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APPLICATION OF INNOVATIVE ELECTROMAGNETIC SCREENS FOR RECONSTRUCTION AND RESTORATION OF BUILDINGS

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Abstract

Protective properties of composite electromagnetic screens on the base of conventional commercial paints were studied. The shielding fillers included metal-containing products from industrial wastewater treatment. Such compositions with a thickness of 100 to 150μm, were found to allow reaching high-frequency electromagnetic radiation shielding coefficients up to 3.0-3.5. Reflection coefficients of electromagnetic waves reach up to 0.3, which meets contemporary technical requirements.

***Keywords**: Electromagnetic screen; Composite material; Reflection coefficient; Reconstruction*

Introduction

The issue of reconstruction and restoration of buildings is particularly relevant for Ukraine due to the fact that a large part of buildings, including historical ones, were damaged as a result of military operations. Historical buildings are rather specific as most of them were built in conditions of no applicable construction and sanitary standards for life safety and civil protection. Currently, there are adverse technogenic factors in buildings of any purpose. First of all, these factors include electromagnetic fields of a wide frequency range. Their sources include power supply systems, high-frequency fields of wireless communication sources. Quantitative values of the latter tend to increase due to increasing numbers of transmitters and consumers and higher operating frequencies. Both globally and in Ukraine, there is a gradual transition to 5G wireless communication, which operates at frequencies from 3GHz and higher. This requires development of adequate means of protecting people in certain areas, premises, individual buildings. Shielding is the most efficient option for protection of buildings against ultrahigh and higher frequency radiation. Most products for shielding electromagnetic fields are made in the form of plates, rolled materials of high thickness, with multilayer structures. Such materials are not acceptable for use in buildings that have historical significance, due to the fact that it is difficult to apply them to non-uniform surfaces, they require additional lining with finishing materials. This will distort buildings' appearance and their interior.

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Therefore, it is advisable to use liquid protective mixtures based on paint and varnish products for use in historical buildings. But the problem is associated with obtaining a shielding filler for paints of sufficient efficiency and acceptable cost. One of the options to address the problem is associated with use of metal-containing materials obtained as a result of wastewater treatment after industrial processes, for example, in electroplating facilities. This will allow to dispose of production waste and obtain fillers for protective materials. The above considerations determine relevance of studying protective properties of mixtures with fillers of metal-containing compounds obtained as a result of industrial wastewater treatment.

A modern trend in the sphere of electromagnetic safety is associated with development and production of composite materials for shielding electromagnetic fields. Availability and application of such materials is a requirement of the EU Electromagnetic Safety Directive [1]. This is due to strict requirements regarding levels of electromagnetic fields in buildings and structures, regulated by the International Commission on Non-Ionizing Radiation Protection [2].

Traditional metal protective structures, even in the form of nets/grids, are effective in protecting against the magnetic component of the industrial frequency electromagnetic field [3]. In the case of high-frequency radiation, shielding nets with a well-defined wire pitch are used. Such materials are monochrome and protect against electromagnetic radiation of one frequency with a very high Q factor of the oscillating system, which is inherent to radar equipment. Composite metal-containing materials have certain absorption bands, for example, to protect computer equipment. It has regulated control frequency bands, so the screen should be effective in two bands [4].

A wide frequency band of electromagnetic radiation is absorbed by gradient screens [5]. But the existing gradient screens have a high thickness (more than 3mm), which makes them unsuitable for facing historical buildings. Thinner materials, even with a certain absorption band, are produced in the form of rolls. This makes it impossible to cover the surfaces of complex shape [6]. In recent years, relevant nanotechnologies were developed. Protective materials containing shielding nanoparticles are very efficient [7]. But due to high costs of nanomaterials, such products are not suitable for covering large area surfaces.

A general disadvantage of composite protective materials is related to their degradation under impact of the atmosphere and other physical factors [8]. Therefore, development of compositions should be based on application of a stable paint matrix (for example, paints for exterior works) and a one-component filler, which increases the material's resilience [9].

