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Research Article

Improving Electromagnetic Shielding Ability of Plaster-Based Composites by Addition of Carbon Fibers

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The size of electromagnetic shielding in plaster composites by the means of different volume fractions of carbon fibers was studied in this paper. Conventional types of plaster, which are commonly used in industry, that is, cement, lime, gypsum, and lime cement (Thermo UM), were the base materials of the created composites. The fundamental idea of improving the electromagnetic shielding properties was verified based on a numerical simulation conducted by means of electromagnetic module in Comsol Multiphysics. The carbon microfibers with the above-critical length of 8 mm were added as the reinforcing and simultaneously shielding element into the plaster samples. From the viewpoint of the mechanical properties, fibers shorter than the critical length do not provide sufficient reinforcement. The samples were created at three different volume fractions of the dispersion and one without any reinforcement for the possibilities of their mutual comparison. The results of the carried measurement show that the electromagnetic shielding in the plaster composite grows with the increase of fiber content within the tested ratio proportionately. Also, the dependency of shielding ability on the inner material moisture has been studied. Any measureable influence of the moisture content on to the total shielding effect has not been found. Only in the lime plaster reinforced with fibers, the increased moisture could significantly decrease the shielding effect.

1. Introduction

Over the last few years, there has been mounting concern about the possibility of adverse health effects resulting from exposure to radiofrequency electromagnetic (EM) fields, such as those emitted by wireless communication devices [1]. This phenomenon is connected with extensive development of electronic systems and telecommunications including generation and transmission of electricity, domestic appliances and industrial equipment, and telecommunications and broadcasting, whereas electrical and EM fields in certain frequency bands have wholly beneficial effects, which are applied in medicine, other nonionizing frequencies sourced from extremely low frequencies, power lines or certain high-frequency waves used in the fields of radar, telecommunications, and mobile communications, and they appear to have more or less potentially harmful, nonthermal, biological effects on plants, insects, and animals as well as the human body [2–4].

For the reasons given above, a demand for protection of human beings against undesirable influence of EM signals and troublesome charges (especially for professional use) has been increasing. The best material for shielding or absorption of EM wave must have both high electric conductivity (imparts higher reflection of EM wave especially at lower frequencies) and high magnetic permeability (provides higher absorption of EM wave especially at lower frequencies); therefore, shields based on the use of metals, magnetic alloys, and carbon-based materials are the best ones [5]. The materials used in the shielding of radiofrequency fields are usually copper, aluminum, or silver based (in the form of wires, metal plating, or conductive fillers) [6–10]. These shields work by reflecting the waves because these metals have a high electric conductivity. To shield a magnetic field, materials must have a high magnetic permeability to be able to absorb the fields [5]. Carbon-based materials such as carbon fibers, carbon particles, carbon nanotubes, and so on fully fulfill this requirement [11–13].

One way to protect human beings is to use protective clothing made of textile materials with increased electrical conductivity [14, 15]. These fabrics are usually based on the use of very thin metal fibers incorporated to the structure of yarn from which woven or knitted fabric is made [10]. By these fabrics, sufficient electrical conductivity connected with certain level of electromagnetic shielding protection is achieved, but on the other hand, this method of protection brings some disadvantages. For example, by addition of conductive components (metal fiber), thermophysiological comfort properties of clothes are usually deteriorated [16]. In addition, even the appearance (color) of these special fabrics is also very often influenced [17].

It seems that more robust solution offers controlled insulation of whole buildings. However, it is clear that just the passive instruments, such as wall cladding by damping panels and the use of electro conductive curtains or special wallpapers solve only the consequences and not the causes of electromagnetic radiation. Since in many cases the passive instruments are the only possible solution, they are sometimes necessary and therefore must be addressed.

The most important material in the building industry is cement. Dried cement composites do not contain any free electrical charge carriers. Their specific electrical resistance in the fully dried state is around 10^9 Ωm, making it one of the best insulators, which means they are fully transparent to electromagnetic radiation of higher frequencies [18]. The increased moisture content of cement composites results in a reduction of specific electrical resistance. This is due to salt ions contained in the pore solution. Significant reduction of electrical resistivity accompanied with the increase of electromagnetic shielding ability of cement composites occurs after an addition of a sufficient amount of electrically conductive additives to form conductive paths. The dominant charge carrier in this case is the electron [18].

There are many references in the literature concerning the addition of a varying amount of conductive filler as a reinforcing element to a cement matrix in order to produce an electrically conductive, electromagnetic shielding material with favorable mechanical properties such as tensile strength, compressive strength, or impact strength. For example, Wang et al. [19] prepared multiwalled carbon nanotube (MWCNT)/cement composites and studied the effect of sample thickness and the nanodispersion content on the shielding effectiveness. It was found that at MWCNT content 0.6 wt.%, the cement mortar sample with a thickness of 25 mm remarkably absorbs electromagnetic waves close to the absorbing peaks in the frequency range of 2–8 GHz. Yawen et al. [20] described investigation of main properties of high-structure carbon-black (CB) cement-based composites (CBCCs). It was confirmed that these composites exhibit good performance in the absorption of electromagnetic waves in the frequencies higher than 8 GHz. For CBCC containing 2.5 wt.%, the minimum reflectivity reaches about 20 dB, but compressive strength significantly decreases with the increase of CB content. Unfortunately, both mentioned papers analyze only reflection part of electromagnetic shielding effectiveness, whereas it is expected from theory [5] that for carbon-based materials, main portion of electromagnetic shielding effectiveness will be created by absorption coefficient. Khushnood et al. [21] focused their work on the usage of cost-effective material (pyrolyzed agricultural wastes such as peanut and hazelnut shells) for enhancing the electromagnetic shielding effectiveness of cement composites. Numerically evaluated electromagnetic shielding effectiveness showed that shielding ability of composite is poor at low frequencies (about 0.2 GHz). The shielding ability is close to 10 dB at the highest of evaluated frequency (10 GHz) using the highest portion of conductive component that is 5 wt.% of carbonized peanut shells or 0.5 wt.% of carbonized hazelnut shells.

As mentioned above, the use of fibrous materials as reinforcing elements is favorable especially for its high aspect ratio (length/diameter ratio). It was proven that fibrous materials contribute to improvements in their mechanical properties [22]. In the authors' previous studies [23], it was reported that usage of optimal volume ratio of fibers (1% to 2% of reinforcement) shows significant improvement in the main mechanical properties of plaster composites. With the higher volume of fibers, the improvement is not proportional, and the demanded effect is just minimal.

The aim of the carried work was to find out whether the addition of fibrous reinforcement could improve the electromagnetic shielding ability. To achieve the required effect, some conductive components must be added to the plaster. Carbon fiber shows very good electrical and thermal conductivity, good strength properties, and improved environmental resistance of the final plaster [24].

