EARLY AGE INVESTIGATION AND MEASUREMENT OF REFLECTION AND TRANSMISSION PROPERTIES OF CEMENT-BASED SAMPLES

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ABSTRACT

The results of early age reflection and transmission measurements of mortar samples with different water-to-cement ratios (w/c) at X-band (8-12 GHz) are presented. Nondestructive and contact-less free-space microwave technique has been used, and only are the amplitudes measured hourly by HP Power Meter. It is shown that reflection and transmission measurements change very rapidly at early age of curing, and the chemical reaction (hydration) can be monitored by using reflection measurements. While time dependent reflection curves are monotonic, transmission curves are not monotonic and complex as well. These early age measurement results can be used for the quality detection and control of cement-based samples.

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.

The general method used for determining the compressive strength is to have a cylinder made from the same material as the structure being built. The result of testing give a measure of the potential strength of concrete, not the actual strength of the structure, since they are not cured the same. Another method is to remove and test a core from the structure, which is destructive in nature [1]. However, microwave nondestructive methods have demonstrated the capability of elimination of these disadvantages [2-7].

It is known that dielectric properties of cement-based materials change during 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 [2,3] 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-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.

The method proposed in [2,3] can't provide measurement of reflection and transmission properties of such materials in propagation-related research. The 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 [4]. By means of the free-space method [4-7], the reflection and transmission properties of samples 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, 8].

The investigation of the properties (compressive strength, tensile strength, dielectric permittivity etc.) of cement-based samples at early ages of curing can show the possibility of the properties of these materials at their future life. In that way, the qualities of these samples can be advanced and improved by knowing the properties of early age of them.

In literature, the investigations that have been performed for cement-based samples till now are focused for the measurement starting after curing period of samples (2-3 days). In this paper, the early hourly temporal dependencies of reflection and transmission properties of cement-based samples are presented. First, theoretical foundations of the problem are given. Second, the description of the measurement setup is given. Then, results of the amplitude only measurements of cement paste samples with different w/c ratios are shown. Finally, the results and their expected applications are discussed.

II. THEORETICAL BACKGROUND

The typical situation for the measurement of reflection and transmission properties of cement-samples by using free-space method is shown in Figure 1.

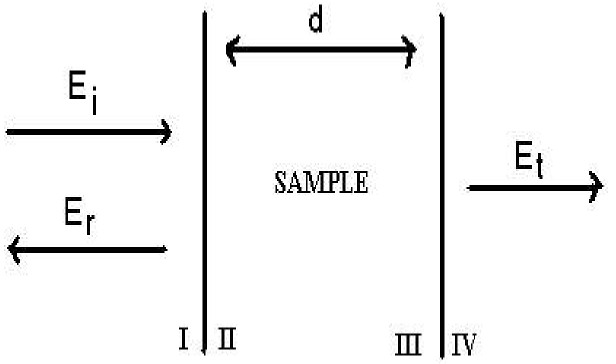

Figure 1. The typical situation for the measurement of reflection and transmission measurements by using free-space method.

The wave travels from the radiating antenna to the receiving antenna through the two media of the air and one medium of sample. Reflection occurs at the interfaces of the air-sample and multiple reflections occur between each sides of the sample. The reflection coefficient denoted by r_{12} is the coefficient for the reflected wave from interface I-II.

The total reflection and transmission coefficients can be written by using the ray-tracing method as [7, 8]

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

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

where

$$\Theta = k_s d, \quad k_s = \alpha + j\beta = \frac{2\pi}{\lambda_o}\sqrt{\varepsilon_{rs}}. \tag{3}$$

Here, d, λ_o and ε_{rs} are the thickness of the sample, wavelength in free-space and relative permittivity of the sample, respectively ($\mu_r = 1$).

For high-loss 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. By using the following assumption

$$e^{-2\operatorname{Im}\{\sqrt{\varepsilon_{rs}}\}k_o d} \ll 1, \tag{4}$$

total r and t are written as

$$r = r_{12} \tag{5}$$

$$t = (1 - r_{12}^2)e^{-j\Theta}. \tag{6}$$

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

$$T = -20\log|t|, \qquad R = -20\log|r|. \tag{7}$$

III. MEASUREMENT SETUP AND SAMPLES

The schematic diagram of the measurement set up is shown in Figure 2.

