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To cite this article: O V Panova *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1164** 012057

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Evaluation of electromagnetic radiation shielding characteristics of facing building materials

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Abstract. The article presents the results of theoretical studies of the protective properties of composite facing materials based on a dielectric matrix with an electrically conductive non-magnetic filler in a wide frequency range of incident electromagnetic radiation. Expressions are got for the values of the transmission, reflection and absorption, and the electromagnetic radiation shielding efficiency calculated on their basis. The dependences of the permittivity and electrical conductivity of the composite on the volume fraction of the electrically conductive additive required for calculations were got based on the hypothesis of similarity, considering the nonzero conductivity of the dielectric matrix. Satisfactory agreement between the calculation results and the measured shielding characteristics of specimens of metal silicate materials based on calcium hydro silicates and copper powder was established. The results presented show the adequacy of the proposed calculation method and indicate that it can be used for preliminary estimates of the shielding characteristics when designing electromagnetic radiation shields based on composite facing materials.

1. Introduction

In modern conditions, with a significant increase in the electromagnetic man-made load on human health, protection from electromagnetic radiation (EMR) is becoming an increasingly important task. It is necessary to consider a relatively new factor in the deterioration of the electromagnetic environment – an increase in the levels of EMR of ultrahigh frequencies, the sources of which are wireless communications and other radio-technical devices. The World Health Organization has extended the ALARA principle (As low as reasonably achievable) to electromagnetic influences. This minimization of technogenic impact is not always possible. In any case, it should be determined by the maximum permissible levels of intensity of electromagnetic radiation, which are contained in the main regulatory acts [1,2].

Besides the effect on human health, EMR penetrating the premises can both disable and affect the quality of operation of electronic equipment. With the development of information technologies using microwave radiation, serious problems have arisen associated with electromagnetic interference.

The most effective way to protect against the harmful effects of EMR is shielding. From this point of view, metal screens are the most effective. Their disadvantage is that, because of the high electrical conductivity of metals, they strongly reflect EMR, which is not always acceptable. EMR absorbent shields are usually designed based on heterogeneous materials, the properties of which can be varied over a wide range by varying the composition and manufacturing technology.

Common composite materials intended for EMR shielding are materials based on dielectrics with metal additives because of their high electrical conductivity and good mechanical properties [3-6]. At the same time, their use is limited by their high weight. This disadvantage is partially eliminated by using carbon black, graphite, charcoal as a conductive component [7-9].

EMR shields with magnetic metal additives, which have high absorption coefficients in the microwave range, are also used [3]. Of particular interest are metal-polymer materials containing finely dispersed iron ore concentrate [10-13].



Recently, EMR shields based on polymeric materials with carbon nanofillers such as graphene, carbon nanotubes, and graphite nanoplates have become the object of many studies [3,14-17]. These materials are distinguished by high electrical and thermal conductivity, lightness, and high corrosion resistance.

Almost all building materials have the property of EMR shielding. At the same time, the effectiveness of such shielding is insufficient. To normalize the indicators following the recognized international standards for electromagnetic safety, specially designed building materials should be used as protective screens in building constructions. In particular, we have previously shown the fundamental possibility of using facing materials based on metal silicate composites as effective EMR shields [5,6].

When designing EMR shields with specified characteristics, a preliminary assessment of the protective properties of the material is required. Such calculations are usually carried out based on previously measured values of electrical conductivity and dielectric permittivity of the material at various concentrations of the conductive additive. [3,14,15].

This work aims to theoretically study the protective properties of composite facing materials based on a dielectric matrix with an electrically conductive non-magnetic filler in a wide range of radiation frequencies, including the development of a mathematical model that would allow not only to correctly evaluate the values of the shielding characteristics but also to assign the optimal composition of the material providing such characteristics.

2. Results and discussion

The primary task in the study of the shielding properties of composite materials is to get theoretical dependencies that give an adequate description of the processes of EMR scattering in the composite's body.

