01 Jan 2002

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Sergey Kharkovsky
Missouri University of Science and Technology

M. F. Akay

U. C. Hasar

C. D. Atis

Recommended Citation

S. Kharkovsky et al., "Measurement and Monitoring of Microwave Reflection and Transmission Properties of Cement-Based Specimens," *IEEE Transactions on Instrumentation and Measurement*, Institute of Electrical and Electronics Engineers (IEEE), Jan 2002.
The definitive version is available at https://doi.org/10.1109/TIM.2002.808081

Measurement and Monitoring of Microwave Reflection and Transmission Properties of Cement-Based Specimens

Sergey N. Kharkovsky, *Member, IEEE*, Mehmet F. Akay, *Student Member, IEEE*, Ugur C. Hasar, *Student Member, IEEE*, and Cengiz D. Atis

***Abstract*—The results of measurement and monitoring of reflection and transmission properties of cement-based specimens (blocks of mortar, concrete) obtained by using a simple and an inexpensive measurement system at microwave frequencies (X-band) are presented. Dependencies of the reflection and transmission coefficients on water-to-cement (w/c) ratio, preparing and curing conditions of the specimens are demonstrated. It is shown that the amplitudes of reflection and transmission coefficients, together with thickness of the specimens, determine the complex dielectric permittivity of the hardened cement-based specimens. The expected applications of the results for the determination of physical properties of cement-based materials are discussed. The causes and effects of measurement errors and uncertainties are also discussed.**

***Index Terms*—Cement-based materials, concrete, curing, dielectric permittivity, free-space method, hydration, microwave measurements, mortar, reflection and transmission coefficients, w/c ratio.**

I. Introduction

CEMENT-BASED materials (cement paste, mortar, concrete) are widely used in the construction industry. Knowledge of the 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 is significantly influenced by the w/c ratio of concrete.

Microwave nondestructive techniques have shown great potential for the determination of physical properties and water content of different materials [1]. Microwave techniques are also capable of evaluating the properties of cement-based materials [2]–[6]. Results of this evaluation are useful for the determination of their quality. Moreover, knowledge of the dielectric properties of cement-based materials is 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 their service time. During the chemical reaction between water and cement (hydration process), their 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 the hydration process in cement-based materials. A strong correlation between the magnitude of the reflection coefficient of microwave signals and the w/c ratio of cement-based materials was shown 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 cannot provide measurement of reflection and transmission properties of such materials for propagation-related research. By means of the free-space method [7]–[9], the reflection and transmission properties of the specimens can be investigated. In the general case, real and imaginary parts of their dielectric permittivity, ε' and ε'', can be determined by the measurements of either reflection coefficient, r, or transmission coefficient, t, or both. Reflection measurements 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 along its path. When the free-space technique is used, measurements are performed without the necessity for physical contact between the structure under test and the 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 multiple reflections, and scattering effects are minimized. It should be noted that in practical applications, particularly in the construction industry, it is very attractive to use a simple microwave technique for material inspection [4].

In this paper, a simple and an inexpensive measurement system is used for the measurement and monitoring of the reflection and transmission properties of cement-based materials.

Manuscript received May 29, 2001; revised September 5, 2002. This work was supported by The Scientific and Technical Research Council of Turkey (TUBITAK).

S. N. Kharkovsky was with the Institute for Radio-Physics and Electronics, National Academy of Sciences of Ukraine, Kharkov, Ukraine. He is now with the Department of Electrical and Electronics Engineering, Cukurova University, Adana 01330, Turkey (e-mail: kharkovsky@mail.cu.edu.tr; kharkovs@yahoo.com).

M. F. Akay was with the Department of Electrical and Electronics Engineering, Cukurova University, Adana, Turkey. He is now with the Department of Electrical and Computer Engineering, Drexel University, Philadelphia, PA 19104 USA.

U. C. Hasar is with the Department of Electrical and Electronics Engineering, Cukurova University, Adana 01330, Turkey.

C. D. Atis is with the Department of Civil Engineering, Cukurova University, Adana 01330, Turkey.

Digital Object Identifier 10.1109/TIM.2002.808081

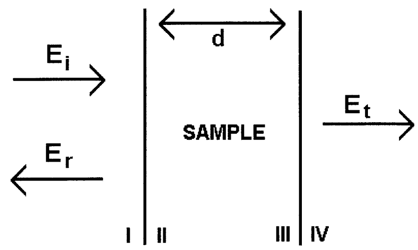


Fig. 1. Reflection/transmission measurement configuration.

The paper is organized as follows: In Section II, theoretical foundations of the problem are analyzed. A description of the measurement set-up used and specimens is given in Section III. In Section IV, results of the daily measurements of the amplitudes of the reflection and transmission coefficients and calculations of complex permittivity for the specimens with different w/c ratios and curing conditions are presented. Finally, in Section V, results, measurement errors, and uncertainties are discussed.

