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APPLYING HETEROGENEOUS BUILDING MATERIALS FOR THE PROTECTION OF PEOPLE AGAINST ELECTROMAGNETIC RADIATION

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The object of this study is the processes of shielding electromagnetic radiation by building and facing materials. The research is aimed at solving the problem of ensuring the electromagnetic safety of people by improving the composition and structures of building and facing materials.

Means for improving the electromagnetic safety of people under industrial and domestic conditions using non-homogeneous building materials have been determined. The shielding properties of reinforced concrete structures were studied. A methodology for increasing their efficiency depending on the amplitude-frequency characteristics of the radiation that needs shielding has been devised. The efficiency of electromagnetic radiation shielding by heterogeneous dielectric building materials based on cement concrete and basalt fibers was determined. It was established that shielding through the refraction of electromagnetic waves on inhomogeneities does not give an acceptable effect. The expediency of covering basalt fibers with a conductive substance to increase the protective properties of materials was substantiated. The protective properties of flat facing material with carbonyl iron content were studied. It has been shown that the properties of materials can be effectively controlled by adjusting the filler. The material's transmission coefficient of ultra-high frequency electromagnetic radiation does not exceed 0.40, and the reflection coefficient – 0.25 with a filler content in the base of 14–15 % by volume. This makes it possible to simultaneously ensure the electromagnetic safety of people and the stable functioning of wireless communication devices. The advantage of the material is the low coefficients of reflection of electromagnetic waves, which does not lead to deterioration of the electromagnetic situation in other areas where people stay. It has been established that the addition of boron nitride to the facing material significantly increases the thermal insulation characteristics of the coating and contributes to the solution of energy saving problems. Adding a layer containing boron nitride to the material provides thermal conductivity coefficients of 0.030–0.031 W/m·K, which is better than known analogs

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1. Introduction

There is a constant increase in the electromagnetic load on people and the environment as a whole. To a large extent, this is predetermined by an increase in the number of sources of ultra-high and higher frequency radiation and an increase in the operating frequencies of all wireless information transmission systems, as well as an increase in the branching of household, public, and industrial networks.

Under such conditions, the task to protect people in the industrial and household environment from electromagnetic influences is relevant. This especially applies to the housing of healthcare, educational, etc. institutions. The requirement to reduce the levels of electromagnetic radiation is contained in the European directive on electromagnetic safety under industrial conditions – Directive 2013/35/EU [1]. The International Commission on Protection against Non-Ionizing Radiation in Limiting Exposure to Electromagnetic Fields regulates electromagnetic radiation under household conditions at the level from 100 kHz to 300 GHz [2]. At the same time, according to [2], the permitted values of high-frequency radiation in the environment are up to 1000 μW/cm^2, and in residences they should not exceed 10 μW/cm^2. The problem arises of reducing the levels of ultrahigh, superhigh, and extremely high frequency radiation in buildings and structures. The use of additional cladding on buildings is not always convenient and expedient. This complicates the design, distorts its appearance, and requires additional costs. In addition, along with the protection of people from electromagnetic influences, it is necessary to ensure the reliable functioning of all types of wireless communication. The addition of metal and metal-containing admixtures to building materials for electromagnetic radiation shielding is not justified. The most effective means of protection against electromagnetic influences is shielding. The efficiency indicator is the overall shielding coefficient in the frequency ranges of ultra-high, super-high, and extremely high frequencies. A significant part of the protective properties of materials is due to the reflection of electromagnetic waves. But in many cases, reflection occurs in undesirable directions and worsens the electromagnetic situation in other areas. Therefore, for high-frequency radiation, it is desirable to provide high absorption coefficients of electromagnetic waves by materials and minimize their reflection coefficients.

Shielding additives to building and facing materials, to ensure high efficiency, should have concentrations at the threshold of the percolation effect – the phenomenon of a sharp increase in electrical conductivity and an increase in the protective properties of the material. And such a concentration is about 15 % by volume. This leads to a decrease in the main functionality of building materials – the values of elastic modules, which determine the strength characteristics.

Thus, the most rational way for providing building and facing materials with protective properties is the design of artificial or the use of structural inhomogeneities of materials for the purpose of shielding electromagnetic radiation. This can be reinforcement of reinforced concrete products, cavities of foam and aerated concrete, elements of thermal insulation, etc.

