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Influence of Washing on the Electric Charge Decay of Fabrics with Conductive Yarns

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Abstract
The aim of the research was to reveal features of the electrical charging and dissipation of charges in fabrics containing conductive yarns after washing. All fabrics investigated were woven at the Lithuanian Textile Institute as protective fabrics from incendiary discharges. Conductive yarns were inserted into the fabrics at specified intervals. The surface and volume resistance, shielding factor and half decay time were determined for the fabrics before and after 5 washing cycles. The influence of the shielding effectiveness of PES/Cotton woven fabrics with silver plated filaments was investigated at different RH. Although the quantity of conductive yarns in the fabrics improves their electrostatic properties, the washing of the fabrics decreases all resistance values measured. The washing does not have a very big influence on the shielding factor and half decay time. It is shown that the vertical electrical resistance and surface resistivity are parameters whose values are very sensitive to the quantity of conductive PES/INOX yarns in the fabrics. Although knitted fabrics shrink more than woven ones, they have better electrostatic properties. Notwithstanding the influece of washing the fabrics tested have a sufficient shielding effect and can be used in work clothing to prevent the build-up of static charge.

Key words: *charge dissipation, vertical resistance, surface resistivity, shielding factor, half decay time, washing, relative humidity.*

Introduction

Nowadays instead of heavy metallic shields it is more common to use various types of textiles because they have good mechanical properties, being flexible and lightweight [1 - 3, 6, 8, 9].

Manufacturing particular individual textile protection products often requires the use of synthetic fibers with very low electrical conductivity which accumulate electric charges [3, 4]. There are many methods of improving fabric conductivity, such as laminating conductive layers onto fabrics or adding conductive fillers [5]. Conductive threads are inserted into the fabric (mostly used in materials for personal protective products) to limit the surface potential. A Low surface potential limits the risks of damage by direct electrostatic discharge and indirect induction effects [6, 7].

Textiles with different levels of electrical conductivity are mainly required for two applications: static control and electromagnetic interference (EMI) shielding [8].

Static electricity arises when surfaces that were in contact are separated [8 - 11]. Indeed, the rubbing of two insulating materials against each other can give rise to a static buildup of up to several thousand volts. The build-up charge is then suddenly released, either by a spark or a surge, when a certain voltage is reached; the latter is influenced by several factors like the conductivity of the charged body, the humidity of the environment, etc. [8, 9].

The degree of the charge depends on the kind of fibre. Natural fibres of plant-origin (hemp and flax) and artificial cellulose fibres have the smallest charging ability, whereas natural fibres of animal-origin have a significantly greater ability to charge (wool and natural silk). Synthetic fibres and artificial acetate fibres, on the other hand, are characterised by an incomparably high charging ability. The tendency to accumulate electrostatic charges is a negative fibre feature, accompanied by disturbances in the proceeding of the processes of fibre manufacturing, a decrease in the usability value of textile products, as well as by the possibility of creating threatening states for humans and a negative influence on the human organism [12].

An electrical charge that appears on the surface or in the volume of fibres, yarns, warp or weft or ultimately on the textile product itself may be the source of an electric field in its structure as well as in its neighborhood. Depending on the function the textile, the effects associated with the appearance of a strong electric field may be considered as positive (high filtering efficiency of electric fillers made of polymeric non-woven fabrics) or negative (electrical charges from clothing and discharges from fabric containers) [13]. However, when clothing material is worn it carries practically no risk because the energy of the discharge from the material surface is relatively low [14].

The performance required for most static control purposes lies in the semi-conductor range or half decay time of the electric field strength $t_{50} < 4$ s or shielding factor $S > 0.2$ or a surface resistance of less or equal to 2.5×10^9 Ω [8, 15].

The electrostatic properties of polyester wale-knitted fabrics with carbon compounds were investigated in [4]. The surface and through (vertical) resistances, times of half-decay and screening coefficients (shielding factors) were measured at a distance between the electro-conductive bands of 10 mm. In this case, neutralisation of the charge accumulated on the sample started very quickly and then proceeded slowly. The rapid accumulation resulted from the carbon compound and became slower because of the polyester. The analysis also indicated that the electrostatic properties also depend on the structural features of the background.

The influence of washing on the electrostatic properties of polyester woven fabrics containing S-Shield conductive yarns was studied in [16]. The vertical electrical resistance, surface resistivity, shielding factor and half decay time were measured for fabrics before and after 5 washing cycles. It was found that the values of vertical resistance and surface resistivity of the fabrics tested were less, and the half decay time of charges was shorter. The shorter half decay time resulted in an increase in the shielding factor. Although washing the fabrics impaired their anti-electrostatic properties, the fabric with the biggest quantity of conductive PES/INOX weft yarns, washed and unwashed, met the requirements of European Standard EN 1149-5 and can be used in work clothing to prevent the build-up of static charges.

