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METHODOLOGY FOR DESIGNING FACING BUILDING MATERIALS WITH ELECTROMAGNETIC RADIATION SHIELDING FUNCTIONS

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Abstract

A calculation method for designing facing building materials with the functions of shielding electromagnetic waves has been developed. The method makes it possible to design materials with the required shielding efficiencies and adjustable coefficients of absorption and reflection of electromagnetic waves. The dependence of the shielding efficiency on the mode of pressing the material has been studied. Verification of the calculation apparatus showed satisfactory convergence of theoretical and experimental data.

***Keywords**: Shielding; Electromagnetic waves; Facing material; Calcium hydrosilicate.*

Introduction

The territories of modern cities are characterized by a complex electromagnetic environment. This is due to the dense placement of radio engineering facilities - base stations for mobile communications, the branching and high power of the power supply network, etc. The problems of the electromagnetic environment are of particular relevance due to the process of gradual transition to 5G wireless communication. This standard operates with ultra-high frequencies of electromagnetic fields. Therefore, a forced measure is to increase the power of the emitters due to the rapid attenuation of high-frequency waves with distance. Under such conditions, the task of reducing the levels of electromagnetic fields in buildings and structures is of special significance. The most effective means of solving this problem is the shielding of electromagnetic fields with protective materials. Most of the existing materials are intended for additional application to the surfaces of building structures. This complicates their application both from a technological and aesthetic point of view. Therefore, it is advisable to create facing materials with the functions of shielding electromagnetic fields.

To date, many modern materials have been developed to shield electromagnetic fields and radiation. Most of them are metal polymers. In [1], the results of a study of the effectiveness of screens based on polymers with natural metal-containing materials as a screening filler are given. Their disadvantage is low efficiency (small shielding factors even in the high-frequency region of the electromagnetic spectrum). Ferrite-based materials are more efficient [2]. However, the ferrite

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fillers used need to be processed separately, which increases the cost of the final product. The study [3] presents the results of testing the effectiveness of a broadband screen with metal additives with high corrosion resistance. However, in all the materials considered above, the matrix is polyvinyl chloride, which degrades under the influence of physical factors (temperature, light, etc.). That is, the terms of their guaranteed operation are limited. In addition, their installation on the surfaces of buildings (external and internal) is complicated due to their significant thickness and rigidity. More promising in terms of application are protective compositions based on liquid polymers or paints. In [4], a thin material containing finely dispersed magnetite is proposed. But with a small thickness, its efficiency is insufficient, therefore, high conductivity carbon is added to the matrix. This significantly increases the cost of the material, and the use of several components makes the material metastable concerning mechanical and chemical properties [5]. The same drawbacks are inherent in water-based materials [6]. As shown in [7], the tendency to degradation is inherent in all multicomponent mixtures that are polymerized or dried during application. This phenomenon can be avoided if protective properties are given to the facing material used in the construction and reconstruction of buildings. Fundamentally, this possibility was shown in [8]. However, the development of such composites, which are based on well-developed building materials containing a conductive substance, requires large amounts of experimental research. This is due to the need to obtain materials that correspond to a specific electromagnetic environment and are costly and time-consuming. Therefore, an urgent task is to develop a calculation methodology for designing facing building materials with the functions of shielding electromagnetic radiation.

Materials and methods

The metal silicate facing materials produced by pressing are investigated. The main components are amorphous dispersed calcium hydrosilicate and granulated copper (particle sizes up to 60 microns). The dependences of the total shielding efficiency, the shielding efficiency due to the reflection and absorption of electromagnetic waves on the content of the metal filler, the frequency of electromagnetic radiation, and the pressing pressure were determined.

The basis of research is calculation methods based on the fundamental relations of the electrodynamics of continuous media. Verification of the results of theoretical studies was carried out using standard calibrated measuring equipment in laboratory conditions.

