# ELECTROMAGNETIC PROPERTIES OF CEMENT-BASED MATERIALS OVER TIME AT MICROWAVE FREQUENCIES

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*Keywords – Microwave frequencies, cement-based materials, mortar, concrete, hydration, water-cement ratio, curing, dielectric permittivity, attenuation, phase velocity, penetration depth*

## ABSTRACT

**The results of measurement and calculation of electromagnetic properties of cement-based materials (mortar and concrete) during several months of their service lives, and at different curing conditions at microwave frequencies (X-band) are presented. Dependencies of complex dielectric permittivity of the materials, attenuation, phase velocity, wavelength and penetration depth of electromagnetic waves on water-cement ratio, preparing and curing conditions of the specimens are demonstrated. The complex dielectric permittivity of the cement-based materials is calculated by a new method using only the amplitudes of the reflection and transmission coefficients of the electromagnetic wave. The expected applications of the results are discussed.**

## I. INTRODUCTION

Cement-based materials (cement paste, mortar, concrete etc.) are widely used in many structures of the construction industry. Knowledge of physical properties of such materials is important for determination of their quality. For example, one of the most important parameters associated with concrete is its compressive strength, which depends on water-cement ratio, density etc.

Microwave non-destructive techniques have shown great potential for the determination of properties and water content of different materials [1]. On the other hand, knowledge of the electromagnetic properties of cement-based materials are needed in propagation-related research, for example, microwave propagation modeling to develop indoor wireless communication systems [2,3]. This is because the reflection and transmission characteristics of buildings, walls etc are governed by these dielectric properties.

It is known that dielectric properties of cement-based materials change during the service time. During the hydration process the water and cement molecules chemically combine into a binder, transforming the initial free water into bound water, consequently, dielectric properties of the material change. Recent investigations [4,5] have demonstrated the capability of microwaves to detect the state and degree of chemical reaction (hydration) in cement-based materials. It was shown a strong correlation between the magnitude of the reflection coefficient of microwave signals and the water-cement ratio of cement-based materials by using a near-field microwave inspection technique. Although the results are promising, only reflection properties of smooth plane surfaces of the specimen can be investigated by this contacting method. Besides, it can’t provide measurement of reflection and transmission properties of such materials in propagation-related research. By means of the free-space method [6-9], penetration of microwaves in lossy specimens with smooth, rough and non-plane surfaces and their reflection and transmission properties can be investigated. In practical applications it is very attractive to determine the dielectric properties of the materials by using only amplitudes of the reflection and transmission coefficients [7-9].

In this paper the temporal dependencies of electromagnetic properties of cement-based materials are presented. First, theoretical foundations of the problem are given. Then, results of the measurement and calculation of cement-based materials’ properties during several moths of their service lives with different curing conditions are presented. Finally, the results and their expected applications are discussed.

## II. THEORETICAL FOUNDATIONS

When an electromagnetic plane wave is transmitted in lossy dielectric, the attenuation constant, $\alpha$, the phase constant, $\beta$, the penetration depth, $\delta$, phase velocity, $v$, and wavelength, $\lambda$, in the dielectric can be expressed as

$$\alpha = \omega(\frac{\mu_0 \varepsilon' \varepsilon_0}{2})^{1/2}[(1+(\varepsilon''/\varepsilon')^2)^{1/2}-1]^{1/2} \quad (1)$$

$$\beta = \omega(\frac{\mu_0 \varepsilon' \varepsilon_0}{2})^{1/2}[(1+(\varepsilon''/\varepsilon')^2)^{1/2}+1]^{1/2} \quad (2)$$

$$\delta = 1/\alpha \quad (3)$$

$$v = \omega/\beta \quad (4)$$

$$\lambda = v/f \quad (5)$$

Here, $\omega$, $\lambda_0$, $\varepsilon'$, $\varepsilon''$ and $\mu_0$ are the angular frequency of the incident wave, the wavelength in free-space, real and imaginary parts of the dielectric permittivity, and permeability of the material, respectively ($\mu_r$ =1).

In experimental techniques, the attenuation A is measured in decibels at a distance d defined as

$$A = -20\log[\exp(-\alpha d)] \quad (6)$$

From the above expressions, it is seen those $\alpha, \beta, \delta, v, \lambda,$ and $A$ are functions of complex dielectric permittivity $\varepsilon = \varepsilon' - j\varepsilon''$. Using the measured values for amplitude of the reflection and transmission coefficients, the complex permittivity can be determined by graphical or numerical methods.