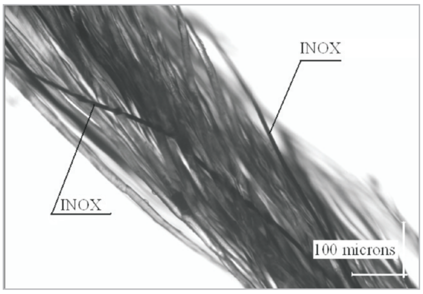

Figure 1. *Longitudinal view of S-Shield PES yarn.*

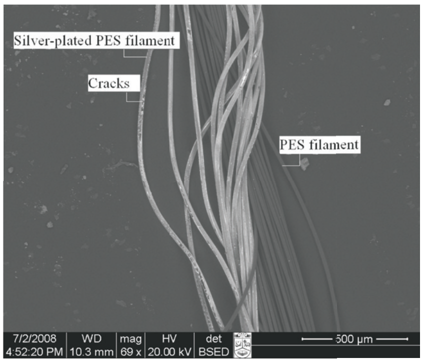

Figure. 2. *Longitudinal view of Silverflex-170 yarn.*

The aim of this research was to reveal features of the electrical charging and dissipation of charges in polyester/cotton knitted and woven fabrics containing conductive fibers and filaments appropriate for protective clothing to avoid incendiary discharges. This study was also designed to explore which conductive yarn is more suitable to use in protective clothes in order to get the best shielding effect.

Materials and experimental methods

Seven knitted and ten woven fabrics differing in the kind and quantity of conductive yarns inserted were manufactured at the Lithuanian Textile Institute for this study. All the knitted fabrics were manufactured using PES/Cotton (8:92%) yarn with conductive yarns knitted into the fabrics at specified intervals. Woven fabrics were made from PES/Cotton (65:35%) yarns with conductive yarns inserted into the fabrics at specified intervals. For the four knitted and five woven fabrics, conductive yarns, produced by Schoeller GmbH & CoKG and known as S-Shield PES yarns (20 tex), were inserted/knitted in the cross direction at different specified intervals. S-Shield PES yarn consists of 80% Polyester and 20% INOX. This yarn consists of INOX fibers 12 μm in diameter and about 7 mm long. INOX is also known as a stainless steel that contains at least 10.5% of chromium [17]. Into the other three knitted fabrics and the five woven, conductive Silverflex-170 (Z 300 m^{-1}) filament yarns, which consist of two twisted components: Polyester 11,3 tex f32 and Polyester silver-plated 4 tex f15, were inserted/knitted into the fabrics at different specified intervals. "Lantex A S" produces Silverflex-170 yarns. Longitudinal views of the conductive yarns are presented in ***Figures 1*** and ***2***.

The specified intervals between conductive yarns inserted/knitted into the fabrics are presented in ***Tables 1*** and ***2***.

Knitted and woven PES/Cotton fabrics of identical structure but without any conductive yarns were used as control fabrics.

The course density of rib 1+1 knitted fabrics with S-Shied PES yarns is 20 cm^{-1}, and the wale density is 14 cm^{-1}; the course density of plain plated laid-in knitted fabrics with Siverflex-170 – 18 cm^{-1} and the wale density – 15 cm^{-1}. The warp density of all plain weave woven fabrics (with S-Shield PES and Silverflex-170) is 22 cm^{-1} and the weft density – 22 cm^{-1}.

Vertical and surface resistances, the shielding factor and half decay time were measured for the fabrics as received and for those after 5 washing cycles (40 °C). The washing and drying were carried out according to Standard EN ISO 6330: 2002 [18]. Washing was conducted in a WASCATOR FOM71MP-Lab machine using procedure 5A (40 °C) with an ECE non phosphate reference detergent (A) without optical brightener, and finally procedure A was used for drying – line drying.

According to the EN 1149 series of standards [19 - 21], five circular specimens of a fabric of 110 mm diameter were cut to measure its surface and vertical resistances. In order to determine whether there is any difference in the measured values of the half decay time and shielding factor from the test area of the specimens, five additional specimens of 300 mm × 300 mm and 150 mm × 150 mm were cut. Prior to the measurements, the specimens were conditioned for not less than 24 hours in the following atmosphere: air temperature (23 ± 1 °C), relative humidity (25 ± 5%). The measurements were carried out in the same atmosphere. Furthermore, the characteristics of charge decay were established for some woven fabrics with Silverflex-170 yarns at relative humidities of 25%, 40% and 65%.

Table 1. *Specified intervals between conductive yarns knitted into the PES/Cotton knitted fabrics.*

Number of courses of PES/Cotton yarns between conductive yarns knit in the fabric	Conducive yarn used	
	S-Shield PES	Silverflex-170
	14	7
	19	15
	29	31
	59	-

Table 2. *Specified intervals between conductive yarns inserted into the PES/Cotton woven fabrics.*

Number of weft PES/Cotton yarns between conductive yarns inserted into the fabric	Conducive yarn used	
	S-Shield PES	Silverflex-170
	12	12
	22	22
	33	33
	45	45
	55	55

The difference between the measurement methods of both resistances is that during the measurement of vertical resistance, the specimen is placed on a base plate electrode, while during the measurement of surface resistance, the specimen is placed on an insulating plate. In both cases the specimens are pressed by a load of about 10 N with an assembly of cylindrical and annular electrodes arranged concentrically.

