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Electrical Conductive Textiles Obtained by Screen Printing

Abstract

Due to the emergence of smart textiles and wearable textile systems, the need for electrically conductive textiles has become increasingly clear. Often this conductivity is achieved by integrating metal particles, fibres or yarns into textiles or by coating a textile with a metallic layer. In this research, the potential of another method is explored, namely screen printing a textile with conductive ink. This printing technique is an interesting alternative because it is flexible and cost effective. In this study the conductivity was investigated by measuring the square resistance at different stages (i.e. after printing, abrading and washing, respectively). The printed textiles studied herein exhibit good electrical properties after printing and abrading, respectively. However, after twenty washing cycles, the conductivity decreased considerably. Therefore, in order to improve washability, a protective polyurethane layer was put on top of the printed samples, which resulted in the good conductivity of the fabrics, even after washing.

Key words: electrically conductive textiles, square resistance, screen printing on textiles, conductive ink, thermoplastic polyurethane layer.

■ Introduction

Nowadays, terms such as 'Smart Textile', 'Intelligent Textile' and 'Wearable Computing' are commonly used in everyday contexts. These terms refer to textiles that are able to sense stimuli from the surrounding environment as well as to react and adapt to them.

Their history can be traced back to the 1960s, when the discovery of shape memory materials marked a new era of innovations in materials. This was followed by the invention of polymeric gels in the 1970s, which introduced smart materials. In the 1990s researchers started to integrate these smart materials into textiles, thus creating smart textiles.

Later on, researchers started to examine the combination of textiles and electronics, which led to the development of wearable textile systems. The first electronic textile introduced on the market was the ICD+ (Industrial Clothing Design Plus) jacket in 2000 by Levi Strauss & Co. and Philips Research Laboratories [1]. Subsequently, several communication systems, such as mobile phones, MP3 players, computers and GPS became integrated into garments. In order to allow these devices to oper-

ate as 'Wearable Computers', different conductive materials, wires and batteries were used [2, 3]. From a textile point of view, the challenge for researchers is to make as many components as possible out of textile materials. Therefore, it is necessary to develop electroconductive textiles, which can be obtained in several ways, for example by integrating conductive fibres or yarns, applying conductive coatings, or using conductive inks [4 - 6].

Conductive inks have found use in many applications, including electronics, computers and communications. More specifically, they have been used for PCBs (Printed circuit boards), RFID tags (Radio-frequency identification) or wiring boards [7]. To these rigid substrates, which are altogether different from textiles, diverse technologies have been applied, most notably screen printing.

In the last decade, carbon electrodes, circuits, wearable computers and embedded systems for monitoring vital signs have been printed by screen printing conductive silver-based inks on different woven and nonwoven fabrics [8 - 12]. For textile applications, the technique is suitable for coarse structures such as patch antennas, ground planes, feed lines or simple one-layer routing structures [13], resulting in flexible and lightweight components. However, when integrated in wearable textile systems, consumers will only accept them if they do not require any special maintenance other than regular washing processes, preferably without removing all devices.

In this paper, we present a method to obtain washable, screen printed electroconductive textiles.

The screen printing method was specifically selected because it is an inexpensive, flexible and fast way to obtain lightweight conductive coated textiles that can be integrated into smart textiles. In order to examine the influence of different kinds of ink on textile materials, we screen printed two silver-based conductive inks on different woven textiles.

The electrical properties were evaluated by measuring the square resistance of the printed textiles during different stages, such as after printing, abrading and washing. Since the electrical properties were not so good after washing, it was decided to put a protective layer on top of the conductive layers. Again, the electrical properties of the samples were assessed before and after washing.

We found that the electroconductive textiles obtained from screen printing with both silver-based inks are washable. Their values of square resistance obtained varied between 0.010 and 0.171 Ω/sq , which is perfect for applications that need a relatively low resistivity level.

■ Materials and methods

Textile materials

In this study, 14 woven textile substrates were selected, made of different materials: natural, synthetic and also blended fibres: Cotton (CO), Viscose (CV),

Table 1. Properties of woven textiles applied; (1 - ISO 7211-2, 2 - ISO 7211-1, 3 - ISO 5084, 4 - ISO 3801, 5 - EN ISO 9073-6:2003).