Results and Discussions

The total shielding efficiency of electromagnetic radiation by the material SE_T=10log(1/T), as well as the shielding efficiency due to reflection SE_R = 10log(1/(1–R)) and absorption $SE_A = SE_T - SE_R$, can be calculated if the reflection R, transmission T and absorption A coefficients of an electromagnetic wave incident on a screen located between air and an arbitrary medium are known [9]. The solution of the Maxwell equations for the amplitude of a plane wave in the plane with the coordinate z of a medium with absorption has the form: $\mathrm{E}_0 \exp(-\alpha z)$, where E_0 is the electric field strength at $z = 0$; $\alpha = (\omega\kappa)/c$ is the amplitude absorption coefficient of an electromagnetic wave; ω is the cyclic frequency of radiation; c is the speed of light in vacuum; κ is the imaginary part of:

$$\sqrt{\hat{\varepsilon}} = n + i\kappa; \tag{1}$$

$$\hat{\varepsilon} = \varepsilon' + i\varepsilon'' = \varepsilon + i\frac{\sigma}{\omega\varepsilon_0}, \quad (2)$$

is the complex permittivity of the screen material; ε is the permittivity, and σ is the electrical conductivity of the material; ε_0 is the vacuum permittivity. Then, considering multiple reflections assuming (to simplify calculations) that the first and third media are vacuum (air), we obtain:

$$R = R_{12}\left(1 + \left(1 - R_{12}\right)^2 \exp\left(-4\alpha d\right)\cdot\left(1 - R_{12}^2 \exp\left(-4\alpha d\right)\right)^{-1}\right), \quad (3)$$

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

$$A = \left(1 - R_{12}\right)\left(1 - \exp\left(-2\alpha d\right)\right)\cdot\left(1 - R_{12}\exp\left(-2\alpha d\right)\right)^{-1}. \quad (5)$$

In (3)-(5) d is the screen thickness, and R_{12} is the reflection coefficient at the vacuum-material interface. Assuming normal wave incidence from the air, R_{12} is determined by the relation:

$$R_{12} = \frac{\left(n-1\right)^2 + \kappa^2}{\left(n+1\right)^2 + \kappa^2}. \quad (6)$$

Multiple reflections make a significant contribution to the calculation results at low κ , ω and d. Otherwise, multiple reflections can be ignored. Then, if we assume that the wave reflected from the rear surface of the screen is completely absorbed by the substance, expressions (3) - (5) for the values R, T, and A are simplified and take the form:

$$R = R_{12}\left(1 + \left(1 - R_{12}\right)\exp\left(-2\alpha d\right)\right), \quad (7)$$

$$T = \left(1 - R_{12}\right)^2 \exp\left(-2\alpha d\right), \quad (8)$$

$$A = \left(1 - R_{12}\right)\left(1 - \exp\left(-2\alpha d\right)\right). \quad (9)$$

It should be noted that the assumption about the contact of both faces of the screen with air, used in obtaining the above formulas, does not correspond to the actual conditions in which the screening facing material is used. Usually, the rear surface of the screen is in contact with the wall material, for which, unlike air, $\varepsilon \neq 1$. In this case, the reflection coefficient at the boundary of the screen (medium 2) and wall material (medium 3) should be calculated according to the formula:

$$R_{23} = \left|\frac{\sqrt{\hat{\varepsilon}_2} - \sqrt{\hat{\varepsilon}_3}}{\sqrt{\hat{\varepsilon}_2} + \sqrt{\hat{\varepsilon}_3}}\right|^2, \quad (10)$$

where $\sqrt{\hat{\varepsilon}_2}$, $\sqrt{\hat{\varepsilon}_3}$ are determined by (1). If we assume that the wall material is a dielectric (σ_3=0), then from (10) we obtain:

$$R_{23} = \frac{\left(n_2 - n_3\right)^2 + \kappa_2{}^2}{\left(n_2 + n_3\right)^2 + \kappa_2{}^2}. \quad (11)$$

