PREDICTIVE ANALYSIS OF THE ELECTROMAGNETIC SHIELDS EFFECTIVENESS

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This paper presents a predictive analysis of the electromagnetic attenuation effectiveness for conductive textile materials obtained by coating with polypyrrole, conductive paste-based aluminum, nickel, copper, silver, and graphene oxide. The predictive analysis was provided by the multiple regression modeling of the effectiveness of electromagnetic attenuation at 5 MHz, respective 700 MHz frequency depending on independent variables such as mass (M [g/m^2]) and thickness (δ [mm]) of the fabric coated with the conductive paste by screen printing. Usually, flexible electromagnetic shields, based on textile materials, are necessary for shielding electric fields, representing a potential reference for cables and filters and ensuring the return path of parasitic currents. Protection against the harmful action of electromagnetic fields can be achieved using textile screens based on conductive coatings that ensure the reflection of the waves when they meet the surface, respectively, the absorption of the waves. In general, the wave representing the incident electromagnetic field propagates in the direction of the screen, undergoing a reflection at contact with the screen, then repeated internal reflections inside it, part of the wave being transmitted into the protected space.

Keywords: textile, electromagnetic shielding. predictive

INTRODUCTION

The disruptive presence of electromagnetic fields is the cause of numerous malfunctions of equipment used in various fields of activity (Deruelle, 2020). In addition, electromagnetic waves can generate harmful activity (Moon, 2020) in living organisms (Saunders, 2003; Stuchly, 2003; Ahlbom *et al*., 2008; Seitz *et al*., 2005; Matthes *et al*., 2003; Perrin and Souque, 2012), materializing cellular anomalies (e.g., cancers (Hendee and Boteler, 1994)). Currently, the share of electromagnetic fields is in the range of tens and hundreds of MHz, where a wide variety of radio-electronic equipment works by emitting and receiving electromagnetic radiation.

International bodies recommend measures to reduce the negative impact of electromagnetic fields (Aldrich and Easterly, 1987; Vecchia *et al*., 2009; Modenese and Gobba, 2021) generated by the great diversity of equipment and their inclusion in electromagnetic compatibility requirements.

The electromagnetic field is the consequence of the electric and magnetic fields generated around a conductor traversed by a variable (electric) current (in time). Electromagnetic waves represent (periodic) variations in the time and space of the electromagnetic field. They are generated around the emission antennas, representing open oscillating systems and propagating in space at the speed of light. They are characterized by a series of parameters such as intensity, polarization, wavelength, etc.

In their propagation, electromagnetic waves are subject to reflection, refraction, diffraction, change of polarization plane, etc. The particularities of the propagation depend primarily on the frequency.

Some researchers identified a harmful effect of exposure to the electromagnetic field at 300 Hz - 10 MHz depending on the dosimetry limits (Vecchia *et al*., 2009; Litvak *et*

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al., 2002). Generally, some concerns are related to exposure to electromagnetic fields from mobile phones (Röösli, 2010; Frank, 2021; Seitz *et al*., 2005).

EXPERIMENTAL PART

The experimental model based textile support and having conductive properties were developed (Table 1) by applying different pastes/dispersions based on polymeric matrices (polyvinyl alcohol (PVA – samples 1-3, 7-9), polypyrrole (PPY – samples 3 and 6), polyvinylpyrrolidone (PVP – samples 4 and 5)), microparticles of copper (Cu) having the size of microparticles < 25 µm, nickel (Ni) having the size < 150 µm, aluminum (Al), silver (Ag) and graphene oxide (GO). Using deposition technologies such as immersion, rinsing and ultrasound, followed by free drying at 20...22°C for 24h, and crosslinking for 3-5 minutes at 140...160°C for samples functionalized by rinsing, respectively drying at 100...105°C, for 5-6 minutes for samples functionalized by ultrasound. The experimental models of functionalized fabrics (9) were evaluated in order to determine the effectiveness of electromagnetic shielding (SE_{dB}) according to the ASTM ES7-83 standard, using specific equipment (from the INCDIE ICPE-CA endowment): coaxial cell model TEM 2000. The measurements were performed for the frequency f [MHz] between 0.1 MHz – 1000 MHz. Table 1 shows the physical, mechanical and electrical characteristics and the effectiveness of electromagnetic shielding (SE_{dB}) for the maximum areas recorded at 5 MHz and 700 MHz, respectively.

Table 1. Physico-mechanical and electrical properties of the samples developed using polymer pastes containing metal microparticle

Sample No.	PPY	Ni	Cu	Al	Ag	GO	Etanol	Distilled water	Rs [Ω]	M [g/m^2]	δ [mm]	SEdB, f=5MHz	SEdB, f=700 MHz
1	-	x	x	-	-	-	-	x	10^7	623.2	1.424	0.5	1.2
2	-	-	x	-	-	-	-	x	10^{11}	623.6	1.42	0	0.1
3	x	-	-	-	-	-	-	x	10^8	513.6	1.472	0	0
4	-	-	-	-		x	-	x	10^{10}	671	1.51	0	0.7
5	-					x	x	-	10^{10}	518.8	1.37	0	0.6
6	x	-	-	-	-	-	-	-	10^5	513.6	1.472	0.2	0
7	-	x	-	-	-	-		x	10^3	834	1.71	22.9	14.6
8	-	-	-	-	x	-		x	10^8	608	2.096	0.1	0
9	-	x	-	x	-	-		x	10^3	769.6	3.878	18.1	20.8

PREDICTIVE ANALYSIS

To develop the mathematical models for predictive analyses the multiple regression modeling was used, studying the correlations between the independent variables (mass (M [g/m^2]), thickness (δ [mm]) and dependent variable electromagnetic attenuation effectiveness SE_{dB} [dB] having frecquency of 5MHz, respective 700MHz.

$$Y=a_1+b_1*X_1+b_2*X_2+b_3*X_3+....+b_kX_k \quad (1)$$

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where:
Y is the estimated value for the dependent variable;
$X_1,X_2,X_3,....X_k$ are the values of the k predictor variables;
a_1 is the point of origin;
$b_1,b_2,b_3,...b_k$ are the coefficients for the k predictor variables.