Woven textile materials	Yarn density of fabric, threads/cm		The type of textile weave	Thickness, mm	Basis weight, g/m ²	Absorption capacity, %
	Warp	Weft				
CO 1	24	16	Twill 3/1	0.864	435	124
CO 2	42	29	Twill 3/1	0.414	233	77
CO 3	52	24	Twill 2/2	0.390	238	98
CO 4	47	26	Twill 4/1	0.468	283	100
CV 1	18	11	Plain 1/1	0.488	254	101
CV 2	20	19	Plain 1/1	0.310	132	152
CV 3	32	20	Plain 1/1	0.378	191	88
PA 1	45	32	Twill 2/2	0.198	99	135
PES 1	46	25	Plain 1/1	0.380	163	128
PES 2	55	48	Twill 1/2	0.140	101	64
PES 3	57	46	Twill 2/1	0.146	104	64
PES 4	21	22	Plain 1/1	0.478	177	162
CO/PES 1	46	26	Twill 3/1	0.296	113	161
PES/CV 2	45	25	Twill 3/1	0.246	108	153

Table 2. Properties of silver-based conductive inks applied.

Properties	Ink type	
	Electrodag PF 410	5025 Silver Conductor
Viscosity, Pa·s	10 - 25	20 - 30
Surface tension, mN/m	35	37
Solid content, %	73.5 - 76	68 - 72
Cure conditions at 120 °C, min	15	5 - 7
Surface resistivity, Ω/sq	< 0.025	0.012 - 0.015

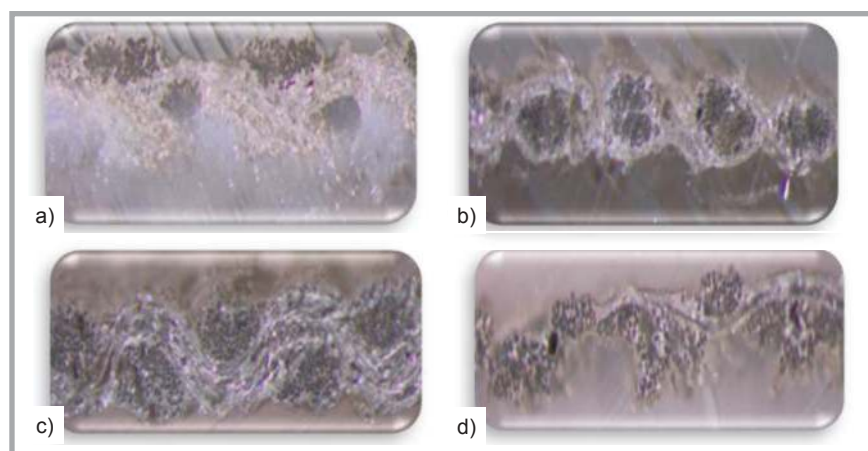


Figure 1. Stereoscope cross-section images of: a) CO 2, b) CV 2, c) PES 4 and d) CO/PES (printed with conductive ink Electrodag PF 410).

Polyamide (PA), Polyester (PES), Cotton/Polyester (CO/PES) and Polyester/Viscose (PES/CV).

The physical and mechanical properties (e.g. density, structure and thickness) were determined according to ISO standards and are listed in **Table 1**. These properties influence the outcome of the printing and therefore also the conductive properties of the printed samples.

Conductive inks

Copper, silver and gold (limited) are metals used in conductive inks. The conduc-

tive ink that is applied in screen printing consists of a dispersion of metal particles and suitable resins in an organic or inorganic solvent [9]. The use of copper ink causes some difficulties, because it is thermodynamically unstable in atmospheric conditions due to oxidation [14]. Since gold ink is very expensive, silver-based ink is the best option.

Two silver-based inks (**Table 2**) were applied in this study: Electrodag PF 410 conductive ink, produced by Acheson [15], and 5025 conductive ink by DuPont [16]. Electrodag PF 410 consists

of a PES resin with silver particles with a size of $\leq 3 \mu\text{m}$, and ink 5025 consists of Epoxy resin with particles size of $\leq 2.5 \mu\text{m}$. These commercially available inks are mainly used in low voltage circuitry printed on flexible substrates such as polyester, polyamide, paper and epoxy glass. Furthermore these inks are suitable for manual screen printing. As can be seen in **Table 2**, Electrodag PF 410 has the lower viscosity and surface tension, which implies that it will penetrate more easily into a textile structure than ink 5025. The viscosity, cure conditions and surface resistivity are given by the producers, and the surface tension is measured by the Wilhelmy Plate Method

Screen printing

Screen printing is a traditional way of printing that was introduced at the end of the 9th century. The technique is used on a whole range of materials, such as textiles, ceramics, glass, polyethylene, polypropylene, paper, metal and wood. It is often preferred to other processes like hand block printing, engraved roller printing, heat transfer printing and inkjet printing because it is a low-cost and easy process. With this printing technique, a design is imposed on a screen of fine mesh, containing blank areas coated with an impermeable substance. The ink is then forced through the mesh onto the printing square by moving a squeegee across the mesh.

