Electromagnetic Properties of Concrete at Microwave Frequency Range

by Hong C. Rhim and Oral Büyüköztürk

Electromagnetic properties of hardened concrete specimens are measured over a microwave frequency range from 0.1 to 20 GHz. The experimentally obtained values provide information about the behavior of concrete as a material in its interaction with electromagnetic waves. In addition to the frequency variation, the effect of different moisture contents on the electromagnetic properties are studied. Properties of mortar specimens and constituents of concrete—that is, coarse aggregates, sand, and cement—are also measured. An open-ended coaxial probe method is used for the measurement of real and imaginary parts of complex permittivity of concrete. The physical significance of the measured data in nondestructive testing including penetration depth and detectability is discussed and demonstrated through radar measurement results. The results of this research work will serve as a basis in applying wideband microwave imaging techniques for nondestructive testing of concrete using radar.

Keywords: concrete; electromagnetic properties; microwave imaging; nondestructive testing; probe method.

INTRODUCTION

With a growing concern about the state of deterioration of the national and worldwide infrastructure, the demand for the development of reliable nondestructive testing techniques (NDT) for construction materials and constructed facilities is ever increasing. Among the few available methods, an imaging technique using a wideband radar system seems promising for nondestructive testing of concrete structures. The acronym RADAR stands for radio detection and ranging. The radar method is flexible in optimizing detection and penetration capabilities. It is sensitive to metallic objects such as steel reinforcing bars embedded inside concrete, and it allows remote sensing of the targets.

In applying the radar method to concrete structures, it is essential to fully understand concrete as a material with its electromagnetic (EM) properties. Electromagnetic properties of concrete affect various aspects of radar measurements by determining the velocity and wavelength of the electromagnetic wave inside concrete, and the amount of reflection from concrete targets. Compared to the extensive information available for the mechanical properties of concrete, knowledge about the electromagnetic properties of concrete for nondestructive testing purposes is very limited, especially over the wide frequency range. Previous research work has been directed toward either the measurements of the electromagnetic properties of hardened concrete specimens at a limited frequency range (generally up to 1 GHz), or the measurements of changing electromagnetic properties of fresh concrete or cement pastes at their early ages of curing to monitor hydration process. Thus, there is a need to develop a database for the electromagnetic properties of hardened concrete over a wide frequency range of 0.1 to 20 GHz to be used for nondestructive testing of existing concrete structures.

In general, the development of the radar method as a tool for NDT of concrete systems requires three areas to be studied: 1) understanding and development of electromagnetic properties of concrete as a function of frequency, moisture content, density, and the other factors such as chemical components; 2) development of computer simulation techniques which can be used in predicting and interpreting radar measurement results using a modeling scheme; and 3) development of radar hardware system which is suitable for specific application areas of NDT. These developments can be made through a parametric study by investigating each measurement parameter including center frequency, frequency bandwidth, polarization, measurement distance and angle, and geometric and material properties of concrete. In performing the above tasks, the electromagnetic properties are essential.

This paper describes the significance of the electromagnetic properties of concrete in NDT and provides results of the measurements on concrete, mortar specimens, coarse aggregates, sand, and cement. Measurements of reference materials of water, ethylene glycol, and methanol are also provided. From the measured values of real and imaginary parts of complex permittivity, loss tangent and conductivity,

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are derived. The measured data is obtained over the frequency range of 0.1 to 20 GHz with a moisture content variation.

**RESEARCH SIGNIFICANCE**

Electromagnetic properties of concrete affect many aspects of NDT of concrete using radar. The velocity and wavelength of the wave inside concrete, and the amount of reflection from concrete are determined by the EM properties. Thus, in conducting numeric modeling prior to radar measurements, in performing actual radar measurements, and in interpreting the measurement results, it is essential to understand and develop a database for the properties. This paper provides fundamental information about EM properties of concrete as a material and their physical significance in NDT. The developed data for the EM properties of concrete over the wide frequency range from 0.1 to 20 GHz will serve as a basis for the use of the properties for modeling, radar measurements, and imaging.