2. Materials and Preparation

In the previous works of the author [23, 25], all realistic combinations of plasters and fibers have been tested with respect to their mechanical properties (Figure 1). Some glass, carbon, basalt fibers, and even polyvinyl butyral nanofibrous dispersion have been used as the reinforcing element of composites. The thickness of plasters has been chosen based on the real values used in the construction industry. The results show that the mechanical properties (flexural tensile strength, compressive strength, and impact strength) of plasters could be significantly improved by using the weight ratio of fiber reinforcement of 1% to 2%. Higher content of carbon reinforcement does not have any equivalent effect or could even worsen the mechanical parameters [23]. The content of the fibrous reinforcement in concrete materials is usually 6%. However, a mixture of the plasters and fibers with such high contents usually causes problems in their bonding [23, 26]. For this reason, the content of the fibrous reinforcement has been set to 1%, 2%, and 3%. The calculation (1) of the mixing ratio [27] is based on the percentage of the components in the composite and their densities.

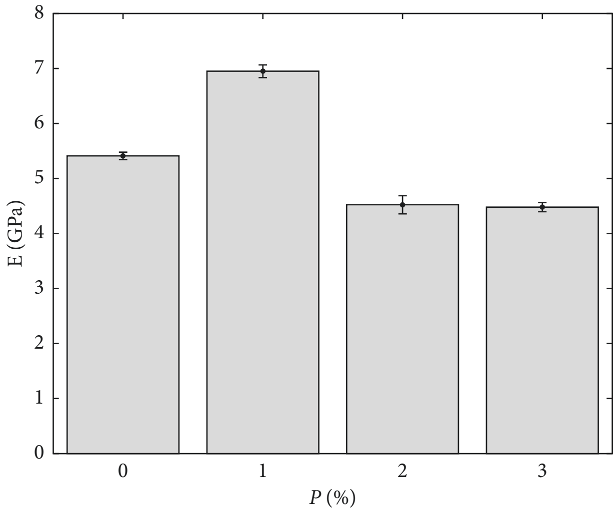

Figure 1: Comparison of the modulus of elasticity in the tension E (GPa) of the Thermo UM Xtra plaster with different volume fractions (P (%)) of the carbon reinforcement.

The mutual conversion between the mass and volume fraction is in Table 1.

$$w_i = \frac{V_i \times \rho_i}{\sum V_i \rho_i}, \tag{1}$$

where w_i (%) is the mass fraction of the ith component, V_i (%) is the volume fraction of the ith component, and ρ_i (kg/m^3) is the density of the ith component.

With the higher volume fraction, the mechanical properties suddenly start falling down because the reinforcement is transformed into a bundle of stress concentrators and the rupture initiators. Based on these results, four types of plasters, whose mechanical properties could be improved or at least not worsened, have been chosen. For the mutual comparison and consistency of the results, pure plasters without any fiber dispersion were tested. Because of the natural climatic loading of the plasters, the samples were also tested at different humidities (0.8%, 2.2%, and "wet"–not physically possible to measure). The individual plasters were prepared according to the recommended manufacturer's technical standards. The inner moisture content was measured after acclimatization of the samples in the standardized ambient conditions, and the so called "wet" was achieved by simultaneous spraying of the samples by water. The carbon fibers with the declared mean diameter 1.76 μm were selected to achieve the shielding effect. For plaster composites with microfiber reinforcement, it was necessary to compute the critical fiber length: the final length of carbon fibers is 8 mm. The fiber distribution in the tested parts was assessed by image analysis on randomly selected samples. However, it is possible to say, that after approx. 20 min of mixing, the distribution is equal. The main physical properties of the used materials are given in Table 2.

2.1. Plaster. The type and amount of the used binder influences the resulting plaster properties, so it is one of the main criteria based on which the plasters could be divided. The first plaster selected for the study was the lime-cement. This plaster belongs among extremely effective heat-insulating plasters with the trade name Thermo UM (this designation is used in this study). Another significant feature of this material is low bulk density; compared to commonly used plasters, it could be up to 4 times lighter. Due to its low bulk density and low modulus of elasticity, the plaster eliminates the volume or shape changes in the base wall material, thus creating no cracks. Above all, the Thermo UM plaster is characterized by a high value of the thermal conductivity coefficient, and the chemical composition of the plaster eliminates growth of microorganisms, algae, and fungi on its surface [28].

Table 1: Volume fraction of the individual components.

Volume fraction w_i	1%	2%	3%
		Mass fraction (%)	
Thermo UM	3.98	7.74	11.28
Cement	0.75	1.51	2.27
Lime	1.79	3.55	5.29
Gypsum	1.96	3.87	5.75

Table 2: Mechanical properties of the base used materials.

Material	Length (mm)	Diameter (μm)	Density (kg·m^{-3})	E (GPa)	υ (–)
Carbon fiber	8	1.6	1800	241	0.27
Thermo UM	—	—	551	5.4	0.18
Gypsum	—	—	1100	14	0.27
Cement	—	—	3020	39	0.2
Lime	—	—	1250	8.8	0.21

Another type, the gypsum plaster, is generally cheaper material characterized by good thermal and acoustic resistance. Due to its thermal properties, the plaster is perceived as a hygroscopic material, which allows the regulation of the microclimate in the room [29, 30]. This plaster is vapor-permeable, does not close the water in the construction, and at the same time allows the natural drying of residual water from the blocks. The gypsum plaster is suitable for antibacterial environments because the smoothness of its surface prevents dust from settling on. At high temperatures, gypsum is released by water vapor, which is often used to increase fire resistance [31].

The cement plaster [32] exceeds especially with the high strength, resistance to mechanical damage, and very good adhesion to the basic substrate. This kind of plaster is therefore commonly used for highly loaded areas and areas where frost and weather-resistant is also required.

The lime plaster is characterized by very good water vapor permeability and ability to absorb moisture from surrounding bricks. It does not retain capillary water and it also dries very well. These properties allow lime plasters to regulate indoor climate. Lime plaster is very flexible, making it suitable for uneven surfaces. Another advantage is its ability to absorb all odors [33]. The microimages of the individual types of plaster with the carbon dispersion are in Figure 2.