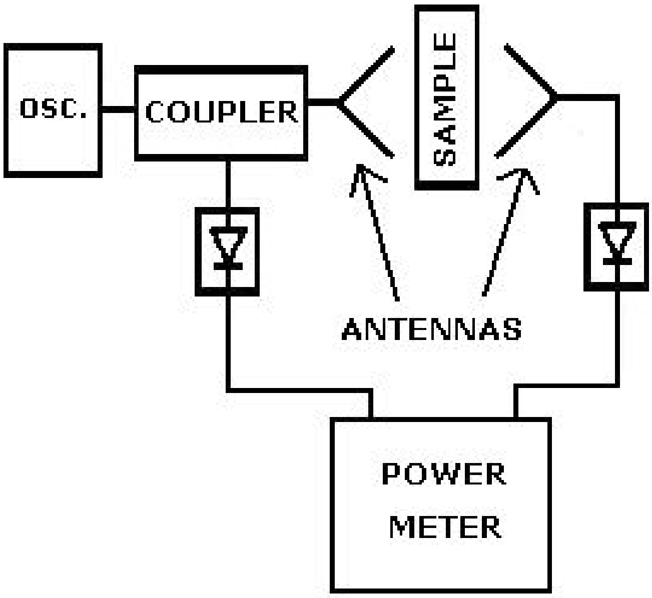

Figure 2. Schematic diagram of the measurement set up.

Microwave oscillator (OSC) modulated by a 1 kHz signal feeds the system. The sample is 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.

The reference level of reflection measurements is assumed for a case when metal plate is present instead of the sample under test. The reference level of transmission measurements is assumed for a case there is no sample between antennas.

Two directional couplers are used in the measurement system, one for the measurement of power level of incident wave, and the other for the measurement of power level of reflected wave.

The HP Power Meter is used for the relative measurement of the reflected and transmitted power levels. The relative values of the powers are arranged according to the reference levels of the reflection and transmission coefficients.

Several mortar specimens with different water-to-cement ratios were produced. They have dimensions 150x150x100 mm^3. 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. According to the weight, sand-to-cement ratio (s/c) is 2, w/c ratios are 0.40:0.65 with 0.05 increment.

IV. RESULTS AND DISCUSSION

The hourly early age measurement of reflection and transmission properties of cement-based samples with different water-to-cement ratios (w/c) has been conducted at X-band (8–12 GHz) by the free-space method.

For example, Figure 3 shows the results of the hourly measurements of |r| at 8.543 GHz for mortar specimens with different w/c ratios.

It can be seen from these time dependent curves that the higher amplitude of reflection coefficient corresponds to higher w/c ratio at early ages. This is the same result of the papers [1, 2, 7]. In addition, the measured amplitude difference of mortar samples with w/c=0.4 and w/c=0.45 is greater than that of every two mortar samples whose w/c ratio difference is 0.05. This may be because of the rapid evaporation of the free water. Besides, there is a general tendency for |r| to be decreasing at early ages of curing. In order to better visualize that tendency, time dependent reflection curves during 20 – 34 hours for each sample are curve fitted as shown in Figure 4.

Figure 5 shows the result of the hourly measurements of |t| at 8.543 GHz for mortar specimens with different w/c ratios.