2. Literature review and problem statement

At present, researchers around the world are actively designing protective materials for shielding electromagnetic fields and radiation. These are mainly composites based on metallopolymers. Such research is carried out in several areas – design of materials for shielding electromagnetic radiation of ultra-high and higher frequencies, magnetic fields of ultra-low frequencies, and the design of broadband materials.

Materials for shielding broadband electromagnetic fields [3], as a rule, have insufficient efficiency either at low frequencies or at ultrahigh ones. The use of meta surface structures reduces reflection coefficients but does not provide shielding coefficients of industrial frequency electromagnetic fields higher than 1.5–2.0. Attempts to obtain high protective properties lead to the complication of material manufacturing technologies and the use of many components [4]. In the studied materials, thermally expanded graphite, graphitized carbon black, ferromagnet are used, and the matrix is polyvinyl butyral. Given the high cost, such coatings should be used only for the protection of special purpose objects. Water-containing materials have sufficiently high absorption coefficients of electromagnetic energy, but their use is very limited because of technological problems [5]. Retention of water in a metastable structure is impossible for a long time. Such materials are promising but the thickness does not allow them to be used as facing materials. Many protective materials manufactured using nanotechnology have been studied [6]. A common disadvantage of all composites with a complex structure is their tendency to degrade during operation [7]. It is shown that under the influence of physical factors such as mechanical load, temperature changes, etc., the integrity of the material is compromised. In addition, all of them are intended for additional application on building or facing materials. Moreover, complex compositions are difficult to design. Calculation methods for predicting material shielding coefficients [8] do not give satisfactory results. This is because of imperfection of the empirical correlations for the number of components more than two. Work [9] devised principles of designing building materials with the function of protection against electromagnetic radiation. The disadvantage of the study is the consideration of a model material, copper balls in a cement matrix, which cannot be used in construction. It is shown that in order to obtain high protective properties, the content of the filler should be at least 15 % by volume. Such content sharply reduces the strength of the material, which is unacceptable. But the constructed mathematical apparatus gives a small error compared to the experiment. Therefore, it can be used to design materials with inhomogeneities. In [10], the results of tests of liquid facing materials for electromagnetic radiation shielding are reported. At small thicknesses, the shielding coefficients are quite high – 4.0–6.0. The addition of graphite to the paint matrix in addition to magnetite makes the material suitable for facing only internal surfaces. The presence of two filler components can negatively affect the stability of the material over long-term operation.

Our review reveals that in order to preserve the basic functionality of building materials, such as strength, manufacturability, it is advisable to investigate the possibilities of using their inhomogeneities for electromagnetic radiation shielding. This is due to the wide range of applications of linear and mesh structures in the construction industry. Flat protective structures should preferably be designed with one type of filler. At the same time, the environmental indicators of the components should be taken into account.

3. The aim and objectives of the study

The purpose of our study is to identify patterns of changes in the effectiveness of electromagnetic field shielding by building and facing materials depending on their composition and design features.

To achieve the goal of the research, the following tasks are defined:

– to investigate the protective properties of building materials with regular ferromagnetic inhomogeneities and to determine theoretical and technological approaches to their improvement depending on the amplitude-frequency characteristics of radiations that require shielding;

– to investigate the protective properties of heterogeneous dielectric building materials and to determine the shielding coefficients of electromagnetic radiation through the refraction of electromagnetic waves;

– to investigate the protective properties of flat non-homogeneous cladding materials and to determine the conditions of their most effective application for shielding electromagnetic radiation of ultra-high, extremely high frequencies, and radiation in the infrared range.

4. The study materials and methods

The object of our study is the shielding of electromagnetic radiation by building and facing materials of various compositions and structures. The research hypothesis assumes the possibility of increasing the absorption coefficients and decreasing the reflection coefficients of electromagnetic waves through changes in the composition and construction of building and facing materials without losing their main functionality – elastic modules, technological application, etc. When conducting the study, it was considered that the building and facing materials had inhomogeneities without any tolerances on their location and were considered a regular structure. It was believed that the linear inhomogeneities of building materials had a smooth surface with a rounded cross-section. The mesh reinforcement was perfectly flat of continuous composition with cells of the same size. The inhomogeneities of facing materials have a spherical shape with an isotropic arrangement in the body of the matrix.

