Coaxial Transmission Lines: Development of Test Procedures for Concrete

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ABSTRACT: The use of ground-penetrating radar as a nondestructive investigative technique has gained increasing acceptance both in the United States and in Europe for assessing the structural integrity of concrete structures. However, without an accurate knowledge of the electrical properties of concrete at radar frequencies, it is difficult to quantitatively assess the results of a ground-penetrating radar survey. This paper reports the simultaneous, but independent, developments of two coaxial transmission line systems at Virginia Tech and The University of Liverpool. Both are designed to measure the relative permittivity and conductivity of concrete over a range of frequencies from 100 MHz to 1 GHz. This paper discusses the development of the two transmission lines, and a comparison of the two methods of measurement and interpretation of results.

INTRODUCTION

The use of electromagnetic radiation transmitted through air to detect airborne targets or ships is a well-known technique in the twentieth century. Somewhat less known is ground-penetrating radar (GPR), which has the ability to transmit electromagnetic waves through solid objects and to detect subsurface features. Ground-penetrating radar was initially developed for military purposes, but was later modified by geophysicists and used as a means of evaluating underground features. More recently GPR has been used by civil engineers to evaluate the structural integrity of reinforced concrete elements such as highway bridge decks (Clemena 1991; Maser 1991) or to detect subsurface targets such as voids (Daniels 1996; Halabe et al. 1997), reinforcing steel (Bungey and Millard 1993), or prestressing ducts (Bungey et al. 1997).

Although the application of GPR to concrete structures has proved to be a powerful nondestructive testing tool and the interest in its application and demand for GPR surveys to be carried out is increasing, a number of difficulties are currently present. The main difficulty is manifested in the data interpretation of GPR output, and this falls into two broad areas:

1. Unlike an X-ray picture resulting from a through transmission of electromagnetic radiation from a transmitter to a receiver, GPR is normally conducted in monostatic mode, where the transmitter and receiver are positioned adjacent to each other. The images thus obtained from the reflected signals bear very little visual resemblance to the features that are beneath the surface being investigated and hence a considerable amount of experience and operator skill may be required to interpret the collected data. Research has been carried out (Molyneaux et al. 1995) and is ongoing at The University of Liverpool to explore the potential for using neural networks and artificial intelligence to facilitate a more correct and accurate interpretation of results.

2. Determination of the exact location of a reflecting feature beneath the surface relies upon a prior knowledge of the speed of the radar signal within the solid media. This is a function of the electromagnetic properties of the material.

At radar frequencies in the range of 1 MHz to 1.5 GHz, the electromagnetic properties of concrete are not well known and this lack of basic material properties may hamper the effective use of GPR for assessing concrete elements. By coincidence two different research groups at The University of Liverpool and Virginia Tech addressed this problem independently using a large diameter transmission line approach. The objective of this paper is to compare the development of the two transmission line measurement methods and the respective methods of analyzing results. A comparison of the results obtained from measuring the dielectric properties of different concrete mixes at radar frequencies by the two research groups will be the subject of another paper.

PRINCIPLES OF SUBSURFACE RADAR

The most common method of using subsurface radar is when the transmitting and receiving antennas are both fixed together (monostatic) and are scanning together over the surface of interest. The transmitted radar signal is a divergent beam, with a typical angle of 45° on each side of the centerline. Subsurface features will reflect the radar signal from either side of the antenna location (Fig. 1). However, the return time will be shortest when the antenna is located directly above a feature and hence the lateral position of the feature can be easily ascertained. A cylindrical steel bar for example will produce a hyperbolic reflected signal pattern, where the center of the bar is located beneath the apex of the hyperbola.

Locating the depth of a reflective feature beneath the surface of the concrete requires knowledge of the propagation speed of the radar signal through the concrete. This can be by a simplified expression

$$v = \frac{c}{\sqrt{\mu_r \varepsilon_r}} \tag{1}$$

where c = speed of light in free space (300 mm/ns); μ_r = relative magnetic permeability; and ε_r = relative permittivity (dielectric constant) of concrete.

