand and the bulk of the liquid on the other hand, which is known as the electrokinetic or zeta potential. Electrophoresis is the displacement of the oppositely charged layers relative to one another under the influence of an applied electrical field; the electrokinetic potential can be calculated from the electrophoretic mobility of a particle in a field of known strength. For fibres, the most important phenomenon is the streaming potential, which is the potential difference produced when a liquid is forced through a porous membrane such as a plug of fibres, or through a capillary tube. The streaming potential has been most widely used for calculating zeta potential values of fibres for use as an analytical tool for comparing the charging properties of fibre surfaces, including modified fibre surfaces, and for fundamental investigation of the effect of charging properties on dyeing processes. However, the establishment of a streaming potential between fibres and a liquid, the separation of the two phases, is a means of producing an electrostatic charge on the fibres, and extrusion of fibres through a capillary during manufacture can lead to freezing-in of the mobile charge during solidification (Holme et al., 1998).

2.6. Charge Decay mechanism

In taking steps to minimise the accumulation of charge on textiles it is sometimes possible to prevent the charging process, but often it is necessary either to shield the charge formed from locations where its influence would be deleterious, or to arrange local neutralisation of the charge within the structure, or to accelerate the processes of charge dissipation, thus reducing the maximum charge attained (Holme et al., 1998).

3. CHARGE DISSIPATION OR ELECTROSTATIC DISCHARGE OF TEXTILES

Air is a good insulator under normal environmental conditions. However, if the electrostatic field strength reaches about 3 MV/m, the insulating property of air weakens and electrostatic discharge occurs. The type of discharge depends on different factors, among others the nature and geometry of the material in which it develops (Nurmi et al., 2007).

The corona discharge usually happens on conductors with pointed edges. The electric field increases above the breakdown field locally at the sharp surface and charge will discharge. The strength at the edge is typically about 3 MV/m (Nurmi et al., 2007).

If single polarity charges are not accumulated on a single layer of a non-conductive surface, but charges of different polarity are accumulated on two surfaces of non-conductive fabric layers of opposite charge, it is likely that a glow discharge will occur. The density of energy during glow discharge is higher than during corona discharge and may be sufficient to ignite flammable gases, liquids or powders (Nurmi et al., 2007).

Spark discharge is the best-known type of electric discharge. It happens between two conductors which have a high voltage difference between them. The best-known electrical spark discharge is lightning (Nurmi et al., 2007).

If the charges are not arranged in the form of one single layer of one polarity on a non-conducting surface but in the form of a double layer of charges of opposite polarity on the opposite surfaces of a non-conducting material in the form of a sheet, propagating brush discharges may occur. The energy density in a brush discharge is higher than in corona discharge and it may be enough to ignite flammable gases, liquids or powders (Nurmi et al., 2007).

Insulating fabrics with extremely conductive fibres are able to dissipate static charges even without grounding. Research has shown that fibres cause corona charge dissipation when highly charged. The ions thus created neutralize fabrics until their electrical potential becomes less than the corona electric charge potential at the beginning, which is a function of the conductive fibre diameter. Such fabrics (with metal fibres) are not capable of causing the spreading of combustible charge. Some fibres are designed with a trilobal core, the structure of which is designed so that corona charge dissipation occurs faster with high surface potential when high surface resistance is maintained at low voltages. This makes the fabrics safe to use in situations where there are high voltage and low surface resistances and where such environmental conditions pose a risk. However, it seems that textiles that incorporate a highly conductive mesh, formed by inserted conductive yarns, are capable of carrying the entire network charge, similar to spark charge dissipation—and therefore, for such materials, the entire surface charge—just like the charge density—is critical (Kathirgamanathan et al., 2000; Kessler and Fisher, 1997; Nelson et al., 1993; Kalliohaka et al., 2005).