Samples of heterogeneous materials were made from standard components intended for the production of building and facing materials. Cement concrete and varnish of the XC family were used as matrices. The following were used as inhomogeneities:

– standard reinforcing steel with a diameter of 10 mm with a step of location in the product of 0.1 m;

– mesh reinforcing basalt structure with a fiber thickness of 0.3 mm and cell sizes of 5×5 mm;

– finely dispersed carbonyl iron with a dispersion of 6–8 μm;

– boron nitride with a dispersion of 20–22 μm.

The content of carbonyl iron in the matrix made of XC varnish was 40 % by mass, and boron nitride in XC varnish was 15 % by mass. The thickness of the sample based on carbonyl iron was 5 mm.

Separate samples were made to scatter infrared radiation. A mixture of carbonyl iron and XC varnish (iron content – 40 % by weight) and a mixture of boron nitride and XC varnish (boron nitride content – 15 % by weight) were successively applied to the fiberglass substrate.

All components are environmentally friendly and approved for use in the construction materials industry. The measurement of the energy flow density of electromagnetic radiation was carried out using a calibrated P3-31 electric and magnetic field intensity meter according to the operating instructions.

The source of high-frequency radiation was a high-frequency generator with a pin antenna. The measurements were carried out on a bench measuring 1.5×1.5 m, which is made of dielectric material covered with aluminum foil. The dimensions of the bench exclude the penetration of radiation outside the sample and through diffraction phenomena. A hole measuring 0.15×0.15 m was made in the plane of the material of the bench, impermeable to electromagnetic radiation.

The coefficient of transmission of electromagnetic waves was determined by the difference between the readings of the device in the absence of a sample that blocked the hole in the bench and in its presence. The measuring antenna was placed behind the screen.

The reflection coefficient of the samples was determined by the difference between the readings of the device in the presence of the sample in the opening of the bench and its absence. The measuring antenna was placed between the source of electromagnetic radiation and the hole in the plane of the bench.

Determination of thermodynamic parameters was carried out with a professional thermal imager Testo 8821-2 Profi 0563 0881 V6 (Germany).

5. Results of devising principles for the use of heterogeneous building materials to protect people from electromagnetic radiation

5. 1. Research of protective properties of building materials with regular ferromagnetic inhomogeneities

The most common inhomogeneity in structural materials is steel reinforcement with different steps of its location. In fact, such a structure can be considered as an electromagnetic crystal. Its main feature is the presence in it of an absolutely forbidden zone (a strip of no transparency). The existence of such a zone means that electromagnetic radiation of a certain wavelength cannot propagate in this structure. For the location step of a regular conductive structure of 0.1 m, the amplitude-frequency characteristics of the transmission coefficient of electromagnetic radiation are shown in Fig. 1. To summarize the results, the amplitude-frequency characteristics are given in terms of the wave number *K* (frequency characteristics) and the radiation amplitude *a* (amplitude characteristics). The coefficient 2π characterizes the relationship between the frequency and the circular frequency in the standard wave equation.

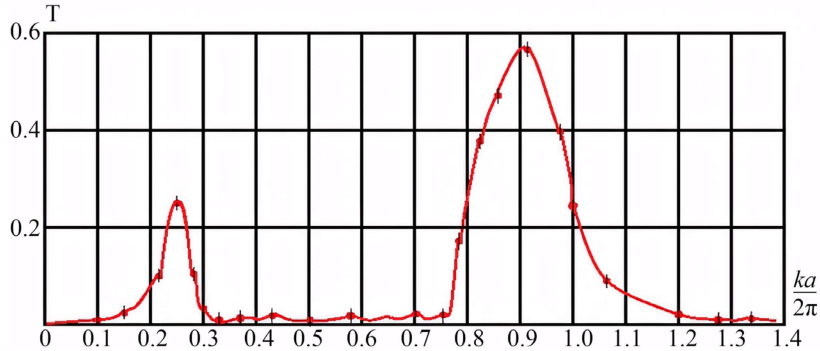


Fig. 1. Amplitude-frequency dependence of the transmission coefficient of an electromagnetic wave (*T*) of a structure with one row of metal rods

Our result is in reasonable agreement with the calculations of the reflection coefficients of the regular structure *R*. If the transmission bands of the material are equal to approximately 0.23–0.28 and 0.75–1.10, then the effective reflection bands are 0.2–0.3 and 08–1.0, respectively. Some discrepancies are due to the limited size of the samples in the process of measuring transmission coefficients and the difficulty of taking into account the effective cross-section of the metal reinforcement in the calculations.

