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Analysis of the influence of electrical parameters of concrete and reinforcement inside concrete walls on the values of the electric field intensity

Abstract. *The aim of the article is to analyze the influence of the variability of the electrical parameters of non-ideal and absorbing dielectric (usual concrete) on the values of the electric field intensity. A detailed analysis was also made of the influence of the reinforcement diameter, the number of rows and the spacing between the bars on the values of the electric field intensity. The subject of the research was a model containing a load-bearing wall made of concrete (absorbing dielectric) with reinforcement in the form of steel rods (conductor). Four reinforcement systems commonly used in construction were analyzed. Additionally, the discussion covered the influence of electrical parameters (electric permittivity, conductivity) on the field intensity values calculated for heterogeneous, complex material structures. The results of the field generated by the wireless communication system operating at the frequency f = 5 GHz are presented. The numerical finite difference time domain (FDTD) method was used. The influence of the values of electric permittivity and conductivity of concrete on the field intensity values was discussed in detail.*

Streszczenie. *Celem publikacji jest analiza wpływu zmienności wartości parametrów elektrycznych nieidealnego i absorbującego dielektryka (beton zwykły) na wartości natężenia pola elektrycznego. Również dokonano szczegółowej analizy wpływu średnicy zbrojenia, liczby rzędów oraz rozstawu pomiędzy prętami na wartości natężenia pola elektrycznego. Przedmiotem badań był model zawierający ścianę nośną wykonaną z betonu (absorbujący dielektryk) wraz ze zbrojeniem w postaci stalowych prętów (przewodnik). Analizowano cztery, powszechnie stosowane w budownictwie układy zbrojenia. Dodatkowo dyskusji poddano wpływ parametrów elektrycznych (przenikalność elektryczna, konduktywność) na wartości natężenia pola obliczone dla niejednorodnych, złożonych struktur materiałowych. Zaprezentowane zostały wyniki pola generowanego przez system komunikacji bezprzewodowej pracujący przy częstotliwości f = 5 GHz. Zastosowano numeryczną metodę różnic skończonych w dziedzinie czasu (FDTD). Szczegółowo omówiono wpływ stosowanych w literaturze wartości przenikalności elektrycznych oraz konduktywności betonu na wartości natężenia pola.* ***(Analiza wpływu parametrów elektrycznych betonu oraz zbrojenia wewnątrz betonowych ścian na wartości natężenia pola elektrycznego).***

Keywords: building materials, electrical parameters of concrete, reinforced concrete, electromagnetic waves propagation, FDTD, wireless communication.
Słowa kluczowe: materiały budowlane, parametry elektryczne betonu, beton zbrojony, propagacja fal elektromagnetycznych, FDTD, komunikacja bezprzewodowa.

Introduction

Concrete is the main building material in construction. Classification of concretes in terms of their dry volume weight includes: heavy, normal and light concrete. Due to the variety of factors influencing the obtaining of hardened concrete, determining the values of electrical parameters is the subject of numerous studies [1-8]. In the available literature, the most frequently modeled structures are described as ordinary concrete. In many cases, information about the type of concrete and its components is omitted. The electrical parameters of concrete depend mainly on the amount and type of concrete mix components and the quality of the cement mortar (water/cement ratio marked as w/c) [9].

To strengthen the structure, reinforcement in the form of metal bars is used. The complexity and variety of material parameters affect both construction and electrical properties [1, 5, 10, 11]. Due to electromagnetic phenomena, the method of describing the material structure is of great importance. The introduction of metal inserts to the structure causes the distortion of the propagating electromagnetic wave, which leads to changes in the field distribution and, consequently, affects, inter alia, on the quality of wireless communication. In the case of wireless power transfer of everyday devices, especially by means of wireless energy transmission, the location of the field source is important, and more precisely the influence of the dielectric like a wall on the quality of data transmission [12-14].

The distribution of reinforcement inside structural elements depends, among others, on from design assumptions [10]. The spacing between the bars (L) depends, among others, on from calculation diagrams and the magnitude of forces and moments loading the structure. The nominal diameter of the reinforcement bars is $fi \in \langle 0.005;\ 0.04 \rangle$ m. Reinforcement assembly and the spacing between reinforcing bars are strictly defined for the respective structural elements [4, 10].