The values of resistances were determined with a Tera-Ohm-Meter 6206 produced by Eltex with a range of 10^5 Ω to 10^{14} Ω and an accuracy of ≤ 5% for 10^{12} Ω. The device selected the voltage automatically to measure resistances depending on their magnitude. The values measured were taken after 15 s from the beginning of measuring. Arithmetic means of five individual measurements of all the parameters tested are presented in this paper as measured values.

The surface resistivity (ρ) of the fabrics was calculated from the measured surface resistance using equation [19]:

$$\rho = k \cdot R_s \qquad (1)$$

where R_S is the surface resistance measured, k is the geometrical factor of the electrode.

Factor k was calculated by the following equation [19]:

$$k = \frac{2\pi}{\log_e(\frac{r_2}{r_1})}, \qquad (2)$$

where r_1 is the radius of the inner electrode (mm) and r_2 is the inner radius of the outer electrode in mm.

The geometrical factor (k) of the electrode used for the measurements was 19.8.

The coefficients of variation of surface resistivity did not exceed 8.5%, and those of vertical resistance did not exceed 8.0%.

Characteristics of the charge decay were determined with an ICM-1 electric charge meter (induction charge method), produced by STFI. The instrument is controlled by a microprocessor and makes measurements with automatic calculations and display of the data measured. The distance between the bottom of the field-measuring probe and the top of the ring was 50 mm. The resolution of an electronic electrometer is 0.05 pC, and the maximum output voltage is ± 20 V. A fabric specimen applied to measure the half decay time and shielding factor was clamped between the outer and inner rings over the field electrode.

Characteristics of the charge decay were computed automatically; the shielding factor (S) was calculated using equation [21]:

$$S = 1 - \frac{E_R}{E_{max}}, \qquad (2)$$

where E_R is the maximum electric field strength indicated on the recording device with the test specimen in the measuring position, and E_{max} is the electric field strength indicated on the recording device with no test specimen present.

The half decay time of the electric field strength means the time in which the electric field decreases from E_{max} to $E_{max}/2$.

The coefficients of variation of the values of the half decay time was less than 5.5%, while for the shielding factor it was less than 1.5%.

Results and discussion

Dimensional changes during washing and drying were measured for the test fabrics according to Standard EN ISO 5077:2008 [22]. The measurements showed that knitted fabrics with S-Shield PES yarns shrank about 2% in the wale direction and about 0.5% in the course direction, whereas the knitted fabrics with Silverflex-170 yarns shrank about 3.5% in the wale direction and in course direction by about 0.5%. The woven fabrics shrank in both the warp and weft directions by about 0.5%.

Knitted fabrics

The experiments showed that the surface resistivity of PES/Cotton knitted fabrics with S-Shield PES yarns in their structure, before and after washing, is of the same magnitude as that of polyester wale-knitted fabrics with an electro-conductive component, as investigated by A. Pinar and L. Michalak [4]. It is at a scale of 10^5 Ω.

The test results showed that the surface resistivity increases with the lengthening of distances between conductive S-Shield PES yarns in the knitted fabrics. For example, the surface resistivity of control fabric is 4.24×10^{10} Ω, that of fabric with 19 nonconductive yarns between conductive ones is 2.06×10^5 Ω, and for fabric with 29 PES/Cotton course yarns between S-Shield PES yarns it is 2.65×10^5 Ω. The insertion of conductive yarns in the fabrics results in a decrease in resistivity from a scale of magnitude of 10^{10} Ω (as was measured for the control fabric) to 10^5 Ω. The surface resistivity of the fabrics after washing remains at the same scale of magnitude as for fabrics before washing (see ***Figure 3***); the values are, however, a little higher (e.g. for washed control fabric the surface resistivity is 7.29×10^{10} Ω, for fabric with 19 nonconductive course yarns between conductive ones it is 3.64×10^5 Ω).

As is seen from ***Figure 3***, the coefficient of determination of the linear curve for test results of unwashed fabrics is equal to 0.99, and the coefficient of determination of the logarithm curve is 0.96, i.e. it is sufficiently high.

The through (vertical) resistance of unwashed fabrics with conductive yarns in their structure is at a scale of magnitude of 10^5 Ω, which depends on the number of PES/Cotton courses between S-Shield PES ones. More antistatic yarns are under the electrode during measurement; the remainder are the resistances measured. Thus for fabric with 14 non-conductive course yarns between yarns with stainless steel fibres, the vertical resistance is 2.38×10^5 Ω, whereas for fabric with 59 non-conductive course yarns between conductive yarns it is 5.74×10^5 Ω (see ***Figure 4***).