In recent years, a number of studies were conducted on matters of development and research of protective properties of materials based on liquid carriers, for example, [10]. Their results suggest that acceptable shielding coefficients are achieved with a content of shielding material (magnetite) in a commercial paint of 45-60% by weight. At such concentrations, adhesive properties of the mixture (adhesion to the surface) decrease sharply and the coefficient of reflection of electromagnetic waves increases, which is undesirable. But such materials have a low thickness, which makes them promise for covering complex shape surfaces without distorting their appearance.

Accounting for the above considerations, it is advisable to study the possibility of using other metal-containing fillers for the manufacture of paint-based electromagnetic screens [11]. Such fillers can be made from metal compounds obtained as a result of industrial wastewater treatment.

Materials and methods

Samples for the study were made on the base of standard commercial paint for exterior works with addition of metal-containing powders in the amount of 15% by weight (Table 1).

Table 1. Metal-containing fillers for electromagnetic radiation shielding

Sample #	Sample composition
1	$NiFe_2O_4$
2	$ZnFe_2O_4$
3	$CuFe_2O_4$
4	$Ni_{0.5}Zn_{0.5}Fe_2O_4$
5	$Ni_{0.5}Cu_{0.5}Fe_2O_4$
6	$Zn_{0.5}Cu_{0.5}Fe_2O_4$
7	$Zn_{0.5}Mn_{0.5}Fe_2O_4$
8	$Ni_{0.5}Zn_{0.5}Al_{0.15}Fe_{1.85}O_4$
9	$CrFe_2O_4$
10	Fe_2O_3
11	Fe_3O_4 + FeO + Fe
12	Iron ore concentrate
13	70% (Fe_3O_4 + FeO + Fe) + 20% (graphite) + 10% (soot)

Liquid mixtures were applied to iron plates with dimensions of 0.15×0.15m. Thickness of the single-layer coating did not exceed 100–150μm. Sample "0" was the paint coated sample without filler. Determination of protective properties was carried out for electromagnetic radiation with frequencies of 3.3 GHz and 8.4GHz. Measurements were made on Keysight P9375A analyser using the two-port method.

Electromagnetic waves energy of the first port of the analyser entered its second port by passing through the resonator. Standard copper resonators operating in H_{011} resonant mode were used for measurements. One of the copper end caps was replaced by a sample under study. Amplitude-frequency characteristics of samples - IL (F) - were estimated, where ILs are losses introduced by the resonator into the high-frequency signal. Two parameters were determined - the maximum amplitude of the resonance peak IL (F_0), which corresponds to the resonance frequency F_0, and the loaded Q factor Q_0, which was calculated from the amplitude-frequency characteristics.

Samples for determination of amplitude-frequency characteristics of the shielding efficiency of fillers (without a paint matrix) were made from powders ## 6, 10, 11, 12, 13 in the form of rectangles with dimensions of 23×10mm, which corresponds to the dimensions of a rectangular waveguide. Thickness of the samples was 1 mm. Measurements were performed in a contact manner in the waveguide system by the reflectometry method using a P2-61 linear analyser. Collection, storage, averaging and digital processing of the obtained amplitude-frequency characteristics of shielding efficiency of the studied samples were conducted with application of an analog-to-digital converter.

Results and Discussions

Q factor of the resonator (Q0) was determined from the ratio:

$$Q_0 = \frac{2\pi F_0 W}{W_d}, \tag{1}$$

where W is the energy stored in the resonator, W_d is the lost energy, and F_0 is the resonant frequency.
Energy losses occur in the flat caps of the resonator:

$$W_d = W_1 + W_2, \tag{2}$$

where W_1 and W_2 are energy losses in the upper and lower caps of the resonator, i.e.:

$$\frac{1}{Q_0} = \frac{1}{Q_1} + \frac{1}{Q_2}, \tag{3}$$

where Q_1 and Q_2 are the Q-factors of the upper and lower caps of the resonator.
It was considered that the Q factor of the resonant system under load:

$$\frac{1}{Q_L} = \frac{1}{Q_0} - \frac{1}{Q_C}, \tag{4}$$

where Q_L is the Q factor of the resonant system under load, Q_C is the Q factor of the high-frequency measuring conduit.

