Statistical analysis of textile structures based on conductive yarns

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ABSTRACT – REZUMAT

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This work presents a series of textile structures fabricated by weaving and knitting using insulating, conductive and antistatic yarns. The physical-mechanical (thickness, water vapour permeability, mass and air permeability), electrical (electrical resistivity), and morphological (SEM, EDAX) properties of the textile structures were analysed to highlight their application potential in interactive products. The statistical analysis of the correlations between physical-mechanical and electric properties was conducted by correlation analysis using the electrical surface resistivity values as dependent variables and the mass (M), thickness (δ) and water vapour permeability (Pv) as independent variable.

Keywords: *textile, conductive, interactive, resistivity*

Analiza statistică a structurilor textile pe bază de fire conductive

Această lucrare prezintă o serie de structuri textile realizate prin țesere și tricotare utilizând fire izolatoare, conductive și antistatice. Au fost analizate proprietățile fizico-mecanice (grosime, permeabilitate la vaporii de apă, masă și permeabilitate la aer), electrice (rezistivitatea electrică) și morfologice (SEM, EDAX) ale structurilor textile pentru a evidenția potențialul de utilizare în cadrul unor produse interactive. Analiza statistică a corelațiilor dintre proprietățile fizico-mecanice și electrice a fost efectuată prin analiza coeficientilor de corelație utilizând ca variabile dependente valorile rezistivității electrice de suprafață și masa (M), grosimea (δ) și permeabilitatea la vapori de apă (Pv) ca variabilă independentă.

Cuvinte-cheie: *textil, conductiv, interactiv, rezistivitate*

INTRODUCTION

In general, woven or knit materials fabricated with conductive yarns can be used as e-textiles, such as transmission lines or heating textile-based copper filaments, or as antistatic materials or odour absorbers (filaments based on carbon coating). E-textiles can generate heat, transmit electrical signals or be used as storage energy materials [1, 2].

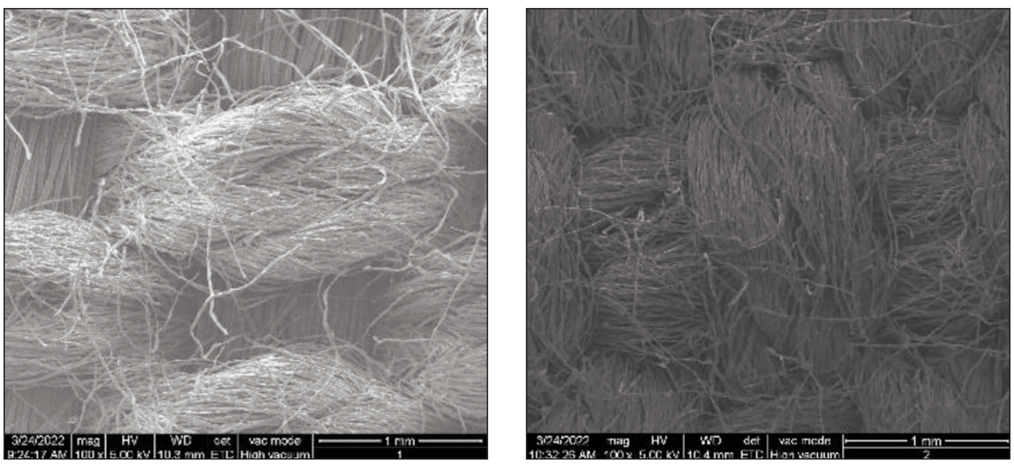
It is well known that heat can generate changes in the volume resistivity of 3D textiles or the electrical surface resistance of the 2D surfaces of fabrics or 1D conductive yarns. The electrical charge and discharge of antistatic fabrics can be controlled by weaving electrically conductive fibres into the fabric and by the density of these yarns in the weft or warp directions [3–5]. The utilization of antistatic textiles for pressure sensor manufacturing has been presented in numerous studies [5–12], and it is still a challenge for many researchers to achieve position detection or gait evaluation [12]. In addition, nanomaterial-based carbon black or graphene can be used for the development of textile coatings [13, 14], antistatic yarns and fibres with segmented structures or coated with graphene/carbon black [15–18]. Some studies indicate that CNT-coated yarns can be used as wefts, core-spun metallic yarns can be used as electrodes and polyester with yarns in the warp direction [19–22] or copper filaments [23–26] can be used as heating textiles [27, 28].