After 5 washing cycles the vertical resistance of knitted fabrics increases from a scale of magnitude of 10^5 Ω to that of 10^6 Ω. The main reason possible for the increase in the resistance of the fabrics after washing is the loss of some metal fibres due to abrasion impacts in the washing machine. For example, after washing, the vertical resistance increases from 2.81×10^5 Ω to 4.5×10^5 Ω for fabric with 29 PES/Cotton course yarns between S-Shield PES yarns (see ***Figures 4*** and ***5***).

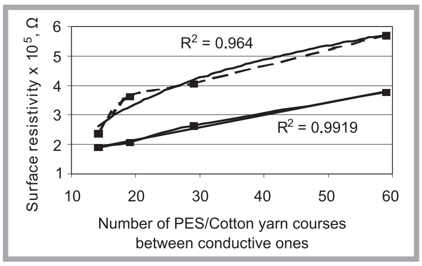

Figure 3. *Surface resistivity of knitted fabrics with conductive S-Shield PES yarns (——— before washing; – – – after 5 washing cycles) (Control fabric: before washing ρ = 4.24×10^{10} Ω; after 5 washing cycles ρ = 7.29×10^{10} Ω).*

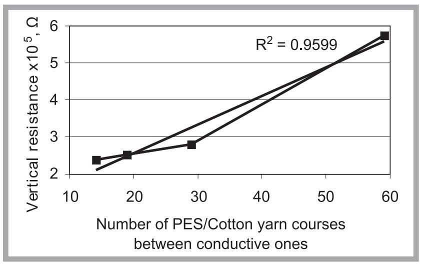

Figure 4. *Vertical resistance of knitted fabrics with conductive S-Shield PES yarns before washing (Control fabric: before washing R = 1.08×10^8 Ω).*

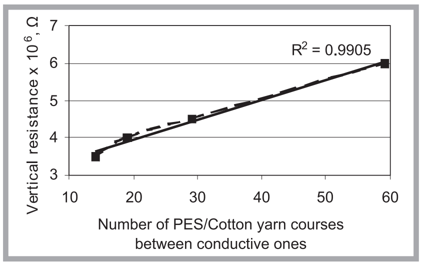

Figure 5. *Vertical resistance of knitted fabrics with conductive S-Shield PES yarns after 5 washing cycles (Control fabric: after 5 washing cycles R = 1.64×10^8 Ω).*

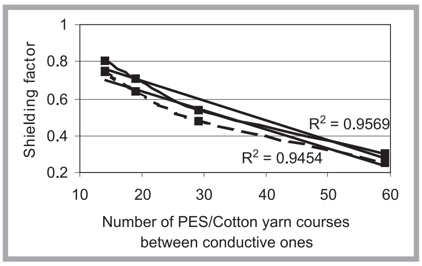

***Figure.* 6.** *Shielding factor of knitted fabrics with conductive S-Shield PES yarns (——— before washing; — — — after 5 washing cycles) (Control fabric: before washing S =0; after 5 washing cycles S=0).*

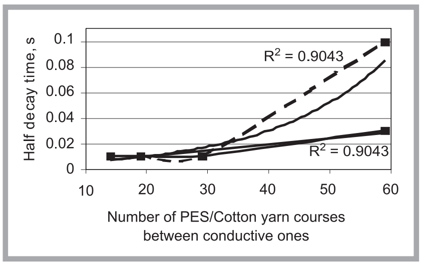

Figure 7. *Half decay time of knitted fabrics with conductive S-Shield PES yarns (——— before washing; — — — after 5 washing cycles) (Control fabric: before washing t_{50} = 0.81 s; after 5 washing cycles t_{50} = 3.2 s).*

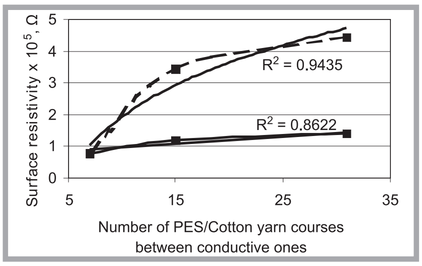

Figure 8. *Surface resistivity of knitted fabrics with conductive Silverflex-170 yarns (——— before washing; — — — after 5 washing cycles) (Control fabric: before washing ρ = 7.29×10⁹ Ω; after 5 washing cycles ρ = 7.33×10⁹ Ω).*

The vertical resistance of only PES/Cotton fabric after washing is of the same scale of magnitude as before washing, with the value slightly increasing from 1.08×10^8 Ω to 1.64×10^8 Ω after washing.

The shielding factor of knitted control fabric (before and after washing) is found to be zero. It means that control fabric has no shielding effect. The insertion of conductive yarn results in an increase in the shielding factor (see ***Figure 6***), i.e., in the shielding effect. For example, the shielding factor of fabric with 59 PES/Cotton yarns between S-Shield PES yarns is 0.3, whereas that of fabric with 19 nonconductive yarns between conductive ones is 0.71 etc.