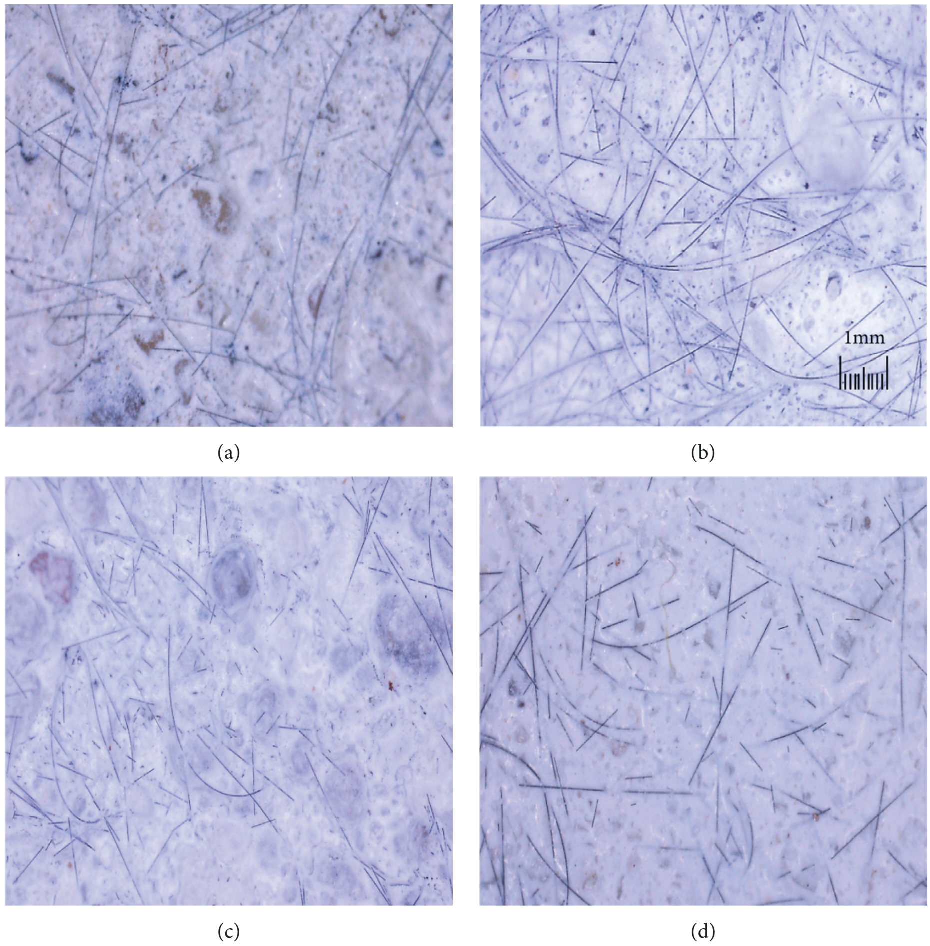

Figure 2: The studied plasters reinforced with carbon fibers: (a) cement, (b) gypsum (c) Thermo UM, and (d) lime.

2.2. Fiber Dispersion. The carbon "*An old but still new material*" and its natural or synthetic compounds exceed the number of all the compounds of all other elements together, which is about a million. This is possible even though the carbon materials are composed of only one element. The properties of these materials could not be predicted or estimated based on the known composition, as is the case of, for example, conventional metal alloys. The fibers are commercially available on fiber coils of several hundred meters in length, and each bundle consists of 1000 to 10000 filaments with a diameter of 5–12 μm. Standard carbon fibers have a tensile strength between 3 and 4 GPa, and the modulus of elasticity of 230–300 GPa [34, 35]. Carbon fibers have the largest range of properties. High strength, modulus, and heat resistance with low density are associated with carbon fibers. Very good thermal and electrical conductivity were the important criterion for selecting this fiber for our study [36]. The importance of carbon fibers is growing steadily despite the fact that compared to glass fibers, their price is ten to hundred times more expensive. However, due to their characteristics, customers' constant interest could be expected. In recent years, the carbon fibers have become an integral part of modern civil engineering. They are primarily used to increase the load-bearing capacity of building components and to perform building reconstructions. In such cases, not only the simple carbon fiber is used, but carbon reinforcement in the form of rods, lamellas, and carbon fabric is used as well.

The potential of using those fibres also in the civil engineering could lay in utilization of some wasted carbon fibres, remaining in a big amounts from manufacturing of composite parts for vehicles and airplanes. Due to the fact that once the fibers are cut or split, there is no possibility to merge or dissolve them again, and they are usually just energetically utilized by burning in the heating plants. To add them into building materials is significantly a better idea.

The conductance (2) is a physical parameter that describes the material ability to lead an electrical current.

$$G = \frac{I}{U} = \sigma \frac{S}{l} = \frac{1}{R}, \tag{2}$$

where I (A) is the electric current flowing through the conductor, U (V) is the voltage at the ends of the conductor, σ (SI) is the conductivity of the substance, S (m^2) is the cross-sectional area, l (m) is the length of the conductor, and R (Ω) indicates the electrical resistance.

3. Modeling

The created model of the electromagnetic absorption has been created in the Comsol Multiphysics. The model uses

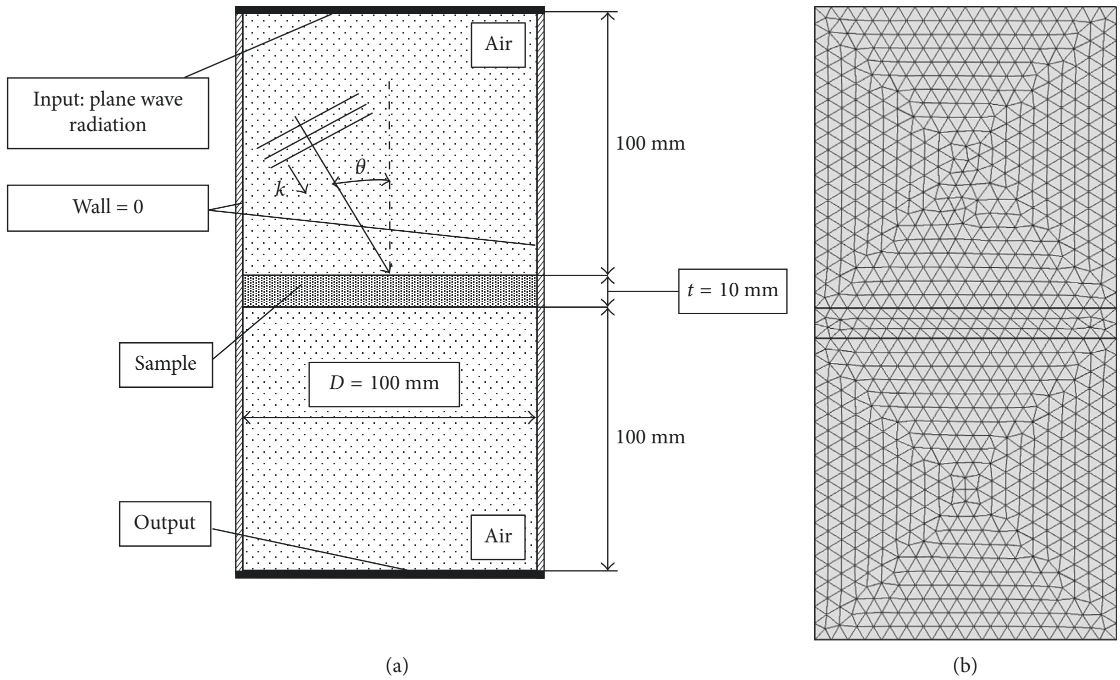

Figure 3: Scheme of the created FEM model and boundary conditions (a) and FEM model (b).

a 2D geometry of such a system (Figure 3). The aim of the model is to characterize the absorption properties—more specifically, the specific surface impedance with and without the conductive reinforcement. The base models of the four samples (Thermo UM, gypsum, cement, and lime) were created using the module Acoustic-Electromagnetic Interaction and Radiation, with the frequency domain. Layers are also assumed to be infinite in the lateral dimensions; the only geometric information is then the sample. The surrounding fluid is air. The incident angle is given as (3). The task was solved with two directions of acting waves 0° and 45° as could be seen in Figure 4. As shown in Figure 5, the only solid body in the created model was the desk with diameter $D = 100$ mm, thickness $t = 10$ mm, and material properties of the individual materials (density, conductivity, moisture, and resistivity). The maximal frequency in the model is 1000 Hz.

$$k = k_0 (\sin\theta, \cos\theta), \quad (3)$$

where θ is the incidence angle and k_0 is the wave number in the free field.