**DEFINITION AND TERMINOLOGY**

Constitutive relations provide information about the physical environment in which electromagnetic fields occur, such as free space, water, or concrete. Mathematically, a medium is characterized with a complex permittivity \(\varepsilon^*\) and a complex permeability \(\mu^*\) as follows:

\[
\begin{align*}
\vec{D} &= \varepsilon^* \vec{E} \\
\vec{B} &= \mu^* \vec{H}
\end{align*}
\]

where \(\vec{D}\) is electric flux density (Coulombs/m\(^2\)), \(\vec{E}\) is electric field strength (V/m), \(\vec{B}\) is magnetic flux density (webers/m\(^2\)), and \(\vec{H}\) is magnetic field strength (\(\text{A/m}\)). In general, \(\varepsilon^*\) and \(\mu^*\) can be functions of several parameters. When \(\varepsilon^*\) or \(\mu^*\) is a function of the frequency, the medium is called to be dispersive.

**Dielectric constant, loss factor, and loss tangent**

Every material has a unique set of EM properties affecting the way in which the material interacts with the electric and the magnetic fields of the electromagnetic waves. Concrete is a dielectric (nonmetallic) material. A dielectric material can be characterized essentially by two independent electromagnetic properties: the complex permittivity \(\varepsilon^*\) and the complex (magnetic) permeability \(\mu^*\). In general, four independent measurements are necessary to establish the quantities of both real and imaginary parts of \(\varepsilon^*\) and \(\mu^*\).

However, most common dielectric materials including concrete are nonmagnetic, making the permeability \(\mu^*\) very close to the permeability of free space (\(\mu_0 = 4\pi \times 10^{-7}\) Henry/meter). Thus, the focus of the discussion is on the complex permittivity \(\varepsilon^*\) which will be defined as:

\[
\varepsilon^* = \varepsilon' - j\varepsilon''
\]

where \(\varepsilon'\) is the real part of the complex permittivity, \(\varepsilon''\) is the imaginary part of the complex permittivity, and \(j = \sqrt{-1}\). Dividing Eq. (3) by the permittivity in free space \(\varepsilon_0\), the property becomes dimensionless and relative to the permittivity of free space:

\[
\begin{align*}
\varepsilon_r^* &= \frac{\varepsilon'^*}{\varepsilon_0} - j\frac{\varepsilon''^*}{\varepsilon_0} \\
\varepsilon_r &= \frac{\varepsilon_r'^*}{\varepsilon_0} - j\frac{\varepsilon_r''^*}{\varepsilon_0}
\end{align*}
\]

where \(\varepsilon_r^*\) is the relative complex permittivity, \(\varepsilon_r'\) is the real part of the relative complex permittivity or dielectric constant, \(\varepsilon_r''\) is the imaginary part of the complex permittivity or loss factor, and \(\varepsilon_0\) is permittivity in free space (a lossless medium) = 8.854 \times 10^{-12} \text{ Farad/m}.

The real part of the relative complex permittivity, or dielectric constant, \(\varepsilon_r'\), is a measure of how much energy is stored in an external electric field is stored in a material. The dielectric constant \(\varepsilon_r'\) is greater than 1 for most solids and liquids. The imaginary part of the relative complex permittivity \(\varepsilon_r''\) is a measure of how dissipative or lossy a material is to an external electric field and is referred to the relative loss factor or simply loss factor. The loss factor \(\varepsilon_r''\) is always greater than 0 and is usually much smaller than \(\varepsilon_r'\) for dielectric materials.

The ratio of the energy lost to the energy stored in a material is given as loss tangent:

\[
\tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\varepsilon_r''}{\varepsilon_r'}
\]

where \(\tan\delta\) is loss tangent or tangent loss. In dielectric materials, energy losses occur as a consequence of current conduction or dielectric hysteresis effects.