The determination of electrical parameter values is relatively difficult in many cases. For this reason, for example, in the publication [15] to analyze the influence of a reinforced concrete slab on radio communication, despite the wide frequency range ($f \in \langle 0.1;\ 6 \rangle$ GHz), constant material parameters of concrete were adopted, often used only for f = 1 GHz. In most of the analyzes of the distribution of the electromagnetic field inside the structure with the use of concrete, the information on its components, moisture and hardness is omitted. Most of the authors use the data on the electrical properties of concrete that relate to the material after the complete hydration of the cement slurry, as well as the production and processing process. The range of the assumed values is quite wide, i.e. the relative electric permittivity $\varepsilon_r' \in \langle 3;\ 12 \rangle$ and the conductivity $\sigma \in \langle 0;\ 0.3 \rangle$ S/m.

The aim of this study is to analyze the influence of the concrete wall structure and the wall with reinforcement on the field strength values at the frequency used in wireless communication (f = 5 GHz). The study also analyzed the influence of the variability of electric permittivity and conductivity on the values of electric field intensity. The influence of the reinforcement inside the load-bearing wall, its diameter and the spacing between the bars on the distribution of the electromagnetic field was also analyzed. Four typical dimensions of the reinforcement diameter and two variants of the spacing between the bars were also taken into account. Calculations and discussion of the results obtained with the most frequently used electrical parameters of concrete were carried out.

The selection of the values of the parameters of the modeled material has a large impact on the results of calculations, which are to facilitate the understanding of wave phenomena, determine the attenuation of a given material, or help in planning the location of field sources for wireless networks in order to obtain good communication quality.

Electrical parameters of concrete

Concrete is created as a result of setting and hardening of a mixture consisting of a binder (cement), filler (aggregate) and water, and possible additives giving the desired features [9, 10].

The composition of the mixture is selected so as to obtain concrete with the expected mechanical strength and resistance to external factors. Additives and admixtures improve the properties of concretes, e.g. increase workability, frost resistance, water tightness, but at the same time differentiate their electrical properties [9]. The concrete classification depends on the dry density (i.e. heavy concrete, normal concrete, lightweight concrete). The main purpose of ordinary concrete is the construction of load-bearing walls, columns and ceilings (with the use of reinforcement), which constitute the structure of the structure, especially in large-panel technology.

Concrete acquires its properties through the hydration of the cement. For this reason, an important parameter is w/c ratio, which determines the strength, compactness, and thus long-term durability of the concrete casting [9]. The reduction of the w/c ratio results in a more compact and resistant surface of the concrete casting which delays the penetration of e.g. mineral salts, oxygen, moisture and carbon dioxide and therefore significantly increases the service life of the concrete structure. Design requirements and standards [10] strictly define the permissible amount of cement and the value of the w/c ratio.

Due to the variety of factors influencing the obtaining of hardened concrete, determining the values of electrical parameters is the subject of numerous studies [11, 16, 17]. In the available literature, ordinary concrete is the most frequently considered in terms of electrical parameters. In many cases, information about the type of concrete and its components is omitted. The authors occasionally deal with lightweight concrete [1, 6]. The electrical parameters of concrete depend on:

- the amount and type of concrete mix components, e.g. grain size and shape;
- the quality of the cement mortar, in particular the value of the w/c ratio.

Table 1 shows the assumed electrical values depending on the frequency, collected on the basis of the available literature.

Most of the authors use electrical parameters that relate to the material after the complete hydration of the cement slurry as well as the production and processing process. The publications [6, 40] take into account the type of analyzed concrete (eg dry, wet, 40-year-old). Based on the article [40], it can be concluded that the real component of the concrete dielectric permittivity ε_r' reaches a constant value only one month after pouring, when the hydration process is practically completed. The stabilization of the imaginary component value ε_r'' depends on the moisture reduction process and it is assumed that this period is approximately 14 months.