EXPERIMENTAL METHODS

Fabrics were generated with experimental textile structures (P1–P12) of weaving (P1–P3, P6–P12) and knitting (P4–P5) using insulating, conductive and antistatic yarns. Physical-mechanical, electrical (table 1) and morphological (table 3) evaluations of the fabrics were carried out in the laboratory to highlight the application potential of these materials in interactive products. The surface electrical resistivity was measured using a PRS-812 Prostate Resistance Meter based on concentric electrodes. Table 1 presents the physical-mechanical and electrical characteristics of the tested fabrics and knitwear. Table 2 shows the connections between the textile structures and the fibrous composition of the yarns. The surface morphology of the fabrics and knitwear made with yarns with electroconductive properties was investigated by scanning electron microscopy (table 3). Figure 1 shows the SEM images of samples P1 (figure 1, *a*) and P2 (figure 1, *b*) using 100x magnification, and figures 2 and 3 show the EDAX spectra of the fabric variants P1 (figure 2) and P2 (figure 3). Figures 4–7 show the 3D representations of surface

Table 1

PHYSICAL-MECHANICAL AND ELECTRICAL PROPERTIES												
Tests	**Samples**											
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**
Mass (g/m^2)	372.4	383.6	304.4	405.2	519.6	135.6	156.4	158	161.2	167.2	168.8	161.6
Density Du (no. of yarns/10 cm)	224	224	170	-	-	176	170	180	170	174	175	180
Density Db (no. of yarns/10 cm)	120	120	84	-	-	190	210	170	170	174	170	180
Thickness δ (mm)	1.388	1.413	1.056	2.311	2.564	0.532	0.55	0.52	0.53	0.51	0.52	0.50
Water vapour permeability Pv (%)	26.8	26.3	28.5	29	27.1	27.1	26.94	25.28	28.60	26.38	28.65	26.71
Air permeability Pa at 100 Pa (l/m^2/sec)	116.9	122.8	1141	2305	435.6	1141	932.6	999.9	1580	1206	1843	1095
	407.7	223.9	1799	3890	743.6	1799	1473	1640	2527	1960	2917	1824
Knit density Do	-	-	-	42	79	-	-	-	-	-	-	-
Knit density Dv				64	90							
Surface resistivity ρ (Ωm)	5.46 x 10^{13}	4.39 x 10^{13}	6.19 x 10^{13}	2.10 x 10^{13}	1.21 x 10^{13}	2.27 x 10^{13}	3.52 x 10^{13}	2.6 x 10^{13}	**1.2 x 10^{12}**	**8.4 x 10^{12}**	1.32 x 10^{13}	5.10 x 10^{13}



a *b*

Fig. 1. SEM images of samples P1 and P2: *a* – SEM image – sample P1 based on viscose filamentary yarn coated with carbon; *b* – SEM image – sample P2 based on 100 % cotton