Washing the fabrics slightly impairs the shielding effectiveness. As can be seen from ***Figure 6***, the shielding factor of fabric with 29 PES/Cotton yarns between yarns with stainless steel fibres decreases from 0.54 to 0.48, whereas that of the test fabric with the smallest distances between conductive yarns decreases from 0.81 (before washing) to 0.75 (after washing).

The charge decays less than 0.01 s for knitted fabrics with 14, 19, 29 courses of PES/Cotton yarns between S-Shield PES yarns, which stays the same for these fabrics even after washing (see ***Figure 7***). For fabric with 59 nonconductive yarns between conductive ones, the half decay time is 0.03 s, whereas for control fabric (PES/Cotton yarns only) it is 0.81 s. The half decay time becomes longer for fabric with the longest distances between conductive yarns (till 0.1 s) and for control fabric (till 3.2 s).

As is seen from ***Figure 7***, the coefficient of determination of the linear curve for test results of unwashed fabrics is equal to 0.90, and the coefficient of determination of the logarithm curve for test results of washed fabrics is also 0.90, i.e. it is sufficiently high.

Figure 8 shows the surface resisitivity of knitted fabrics with Silverflex-170 in its structure. As with knitted fabrics with PES/INOX conductive yarns, the resistivity increases with an increase in conductive yarns in the fabric structure. Silverflex-170 decreases the surface resistivity of fabrics from a magnitude of 10^9 Ω (as was measured for control fabric) to 10^5 Ω. The values of resistivity of fabric with the shortest distances between conductive yarns remain the same before and after washing. For other fabrics these values increase after washing.

The visual assessment showed that the fabrics shrank after washing, and the air gaps in the loops became smaller. Microscopic analysis of the yarns plated with silver PES filaments showed that the coating cracked in some places, which is possibly the main reason why surface resistivity decreases after washing.

The test results showed that the surface resistivity of 1+1 rib PES/Cotton knitted fabric is bigger, which is at a scale of magnitude of 10^{10} Ω, than that of plain plated laid-in knitted fabrics, which is at a scale of magnitude of 10^9 Ω (see ***Figures 3*** and ***8***). Hence, we can conclude

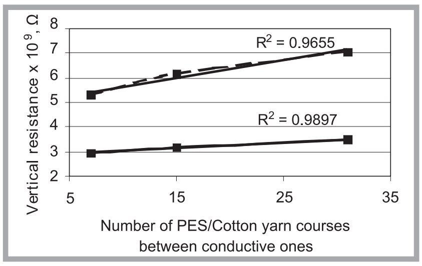

Figure 9. *Vertical resistance of knitted fabrics with conductive Silverflex-170 yarns (——— before washing; — — — after 5 washing cycles) (Control fabric: before washing R = 4.73×10⁸ Ω; after 5 washing cycles R = 4.80×10⁸ Ω).*

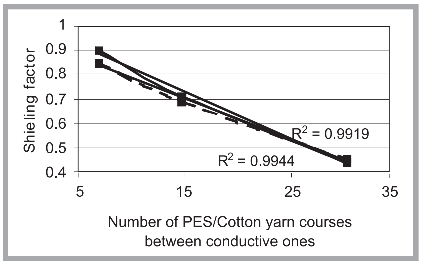

Figure 10. *Shielding factor of knitted fabrics with conductive Silverflex-170 yarns (——— before washing; — — — after 5 washing cycles) (Control fabric: before washing S =0.02; after 5 washing cycles S=0).*

that the structure of the fabric has an influence on the surface resistivity.

As is seen from ***Figure 8***, the coefficient of determination of the linear curve for test results of unwashed fabrics is equal to 0.86, whereas the coefficient of determination of the logarithm curve for test results of washed fabrics is 0.94, i.e. it is sufficiently high.

As well as with other fabrics with conductive yarns examined, the vertical resistance of knitted fabrics with Silverflex-170 yarns increases with an increase in antistatic yarns in the fabric structure. Washing impairs the measured values. Although the silver-plated filaments cracked after washing, the scale of magnitude of the vertical resistance remained the same for these knitted fabrics.

