CORRELATIVE AND COVARIANCE ANALYSIS OF THE ELECTROCONDUCTIVE FABRICS

DOI: 10.35530/TT.2021.42

R.M. Aileni*, L. Chiriac

National Research Development Institute for Textiles and Leather, Romania
(E-mail: aileni.raluca@incdtp.ro, laura.chiriac@incdtp.ro)

Abstract: This paper presents the correlation and covariance analysis of the electrical resistance dependence of mass, thickness and air permeability of textile structures coated with magneto-conductive materials and used for protection against electromagnetic waves. For this scientific approach, 9 experimental models of composites-based fabrics with electroconductive properties were made by applying different pastes based on organic polymeric matrices polyvinyl alcohol (PVA), copper (Cu), aluminium (Al), zinc (Zn), iron oxide (Fe_3O_4) and polypyrrole (PPY) solution using a classical deposition method such as scraping. The surface resistance was evaluated using a resistance meter device based on two parallel electrodes. From all samples analysed 5 samples based PPY, PVA-Ni, PVA-Ni-Al and PVA-Zn present a surface resistance between 10^3 and $10^5 \Omega$. Because the surface resistance has a lower value this means that the samples have a good conductivity to be used as layers for electromagnetic shielding systems.

Keywords: coating, conductive, electrical resistance, electromagnetic shielding, textile

1. INTRODUCTION

The investigation of the electrical properties of textiles was a challenge in numerous scientific papers because of the variation with temperature and moisture [1]. However, the ambient temperature and humidity, in real condition, is impossible to be controlled and this leads to variation in the surface resistance of the textile materials which tends to increase the conductivity with moisture contents even if are not previously treated with conductive pastes. In addition, the temperature and moisture at the skin level cannot be controlled and this can lead also to a variation of the surface resistance in the case of the textile conductive electrodes in contact with the skin. An increasing interest is in using the conductive inks composed of a polyurethane-based elastomer containing Ag flakes or polypyrrole [2,3] for smart textile applications [4-6]. In addition, the practical methods to obtain the conductive fabrics include metal or graphene coating and conducting polymer (polyaniline, polythiophene, PEDOT: PSS, and polypyrrole) coating [7-11].

The scientific literature presents several aspects concerning the influence of textile moisture or temperature on the surface electrical resistance of textiles [12-14]. The use of copper-coated lyocell cellulose fabric for flexible strain sensor [15] or nano copper loaded nonwoven polypropylene-based textile ECG electrodes was presented in numerous scientific papers [16-18]. In addition, the use of coatings-based nickel and titanium presents a good application for actuators [19,20]. Special attention is on using the Fe_3O_4 nanoparticles on cotton fabrics by the Pad-Dry-Cure process for the elaboration of magnetic and conductive

textiles [21]. Aluminium and nickel were applied in numerous applications for electromagnetic shielding [22,23].

In the context of electroconductive textile development and characterization, this paper is divided into the following parts: experimental part section introduce the specific aspects of the coatings and materials physico-mechanical and electrical characterization; correlative/covariance analysis section introduces the main aspects concerning the covariance and correlation matrix, principal components analysis and correlation coefficients; the discussions section introduce explanations about correlation coefficient values signification and finally, the conclusion section concludes the paper.

2. EXPERIMENTAL PART

In the framework of the 3D Electrotex project, 9 experimental samples were obtained using different pastes based organic polymeric matrices PVA and metallic nonferrous or ferrous microparticles such as zinc (Zn), copper (Cu), nickel (Ni), aluminium (Al), iron oxide (Fe₃O₄) and polypyrrole (PPY). The physico-mechanical and electrical properties were evaluated in the laboratory. In table 1 are presented the investigation results for the 9 samples treated with conductive pastes and the standard sample (M).