**Conductivity**

EM wave attenuation occurs as a result of conduction currents through the lossy dielectric. The equivalent conductivity \(\sigma\) can be expressed in terms of the imaginary part of the complex permittivity, \(\varepsilon''\), as follows:

\[
\begin{align*}
\sigma &= \varepsilon''\omega \\
&= (\varepsilon'\tan\delta)\omega \\
&= (\varepsilon_r'\varepsilon_0\tan\delta)\omega \\
&= (\varepsilon_r\varepsilon_0\tan(2\pi f))
\end{align*}
\]
where \( \sigma \) is conductivity (mhos/m), \( \omega \) is angular frequency (rad/sec), and \( f \) is the number of cycles per second (Hz).

It is important to note that these EM properties are not constant. They change with frequency, temperature, moisture, and mixture of the material.

**SIGNIFICANCE IN NONDESTRUCTIVE TESTING**

Electromagnetic properties of concrete affect many aspects of NDT of concrete using radar. They determine the speed, reflection, and the optimum shooting angle in measurements, and are needed for numerical modeling of wave scattering for a theoretical study and for image reconstruction. In what follows, the effect of EM properties in the use of radar for NDT of concrete is discussed.

**Dielectric constant**

The dielectric constant is the real part of the relative complex permittivity in Eq. (5) and is denoted by \( \varepsilon_r' \).

*Velocity of the wave inside concrete*—In vacuum or air, electromagnetic waves travel at the velocity of light, \( c \). The velocity is changed and determined by the medium through which the wave is propagating. Within the media other than vacuum, waves propagate with velocities lower than the velocity in free space as:

\[
\nu = \frac{c}{\sqrt{\varepsilon_r'}}
\]  

(8)

where \( \nu \) is the velocity of the wave inside concrete (a dielectric medium) and \( c \) is the velocity of light in free space (a vacuum) = 3 \( \times \) 10\(^8\) m/sec. Since the velocity is the main parameter affected by the EM properties of the medium, most NDT techniques rely on this delay of velocity to detect change of properties and configuration of the object under testing. The reflected echo delayed by the presence of a dielectric material is picked up by a receiving antenna, which is usually the same as the transmitting antenna.

*Wavelength inside concrete*—The wavelength \( \lambda \) is a function of the oscillation frequency \( f \) and the wave velocity \( \nu \) which is determined by the dielectric constant of the medium as defined in Eq. (8):

\[
\lambda = \frac{1}{f} \times \nu = \frac{1}{f} \times \frac{c}{\sqrt{\varepsilon_r'}}
\]  

(9)

where \( \lambda \) is the wavelength inside concrete and \( \nu \) is the velocity of the wave inside concrete.

For example, in free space, a 1 GHz wave has a wavelength of 0.3 m. Its wavelength is shortened to 0.1 m in concrete if the concrete has a dielectric constant of 9. As the wavelength decreases inside concrete, detectability increases since the wavelength of the transmitted wave into concrete must be smaller than the object size embedded inside concrete in order to detect it. Thus, a larger dielectric constant is better for good detection. However, in general, as the value of the dielectric constant increases, loss factor of the material also increases; this limits the penetration depth of the wave into concrete. The tradeoff between the detectability and the penetration depth has to be considered based on the EM properties of the material which vary as a function of frequency.

*Reflection and transmission of the waves at an interface*—When a uniform plane wave impinges on the boundary at an oblique angle, the normal of the boundary and the incident ray form a plane called the plane of incidence. The mismatch between the dielectric constants at the boundary of the two different media causes some of the incident waves to reflect and the rest to be transmitted into the new medium. This interaction permits the nondestructive inspection of the material's interior for property determination and the detection of anomalies. Mathematical expressions of the reflected wave can be written as

\[
R_{TE} = \frac{\sqrt{\varepsilon_{r1}} \cos \theta_i - \sqrt{\varepsilon_{r2}} \cos \theta_i}{\sqrt{\varepsilon_{r1}} \cos \theta_i + \sqrt{\varepsilon_{r2}} \cos \theta_i}
\]  