The orthogonal impact of the wave to the partition is the worst case in terms of shielding. Therefore, it is not necessary to calculate any other impacting angles for comparison of the numerically obtained results with the experiments. In order to determine the shielding efficiency, it is necessary to determine the value of the incident electromagnetic waves H_t transmitted through the insulated sample described by the parameters μ, G, and the sample thickness t. Where μ is the permeability of vacuum ($\mathrm{H{\cdot}m^{-1} = N{\cdot}A^{-2}}$). Parameters of the free continuum filled with air around the simulated sample are the permeability constant $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{H{\cdot}m^{-1}}$ and the vacuum permittivity $\varepsilon_0 = 8854 \times 10^{-12}\,\mathrm{F{\cdot}m^{-1}}$. The characteristic impedance of the free space on both sides of the sample is Z_0 (4), and the characteristic impedance of the sample is Z_S *je* (5). Subsequently, the shielding efficiency can be expressed by impedance according to the following:

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}, \quad (4)$$

$$Z_S = \sqrt{\frac{j\mu\omega}{G}}, \quad (5)$$

$$SE = 20 \cdot \log\left|\frac{(Z_0 + Z_S)^2}{4Z_0 Z_S} \cdot e^{\gamma t} \cdot \left[1 - \left(\frac{Z_0 - Z_S}{Z_0 + Z_S}\right)^2\right] \cdot e^{-2\gamma t}\right|, \quad (6)$$

where γ denotes the number of wavelengths per unit length (propagation constant) of the electromagnetic wave in space $\gamma = \sqrt{j\omega\mu(G + j\omega\mu)} = \alpha + j\beta$, where α ($\mathrm{dB{\cdot}m^{-1}}$) is the attenuation constant and β ($\mathrm{rad{\cdot}m^{-1}}$) is the phase constant. The overall shielding efficiency can be broken down into several components. The reflection of electromagnetic wave occurs when the wave arrives from the free space to the sample surface and then again when passing through the sample into the free space. The total attenuation caused by reflection R (the electrical resistance—already defined in (2)) defined according to (7) could be subsequently described by 2 parameters R_1 and R_2. The characteristic reflection on the first (input) and on the second partition interface, where a part of the unattenuated wave and a part of the attenuated wave, is shown in Figure 5.

$$R = R_1 + R_2 = 20 \cdot \log\left|\frac{Z_0 + Z_S}{2Z_S} \cdot \frac{Z_0 + Z_S}{2Z_0}\right|. \quad (7)$$

When some shielding material is used, the greatest number of the reflected waves belongs to the first interface. This phenomenon could be easily observed on some metallic

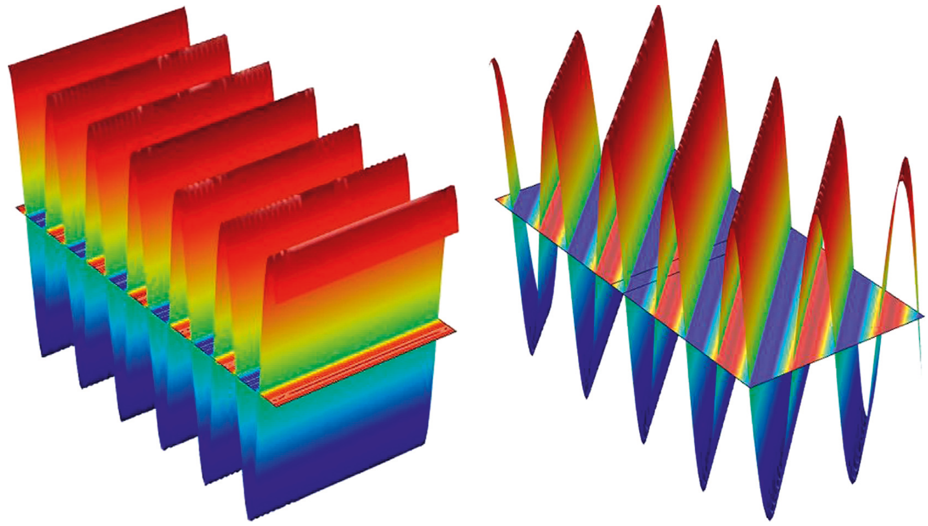

Figure 4: FEM model: examples of the incident waves in the two computed directions $\theta = 0^\circ$ (a), $\theta = 45^\circ$ (b).

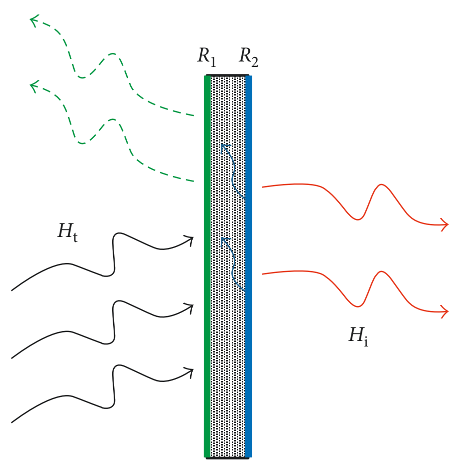

Figure 5: Model scheme of propagation, reflection, and attenuation of an electromagnetic wave in a solid partition.

materials where the best possible conductivity is necessary to obtain the highest shielding efficiency. When the electromagnetic wave passes through a metal wall of the enclosure, portion of its energy is dissipated to heat. The size of the absorbed portion of the energy depends on the wall material, its thickness, and frequency of the waves. Therefore, in a case of modeling of nonmetallic materials with just a minimal primary conductivity, such are the tested materials: Thermo UM, gypsum, cement and lime, it is necessary to use conductive dispersion that could affect their permeability because the greatest absorption $\vartheta(\mathrm{dB})$ can be achieved by a composite material with high permeability, whose thickness exceeds the wavelength of the penetrating waves

$$\vartheta = 20 \cdot \log e^{t/\delta}, \tag{8}$$

where t is the material thickness and δ is the depth of the impacting wave penetration, which is dependent on field frequency, permeability, and material resistance $\delta = \sqrt{(2\rho/\omega\mu)}$, where ρ is the specific resistance ($\Omega\cdot\mathrm{mm}^2\cdot\mathrm{m}^{-1}$).

The dispersion used in the form of added fibers affects the resulting permeability and the overall absorption shielding. However, the problem could be to determine the optimal amount of the fiber dispersion. The optimal added fiber ratio could cause positive increase, whereas in the case of nonoptimal amount, the reflected and pulsed waves within the structure may have even a negative effect on the overall shielding efficiency. The shielding efficiency caused by multiple reflections $\vartheta_{\mathrm{M}}(\mathrm{dB})$ could be then expressed as

$$\vartheta_{\mathrm{M}} = 20 \cdot \log\left\|\left[1 - \left(\frac{Z_0 - Z_{\mathrm{S}}}{Z_0 + Z_{\mathrm{S}}}\right)^2 \cdot e^{-(2t/\delta)} \cdot e^{-j(2t/\delta)}\right]\right\|. \tag{9}$$

When the shielding structure is designed from the material where $Z_0 \gg Z_{\mathrm{S}}$ and when the wall thickness is greater than the wave's penetration depth $t \gg \delta$, then the value of ϑ_{M} is approaching zero, and therefore, the effect of multiple reflections of electromagnetic waves on the overall shielding could be neglected. The reflected wave is easily converted to heat by the means of absorption attenuation. However, if the wall thickness is less than the penetration depth, of the ratio $(t/\delta) \leq 1$, then ϑ_M achieves negative values, and thereby, the overall shielding efficiency is reduced, as stated by Mardiguian or Chatterton et.al. [37, 38].