The problem of finding the reflection R and the transmission T of a plane electromagnetic wave incident on a plane-parallel layer of matter, which is between a vacuum and an arbitrary medium, has a rigorous solution [18]. In this case, however, the resulting expressions cannot be used for practical calculations because of their complexity. Using the corresponding formulas becomes possible under certain conditions when they are significantly simplified. So, if the complex permittivity $\hat{\varepsilon}$ of the layer of the composite material containing nonmagnetic electrically conductive additives is very high, and the third medium is a vacuum, then at normal incidence of the wave on the layer under the condition $1/|\hat{\varepsilon}| \ll (\omega d)/c \ll 1/|\hat{\varepsilon}|^{1/2}$ where ω is the radiation frequency; d is the layer thickness; c is the speed of light in vacuum, expressions for R и T take the form:

$$R = 1 - \frac{4c\varepsilon''}{\omega d |\hat{\varepsilon}|^2}, \quad T = \frac{4c^2}{\omega^2 d^2 |\hat{\varepsilon}|^2}. \quad (1)$$

If $(\omega d)/c \ll 1/|\hat{\varepsilon}|$, then:

$$R = \frac{\omega^2 d^2}{4c^2} |\hat{\varepsilon}|^2, \quad T = 1 - \frac{\omega d \varepsilon''}{c}. \quad (2)$$

In these expressions ε'' is the imaginary part of the complex permittivity

$$\hat{\varepsilon} = \varepsilon_d + i \frac{\sigma}{\omega \varepsilon_0}, \quad (3)$$

where σ is the electrical conductivity of material; ε_d is the permittivity of a dielectric matrix; ε_0 is the vacuum permittivity (we use the SI system of units).

It should be noted that these conditions are met in a limited number of cases. So, for the example of an EMR shield considered below based on a metal silicate material 0.5 mm thick, relations (1) can be used for $\nu < 10^7$ Hz. If, as in our case, $\nu \sim 10^{10}$ Hz, (1) are applicable for EMR shields with a thickness $d < 10 \mu\text{m}$. Such thin EMR shields are currently based on polymer compositions containing carbon

nanotubes [19]. In most cases, the thickness of the shielding material is 1 - 5 mm, and if the incident radiation belongs to the microwave range, the above expressions are not valid.

It is shown below that to estimate the transmission and reflection at normal incidence of EMR on the material, approximate relations can be applied, which are got using the expression for the amplitude of a wave propagating in a medium with absorption, which gives the solution of Maxwell's equations for this case: $E_0 \exp(-\alpha d)$, where $\alpha = (2\omega\kappa)/c$ is the absorption coefficient, κ is the imaginary part of $\sqrt{\hat{\epsilon}} = n + i\kappa$.

Then, considering multiple reflections from the inner surfaces of the layer under the assumption that the first and third medium is a vacuum (air), we get:

$$R = R_{12} \left(1 + (1 - R_{12})^2 \exp(-2\alpha d) M \right), \quad T = (1 - R_{12})^2 \exp(-\alpha d) M. \quad (4)$$

In expressions (4) R_{12} is the reflectivity from a semi-infinite medium with a permittivity equal to the permittivity of a material:

$$R_{12} = \frac{(n - 1)^2 + \kappa^2}{(n + 1)^2 + \kappa^2}, \quad (5)$$

n и κ are determined by the relations:

$$n = \left(\frac{\epsilon' + (\epsilon'^2 + \epsilon''^2)^{1/2}}{2} \right)^{1/2}, \quad \kappa = \left(\frac{-\epsilon' + (\epsilon'^2 + \epsilon''^2)^{1/2}}{2} \right)^{1/2}, \quad (6)$$

where ϵ' is the real part of the complex permittivity.

Factor

$$M = \left(1 - R_{12}^2 \exp(-2\alpha d) \right)^{-1} \quad (7)$$

determines the contribution of multiple reflections. It should be noted that taking M into account significantly affects the values of R and T under the condition: $d < 3\delta$, where $\delta = 1/\alpha$ is the layer thickness at which the wave intensity decreases by a factor of e . This condition is satisfied at small κ , which determines the absorption of radiation by the material, at low frequencies of the incident radiation, or for very thin EMR shields. Otherwise, multiple reflections can be ignored.

Having determined the values of reflection and transmission, it is possible to estimate the EMR absorption from the condition: $A = (1 - R - T)$.

Thus, knowing the values of the real and imaginary parts of the dielectric permittivity of samples with different contents of the electrically conductive component, it is possible to calculate the dependences of R , T , and A on the volume content of the conducting additive and the frequency of the incident electromagnetic wave.

Expressions for the dependences of the electrical conductivity and permittivity of the composite on the volume fraction of the conducting component θ were got by us earlier [5,20] for a quasi-stationary electromagnetic field based on the similarity hypothesis [21,22] (analogy with the theory of phase transitions) considering the nonzero conductivity of the dielectric matrix.

