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Measurement and Monitoring of Microwave Reflection and Transmission Properties of Cement-Based Materials for Propagation Modeling

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Abstract

In this paper a non-destructive, contactless free-space method is used for measurement and monitoring of cement-based materials' properties. The propagation factor, penetration depth and reflection and transmission coefficients of the plane wave, interacting with the high lossy specimen, is analysed.. Results of the measurement and monitoring of cement-based materials properties during all stages of their lives and different curing conditions are presented. The expected applications of the results for propagation modelling are discussed.

1. Introduction

Cement-based materials (cement paste, mortar, concrete etc.) are widely used in many structures of the construction industry. Knowledge of dielectric properties of such materials is important in propagation-related research, for example, microwave propagation modeling to develop indoor wireless communication systems [1,2]. This is because the reflection and transmission characteristics of building, walls etc are governed by these dielectric properties. It is known that dielectric properties of cement-based materials change during the service time. The water-to-cement ratio is one of the most influential factors in determining the dielectric properties of cement-based materials. 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 [3] 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-to-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 contact 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 [4,5], penetration of microwaves in different specimens with smooth, rough and non-plane surfaces and their reflection properties can be investigated. This method is not only non-destructive but also contactless. In general case, real and imaginary parts of the dielectric permittivity, ε' and ε'', can be determined by measurements of either reflection coefficient, r, or of the transmission coefficient, t, or of both. Reflection measurements require that the reference plane be well defined and the higher the more they are affected by the surface characteristics. However, they are convenient in some instances because the sensor can be placed on one side of the material. Transmission measurements have the advantage of providing more information on the whole volume, because the wave propagates through all the material in its path. When free space techniques are used, measurements are performed without the necessity for physical contact between the structure under test and sensor and in most instances there is no need for special structure preparation. Accurate measurements of r and t are obtained if edge diffraction, internal reflections and scattering effects are minimised.

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 [6].

In this paper a non-destructive, contactless free-space method is used and results of the measurement and monitoring of cement-based materials properties' are presented. First, the propagation factor, penetration depth and reflection and transmission coefficients of the plane wave interacting with the cement-based specimen has been analysed. It is shown that their complex dielectric permittivity can be determined by measuring the

amplitudes of reflection and transmission coefficients, $|r|$ and $|t|$, respectively, via free-space method and numerical calculation. Next, a description of the used modified free-space method is given. Then, results of the measurement and monitoring of cement-based materials' properties during all stages of hydration process and different curing conditions are presented. Finally, the results and their expected applications are discussed.
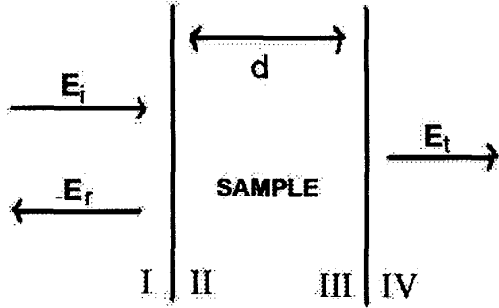

Fig.1. Typical situation in the measurement of the permittivity of a material using the free-space method.

2. Theoretical Foundations

A typical situation in the measurement of the permittivity of material using the free-space technique is shown in Fig.1.

The wave travels from the radiating antenna to the receiving antenna through the two media of the air and sample. Reflection occurs at the interfaces of the air-sample I and multiple reflections occur between each sides of the sample. The reflection coefficients are denoted by r_{12} at I, r_{21} at II, r_{23} at III and the transmission coefficients are denoted by t_{12} at I, t_{21} at II and t_{23} at III, respectively. Using the ray-tracing method, the total reflection coefficient can be written as

$$r = r_{12} + t_{12}r_{23}t_{21}e^{-j2\Theta} + t_{12}r_{21}r_{23}^{2}t_{21}e^{-j4\Theta} + \dots \quad (1)$$

where

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

$$\alpha = w(\frac{\mu_0\varepsilon'\varepsilon_0}{2})^{1/2}[(1+(\varepsilon''/\varepsilon')^2)^{1/2}-1]^{1/2}$$
$$\quad (3)$$

In the foregoing equations w, λ_0, d, ε and μ_0 are the frequency of the incident wave, the wavelength in free-space, thickness, dielectric permittivity and permeability of the material, respectively, $\mu_r = 1$.