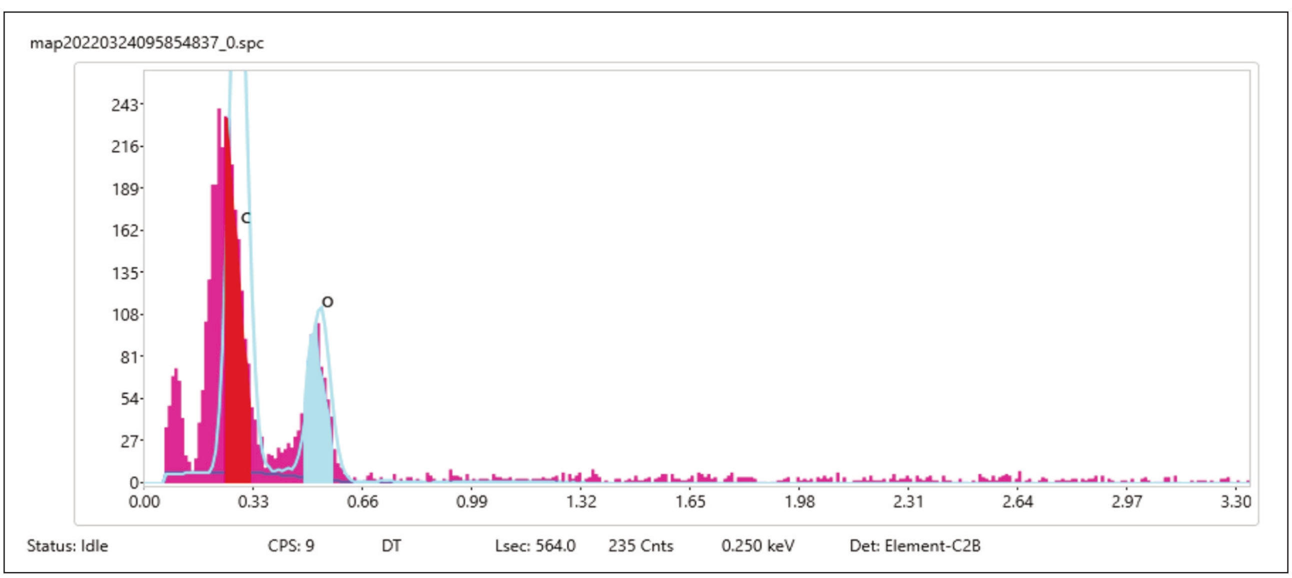
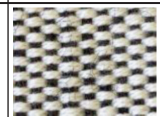
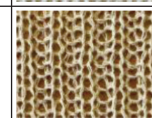
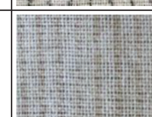
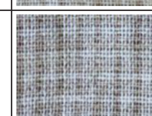
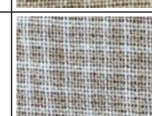


Fig. 2. EDAX of sample P1

Table 2

STRUCTURE AND FIBROUS COMPOSITION			
Sample	**Structure**	**Fibrous composition**	**Image**
P1	canvas	51.9% cotton + 48.1% viscose filamentary yarn coated with carbon	
P2	canvas	100% cotton	
P3	canvas, twisted threads inserted in the weft direction (cotton yarn + copper filament)	95.7% cotton + 4.3% metallic yarn	
P4	rib-knit 1:1 with metallic yarns	58.5% cotton+ 41.5% metallic yarn	
P5	double flat knit	white knit: 87.3% Pes + 12.7% Pa; interior: viscose filamentary yarn coated with carbon	
P6	canvas, carbon-coated viscose filament yarns (4 cotton yarns, 2 viscose yarns) inserted in the warp direction	90% cotton + 10% Viscose filamentary yarn covered with carbon	
P7	canvas	95% cotton + 5% filamentary yarn coated with carbon	
P8	canvas	92.9% cotton + 7.1% metallic yarn	
P9	canvas	80% cotton + 20% metallic yarn	
P10	canvas	86.4% cotton + 13.6% metallic yarn	
P11	canvas	73.7% cotton + 26.3% metallic yarn	
P12	canvas	89% cotton + 11% metallic yarn	

electrical resistivity as a function of thickness, water vapour permeability, mass and air permeability.