II. Theoretical Foundations

A typical situation in the measurement of the reflection and transmission properties of slab specimens 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 specimen. Reflection occurs at the interfaces of the air–specimen I, and multiple reflections occur between each side of the specimen. The reflection coefficient at I is denoted by r_{12}. In this case, the total reflection and transmission coefficients are given by [10]

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

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

where

$$\Theta = k_o\sqrt{\varepsilon_r}\, d, \qquad k_o = \frac{2\pi}{\lambda_o}, \qquad \varepsilon_r = \varepsilon_r' - j\varepsilon_r''. \tag{3}$$

Here, ε_r is the relative permittivity of the specimen, and λ_0 is the wavelength in free space. The specimen is nonmagnetic (i.e., the relative magnetic permeability is equal to one).

For lossy materials, the expressions for r and t can be simplified. We assume that the attenuation of the wave inside the specimen is large enough that the multiple reflections between the two surfaces of the specimen can be neglected. Then, r and t are written as

$$r = r_{12} = \frac{\sqrt{1} - \sqrt{\varepsilon_r}}{\sqrt{1} + \sqrt{\varepsilon_r}} \tag{4}$$

$$t = (1 - r_{12}^2)e^{-j\Theta}. \tag{5}$$

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

$$T = -20\log|t|, \qquad R = -20\log|r|. \tag{6}$$

From (4)–(6), it is seen that the amplitudes of reflection and transmission coefficients are functions of complex permittivity, which is a function of water content, density, etc. If $|r|$ and $|t|$ determine the complex permittivity uniquely, then they can be used in order to evaluate physical properties of the specimens. It is possible to show this by using numerical methods, for example, the graphical method and/or the root-finding methods.

For given measured values of the amplitudes of the reflection and transmission coefficients (R and T), we can obtain the constant value lines of the reflection and transmission coefficients expressed by CR and CT [9]. The necessary and sufficient condition for determining the permittivity from them is that there is just one cross point between the lines CR and CT. In Fig. 2, the lines CR and CT with several different measured values of R and T for a lossy dielectric are shown. In the calculation, the frequency is $f = 10.38$ GHz, and the sample thickness is $d = 150$ mm. The ranges of ε_r' and ε_r'' are chosen according to well-known results of measurement of dielectric properties of cement-based materials [6]. The graphical method is very clear and useful for the primary evaluation of the dielectric properties of lossy samples.

To find the permittivity by using any root-finding method, in (4) and (5) should be solved simultaneously. In order to simplify the solution of the equations, let $\sqrt{\varepsilon_r} = a - jb$. The expressions for reflection and transmission coefficients then become

$$r = r_{12} = \frac{1 - (a - jb)}{1 + (a - jb)}, \qquad t = \frac{4(a - jb)e^{-j\Theta}}{(1 + a - jb)^2} \tag{7}$$