When the equation (1) is simplified, we get

$$r = r_{12} + \frac{r_{23}t_{12}t_{21}e^{-j2\Theta}}{1-r_{21}r_{23}e^{-j2\Theta}} \quad (4)$$

by regarding the following well-known equations in (5).

$$r_{21} = -r_{12}, r_{23} = -r_{12}$$
$$t_{12} = 1+r_{12} \quad (5)$$
$$t_{21} = 1+r_{21} = 1-r_{12}$$

As a result reflection and transmission coefficients can be expressed as

$$r = \frac{r_{12}(1-e^{-j2\Theta})}{1-r_{12}^{2}e^{-j2\Theta}} \quad (6)$$

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

For high-lossy materials, the expressions for r, α 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. According to this assumption, only the first terms of the geometric series are sufficient to represent the reflection and transmission coefficients. When this is the case, r and t are written as

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

and α as

$$\alpha = w(\frac{\mu_0\varepsilon''\varepsilon_0}{2})^{1/2} \quad (9)$$

The penetration depth is defined as the distance from the surface of the material at which the power drops to $1/e$ from its value at the surface, that is,

$$D_p = \frac{1}{2\alpha} \quad (10)$$

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

$$T = -20\log|t|, \qquad R = -20\log|r| \quad (11)$$

From the above expressions, it is seen that R and T are functions of permittivity. That is,

$$R = R(\varepsilon', \varepsilon'') \quad (12)$$
$$T = T(\varepsilon', \varepsilon'')$$

For given measurement values of the amplitudes of the reflection and transmission coefficients (R_{mea} and T_{mea}), we can obtain the constant value lines of the reflection and transmission coefficients expressed by CR and CT:

$$CR = CR(\varepsilon', \varepsilon'') \quad (13)$$
$$CT = CT(\varepsilon', \varepsilon'')$$

The lines CR and CT are different than the measured values R_{mea} and T_{mea}. Using the numerical method, the lines CR and CT can be obtained. The necessary and sufficient condition for determining the complex permittivity from the measured values of R_{mea} and T_{mea} is that there is just one cross point between the lines CR and CT [6].

In **Fig.2** the lines *CR* and *CT* with several different measured values of R_{mea} and T_{mea} are shown. In the calculation, the frequency $f = 10.38$ GHz and the sample thickness $d = 150$ mm.
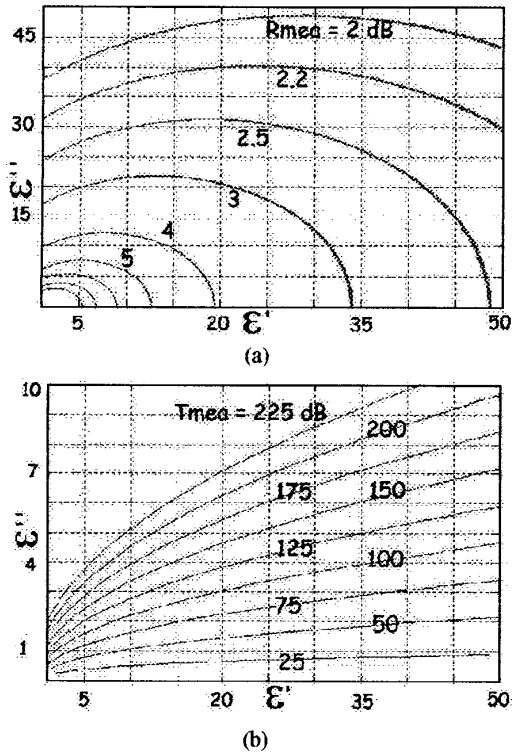

(a)

(b)

Fig.2. The constant value lines for the measured amplitudes of the reflection and transmission coefficients (a) CR (b) CT.

3. Method of the measurement

The investigations at X-band (8 – 12 GHz) are made for a variety of typical cement-based structures with different content, and dimensions, by the free-space method. The schematic diagram of the designed system is shown in **Fig.3**.

The microwave part of the measurement system is setup to determine the amplitudes of incident, reflected and transmitted waves as three separate parameters. The wave from the oscillator is used to feed the system. The waves, that are incident wave P_i, reflected wave P_r and transmitted wave P_t are used to measure the transmission and reflection coefficients.