If the fabric is conductive, it will retain the electrical charge until the fabric is grounded. This charge is called a mobile charge. When the electric field is created in the fabric, mobile charge carriers, i. e. positive charges will move in the field direction and negative charges in the opposite direction. If the fabric is an insulator, the electrical charge is stationary and remains until it will be somehow neutralized (Nurmi et al., 2007; Lerner, 1985).

Two types of electrostatic forces can act in particle motion: Coulomb and reflection forces. The Coulomb effect occurs when an electrified particle is carried by an electric field, and the reflection force is a polarization phenomenon that occurs when the electrically-driven particle is carried to the conductive surface. The Coulomb effect can be attractive or repulsive, and the reflection effect is always attractive (Lai, 2006).

The electric charges act on each other with forces that create an electric field. If the force acting on the charge q is F, the field strength E is defined by (Nurmi et al., 2007):

$$F = qE \qquad (2)$$

In the electric fields, charges of the same polarity repel each other and charges of opposite polarity attract each other. If the charge q is a point charge at distance r, it will create an electric field E (V/m) which can be calculated using the formula (Nurmi et al., 2007; Jonassen, 2013):

$$E = \frac{q}{4\pi\varepsilon r^2} \tag{3}$$

From a small charged object the electric field strength often decreases with distance r (Nurmi et al., 2007).

For most materials, including the majority of textile fibres, Ohm's law of current density is valid, which describes the linear relationship between the current density j flowing through the fabric and the electric field strength E (Jonassen, 2013; Matukonis et al., 1976):

$$j = \gamma E \tag{4}$$

The coefficient γ, which is different for various materials, is called the specific electrical conductivity. The parameter ρ, which is inversely related to the specific electrical conductivity, is called the specific resistivity of the fabric (Jonassen, 2013, Matukonis et al., 1976) and vice versa—the parameter, inverse to the resistivity of the fabric, is called the specific electrical conductivity of the material:

$$\rho = \frac{1}{\gamma} \tag{5}$$

In total, Ohm's law states that the current I (A) between two points of the conductor is proportional to the voltage or potential difference U (V), between the two points and reciprocally proportional to the resistance of the conductor:

$$I = \frac{\mathrm{U}}{\mathrm{R}} \tag{6}$$

For a metallic conductor, R is independent of the applied voltage, which means that the electrical characteristic (I as a function of U) is linear. This characteristic makes it possible to distinguish conductors from semiconductors.

If the electrical resistance of the fabric is low enough, any charge accumulated on the surface of the fabric can be dissipated through the fabric surface or perpendicularly through the fabric, thereby reducing the density of the existing charge, or grounding through a particular connection. Some materials used to control static charge (electrification) have inherent conductive properties. There are three phenomena that can cause static discharge and the charge on heterogeneous dissipating fabrics is neutralized (Nurmi et al., 2007; Tappura and Nurmi, 2003; Gasana et al., 2006; Jonassen, 2013):

1) If the material is grounded, the conductive charge on or near the conductive element will be brought to the ground.
2) The charge on the insulating substrate induces a charge of opposite polarity on the grounded conductive yarn leading to partial neutralization of the whole charge. This phenomenon can also be understood as an increase in the vertical resistance caused by the grounded yarns which charge potential is lower. The charge of one polarity (in contrast to the base fabric) stays on the conductive yarn, while the charge of the opposite polarity is brought to the ground. In other words, by bringing a grounded conductor closer to the charge on the substrate fabric, its conductivity increases, and hence its potential decreases. The inner structure of the fabric, especially the distances between the grounded conductive yarns, has the greatest influence on the potential of the fabric during induction.
3) Partial neutralization of charges on the substrate fabric may also occur due to air ions formed during corona discharge when the large corona field strength is created in one place. Density and shape of the thread diameter will have a major impact on the high corona field strength. The corona mechanism does not require grounded yarns, but the surface charge density must be large enough to initiate the corona discharge.

The only phenomenon out of three, associated with the specific resistance of the fabric is conductivity. Conductivity and induction depend on the grounding of conductive yarns.