Table 1. Electrical properties assumed for the description of concrete

f [GHz]	ε_r'	ε_r''	σ [S/m]	References
10^{-6}÷0.1	13	-	0.0001÷0.02	[18]
0.15÷0.6	6	-	-	[19]
0.245	4.7÷7.6	-	-	[20]
0.3÷35.0	4.0÷7.5	0.38÷1.4	-	[11]
0.4÷4.0	3	-	-	[21]
0.5÷2.0	6	0.01	-	[22]
0.5 0.9 2.5	5.0÷12.0	-	-	[23]
0.8	7.1÷7.5	-	-	[24]
0.9	6.26	-	0.037	[25]
0.9	3	-	$1.95\cdot10^{-3}$	[26]
0.9	6.1	-	$1.95\cdot10^{-3}$	[26]
0.9	6 7 8	0.25 0.3 0.35	-	[27, 28]
0.948	5	-	0.004	[29]
1.0÷2.0	6.07÷5.87	-	0.0684÷0.083	[30]
1.0÷2.0	6	-	0.1	[30]
1.0÷3.0	3.0÷6.0	-	$1.95\cdot10^{-3}$	[31]
0.1÷6.0	6	-	$1.95\cdot10^{-3}$	[15]
1.0÷95.9	6.2÷7.0	0.34÷0.85	-	[6]
1.5	6.398	-	0.182	[17]
1.5	5.113	-	0.031	[17]
1.5	6	-	0.01 (0.05÷0.25)	[17]
1.8	6	-	$1.95\cdot10^{-3}$	[32]
1.8	7	0.3	-	[33]
1.8	6	-	$1.95\cdot10^{-3}$	[5, 32]
1.8	7	0.35	-	[27]
1.8	7	0.3	-	[34]
1.8	7	0.25 0.30	-	[27]
1.865 2.14	5	-	0.004	[29]
2.4	6	-	$1.95\cdot10^{-3}$	[5, 35, 36]
2.4	8	-	0.01	[35]
3	3	0.03	-	[33]
3.1÷10.6	6	-	-	[19]
3.0 9.0 24.0	5.0÷7.0	0.1÷0.7	-	[6]
5	5.5	-	0.0501	[37]
5	4.6	-	0.0668	[2]
10	5.1	0.4	-	[16]
10	6	1	-	[16]
10.38	6	-	-	[38]
57.5	2.55	0.084	-	[39]
57.5	2.55	0.081	-	[40]
57.5	6.5	0.43	-	[40]
60	6.4954	-	1.43	[2]

In the article [11] were presented the results of the research in which the changes in the real and imaginary components of concrete dielectric permittivity as a function of frequency were determined. Three variants of the w/c ratio were taken into account. In the analyzed band from 0.1 GHz to 100 GHz, the characteristics show a typical course. The real component of permittivity decreases, but in the case of dry concrete (w/c = 0.1), the decrease from the value of $\varepsilon_r' = 4.2$ (f = 0.1GHz) does not exceed 7%. With an increase in the proportion of water (w/c = 0.3), the value of the real component is subject to changes up to 25%, with f = 0.1 GHz being 7.3. The imaginary component characteristics for each material sample (w/c changes) reach their maximum at a frequency of approx. 100 GHz. Increasing the proportion of water leads to an intensification of the effects related to the occurrence of losses due to displacement currents, i.e. a higher value of the w/c coefficient means an increase in the value of the imaginary component of permittivity. This is due to the increase in the number of ions formed as a result of the dissociation of selected components in water.

Construction of numerical models

At the beginning, the influence of electric permittivity and conductivity of concrete on the values of electric field intensity was analyzed. In the next step, the reinforcement in the form of steel rods was introduced in the earlier model, and on this basis, the analysis of the obtained results was carried out. The numerical model assumed that on both sides of the wall there is an open space with the properties of air, devoid of other elements that may disturb the propagating electromagnetic wave and affect the field distribution in the system. It was assumed that the dimensions of the wall perpendicular to the direction of wave propagation (wall width and height) are much greater than the wavelength. Therefore, it was possible to:

- application of a two-dimensional numerical model of the analyzed system;
- reducing its size by applying appropriate boundary conditions, including the periodicity of the field distribution.

The adopted assumptions allow to determine the influence of the building material (concrete or concrete with reinforcement) on the field strength values. The analysis was carried out on the basis of the observation of the electric field strength in the area of 3 m behind a wall with a thickness of b = 0.24 m. The analysis was carried out at the frequency f = 5 GHz.