In this study a polyester mesh was used, monofilament 90 T, with a sieve thickness of $110 \mu\text{m}$ and a sieve opening of 45%. The printing pattern was a square with dimensions of 6 by 6 cm.

For most of the samples, ten print passes were applied, which means that the squeegee was passed over the stencil ten times. However, for some samples, only five print passes were applied because the ink penetrated through the textile substrate (**Figure 1**).

Of each woven textile substrate, three samples were printed with both conductive inks (**Figure 2.b**), resulting in a total of 42 printed samples. In order to bond and fix the ink to the substrate, the samples were cured in an oven under conditions specified in **Table 2**. Next, the samples were placed in a standard atmosphere for 24 hours (RH = $65 \pm 2\%$ and T = $20 \pm 2 \text{ }^\circ\text{C}$) before their electrical properties were measured.

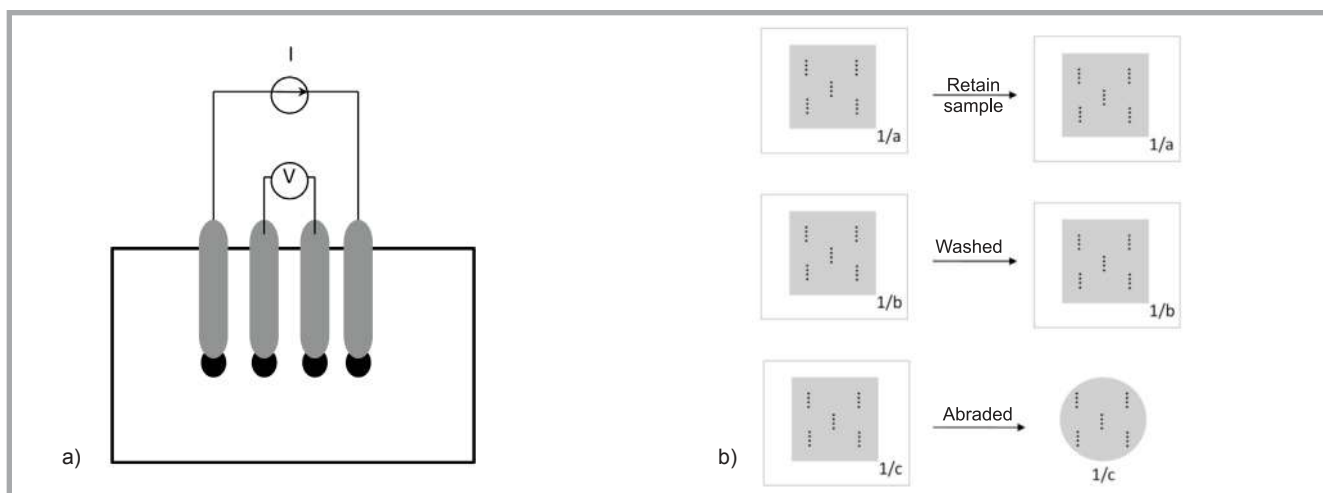


Figure 2. Four point-probe setup (a) and square resistance measurements at five different spots on the sample (b).

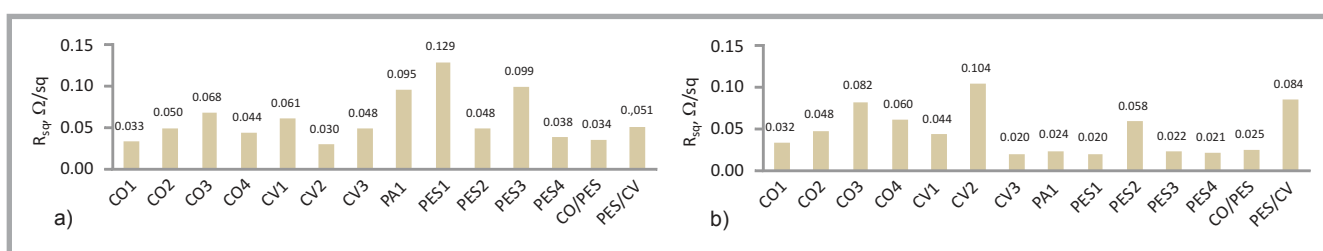


Figure 3. Square resistance of printed samples printed with conductive ink Electrodag PF 410 (a) and ink 5025 (b).