Recalculation of the Q factor under load into its own quality factor is carried out from the ratio:

$$Q_0 = \frac{Q_L}{1 - 10^{\frac{IL}{20}}}. \tag{5}$$

At the beginning of the experiments, inherent Q factors of resonators with copper caps were estimated for resonance frequencies of 3.3GHz and 8.4GHz. They were 29806 and 22671, respectively. Since the caps are identical, the Q factor of one cap was calculated. After that, one cover was replaced with the sample under study. Shielding efficiency was measured by power losses (P). Losses in sample # 0 (native paint without shielding fillers) were considered as a baseline: P0 = 1. Power losses in all other samples were determined relatively to the baseline as Pn/P0. Measurement results are shown at Figure 1.

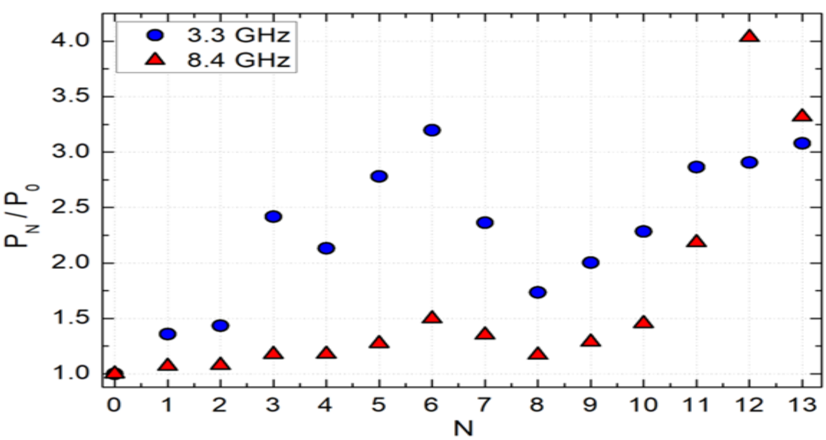

Fig 1. Dependence of power losses in protective mixtures of different chemical composition (N – sample number in Table 1)

Power losses in samples with different chemical compositions and a comparison of the results with a standard copper screen are shown in Tables 2 and 3.

Table 2. Shielding efficiency of the developed materials for electromagnetic radiation with a frequency of 3.3GHz

Sample	IL (dB)	Q_l	F (GHz)	Q_o	Q sample	P_n/P_0
0	-26.433	7591.7	3.32917	7971.80783	9202.41729	1
1	-28.666	5859.1	3.33357	6083.40917	6774.76701	1.35834
2	-29.184	5591.1	3.33218	5792.31107	6415.69737	1.43436
3	-33.226	3499.3	3.32741	3577.32952	3805.70841	2.41806
4	-32.145	3924.5	3.33087	4023.90253	4315.18071	2.13257
5	-34.281	3074.7	3.33272	3135.26536	3309.31533	2.78076
6	-35.634	2700.3	3.3324	2745.68908	2878.25827	3.19722
7	-32.999	3573.6	3.33256	3655.44463	3894.23914	2.36308
8	-30.468	4725.4	3.33229	4871.36567	5304.86298	1.73471
9	-31.732	4154.6	3.33094	4265.09137	4593.7599	2.00324
10	-32.682	3685.9	3.33257	3773.52897	4028.53868	2.28431
11	-34.586	2990.8	3.32994	3047.64128	3211.84378	2.86515
12	-34.745	2950.5	3.33102	3005.53924	3165.1175	2.90745
13	-35.105	2845.4	3.33058	2896.28518	3044.18723	3.02295
Cu	-15.981	25072	3.33384	29806.32973	59612.65945	0.15437

Table 3. Shielding efficiency of the developed materials for electromagnetic radiation with a frequency of 8.4GHz