From (11) it follows that the reflection from the back surface is less than the calculation by (6) gives. If, in addition, the screen parameters and the radiation frequency are such that the condition $d<3/\alpha$ is not satisfied, then the reflection from the rear surface can be neglected altogether. Then for the reflection and transmission coefficients from (7) and (8) we find:

$$R = R_{12}, \quad (12)$$

$$T = \left(1 - R_{12}\right)\exp\left(-2\alpha d\right). \quad (13)$$

The absorption coefficient *A*, which in this case is still calculated according to (9), shows the fraction of the incident radiation power absorbed by the screening layer. A more informative characteristic of the absorption of electromagnetic radiation by a material is a value that allows you to determine the proportion of absorbed radiation that has passed through the front surface of the screen [9]:

$$A_{eff} = \frac{A}{1-R}. \tag{14}$$

Considering (9), (12):

$$A_{eff} = \left(1-\exp\left(-2\alpha d\right)\right). \tag{15}$$

And, finally, for screening efficiencies, considering (12), (13), and (6), we get:

$$SE_T = 10\log\left(\frac{\left(n+1\right)^2+\kappa^2}{4n}\right)+20\alpha d\log e, \tag{16}$$

$$SE_R = 10\log\left(\frac{\left(n+1\right)^2+\kappa^2}{4n}\right), \tag{17}$$

$$SE_A = SE_T - SE_R = 20\alpha d\log e, \tag{18}$$

where the values *n* and κ, as follows from (1), are determined by the relations:

$$n = \left(\frac{\varepsilon' + \left(\varepsilon'^2 + \varepsilon''^2\right)^{1/2}}{2}\right)^{1/2}, \tag{19}$$

$$\kappa = \left(\frac{-\varepsilon' + \left(\varepsilon'^2 + \varepsilon''^2\right)^{1/2}}{2}\right)^{1/2}. \tag{20}$$

Expressions for the dependences of the electrical conductivity and permittivity of the composite on the volume fraction of the conducting component were obtained earlier [10]. At the contents of the conductive component θ corresponding to the region $\tau = \left(\theta - \theta_c\right) < 0$, where θ_c is the percolation threshold - the critical volume fraction of the conductive additive at which the metal-dielectric phase transition occurs we have:

$$\varepsilon''\left(\omega,\theta\right) = \frac{\sigma_m}{\omega\varepsilon_0}\left(\left(B_0 h\left(-\tau\right)^{-q} + B_1\left(h^2 - \left(\frac{\omega\varepsilon_0\varepsilon_d}{\sigma_m}\right)^2\left(-\tau\right)^{-p}\right)\right)\right) \tag{21}$$

$$\varepsilon'\left(\omega,\theta\right) = B_0\varepsilon_d\left(-\tau\right)^{-q}, \tag{22}$$

where $h = \sigma_d / \sigma_m$; σ_d i ε_d are the electrical conductivity and permittivity of the matrix; σ_m is the electrical conductivity of the additive.

At $\tau > 0$

$$\varepsilon''\left(\omega,\theta\right) = A_0\frac{\sigma_m}{\omega\varepsilon_0}\tau^t, \tag{23}$$

$$\varepsilon'\left(\omega,\theta\right) = A_1\varepsilon_d\tau^{-q}. \tag{24}$$

(21) - (24) are applicable for $\left| \tau / \theta_c \right| >> \Delta$, where:

$$\Delta = \left(\left(\frac{\sigma_d}{\sigma_m} \right)^2 + \left(\frac{\omega \varepsilon_0 \varepsilon_d}{\sigma_m} \right)^2 \right)^{\frac{s}{t}}. \qquad (25)$$

In expressions (21) - (25) q, p, t and s are the critical indices of the percolation theory [11]; $B_0 > 0$, $B_1 < 0$, A_0, A_1 are the constants. In addition, (23) is satisfied for such values of θ for which $\sigma(\theta) << \sigma_m$, and (22), (24) - for $\varepsilon(\theta) << \varepsilon(\theta_c)$. Note that for $\theta >> \theta_c$ the dependence (24) is not valid. At such additive contents, the conductive clusters are combined to form a continuous conductive skeleton, which leads to a metallic type of electrical conductivity of the material and $\varepsilon'(\theta)$ can become negative.