Table 1. Physico-mechanical and electrical characterization

No.	PPY	Ni	Cu	Al	Zn	Fe ₃ O ₄	H ₂ O	Rs [*] (Ω)	M ^{**} (g/m ²)	δ ^{***} (mm)	Pa ^{****} (l/m ² /sec)
M	-	-	-	-	-	-	x	10 ¹²	518	1.36	107
1	-	x	-	-	-	-	x	10 ³	590.8	1.5	113.4
2	-	x	x	-	-	-	x	10 ⁷	623.2	1.424	109.4
3	-	-	x	-	-	-	x	10 ¹¹	623.6	1.42	121.8
4	x	-	-	-	-	-	x	10 ⁸	513.6	1.472	187.4
5	x	-	-	-	-	X	-	10 ⁵	513.6	1.472	55.68
6	-	-	-	-	-	x	x	10 ⁸	602.8	2.408	55.73
7	-	x	-	x	-	-	x	10 ³	769.6	3.878	143
8	-	-	-	x	-	-	x	10 ⁵	577.2	1.25	88.14
9	-	-	-	-	x	-	x	10 ⁵	559.2	1.684	16.2

Note: *Rs – electrical resistance; **M - mass; ***δ – thickness; ****Pa – air permeability. Pressure difference used: 200 Pa; Standard conditions: T=20,2°C, RH=64,5%.

In table 2 are presented the optical view of the samples captured using the optical microscope with a magnification of 60x.

2. CORRELATIVE/COVARIANCE ANALYSIS

Using the results from physico-mechanical and electrical investigations were evaluated the correlations and covariance between dependent (Rs) and independent variables (M, δ, Pa) using the analysis of principal components (ACP) to resolve the following issues:

- ➔ Data complexity reduction and correlation/covariance matrix (table 3-9);
- ➔ Establishing of the correlations and covariances (table 3 and table 6);
- ➔ The determination of the latent variables and the behaviour. However, the variant of the variables measured can be found in the variant of hidden variables (influencing factors), which are determined by the association. In addition, considering the variables $x_1, x_2, \dots, x_p$, it is necessary to determine certain components $C_1, C_2, \dots, C_m$, where $C_i = w_{i1}X_1 + w_{i2}X_2 + \dots + w_{ip}X_p$, to obtain $m \ll p$.

Table 2. Analysis of the surface topography of the fabric by optical digital microscopy

- Correlative analysis

Table 3. Eigen analysis of the Correlation Matrix

Eigenvalue	1.9947	1.0649	0.7666	0.1738
Proportion	0.499	0.266	0.192	0.043
Cumulative	0.499	0.765	0.957	1.000

Table 4. Eigenvectors

Variable	PC1	PC2	PC3	PC4
Rs	-0.327	0.608	0.714	0.117
M	0.667	0.029	0.162	0.727
Δ	0.638	0.029	0.378	-0.670
Pa	0.204	0.793	-0.567	-0.092

- Covariance analysis

Table 5. Eigen analysis of the Covariance Matrix

Eigenvalue	9.87726×10^{22}	5516	2121	-3
Proportion	1.000	0.000	0.000	-0.000
Cumulative	1.000	1.000	1.000	1.000

Table 6. Eigenvectors

Variable	PC1	PC2	PC3	PC4
Rs	1.000	0.000	0.000	-0.000
M	-0.000	0.964	0.267	-0.009
δ	-0.000	0.008	0.003	1.000
Pa	0.000	0.267	-0.964	0.001

Table 7. Unrotated Factor Loadings and Communalities

Variable	Factor1	Factor2	Factor3	Factor4	Communality
Rs	-0.462	0.627	0.625	0.049	1.000
M	0.942	0.030	0.142	0.303	1.000
δ	0.901	0.030	0.331	-0.280	1.000
Pa	0.288	0.818	-0.496	-0.038	1.000
Variance	1.9947	1.0649	0.7666	0.1738	4.0000
% Var	0.499	0.266	0.192	0.043	1.000