A study of the dependence of the transmission coefficient of a regular structure on the number of frontal layers of reinforcement in the depth of the material was conducted. It was found that with the number of layers 4–5, the maximum reduction of the transmission coefficient is achieved, therefore further increase in the number of layers is impractical (Fig. 2).

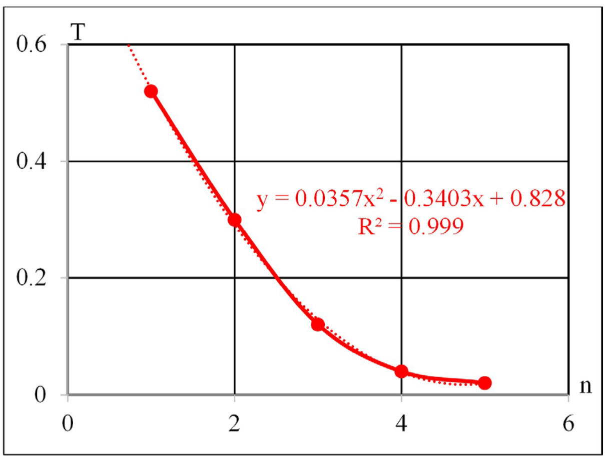


Fig. 2. Dependence of the transmission coefficient of a regular structure (*T*) on the number of layers (*n*), frequency of electromagnetic radiation – 3 GHz

The given dependence corresponds to the analytical function $T=0.0357n^2-0.3403n+0.828$.

To adjust the transmission coefficients and general shielding of electromagnetic radiation, it is possible to shift the layers of reinforcement relative to each other. In this way, the density of regular shielding elements increases. At the same time, their total number does not change and does not affect the strength of the structure.

The given category of materials are magneto-dielectrics, which contain regular ferromagnetic structures based on iron in a dielectric matrix. Their protective properties, in addition to the density of the metal longitudinal structures, are determined by the magnetic properties of the ferromagnet – complex magnetic permeability μ: $\mu=\mu_1+j\mu_2$.

At the same time, different values of absorption permeability μ_k and refraction μ_n in ferromagnetic rods and wires should be taken into account: $\mu_1=\sqrt{\mu_n\cdot\mu_k}$, $\mu_2=(\mu_k-\mu_n)/2$. The magnetic permeability of ferromagnets has frequency dependences, which is important for the design of protective materials. Therefore, changes in the magnetic permeability of the common structural steel grade 45 were investigated (Fig. 3).

The dependences shown in Fig. 3 correspond to analytical functions $\mu_k=1131.7f^{0.399}$; $\mu_n=567.56f^{0.466}$.

Existence of such dependences can introduce significant errors under the real conditions of using structures with electromagnetic radiation shielding functions. Therefore, in the process of designing materials and buildings, it is necessary to have information about the amplitude-frequency characteristics of electromagnetic radiation that requires shielding.

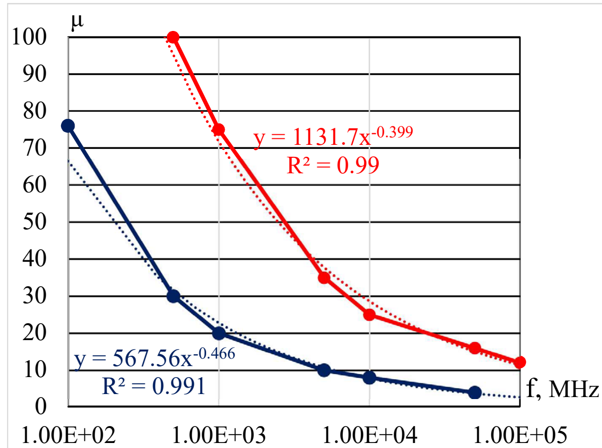


Fig. 3. Frequency dependences of magnetic permeability by absorption μ_k and by refraction μ_n of structural steel grade 45:
— magnetic permeability by absorption μ_k;
— refraction magnetic permeability μ_n