In the range of the content of the conductive component Δ near θ_c, the values of ε'' for specimens of finite sizes are not determined, and ε' has a finite limit:

$$\varepsilon'(\omega, \theta_c) = \omega_d \left(\frac{\sigma_m}{\omega \varepsilon_0 \varepsilon_d} \right)^{1-s}. \qquad (26)$$

In practical calculations, θ_c is first determined based on the measured dependence $\sigma(\theta)$ at any value of ω (θ_c does not depend on ω). Then, considering that in the case of a uniform distribution of the particles of the conductive component over their sizes and volume of the material, for the critical indices t and q the values of 1.6 and 1.0 are used, respectively [11]. p and s are related to t and q by the following relations:

$$q = \frac{t(1-s)}{s}, \; p = t\left(\frac{2}{s} - 1 \right). \qquad (27)$$

The constants B_0, B_1, A_1 are estimated from the conditions: $\sigma(\theta) = \sigma_d$, $\varepsilon(\theta) = \varepsilon_d$ at $\theta = 0$, $A_1 = B_0$. A_0 is determined from the dependence graph $\sigma(\tau)$, plotted on a logarithmic scale.

The applicability of the proposed calculation method was confirmed by a satisfactory correspondence between experimental and calculated shielding characteristics of metal silicate materials based on amorphized dispersed calcium hydrosilicate and granular copper (particle sizes up to 60μm), uniformly distributed in the volume of the material, with the contents of the conductive component $\theta < \theta_c$ [8]. It was found that at such values of θ the multiple reflections play a significant role, which leads to an increase in the values of R. In this case, there is a low reproducibility of the specimens in terms of screening characteristics at θ close to θ_c, which is due to significant fluctuations of the local parameters of the composite in a given range of metal concentrations. All this makes it difficult to use such materials as effective electromagnetic radiation shields at conductive additive contents below the threshold.

Fig. 1 shows experimental and calculated by the method described above dependences of transmission, reflection, and absorption, and Fig. 2 shows the shielding efficiencies of metal silicate material specimens in the practical point of view the most important range of concentrations $\theta > \theta_c$ (θ_c=0.162 according to the results of measurements) and an incident radiation frequency of 20GHz.

The experimental technique - preparation of specimens – tiles (125×66×5mm), measurement of their permittivity and electrical conductivity, transmission, reflection and absorption coefficients are described in [12].

As can be seen from Figure 1, there is a satisfactory agreement between the calculated and measured dependences, which indicates the applicability of the proposed calculation method.

When $\theta > \theta_c$, the electrical losses increase as θ increases. In this case, despite a sharp decrease in ε' as we move away from the percolation threshold, the reflection R slowly decreases due to a simultaneous increase in the electrical conductivity of the composite. At the same time, due to the increase in absorption, the transmission value T also decreases. As a result, as can be seen from Figure 2, the absorption contribution to the total shielding efficiency becomes preferable at $\theta > 0.18$. At such contents of the conductive component, the value of A_{eff} approaches unity (Fig. 3), i.e., almost all radiation passing through the front surface of the screen is absorbed by the material. Figure 3 also shows for comparison the dependence of the amplitude absorption coefficient α on the content of the conductive additive, which correlates with the dependence $A_{eff}(\theta)$. In this concentration range, the shielding efficiency corresponds to commercially acceptable SE_T values greater than 20dB and reaches 42dB at $\theta = 0.2$.

