지진손상도 파악을 위한 콘크리트의 전자기적 특성 측정 실험

Experimental Measurements of Electromagnetic Properties of Concrete for Assessing Damage by Earthquake

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국문요약

레이다를 이용한 콘크리트 구조물의 지진으로인한 손상도를 파악하기 위해, 콘크리트의 전자기적 특성(dielectric properties)을 레이다 작동 주파수 대역인 200 MHz에서 6 GHz 영역까지 측정하였다. 이의 측정을 위해 실험실에서 콘크리트의 전자기적 특성 계측을 가능하게 하는 회로망분석기(network analyzer)를 사용하였다. 콘크리트의 전자기적 특성은 open-ended coaxial probe를 회로망 분석기에 연결하여 측정하였고, 실험전 측정값을 보정(calibration)하는 기법을 찾아내었다. 주파수의 변화와 함께 콘크리트 시편안에 포함된 수분의 양을 조절함으로써, 실제 콘크리트 구조물이 가질 수 있는 상태를 시편을 통해 측정하였다. 측정결과는 콘크리트의 전자기적 특성이 주파수와 수분함량에 따라 변하는 것을 보여주었으며, 이는 레이다를 이용한 콘크리트 구조물의 지진 손상도 파악 방법 개발에 필요한 자료를 제공하였다.

1. Introduction

A successful application of a radar method to concrete structures for nondestructive testing (NDT) requires a clear understanding of the electromagnetic (EM) properties of concrete. Many aspects of electromagnetic wave propagation in a material are dependent on the electromagnetic properties of that material. Generally, the interaction of electromagnetic waves with a given material is frequency-dependent, and furthermore, this interaction at a given frequency strongly depends on the electromagnetic properties of the material.

This necessitates the need to develop a data base for electromagnetic properties of concrete as a function of frequency. In addition to the frequency dependency of the electromagnetic properties of concrete, the inherent characteristics of concrete such as moisture content and density variations further complicate the problem requiring an in depth study of the material behavior in its interaction with electromagnetic waves.

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2. Fundamentals of Electromagnetic Properties

Physically, the constitutive relations provide information about the environment in which electromagnetic fields occur - for example, free space, water, or concrete. Mathematically, a medium is characterized as follows with a permittivity ε^* and a permittivity μ^*[1].

In general, ε^* and μ^* can be functions of many parameters. When ε^* or μ^* is a function of the frequency, the medium is called dispersive. Concrete is a dispersive medium.

2-1. Dielectric Constant and Loss Factor

Every material has a unique set of electromagnetic (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 ε^* and the complex (magnetic) permeability μ^*. Most common dielectric materials including concrete are nonmagnetic, making the permeability μ^* very close to the permeability of free space. So, the focus of the discussion is on the complex permittivity ε^* which is defined as:

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \qquad \text{Eq. (1)}$$

where ε^* is the complex permittivity, ε' is the real part of the complex permittivity, ε'' is the imaginary part of the complex permittivity, and $j = \sqrt{-1}$. By dividing Eq. (1) by permittivity in free space ε_0, the property becomes unitless and relative to the permittivity of free space:

$$\frac{\varepsilon^*}{\varepsilon_0} = \frac{\varepsilon'}{\varepsilon_0} - j\frac{\varepsilon''}{\varepsilon_0} \qquad \text{Eq. (2)}$$

$$\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r'' \qquad \text{Eq. (3)}$$

where ε_r^* is the relative complex permittivity, ε_r' is the real part of the relative complex permittivity or dielectric constant, ε_r'' is the imaginary part of the complex permittivity or loss factor, and ε_0 is permittivity in free space (a lossless medium) = 8.854×10^{-12} Farad/meter.

The real part of the relative complex permittivity ε_r' is a measure of how much energy from an external electric field is stored in a material and is more commonly called as the dielectric constant. The dielectric constant ε_r' is greater than 1 for most solid and liquids.

The imaginary part of the relative complex permittivity ε_r'' is a measure of how dissipative or lossy a material is to an external electric field and is referenced to the relative loss factor or simply loss factor. The loss factor ε_r'' is always greater than 0 and is usually much smaller than ε_r' for dielectric materials.