At the contents of the conducting component corresponding to the subthreshold region $\tau = (\theta - \theta_c) < 0$ (θ_c is the percolation threshold), the dependencies $\epsilon''(\omega, \theta)$ and $\epsilon''(\omega, \theta)$ have the form:

$$\epsilon''(\omega, \theta) = \frac{\sigma_m}{\omega\epsilon_0} \left(B_0 h(-\tau)^{-q} + B_1 \left(h^2 - \left(\frac{\omega\epsilon_0\epsilon_d}{\sigma_m} \right)^2 (-\tau)^{-p} \right) \right), \quad (8)$$

$$\varepsilon'(\omega, \theta) = B_0 \varepsilon_d (-\tau)^{-q}, \tag{9}$$

where $h = \sigma_d / \sigma_m$ and σ_d, σ_m are the electrical conductivity of a dielectric matrix and a conductive additive; q и p are the critical indices of the percolation theory [21,23,24]; B_0, B_1 are the constants.

When the content of the conductive component is above the threshold ($\tau > 0$):

$$\varepsilon''(\omega, \theta) = A_0 \frac{\sigma_m}{\omega \varepsilon_0} \tau^t, \tag{10}$$

$$\varepsilon'(\omega, \theta) = A_1 \varepsilon_d \tau^{-q}, \tag{11}$$

where t is the critical index; A_0, A_1 are the constants.

Expressions (8) - (11) are valid for $|\tau| \gg \Delta$. Here

$$\Delta = \left(h^2 + \left(\frac{\omega \varepsilon_0 \varepsilon}{\sigma_m} \right)^2 \right)^{\frac{s}{2t}}, \tag{12}$$

is the interval near the percolation threshold, where there is a transition from dependences (8), (9) to dependences (10), (11); s is another critical index. Besides, (10) is performed for such values of θ , for which $\sigma(\theta) \ll \sigma_m$, and (9), (11) – for $\varepsilon(\theta) \ll \varepsilon(\theta_c)$. Note that for θ that are far enough from θ_c relation (11) does not describe the behavior of $\varepsilon'(\theta)$. With such contents of a conducting additive, free electrons lead to the appearance of an imaginary part of ε_m and $\varepsilon(\theta)$ can become negative.

In the range of concentrations of the conducting component near θ_c , equal to Δ , the values of ε'' for samples of finite dimensions are not determined, and ε' tend to the finite limit, the value of which can be estimated from:

$$\varepsilon'(\omega, \theta_c) = a_0 \varepsilon_d \left(\frac{\sigma_m}{\omega \varepsilon_0 \varepsilon_d} \right)^{1-s}, \tag{13}$$

where a_0 is the constant.

From (9), (11), and (13) it follows that when approaching from both sides to the percolation threshold, a sharp increase in the real part of the permittivity should be observed. Qualitatively, this can be interpreted based on the following considerations. Each pair of the nearest conducting clusters, which are separated near the percolation threshold by a thin dielectric layer, can be considered as a capacitor. Then, when approaching the percolation threshold, the effective surface of such a capacitor increases sharply, because of which the effective capacity of the system should sharply increase.

In practical calculations, the percolation threshold θ_c is first determined based on the measured dependence $\sigma(\theta)$ at any value of ω , including direct current (θ_c does not depend on ω). Then it is taken into account, that with a uniform distribution of the particles of the conducting component over their sizes and volume of the material, the process of electric transfer in such systems is satisfactorily described within the framework of the site percolation model. In this case, the values of 1.6 and 1.0 are used for the values of t and q , respectively [21,23]. The critical indices p and s are associated with the t and q by expressions:

$$q = \frac{t(1-s)}{s} \text{ and } p = t \left(\frac{2}{s} - 1 \right), \tag{14}$$

which follow from the Kramers – Kronig relations. Constants B_0, B_1, A_0, A_1 are estimated from the conditions: $\sigma(\theta) = \sigma_d, \varepsilon(\theta) = \varepsilon_d$ at $\theta = 0, \sigma(\theta) = \sigma_m$ at $\theta = 1, A_1 = B_0$.