Measurement of square resistance with the four-point method

The square resistance of the printed samples was measured with the four-point method by means of an MR-1 instrument, manufactured by Schuetz Messtechnik [17]. This is an electrical impedance measuring technique that uses separate pairs of current-carrying and voltage-sensing electrodes to improve accuracy, as compared to the traditional two-point sensing method. The current I is fed through the outer contacts and the voltage V is measured across the inner electrodes, as shown in **Figure 2.a**. To avoid any damage or burnouts of the printed square, the MR-1 instrument guarantees that the lowest possible current flow (100 mA) is used.

Square resistance measurements were performed before washing, after washing (5, 10, 15, 20 times) and after each number of abrading cycles determined.

Before measuring the square resistance, the samples were conditioned in a standard atmosphere for 24 hours. For each printed sample, five measurements of the square resistance were made, each time at different spots on the sample, as shown

in **Figure 2.b**. The average of these five measurements was taken as a value of the square resistance.

Square resistance after printing

The square resistance of the conductive layer on the 14 printed textile samples was measured after the samples were printed and cured in the oven. The values obtained are illustrated in **Figures 3**.

Firstly, for the conductive layers of both inks we observed that the resistance of the conductive layer obtained depended on the textile material that was used. For ink Electrodag PF 410 this ranged from 0.030 to 0.129 Ω/sq , while for ink 5025 the data varied between 0.020 and 0.104 Ω/sq . We also noticed that the spreading was not the same for both inks: with ink Electrodag PF 410, the lowest resistance was 0.030 Ω/sq for fabric CV 1, but with ink 5025 the lowest resistance values were reached for fabrics CV 3 and PES 1. Similarly the highest resistance levels were measured on the conductive layers of different substrate materials: 0.129 Ω/sq for PES 1 with Electrodag PF 410 and 0.104 Ω/sq for CV 2 with ink 5025.

Secondly, we noted that the resistance values for the conductive layers of ink

Electrodag PF 410 varied between 0.030 and 0.129 Ω/sq , which is much higher than the resistivity given in the datasheet ($< 0.025 \Omega/\text{sq}$). For the conductive layers of ink 5025, the resistances obtained on the textile substrates were also remarkably higher (0.020 and 0.104 Ω/sq) than the value in the datasheet (0.012 and 0.014 Ω/sq). This can be explained by the fact that the textile material partly absorbs the ink, which does not happen on the rigid flat substrate used to determine the ink's resistivity.

Finally, it is clear that a conductive layer of ink Electrodag PF 410 generally provides a higher square resistance than one of ink 5025, which is in accordance with the values on the data sheet, showing that the surface resistivity of conductive layers with Electrodag PF 410 ink is twice that of conductive layers with 5025 ink.



Figure 4. Abrasion resistance apparatus

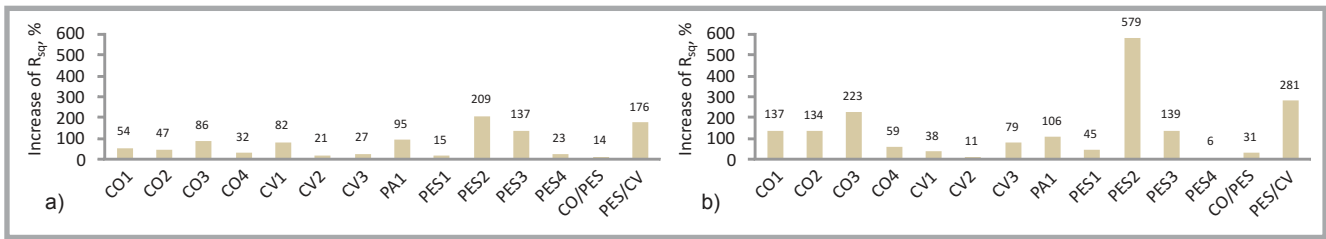


Figure 5. Increase in square resistance after 5000 abrasion cycles printed with conductive ink Electrodag PF 410 (a) and ink 5025 (b).