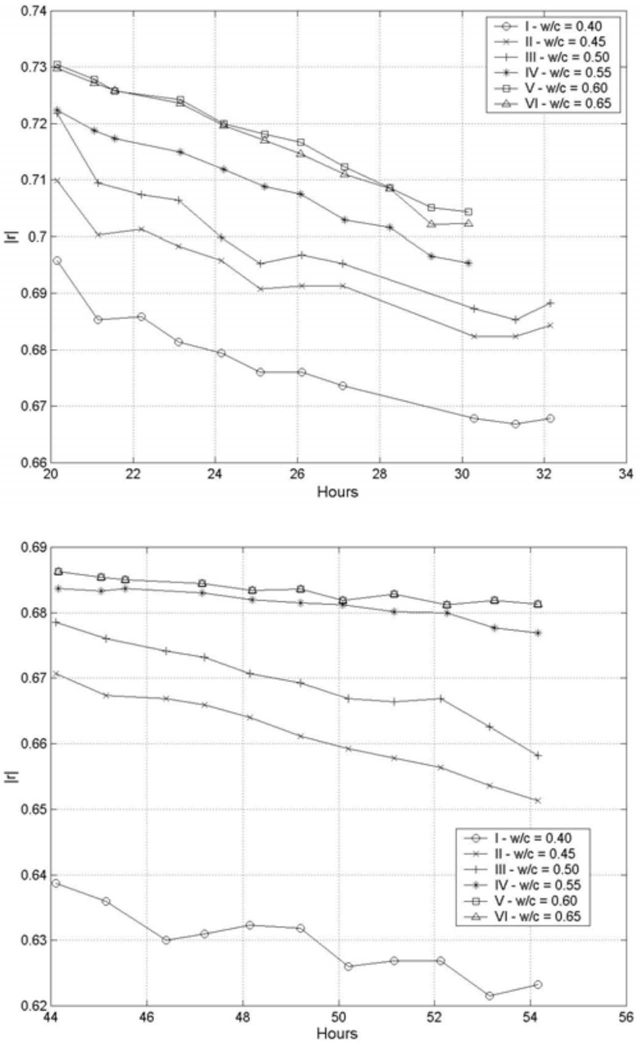

Figure 3. Early age hourly reflection properties of mortar samples with different w/c ratios at 8.543 GHz.

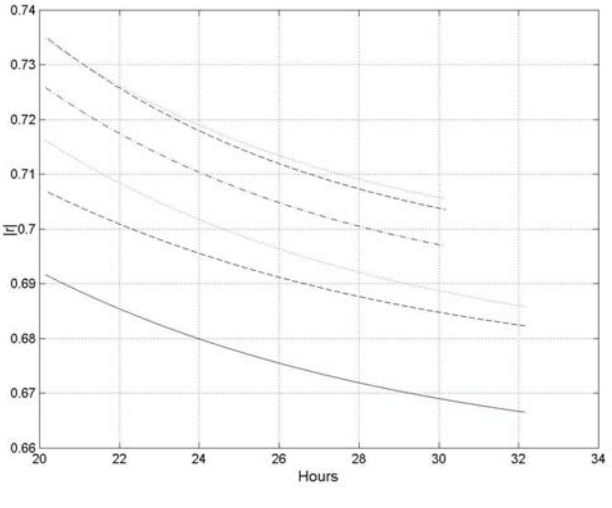

Figure 4. Curve fitted early age hourly reflection properties of mortar samples with different w/c ratios at 8.543 GHz during 20 – 34 hours.