4. Experiment and Testing

Electromagnetic shielding effectiveness (SE) of composites was measured according to ASTM D 4935-10 [39] for planar materials using a plane-wave, far-field EM wave. SE of samples was measured over the frequency range of 30 MHz to 3 GHz. The most common wireless technologies such as the broadcasting television and radio, cell phones, satellite radio and TV, wireless computer networks, Bluetooth, GPS, and so on use radio frequencies, which extend from about 10 kHz to 300 GHz and match wavelengths within the range 30 km to 0.1 mm. Majority of practical applications is working at frequencies below 30 GHz. Table 3 summarizes the approximate frequency bands used by the most present wireless technologies [2], which means that the measured frequency range includes working frequencies of the most common equipment for public communication and data transfer.

The setup consisted of a sample holder with its input and output connected to the network analyzer (Figure 6). A shielding effectiveness test fixture (Electro-Metrics, Inc., model EM-2107A) was used to hold the sample. The design and dimension of the sample holder follows the ASTM method mentioned above. Network analyzer Rohde & Schwarz ZN3 was used to generate and receive the electromagnetic signals. Sinusoidal signal was generated over the mentioned frequency range with the use of 50 Ω output impedance to minimize reflections caused by mismatches. The standard mentioned above determines the electromagnetic shielding effectiveness of the fabric using the insertion-loss method. A reference measurement for the empty cell was required for the shielding effectiveness assessment.

Samples were air-conditioned before testing ($T = 22^{\circ}\mathrm{C} \pm 3$, RH = 50% ± 10%). In addition, effect of moisture content was studied. Samples of dimensions 10 × 150 × 150 mm were produced for this testing. Five samples were produced for each conductive component content in order to the conduct subsequent statistical analysis.

The total shielding of a solid material with no apertures is equal to the sum of the absorption loss (A) plus the reflection loss (R) plus a correction factor (B) to account for multiple reflections in thin shields. Total electromagnetic shielding effectiveness therefore can be written as (10) [5]:

$$\mathrm{SE} = A + R + B \ \ (\mathrm{dB}). \tag{10}$$

The reflection is usually the primary mechanism of electromagnetic interference shielding. The wave, which is incident to the boundary with the second medium, is partially reflected back and partially transmitted to second medium. The same situation occurs at the interface between the second and third material. Reflection loss for plane waves is greater at low frequencies and for high conductivity materials [5].

Table 3: Frequency range for different applications [40].

Application	Frequency or frequency range
AM broadcast	530 kHz~1.7 MHz
Broadcast TV	54~88, 174~261, 470~698 MHz
FM broadcast	88~108 MHz
Cell phones	~850, ~900, ~1800, ~1900 MHz
GPS	~1.5 GHz
Satellite radio	~2.3 GHz
Wireless Comp. Network	2.4 & ~5.8 GHz
Satellite TV	~12 GHz

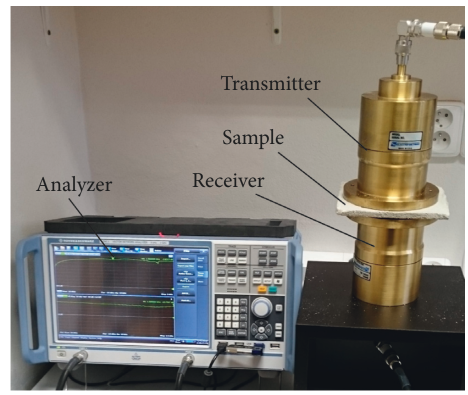

Figure 6: The testing equipment.

Secondary mechanism of EMI shielding is usually absorption. When an electromagnetic wave passes through a medium, its amplitude decreases exponentially. This decay occurs because currents induced in the shield produce ohmic losses and heating of material. General expression for absorption loss can be written as (11) [20]:

$$A = 0.0848t\sqrt{f\mu_r\sigma_r} \ \ (\mathrm{dB}), \tag{11}$$

where t is the thickness of the shield in meters. For significant absorption of the radiation by the shield, the shield should have electric and/or magnetic dipoles, which interact with the electromagnetic fields in the radiation. The electric dipoles may be provided by materials having a high value of the dielectric constant. The magnetic dipoles may be provided by materials having a high value of the magnetic permeability.

The absorption loss is a function of the product $\sigma_r \cdot \mu_r$, whereas the reflection loss is a function of the ratio (σ_r/μ_r), where σ_r is the electrical conductivity relative to copper and μ_r is the relative magnetic permeability. Silver, copper, gold, and aluminum are excellent for reflection due to their high conductivity. Super-malloy and mu-metal are excellent for absorption due to their high magnetic permeability. The reflection loss decreases with increasing frequency, whereas absorption loss increases with increasing frequency [5].

Other than reflection and absorption, a mechanism of shielding is based on multiple reflections (B), which refer to the reflections at various surfaces or interfaces in the shield. This mechanism requires the presence of a large surface area or interface area in the shield. An example of a shield with a large surface area is a porous or foam material. The loss due to multiple reflections can be neglected when the distance between the reflecting surfaces or interfaces is large compared to the skin depth.

Operation of the electromagnetic shield could be characterized by the so called shielding attenuation coefficient (dimensionless) defined as a ratio between electromagnetic field power density in a specific place of shielded space P_t and incident electromagnetic wave power density P_i (W/m^2)

$$\mathrm{SE} = \frac{P_t}{P_i}\ (-). \tag{12}$$

Logarithmic size of this coefficient called electromagnetic shielding effectiveness (SE) is used more frequently:

$$\mathrm{SE} = 10\ \log\frac{P_t}{P_i} = 20\ \log\frac{H_t}{H_i}\ (\mathrm{dB}), \tag{13}$$

where H_t, E_t, and P_t are the electric field strength, magnetic field strength, and electromagnetic field density values measured in the presence of the textile material, whereas H_i, E_i, and P_i are the same values measured without the textile material.

For the analysis of the shielding effectiveness of test samples, a formula expressing absorption loss A_{sheet} (dB) and reflection loss R_{sheet} (dB) can be used expressed as

$$A_{\mathrm{sheet}} = 0.0848 \times t\sqrt{\frac{K}{K_C}f}, \tag{14}$$

$$R_{\mathrm{sheet}} = \mathrm{C} + 10\ \log\left(\frac{K}{K_C f}\right), \tag{15}$$

where the constant C is listed in Table 4 for plane waves, electric fields, and magnetic fields, respectively. K (S/cm) is the volume conductivity, K_C (S/cm) is cooper conductivity, f (MHz) is the frequency, and t (m) is thickness of the shield [41].

During the experiment, the dependency of inner material moisture has also been measured. The measured moistures were 0.8% for the dried samples, 2.2% for the normalized samples, and for the higher level of the inner humidity, it was not possible to set the value because of the physical limits of the measuring tools.