RESULTS AND DISCUSSION

Statistical analysis and discussion

To evaluate the relationship between the physical-mechanical and electric properties, correlation analysis was used. By analysing the values of the correlation coefficients (1, 2, 3) between the surface electrical resistivity vector and vectors such as the mass (M), thickness (δ) and water vapour permeability (*Pv*), the following was observed:

- The value of the correlation coefficient between the surface electrical resistivity and mass ($R(\rho, M)$ = 0.1745) was positive and indicated that there was a positive direct correlation, and the increase in the mass value per unit length generated an increase in the value surface electrical resistivity:

$$R(\rho, M) = \begin{vmatrix} 1.0000 & 0.1745 \\ 0.1745 & 1.0000 \end{vmatrix} \Leftrightarrow \qquad (1)$$
$$\Leftrightarrow R1{,}2_{\rho,M} = R2{,}1_{\rho,M} = 0.1745$$

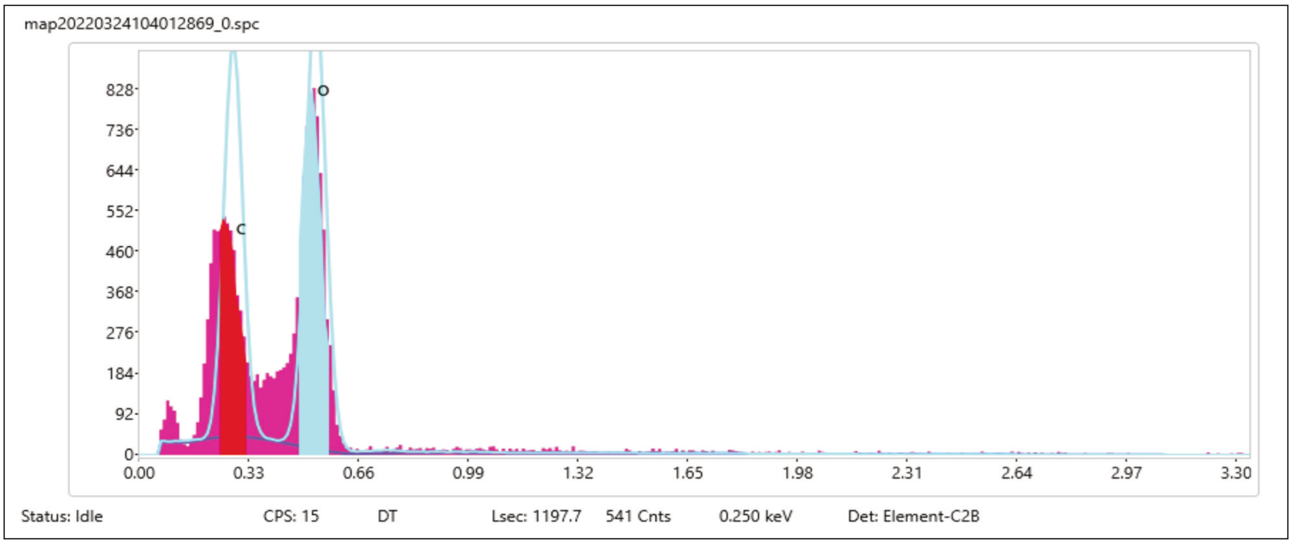


Fig. 3. EDAX of sample P2

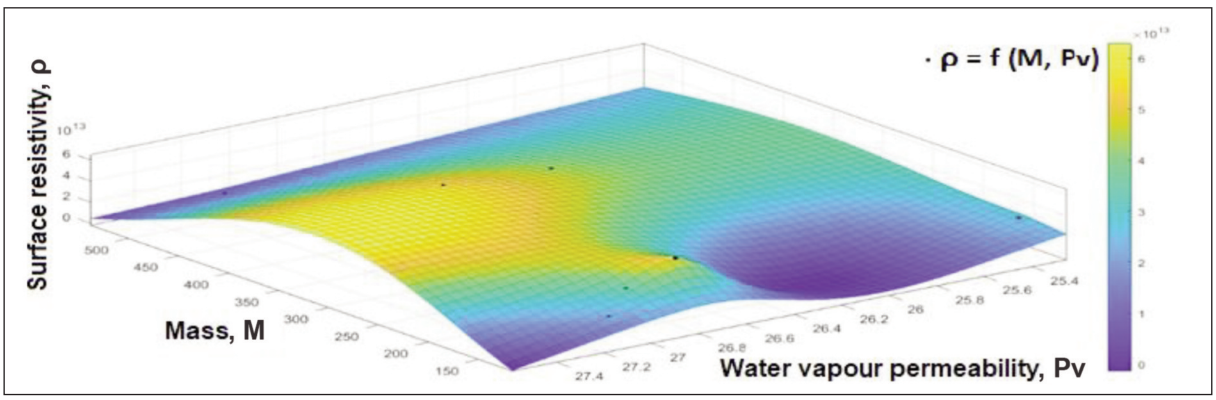


Fig. 4. 3D graphical representation of surface electrical resistivity (ρ) as a function of mass (M) and water vapour permeability (Pv)