(10)

where \( R_{TE} \) is reflection coefficient for perpendicular polarization or transverse electric (TE), \( \varepsilon_{r1} \) is dielectric constant for Medium 1 (for air, \( \varepsilon_{r1} = 1 \)), \( \varepsilon_{r2} \) is dielectric constant for Medium 2 (for concrete, \( \varepsilon_{r2} = 4 \sim 15 \)), \( \theta_i \) is the angle of incidence, and \( \theta_i \) is the angle of transmission. And

\[
R_{TM} = \frac{\sqrt{\varepsilon_{r2}} \cos \theta_i - \sqrt{\varepsilon_{r1}} \cos \theta_i}{\sqrt{\varepsilon_{r2}} \cos \theta_i + \sqrt{\varepsilon_{r1}} \cos \theta_i}
\]  

(11)

where \( R_{TM} \) is the reflection coefficient for parallel polarization or transverse magnetic (TM).

The term polarization refers to the direction of the electric field. If the electric field of the wave is perpendicular to the plane of incidence, it is called perpendicular polarization or transverse electric (TE) for the reason that the electric field is transverse to the plane of incidence. Similarly, if the electric field is parallel to the plane of incidence, it is called parallel polarization or transverse magnetic (TM) for the reason that the magnetic field is transverse to the plane of incidence. It is beneficial to have different polarizations because any anomalies inside concrete as steel reinforcing bars (rebars) oriented parallel to the polarized direction of the electric field will show strong response and may be easily detected.

In Eq. (10) and Eq. (11), dielectric constants for Media 1 and 2 are assumed to be known as well as the angle of incidence \( \theta_i \). To obtain the angle of transmission \( \theta_i \), a relationship from the Snell's law is needed, which states

\[
\sqrt{\varepsilon_{r1}} \sin \theta_i = \sqrt{\varepsilon_{r2}} \sin \theta_i
\]  

(12)

Square of reflection coefficient \( |t|^2 \) is called reflectivity and denoted as \( r \). The transmissivity \( t \) is obtained as

\[
t = 1 - r
\]  

(13)

Thus, the energy is conserved at the interface of the two media.
Brewster angle of concrete—For parallel polarization (TM), there is always an angle $\theta_b$ such that when the angle of incidence $\theta_1 = \theta_b$ the wave is totally transmitted to a dielectric material and the reflection coefficient RTM is zero. For perpendicular polarization (TE), however, there is no such angle. This angle, $\theta_b$, called the Brewster angle of the dielectric material is given by

$$\theta_b = \tan^{-1} \left( \frac{\varepsilon_{r2}}{\varepsilon_{r1}} \right)$$

(14)

where $\varepsilon_{r1}$ is the dielectric constant of Medium 1 (for air, 1), and $\varepsilon_{r2}$ is the dielectric constant of Medium 2 (for hardened concrete, 4 ~ 15).

The use of Brewster angle of concrete can improve the detectability of objects by minimizing the backscattering from the concrete. If the angle of incidence of the antenna coincides with the Brewster angle of the concrete, nearly all of the incident power is transmitted into the medium with no surface reflected field other than a rough surface backscatter, while the magnitude of reflection from the embedded targets, e.g., rebars, do not change. This allows to maximize the possibility of imaging the objects embedded inside concrete by separating the reflection from the targets from the reflection from the concrete itself. Brewster angle depends on the dielectric constant of concrete. This justifies again the necessity of establishing EM properties of concrete at different frequencies, which is essential to many aspects of the radar method.

Loss factor

The loss factor refers to the imaginary part of the relative complex permittivity $\varepsilon_r^* = \sigma / \omega$ in Eq. (5), and is related to the conductivity $\sigma$ of a material expressed by Eq. (7).

Attenuation of the wave inside concrete—The propagation of electromagnetic waves is governed by the Maxwell’s equations. A plane wave propagating along z-direction is of the form:

$$\vec{E} = \hat{y}E_0 \exp(-jk_z z + j\sigma \tau)$$

(15)

where $\vec{E}$ is electric field vector, $\hat{y}$ is a unit vector in y-direction, which is perpendicular to the direction of wave propagation (or it can be $\hat{z}$ for x-direction), $E_0$ is the initial amplitude of the wave’s electric field, and $k_z^* = \sqrt{k_z^2 - j\sigma / \omega}$ is complex wave number in z-direction.