The electrostatic properties of the materials determine the following parameters to the greatest extent (Jachowicz, 2013):

1) Leakage resistance R_u, i. e. the resistance of the path over which leakage current flows, which primarily determines the possibility for the accumulation of an electrostatic charge on the material. This refers to the total electrical resistance, measured between the surface of the object and the ground. It is, therefore, a transition resistance to the ground, the value of which, in addition to the conductivity of the material, is also affected by the resistance of separating it from ground construction materials. An electrostatic

charge cannot be accumulated on objects where leakage resistance fulfils the condition $R_u<10^6\ \Omega$.

2) Permittivity – the ability of a material to produce and maintain an electrostatic charge. Knowledge of the relative permittivity ε facilitates an approximate assessment of the expected electrification of a given material. In particular, the degree of its static electricity charge, achieved in contact with different materials, is greater the bigger the difference between the electrical permeability of this material and the permeability of the material in contact with it.
3) The relaxation time of an electrostatic charge τ determines the rate of removal of the electrified material or object. This is the time during which the degree of static electricity in the material is reduced to about 27 % of the initial value of the generated charge. It can be expressed as the product of the permittivity $\varepsilon_0\varepsilon$ and vertical resistance R_v of a material ($\tau=\varepsilon_0\varepsilon\varsigma_v$) or the product of leakage resistance R_u and electric capacity C if the electrostatic charge is accumulated in the isolated form with a ground conductive object ($\tau=R_uC$). The above takes place when a loss of charge takes place through leakage resistance R_u, a situation which is not taken into account when the process of discharging conditions plays a dominant role e.g. by the depolarization of a material or the desorption of ions. It is accepted, that the total disappearance of electrostatic charge takes place after the passage of the so-called time of complete discharge t_w ($t_w=5\tau$).

The electrical conductivity of materials, which plays a decisive part in maintaining the electrified state of an object, is expressed by the value of vertical resistance R_v and surface resistance R_s.

The surface resistivity (ρ) of a fabric is the surface resistance (R_s) (Ω) between the opposite edges along the fabric surface (EN 1149-1: 2006). The vertical resistance (R_v) (Ω) is the electrical resistance perpendicular to the surface of the material (EN 1149-2: 2000).

The electrical resistance of a piece of material is commonly measured with an Ohmmeter.

The electrical resistance R (Ω) of a conductor of length L (m) with cross section A (m^2) made out of a conductive material with electrical resistivity ρ is expressed by Pouillet’s Law.

$$\rho=\frac{\mathrm{RA}}{\mathrm{L}} \tag{7}$$

The cross section of yarn is considered as the sum of the cross sections of the electroconductive filaments or fibres. Therefore, the conductivity of conductive yarns is expressed as a resistance for a given length expressed as a linear resistance (Ω/m). This value is obtained by measuring the resistance of a certain length of yarn, without taking the cross section into consideration.

In general, materials that become electrified share the following characteristics (Jachowicz, 2013):

- small electrical conductivity, for which vertical resistance is $R_v>10^4$ Ωm or surface resistance is $R_s>10^7$ Ω,
- conductivity, for which vertical resistance $R_v \leq 10^4$ Ωm or surface resistance is $R_s \leq 10^7$ Ω, and materials are isolated from the ground with a non-conductive material, for which vertical resistance is $R_{\mathrm{v}}>10^7$ Ωm or surface resistance is $R_s>10^{10}$ Ω.

For permanent electrification to occur, vertical resistance of $R_v>10^7$ Ωm or surface resistance $R_s>10^{10}$ Ω must be present; the electrification of such materials generally results in disturbances in the surrounding environment or production processes have been carried out with their participation (Jachowicz, 2013).

Materials of vertical resistance 10^4 Ωm$<R_v \leq 10^7$–10^8 Ωm or surface resistance 10^7 Ω$<R_s \leq 10^{10}$ Ω generally show a slight capability of electrification and in contact with the grounded, conductive elements of the production equipment, quickly lose their generated charge (Jachowicz, 2013).