2-2. Significance of Electromagnetic Properties

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 EM properties. Thus, in conducting numerical modeling[2], in performing actual radar measurements[3], and in interpreting the measurement results, it is essential to understand and develop a data base for the properties.

3. Development of Measurement Technique

In order to accurately measure the electromagnetic properties of concrete, an appropriate measurement method needs to be selected and a measurement procedure must be developed. Among available methods, an open-ended coaxial probe method is used because it can be used in measuring the EM properties over the wide frequency range from 200 MHz to 6 GHz and it is convenient to use for different size of concrete specimens.

A schematic diagram of the measurement network is shown in Figure 1.

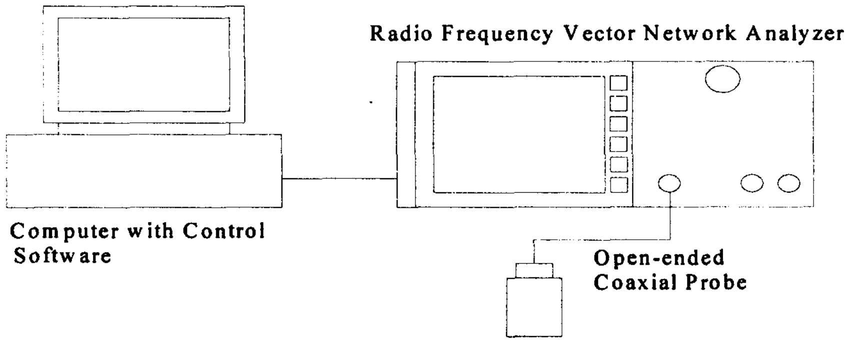

Figure 1. A Schematic Diagram of Measurement System

4. Calibration and Measurement Accuracy

Calibration of the experimental system using the probe was made by measuring methanol, short, and air. Methanol was used because its electromagnetic properties were relatively close to those of concrete compared to the other possible calibration materials over the wide frequency range of interest.

The calibration was checked by measuring materials with known EM properties. The calibration results are shown in Figures 2 and 3. The measured values showed good agreement with published values with error less than 10%[4].

5. Results of Electromagnetic Property Measurements

Concrete specimens were cast with water, cement, sand, and coarse aggregates. Portland cement of Type I was used. The experimentally obtained values of the dielectric constant of three different groups of concrete specimens are shown in Figures 4 and 5. Three different moisture conditions of the specimens considered for the measurements are: i) wet specimens with water on the surface, ii) saturated specimens which contained moisture only inside; and iii) air dried specimens with zero moisture content by weight.