If only the spatial term in Eq. (15) is considered and the complex wave number is replaced by its real and imaginary parts ($k_z^* z = k_z z - jk_z^\sigma z$), Eq. (15) becomes

$$\vec{E} \propto \exp(-jk_z z) \exp(-jk_z^\sigma z)$$

(16)

The second term in Eq. (16) represents the amplitude loss of the electric field with distance (in z-direction) due to material attenuation. More concisely, Eq. (16) can be written as

$$\vec{E} \propto \exp(-k_z^\sigma z)$$

(17)

only considering the amplitude loss. The loss is exponential in nature as $k_z^\sigma$ increases. $k_z^\sigma$ is the imaginary part of the complex wavenumber. For dielectric materials with low conductivity, it is approximated as

$$k_z^\sigma = \frac{\sigma}{2 \sqrt{\varepsilon_r}}$$

(18)

where $k_z^\sigma$ is often termed as the attenuation coefficient. It determines the amplitude loss of the wave in a dielectric material and changes as a function of conductivity and the real part of the complex permittivity, which in turn changes as frequency changes. The significance of the attenuation coefficient for nondestructive evaluation is that its inverse determines the penetration depth of the wave in a dielectric medium.

Penetration depth in concrete—A penetration depth $d_p$ is a distance through a lossy dielectric over which the field strength falls by 1/e, where $e$ is the natural logarithm constant, due to energy absorption. For dielectric materials with low conductivity, the penetration depth is approximated as

$$k_z^\sigma d_p = 1$$

(19)

$$d_p = \frac{1}{k_z^\sigma} = \frac{2}{\sigma \sqrt{\varepsilon_r \mu_0}}$$

(20)

It should be noted that both attenuation and penetration depth depend on the conductivity of the material, and consequently on the frequency of the wave. Thus, penetration capability of the wave into concrete depends on both the frequency of the wave and the conductivity of the concrete.

MEASUREMENT TECHNIQUE AND CALIBRATION

In order to accurately measure the EM properties of concrete, an appropriate measurement method needs to be selected and a measurement procedure must be developed. Two factors were considered in the selection of a method: first, the measurement must be good for the wide frequency range from 0.1 to 20 GHz; second, the equipment must be suitable for measuring a concrete specimen. The reason for measuring the properties from 0.1 to 20 GHz is that the wide-band radar system available for the research is capable of transmitting waves over that frequency range. Consequently, information about the EM properties of concrete over the same frequency range is required.

Available methods are the resistivity cell method, the parallel plate method, the open-ended coaxial probe method, the transmission line method, the resonant cavity method, and the free space method. Among those, the open-ended coaxial probe method is used. The method allows measurement of EM properties over the wide frequency range from 0.1 to 20 GHz, and is convenient for use with different size of concrete specimens. A schematic diagram of the measurement network is shown in Fig. 1.
The principle of the probe method is that a measurement of the reflection from a material under test along with a knowledge of its physical dimensions provides the information to characterize the permittivity and permeability of the material. A vector network analyzer makes swept high-frequency stimulus-response measurements from 300 KHz to 110 GHz. A vector analyzer consists of a signal source, a receiver, and a display. The source launches a signal at a single frequency to the material under test. The receiver is tuned to that frequency to detect the reflected and/or transmitted signals from the material. The measured response produces the magnitude and phase data at that frequency. The source is then stepped to the next frequency and the measurement is repeated to display the reflection and/or transmission measurement response as a function of frequency. The measurements were performed at 0.4 GHz frequency steps.

The open-ended coaxial probe is a cut off section of transmission line. The material is measured by bringing the probe in contact with a flat face of a solid or immersing it into a liquid. The fields at the probe end "fringe" into the material and change as they come into contact with the material under test. The reflected signal (S_{11}) can be measured and are mathematically related to the parameters of the scattering matrix model. The four parameters of this model, scattering parameters of S_{11}, S_{21}, S_{12}, and S_{22}, are determined after a calibration process using a network analyzer as a function of frequency or by transformation techniques of time waveforms recorded by a digital sampling oscilloscope.