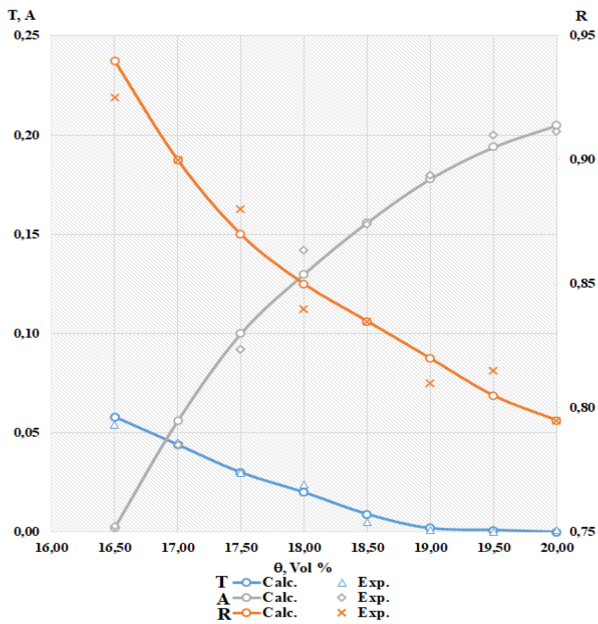

Fig. 1. Transmission T, absorption A and reflection R coefficients of metal silicate material

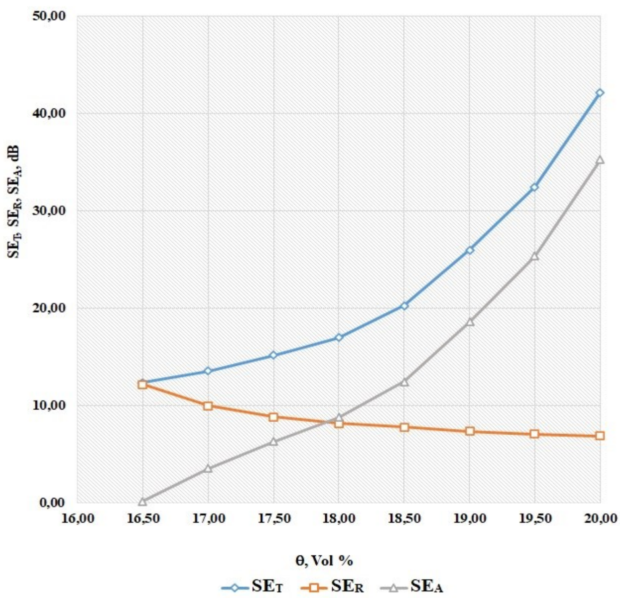

Fig. 2. Shielding efficiencies SE_T, SE_R, and SE_A of metal silicate material

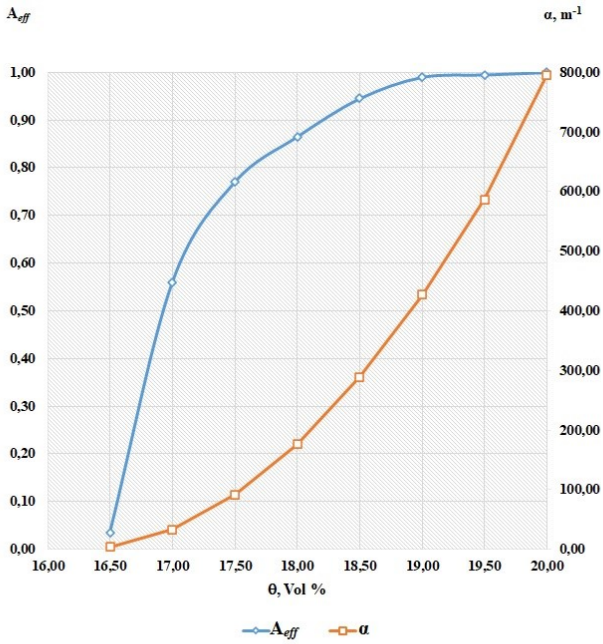

Fig. 3. Absorption A_{eff} and the amplitude absorption coefficients α of metal silicate material

As follows from (23), as ω increases, ε'' should decrease. In addition, at high θ and high frequencies, ε'' can also decrease due to the skin effect. As a result, as the frequency increases, the shielding efficiency should decrease.