Sample	IL (dB)	Q_l	F (GHz)	Q_o	Q sample	P_n/P_0
0	-23.24	5275.8	8.37751	5665.98968	6475.12268	1
1	-23.70333	4997.33333	8.38027	5346.38831	6061.05745	1.06832
2	-23.54333	4953.23333	8.38089	5306.09837	6009.32833	1.07751
3	-24.44333	4616.9	8.37001	4911.36634	5507.97634	1.17559
4	-24.73933	4621.73333	8.368	4906.02428	5501.25848	1.17703
5	-24.92333	4312.26667	8.37319	4571.62736	5084.24484	1.27357
6	-26.261	3756.63333	8.37374	3948.67775	4325.35518	1.49702
7	-25.135	4095.3	8.37598	4335.33388	4793.67319	1.35076
8	-24.38767	4637.3	8.38062	4935.09119	5537.83277	1.16925
9	-25.06267	4277.56667	8.373	4530.50415	5033.43353	1.28642
10	-25.75667	3845.4	8.3778	4054.3731	4452.50226	1.45427
11	-29.12667	2685.26667	8.36978	2782.56653	2964.49131	2.18423
12	-33.99667	1519.1	8.37128	1550.03922	1604.90325	4.03459
13	-32.40333	1826.53333	8.36232	1871.40806	1951.97152	3.31722
Cu	-14.14	18220	8.40639	22671.16684	45342.334	0.14281

Analysis of the results presented in Tables 2 and 3 shows that the greatest efficiency was observed for samples # 6, ## 10-13.

Accounting for low thickness of the protective layer (up to 150μm), shielding coefficients of 2 to 3 can be considered satisfactory. At the same time, shielding efficiency of multilayer coatings would increase dramatically.

A disadvantage of many protective materials and designs is associated with their efficiency at one single frequency or in a narrow frequency range. Therefore, it is advisable to study amplitude-frequency dependencies of the shielding efficiency. At the same time, it is important to ascertain what a contribution reflection of electromagnetic waves makes into the overall shielding coefficient.

Dependence of radiation power losses on its frequency in the developed materials is shown at Figure 2.

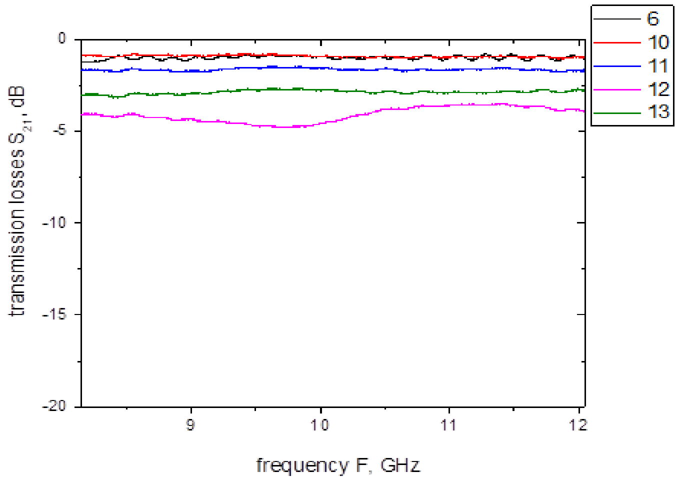

Fig. 2. Amplitude-frequency dependence of power losses in the course of transmission of electromagnetic radiation through samples # 6, ## 10-13.

As can be seen from Figure 2, material # 13 demonstrates a slight dependence on radiation frequency. Exact values of these parameters are provided in Table 4.

Table 4. Amplitude-frequency characteristics of S_{21} electromagnetic radiation energy losses at transmission through protective material

Sample #	$<S_{21}>$, dB	ΔS_{21}, dB	S_{21}(min), dB	S_{21}(max), dB
6	-1.0	0.4	-1.2	-0.8
10	-0.9	0.25	-1.05	-0.8
11	-1.6	0.25	-1.75	-1.5
12	-4.1	1.3	-4.8	-3.5
13	-2.9	0.4	-3.1	-2.7

Parameters of electromagnetic waves reflection losses for samples # 6, ## 10-13 are shown at Figure 3 and in Table 5.