The shielding factor for fabrics with Silverflex-170 yarns is almost the same before and after washing (see ***Figure 10***). The fabrics may be washed and they will still protect from incendiary discharges. Comparing the results of these fabrics to those of fabrics with stainless steel fiber yarns, we can see that Silverflex-170 yarns give a more shielding effect for knitted fabrics with the shortest distances between conductive yarns (values

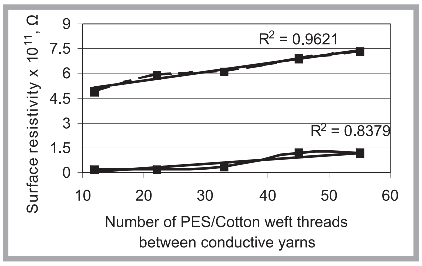

***Figure 11.** Surface resistivity of woven fabrics with conductive S-Shield PES yarns (—— before washing; — — — after 5 washing cycles) (Control fabric: before washing ρ = 9.85×10^{11} Ω; after 5 washing cycles ρ = 3.56×10^{12} Ω).*

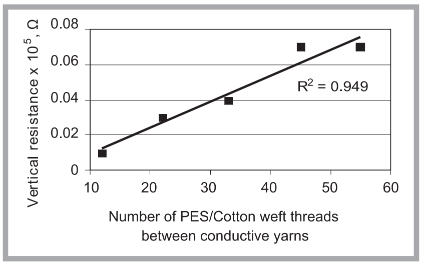

***Figure 12.** Vertical resistance of woven fabrics with conductive S-Shield PES yarns before washing (Control fabric: before washing R = 2.3×10^{10} Ω).*

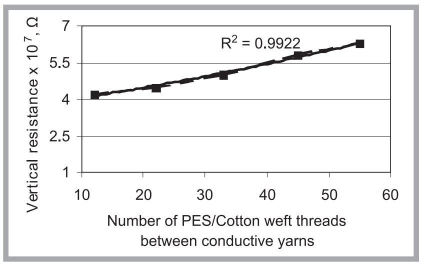

***Figure 13.** Vertical resistance of woven fabrics with conductive S-Shield PES yarns after 5 washing cycles (Control fabric: after 5 washing cycles R = 3.2×10^{10} Ω).*

are close to the unity) than fabrics with INOX/PES yarns.

The half decay time of control PES/Cotton knitted fabric is quite short, i.e. 0.19 s, which becomes longer for this fabric after five washing cycles (t_{50} = 0.38 s). However, regarding Silverflex-170 conductive yarns, the half decay time of all knitted fabrics with conductive Silverflex-170 yarns is very rapid and remains the same before as well as after washing, which is less than 0.01 s.

The half decay time depends on the structure of the fabrics. The half decay time is quicker for fabrics with 1+1 rib weave knitted fabric than for plain plated laid-in knitted fabrics.

Charge decay experiments for all knitted fabrics tested were carried out on specimens of different sizes (of 300 mm × 300 mm and 150 mm × 150 mm). The measured half decay time and shielding factor values of these fabrics were the same. Hence, we can say that for the measurements of the shielding factor and half decay time, the size of specimens do not have any influence on the test results.

Woven fabrics

The surface resistivity of woven fabrics and knitted fabrics increases when the distances between conductive yarns are lengthened. Values of the surface resistivity for woven fabrics with S-shield PES yarns are at a scale of magnitude of 10^{11} Ω (see ***Figure 11***). The washing procedure impairs the values of resistance measured, e.g. the surface resistivity of woven fabric with 33 nonconductive threads between conductive ones increases from 0.34×10^{11} Ω to 6.14×10^{11} Ω.

By shortening the distances between conductive weft yarns, the vertical resistance increases for woven fabrics (see ***Figure 12***). However, after treatment of 5 washing cycles the resistance measured increases very distinctly (see ***Figure 13***). Washing increases the values of vertical resistance from a scale of magnitude of 10^5 Ω up to 10^7 Ω. The main reason possible for the increase in resistance of the woven and knitted fabrics after washing (see ***Figures 4*** and ***5***) is a loss of some metal fibres due to abrasion impacts in the washing machine.

The shielding factor is the best for woven fabric with 12 PES/Cotton yarns between S-Shield PES yarns. Control fabric has no shielding effect; it is equal to zero. The screening factor decreases the distance between conductive yarns, but for fabric with 55 nonconductive threads between conductive ones, it is a little bit higher than for fabric with 45 PES/Cotton yarns between S-Shield PES yarns.

As is seen from ***Figure 14***, the coefficients of determination of the 4th polynomial curve for test results of both unwashed and washed fabrics is the same and equal to 1, i.e. it is sufficiently high.

The half decay time is very short for fabrics with 12 ÷ 33 PES/Cotton weft yarns between conductive yarns. The more non-antistatic yarns in their structure, the longer the half decay time. The charge decay time of fabric with 55 PES/Cotton weft yarns between conductive yarns is 0.19 s. The charge decays quicker for this fabric than for that with 45 nonconductive yarns between S-Shield PES yarns. Washing the fabrics makes charges decay more slowly.

The coefficients of determination of the 5th polynomial curve for test results of both unwashed and washed fabrics is equal to 1, i.e. it is sufficiently high.