Table 8. Rotated Factor Loadings using Quartimax Rotation and Communalities

Variable	Factor1	Factor2	Factor3	Factor4	Communality
Rs	-0.173	0.045	0.984	-0.003	1.000
M	0.927	0.114	-0.160	0.318	1.000
δ	0.960	0.023	-0.041	-0.276	1.000
Pa	0.114	0.992	0.044	0.003	1.000
Variance	1.8246	1.0007	0.9971	0.1776	4.0000
% Var	0.456	0.250	0.249	0.044	1.000

Table 9. Factor Score Coefficients

Variable	Factor1	Factor2	Factor3	Factor4
Rs	0.110	-0.059	1.039	0.222
M	0.506	-0.067	0.098	1.740
δ	0.582	-0.067	0.100	-1.620
Pa	-0.077	1.020	-0.061	-0.173

In figures 1 – 3, are presented the 3D representations for the Rs depending on the mass (M), thickness (δ), and air permeability (Pa).

Figure 1. 3D surface representation $R_s = f(Pa, M)$

Figure 2. 3D surface representation $R_s = f(Pa, \delta)$

Figure 3. 3D surface representation $R_s = f(M, \delta)$

In the math expressions 1-6 are presented the correlation coefficients $r_{R_s, Pa}$, $r_{R_s, M}$, $r_{R_s, \delta}$, $r_{M, \delta}$, $r_{M, Pa}$, $r_{\delta, Pa}$.

$$r_{R_s, Pa} = \begin{vmatrix} 1.0000 & 0.0684 \\ 0.0684 & 1.0000 \end{vmatrix} \Leftrightarrow r_{12_{R_s, Pa}} = r_{21_{R_s, Pa}} = 0.0684 \quad (1)$$

$$r_{R_s, M} = \begin{vmatrix} 1.0000 & -0.3131 \\ -0.3131 & 1.0000 \end{vmatrix} \Leftrightarrow r_{12_{R_s, M}} = r_{21_{R_s, M}} = -0.3131 \quad (2)$$

$$r_{R_s, \delta} = \begin{vmatrix} 1.0000 & -0.2043 \\ -0.2043 & 1.0000 \end{vmatrix} \Leftrightarrow r_{12_{R_s, \delta}} = r_{21_{R_s, \delta}} = -0.2043 \quad (3)$$

$$r_{M,\delta} = \begin{vmatrix} 1.0000 & 0.8116 \\ 0.8116 & 1.0000 \end{vmatrix} \Leftrightarrow r_{12_{M,\delta}} = r_{21_{M,\delta}} = 0.8116 \quad (4)$$

$$r_{M,Pa} = \begin{vmatrix} 1.0000 & 0.2132 \\ 0.2132 & 1.0000 \end{vmatrix} \Leftrightarrow r_{12_{M,Pa}} = r_{21_{M,Pa}} = 0.2132 \quad (5)$$

$$r_{\delta,Pa} = \begin{vmatrix} 1.0000 & 0.1297 \\ 0.1297 & 1.0000 \end{vmatrix} \Leftrightarrow r_{12_{\delta,Pa}} = r_{21_{\delta,Pa}} = 0.1297 \quad (6)$$

4. RESULTS AND DISCUSSIONS

The results obtained following the experimental plan (Table 1), in comparison with an insulative material (M), consists in:

- 5 samples (1, 5, 7, 8, 9) based on Ni, PPY+Fe₃O₄, Ni+Al, Al and Zn having the electrical resistance specific to the conductive materials (10³-10⁵Ω) with potential to be used such as electrodes in sensors, actuators or electromagnetic shield for electromagnetic waves attenuation;
- 4 samples (2, 3, 4 and 6) based on Ni+Cu, Cu, PPY and Fe₃O₄ having the electrical resistance specific to the static dissipative materials (10⁷-10¹¹ Ω) with potentially safe in ESD (electrostatic discharge) environment and prevent the damage of the sensitive equipment.