As is seen from the figure of the setup, the sample can be placed between two horn antennas. The distance between the two antennas is adjusted according to the fact that maximum amount of wave should be received by the receiving antenna when there is no sample between the antennas.
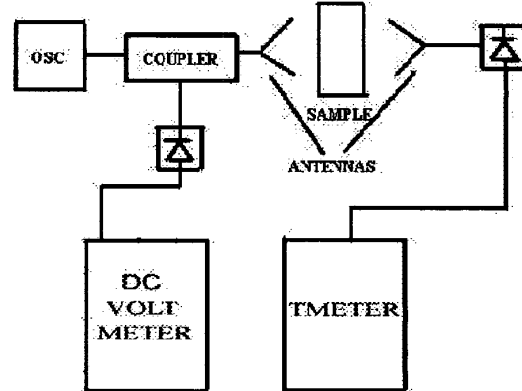

Fig.3. Schematic diagram of the measurement set up.

The electromagnetic wave coming from the oscillator is transmitted through a rectangular waveguide. Similarly; in the receiving part, the received wave collected by the receiving antenna is also transmitted through a rectangular waveguide. There are two directional couplers in the transmitting side. They are used for detecting the amplitudes of the incident and reflected waves.

The reference wave, reflected wave and transmitted wave are measured to determine $|r|$ and $|t|$. The reference levels of $|r|$ is set as 0 dB for full reflection and the $|t|$ is set as 0 dB for free space. For example, the detector output in the reflected arm is proportional to $A_p \sim p|r|^2$, and the constant of proportionality p have been found by using the metal plate.

Reflection coefficients for oblique incidence have been measured, too. They also will be calculated by using the same formulas. Then measured and calculated data will be compared to obtain empirical formulas or numerical methods for determination of the cement-based structure properties.
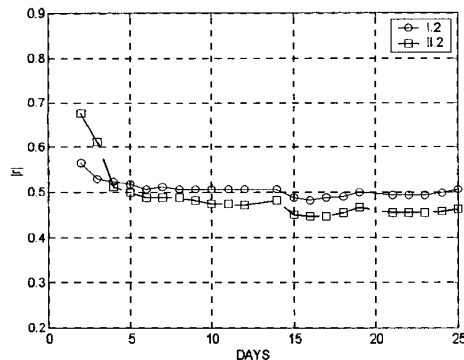
4.Results

Several cubic mortar and concrete specimens with different water-to-cement ratios were produced. Measurements of their reflection and transmission properties from all sides with different conditions were conducted daily during 28-day curing period at several frequencies of X-band (8 – 12 GHz).

For example, **Fig. 4** shows the results of the daily measurements of $|r|$ at 10.380 GHz for two mortar specimens with different water-to-cement ratio (I – w/c = 0.4, II – w/c = 0.7). Curves I.1 and II.1 correspond to sides with "wet" curing conditions, and curves I.2 and II.2

with "dry" curing conditions. "Dry" curing conditions correspond to the case where the measured side of the cement specimen is left unshielded when measurement process is not carried out. In this case, fast evaporation takes place. For "wet" curing conditions, the measured side of the specimen is enclosed when measurement process is not carried out. Therefore, "wet" curing conditions prevent the fast evaporation of water inside the cement specimen.
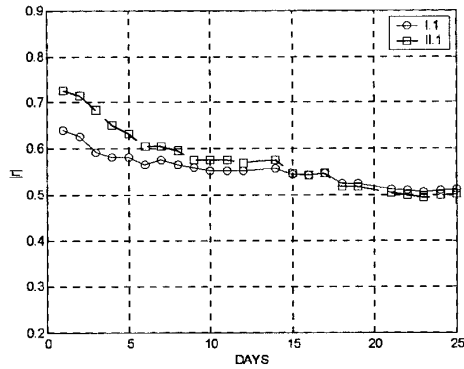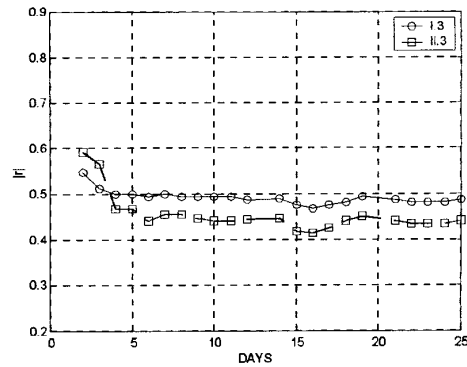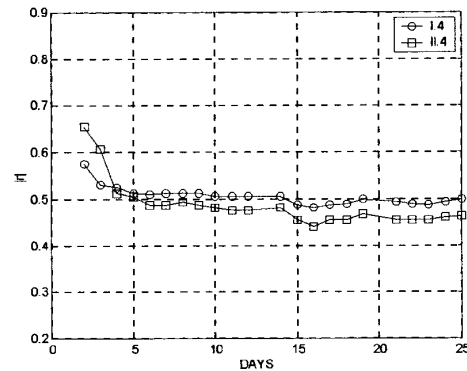