When the wave travels from the radiating antenna to the receiving antenna through the two media of the air and sample with thickness d, the reflection occurs at the interfaces of the air-sample and multiple reflections occur between each sides of the sample. If the reflection coefficient at the first interface air-sample is denoted by $r_{12}$, **t**he total reflection coefficient and transmission coefficient can be written as:

$$r = \frac{r_{12}(1 - e^{-j2\Theta})}{1 - r_{12}{}^2 e^{-j2\Theta}} \quad (7)$$

$$t = \frac{(1 - r_{12}{}^2)e^{-j\Theta}}{1 - r_{12}{}^2 e^{-j2\Theta}} \quad (8)$$

where

$$\Theta = k_s d, \quad k_s = \alpha + j\beta = \frac{2\pi}{\lambda_0}\sqrt{\varepsilon} \quad (9)$$

For high-lossy materials, the expressions for *r* and *t* can be simplified. We assume that the sample has large enough attenuation that the multiple reflections between the two surfaces of the sample can be neglected. Then *r* and *t* are written as

$$r = r_{12} \quad (10)$$

$$t = (1 - r_{12}{}^2)e^{-j\Theta} \quad (11)$$

In experimental techniques, the amplitudes of reflection and transmission coefficients $|r|$ and $|t|$ are measured in decibels defined as

$$T = -20\log|t|, \qquad R = -20\log|r| \quad (12)$$

To find the permittivity by a numerical method, equations in (10) and (11) should be solved together by using the appropriate root-finding algorithm methods, for example the interval-halving method [10].

## III. MATERIAL PROPORTIONS

The raw materials of the specimens are shown in the Table1.

**Table 1**. Mass percentages of raw materials for the cement-based specimens.

| | | Water | Cement | Sand | Gravel | Water/cement |
|---|---|---|---|---|---|---|
| Mortar | I | 13.79 | 34.48 | 51.73 | -- | 0.4 |
| Mortar | II | 21.87 | 31.25 | 46.88 | -- | 0.7 |
| Concrete | I | 6.78 | 16.95 | 25.42 | 50.85 | 0.4 |
| Concrete | II | 11.29 | 16.13 | 24.19 | 48.39 | 0.7 |

Cement is Portland-cement, 100 % of the sand mass consists of particles less than 4 mm in diameter, 100 % of gravel consists of particles more than 4 mm in diameter. Coarse aggregates have a maximum size of 16 mm. The used aggregates are natural one's obtained from the river and they are round shaped.

## IV. RESULTS AND DISCUSSION

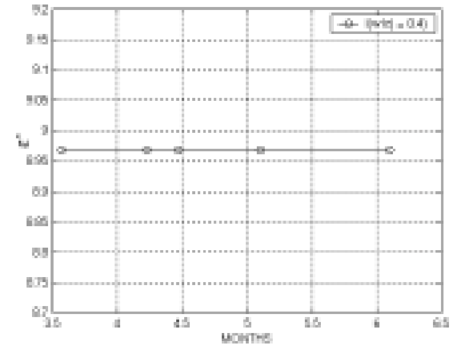
Measurements of specimens' reflection and transmission properties were conducted during several months at frequencies of X-band (8 – 12 GHz) by using an automated reflection/transmission measurement set –up [8]. The samples were saved at ordinary room conditions.

Fig.1 and Fig.2 show results of the numerical calculation of the complex dielectric permittivity of mortar by using measured values of | r | and T. They were obtained for approximately constant amplitude of reflection coefficients: $|r| = 0.5 \pm 0.0001$ for w/c = 0.4 and $|r| = 0.46 \pm 0.0001$ for w/c = 0.7. In an ideal case | r | decreases a little with time, but in a real situation there are some variations in the values of | r | due to environment influence. Measured values of T are shown in the Table 2.

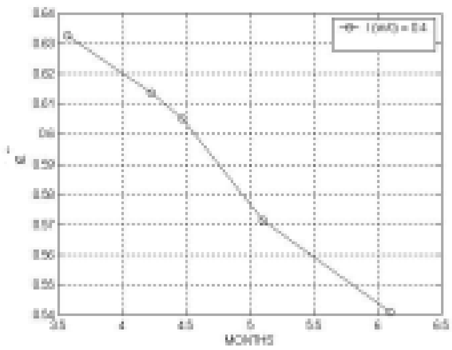
It can be seen from Fig.1 and Fig.2 that the real part of permittivity is approximately constant, while the imaginary part decreases with time because the imaginary part of the dielectric permittivity mainly determines the transmission coefficient. It was expected that the imaginary part of the permittivity of each specimen decrease with the decrease of water content because of desiccation of water.

**Table 2**. The transmission coefficients over time for different water-cement ratios with (w/c) = 0.4 for $T_I$ and (w/c) =0.7 for $T_{II}$.

| Time (Months) | $T_I$ (dB) | $T_{II}$ (dB) |
|---|---|---|
| 3.57 | 32.4 | 20.00 |
| 4.23 | 31.5 | 18.70 |
| 4.47 | 31.1 | 18.25 |
| 5.1 | 29.5 | 17.50 |
| 6.1 | 28.05 | 15.50 |




(a)



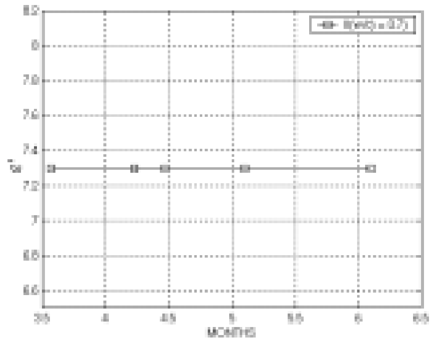

(b)