5. 2. Investigating protective properties of heterogeneous dielectric building materials

In recent years, structures in which non-metallic materials are used as reinforcement have become widespread throughout the world. Mostly these are basalt fibers of different thicknesses. At small thicknesses of basalt fibers – 0.1–0.3 mm, they are used in the form of a grid, at larger thicknesses – in the form of linear regular structures of various pitches. Binders are epoxy resins and concrete solutions of various compositions. Such compositions are completely dielectric.

The dielectric properties of the composition components are determined by the complex dielectric permittivity $\varepsilon=\varepsilon_1+j\varepsilon_2$.

A decrease in the level of electromagnetic radiation occurs through the refraction of electromagnetic waves *n* and absorption *k*. They are related as:

$$n^2-k+2jnk=\varepsilon, \quad (1)$$

n is the refractive index of electromagnetic waves in the material;

k – absorption coefficient of the medium – the rate of attenuation of the wave when it propagates through the material.

In the general case, based on the relations of electrodynamics of continuous media, the refractive and absorption coefficients are determined as:

$$n=\sqrt{\frac{\varepsilon_1+\sqrt{\varepsilon_1^2+\varepsilon_2^2}}{2}}, \quad (2)$$

$$k=\sqrt{\frac{-\varepsilon_1+\sqrt{\varepsilon_1^2+\varepsilon_2^2}}{2}}. \quad (3)$$

Attenuation of the electromagnetic wave in non-magnetic materials occurs due to the presence of conductive properties. Basalt fibers and cement concrete are effective dielectrics. Therefore, the shielding effect of their compositions can only be expected due to the refraction of electromagnetic waves.

Refractive indices for basalts and cement concrete differ significantly through different effective dielectric constants. For basalt fibers and rods, dielectric constants in the range of ultra-high frequencies are equal to 2.65–3.15; for cement concrete – 6.0–10.0.

The influence of the presence of boundaries of the composition based on the mesh basalt structure in the cement concrete matrix was investigated (Fig. 4).

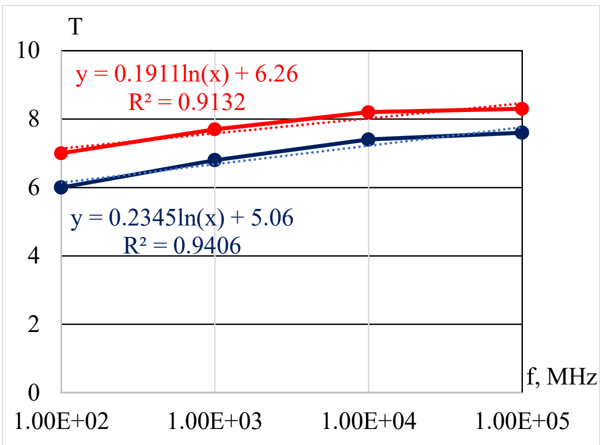


Fig. 4. Frequency dependence of transmission coefficients (*T*) of electromagnetic radiation by dielectric materials: — solid cement concrete; — mesh basalt structure in a cement-concrete matrix

The dependences shown in Fig. 3 correspond to the analytical functions T T=0.1911ln(f)+6.26 for continuous cement concrete; T=0.2345ln(f)+5.06 for a mesh basalt structure in a cement concrete matrix.

As can be seen from the results shown in Fig. 4, the effect of a regular structure with a dielectric constant different from the matrix material does not significantly affect the transmission coefficient of electromagnetic waves. Therefore, such a structure cannot be considered a means of increasing the shielding properties of structural and facing materials.

For conductive materials, the imaginary component of the complex dielectric constant is large compared to the real component:

$$\varepsilon_2 = \frac{4\pi\sigma}{\omega}, \quad (4)$$

where σ is the specific conductivity of the material;

ω is the circular frequency of electromagnetic radiation.