For calibration of the open-ended coaxial lines, usually three standards are connected at the reference plane whose reflection coefficients (\Gamma_i; i = 1,2,3) are known as functions of frequency. This can be expressed as follows:

\[ S_i = S_{11} + \frac{S_{12}S_{21}\Gamma_i}{1 - S_{22}\Gamma_i}; \quad i = 1,2,3 \]  
(22)

From the above reflections coefficients, the terminating load admittance is found from the equivalent circuit, which is then related to the electromagnetic properties of the material under testing.

**Table 1—Material parameters for calibration**

<table>
<thead>
<tr>
<th>Material</th>
<th>( \varepsilon_0 )</th>
<th>( \varepsilon_{inf} )</th>
<th>( \tau )</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water @ 26 C</td>
<td>78.2</td>
<td>4.21</td>
<td>8 \times 10^{12}</td>
<td>0.0124</td>
</tr>
<tr>
<td>Methanol @ 25 C</td>
<td>32.6</td>
<td>5.6</td>
<td>48 \times 10^{12}</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Calibration of the experimental system using the probe was made by measuring methanol, short, and air. Calibration can also be made by using air/short/load, air/short/water, or any other known material. Methanol was used because its electromagnetic properties were relatively close to those of concrete compared to the other possible calibration material over the wide frequency range of interest.

Four material parameters are needed as calibration standards. The parameters are used in the following Cole-Cole dielectric model equation\(^{14}\) to compute \( \varepsilon^* \) for any frequency \( f \):

\[
\varepsilon^*(f) = \varepsilon_{inf} + \frac{(\varepsilon_0 - \varepsilon_{inf})}{1 + (j2\pi f \tau)^{(\alpha - 1)}}
\]  
(23)

Table 1 lists those parameters for water and methanol.

The measurement results can be greatly affected by the accuracy of the calibration. Different calibration techniques are discussed by other investigators.\(^ {15-17} \)

The calibration was checked by measuring materials with known EM properties prior to the actual measurement of concrete specimens. The results are shown in Fig. 2, 3, 4, and 5. The measured values show good agreement with published values\(^ {18} \) with error less than 10 percent.

**EXPERIMENTALLY OBTAINED VALUES OF ELECTROMAGNETIC PROPERTIES**

The open-ended coaxial probe method described in the preceding section was used to measure the real and imaginary parts of the complex permittivity of hardened concrete, mortar, sand, aggregates, and unhydrated cement over a wide frequency range from 0.1 to 20 GHz at 0.4 GHz steps. In addition to the frequency variation, different moisture
content was introduced as the second parameter to examine the effect of moisture on the EM properties of concrete.

Concrete

Cylindrical concrete specimens were cast with water/cement/sand/coarse aggregate mix ratio of 1:2.22:5.61:7.12 (by weight). Portland cement of Type I was used. Coarse aggregates have maximum size of 3.81 cm (1.5 in.). Dimensions of the specimens are 7.62 cm (3 in.) diameter × 15.24 cm (6 in.) height. The age of the specimens at the time of the measurements was 4 weeks. The uniaxial compression strength of the specimen was 21 MPa (3.05 ksi) at 28 days. Four different moisture conditions of the specimens were considered for the measurements: 1) wet specimens with water on the surface; 2) saturated specimens which contained moisture only inside; 3) air dried specimens exposed to ambient room temperature and humidity for four weeks; and 4) oven-dried specimens with zero moisture content by weight.

The experimentally obtained values of the dielectric constants $\varepsilon'_r$ of four different groups of concrete specimens are shown in Fig. 6. It appears that at dry conditions, the dielectric constant does not vary much over the measured frequency range. However, the change of the dielectric constant becomes significant as the moisture level increases. The dielectric constant of the saturated specimen is almost twice of that of the oven dried specimen. This is due to the high value of the dielectric constant of water as seen in Fig. 2. Consequently, the increase of water content in concrete greatly affects the change in the dielectric constant of the concrete. Moisture content is one of the major constituents which influence the EM properties of concrete.