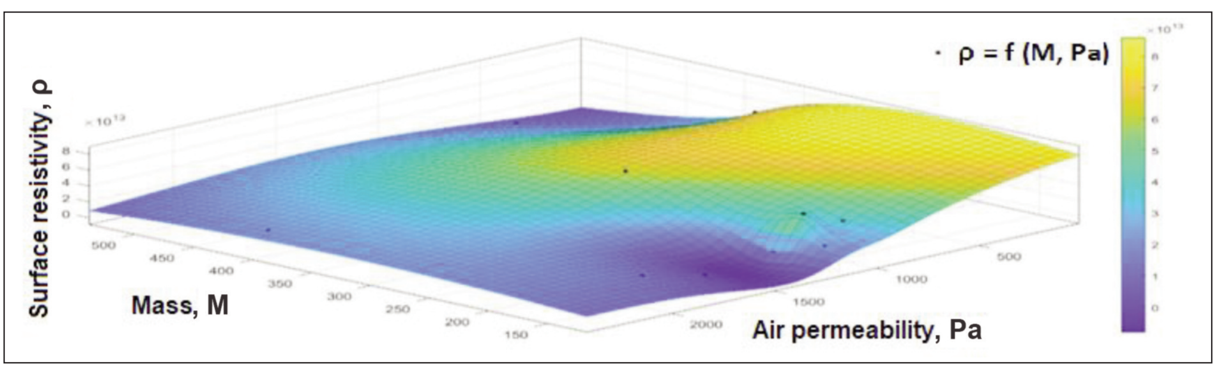


Fig. 5. 3D graphical representation of surface electrical resistivity (ρ) as a function of mass (M) and air permeability (Pa)

- The value of the correlation coefficient between the surface electrical resistivity and thickness ($R(\rho, \delta)$ = 0.0139) was positive and indicated that there was a direct positive correlation; as the thickness of the textile material increased, the resistivity value minimally increased. The surface electrical resistivity in this case can be defined as follows:

$$R(\rho,\delta) = \begin{vmatrix} 1.0000 & 0.0139 \\ 0.0139 & 1.0000 \end{vmatrix} \Leftrightarrow \qquad (2)$$

$$\Leftrightarrow R1{,}2_{\rho,\delta} = R2{,}1_{\rho,\delta} = 0.0139$$

- The value of the correlation coefficient between the surface electrical resistivity and water vapour permeability ($R(\rho, Pv)$ = –0.1784) was negative and indicated that there was a negative inverse correlation; as the value of the water vapour permeability increased, the value of surface electrical resistivity decreased:

$$R(\rho,Pv) = \begin{vmatrix} 1.0000 & 0.1784 \\ 0.1784 & 1.0000 \end{vmatrix} \Leftrightarrow \qquad (3)$$