and the amplitudes of reflection and transmission coefficients can be written as

$$|r| = \frac{\sqrt{(1 - a)^2 + b^2}}{\sqrt{(1 + a)^2 + b^2}} \tag{8}$$

and

$$|t| = \frac{4\sqrt{a^2 + b^2}\, e^{-k_o db}}{(1 + a)^2 + b^2}. \tag{9}$$

From (8) and (9), we get the final equation as

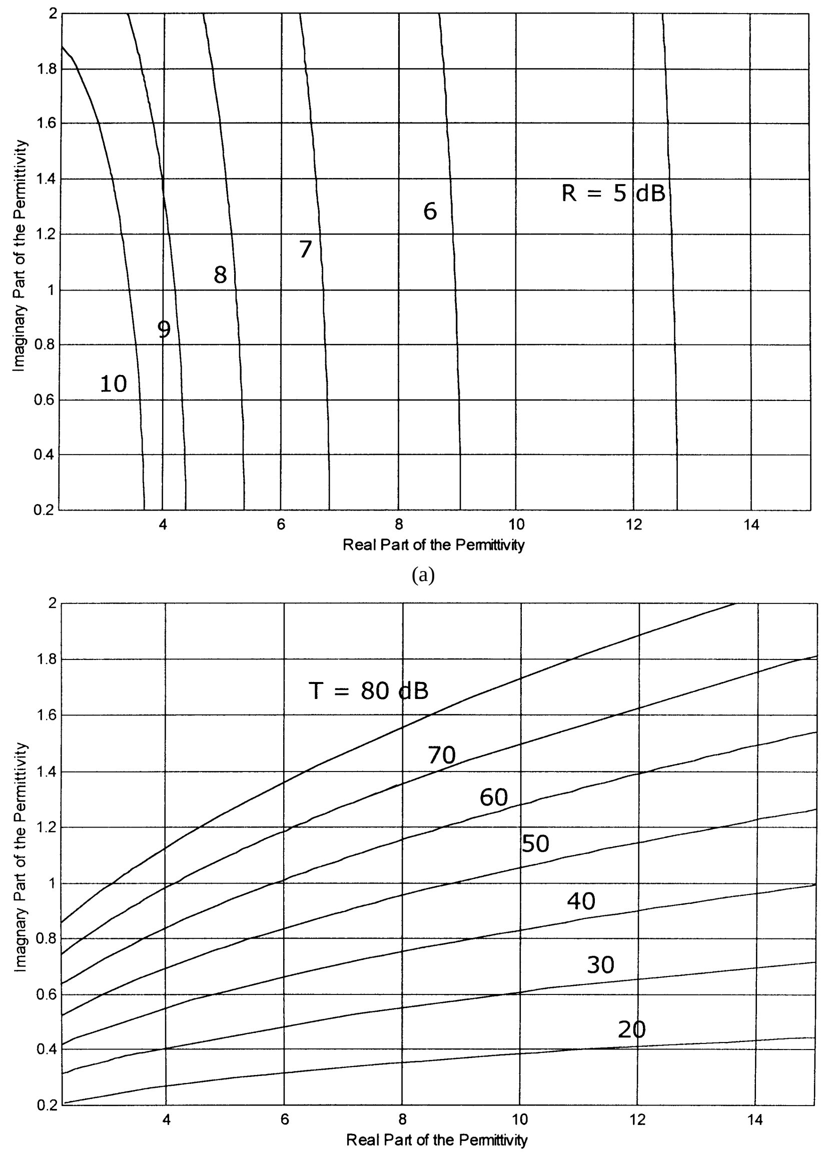
$$\sqrt{2a(1 - |r|^4) - (1 - |r|^2)^2} \cdot \exp\left\{-k_o\, d\sqrt{\frac{2a(1 + |r|^2)}{(1 - |r|^2)} - (1 + a^2)}\right\} - |t|a = 0 \tag{10}$$

that depends only on a.

Equation (10) can be solved to find the value of a by means of an appropriate root-finding method, for example, the interval-halving method [11]. The real and imaginary parts of the permittivity are then calculated by using the following simple formulas

$$\varepsilon_r' = a^2 - b^2 \quad \text{and} \quad \varepsilon_r'' = 2ab. \tag{11}$$

It can be seen from Fig. 2 and the (8)–(11) that the amplitudes of reflection and transmission coefficients together with the thickness of the specimen uniquely determine the complex dielectric permittivity of cement-based specimens.



(a)

(b)

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

III. Measurement Setup and Specimens

The schematic diagram of the measurement setup is shown in Fig. 3. A microwave oscillator (OSC) modulated by a 1-kHz signal feeds the system. The output power of the oscillator is not greater than 10 mW at frequencies of the X-band (8–12 GHz). The specimen is placed between two horn antennas. The distance between the two antennas is adjusted according to the following facts: 1) the maximum amount of wave should be received by the receiving antenna when there is no sample between the antennas; 2) the minimum amount of wave should be scattered by the edges of the specimen.

A simple reflectometer built from discrete components (a directional coupler, a square-law detector and a dc voltmeter) is used to determine the amplitude of the reflection coefficient. The directional coupler has directivity greater than 40 dB. The square-law detector output is proportional to $|r|^2$. The constant of proportionality is found by using a reflection from an aluminum plate whose absolute reflection coefficient is considered to be one.

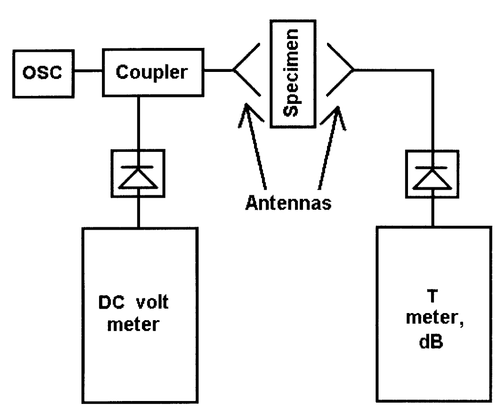


Fig. 3. Schematic diagram of the measurement setup.

In the receiver side, the microwave signal modulated by the 1-kHz signal is fed to a square-law detector and then to

TABLE I
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
	II	21.87	31.25	46.88	--	0.7
Concrete	I	6.78	16.95	25.42	50.85	0.4
	II	11.29	16.13	24.19	48.39	0.7

a T-meter. The T-meter is a custom device with a precision attenuator, an amplifier and an indicator. It is used to measure the amplitude of the transmission coefficient T in dB. The reference level of this measurement is determined for a case when there is no specimen between antennas.

Several cubic mortar and concrete specimens with different w/c ratios were produced. They have dimensions of 150 $\times$ 150 $\times$ 150 mm^3. The raw materials of the specimens are shown in the Table I.

