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

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Abstract - The results of measurement and monitoring of reflection and transmission properties of cement-based specimens (blocks of mortar, concrete) during long time of their service live, including hydration process, and different curing conditions at microwave frequencies (X-band) are presented. A simple and inexpensive measurement system that utilizes the non-destructive and contactless free space method is used. Dependencies of the reflection and transmission coefficients on water-to-cement ratio, preparing and curing conditions of the specimens are demonstrated. It is shown that the reflection coefficient is approximately stable after hydration process while the transmission coefficient changes during long time of the specimen's service live. 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. The expected applications of the results are discussed.

Keywords - Microwave measurements, reflection and transmission coefficients, free-space method, cement-based materials, mortar, concrete, hydration, water-to-cement ratio, curing, dielectric permittivity.

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-to-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 dielectric 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-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 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 [6-8], penetration of microwaves in different specimens with smooth, rough and non-plane surfaces and their reflection and transmission 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, $\varepsilon'$ and $\varepsilon''$, 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 frequency is, 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 minimized.

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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 \[9\].

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, theoretical foundations of the problem are analyzed. It is shown that complex dielectric permittivity of the cement-based materials can be determined by using only measured amplitudes of reflection and transmission coefficients, \( |r| \) and \( |t| \), respectively, and numerical calculation. Next, a description of the used simple and inexpensive measurement method is given. Then, results of the measurement and monitoring of cement-based materials' properties during all stages of their service lives with different curing conditions are presented and complex permittivity of the specimens are calculated. Finally, the results and their expected applications 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.

![Fig. 1. The reflection/transmission measurement configuration.](image)

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, \( r_{23} \) at II, \( r_{23} \) at III and the transmission coefficients are denoted by \( t_{12} \) at I, \( t_{23} \) at II and \( t_{32} \) at III, respectively. Using the ray-tracing method, the total reflection coefficient and transmission coefficient can be written as \[10\]:

\[
\begin{align*}
\hat{r} &= \frac{\gamma_2(1-e^{-j2\Theta})}{1-\gamma_2 e^{-j2\Theta}} \\
\hat{t} &= \frac{(1-\gamma_2^2)e^{-j\Theta}}{1+\gamma_2^2 e^{-j2\Theta}} \\
\Theta &= k_d d, \quad k_d = \alpha + j\beta = \frac{2\pi}{\lambda_0} \sqrt{\varepsilon}, \quad \varepsilon = \varepsilon' - j\varepsilon''
\end{align*}
\]

Here

\[
\begin{align*}
\alpha &= \omega \left( \frac{\mu_0 \varepsilon}{2} \right)^{1/2} \left. \left[ 1 + \left( \frac{\varepsilon''}{\varepsilon'} \right)^2 \right]^{1/2} \right| -1 \right]^{1/2} \\
\beta &= \omega \left( \frac{\mu_0 \varepsilon}{2} \right)^{1/2} \left. \left[ 1 + \left( \frac{\varepsilon''}{\varepsilon'} \right)^2 \right]^{1/2} + 1 \right]^{1/2}
\end{align*}
\]

In the foregoing equations \( \omega, \lambda_0, \varepsilon \) and \( \mu_0 \) are the angular frequency of the incident wave, the wavelength in free-space, dielectric permittivity and permeability of the material, respectively (\( \mu = 1 \)). For high-lossy materials, the expressions for \( r, \alpha \) 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

\[
\begin{align*}
r &= \gamma_2 \\
t &= (1-\gamma_2^2)e^{-j\Theta}
\end{align*}
\]

and

\[
\alpha = \omega \left( \frac{\mu_0 \varepsilon}{2} \right)^{1/2}
\]

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

\[
\begin{align*}
T &= -20 \log |r|, \\
R &= -20 \log |t|
\end{align*}
\]

From the above expressions, it is seen that \( R \) and \( T \) are functions of permittivity. For given measurement values of the amplitudes of the reflection and transmission coefficients \( R_{\text{mea}} \) and \( T_{\text{mea}} \), we can obtain the constant value lines of the reflection and transmission coefficients expressed by \( CR \) and \( CT \). 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 $CT$ [9]. 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.

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III. MEASUREMENT SET UP AND SPECIMENS

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 measurement set up is shown in Fig. 3. 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. Square-law detector and VSWR meter are used as an attenuation meter to measure the amplitude of the transmission coefficient. The reference level of these measurements is determine for a case when there is no sample between antennas. A simple reflectometer built from discrete components (a directional coupler, a detector and DC voltmeter) is used to determine the amplitude of the reflected coefficient. The square-law detector output is approximately proportional to $|r|^2$. The constant proportionality are found by using short-circuit standard. Although an adequate calibration procedure is conducted the reflection measurement precision cannot be so high. As noted in paper [4], the cure-state prediction and early water-to-cement ratio determination are based on temporal behavior of $|r|$. Therefore the results obtained using the reflectometer are suitable for analysis of the problem at hand.

Several cubic mortar and concrete specimens with different water-to-cement ratios were produced. They have dimensions 150x150x150 mm³. The raw materials of the specimens are shown in the Table 1.
### IV. RESULTS

Measurements of specimens' reflection 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.

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.

The main reflection measurement 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 [4]. Speed of this process is different for different sides of the specimen and depends on w/c ratio and curing conditions.

3) After 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].

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.

---

#### Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Cement</th>
<th>Sand</th>
<th>Gravel</th>
<th>Water/cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mortar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>13.79</td>
<td>34.48</td>
<td>51.73</td>
<td>--</td>
<td>0.4</td>
</tr>
<tr>
<td>II</td>
<td>21.87</td>
<td>31.25</td>
<td>46.88</td>
<td>--</td>
<td>0.7</td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>6.78</td>
<td>16.95</td>
<td>25.42</td>
<td>50.85</td>
<td>0.4</td>
</tr>
<tr>
<td>II</td>
<td>11.29</td>
<td>16.13</td>
<td>24.19</td>
<td>48.39</td>
<td>0.7</td>
</tr>
</tbody>
</table>

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

6) After 25 days, reflection coefficients are approximately stable and depend on only 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].

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 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 $3^{rd}$ and $6^{th}$ months are shown in Fig. 6.

It was expected that $T$ of each specimens increases with the decrease of water content because of desiccation of water [2]. 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 [11].

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.

Fig. 7 shows results of the numerical calculation of the complex dielectric permittivity from (6), (7) and measured values $|r|$ and $T$.

The values of the complex dielectric permittivity and their temporal dependencies confirm the transmission/reflection measurement results. So, the rate of reduction in the imaginary parts is much greater than that in the real parts because the imaginary part of the dielectric permittivity mainly determines the transmission coefficient. The higher rate of the imaginary part corresponds to higher water-to-cement ratio.
ratio of hardened cement-based specimens. It is shown that the complex dielectric permittivity of the cement-based materials can be determined by measuring only the amplitude of the reflection and transmission coefficients. The rate of reduction in its imaginary part is much greater than that in its real part and the imaginary part of the dielectric permittivity mainly determines the transmission coefficient. A higher rate of the imaginary part corresponds to higher water-to-cement ratio.

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 modeling to develop indoor wireless communication system.

REFERENCES