Neglecting ε_1 compared to ε_2 in equations (2), (3), we obtain:

$$n = k = \sqrt{\frac{2\pi\sigma}{\omega}}. \quad (5)$$

That is, by giving the material conductive properties, it is possible to dramatically increase the shielding coefficients of electromagnetic radiation. One of the ways to improve effectiveness of the shielding composition based on cement concrete and basalt reinforcement is to apply a metallic conductive substance to the basalt surface. The search for such possibilities makes sense because of the fact that the surface coating of basalt can significantly expand the use of concrete-basalt compositions for various purposes.

It is known that the limitation of the use of basalt reinforcement in cement concrete is due to the partial destruction of basalt by alkaline components of cement concrete [11]. Therefore, when basalt fibers are given conductive properties by applying a suitable metal coating on them, at the same time, the reinforcement is protected from chemical influence. But such work requires thorough theoretical and experimental research.

5. 3. Investigating the protective properties of flat heterogeneous facing materials

To achieve high efficiency of flat cladding materials, dielectric matrix fillers must have acceptable electrophysical and magnetic properties. Analysis of the properties of magnetic conductive materials allowed us to conclude that carbonyl iron FeC is a promising filler for protective compositions. This filler has a number of advantages compared to other metal and metal-containing magnets. Carbonyl iron consists of pure magnetically soft iron (97–99.5 %) covered with a layer of carbon, which determines its high corrosion resistance. The advantage of the material is that it does not need to be crushed to the required dispersion. Carbonyl iron is produced by industrial enterprises in the form of powders with a dispersion of 3.5 to 25 µm. At the same time, powders with a dispersion of 6–8 µm are the most common. If there is contact between the grains, the material has a guaranteed electrical conductivity of the order of 10^5 cm. The relative magnetic permeability is 10–15. The minimum effective magnetic permeability is 4–5.

The results of testing the protective properties of the material are shown in Fig. 5.

Dependences shown in Fig. 5 are non-monotonic. Deviations from linear dependence are random and may be the result of resonance phenomena in the process of reflection and absorption of electromagnetic waves. This is due to short wavelengths (1.51–0.75 cm) and coating thickness (5 mm). In addition, the surface of the samples is not perfectly smooth. This makes the changes of the corresponding coefficients when changing the frequency somewhat random. Therefore, it is impractical to determine analytical functions of changes in these coefficients.

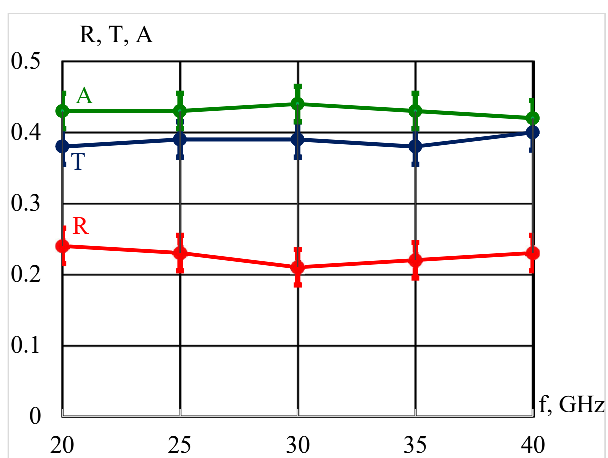


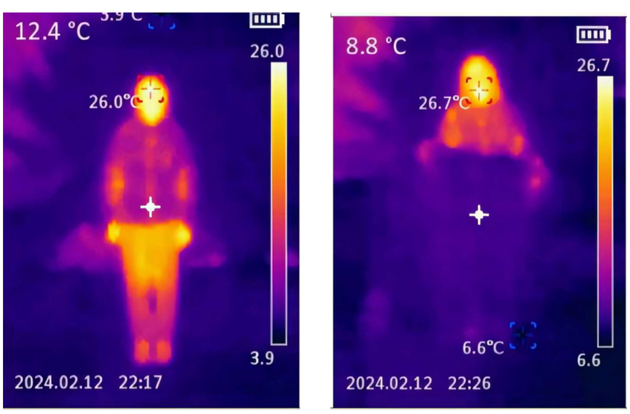
Fig. 5. Coefficients of reflection (*R*), transmission (*T*), and absorption (*A*) of a single-layer material 5 mm thick with a carbonyl iron content of 14–15 % by volume

As can be seen from data shown in Fig. 5, the single-layer material has stable, within the measurement error (up to 1 dB), protective properties. At the same time, the reflection coefficients are lower than the indicators of known analogs based on non-magnetic metals and ferrites. Given the frequency range, such coatings are promising for creating electromagnetic camouflage.