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

The cement-based specimen used for the measurements is shown in Fig. 4. The side surfaces are labeled as N.2 and N.4 according to their positions during the fabrication of the specimen, whereas the bottom and top surfaces are labeled as N.1 and N.3, respectively.

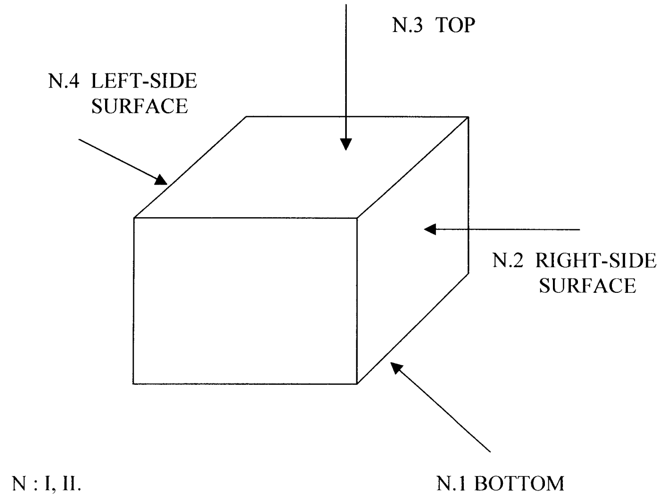


Fig. 4. Cement-based specimen.

IV. RESULTS

Measurements of specimen reflection properties from all sides with different conditions were conducted daily during the 28-day curing period at several frequencies of the X-band (8–12 GHz). For example, Fig. 5 shows the results of the daily measurements of $|r|$ at 10.380 GHz for two mortar specimens with different w/c ratios (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 the 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 the measurement process is not carried out. Therefore, "wet" curing conditions prevent the fast evaporation of water inside the cement-based specimen.

Fig. 6 shows 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 the side surface of the specimens. Differences between the curves are due to the different preparing conditions.

The main reflection measurement results are the following:

1) The values of $|r|$ in the first days of hydration are higher for higher w/c ratio specimens. They rapidly decrease during the first several days of hydration. After several days, the measured values of $|r|$ for lower w/c ratio specimens are higher than those for higher w/c ratios. This is a result of the evaporation of free water from the cement-based specimen and the hydration process occurring inside it.

2) The speed of the hydration process is different for different sides of the cubic specimen and depends on w/c ratio and curing conditions.

3) The differences between measured values of $|r|$ for different sides of the specimen for lower w/c ratio specimens are less than those for higher w/c ratios. These differences decrease during curing for all ratios and depend on the conditions in which the specimen is left to cure.

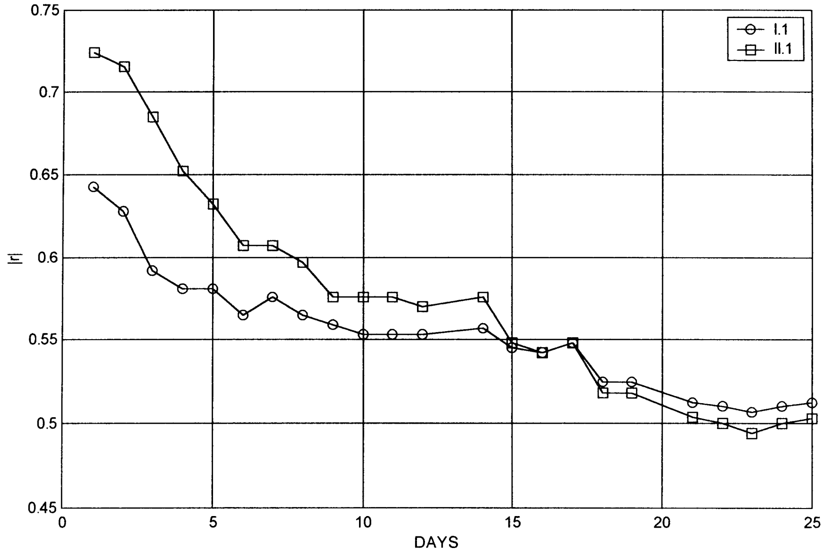
It should be noted that after 25 days, reflection coefficients are approximately stable and depend on only the w/c ratio.

The transmission coefficients are very low for fresh cement-based specimens. They change during the long time of the specimens' service lives. The results of the measurement of transmission properties for two mortar specimens during their service lives between the 3rd and 6th months are shown in Fig. 7. In this case, the specimen is located so that the wave incidents on one side surface and goes out through the other side surface. It should be noted that there is not a marked dependency of T on the orientation of the specimen. The measured $|r|$ is about constant for each specimen, $|r| = 0.5$ ($R = 6.02$ dB) for $w/c = 0.4$ and $|r| = 0.46$ ($R = 6.74$ dB) for $w/c = 0.7$.