Evaluating the math expressions 1-6 concerning the correlation coefficients $r_{Rs, Pa}$, $r_{Rs,M}$, $r_{Rs,\delta}$, $r_{M,\delta}$, $r_{M, Pa}$ and $r_{\delta, Pa}$, we found that:

- ➔ The greatest correlation coefficient is between the mass and thickness and the lowest one is between the surface resistance and the mass: $r_{M,\delta} > r_{M, Pa} > r_{\delta,Pa} > r_{Rs,Pa} > r_{Rs,\delta} > r_{Rs,M}$. This means that between the mass and thickness it is a strong dependence. Withal, between surface resistance and mass is a moderate negative correlation which means if the independent variable (mass) increases, the dependent variable (surface resistance) tends to decrease.
- ➔ Between surface resistance and air permeability it is a strong and positive correlation and which means that by increasing the air permeability (independent variable) of the fabric, the discontinuities and pores in the fabric increase and the distance between metallic conductive particles increase and this led to the reduction of the surface conductivity and increasing the surface resistance (dependent variable). As a result, the surface resistance has increased due to the air insulation and the reduction of the distance between the conductive microparticles in a certain level of the fabric.
- ➔ Between the surface resistance and thickness, it is a negative dependence which means if the independent variable (thickness) increases due to the conductive layer thickness, the dependent variable (surface resistance) tends to decrease.

5. CONCLUSIONS

In conclusion, the samples obtained have an electrical resistance specific to the conductive materials (10³-10⁵ Ω) used for sensors, actuators or EM shields, respective for dissipation of the static energy (10⁷-10¹¹ Ω).

In addition, the analysis of the principal components is important because it generates:

- ➔ the reduction of the redundant data;
- ➔ establish the correlations and covariance between variables necessary in the prediction of the variable's dependencies;
- ➔ discover the latent variables;
- ➔ establish the correlation and covariance matrix.

The analysis of the correlation coefficient conducts to conclusions that the surface resistance is not in a dependent relationship with the mass and thickness, and is in a dependent

relationship with air permeability. However, a higher value of the air permeability means that the conductive layer is not perfectly continuous, the conductivity is reduced and the surface resistance increase with the density of the air gaps in the fabric, because the air is a good insulator having a resistivity between 1.3×10^{16} to $3.3 \times 10^{16} \Omega$.

ACKNOWLEDGEMENTS

The research presented in this paper was prepared in the INCDTP laboratories. Funds support this work from MCI, National Project "Materiale textile composite electroconductive pe bază de matrici polimerice 3D pentru sisteme senzoriale de monitorizare și de atenuare a undelor electromagnetice (3D ELECTROTEX)", Contract PN 19 17 01 01.