In addition, the viscosity and surface tension of ink Electrodag PF 410 is lower (Table 2) than those of ink 5025, which causes a deeper penetration of the ink into the textile substrate and thus a higher resistance of the printed conductive layer.

Square Resistance after abrading

The abrasion resistance of the printed textile samples is an important property since these conductive textiles are meant to be used in clothes. As clothing is used on a daily basis, there will be abrasion between the fabric and the skin, as well as between two different fabric layers, or between the fabric and surfaces of the surrounding materials. Therefore it was necessary to examine the effect of abrasion on the square resistance of the

printed textiles. This test was performed by means of the Martindale method (Figure 4, see page 59), in compliance with the International Standard ISO 12947-2:1998 [18] for 500, 1000, 2000, 3000, 4000 and 5000 abrasion cycles.

The principle of this test is that a circular specimen, which is mounted in a specimen holder with a load of 12 kPa, is rubbed against a 100% wool textile. The specimen holder is rotatable around its own axis, perpendicular to the plane of the specimen.

After the abrading test, the wool fabric showed a gray spot on the area where it had rubbed against the conductive layer, indicating that much of the conductive layer had come off, resulting in a higher

resistance. We expressed that as the increase in square resistance ΔR_{sq} , calculated as follows:

$$\Delta R_{sq} = \frac{R_M - R_O}{R_O} \quad (1)$$

R_M - square resistance after abrading

R_O - square resistance before abrading

Figures 5 confirm that a considerable increase in resistance was measured after 5000 abrading cycles.

When the two inks were compared after the abrading tests, the resistance of ink 5025 was generally much higher. This can be explained by the high viscosity and surface tension of the ink, which does not make it easy for it to penetrate deep into the textile structure. Consequently, the ink abrades more easily and the resistivity increases with additional abrading cycles.

We also observed that PES 2 shows the highest increase in resistance for the conductive layers with both inks (i.e. 209% for ink Electrodag PF 410 and up to 579% for ink 5025). As is shown in Table 1, this material has a very low absorption capacity (63.73%), which means that the textile material does not absorb the ink very well. In addition, for CO/PES, which has a very high absorption capacity (161.48%), the resistance of conductive layers increased only slightly (14% for ink Electrodag PF 410 and 31% for ink 5025).

The absolute values of square resistance after the abrading test for the conductive layers printed with Electrodag PF 410 ink varied from 0.036 to 0.234 (Ω/sq). For those printed with 5025 ink, the values ranged from 0.022 to 0.396 (Ω/sq), showing an increase in R_{sq} .

Square Resistance after washing

The 'smart textiles' that are now available on the market, like O'Neil's NavJacket with an integrated GPS [19], require the removal of all electronic devices prior to washing. From a consumer point of view,

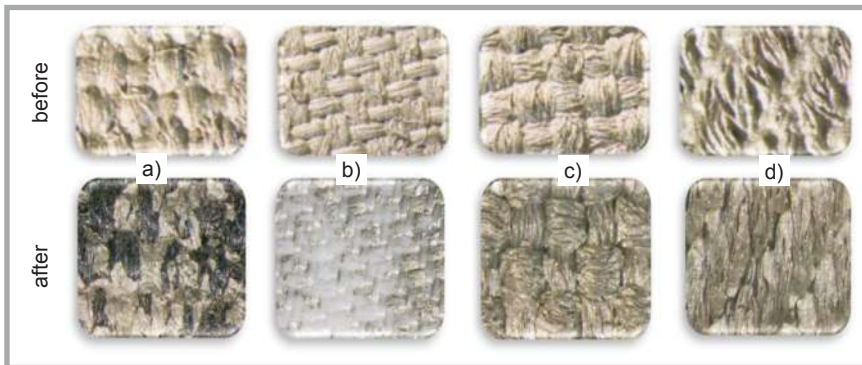


Figure 6. Samples before washing and after 20 washing cycles: a) CV 3, b) PA 1, c) PES 1, d) CO/PES (printed with conductive ink Electrodag PF 410)