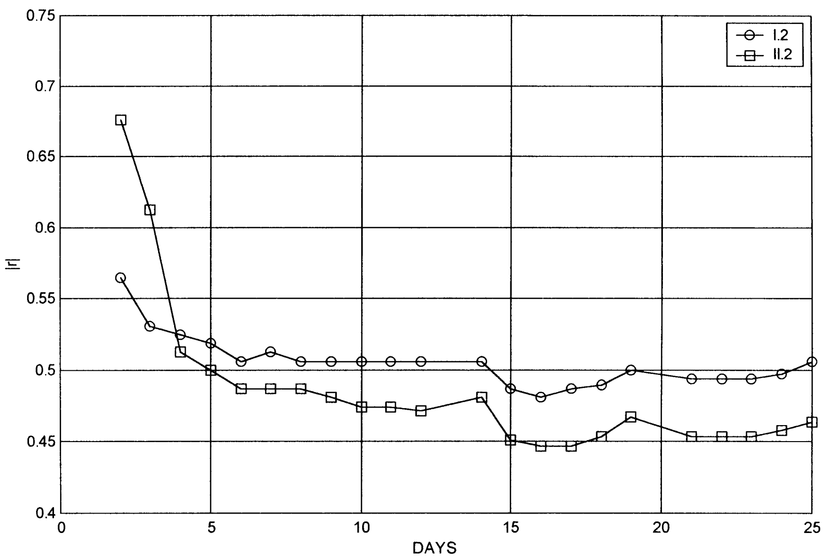
It can be seen from Fig. 7 and (6) that the transmission coefficient $|t|$ of the specimens increases with time, indicating a desiccation of water from the whole specimen as an effect of aging. However, a higher transmission coefficient corresponds to a higher w/c ratio. This indicates the existing differences between structures or densities inside the specimens with different w/c ratios. The main reason can be porosity inside the specimens. It is well known that the higher porosity corresponds to higher w/c ratio [12].

Thus, the temporal dependencies of $|r|$ and T show that after about 25 days, the porosity for higher w/c ratio specimens is higher than that for lower w/c ratio specimens.

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



(a)



(b)

Fig. 5. Amplitude of the reflection coefficient, $|r|$, of the two mortar specimens with different w/c ratios over time for (a) "wet" and (b) "dry" curing conditions.

Fig. 8 shows the results of the numerical calculation of the permittivity from (8)–(11) and measured values of $|r|$ and T. It can be seen that the values of ε_r' and ε_r'' are in the ranges of well-known data for cement-based materials obtained from measurement of the complex reflection coefficient using a vector network analyzer [6]. The relative values of the permittivity of the specimens with different w/c ratios and temporal dependencies of ε' and ε'' confirm the transmission/reflection measurement results. The higher value of the imaginary part of the permittivity corresponds to the higher w/c ratio because the imaginary part mainly determines the transmission coefficient. The real part of the permittivity is constant for each specimen, and the higher value of this constant corresponds to the lower w/c ratio because the real part mainly depends on the reflection coefficient.

V. Discussion

It is shown that the temporal characteristic of $|t|$ and $|r|$ depends on the w/c ratio of the specimen. Because of this, daily measurements of $|r|$ and $|t|$ can be used to determine the w/c ratio at almost all stages. For this purpose, a simple reflectometer provides monitoring of the cement-based specimen properties at the early stages of the hydration process, excluding three to six days because of the crossover of temporal curves of $|r|$ for different w/c ratios.

The reflection measurements show differences among the sides of the specimen due to different curing conditions. It demonstrates the sensitivity of these measurements. However, it is necessary to take into account that reflection measurements sense only the surface characteristics of the specimen.

On the other hand, the transmission measurements indicate the existence of differences between structures inside the specimens with different initial w/c ratios. They show opportunities to indicate the initial w/c ratio and variations of the specimens due to the effects of aging.

Thus, the measurement results are promising, but their reliability depends on total measurement uncertainty and error.