**Fig. 1.** The real(a) and imaginary(b) parts of the permittivity of mortar with w/c=0.4 over time.

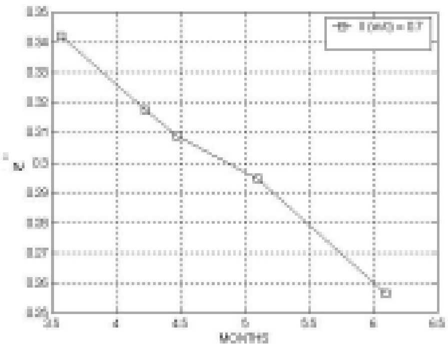
However, it can be seen from Fig.1 and Fig.2 that a lower value of $\varepsilon$" corresponds to higher water-cement ratio. This indicates the existing differences between structures or densities inside the specimens with different water-cement ratio. The main reason can be porosity inside the specimens. It is well known that the higher porosity corresponds to higher water-cement ratio [11]. It should be noted that higher relative rate of the imaginary part corresponds to higher water-cement ratio. The values of the real part of the permittivity have a good agreement with well-known data at about 10 GHz [12].

Temporal dependencies of the attenuation constants, phase constants and penetration depths for two values of water-cement ratio are shown in Figures 3, 4 and 5, respectively.

In general, they confirm the conclusions from results of the dielectric permittivity calculation.




(a)




(b)

**Fig. 2.** The real(a) and imaginary(b) parts of the permittivity of mortar with w/c=0.7 over time.

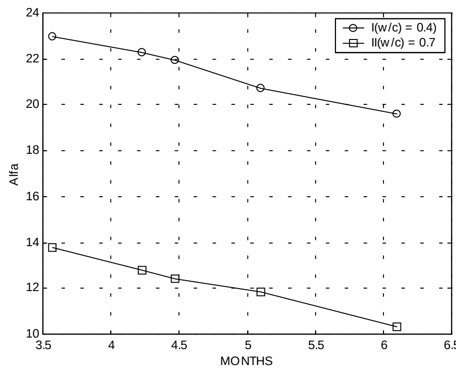



**Fig. 3.** The temporal dependences of attenuation constants for two water-cement ratio values.

We can note that the difference between the values of the attenuation constants and penetration depths for the different water-cement ratios is experimentally measurable, and these values or the attenuation in dB can be used to monitor the water-cement ratio of hardened cement-based specimens. Besides, the phase constant is approximately stable for each specimen. It means that phase velocity and wavelength for these specimens are constant and that they are determined by the real part of the dielectric permittivity for used preparing and curing conditions of the specimens. The common features of considered electromagnetic properties for mortar and concrete specimens are the same.

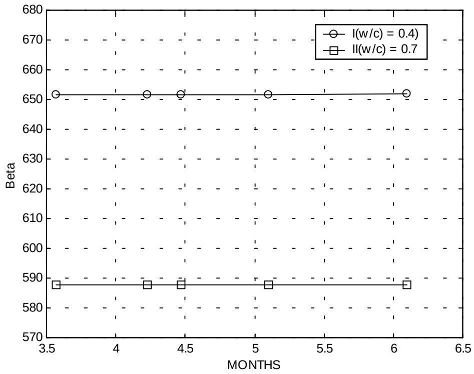



**Fig. 4.** The temporal dependences of phase constants for two water-cement ratio values.

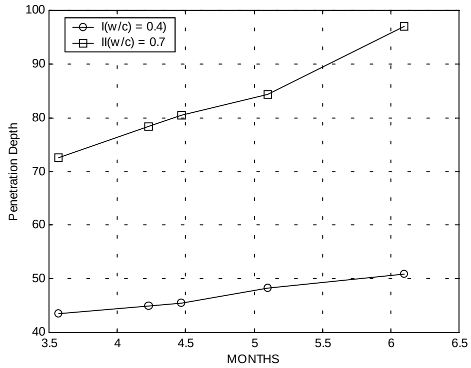



**Fig. 5.** The temporal dependences of penetration depths for two water-cement ratio values.

## V. CONCLUSION

The temporal dependence of electromagnetic properties of cement-based materials (mortar and concrete) at microwave frequencies (X-band) has been investigated. It is shown that for used ordinary room curing conditions for the materials the imaginary part of their dielectric permittivities and attenuation constant of the wave significantly decrease with time, while phase constants are approximately constant with time. It is discovered that a lower values of the imaginary part of the permittivity and attenuation constant corresponds to higher water-cement ratio. This indicates the existing differences between structures or densities inside the specimens with different water-cement ratio. The main reason can be porosity inside the specimens. Since the difference between the values of the wave attenuation for small difference of water-cement ratio is experimentally measurable, these values can be used to monitor the water-cement ratio of hardened cement-based specimens. These results can be used for quality control of cement-based structures of the construction industry. Besides, they can give useful information for propagation–related research, for example, microwave propagation modelling to develop indoor wireless communication system.


## ACNOWLEDGMENT

The authors would like to thank to the TUBITAK (The Scientific and Technical Research Council of Turkey) for supporting this work.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