The 5G standard mobile communication is being gradually introduced. In this regard, the maximum permissible levels of electromagnetic radiation of ultra-high and super-high frequencies are being increased in all countries of the world. This is due to the faster fading of waves of these frequencies in the atmosphere and the impossibility of increasing the density of the location of base stations, including through economic factors. Therefore, the protective properties of the material at 5 GHz frequencies, which are fundamental for the flexible application of the 5G communication standard, were tested.

As a result of our experiments, it was established that the reflection coefficients slightly increase to 0.30–0.35. At the same time, the absorption coefficients of electromagnetic waves decrease to 0.30–0.35. This causes the pass rate to 0.30. In general, the protective properties from the point of view of protecting people under domestic and industrial conditions can be considered satisfactory.

Dissipation of electromagnetic energy in the body of materials occurs through thermal effects. Therefore, we investigated the efficiency of absorption of electromagnetic radiation in the infrared range, which is thermal radiation. The main indicator of the effectiveness of blocking thermal radiation is the coefficient of thermal conductivity. This indicator is known for all metals and dielectrics but is not a reference for composite materials. The addition of the boron nitride layer is due to its high heat capacity, 298 J/mol·K. Temperature indicators of the radiation source, external and internal surfaces were determined using a thermal imager. The results of the measurements are shown in Fig. 6.



a *b*

Fig. 6. Image of an object: *a* — in the infrared region of the electromagnetic spectrum; *b* — protected by absorbent material

The thickness of the sample was 1 mm, the temperature difference between the outer and inner surfaces of the samples was 3 K. The power of thermal radiation falling on the outer surface of the sample was 90 W/m^2.

Based on the heat transfer ratio:

$$dQ = -\lambda \frac{\partial T}{\partial x} dS, \qquad (6)$$

where Q is the amount of heat transferred by the material, J; λ is the coefficient of thermal conductivity of the material; $\frac{\partial T}{\partial x}$ is the temperature gradient in the material, K/m; dS is the material area, m^2, and our experimental data, the coefficient of thermal conductivity of the obtained composite material was 0.030–0.031 W/m·K.

It is known from reference sources that the coefficient of thermal conductivity of bark coatings is 0.042 W/m·K, glass wool – 0.037 W/m·K.

Thus, such heterogeneous material can be used for thermal insulation. The combination with carbonyl iron makes it possible to shield all high-frequency radiation along with radiation from the infrared part of the electromagnetic spectrum. Given its small thickness and high efficiency, this material could be used for the production of infrared camouflage.

6. Discussion of results of investigating the efficiency of heterogeneous materials for electromagnetic radiation shielding

Our study on the effectiveness of shielding electromagnetic radiation by building materials with the presence of regular ferromagnetic structures indicates the existence of frequency bands of opacity and transparency for radiation (Fig. 1). These frequency bands can be adjusted either by reinforcement pitch or by shifting individual layers relative to each other. If one layer of the reinforcement relative to the other is shifted by half the step of the arrangement of the reinforcement, then the actual step of the shielding inhomogeneity will be half as much during the frontal incidence of the electromagnetic wave. Similarly, the third layer of reinforcement can be shifted relative to the second, so the zone of transparency of the structure for electromagnetic radiation is further reduced. At the same time, the strength of the building structure does not decrease. Such regulation makes it possible to reduce the electromagnetic load on the environment of buildings while simultaneously ensuring the stability of mobile communication. For the purposes of electromagnetic safety, 4–5 layers of reinforcement are sufficient (Fig. 2).

In the process of evaluating the protective properties of building materials, the frequency dependence of the magnetic permeability of ferromagnetic components should be taken into account, both by absorption and by refraction (Fig. 3). Studies have proven that dielectric building materials with a large difference in the refraction coefficients of electromagnetic waves of the main material and basalt inhomogeneities are not sufficiently effective electromagnetic shields (Fig. 4). To increase the protective properties of such structures, it is advisable to cover basalt fibers with a conductive substance – metal, carbon. In addition to the goals of electromagnetic safety, this will increase the scope of application of basalt reinforcement through the protection of its surface from the alkaline environment of cement concrete.