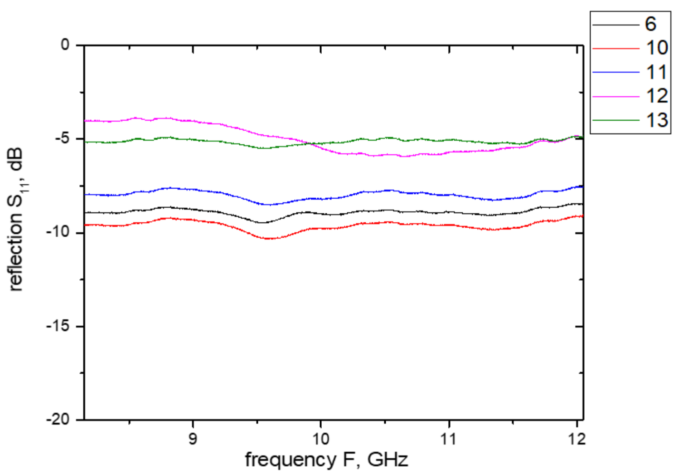

Fig. 3. Amplitude-frequency dependences of electromagnetic waves reflection losses.

Table 5. Amplitude-frequency characteristics of electromagnetic waves reflection losses S_{11}

Sample #	$<S_{11}>$, dB	ΔS_{11}, dB	S_{11}(min), dB	S_{11}(max), dB
6	-8.95	1.0	-9.45	-8.45
10	-9.7	1.2	-9.1	-10.3
11	-8.0	0.95	-8.5	-7.55
12	-4.9	2.05	-5.9	-3.85
13	-5.2	0.65	-5.5	-4.85

As data of Figure 3 and Table 5 suggest, reflection values range from -3.9dB (sample # 12) to -10.3 dB (sample # 10). In terms of dimensionless coefficients, they correspond to the range of 0.3 - 0.6. At the same time, parameters for samples # 6 and # 11 approach values of about 0.3. Such reflection coefficients are considered to be the most achievable for use in cases where, together with low reflection coefficients, high absorption properties of the material are also required.

The main indicator of any protective material is its ability to absorb (dissipate) electromagnetic energy. But in many cases, absorption occurs at one single frequency or in a narrow frequency band of electromagnetic radiation. Therefore, amplitude-frequency characteristics of electromagnetic energy dissipation losses were studied.

On the basis of the experimentally obtained parameters of the scattering matrix, losses of electromagnetic radiation associated with its absorption in the samples' media were calculated. Figure 4 shows relative values of electromagnetic radiation absorption for the samples studied.

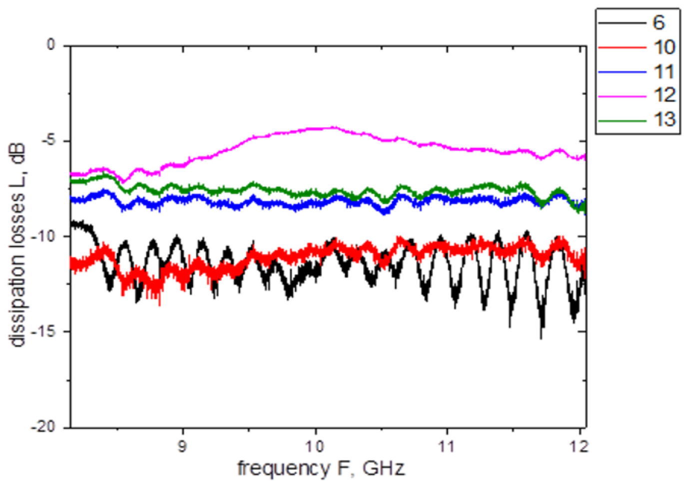

Fig. 4. Amplitude-frequency dependences of electromagnetic energy dissipation losses

Exact quantitative data are provided in Table 6.