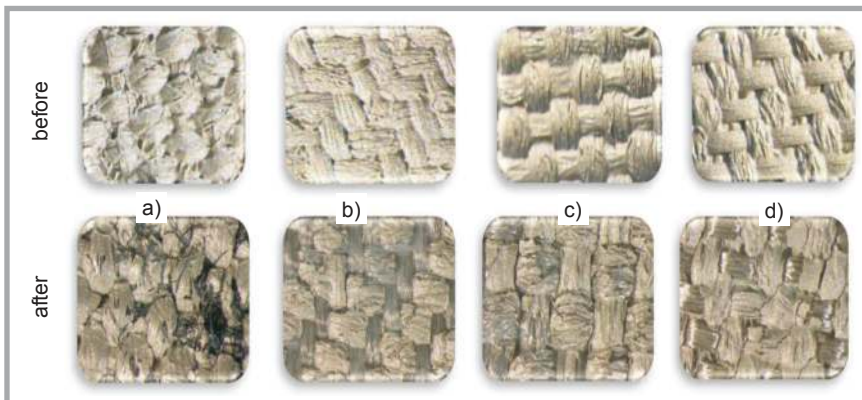


Figure 7. Samples before washing and after 20 washing cycles: a) CV 3, b) PA 1, c) PES 1, d) CO/PES (printed with conductive ink 5025)

this is not a desired situation because it complicates maintenance. Consequently, if the printed ‘conductive textiles’ are intended to be used in smart textile applications, good washability properties are crucial.

In this study, the domestic washing behaviour of the printed textile samples was evaluated according to International Standard ISO 6330:2000 [18]. Washing programme 6 A, which washes at a temperature of 40 ± 3 °C, was chosen because it is relevant to the function of the printed samples. Each printed sample was washed 5, 10, 15 and 20 times, and in between every five cycles the square resistance was measured, as described in Section 3. After 20 washing cycles, nearly half of the samples had lost their conductivity, and the remaining samples presented very high square resistances (see **Table 3**). Therefore no further washing cycles were conducted.

Of the samples that remained conductive after 20 washing cycles, the values of square resistance appeared to be very high; values between 2 Ω/sq and 244 Ω/sq were measured. For ink Electrodag PF 410, CO 4 had the highest value of 71 Ω/sq and CO/PES had the lowest - 2 Ω/sq, while for ink 5025 it was PES 4 that had the highest value of 244 Ω/sq, whereas the lowest value of 4 Ω/sq was obtained for CO/PES.

To conclude, conductive ink Electrodag PF 410 showed a lower value of square resistance after washing than conductive ink 5025, while it was the other way around before washing.

The values of square resistance after washing and after abrading for conductive ink 5025 were very high in comparison with those before washing. They were also the highest compared to conductive ink Electrodag PF 410.

After 20 washing cycles nearly half of the samples, for each conductive ink used, had lost their conductivity (**Figures 6 & 7**).

The following pictures illustrate that the conductive layer has gone off the surface of the printed textile.

Measurement of square resistance with the Van Der Pauw method

In order to avoid cracks in the printed surface or pieces of ink coming off after

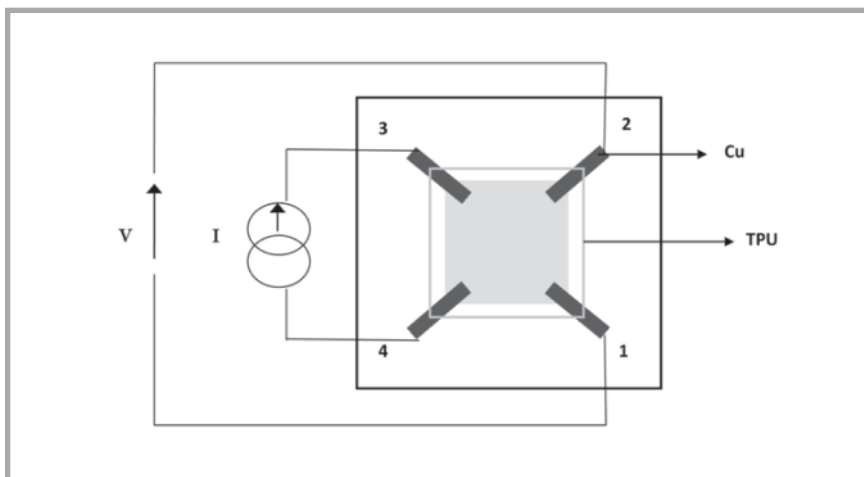


Figure 8. VDP measurement of printed sample with four contacts on the vertices and thermoplastic polyurethane foil on top.