(a)

(b)

Fig.4. Amplitude of the reflection coefficient, | r |, of the two mortar specimens with different water-to-cement ratios over time for "wet" (a) and "dry" (b) curing conditions.

Fig. 5 shows the similar measurement results for "dry" curing conditions and different surfaces of the specimens. Curves I.3 and II.3 correspond to the reflection properties from the top surface whereas curves I.4 and II.4 correspond to the reflection properties of side surface of the specimen. Differences between the curves are due to the different preparing conditions.

(a)

(b)

Fig.5. Amplitude of the reflection coefficient, | r |, of the two mortar specimens with different water-to-cement ratios over time for dry curing conditions (a) side surface (b) top surface.

The main results are the following:
1) The values | r | in first days of hydration are higher for higher water-to-cement ratio specimens.
2) They rapidly decrease during the first several days of hydration. This is a result of the evaporation of free water from cement-based specimens. Speed of this process is different for different sides of the specimen and depends on w/c ratio and curing conditions.
3) After the first several days the measured | r | for lower water-to-cement ratio specimens are higher than those for higher water-to-cement ratios. This is a result of the influence of the bound water in the specimens.
4) The differences between measured | r | for different sides of the cubic for lower w/c ratio specimens are less than for those for higher water-to-cement ratios.

5) These differences increase during curing for the all ratios and depend on conditions in which the specimen is left to cure.

6) The common features of measured |r| for the mortar and concrete specimens are the same.

The transmission coefficients are very low for fresh cement-based specimens. They change during long time of specimens service lives. The results of the measurement of transmission properties for two mortar specimens during their service lives between 3rd and 6th months are shown in Fig.6.
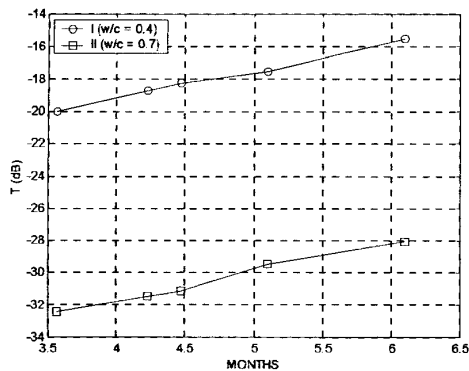

Fig.6. The transmission coefficient, T, in dB, of the two mortar specimens with different water-to-cement ratios over time.

It was expected that T of each specimens increases with the decrease of water content because of desiccation of water [1]. However, it can be seen from Fig.6 that a higher transmission coefficient corresponds to higher water-to-cement ratio. This indicates the existing differences between structures or densities inside the specimens with different water-to-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.

Thus, the reflection measurements demonstrates the potential of the indication of the water-cement ratio, hydration and curing of cement-based specimens at early stages of their service lives, while transmission measurements show opportunities to determine water-cement ratio, hydration and desiccation of water during long time of cement-based specimens service live. It should be noted that since the difference between the values of the transmission coefficients for small difference of water-to-cement ratio is experimentally measurable, these values can be used to monitor the water-cement ratio of hardened cement-based specimens. The common features of measured |r| and T for mortar and concrete specimens are the same.

5. Conclusions

The reflection and transmission properties of cement-based (mortar, concrete) materials by using the simple and contactless free-space technique have been investigated. The measurements indicated that the reflection coefficient changes during few days and then it is stable. In contrast, transmission coefficient changes during all service life. These coefficients depend on water-to-cement ratio and curing conditions. It is shown that a higher transmission coefficient corresponds to higher water-cement ratio. Since the difference between the values of the transmission coefficients 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 give useful information for propagation–related research, for example, microwave propagation modeling to develop indoor wireless communication system.

6. Literature

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