As for the other fabrics tested, the surface resistivity of woven fabrics with Silverflex-170 yarns increases with lengthening distances between conductive yarns. The values of resistivity of the fabrics remain at the same magnitude before

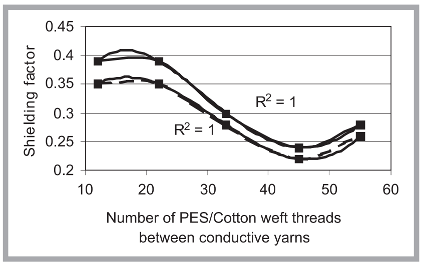

***Figure 14.** Shielding factor of woven fabrics with conductive S-Shield PES yarns (—— before washing; — — — after 5 washing cycles) (Control fabric: before washing S =0; after 5 washing cycles S=0).*

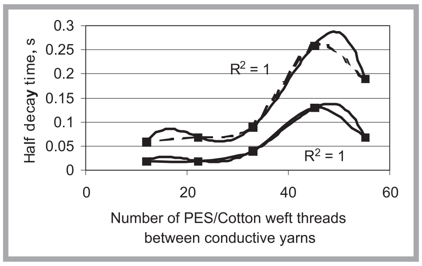

***Figure 15.** Half decay time of woven fabrics with conductive S-Shield PES yarns (—— before washing; — — — after 5 washing cycles) (Control fabric: before washing t_{50} = 0.65 s; after 5 washing cycles t_{50} = 0.75 s).*

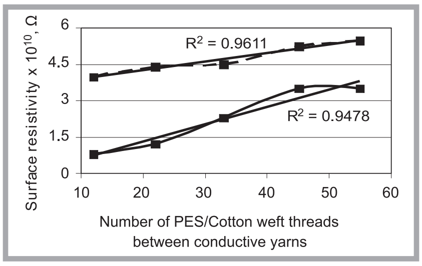

***Figure 16.** Surface resistivity of woven fabrics with conductive Silverflex-170 yarns (—— before washing; — — — after 5 washing cycles) (Control fabric: before washing ρ = 9.85×10^{11} Ω; after 5 washing cycles ρ = 3.56×10^{12} Ω).*

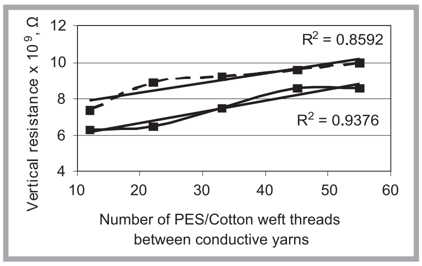

Figure 17. *Vertical resistance of woven fabrics with conductive Silverflex-170 yarns (—— as received; — — — after 5 washing cycles) (Control fabric: as received R = 2.3×10^{10} Ω; after 5 wash. cycles R = 3.2×10^{10} Ω).*

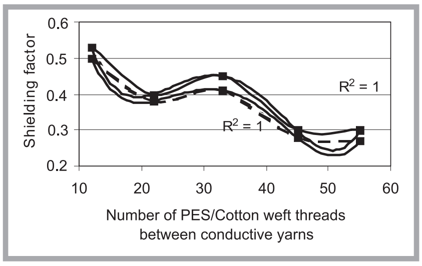

Figure 18. *Shielding factor of woven fabrics with conductive Silverflex-170 yarns (—— before washing; — — — after 5 washing cycles) (Control fabric: before washing S =0; after 5 washing cycles S=0).*

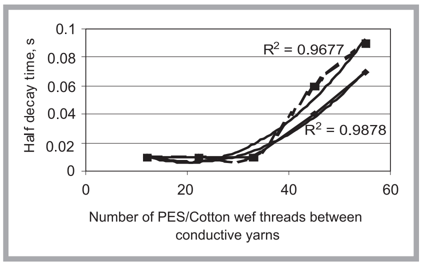

Figure 19. *Half decay time of woven fabrics with conductive Silverfelx-170 yarns (—— before washing; — — — after 5 washing cycles) (Control fabric: before washing t_{50} = 0.65 s; after 5 washing cycles t_{50} = 0.75 s).*

and after washing, i. e. 10^{10} Ω (see ***Figure 16***). The surface resistivity of woven fabrics increases after washing, e.g. from 0.8×10^{10} Ω to 4×10^{10} Ω for fabric with the shortest distances between conductive yarns, and from 3.5×10^{10} Ω to 5.5×10^{10} Ω for fabric with 55 nonconductive yarns between Silverflex-170 ones.

The vertical resistance of the fabrics varies depending on the distances between conductive yarns (see ***Figure 17***). The quantity of Silverflex-170 yarns decreases the values of vertical resistance, compared to those for control PES/Cotton fabric; washing the fabrics impairs these values. The reason for the increase in the values of resistance may be little cracks on the surface of polyester silver plated filaments that emerge after washing, which can be seen through a microscope (see ***Figure 2***).

Screening factor value depends on the quantity of conductive yarns. More antistatic yarns are in the structure of woven fabrics; better is the shielding effect and the value of the shielding factor impending to unity. The shielding factor of control fabrics with no conductive yarns is equal to zero.