Materials with vertical resistance $R_v \leq 10^4$ Ωm and surface resistance $R_s \leq 10^7$ Ω are considered to be conductive, i. e. unable to accumulate an electrostatic charge, under the condition that they are not isolated from the ground with non-conductive materials (Jachowicz, 2013).

Electrostatic discharge is dangerous, when its energy W_w reaches the value of the so-called minimum energy of ignition $W_{z\mathrm{min}}$ of combustible material. It is possible to be within the range of this discharge, i. e. when $W_w \geq \mathrm{W}_{z\mathrm{min}}$, where W_{zmin} is understood as the lowest energy of electrostatic discharge, which in determined conditions is still sufficient to cause ignition of a given combustible or explosive medium (Jachowicz, 2013; Jonassen, 2013).

Energy W, which occurs during the charge dissipation from the non-conductive fabric surface, depends on the total amount of charge carried by the electric current during the charge dissipation and from the electrostatic material, and the arrangement of the dissipation system (adjacent grounded objects). The energy generated by the dissipation of the charge can be calculated by the formula (Kacprzyk and Mista, 2006):

$$W = \frac{(V_A - V_B)Q}{2}; \qquad (8)$$

where: Q– charge, carried during the dissipation; V_A and V_B– mean surface potential before and after charge dissipation, respectively.

Where the fabric is laid on a conductive and grounded surface, formula (8) can be rewritten as follows (Kacprzyk and Mista, 2006):

$$W = \frac{\varepsilon_0 \varepsilon S}{2d} V_A^2; \qquad (9)$$

where: ε_0– electrical conductivity of the free environment (8.855×10^8 F/m); ε– specific electrical conductivity of the fabric; d– thickness of the fabric; and S– the surface area of the fabric where the charge dissipation occurred.

This formula is derived for flat fabrics, assuming there is no air gap between the fabric and the grounded conductive surface, and that the surface potential after charge dissipation V_B is zero (Kacprzyk and Mista, 2006).

D. Montgomery and colleagues have investigated the influence of filament diameter on charge transfer among filaments during rubbing when the environment and rubbing conditions were controlled. Filaments of various diameters and mean specific resistivity (polyamide, about 10^{12} Ω/cm) were rubbed with filaments with lower specific resistivity values (tantalum, about 10^{-5} Ω/cm), and with filaments with higher specific resistivity values (polyethylene, about 10^{15} Ω/cm), under different perpendicular rubbing forces. When the polyamide was rubbed with tantalum, the transferred charge was proportional to the square root of the filament diameter and perpendicular to the rubbing force between the filaments. When the polyamide was rubbed with polyethylene, the transferred charge was proportional to the square of the perpendicular rubbing force and was almost independent of the diameter. These findings formed part of the hypothesis that the transferred charge accumulates only at the point of filaments contact (i. e. at the point of the material above which the molecules penetrate deep into the material during the rubbing), on the low conductivity object (Montgomery et al., 1961).

Hersh and Montgomery, (1956), noted that when the rubbing speed between the yarns increases, two factors were noticed: the time of charge flow through the spacing between yarns and leakage from the point of contact decreases; the temperature at the rubbing point increases significantly, but it did not affect the results of the study.

4. ELECTRICAL CONDUCTIVITY AND ELECTROSTATIC SHIELDING OF TEXTILES

The electric conductivity scale of solid materials in Figure 4.1 demonstrates that the conductivity values of the most commonly used textile fibres fall into a region below 10^{-7} S/m, which corresponds to the best insulators. The most commonly used conductive materials, such as metal, show much higher values: from 10^{7} S/m for steel to 10^{9} S/m for copper and silver (Marchini, 1991).