5. Result and Discussion

First of all, the theoretical model was prepared to study electromagnetic shielding ability of plaster composites with different thicknesses, containing different fiber reinforcements, and applying different types of incident wave. Based on findings gained from modeling, real composite samples were produced, and effect of plaster type, effect of conductive reinforcement content, and effect of moisture content on total electromagnetic shielding effectiveness were studied. A comparison of the FEM model and experimental measurement revealed similar results of electromagnetic shield by testing materials obtained from the measurements; however, Figure 7 shows a uniform course. The FEM model also shows a study of the absorption coefficient where it is evident that in the mixture of the selected plaster types without fiber dispersion the absorption coefficient of the electromagnetic waves is low and remains almost unchanged. Improvement can be achieved by adding conductive carbon fibers with value of about ≤3% in our case. As shown in Figures 8 and 9, it is possible to achieve an increase in the effective plaster thickness by the fiber addition and the final electromagnetic shielding could also be improved. As it was already mentioned in the description of materials, the plaster itself, due to brittleness and porosity, does not have the corresponding elastic properties. However, when reinforcing the plaster with just small ratio of fibers (1-2%), composite material with significantly improved elastic and damping properties can be obtained. This phenomenon is illustrated in Figure 9, where the FEM model compares the structure of the pure and the reinforced plaster. Figure 9 shows the overall shielding efficiency, where the density of intensity of the overall attenuation of the electromagnetic shield R is defined by (7), whereas in case of a nonreinforced sample, the shielding intensity decreases steeply beginning by the first contact of waves and material boundary; the increased absorption is evident in the entire thickness of the reinforced sample; thus, less of undamped waves pass through the reinforced sample.

The electromagnetic shielding ability was measured for three sets of samples having 4 different types of plaster with the various carbon fiber weight ratios (from 0 to 3 wt.%). Figure 10 shows the variation in SE for composites with

Table 4: Constants used in (7) and (8).

Type of field	C
Electric field	322
Plane wave	168
Magnetic field	14.6

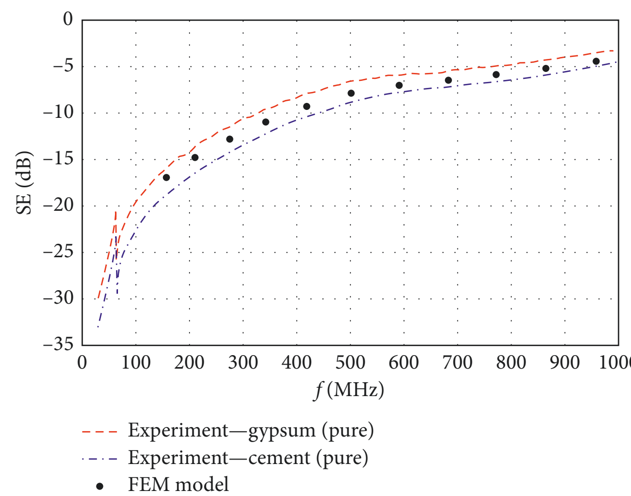

Figure 7: A comparison of the FEM model and experimental measurement.

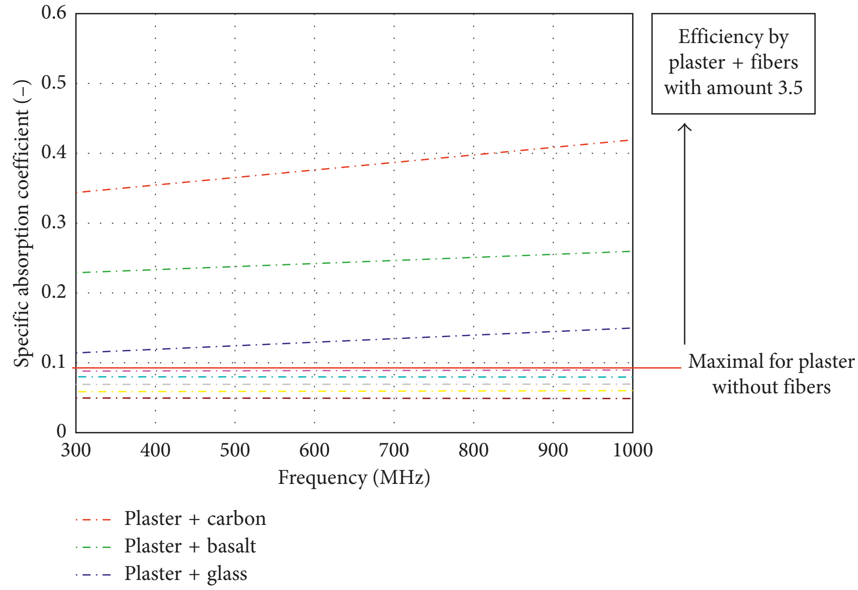

Figure 8: FEM model: study of absorption coefficient for plaster.

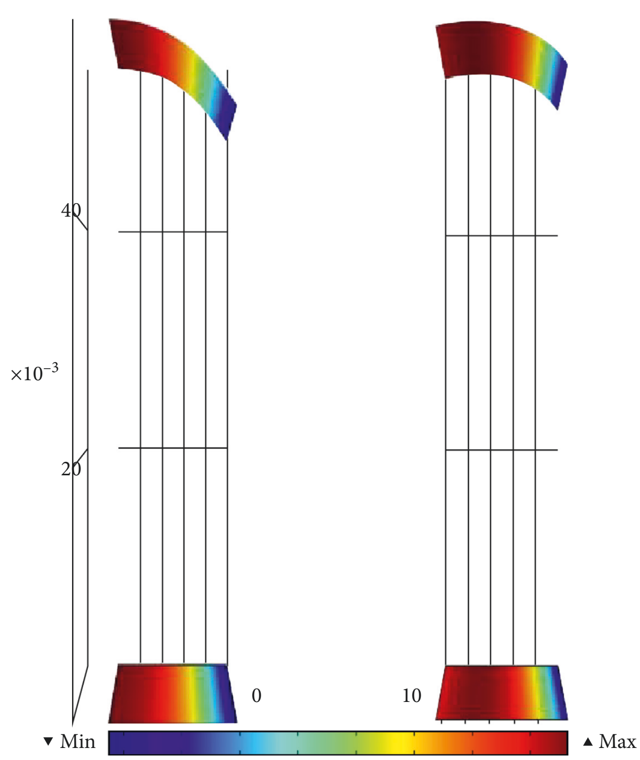

Figure 9: FEM model: comparison of intensity of electromagnetic shielding for the same thickness of sample—the plaster without the fibers (left) and in the plaster with the fibers (right).

incident frequency in the range of 30–3000 MHz. It can be concluded that electromagnetic shielding effectiveness (SE) in (dB) is dependent not only on carbon fiber content but also on the type of plaster. Assumption based on theory saying that addition of conductive component guarantees improved shielding ability of material validated by modeling was also confirmed by experimental evaluation of real samples. It is visible that pure plasters regardless of its type show poor electromagnetic shielding effectiveness higher than −10 dB for frequency range 500–3000 MHz, whereas by addition of carbon fiber, SE can be decreased up to −60 dB for higher frequencies. When studying frequency-dependent behavior, Thermo UM, cement, and lime plaster embody similar behavior with the increase of SE in lower frequencies