For the prediction of electromagnetic shielding effectiveness (SE_{dB}) values, the following mathematical models were developed:

- The mathematical model 1 (2) for predicting the values of the effectiveness of electromagnetic attenuation (SE_{dB} [dB]) depending on the electrical surface resistance (Rs [Ω]) and the thickness of the functionalized material (δ [mm]):

$$z_1 = 3.313 + 6.837*x + 0.059*y \quad (2)$$

where:
$z= SedB_{700\ MHz}$;
$x = \delta$;
y=Rs.

- The mathematical model 2 (3) and 3 (4) for predicting the values of the effectiveness of electromagnetic attenuation (SE_{dB}5MHz [dB], respectively SE_{dB}700MHz [dB]) depending on the electrical surface resistance (Rs [Ω]) and the mass of the functionalized material (M [g /m^2]).

$$z_2 = -0.506 - 4.132*x + 0.675*y + 1.489*x^2 - 7.079*x*y + 2.108*y^2 \quad (3)$$

where:
$z= SedB_{700MHz}$;
x=Rs;
y=M.

$$z_3 = -2.093 – 6.473*x + 1.659*y+2.566*x^2 -8.348*x*y + 3.992*y^2 \quad (4)$$

where:
$z= SedB_{5MHz}$;
x=Rs;
y=M.

- The mathematical model M4 (5) and M5 (6) for the prediction of the electromagnetic attenuation effectiveness values (SEdB5MHz [dB], respectively SEdB700MHz [dB]) depending on the mass (M [g/m^2]) and the thickness of the functionalized material (δ [mm]). Figure 1 shows the effectiveness of electromagnetic attenuation (Se_{dB}) as a function of mass (m[g/m^2]) and thickness (δ[mm]).

$$z_4 = 0.642 +0.803*x +4.029*y +3.065*x*y + 2.351*y^2 \quad (5)$$

where:

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z= $SedB_{700MHz}$;
x=δ;
y= M.

$$z_5 = 0.619 + 0.815x + 4.801*y + 0.1887*x^2 + 0.5648*x*y + 4.32*y^2 \quad (6)$$

where:
z= $SedB_{5MHz}$;
x=δ;
y= M.

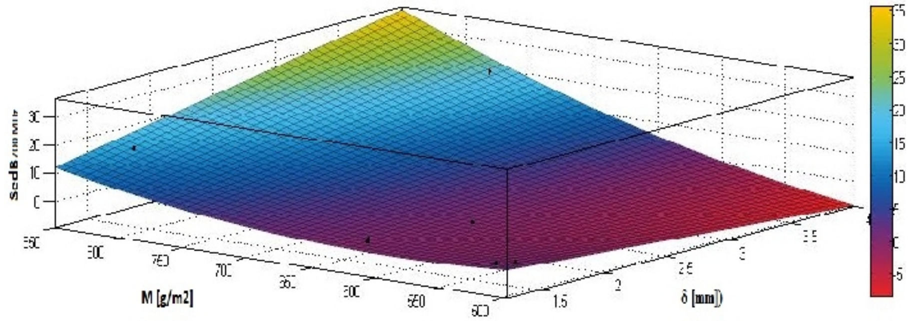

Figure 1. 3D graphical representation of electromagnetic shielding effectiveness depending on the thickness (δ[mm]) and mass (M [g/m^2])

Table 2 presents the elements that define the predictive power of mathematical models, such as the determination coefficient which is the square of the multiple correlation coefficient R^2 (Pal and Bharati, 2019), the square root of the root mean square error (RMSE) and the adjusted coefficient of determination (adjusted R^2). In the case of model no. 1, the RMSE value is 3.789 (Table 2). In the case of model no. 2, the RMSE value is 4.893, respectively in the case of model no. 3 it is 2.025, it can be concluded that these models do not have the necessary accuracy because they generate multiple residual variables. Since the RMSE value is 0.7583 (Table 2) for model no. 4, this model shows good accuracy.

$$RMSE = \sqrt{\frac{1}{T}\sum_{i=1}^{T}(E_1^2(X))} \quad (7)$$

$$E(X) = X^{Prognosis} - X^{Effective} \quad (8)$$

Table 2. Elements that define the predictive power of mathematical models

Model	R^2	Adjusted R^2	RMSE*
1	0.8234	0.7645	3.789
2	0.8527	0.6073	4.893
3	0.9813	0.9502	2.025
4	0.9953	0.9906	0.7583
5	0.9939	0.9836	1.161

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CONCLUSIONS

In conclusion, analyzing the values of the adjusted coefficient of determination (adjusted R^2), it is observed that the predictive power of model no. 3-5 is good. In addition, we observed that the values of the coefficient of determination (R^2) are close to 1 for mathematical model no. 3-5, but the best prediction is provided by model no. 3-5. In contrast, analyzing the square root values of the root mean square error (RMSE), it is observed that the small values, which do not lead to multiple residuals, are found for model no. 4.

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