Having calculated the values of R , T , and A according to the proposed method, we can estimate the total $SE_t = 10\log(1/T)$, the reflection $SE_R = 10\log(1/(1-R))$, and absorption $SE_A = SE_t - SE_R$ EMR shielding efficiency of the material:

$$SE_t = 20\log\left(\frac{(n+1)^2 + \kappa^2}{4n}\right) + 10\alpha d \log e - 10\log M, \quad (15)$$

$$SE_R = 10\log\left(\frac{(n+1)^2 + \kappa^2}{4n}\right) - 10\log\left(1 - \frac{4n((n-1)^2 + \kappa^2)\exp(-2\alpha d)M}{((n+1)^2 + \kappa^2)^2}\right). \quad (16)$$

To illustrate the application of the described calculation method, the previously got results of experimental studies of the electrophysical properties of metal silicate materials were used [5,20].

Metal silicate materials comprising amorphous silicate substances and metal powders [25] have several technological and functional advantages over other building materials designed to protect against EMR. The most important is the ability to control such properties of these materials as electrical conductivity, thermal conductivity, elastic modulus, etc. because of the targeted effect on the microstructure of the composite. High physical-mechanical and construction-technical characteristics make it possible to use metal silicate materials for manufacturing facing (including external) products. By changing the type of silicate component, the durability of the products can also be changed.

The feature of the electrophysical properties of metal silicate materials is that when the volume fraction of the metal component approaches a certain value (percolation threshold), the conductivity of the system increases abruptly (by 6 - 7 orders of magnitude), and the permittivity increases to values of $\sim 10^3$ [5,20]. The presence of such electrophysical characteristics suggests that with optimization of the composition, materials based on metal powders and amorphized silicates can exhibit pronounced shielding properties.

The experimental technique – preparation of specimens, measurement of their permittivity and conductivity, EMR transmission, and reflection is described in [6,26]. Amorphized dispersed calcium hydrosilicates were used as a dielectric matrix in the preparation of specimens. Copper powder with a particle size of no more than 60 μm was used as an electrically conductive additive. Special measures were taken to ensure a uniform distribution of granular copper throughout the volume of the material. The dimensions of the specimens - tiles were 125×66×5 mm. Transmission and reflection measurements were carried out at EMR frequencies in the range of 19 - 26 GHz.

It should be noted that the quasi-stationarity condition ($v \ll c/d$) for the specimens under study in the showed frequency range is not strictly fulfilled. These frequencies are the limit, at which it is still possible to estimate the quantities σ and ε from relations (8) - (11).

Figure 1 shows the dependences of transmission, reflection, and absorption, and Figure 2 shows the shielding efficiency of metal silicate material specimens, calculated by the method described above at the contents of the metal additive corresponding to the subthreshold region ($\theta < \theta_c$, $\theta_c = 0.162$ according to the measurement results), and the frequency of the incident radiation equal to 20 GHz.

As can be seen from Figure 1, where the measured values of T , R , and A are also given for comparison, there is a satisfactory agreement between the theoretical and experimental values, which shows the adequacy of the proposed calculation method. It should be noted that the measurement error of these quantities near the percolation threshold increases because of the spread of the experimental values caused by the significant influence of fluctuations of the local parameters of the composite on the conductivity and dielectric permittivity.

Analysis of the data in Figure 1 shows that the EMR absorption by the material in this range of metal contents becomes noticeable only near the percolation threshold at $\theta > 0.15$. This is because the electrical losses that cause absorption are determined by the imaginary part of the permittivity ε'' . In this case, the first term of (8) is responsible for the Joule losses associated with the conduction, the second describes the dissipation of radiation energy in the material because of the polarization of

isolated conducting clusters and prevails at the radiation frequency for which the calculations and measurements were performed.