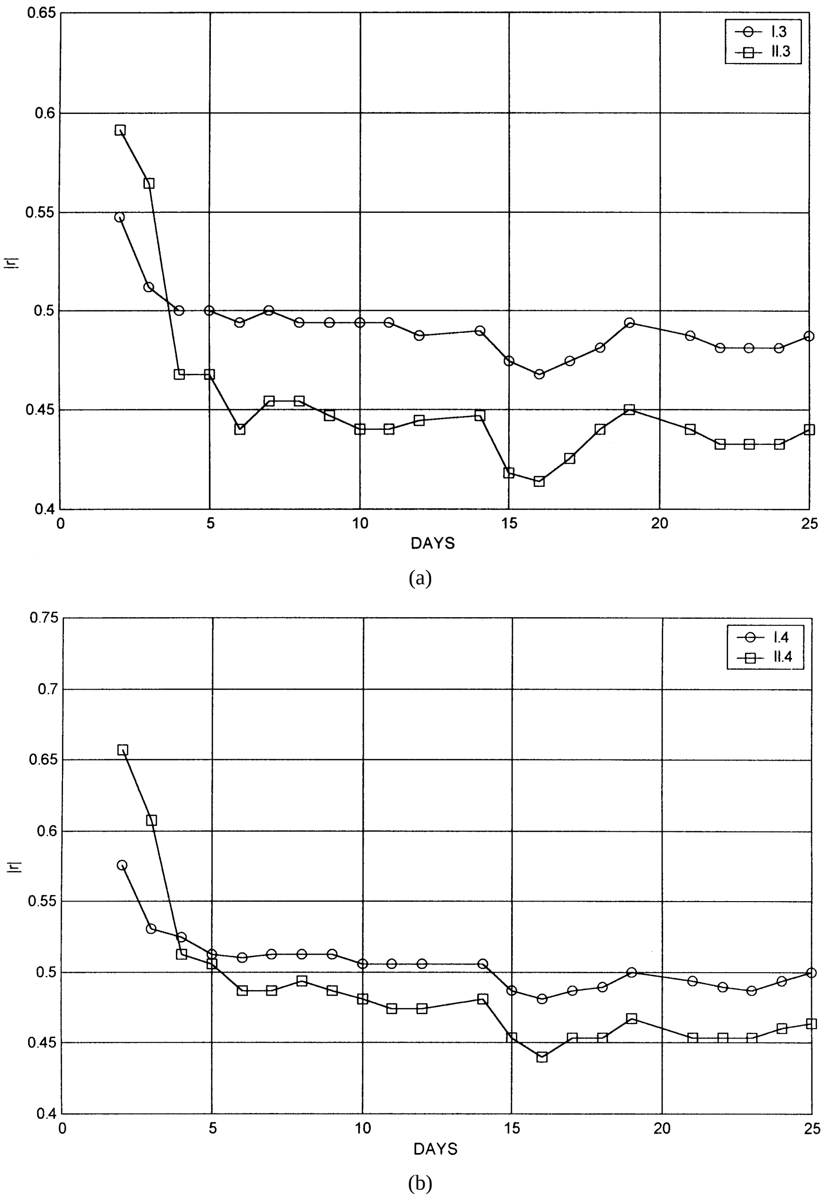


Fig. 6. Amplitude of the reflection coefficient, $|r|$, of the two mortar specimens with different w/c ratios over time for dry curing conditions (a) top surface (b) side surface.

Therefore, it is necessary to evaluate the influence of the measurement uncertainties.

The reflection and transmission measurements are both affected by multiple reflections inside the specimen, multiple reflections between the specimen and the antennas and between the antennas through the specimen, and by surface roughness of the specimen.

The multiple reflections between the two surfaces of the specimen can be neglected if the specimen thickness fulfills the 10-dB attenuation criterion. As can be seen from measured transmission coefficients (15–32 dB) and reflection coefficients (6–7 dB), the thickness of 150 mm provides avoidance of the multiple reflections inside the measured specimens.

The effects of multiple reflections between the specimen and the antennas and between the antennas through the specimen are reduced by selecting the best conditions for matching of the various components of the measuring system.

The coefficients in (1) account only for specular reflection, which occurs for smooth surfaces. When the surface is rough, impinging energy will be scattered in angles other than the specular angle of reflection, thereby reducing energy in the specularly reflected and transmitted components. The specimens must have surface protuberances with height which is less than critical height $h_c = \lambda_o/8$ defined according to the Rayleigh criterion for a smooth surface [3]. The height of a given rough surface is defined as the minimum to maximum surface protuberance. In practice, cement-based specimens are smooth at the X-band.

The accuracy of the transmission measurements also depends on measurement errors and geometrical uncertainties (thickness of the specimen, distance between antennas, etc.). For the transmission measurements the sources of error are partly deviations from the square-law characteristics of a crystal diode and partly errors in the T-meter calibration. In a crystal diode, the devia-

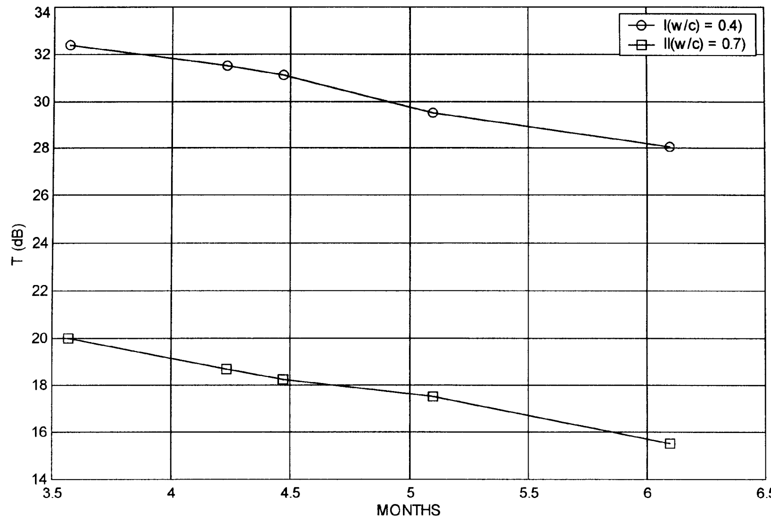


Fig. 7. Transmission coefficient, T, in decibals, of the two mortar specimens with different w/c ratios over time.