The variability of the electrical parameters of concrete (Tab. 1) resulted in a multivariate analysis. Taking into account the available electrical parameters of concrete, the values of the relative permittivity $\varepsilon_r' \in \{5; 6; 7; 8\}$ were adopted for further analysis. The influence of the change in conductivity was also considered ($\sigma \in \langle 0; 0.3 \rangle$ S/m).

For the analysis of the electromagnetic field distribution inside complex structures, differential methods are often used, e.g. Finite Difference Time Domain (FDTD) [41], as well as the Finite Element Method (FEM) [42]. To determine the electric field strength, the finite difference method with direct integration of Maxwell's equations in the FDTD time domain was used [37, 41]. Thanks to the use of this method, it is possible to analyze and visualize wave processes occurring in steady and transient states during the propagation of electromagnetic waves with complex waveforms. The FDTD method is based on Maxwell's equations

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad (1)$$

$$\nabla \times \mathbf{H} = \mathbf{J}_P + \mathbf{J}_D + \mathbf{J}_I. \quad (2)$$

The $\mathbf{J}_P$ conduction current and $\mathbf{J}_D$ shift current density are expressed by the dependencies:

$$\mathbf{J}_P = \sigma \mathbf{E}, \quad (3)$$

$$\mathbf{J}_D = \frac{\partial \mathbf{D}}{\partial t}, \quad (4)$$

and $\mathbf{J}_I$ is the forcing current density vector.

Equation (1) and (2), after applying decomposition in the Cartesian coordinate system, are presented in the form of six scalar, interdependent differential equations describing the individual components of the electric and magnetic field. The determination of the field changes in the model area is performed assuming an appropriate, defined distribution of the components of the electric field intensity **E** and magnetic **H**. The determined spatial distributions of physical quantities $\{E_x, E_y, E_z, H_x, H_y, H_z\}$ are assigned at selected points in the area (x, y, z), taking into account the discrete, finite size of the integration step over the area (Δ_x, Δ_y, Δ_z).

The FDTD method consists in creating a discrete model composed of Yee cells and calculating the field distributions assuming a linear approximation of changes [37, 41]. Due to the linear approximation of the field changes in the differential scheme, the constructed mesh must meet the Nyquist condition [37, 41]

$$\Delta_x \le \frac{\lambda}{2}. \quad (5)$$

Equation (5) is a necessary but not perfect criterion for creating a model. Due to the effects of numerical dispersion of the differential grid and the desire to increase the precision of spatial mapping of field changes, in practice the condition is

$$\max(\Delta_x, \Delta_y, \Delta_z) \le \frac{\lambda}{10}. \quad (6)$$

The behavior of the condition (6) limits the effects of numerical dispersion to the level of 5% compared to the real values of the field in model systems [37, 41].

The analysis of the selection of the size of the differential mesh was made on the basis of the observation of the maximum value of the E_z component denoted by max(E_z) in the area behind the wall. Based on the tests and assumption (6), the calculations assumed the size of the difference cell $\Delta_x = \Delta_y$ =0.5 mm. In the created model, the number of Yee cells per wavelength in the dielectric was in the range of $\langle 42; 53 \rangle$. The lower value corresponds to the value of ε_r' = 8. In the adopted construction of the numerical model, the resolution of the differential grid guaranteed the fulfillment of the Nyquist condition.

The field forcing in the system was a harmonic plane wave polarized linearly, propagating in the direction of the axis *Oy*

$$\mathbf{E}(x, y, t) = E_z \mathbf{1}_z = \sin(\omega t) \cdot 1(t) \cdot \mathbf{1}_z. \quad (7)$$

Propagation in open space were mapped by adopting PML absorption conditions at the edges perpendicular to the direction of plane wave propagation [37, 41]. In line with the described assumptions, periodic conditions were adopted on the surfaces of the model parallel to the direction of wave propagation, guaranteeing the development of the area and periodicity of the field distribution.