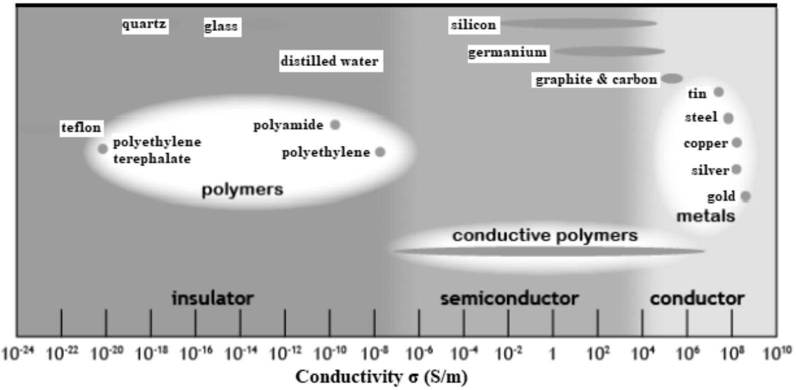

Figure 4.1. The electrical conductivity of materials

The surface resistivity of textiles can be divided into such groups (Lin and Lou, 2003; CEN/TR 16298: 2011):

1) EMI/RFI shielding materials: less than 10^{4} Ω;
2) conductive textiles: less than 10^{6} Ω;
3) static dissipative materials: from 10^{6} to 10^{12} Ω;
4) anti-static textiles: from 10^{10} to 10^{12} Ω;
3) insulation textiles above 10^{12} Ω.

Many synthetic fibres used in the production of textiles are insulators with a specific resistivity of about 10^{15} Ω. This is much higher than the materials used for electromagnetic shielding materials. For example, the best quality anti-static-electrostatic clothing must have a specific surface resistivity of between 10^5 Ω and 10^9 Ω (Lin and Lou, 2003). But, it is enough for the anti-static-electrostatic fabrics to have a specific resistivity of between 10^9 and 10^{13} Ω and for static charge-dissipating fabrics between 10^2 and 10^6 Ω, and for shielding materials less than 10^2 Ω (Chen et al., 2007).

Because simple polymeric materials are electrically non-conducting, the surface resistance of such materials is usually higher than 10^{12} Ω, so electrons may easily accumulate on the polymer surface. Such accumulated electrons create a high voltage in a short time, which can destroy mechanical elements or even cause an explosion. Processes for the production of conductive polymers can be divided into two groups: processes by which the polymer itself is produced as a conductor and where conductive particles (metal powders, fibres, etc.) are inserted into the polymer matrix in the manufacturing process (Lei et al., 2004).

For materials with some electrostatic shielding effects, the E_R measured according to EN 1149-3: 2004 Method 2 is less than E_{max}. Occasionally, a transition peak appears in curves drawn by the recorder. Such peaks are not taken into account when calculating E_R. If $E_R<E_{max}/2$, this is recorded as $t_{50}<0.01$ s. If the field strength displayed in 30 seconds does not decrease to $E_{max}/2$, this is recorded as $t_{50}>30$ s.

The shielding effect of the test fabrics is not sudden, so the results obtained during the test EN 1149-3: 2004 (induction charging method) can be divided into three types: metal, core and homogeneous (see Figure 4.2). Fabrics, whose curves are drawn without any initial spike, are classified as metal. The core material curves have an initial spike E_R which quickly disappears (30-50 μs) to value $E_{max}/2$. If there is no shielding factor for the fabrics, the E_R is equal to E_{max} and fabrics behave like insulators (EN 1149-3: 2004; Paasi et al., 2004).