Facing tiles made of metal silicate materials are produced by pressing. For this technology, it is important to determine the optimal initial concentration of the electrically conductive component, at which the selected pressing pressure ensures the achievement of the required shielding efficiencies.

If we assume that when external pressure is applied, the specimen volume V changes due to the compression of the insulating medium (in our case, calcium hydrosilicate and pore space), while the volume occupied by electrically conductive additives V_m remains unchanged (which is indeed true in most cases), and enter the appropriate compressibility factor $\beta = -\frac{1}{V}\frac{dV}{dp}$, then for the dependence $\theta(p) = {V_м}/{V(p)}$ you can get:

$$\theta(p) = \theta_o exp\left(i(p)\right); \tag{28}$$

$$i(p) = \int_{p_o}^{p} \beta(p)dp, \tag{29}$$

where θ_o is the initial volume fraction of the electrically conductive component; p_o is the initial pressure.

Substituting (28), and (29) into (23) leads to the following expression for $\varepsilon''(p)$:

$$\varepsilon''(p) = A(\theta_o \exp(i(p)) - \theta_c)^t, \tag{30}$$

where $A = {A_0\sigma_m}/{\omega\varepsilon_0}$.

Note that shielding efficiencies (16) – (18) are determined by the values of n and κ, for the estimation of which, as follows from (19), (20), the values ε'' and ε' are needed. At the same time, within the framework of the model used, ε'' and ε' are interconnected by relations (23), (24). Therefore, there is no need to define $\varepsilon'(p)$.

To find the analytical representation of $\varepsilon''(p)$, it is necessary to know the explicit form of the $\beta(p)$ dependence. However, as measurements show, we can assume that in the working pressure range the value of β does not depend on p. Then relation (30), relating the volume fraction of the conductive component in the initial mixture θ_o and the pressing pressure p, required to get a material with a given value of ε'', is simplified, and for θ_o we obtain:

$$\theta_o = \left(\theta_c + \left(\frac{\varepsilon''}{A}\right)^{1/t}\right)\exp\left(-\beta\left(p - p_0\right)\right). \tag{31}$$

In the practical use of the obtained relations, first, based on (16), (19), (20), taking into account (23), (24), the value of ε'', corresponding to the given value of the shielding efficiency, is calculated. Then, the dependence of the change in the volume of the material on the pressing pressure is measured, and the value of the compressibility coefficient is estimated using the formula $\beta = \frac{1}{V}\left|\frac{\Delta V}{\Delta p}\right|$. And, finally, using (31), the optimal initial volume fraction of the electrically conductive component, at which the selected pressing pressure provides the necessary shielding efficiency, is determined.

Conclusions

Theoretical dependences of the values of transmission, reflection, absorption, and shielding efficiency of electromagnetic radiation of the material on the content of the electrically conductive filler and radiation frequency are obtained. Satisfactory agreement between the results of calculations and the measured shielding characteristics of specimens of metal silicate materials in the range of metal additive content of 0.165-0.200 and the incident radiation frequency of 20GHz has been established. The presented results show the applicability of the proposed calculation method for preliminary estimates of shielding characteristics when designing facing building materials with electromagnetic radiation shielding functions .

For facing materials produced by pressing, equations are obtained that allow calculating the optimal initial concentrations of the electrically conductive component, at which the selected pressing pressures ensure the achievement of the required shielding efficiencies.

In general, the proposed equations make it possible to design facing building materials with the shielding efficiency values necessary for specific conditions. This provides a reduction in labour intensity, an increase in the accuracy of obtaining the values of the given shielding efficiencies, a reduction in cost due to the saving of an electrically conductive filler, and an increase in the quality of materials.

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