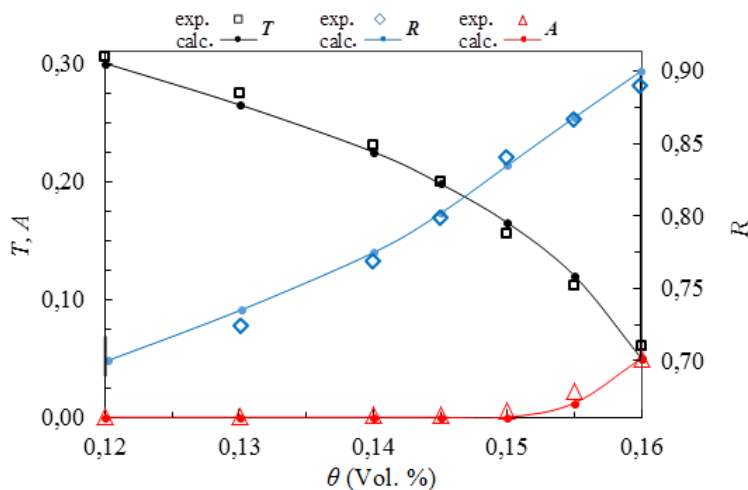


Figure 1. Dependences of the transmission T , reflection R , and absorption A on the content of the metal additive θ in the metal silicate material at $\theta < \theta_c$.

Low absorption in the subthreshold region of metal contents also leads to an increase in radiation intensity losses because of multiple reflections from the inner surfaces of the sample, which causes a significant increase in the values of R at $\theta < \theta_c$.

It should be concluded that the shielding efficiency in the subthreshold metal content range (Figure 2) is low and does not correspond to commercially acceptable values of $SE_t > 20$ dB.

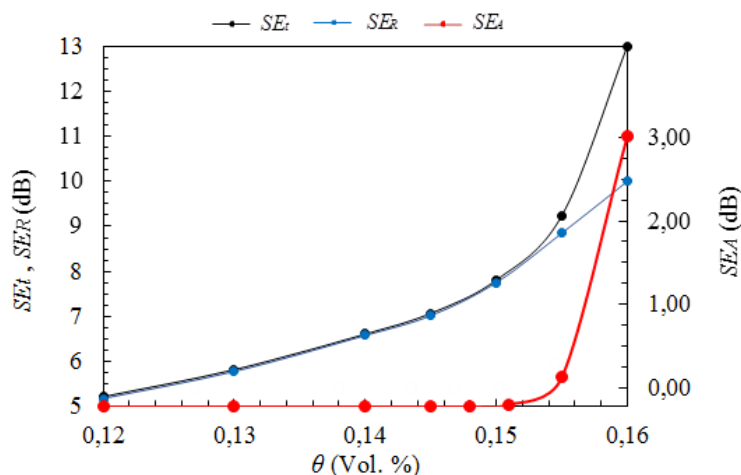


Figure 2. Dependences of the total SE_t , reflection SE_r and the absorption SE_a shielding efficiency on the content of the metal additive θ in the metal silicate material at $\theta < \theta_c$.

At $\theta > \theta_c$ (Figure 3, Figure 4), the electrical losses are determined by the conductivity, which increases with increasing θ . In this case, despite a sharp decrease of ϵ' with departure from the percolation threshold, the reflection value R decreases slowly because of the simultaneous increase in the electrical conductivity of the composite (Figure 3). At the same time, because of an increase in absorption, the transmission value T also decreases. As a result, the contribution of absorption to the total shielding efficiency SE_t becomes dominant (Figure 4). At $\theta > \theta_c$ practically in the entire investigated range of the metal additive content, $SE_t > 20$ dB and reaches 50 dB at $\theta = 0.2$.

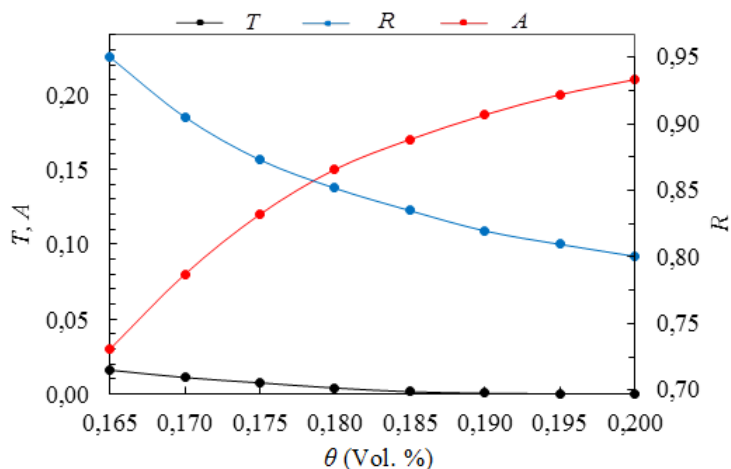


Figure 3. Dependences of the transmission T , reflection R , and absorption A on the content of the metal additive θ in the metal silicate material at $\theta > \theta_c$.