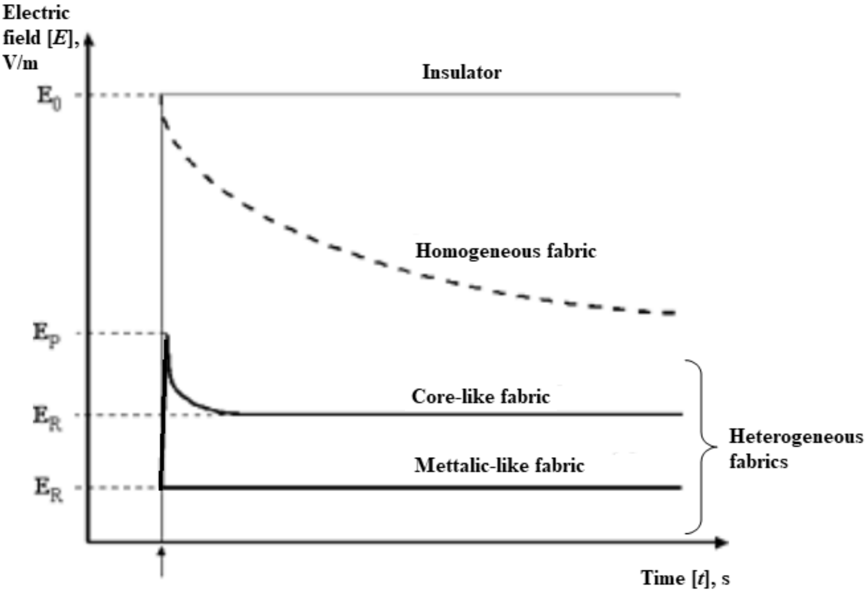

Figure 4.2. Shielding effect of different textile fabrics (Paasi et al., 2004)

The charge-discharge variation can be calculated using the following equation (Vogel et al., 2006):

$$E = E_{\max} e^{\frac{-t}{RC}} \tag{10}$$

where: E_{max}– the strength of the electrostatic field without a sample (initial field strength); E– a variation of electrostatic field strength in time; C– capacitance of the measuring device; R– resistance of the object under investigation; t– time.

Typically, there is a good relationship between homogeneous fabrics, with surface resistivities of less than 10^{11} Ω, and a duration of the charge decay (EN 1149-1: 2000).

Vogel et al. conducted measurements of homogeneous and heterogeneous fabrics with the ICM-1 charge decay device, according to EN 1149-3, method 2. They found that polyester and polyester/cotton fabrics do not have any shielding properties, but the electric charge decay time is lower for multifiber fabric than that of the man-made fabric, and with the incorporation of conductive fibres into these fabrics the charge decay properties significantly improve (Vogel et al., 2006).

The vertical resistance can be an important feature by itself or to complement the specific surface resistivity of the clothing fabric. The low vertical resistance (e.g. less than 10^8 Ω) of the electrostatic charge dissipative clothing, is a useful property to reduce the surface resistivity. However, it is often impossible to rely on this useful property, as the isolation clothing worn under the upper clothing may interfere with the upper clothing's contact with the skin while preventing the electrostatic charge decay directly through the body. For special purposes, such as arc welding protective clothing (when voltage is typically less than 100 V), higher vertical resistance (e.g. greater than 10^5 Ω) may be required to ensure proper insulation (EN 1149-2: 2000).

Polyaniline in its thick form is electrically conductive and soluble in organic solvents such as toluene and xylene. Polyaniline solutions can be used in the finishing of filtration materials in order to improve their water removal properties. Compared to conventional anti-static filtration materials, polyaniline-treated polyester materials are easily converted into various types of filtering materials and bags. Usually, the conductivity values of polyaniline-treated materials are between $10^4 \div 10^9$ S/cm (Järvinen and Puolakka, 2003; Kuhn, 1997; Rivas and Sanchez, 2001; Molina et al., 2009).

Air filters, produced from fibres, are widely used for dust collection and environmental protection. Effective filtering of submicron particles is very important as these particles pose a health threat. Fibrous materials used for air filtration provide high filtration efficiency, low air resistance (because of low-pressure differential across the filter) and show good dust collection efficiency. Fibres in the filter are constantly charged, and electrostatic charges enhance filtration efficiency compared to mechanical filters (Motyl and Lowkis, 2006).

The efficiency of collecting dust particles from electric filters depends on many parameters, such as the density of the fibre charge, the tightness of the filter, the thickness of the filter and the size and charge of the aerosol particles. The efficiency of the collecting increases linearly with the increase of the quantity of the electrical components. Solid aerosol particles block the pores of the electric filters, and the deposited aerosol