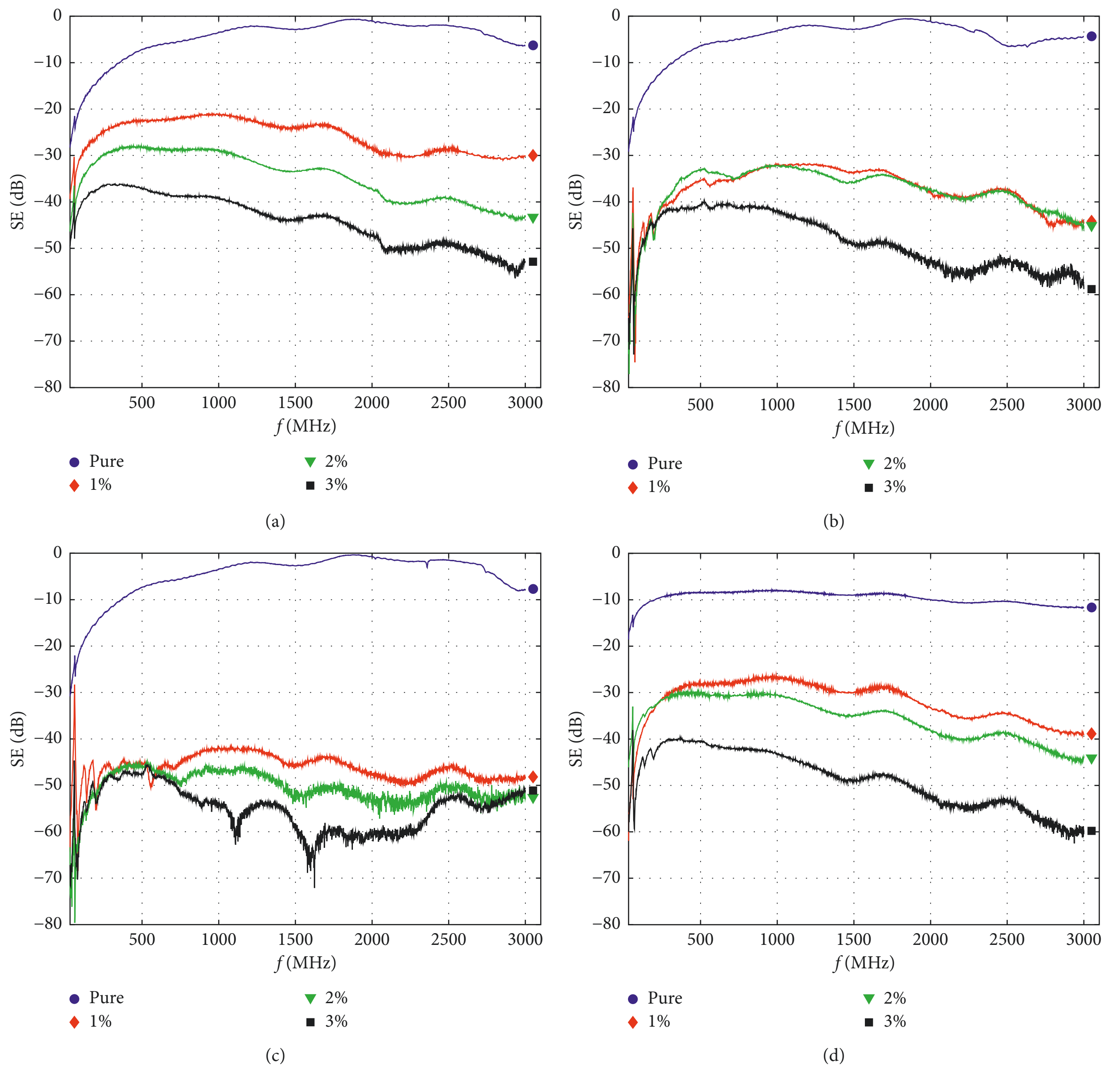

Figure 10: Frequency-dependent electromagnetic shielding ability of samples with different carbon fiber contents and different plaster types: (a) Thermo UM, (b) cement, (c) gypsum, and (d) lime.

($f < 500$ MHz) followed by decrease of SE in a higher frequency range. Gypsum plaster behaves differently having almost constant SE on the whole measured frequency range. In Figure 11, the dependence of SE on carbon fiber weight content for all plaster materials for frequency 1.5 GHz is shown. This frequency was found interesting because many devices use this frequency to operate. It is visible that SE increases with increasing carbon fiber content. Dependence of SE on fiber content can be described using a power function. The solid lines in this graph correspond to the regression models (straight line) with parameters obtained by the minimizing sum of squared errors. High coefficients of determination displayed in the figure indicate the good quality of fit. From this figure, effect of plaster type on SE can also be studied. All pure plasters have very poor shielding ability (SE > −10 dB), whereas gypsum plaster provides the highest SE (SE = 60 dB at 3 wt.% of carbon fiber) compared to other plasters when conductive fibers are added to the composite structure. On the contrast, Thermo UM plaster has the poorest shielding ability accompanied by the highest SE values (SE = 43 dB at 3 wt.% of carbon fiber). This phenomenon is in agreement with electric properties of plasters, namely, its electric conductivity. Thermo UM plaster is thermally insulating plaster having low thermal conductivity and also very low electric conductivity. Gypsum plaster is known for its hygroscopic behavior, which means that this material can attract and hold water molecules from the surrounding

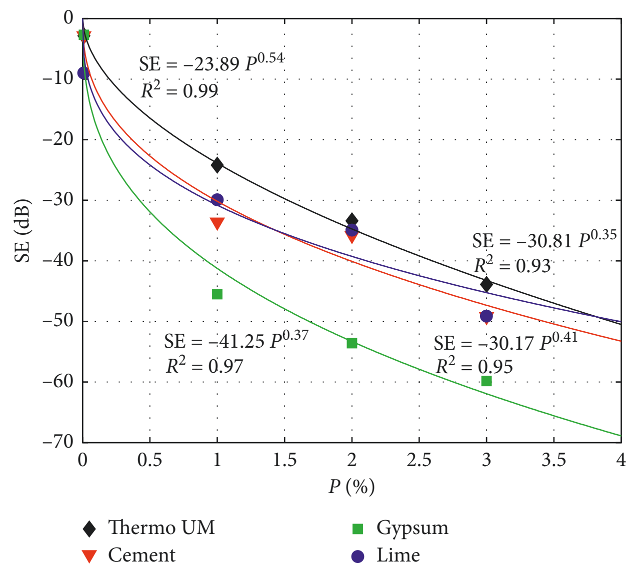

Figure 11: The dependence of SE on carbon fiber content P for all plaster types for frequency 1.5 GHz.

environment, which can cause higher electric conductivity accompanied by greater electromagnetic shielding ability. It is known from theory that shielding effectiveness of material is directly proportional to its electric conductivity, see (14) and (15).

Effect of moisture content on electromagnetic shielding ability of carbon fiber-reinforced plaster-based composites was also studied. It has been found that analyzed moisture content has very low impact on output variable. That is why, only the frequency-dependent SE of samples with 0 and 2% of reinforcement for all plaster types are shown in Figure 12. It is known from theory that increased moisture content increases electric conductivity and also positively influences electromagnetic shielding ability because liquid water has a broad absorption spectrum in the microwave region (300 MHz–300 GHz). It is visible from figures that this effect was not uniquely confirmed. Especially for pure samples, the effect of moisture content is neglectable. Difference in shielding effectiveness of samples with 2% of carbon fiber with different moisture contents was also not statistically significant. The observed phenomenon is presumably caused by very low level of moisture in the structure of composites. To notice the increase of electromagnetic shielding ability, the water content in the sample should be much higher as shown in [10].