The results of the analysis of the model with a wall made of concrete

Based on the multivariate analysis, the influence of the variability of concrete material parameters on the values of the electric field intensity was determined (Fig. 1). In the range of small conductivity values (σ < 0.04 S/m), the highest values of the field strength were observed for ε_r' = 5. However, for higher conductivity values for ε_r' = 5, the values of max(E_z) were the lowest. The inverse relationship was noticed for ε_r' = 8, where for small values of conductivity max(E_z) it was the lowest of all assumed values of electric permittivity. And even 30% lower than for ε_r' = 5. However, above σ = 0.04 S/m, the values of max(E_z) were the highest of all analyzed variants.

With conductivity $\sigma \in \langle 0.04; 0.3 \rangle$ S/m characteristics are already stable. Higher values of the relative electric permittivity of concrete result in an increase in the maximum field values. Increasing the loss of the material causes that the main role is played by wave attenuation during its passage through the dielectric. The wave overlap effects related to the internal reflection at the concrete-air interface are of less importance. This is due to the significant damping of the reflected components when passing through the lossy medium (building material). However, it should be remembered that the basic values of the conductivity of dry concrete are within the range of σ < 0.1 S/m.

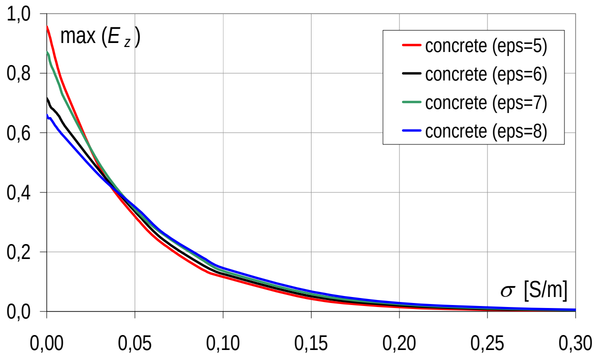


Fig.1. Changes in the max(E_z) value depending on the conductivity for different values of relative dielectric permittivity

Models with a wall made of concrete with reinforcement

The propagation of electromagnetic waves and the phenomena related to it in homogeneous building materials are predictable and can be calculated using analytical methods. On the other hand, complex construction materials, e.g. concrete with reinforcement, require a precise numerical analysis [17]. Based on the previously conducted literature review related to the values of electric parameters of concrete taken for analysis (Tab. 1) and the results of the numerical analysis, in the next step, the influence of the reinforcement on the values of the electric field intensity was analyzed. Various values of electrical parameters of concrete, variability of the reinforcement diameter and four variants of the spacing of reinforcing bars were taken into account.

Two reinforcement systems were considered: with one row of reinforcing bars (1p) and with two rows (2p) (Fig. 2).

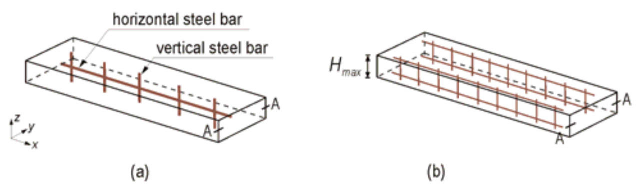


Fig.2. Three-dimensional view of the concrete wall model with reinforcement, where: A-A denotes the plane on which the field intensity distribution for the model was assessed: (a) 1p; (b) 2p

The analysis also took into account two distances between the vertical reinforcement bars (L) (Fig. 3):

- L10(1p): with one row of rebars and spacing L=0.1 m;
- L10(2p): with two rows of rebars and spacing L=0.1 m;
- L20(1p): with a larger spaceing e.g. L=0.2 m and one row of rebars;
- L20(2p): with a larger spaceing e.g. L=0.2 m and two rows of rebars.

Additionally, in each of the models, various variants of the wall were analyzed, taking into account the change in the reinforcement diameter $fi\in$\{0.006; 0.008; 0.01; 0.012\} m.

The field distribution in individual variants was observed on the basis of determining the electric field strength in the area behind the wall. The values of the relative electric permittivity of concrete $\varepsilon_r'\in$\{5; 6; 7; 8\}. Due to the fact that in the publications there is a large discrepancy in the accepted data, additionally, with the selected ε_r', the variability of the electric field intensity value depending on the conductivity $\sigma\in$\{0.00195; 0.004; 0.01\} S/m.