Table 3. Square resistance of the samples before and after washing (printed with conductive ink Electrodag PF 410 and ink 5025).

Woven textile materials	Conductive layer - R_{sq} Ω/sq			
	ink Electrodag PF 410		ink 5025	
	Before washing	20 times washed	Before washing	20 times washed
CO 1	0.033	-	0.032	203
CO 2	0.050	40	0.048	-
CO 3	0.068	-	0.082	-
CO 4	0.044	71	0.060	-
CV 1	0.061	-	0.044	26
CV2	0.030	7	0.104	33
CV3	0.048	36	0.020	11
PA 1	0.095	-	0.024	45
PES 1	0.129	24	0.020	-
PES 2	0.048	-	0.058	-
PES 3	0.099	-	0.022	-
PES 4	0.038	8	0.021	244
CO/PES	0.034	2	0.025	4
PES/CV	0.051	5	0.084	78

washing, some kind of pre-treatment may be conducted; however, in this study we chose to put a thermoplastic polyurethane (TPU) layer from Epurex (LPT, thickness 80 μm) (**Figure 8**) on top of the printed square [20, 21]. However, this meant that the four point probe method was no longer suitable to evaluate the resistance because the conductive layer was now covered. Therefore we opted for another measurement method: the Van Der Pauw (VDP) method [22]. In order to measure the square resistance with this method, four contacts are required on the boundary of the conductive sample. To this end, four strips of copper foil are attached to the printed patch. According to the Van De Pauw method, these contacts can be placed in various positions, such as in the centres of the side, in the vertices, and in the 1/3 or 1/4 of the length of the sides [23]. For this study, the contacts were made in the vertices (**Figure 8**).

To establish a good electroconductive contact between the copper foil and printed patch, electroconductive glue was applied.

The VDP method required that two neighbouring contacts (3 and 4), as shown in **Figure 8**, were used to supply current I, while the other two contacts (1 and 2) measured the voltage V. The current applied in our study was 200, 400 and 1000 mA. Because the resistance changes linearly, the average square resistance was calculated. The measurements were completed at room temperature.

The square resistance is given by:

$$R_{sq} = \frac{\pi \cdot V}{I \cdot \ln 2} \quad (2)$$

$$R_{sq} = 4.53 \cdot \frac{V}{I} \quad (3)$$

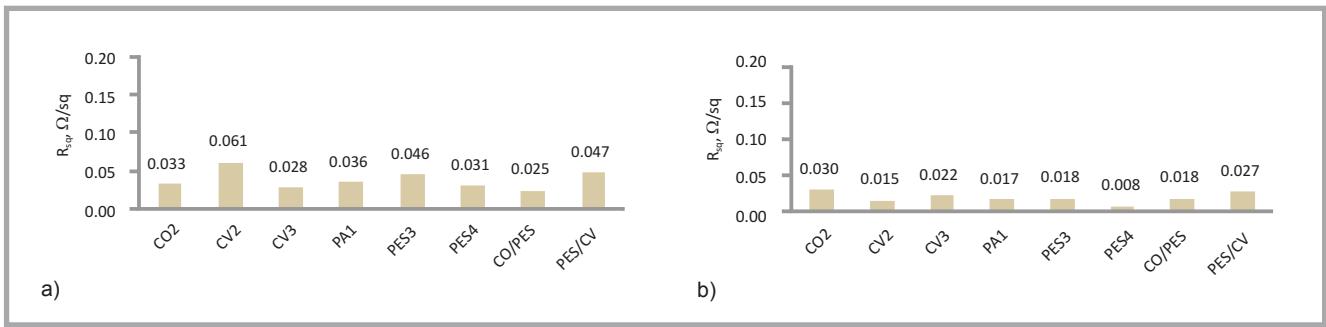


Figure 9. Square resistance of printed samples covered with a TPU layer - printed with conductive ink Electrodag PF 410 (a) and ink 5025 (b).