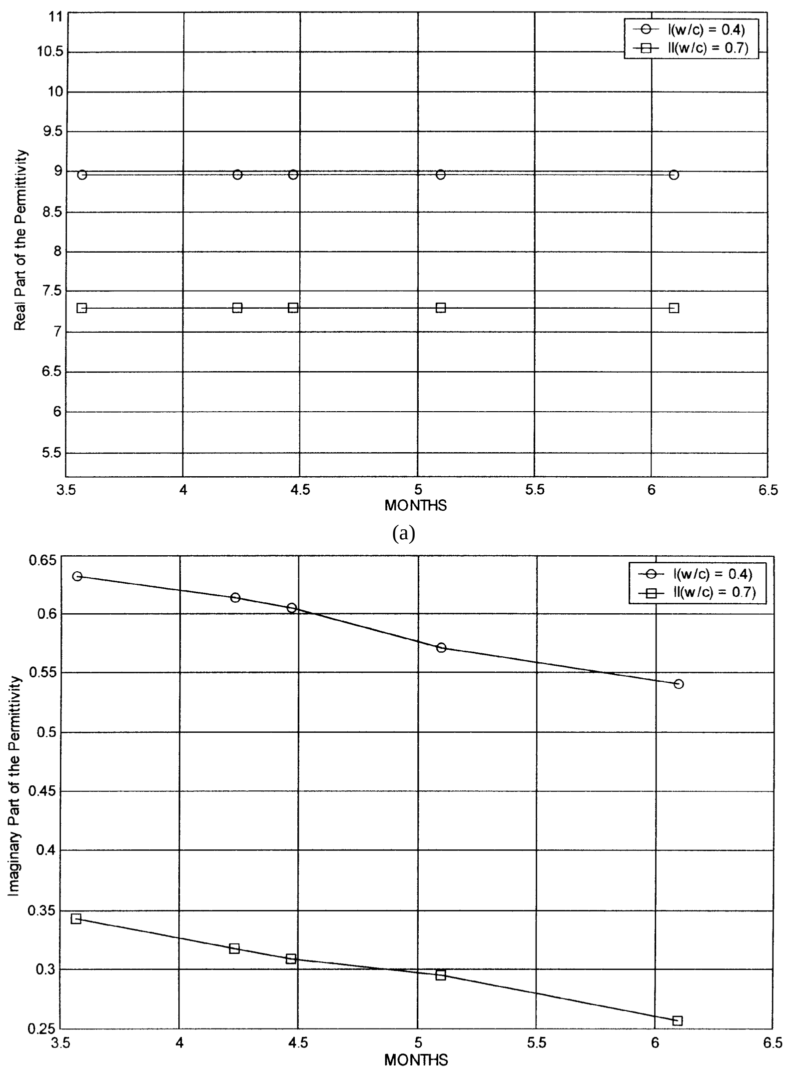


Fig. 8. (a) Real, ε_r', and (b) imaginary, ε_r'', parts of the permittivity of the mortar specimens with different w/c ratios over time.

tion from the square-law is very small at low voltages. The meter scale error is less than ± 0.1 dB per step with a maximum cumulative error of ± 0.2 dB between any two 10 dB steps. In addition, it is easy to show from (5) that a thicker specimen is preferred in order to minimize its measurement uncertainty. However, the specimen thickness should be optimized so that the microwave signal is able to penetrate the whole specimen. Hence, there is a compromise between minimizing the uncertainty due to the increase of thickness and increasing the measurement uncertainty due to the decrease of measured signal level.

The main causes of error of the reflection measurements using a directional coupler can be the finite directivity of the directional coupler and variations in the placement of the reference plate. Evaluation shows that the influence of the finite directivity can be negligible in the case of cement-based material characterization if the directivity of the coupler is greater than 40 dB.

The small value of variations of the reference plate placement, especially angular variations, can change its reflection property significantly. This value is operator dependent and with the appropriate arranging and measurement technique, this measurement cause can be reduced considerably.

