Measurement of radar properties of concrete for *in situ* structural elements

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Interpretation of ground penetrating radar (GPR) surveys applied to concrete structures requires a prior knowledge of the dielectric properties of the concrete under investigation. Most GPR systems used for field investigations produce a broadband pulse, incorporating frequencies between 100 MHz to 1 GHz and above. A traditional laboratory method of measuring the dielectric properties of concrete at one particular frequency is to use a transmission line system. Measurements can be repeated over a range of discrete frequencies. However, this technique can only be used on special laboratory conditioned specimens. A novel method discussed in this paper uses a broadband GPR pulse, reflected from two discrete reinforcing bar targets within an in situ concrete slab to produce the dielectric properties of the concrete over the broadband spectrum of the antenna. Results of the two methods are compared and possible implications for field measurements are discussed.

Introduction

Over the last two decades, there have been increasing applications of GPR as one of the primary non-destructive testing techniques used in the inspection of concrete structures[1]. Most GPR systems manufactured for concrete applications use a broadband RF pulse at centre frequencies in the range of 500 MHz to 1 GHz, with bandwidths in air of 50% to 100%. As a consequence there has been a number of studies of the dielectric properties of concrete within this range of frequencies[2][3][4]. Most of these dielectric property measurements were carried out using a transmission line system, in the frequency domain, using special moisture-conditioned specimens. The moisture content of the concrete has been found to be the most significant parameter influencing the relative permittivity of concrete, with factors such as aggregate type, cement content and strength playing a comparatively minor role[5]. Transmission line measurements can produce highly accurate results but these measurements will not be very useful unless the results can be related to the dielectric properties of the actual concrete in structures of interest. There are three important reasons why this can be a problem:

- Most GPR systems operate in the time domain and utilise a broadband RF pulse, which comprises a range of frequency components rather than using a series of discrete frequencies, measured in the frequency domain.
- One of the major effects produced by coupling a GPR antenna to a dielectric medium such as concrete is a significant decrease of the frequency components of the pulse in that medium[6]. This means that the concrete properties measured at the nominal centre frequency of the antenna in air will not be the same as those measured at centre frequency of the radar signal in the concrete medium.
- Since the specimen size, shape, and material properties such as the moisture content are generally different from those of the actual concrete structures, there is some uncertainty as to how to use the results from frequency domain measurements directly in real site testing.

There is, therefore, a need for a method of measuring or estimating the dielectric properties of concrete directly from the GPR system. In this paper, methods and results of measuring dielectric properties of concrete using both the laboratory transmission line and field GPR systems are discussed.

Dielectric properties of concrete

The dielectric properties of concrete are characterised by its permittivity, ε in F/m and conductivity, σ in S/m. For a lossy medium such as wet concrete, it is common to represent these properties in a form of a complex permittivity and to write it relative to the permittivity of free space, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m as in the equations below:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} - j\frac{\sigma}{\omega\varepsilon_0} \quad (1)$$

$$\varepsilon_r = \varepsilon' - j\varepsilon'' \quad (2)$$

In Equation (1), $\omega = 2\pi f$, is the wave angular frequency in (rad/s) while f, is the frequency in (Hz). In a dispersive medium, both the real and imaginary parts of the complex permittivity are frequency-dependent and the measurements have to be carried out in the frequency range that is relevant to the subsequent applications. The significance of the complex permittivity lies in the fact that while the radar velocity, v in the medium is related to its real part, ε' as approximately given by the following equation:

$$v = \frac{c}{\sqrt{\varepsilon'}} \quad (3)$$

The radar attenuation, on the other hand, is primarily determined by its imaginary part, ε''. The two techniques discussed in this paper concern the measurements of the relative complex permittivity, ε_r of some concrete specimens.

Measurements with a laboratory transmission line system

The transmission line developed in the Department of Civil Engineering of Liverpool University is a co-axial facility with tapered ends[2][5]. The concrete specimen is an annulus which has an inside diameter of 44 mm, outside diameter of 101 mm, and a

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line, in between two air-filled buffer sections as shown in Figure 1. A Hewlett-Packard network analyser, model HP8753B is used to measure two complex scattering parameters, S_{11} and S_{21} of a two-port network formed by the transmission line in the frequency range of 1 MHz to 2 GHz, in 2.5 MHz increments. S_{11} is a complex measure of a signal introduced at Port 1 and reflected back to Port 1. S_{21} is a complex measure of a signal introduced at Port 2 and transmitted through the specimen to Port 1. Both parameters also contain multiple reflections of the signal within the concrete specimen and thus the magnitude of S_{11} and S_{21} will fluctuate with the frequency of measurement, as the signal components interact and go in and out of phase.