As follows from (8), with increasing frequency of the incident radiation, ϵ'' should decrease. Besides, at large θ and high frequencies, when the process of electro transfer in the material occurs according to the metallic type, ϵ'' can also decrease because of the skin effect, which leads to a decrease in electrical conductivity. As a result, as the frequency increases, the shielding efficiency should decrease.

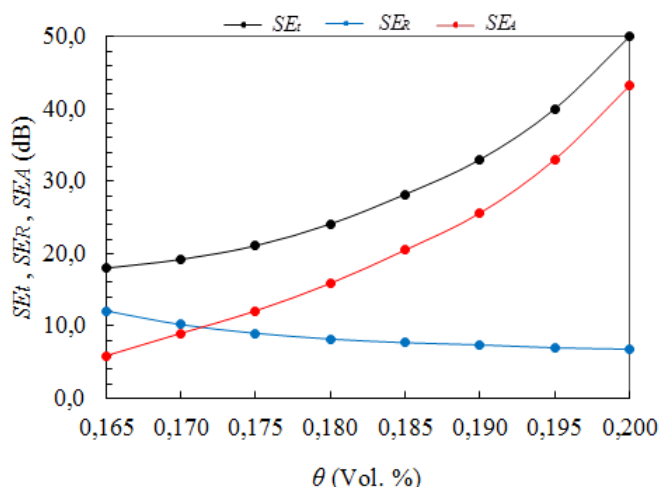


Figure 4. Dependences of the total SE_t , reflection SE_r and the absorption SE_A shielding efficiency on the content of the metal additive θ in the metal silicate material at $\theta > \theta_c$.

Comparing Figures 1, 2 with Figures 3, 4, we can conclude that there is no smooth transition of the corresponding dependences at $\theta < \theta_c$ to the dependences at $\theta > \theta_c$. This can be explained if we consider that the singularity of $\sigma(\theta)$ and $\epsilon(\theta)$ following from (8) - (11) near the percolation threshold extends to the interval θ equal to Δ , which is determined by (12). And, since in this interval the values of ϵ'' are not determined, the calculation of the values of R , T , and A in it becomes incorrect. As for the experimental values, the accuracy of their determination near the percolation threshold is significantly influenced by the fluctuation of the local parameters of the composite.

In conclusion, we note that when carrying out calculations according to the proposed method, it is necessary to consider that the assumptions about the normal fall of EMR on the material and the contact of both sides of the material with air, used in obtaining the working formulas, do not

correspond to the real conditions in which the shielding facing material is used. The back surface of the shield is in contact with a wall material, the impedance of which is closer to the impedance of the EMR shield and, therefore, the real contribution to the shielding efficiency by the reflection will be lower than the calculated one.

3. Conclusions

Theoretical studies of the protective properties of composite facing materials based on a dielectric matrix with an electrically conductive non-magnetic filler in a wide frequency range of incident electromagnetic radiation have been carried out. A calculation technique is proposed that allows one to estimate the values of reflection, transmission, absorption, and the EMR shielding efficiency of the material. Satisfactory agreement of the calculation results with the measured shielding characteristics of specimens of metal silicate materials based on calcium hydrosilicates and copper powder has been established. The results presented show the adequacy of the proposed calculation method and indicate that it can be used for preliminary estimates of the shielding characteristics in the design of EMR shields based on composite facing materials.