The use of flat heterogeneous structures with a filler made of carbonyl iron significantly increases the absorption of electromagnetic energy, compared to fillers made of magnetite, graphite, and graphitized carbon black. At the same time, the reflection coefficient of electromagnetic waves is lower than known analogs (0.21–0.25) for frequencies higher than 20 GHz. For the frequencies of the 5G standard, it does not exceed 0.35. Such indicators allow the material to be used for lining the interior surfaces of premises. Small reflection coefficients make it possible to avoid an increase in the electromagnetic background through reflection and re-reflection of electromagnetic waves from internal sources of radiation. Adding a layer containing boron nitride to the flat material blocks electromagnetic radiation in the infrared range and contributes to the solution of energy saving problems. The coefficient of thermal conductivity of this coating is lower than common thermal insulation materials, such as cork, glass wool.

The limitation of our study is the determination of the protective properties of regular ferromagnetic inhomogeneities without taking into account their real effective cross-sections. The real reinforcement has a ribbed surface of different relief. In practice, the actual average cross-sections of inhomogeneities should be evaluated. The effectiveness of shielding flat heterogeneous structures with micro-sized filler depends on its dispersion. Therefore, in the process of designing the material, it is necessary to evaluate the effectiveness of the protection, taking into account the parameters of the filler.

The disadvantage of the study is the application of ferromagnetic linear inhomogeneities of fixed initial magnetic permeabilities and determination of their frequency changes. Under actual operating conditions, the magnetization of steel reinforcement changes. Two opposite processes occur – demagnetization of the metal over time and magnetization of the reinforcement in the geomagnetic field. These processes are unpredictable and depend on the orientation of the building, the lengths of the reinforcement segments, etc. This cannot be taken into account in the research process.

A promising direction of further research is the substantiation and development of technologies for providing electrical conductivity to basalt fibers, which would ensure high absorption properties of the material. It is advisable to carry out a comprehensive study. First, to investigate the dependence of efficiency of shielding of electromagnetic radiation of ultrahigh and higher frequencies. Secondly, to examine the blocking of infrared radiation from the dispersity of carbonyl iron and boron nitride.

7. Conclusions

1. Our study on the shielding of electromagnetic radiation of ultra-high frequencies by building materials with regularly located conductive linear structures, in the form of reinforcements, shows that they have the properties of electromagnetic crystals. Such structures are characterized by the presence of frequency bands of transparency and opacity in the rest of the frequency range. Determination of transparency bands using the $ka/2\pi$ indicator (k is the wave number, a is the amplitude of the electromagnetic wave) simplifies the process of choosing building materials of the required efficiency, based on the actual amplitude-frequency characteristics of the radiation that requires shielding.

2. The study of the protective properties of heterogeneous building materials based on cement concrete (matrix) and basalt fibers (reinforcement) showed that such structures have insufficient efficiency as an electromagnetic shield. This is explained by the fact that dielectric non-conductive compositions reduce the level of electromagnetic radiation only through the refraction of electromagnetic waves. Since basalt fibers are a promising material for the production of building fittings, it is advisable to apply a conductive substance to the basalt fibers or rods. This will make it possible to dramatically increase the shielding coefficients of electromagnetic radiation, to use a mathematical apparatus for predicting the protective properties of the material, designed for metal regular structures.

3. The protective properties of a flat non-homogeneous facing material based on standard varnish XC (matrix) and carbonyl iron FeC (filler) were investigated. The filler content was 14–15 % by volume. The thickness of the material is 5 mm. It was established that the transmission coefficient of the material of electromagnetic radiation of ultra-high frequencies is not higher than 0.40. The coefficient of reflection of electromagnetic waves does not exceed 0.25, which is a better indicator compared to known analogs. This reflectivity makes the material based on carbonyl iron promising for the production of electromagnetic camouflage. Adding a layer containing boron nitride to the material provides thermal conductivity coefficients of 0.030–0.031 W/m·K, which is better than known analogs.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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