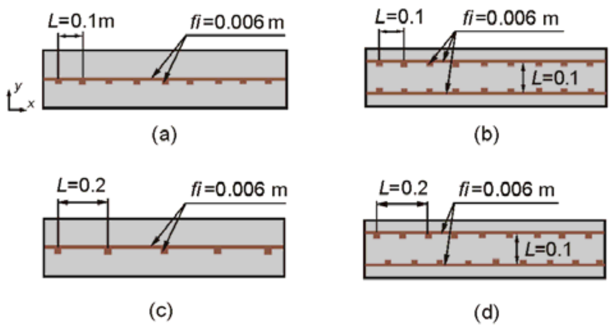


Fig.3. Variants of the analysed walls: (a) L10(1p); (b) L10(2p); (c) L20(1p); (d) L20(2p)

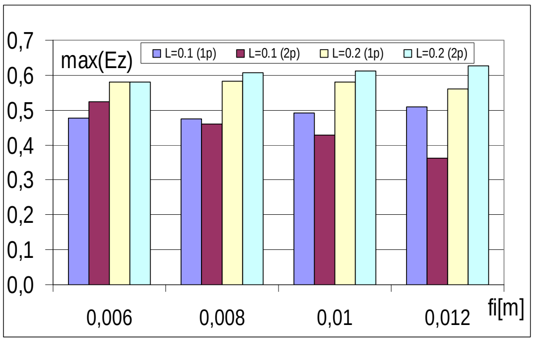
Calculation results of models with reinforcement

Figures 4-6 show the influence of the reinforcement diameter on the field intensity values, taking into account the variability of the electric permittivity, conductivity as well as the number of rows of bars and the spacing between them. The presented results were calculated for the systems in the steady state. The obtained results of the analysis of reinforced concrete walls indicated that:

- irrespective of the conductivity value and the diameter of the reinforcement, at $\varepsilon_r'\in$\{5; 6; 7\}, a doubling of the spacing between the bars (L = 0.2 m) results in an increase in the max(E_z) value in relation to the models with L = 0.1 m (Figs. 4a, 4b, 4c, 5a, 5b, 5c); the greatest differences are visible at ε_r' = 5 between the L10(1p) and L20(2p) models and amount to even 80% (Figs. 4a, 5a, 6a);
- the above relationship does not apply to the analysis of reinforced concrete with a relative permittivity ε_r' = 8, within the range of a small diameter of the reinforcement $fi\in$\{0.006; 0.008\} m (Figs. 4d, 5d, 6d), where the greater spacing reduces the recorded value of the field intensity by a maximum of 11%;
- with the spacing L = 0.1 m, increasing the number of bars 'rows does not change the field value only in the case of ε_r' = 5, σ = 0.004 S/m and fi = 0.01 m (Fig. 4b), and the difference of 1% occurs in the models calculated with assumption: ε_r' = 6, $\sigma\in$\{0.00195; 0.004; 0.01\} S/m at fi = 0.01 m (Figs. 4b, 5b, 6b).

With a larger spacing (L = 0.2 m), the values of the electric field strength are similar (difference up to 1%) between models with one and two rows of reinforcement, provided that the following parameters are maintained: ε_r' = 5, σ = 0.00195 S/m, fi = 0.006 m (Fig. 4a) and ε_r' = 6, σ = 0.004 S/m, fi = 0.01 m (Fig. 5b), as well as at ε_r' = 8, $\sigma\in$\{0.00195; 0.004\} S/m, fi = 0.008 m (Figs. 4d, 5d).
Greater differentiation of values was noticed with different selection of electrical parameters of concrete, diameter of reinforcement or the number of rows of bars. With a larger bar spacing (L = 0.2 m), it was found that, regardless of the reinforcement diameter, the model with two rows of bars and ε_r' = 5, σ = 0.004 S/m (Fig. 5a) has 10% higher max(E_z) values. However, for all analyzed models, with ε_r' = 8, σ = 0.01 S/m for fi = 0.008 m, the field strength values differ only by 10% (Fig. 4b).

a)



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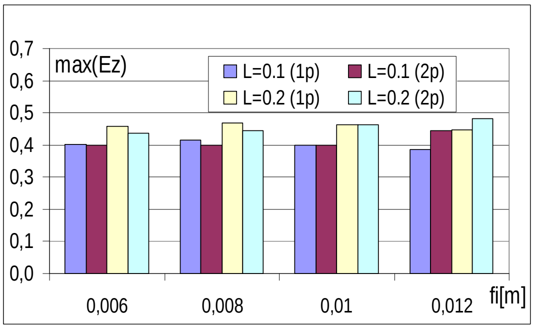