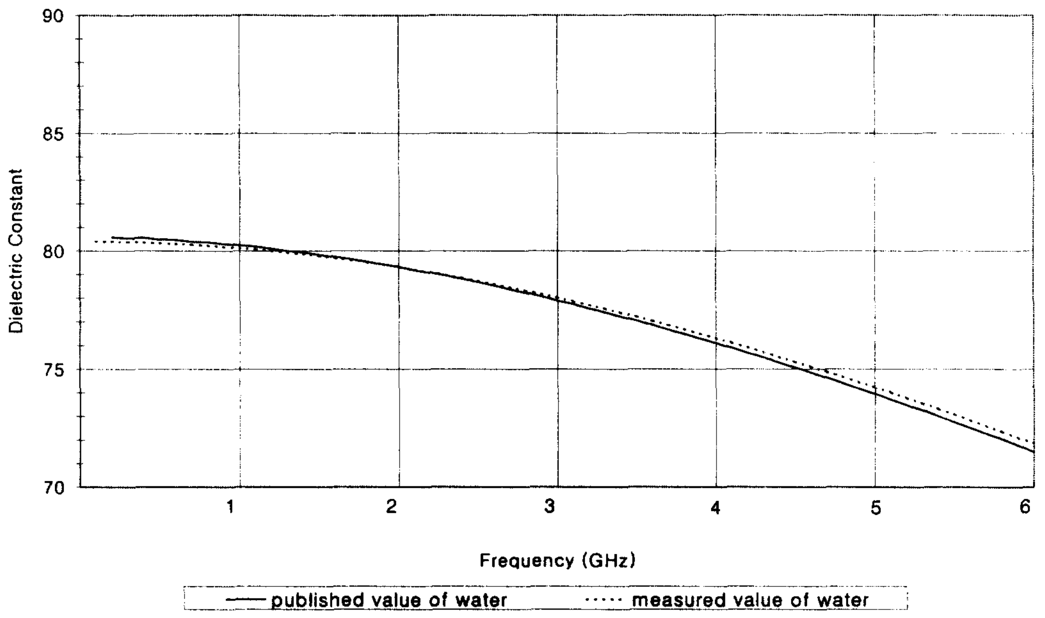

Figure 2. Dielectric Constant of Water as a Reference Material

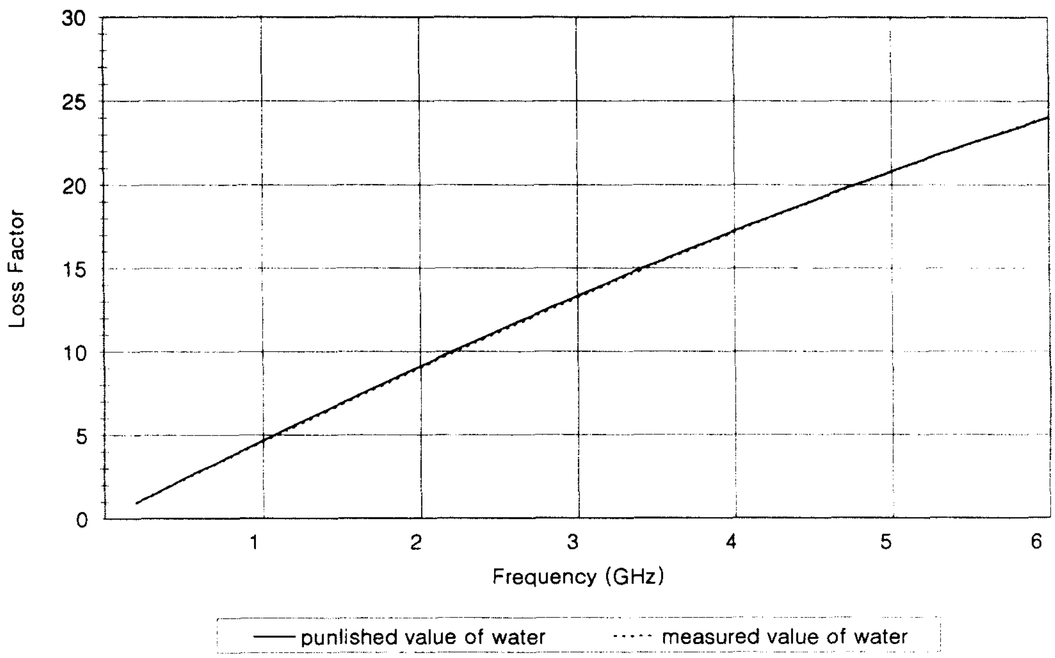

Figure 3. Loss Factor of Water as a Reference Material

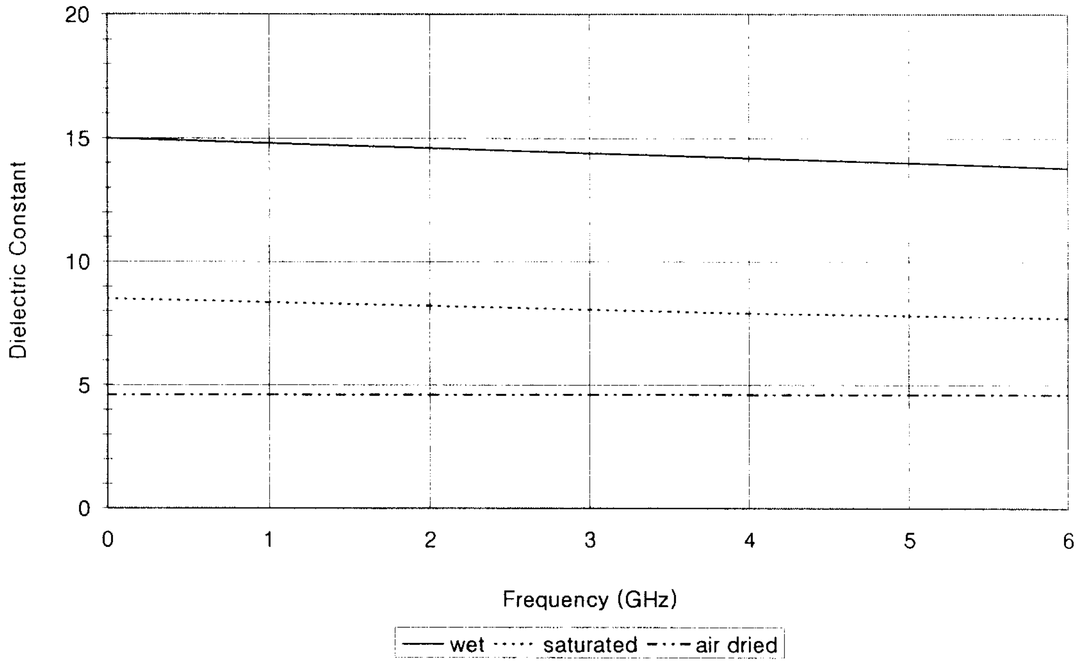

Figure 4. Measured Dielectric Constant of Concrete

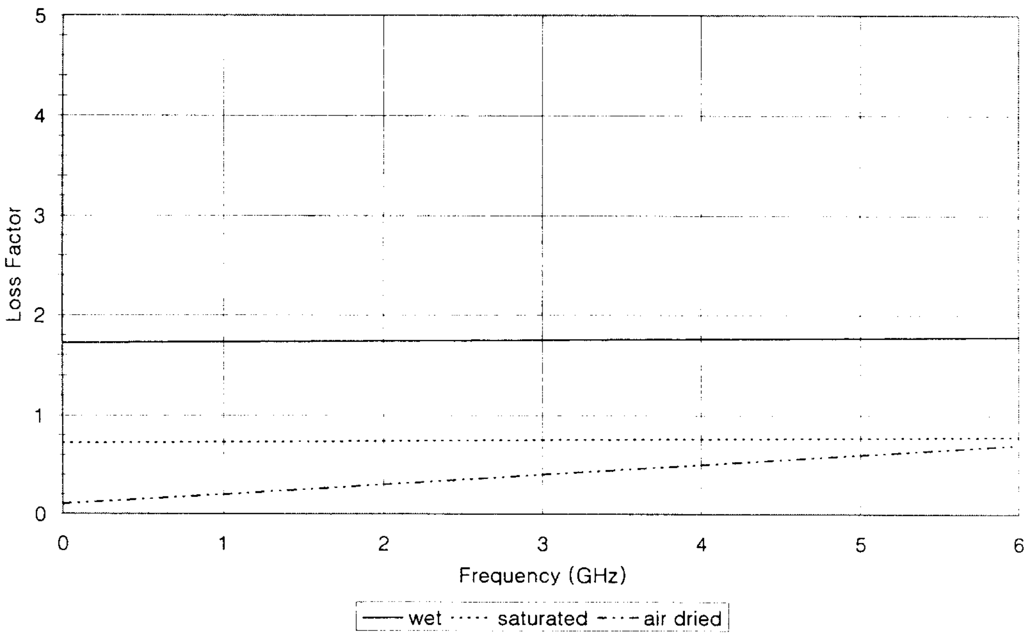

Figure 5. Measured Loss Factor of Concrete

6. Discussion

The results of electromagnetic property measurements indicate that over the frequency range from 200 MHz to 6 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 increases the detectability. The loss factor of concrete determines how deep the wave can penetrate into concrete.

7. Conclusions

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 200 MHz to 6 GHz, which is the operating frequency range for radar measurements of concrete for NDT.

The three different moisture level of concrete represent actual condition of concrete structures under investigation. For the measurements, the open-ended coaxial probe method is used. The measurements made provided a basis for further refined measurements of the electromagnetic properties of concrete for NDT of concrete structures damaged by earthquake.

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