Table 6. Amplitude-frequency characteristics of electromagnetic energy dissipation losses

Sample #	<L>, dB	ΔL, dB	L_{min}, dB	L_{max}, dB
6	-11.8	5.0	-14.3	-9.3
10	-11.5	2.8	-13.9	-10.1
11	-8.2	1.2	-8.8	-7.6
12	-5.7	2.8	-7.1	-4.3
13	-7.7	1.8	-8.6	-6.8

As can be seen, signal losses associated with energy absorption for samples ## 11 and 13 reach 8.2dB and 7.7dB, which are fairly uniform with a variance of 1.2dB and 1.8dB, respectively. Sample # 12 has the highest losses of about 5.7dB with a noticeable absorption maximum of up to 4.3dB with a broad frequency band, which, as noted above, corresponds to a weak resonant interaction of the material at a frequency of about 10GHz with a low Q factor value.

Amplitude-frequency absorption characteristics of sample # 10 show a decrease in losses to 11.5dB with a noticeable minimum at the frequency of 8.8GHz to the value of 13.9dB. The corresponding loss dependence for sample # 6 with the average value of -11.8dB and the largest variance of 5dB has a noticeable resonance interaction at many harmonics of the signal. With a high probability, it can be assumed that such a high-frequency dispersion of sample # 6 is inherent to resonance phenomena in a waveguide of limited cross-section. It is quite likely that dispersion in the real conditions of application of the material will be smaller or disappear altogether due to lack of the resonance phenomena.

The obtained results on protective properties of liquid electromagnetic screens made from conventional commercial paints with fillers from metal-containing materials, that are obtained from industrial wastewater treatment products, can be applied for reconstruction and restoration of historical buildings. A thin layer of a shielding paint does not distort the appearance of the building that can be covered by finishing materials of the desired colour and texture.

Different fillers have different overall shielding coefficients. While acceptable shielding coefficients for sample # 13 were expected due to excessive specific conductivity of the composition (due to added graphite), the sufficiently high shielding coefficients of samples ## 12 and 6 need to be clarified. Fillers of these compositions have conductivity values close to those of ferrites. Therefore, their high absorption values are most likely caused by resonance processes in the material itself. At certain particle sizes of the filler, absorption of electromagnetic energy occurs in a manner similar to the Raman scattering mechanism.

Major differences in values of the general shielding and reflection coefficients can be used to increase electromagnetic safety without significant costs. It is known that the reflection coefficient of electromagnetic waves depends exclusively on electrophysical characteristics of the surface layer. Accounting for a very low thickness of the single-layer coating of the obtained compositions, it is advisable to use two- and three-layer coatings. For example, the upper layer might consist of materials ## 6 and 10, which has the lowest reflection coefficient, and the inner layer might consist of materials ## 12 and 13 with high absorption properties.

This study has certain limitations. In further research studies, it is advisable to determine dependence of protective properties of the compositions on the content of the protective substance with a simultaneous study of changes in the rheological properties of the mixtures. A promising option is to determine effects of particle dispersion and morphology on protective properties of the material.

Conclusions

The studies have proven that, in terms of mass and size parameters (up to 150μm), compositions made from conventional commercial paints and fillers from metal-containing particles, obtained as a result of industrial wastewater treatment, can be used to ensure electromagnetic safety in the case of historical buildings. Shielding coefficients of such materials range from 1.5 to 4.0. This is acceptable for reducing levels of technogenic electromagnetic fields while maintaining stable operation of all wireless communication equipment items.

Reflection coefficients of electromagnetic waves range from -10.3 to -3.8dB. Coefficients approaching 10dB correspond to a value of 0.3, which is much more acceptable than metal screens (0.7-0.9). Under such parameters, it is advisable to use a two- or three-layer structure, which in total has a thickness that does not distort the appearance and interiors of historical buildings. Low coatings' thickness allows one to apply decorative coatings of the desired colour and texture on top of the shielding paint.

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