References

- [1] Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz) 2020 *Health Phys.* **118** (5) 483-524
- [2] Directive 2013/35/EU of the European Parliament and of the Council of 26 June 2013 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) 2013 *Official Journal of the European Union* **56** L179
- [3] Kruzela J, Kvasnicakova A, Hlozekova K and Hudec I 2021 Progress in polymers and polymer composites used as efficient materials for EMI shielding *Nanoscale Adv.* **3** pp 123-172
- [4] Chung D D L 2000 Materials for electromagnetic interference shielding *J. Mater. Eng. Perform.* **9** pp 350-354
- [5] Krasnianskyi G, Maksunov S and Velichko T 1989 *Electrophysical properties of contact hardening metallosilicate materials Proc. 3-rd All-Union Scientific and Practical Conf. Slag-alkali cements, concretes and constructions (Kiev)* **1** (Kiev: KISI) pp 209-10
- [6] Klapchenko V, Krasnyansky G, Glyva V and Aznaurian I 2010 Protective properties of electromagnetic screens based on metal silicate materials in the microwave range *Hygiene of populated places* **56** pp 219-226
- [7] Chuhg Deborah D L 2016 *Carbon Composites: Composites with Carbon Fibers, Nanofibers, and Nanotubes* (New York: Butterworth-Heinemann) p 706
- [8] Boiprav O V, Ayad H and Lynkou L M 2019 Electromagnetic Radiation Shielding Properties of Copper Containing Activated Carbon *Doklady BGUIR* **1** pp 51-55
- [9] Ayad H A, Belousova E S and Pulko T A 2016 Influence of Composite Coatings Based on Powdered Charcoal on Electromagnetic Radiation Shielding *Doklady BGUIR* **3** pp 88-94
- [10] Glyva V A et al 2020 The composite facing material for electromagnetic fields shielding *IOP Conf. Ser.: Mater. Sci. Eng.* **907** 012043
- [11] Glyva V, Barabash O, Kasatkina N, Katsman M, Levchenko L, Tykhenko O, Nikolaiev K, Panova O, Khalmuradov B and Khodakovskyy O 2020 Studying the shielding of an electromagnetic field by a textile material containing ferromagnetic nanostructures *Eastern-European Journal of Enterprise Technologies* **1** **10** (103) pp 26-31
- [12] Glyva V, Kasatkina N, Nazarenko V, Burdeina N, Karaieva N, Levchenko L, Panova O, Tykhenko O, Khalmuradov B and Khodakovskyy O 2020 Development and study of protective properties of the composite materials for shielding the electromagnetic fields of a wide frequency range *Eastern-European Journal of Enterprise Technologies* **2** **12** (104) pp 40-47
- [13] Glyva V, Lyashok J, Matvieieva I, Frolov V, Levchenko L, Tykhenko O, Panova O, Khodakovskyy O, Khalmuradov B and Nikolaiev K 2018 Development and investigation of

- protective properties of the electromagnetic and soundproofing screen *Eastern-European Journal of Enterprise Technologies* **6 5 (96)** pp 54-61
- [14] Vovchenko L et al 2020 Polyethylene Composites with Segregated Carbon Nanotubes Network: Low Frequency Plasmons and High Electromagnetic Interference Shielding Efficiency *Materials* **13** 1118
- [15] González M, Pozuelo J and Baselga J 2018 Electromagnetic Shielding Materials in GHz Range. *Chem Rec.* **18** pp 1-11
- [16] Abbas N and Kim H T 2016 Multi-walled carbon nanotube/polyethersulfone nanocomposites for enhanced electrical conductivity, dielectric properties and efficient electromagnetic interference shielding at low thickness *Macromol. Res.* **24** pp 1084-1090
- [17] Song W L et al 2014 Flexible graphene/polymer composite films in sandwich structures for effective electromagnetic interference shielding *Carbon* **66** pp 67-76
- [18] Landau L D and Lifshitz E M 1984 *Electrodynamics of Continuous Media* (Oxford: Pergamon Press) 460
- [19] Zi Ping Wu et al 2015 Electromagnetic interference shielding effectiveness of composite carbon nanotube macro-film at a high frequency range of 40 GHz to 60 GHz *AIP Advances* **5** 067130
- [20] Klapchenko V, Krasnyansky G and Aznaurian I 2002 *Electrophysical Investigations of Building materials* (Kiev: VIPOL) 84
- [21] Efros A L and Shklovskii B I 1976 Critical behaviors of conductivity and dielectric constant near the metal-nonmetal transition *Phys. Status solidi B* **76 2** pp 475-485
- [22] Balagurov B Ya 1985 On the theory of dispersion of the conductivity of two-component media *JETP* **88** No 5 1664-75
- [23] Kirkpatrick S 1973 Percolation and Conduction *Rev. Mod. Phys* **45 (4)** pp 574-587
- [24] Stauffer D and Aharony A 1992 *Introduction to Percolation Theory* (London: Taylor & Francis) 192
- [25] Glukhovskiy V D, Runova R F and Maksunov S E 1991 *Contact hardening binders and composite materials* (Kiev: Vyscha Shkola) 242
- [26] Krasnianskyi G, Aznaurian I and Kucherova G 2013 Methods of electrophysical research of concrete in the early stages of hardening *Mistobuduvannya ta terytorialne planuvannya* **50** pp 310-315