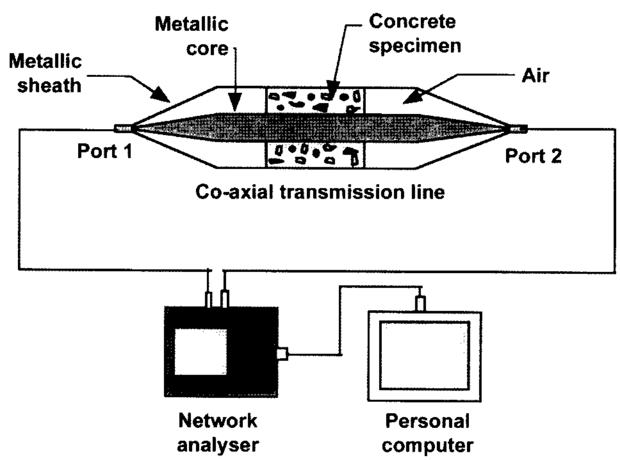

Figure 1. Transmission line measurement arrangement

The relative complex permittivity, ε_r of the specimen can then be computed from S_{11} and S_{21} using the following equations[7]:

$$V_1 = S_{21} + S_{11} \quad \text{.......... (4)}$$

$$V_2 = S_{21} - S_{11} \quad \text{.......... (5)}$$

$$X = \frac{(1 - V_1 V_2)}{(V_1 - V_2)} \quad \text{.......... (6)}$$

$$\Gamma = X \pm \sqrt{X^2 - 1} \quad \text{.......... (7)}$$

$$z = \frac{(V_1 - \Gamma)}{(1 - V_1 \Gamma)} \quad \text{.......... (8)}$$

$$\varepsilon_r = -\left\{\left(\frac{c}{\omega l}\right) ln\left(\frac{1}{z}\right)\right\}^2 \quad \text{.......... (9)}$$

In these equations, Γ is the reflection coefficient at the air-concrete interface, for a medium of complex permittivity ε_r assuming a specimen of infinite width, z is the wave propagation factor in concrete, and l is the length of the specimen. Results from measurements made on two specimens; Sample 1 (dry) and Sample 2 (wet), are shown in Figure 2 over a frequency range from 10 MHz to 2 GHz. From these results it can be seen that the increase of moisture content contributes to an increase of both the real and imaginary parts of the complex permittivity particularly in the lower frequency range and these features are consistent with results from other published reports[2][3][4].

Measurements with a field GPR system

The GPR system used in this study is a model SIR-2 manufactured by Geophysical Survey Systems Inc. (GSSI) using a 900 MHz antenna. A high-frequency antenna would be expected to give a high resolution, enabling discrimination between two closely spaced targets. The greater attenuation of a high-frequency signal, however, in a lossy medium such as wet concrete can give a restricted depth penetration. In dry concrete an effective depth limit of at least 500 mm is expected, whilst in wet concrete this reduces to about 250 mm. The 900 MHz antenna was selected as an acceptable compromise between resolution and depth. In this proposed new technique the dielectric properties of a concrete specimen are determined by analysing time-domain signals from two targets at known depths. The targets used in this case are two reinforcement steel bars of 16 mm diameter, one at a depth of 50 mm and the other at a depth of 150 mm in a 400 mm-thick concrete slab. The arrangements for this measurement are shown in Figure 3, with the antenna containing both the transmitter and receiver being positioned over each target in turn.