Although an adequate calibration procedure has been conducted, the reflection measurement precision cannot be compared to that of a network analyzer. However, the cure-state prediction and early w/c ratio determination can be based on the temporal behavior of $|r|$ (i.e., derivative of $|r|$ versus time), and any minute constant offset error term that is not corrected by the calibration will be nullified, when taking the derivative of the measurements of $|r|$ versus time [4]. Also, if more measurement points are taken in the early stages of curing, the contribution of any erroneous measurement resulting from an operator error will be minimized.

Accuracies of determinations of the dielectric properties of cement-based materials from microwave measurements are based upon the accuracy with which the amplitudes of the reflection and transmission coefficients and the thickness of the specimen can be measured.

The analysis shows that the method used is reliable for monitoring with time and for measurements of the reflection and transmission properties of cement-based specimens. It can be used for the hydration state prediction and the evaluation of physical properties (w/c, compressive strength) of the cement-based specimens. This technique is suitable for the analysis of the problem at hand.

VI. Conclusion

The reflection and transmission properties of cement-based specimens at the X-band have been investigated. The measurements indicated that a simple and inexpensive measurement setup provides monitoring of the cement-based specimen properties at almost all stages of their service lives. The reflection measurements sense the surface characteristics of the specimen, and can determine properties of the specimen at the early stage of the hydration process, while transmission measurements sense the whole specimen and are more suitable for long time monitoring of hardened cement-based specimens. It is shown that a higher transmission coefficient corresponds to the higher initial water-to-cement ratio of hardened specimens because of the existing porosity inside the specimens.

The amplitude of the reflection and transmission coefficients can be used to determine the permittivity of the cement-based materials. It is shown that the reflection coefficient mainly depends on the real part of the permittivity, while the transmission coefficient is mainly determined by the imaginary part of the permittivity.

It should be noted that further investigations must be performed so as to optimize the technique by operating at optimal parameters to minimize measurement errors. The effect of environment and the possibility of transmission measurements at the early stages of the hydration process should also be investigated.

In spite of well-known limitations of this measurement technique, it can be used for quality control of cement-based structures in the construction industry. Besides, it can give useful information for propagation-related research, for example, microwave propagation modeling to develop the indoor wireless communication system.

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Sergey N. Kharkovsky (M’01) was born in Caucasus region, Russia, in 1952. He received the electronics engineering degree from the Kharkov Institute of Radioelectronics, Kharkov, Ukraine, in 1975, the Ph.D. degree from the Kharkov State University, Kharkov, in 1985, and the D.Sc. degree in radiophysics from the Institute of Radio-Physics and Electronics (IRE), National Academy of Sciences of Ukraine, Kharkov, in 1994.

In 1991, he received a Senior Scientist title in radiophysics. From 1975 to 1998, he was with the Research Staff at IRE and from 1994 to 1996, he was a Professor at Kharkov Technical University of Radioelectronics. Since 1998, he has been a Professor with the Electrical and Electronics Engineering Department, Cukurova University, Adana, Turkey. His current areas of research are nondestructive characterization of materials using microwaves, developing and investigation new technique for microwave, and millimeter wave measurements of dielectric properties of materials, including dielectric resonators with whispering gallery modes and solid-state oscillators.

Mehmet F. Akay (S'99) was born in Adana, Turkey, in 1977. He received the B.S. and M.S. degrees (with honors) from the Electrical and Electronics Engineering Department, Cukurova University, Adana, Turkey, in 1999 and 2001, respectively. He is currently pursuing the Ph.D. degree in the Electrical and Computer Engineering Department, Drexel University, Philadelphia, PA.

From 1999 to 2001, he was a Research and Teaching Assistant at Department of Electrical and Electronics Engineering, Cukurova University. In 2001, he received a scholarship from the Turkish Council of Higher Education to pursue Ph.D. degree in the USA. His current research interests include mathematical modeling and simulation of microprocessor architectures, queuing theory, optical interconnection networks, and IP telephony applications.

Ugur C. Hasar (S'00) was born in Kadirli, Adana, Turkey, in 1977. He received the B.Sc. and M.Sc. degrees in electrical and electronics engineering from Cukurova University, Adana, Turkey, in 2000 and 2002, respectively. He is currently pursuing the Ph.D. degree in the Department of Electrical and Electronics Engineering, Cukurova University

He has been working as a Research Assistant in the Department of Electrical and Electronics Engineering, Cukurova University. His current areas of research involve nondestructive characterization of materials using microwaves, performing numerical calculations to determine the dielectric properties of materials.

Cengiz D. Atis was born in Karatas, Adana, Turkey, in 1964. He received the B.Sc. and M.Sc. degrees in civil engineering from Cukurova University, Adana, Turkey, in 1988 and 1991, respectively. He received the Ph.D. degree from Civil Engineering Department of the University of Leeds, U.K., in 1997.

He is currently an Assistant Professor with the Civil Engineering Department, Cukurova University. His research interests include properties of concrete and concrete making materials and the use of industrial waste or by-product materials in concrete, nondestructive testing of cement based materials.