6. Conclusion

Based on the measured data, it is possible to declare that with increasing content of fibers, the shielding ability of the plaster composites grows significantly. For samples containing 1% of fiber reinforcement, the highest value of the elastic module was measured, and at the same time, it was confirmed that the carbon content had a statistically significant effect on the module. Despite this fact, the content of fibrous reinforcement of more than 3% is less suitable because of arising negative impact to the basic mechanical properties and their sudden degradation, as could be read in the author's previous articles, for example [23, 25]. Also, when we consider the value of improved shielding properties achieved with 1-2% of carbon content, it is not effective to try to use more dispersion because the obtained benefits will only be small. In the future work, it would be advisable to consider the possibility of optimizing shielding capabilities using not only the conductive fibers (1-2%) but also conductive particles. This method could lead to the maintenance of optimal mechanical properties to increase the electromagnetic shielding. This could be beneficial especially when using the mentioned wasted composite fibers and particles. From the global manufacturing processes of composite materials, there are a lot of waste carbon fibers, which are not possible to be used again. However, their usage as the plaster filling could be a way to use them. Another possibility could be the use of conductive grids.

The content 1-2% of carbon dispersion, which according to Table 5 means shielding group: good–very good, is the most suitable. From the measured results, it is obvious that the sample's inner moisture does not have a major impact on the shielding effect. The only noticeable differences in shielding occurred in lime plaster. The reason could be the ability of the plaster to accept moisture from the surrounding environment and its good vapor permeability.

The numerical simulation has been one of the fundamental parts of the work. The main problem is to define the constitute equations or parameters in the material model because it is really difficult to obtain some of the required constants, and often it was necessary to rely just on the literature. However, the main dependency on the variable dispersion content has been verified. It could be stated that it is possible to predict the trends in shielding properties based on the simulation with sufficient accuracy.

Therefore, it is advisable to measure, calculate, or estimate the frequency of unwanted signals and based on that

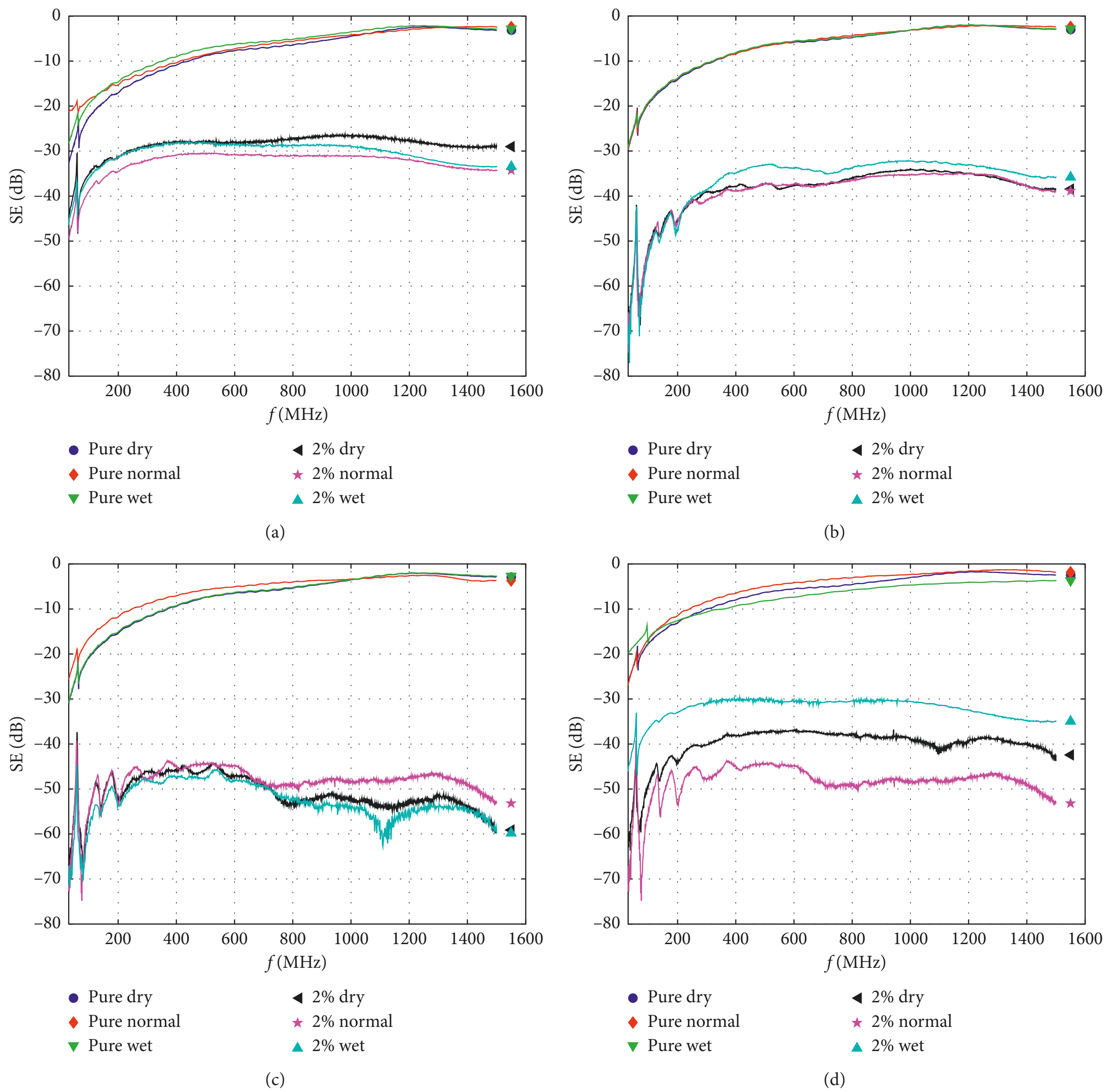

FIGURE 12: Frequency-dependent electromagnetic shielding ability of samples with different moisture content: (a) Thermo UM, (b) cement, (c) gypsum, and (d) lime.

TABLE 5: Classes for professional use [42].

Grade	5, excellent	4, very good	3, good	2, moderate	1, fair
Electromagnetic effectiveness range	SE > 60 dB	60 dB ≥ SE > 50 dB	50 dB ≥ SE > 40 dB	40 dB ≥ SE > 30 dB	30 dB ≥ SE > 20 dB

choose the shielding material and thickness of the enclosure, before designing the main shielding element. It is possible to state that at lower frequencies, the reflection of the waves prevails, whereas the absorption effect increases at higher frequencies. Therefore, the conductive nonmagnetic materials are suitable for reflection, and the thickness of the shielding layer is not a critical parameter. This finding corresponds with the probably most common example of electromagnetic shielding in microwave ovens, where just a thin transparent conductive film on the door provides sufficient protection.

The future of our work should be based on the numerical modeling with the use of numerical optimization in order to set the optimal length and content of fibers and thickness of the base materials.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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