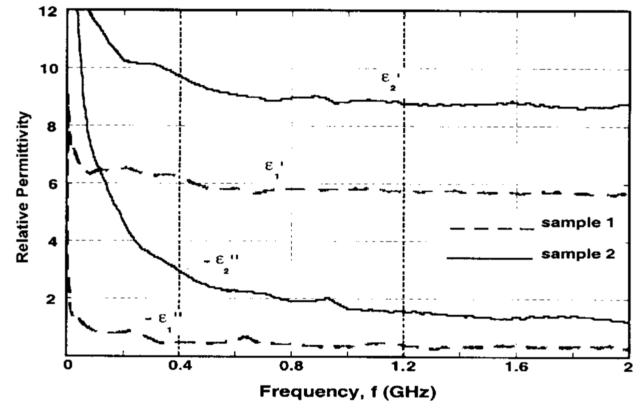

Figure 2. Relative permittivity from transmission line measurements

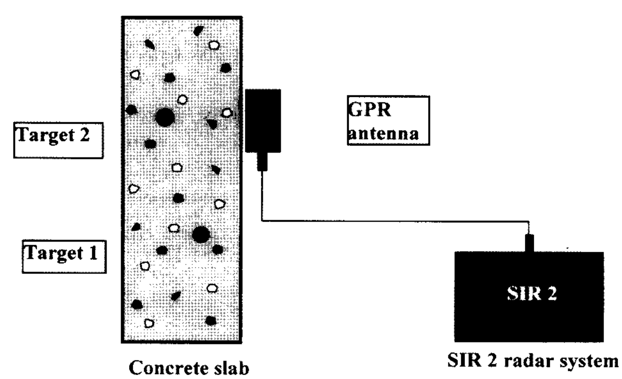

Figure 3. GPR measurement arrangement

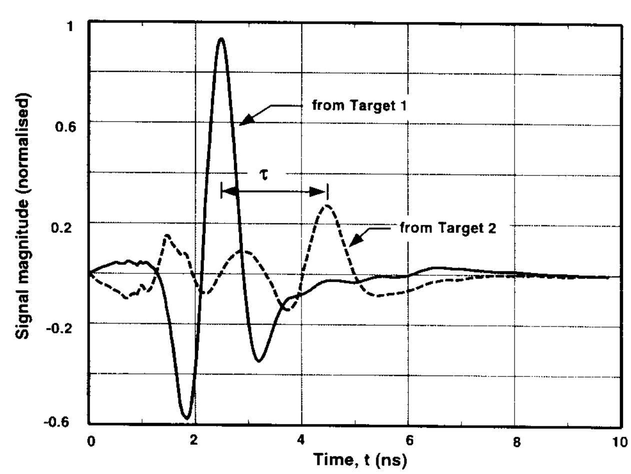

Figure 4. Time domain signals

Results in the form of time-domain signals are shown in Figure 4. It can be seen that τ is the delay time between signals from Target 1 and 2 as measured from the centres of their peaks.

In order to calculate the relative complex permittivity, ε_r of the slab, the propagation factor, z is estimated from the ratio of the Fourier transforms of the two signals and is used in Equation (9) above. Measurements made on the concrete slab are compared with those obtained from a transmission line measurement made on a specimen of the same age and mix.

The results are shown in Figure 5. Both sets of results show relatively close agreement, with a similar exponential decay between frequencies of 1 MHz to 1.3 GHz. The differences in the real parts of these results are likely to be due to the fact that the slab and transmission line specimens are not the same size or geometry. Even though they are both nominally 'dry', they must nevertheless have different actual moisture contents. A simple check on the approximate value of the relative permittivity, ε' of the slab from the time domain signals could be obtained by using the following formula:

$$\varepsilon' = \left(\frac{\tau c}{d}\right)^2 \quad \text{.....(10)}$$

where τ is the time delay, d the propagation distance, and c = 300 mm/ns is the speed of light in air. With d = 200 mm and from Figure 5, τ = 2.0 ns, the relative permittivity, ε' calculated using Equation 10 is equal to 9.0 which is of the same order of magnitude with ε' values in the frequency range of 400 MHz to 1.5 GHz. A relative permittivity of 9.0 would normally be expected to correspond with a concrete that is not totally dry. The transmission line results indicate a relative permittivity of around 7.5 for most of the frequency band of interest. This is much closer to the result expected for much drier concrete and is consistent with the relative ease of drying the small annular concrete specimen, where the maximum distance of any concrete from the air-drying surface is 28.5 mm. It is reasonable to suggest that the SIR-2 results give a more reliable indication of the properties below a relatively thin surface zone.

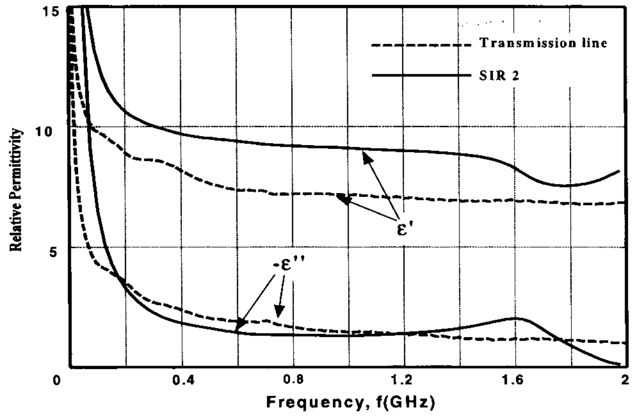

Figure 5. Relative permittivity from transmission line and GPR measurements on dry concrete

There is, however, closer agreement between the imaginary parts of the complex permittivity, despite the fact that this technique is based upon several assumptions. For example, the losses due to mechanisms[8] other than that of the material loss are ignored. There are also problems associated with the fact that all the measurements are made within the near-field of the antenna and this makes it very difficult to include the effects of spatial attenuation on the imaginary part of the results.

Conclusions

Results from transmission line measurements indicate that this laboratory technique is capable of measuring both dry and wet specimens with a high degree of accuracy. However, unless the moisture content of the specimen is known beforehand, there will be limited use for these accurate results. Direct dielectric measurements or estimations using a GPR system, on the other hand, could produce results that are more relevant to the actual properties of the specimens involved. The new method of measurement, providing results in the frequency domain using conventional time domain GPR equipment, promises to provide a quality of results normally only obtainable in the laboratory using an expensive and cumbersome network analyser. Further improvements on some aspects of the technique, in particular on the need for noise-free signals from isolated targets, could lead to a better means of making an *in situ* measurement on the dielectric properties of concrete structures. Further work is planned to determine the range of reinforcing bar configurations normally encountered in reinforced concrete construction that could be used to implement the method described to determine concrete dielectric properties in the frequency domain.

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