The experimentally obtained values of loss factor ($\varepsilon''_r$) and derived values of loss tangent (tan $\theta$) and conductivity (\(\sigma\)) are plotted in Fig. 7, 8, and 9. In Fig. 7, loss factor of concrete, which is the imaginary part of the complex permittivity, is shown. The loss factor is divided by the dielectric constant over the frequency range to obtain the loss tangent values. In Fig. 8, the loss tangent of concrete increases as frequency increases. The effect of the presence of water on the lossiness of concrete is clearly shown as the loss tangent of the concrete specimens with higher moisture content exhibit higher loss tangent values than those with less moisture content. The conductivity of three different groups of concrete specimens are shown in Fig. 9. The significance of conductivity is that the penetration depth of the wave in concrete is inversely proportional to the conductivity.

Mortar

EM property measurements were performed on mortar specimens to examine the difference between the EM properties of concrete and mortar. No coarse aggregates were used for mortar specimens compared to concrete specimens. The mix ratio for mortar specimens was water/cement/sand of 1:2.22:5.61 (by weight). Portland cement of Type I was used. The age of the specimens at the time of the measurements
was 4 weeks. Four different types of specimens were used for the measurements: 1) wet specimens with watery surface; 2) saturated specimens which contained moisture only inside; 3) air-dried specimens exposed to ambient room temperature and humidity; and 4) oven-dried specimens with zero moisture content by weight. Dimensions of the cylindrical specimens are 7.62 cm (3 in.) diameter × 15.24 cm (6 in.) height.

The results of the measurements are shown in Fig. 10, 11, 12, and 13. The dielectric constants of mortar (Fig. 10) show trends similar to those of concrete (Fig. 6). They are frequency independent for air- and oven-dried specimens and decreased over the frequency for saturated and wet specimens. Since the dielectric constant of water decreases as frequency increases (Fig. 2), specimens with more moisture show the nature of dielectric constant variation of water. The dielectric constant of wet mortar specimens is lower than those of concrete specimens. This is attributed to the dielectric constants of cement and sand which are less than that of aggregates. In Fig. 11, loss factor of mortar is shown. Figure 12 shows the loss tangent values which are found by dividing the loss factor by the dielectric constant. The conductivity of mortar is plotted in Fig. 13. As observed in the measurement of concrete, the conductivity of mortar also increases as frequency increases and as moisture level increases.

Aggregate, cement, and sand

The EM properties of coarse aggregate, cement, and sand are measured using the same probe method. Coarse aggregates had maximum size of 3.81 cm (1.5 in.) and were cut using a sharp saw to have very smooth flat surface for good contact with the probe. Several measurements were made for each aggregate sample and average values are plotted. Portland cement Type I was used for the measurements on cement. The unhydrated cement was put into a plastic bag and measured by inserting the probe into the cement bag. Sand was measured in the same way.

Sample measurement results for dielectric constant and loss tangent are shown in Fig. 9 and 10, respectively. For the dielectric constant, coarse aggregates show a higher value than those for cement and sand. Since aggregates are more dense than the others, the result seems reasonable. Cement and sand have dielectric constants of 4 and 2, respectively. Since there was no water in the measurement specimens for the constituents, dielectric constant did not display any variation.

DISCUSSION

Electromagnetic properties of concrete, mortar, and constituents of concrete over a wide frequency range and as a function of moisture level are established as a basis for use in NDE of concrete. The technique used can be applied to other concrete specimens with different mix, as needed.
The results of electromagnetic property measurements indicate that at dry condition the dielectric constant of concrete appear to be frequency independent over the frequency range from 0.1 to 20 GHz. The moisture content of concrete significantly affects the dielectric constant and loss factor of concrete. The significance of the dielectric constant of concrete for radar measurements is that it reduces both the velocity and wavelength of the transmitted wave inside concrete, therefore, increasing the detectability. The loss factor of concrete determines how deep the wave can penetrate into concrete. For radar measurements, the increased loss factor at higher frequency and/or with higher moisture content reduces the penetration depth of the wave in concrete, which compromises the benefit of increased detectability. This phenomenon indicates that there is a tradeoff between the detectability and the penetration depth for radar measurements.