The coefficient of determination of the 4th polynomial curve for test results of fabrics before washing and after washing is equal to 1 (see ***Figure 18***).

The half decay time becomes longer with the lengthening of distances between conductive Silverflex-170 yarns. The value of this parameter for fabrics before and after washing is not very different. The half decay time is less than 0.01 s for fabrics with 12, 22, and 33 nonconductive PES/Cotton yarns between conductive ones before and after washing.

As is seen from Figure 19, the coefficient of determination of the 2th polynomial curve for test results of unwashed fabrics is equal to 0.98, whereas the coefficient of determination of the 2th polynomial curve for test results of washed fabrics is 0.97, i.e. it is sufficiently high.

Charge decay experiments for all the woven fabrics tested were carried out on specimens of different sizes (of 300 mm × 300 mm and 150 mm × 150 mm). The measured half decay time and shielding factor values of these fabrics were the same. Hence, we can say that for the measurements of the shielding factor and half decay time, there is no influence of the size of specimens on the results.

A shielding effectiveness at different relative humidities

Longer distances between conductive yarns results in a decrease in the shielding factor at all the relative humidities. A clear-cut distinction of the shielding factor, determined at different humidities, is seen for fabrics with more than 33 weft yarns between conductive yarns. The fabric with 45 weft yarns between conductive yarns has almost the same shielding factor at all the relative humidities tested.

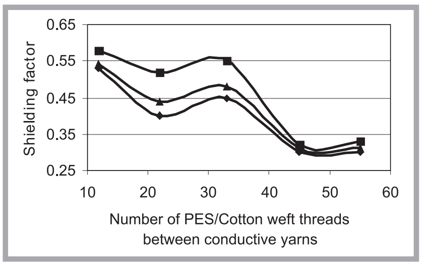

Figure 20. *Shielding factor of the fabrics versus the number of PES/Cotton weft threads between the conductive Silverflex-170 yarns (—◆— at a relative humidity of 25%, —▲— at a relative humidity of 40%, —■— at a relative humidity of 65%).*

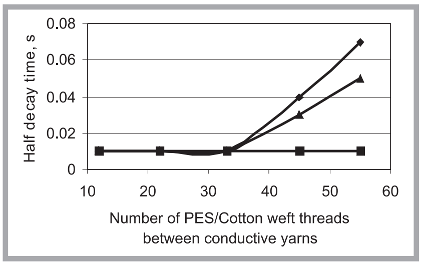

Figure 21. *Half decay time of the fabrics versus the number of PES/Cotton weft threads between the conductive Silverflex-170 yarns (—◆— at a relative humidity of 25%, —▲— at a relative humidity of 40%, —■— at a relative humidity of 65%).*

The half decay time shortens with an increase in moisture in the atmosphere tested. As regards fabric with 45 nonconductive weft yarns between conductive Silverflex-170 ones, the half decay time is longer for fabrics with longer distances between conductive yarns.

According to the European Standard EN 1149-5:2008 [16], which specifies requirements for electrostatic dissipative material, the fabrics after 5 washing cycles should meet requirements: a half decay time for the electric field strength equal $t_{50} < 4$ s or a shielding factor of $S > 0.2$. As is seen from the results of experiments, the values of the half decay time and shielding factor of all the knitted and woven fabrics with conductive yarns in their structure comply with the requirements. Hence, these fabrics can be used for the manufacture of protective clothing used against incendiary discharges.

Conclusions

It is necessary to control static electricity in areas where flammable or explosive atmospheres may be present. The fabrics tested comply with the requirements of Standard EN 1149-5, thus it can be used to make protective clothing against incendiary discharges. The resistances of these fabrics are very sensitive to the quantity of conductive yarns in their structure. The shorter the distances between antistatic yarns, the lower the values of resistances are. The control fabrics do not show any shielding effect; their resistances before and after washing remained almost the same. Better electrostatic properties have fabrics with S-Shield PES yarns in their structure. Although the vertical resistance increases very distinctly after 5 washing cycles, the resistances are still smaller than those of fabrics with Silverlex-170 yarns. The experiments showed that such a difference in the values of vertical resistance may be due to the loss of stainless steel fibers after washing. One way to ensure that stainless steel fibers do not slide from the yarn is to give extra twists to the yarn.

The values of surface resistivity and half decay time of knitted fabrics also depend on the weave. The resistivity is bigger and the half decay time is quicker for 1+1 rib knitted fabrics.

Furthermore, little cracks are seen on the silver plated polyester filaments in the fabrics, but it is not very significant, hence they do not have a big influence on the values of resistance of the fabrics.

Longer distances between conductive yarns result in a decrease in the shielding factor despite the relative humidity. The half decay time shortens with an increase in moisture in the atmosphere tested.

The test results showed that the size of test specimen has no influence on the values of charge decay characteristics.

We can conclude that although knitted fabrics shrank more than woven fabrics, they have better electrostatic properties.

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