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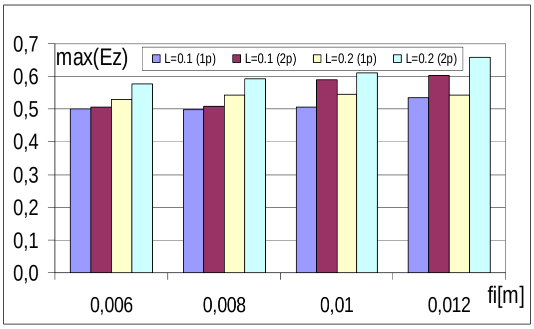

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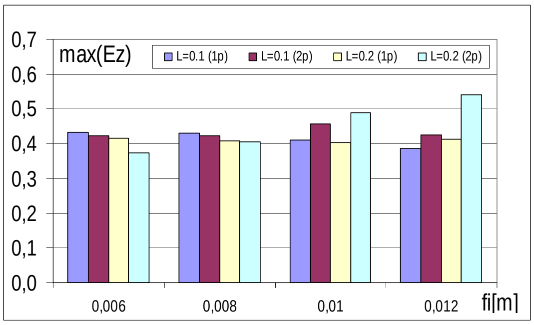
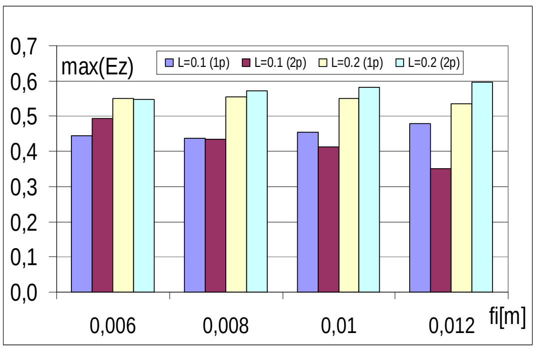


Fig.4. The influence of the diameter of the reinforcement on the max(E_z) value with the conductivity σ=0.00195 S/m and the relative electric permittivity : (a) ε_r'=5; (b) ε_r'=6; (c) ε_r'=7; (d) ε_r'=8

a)



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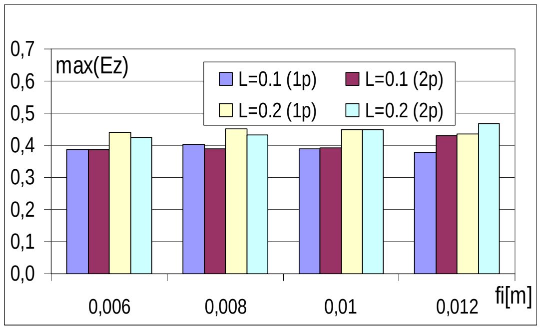

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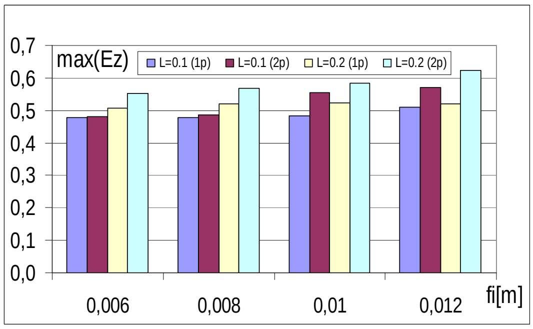