From the experimentally obtained values, the wavelength inside concrete is plotted as a function of frequency for four different groups of concrete specimens in Fig. 16. The wavelength determines the size of embedded objects that can be detected at a given frequency. The other aspect of the electromagnetic properties for concrete is that Brewster angle can be derived from the measured values. The Brewster
angle is the angle at which the wave is totally transmitted into a dielectric material and the amount of reflection is zero. The use of Brewster angle of concrete can improve the detectability of objects by minimizing the unnecessary backscattering from the concrete. If the angle of incidence of the antenna coincides with Brewster angle of the concrete, nearly all of the incident power is transmitted into the medium with no surface reflected field other than rough surface backscatter, while the magnitude of reflection from the embedded targets, e.g., rebar, do not change. Radar measurements at Brewster angle of concrete at a given frequency might improve the detection capability as the reflection from a target object is much stronger relative to the reflection from the concrete itself. In Fig. 17, the Brewster angle of concrete for four different values of moisture content is shown as a function of frequency.

**Radar Measurements on Concrete**

A series of radar measurements was performed on laboratory-sized concrete specimens to analyze the effects of EM properties of concrete on its nondestructive testing using radar. A wideband inverse synthetic aperture radar (ISAR) was used for the measurements due to its ease and versatility in conducting measurements on laboratory-sized concrete specimens. The ISAR system used is capable of transmitting waves at a wide frequency range from 0.1 to 18 GHz. The radar system generates stepped frequency gated continuous wave, which sweeps frequency from the starting frequency $f_1$ to the ending frequency $f_2$ by a given frequency increment. For the work presented here, the frequency range was from 3.4 to 5.8 GHz with an increment of 0.1 GHz. The concrete specimens used for the measurements were cast with the same mix ratios of the specimens used for property measurements. Figure 18 shows the cross section of a concrete specimen having dimensions of $12 \times 4 \times 12$ in. (304.8 x 101.6 x 304.8 mm) with delamination of 1 in. (25.4 mm) thickness located at 2 in. (50.8 mm) depth. Figure 19 shows the onedimensional images obtained by processing the raw data obtained from radar measurements for air dry and wet conditions of the specimen shown in Fig. 18, respectively. The images were obtained by multiplying the received signals, in the frequency domain, from $f_1$ to $f_2$, by a window function, and then, inverse Fourier transforming into time domain. In Fig. 19, the reflections from the front surface and those from the delamination are identified as peaks A and B, respectively. In Fig. 19(b), the reflection from the delamination shown as peak $B$ is significantly decreased due to the high attenuation of EM waves in wet concrete.

**Conclusion**

Significance of the electromagnetic properties of concrete is examined in nondestructive testing of concrete systems using radar. The real and imaginary parts of complex permittivity of concrete are measured as a function of frequency and moisture content. The frequency variation is from 0.1 to 20 GHz, and the moisture content is varied from dry to wet. For the measurements, the open-ended coaxial probe method is used and the calibration technique is explained. Additional measurements are made for mortar specimens and constituents of concrete such as coarse aggregates, cement, and sand. The measured values of the EM properties of concrete and mortar can be used for the numerical modeling of wave propagation and scattering through and by various types of concrete and mortar targets. They can also be used for detecting the optimum combinations of radar measurement parameters for better detection and for measured data interpretation and imaging of concrete targets.

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k* = imaginary part of the complex wavenumber
k_z = complex wavenumber in z-direction
r = \|R\| = reflectivity
R_{TE} = reflection coefficient for perpendicular polarization
R_{TM} = reflection coefficient for parallel polarization
S_{11}, S_{21}, S_{12}, S_{22} = material parameters of EM property measurement
t = transmissivity
\tan \delta = loss tangent
v = velocity of the wave inside concrete

REFERENCES