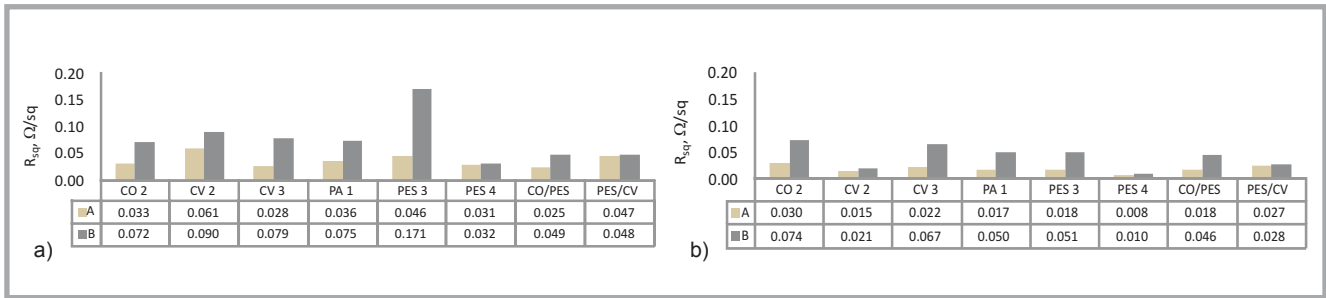


Figure 10. Square resistance of washed samples covered with a TPU layer - printed with conductive ink Electrodag PF 410 (a) and ink 5025 (b); A - before washing, B - 20 times washed.

The value of 4.53 is the correction factor [24].

In the second series of tests, eight fabrics were used: CO 2, CV 2, CV 3, PA 1, PES 3, PES 4, CO/PES and PES/CV. This selection was made on the basis of the evaluation of the electrical properties in previous tests.

The square resistance of these printed textile samples, with both inks and covered by a TPU layer, is illustrated in **Figure 9**.

We did not compare the absolute values of square resistance obtained by four-point probe measurement and the VDP method because our aim was to focus on changes in square resistance when the fabrics were abraded or washed. However, this topic is addressed in [23].

Nevertheless, we once again observe that ink Electrodag PF 410 generally leads to higher resistance values (between 0.025 and 0.061 Ω/sq) than those of ink 5025 (between 0.015 and 0.030 Ω/sq).

Square resistance after washing

The washing test was repeated after the TPU layer was added on the top of the printed samples. For each printed textile sample, 20 washing cycles were applied

and the square resistance measured (**Figure 10**).

Again, we observed an increase in square resistance after 20 washings, but not as pronounced as without the TPU layer on top (section 3.3). For two fabrics, PES 4 and PES/CV, there was nearly no change in resistance after washing, which is quite striking from a practical point of view because the square resistance remained stable after several washings. All resistances measured remained under 0.200 Ω/sq .

Three polyester-based fabrics (PES 4, PES/CV and CO/PES) also showed very good electrical properties after washing. However, PES 3 behaved quite differently with a higher increase in resistance after washing, which may be due to the lower absorption capacity of the material compared to the other polyester-based fabrics. This results in a lower amount of ink after printing, which affects the conductivity level. The thicker the layer, the higher the conductivity level is [25, 26].

Conclusions

The combination of textiles and conductive inks makes it possible to produce flexible, conductive, lightweight, practical and comfortable 'smart textiles'.

The screen printing technique with conductive ink used in this research was not only a traditional but also an inexpensive method of making textiles conductive.

In this paper, two silver-based electroconductive inks (Electrodag PF 410 and 5025) were applied to a selection of woven textile substrates. The electrical properties of the conductive layer on the printed samples were evaluated by means of the square resistance, measured after printing, after abrading and after washing.

The square resistance obtained with both inks was generally higher than that of the inks given in data sheets, which was caused by a deeper penetration of the conductive ink into the textile substrate. The physical properties of the inks, such as viscosity and surface tension, also influence the square resistance of the printed samples. As conductive ink Electrodag PF 410 has the lowest surface tension, it penetrates easily and more deeply into the textile substrate, which results in a higher resistance than that using conductive ink 5025. Thus, the values of square resistance before and after washing for conductive ink Electrodag PF 410 (0.032 – 0.171 Ω/sq) were higher than those for conductive ink 5025 (0.010 – 0.074 Ω/sq).

The printed samples covered and not covered with a polyurethane (TPU) layer were washed up to 20 times. The uncovered printed layer showed cracks and the conductive layer came off during the washing cycles, resulting in a loss of conductivity. However, when the conductive layer was protected with a TPU layer, conductivity was maintained after up to 20 washing cycles.

It was shown that electroconductive textiles obtained from screen printing with silver-based inks and protected with a thermoplastic polyurethane (TPU) layer are suitable for washing.



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