REFERENCES

- [1] Wang, X., et al., *Study on the electrical resistance of textiles under wet conditions*, In: Textile Research Journal, 2009, 79,8, 753-760
- [2] Kuhn, H.H., et al., *Properties and applications of conductive textiles*, In: Synthetic Metals, 1993, 57, 1, 3707-3712
- [3] Attia, N.F., El Ebissy, A.A., Hassan, M.A., *Novel synthesis and characterization of conductive and flame retardant textile fabrics*, In: Polymers for Advanced Technologies, 2015, 26, 12, 1551-1557
- [4] Inoue, M., et al., *Development of highly conductive inks for smart textiles*, In: 14th International Conference on Electronic Materials and Packaging (EMAP), IEEE, 2012, 1-4
- [5] Kim, B., et al., *Electrical and morphological properties of PP and PET conductive polymer fibers*, In: Synthetic Metals, 2004, 146, 2, 167-174
- [6] Grancaric, A.M., et al., *Conductive polymers for smart textile applications*, In: Journal of Industrial Textiles, 2018, 48, 3, 612-642
- [7] Kuhn, H.H., et al., *Properties and applications of conductive textiles*, In: Synthetic Metals, 1993, 57, 1, 3707-3712
- [8] Neves, A.I., et al., *Towards conductive textiles: coating polymeric fibres with graphene*, In: Scientific reports, 2017, 7, 1, 1-10
- [9] Skeifvars, M., Rehnby, W., Gustafsson, M., *Coating of textile fabrics with conductive polymers for smart textile applications*, In: Ambience 08, Borås, Sweden, 2008
- [10] Tseghai, G.B., et al., *PEDOT: PSS-based conductive textiles and their applications*, In: Sensors, 2020, 20, 7, 1881
- [11] Kuhn, H.H., *Characterization and application of polypyrrole-coated textiles*, In: Intrinsically conducting polymers: an emerging technology. Springer, Dordrecht, 1993, 25-34
- [12] Wang, X., Xu, W., Li, W., Cui, W., *Study on the electrical resistance of textiles under wet conditions*, In: Textile Research Journal, 2009, 79, 8, 753-760
- [13] Hearle, J.W.S., *The Electrical Resistance of Textile Materials: III. Miscellaneous Effects*, In: Journal of the Textile Institute Transactions, 1953, 44, 4, T155-T176
- [14] Hearle, J.W.S., *The electrical resistance of textile materials: II. the effect of temperature*, In: Journal of the Textile Institute Transactions, 1953, 44, 4, T144-T154
- [15] Root, W., Wright, T., Caven, B., Bechtold, T., Pham, T., *Flexible textile strain sensor based on copper-coated lyocell type cellulose fabric*, In: Polymers, 2019, 11, 5, 784
- [16] Shaikh, T.N., Chaudhari, S., Patel, B.H., Patel, M., *Study of conductivity behavior of nano copper loaded nonwoven polypropylene based textile electrode for ECG*, In: International Journal of Emerging Science and Engineering, 2015, 3, 4, 11-14
- [17] Jang, S., Cho, J., Jeong, K., Cho, G., *Exploring possibilities of ECG electrodes for bio-monitoring smartwear with Cu sputtered fabrics*, In International Conference on Human-Computer Interaction, Springer, Berlin, Heidelberg, 2007, 1130-1137
- [18] Pani, D., Achilli, A., Bonfiglio, A., *Survey on textile electrode technologies for electrocardiographic (ECG) monitoring, from metal wires to polymers*, In: Advanced Materials Technologies, 2018, 3, 10, 1800008

- [19] Pequegnat, A., Daly, M., Wang, J., Zhou, Y., Khan, M.I., *Dynamic actuation of a novel laser-processed NiTi linear actuator*, In: Smart materials and structures, 2012, 21, 9, 094004
- [20] Lima, P.C., Rodrigues, P.F., Ramos, A.S., da Costa, J.D., Braz Fernandes, F.M., Vieira, M.T., *Experimental Analysis of NiTi Alloy during Strain-Controlled Low-Cycle Fatigue*, In: Materials, 2021, 14, 16, 4455
- [21] Nadi, A., Sbai, S.J., Bentiss, A., Belaiche, M., Briche, S., Gmouh, S., *Application of Fe₃O₄ nanoparticles on cotton fabrics by the Pad-Dry-Cure process for the elaboration of magnetic and conductive textiles*, In: IOP Conference Series: Materials Science and Engineering, 2020, 827, 1, 012021
- [22] Jiang, S.X., Guo, R.H., *Electromagnetic shielding and corrosion resistance of electroless Ni–P/Cu–Ni multilayer plated polyester fabric*, In: Surface and Coatings Technology, 2011, 205, 17-18, 4274-4279
- [23] Palanisamy, S., Tunakova, V., Militky, J., *Fiber-based structures for electromagnetic shielding—comparison of different materials and textile structures*, In: Textile Research Journal, 2018, 88, 17, 1992-2012