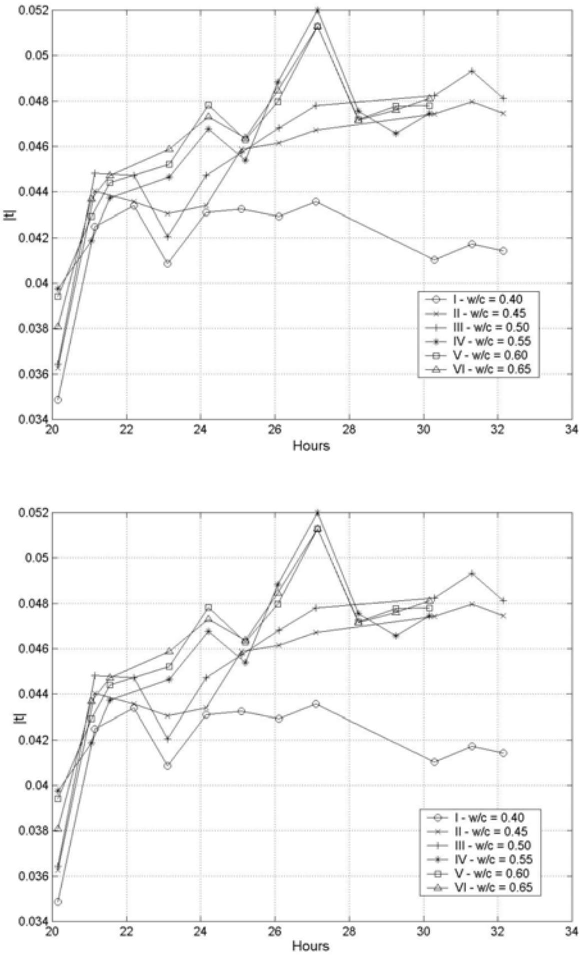

Figure 5. Early age hourly transmission properties of mortar samples with different w/c ratios at 8.543 GHz.

From Figure 5, it is seen that the hourly time dependent transmission coefficient curve is complex, and the non-monotonic behaviour. Besides, the lower transmission coefficient does not correspond to the higher w/c ratio at early age [8]. This can be because of the complex process of the evaporation from the surface of the sample.

V. CONCLUSION

The hourly early age reflection and transmission properties of cement-based specimens at X-band have been investigated. It is shown that while the hourly time dependent curve of reflection coefficient is monotonic and decreasing with time of curing, the hourly time dependent curve of transmission coefficient is not monotonic and has a complex tendency. However, the higher transmission coefficient corresponds to the lower w/c ratio at early ages. The non-monotonic behavior can be because of the complex process of the evaporation from surface of the sample.

The measured amplitude difference in reflection coefficients for mortar with w/c ratios 0.40 and 0.45 is much greater than that of any other combination of the mortar samples whose w/c ratio difference is 0.05. This may be because of the rapid evaporation of the free water.

These results can be used for the early quality detection and control of cement-based structures in the construction industry. Besides, they can give useful information for propagation–related research, for example, microwave propagation modelling to develop indoor wireless communication system.

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REFERENCES

1. A.M. Neville, Properties of Concrete, 4th ed. New York: Wiley, 1996.
2. K.J.Bois, A.D.Benally, P.S.Nowak, and R.Zoughi, Cure-state monitoring and water-to-cement ratio determination of fresh portland cement-based materials using near field microwave techniques, IEEE Trans. Instrum. Meas., vol. 47, no. 3, pp. 628-637, June 1999.
3. K.J.Bois, A.D.Benally, and R.Zoughi, Microwave near-field reflection property analysis of concrete for material content determination, IEEE Trans. Instrum. Meas., vol. 49, no. 1, pp. 49-55, February 2000.
4. K.Sato, T.Manabe, J.Povilka, T.Ihara, Y.Kasashima and K.Yamaki, Measurement of the complex refractive index of concrete at 57.5 GHz, IEEE Trans. Antennas Propagat., vol.44, no. 1, pp. 35-40, January 1996.
5. D.K.Ghodgaonkar, V.V.Varadan, and V.V.Varadan, A free-space method for measurements of dielectric constatnts and loss tangents at microwave frequencies, IEEE Trans. Instrum. Meas., vol. 37, no. 3, pp. 789-793, June 1989.
6. G.L.Friedsam, and E.M.Biebl, A broadband free-space dielectric properties measurement system at millimeter wavelengths, IEEE Trans. Instrum. Meas., vol. 46, no. 2, pp. 515-518, April 1989.
7. Sergey N. Kharkovsky, Mehmet F. Akay, Ugur C. Hasar and Cengiz D. Atis, 'Measaurement and Monitoring of Microwave Reflection and Transmission Properties od Cement-Based Materials', IEEE Instr. & Meas. Trans. Vol.51, No:6, December 2002.
8. S. N. Kharkovsky, C.D. Atis and U.C. Hasar, Characterization of Cement-Based Materials Using Microwave Reflection and Transmission Measurements, Proc. 11th Int. Symp. on Nondestructive Characterization of Materials, Berlin, Germany, Nov. 2002.