$$\Leftrightarrow R1{,}2_{\rho,Pv} = R2{,}1_{\rho,Pv} = 0.1784$$

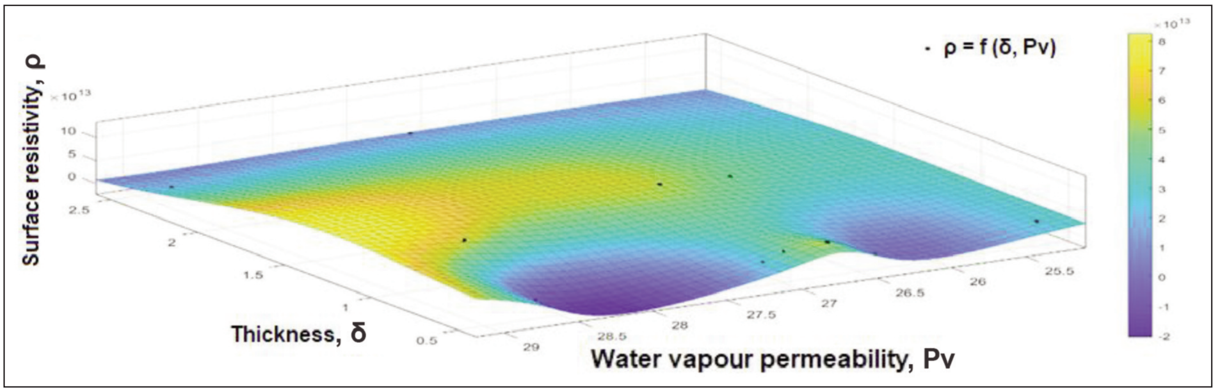


Fig. 6. 3D graphical representation of surface electrical resistivity (ρ) as a function of thickness (δ) and water vapour permeability (Pv)

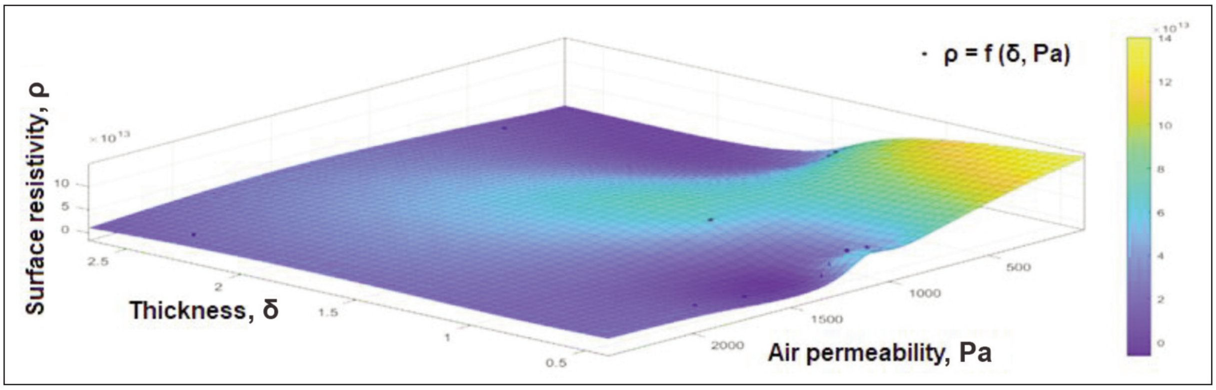


Fig. 7. 3D graphical representation of surface electrical resistivity (ρ) as a function of thickness (δ) and air permeability (Pa)

CONCLUSIONS

In conclusion, by analysing samples P1–P12, the following was deduced:

- There is an inverse relationship between the surface electrical resistivity and water vapour permeability. Because the surface electrical resistivity is the resistance to electrical current along the surface of an insulating material, increasing the vapour permeability (because of the atmospheric humidity or a lower yarn density in the weft or warp directions) generates a reduction in the surface electrical resistivity.
- With the surface electrical resistivity and mass, the respective thickness has a small positive correlation, which means that increasing the mass or thickness has a small effect on increasing the surface electrical resistivity.
- Samples P9 and P10 can offer antistatic protection because their surface resistivity falls within the range typical of materials with antistatic properties ($\rho \leq 10^{12}$ Ωm).
- Samples P1–P8, P11 and P12 can offer electrical protection because their surface resistivity falls within the range typical of electrically insulating materials ($\rho > 10^{13}$ Ωm).

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