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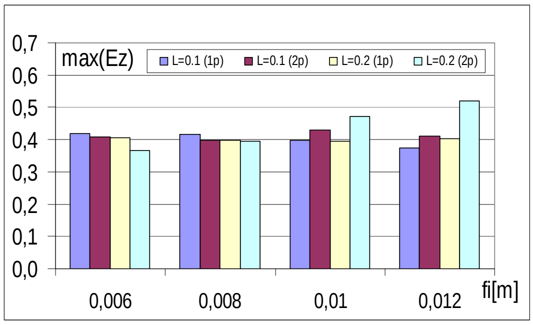
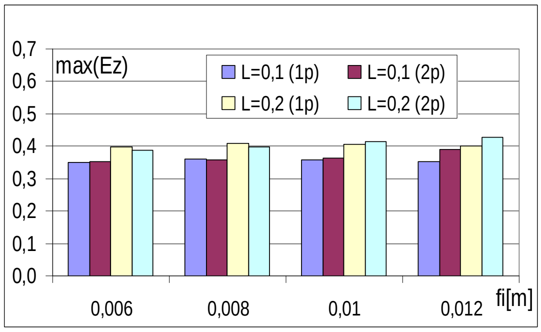


Fig.5. The influence of the diameter of the reinforcement on the max(E_z) value with the conductivity σ=0.004 S/m and the relative electric permittivity : (a) ε_r'=5; (b) ε_r'=6; (c) ε_r'=7; (d) ε_r'=8

a)



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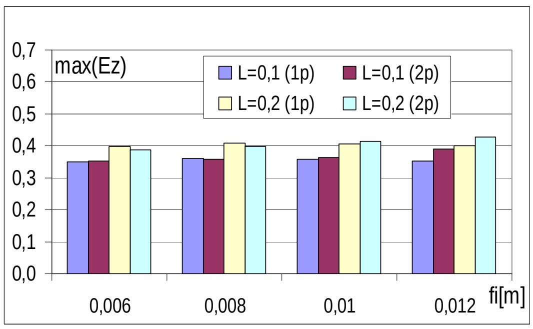

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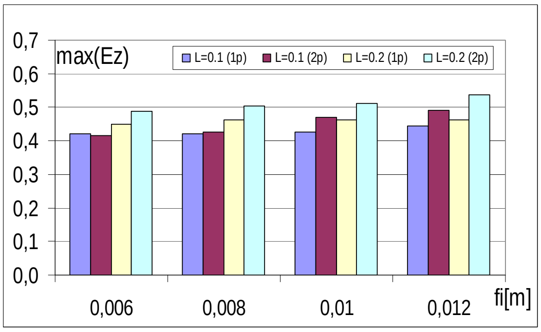

d)

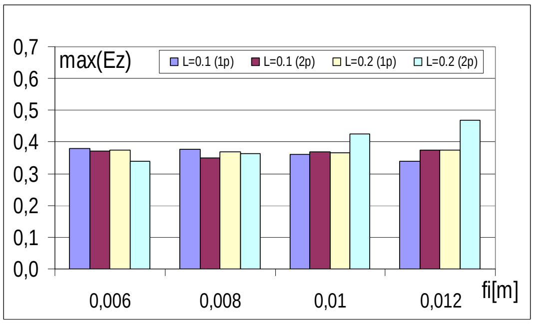

Fig.6. The influence of the diameter of the reinforcement on the max(E_z) value with the conductivity σ=0.01 S/m and the relative electric permittivity: (a) ε_r'=5; (b) ε_r'=6; (c) ε_r'=7; (d) ε_r'=8

Conclusions

The article presents an analysis of the influence of electric parameters of concrete on the values of electric field intensity. Also, a multivariate analysis of the influence of the reinforcement diameter and the spacing between the bars used in reinforced load-bearing walls on the values of the electric field intensity was performed. A detailed analysis of the considered variants showed that a double increase in the number of rows of reinforcement, regardless of the bar spacing and conductivity value, results in a maximum 1% change in the max(E_z) value in models with the analysis parameters ε_r' = 6, also with the same reinforcement diameter (*fi* = 0.01 m) (Figs. 4b, 5b, 6b).

As the analysis shows, the selection of the electrical parameters of concrete has a large impact on the obtained values of the electric field strength. It is an important aspect due to the correct interpretation of wave phenomena occurring inside material structures used in construction. It should be emphasized that each building material is characterized by the variability of electrical parameters resulting, among others, from from atmospheric factors that are often ignored in the analysis of such issues.

The presented analysis proves that due to the complex phenomena related to the propagation of electromagnetic waves through reinforced concrete, the effective value of the field strength behind the wall with reinforcement depends on: the parameters of the concrete, as well as the reinforcement elements directly affecting the size of the effective surface that absorbs the electromagnetic wave.

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