Most concrete mixes are considered nonmagnetic and thus

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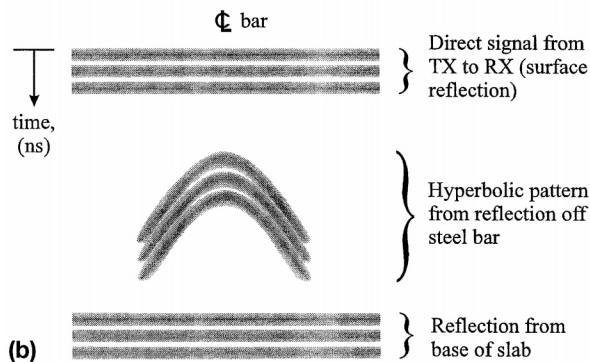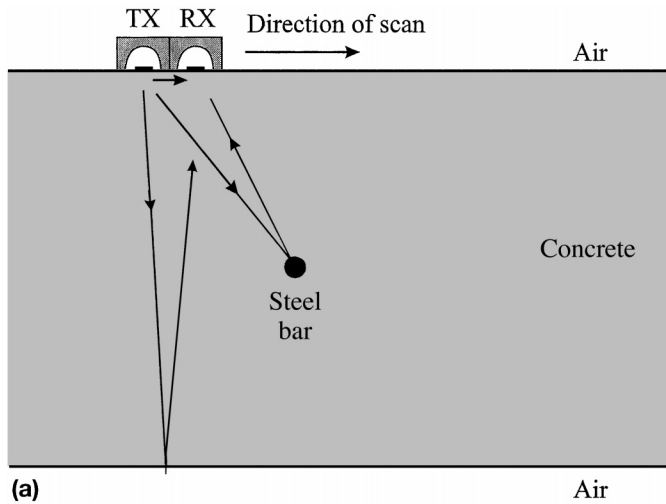
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FIG. 1. Use of Subsurface Radar (GPR): (a) Subsurface Reflections; (b) Signal Reflection Pattern (B-Scan)

their relative magnetic permeability μ_r may be assumed to be unity. The relative permittivity ε_r is given by

$$\varepsilon_r = \frac{\text{Permittivity of material, } \varepsilon}{\text{Permittivity of free space, } \varepsilon_0} \qquad (2)$$

where ε_0 = fundamental constant ($=8.854 \times 10^{-12}$ F/m).

The relative permittivity of concrete is frequency-dependent and is sensitive to concrete parameters, especially the level of moisture in the concrete. Typically in the ultrahigh frequency (UHF) frequency band, ε_r varies from about 3.5 for very dry concrete to more than 12.0 for saturated concrete, after full hydration has occurred. For comparison, ε_r has a value of 1.0 for air and up to 81 for free water. Hence, if the radar signal return time is measured when the transmitting and receiving antennas are positioned directly over a subsurface feature and ε_r is also known, then the depth of the feature can be found.

The influence of moisture in the concrete serves to increase the relative permittivity ε_r and hence decreases the speed of the signal. In addition, there is an increase in the attenuation of the signal with an increase in the moisture level. Therefore, the permittivity is usually expressed as a complex number

$$\varepsilon^* = \varepsilon' - i\varepsilon'' \qquad (3)$$

where ε' represents the property itself (energy stored); ε'' represents the loss due to molecular friction and conductivity; and $i^2 = -1$.

Concrete that is moist has a greater conductivity and hence is more lossy or attenuating. The degree to which a material causes losses in the signal magnitude is usually described by the ''loss tangent'' tan δ, where

$$\tan \delta = \frac{\varepsilon''}{\varepsilon'} \qquad (4)$$

The conductivity σ of the concrete at a frequency f can be expressed, in S/m or Ω^{-1} m^{-1}, as

$$\sigma = \frac{\tan \delta f \varepsilon_r}{1.8 \times 10^{10}} \qquad (5)$$

A radar pulse signal, which is transmitted by most commercial GPR systems, is a broadband signal, where the bandwidth is often similar to the center frequency. For example, a nominal 1 GHz pulse may have frequency components ranging from 0.5 GHz to 1.5 GHz. Initial studies at Liverpool (Shaw et al. 1993) used a measurement of the speed of a broadband pulse in the time domain to evaluate ε_r using (1). While this approach will give an approximate value for ε_r, it will give no information about the variation of ε_r with frequency. Furthermore, since the higher frequency components of the broadband pulse are attenuated more easily in a lossy material than are the lower frequency components, the form of pulse will change as it propagates through the lossy material. The higher frequency components may be significantly attenuated (Shaw 1998). The result of this selective attenuation is that a value of ε_r obtained from a signal pulse propagating a short distance through moist concrete will correspond to higher range of frequency components of a signal pulse propagating over a longer distance.

A second difficulty in using measurements of the signal velocity of a pulse in the time domain to evaluate ε_r is that the moisture levels in a concrete element are usually nonuniform. Unless the concrete is either completely saturated or oven-dried, there would be a moisture variation profile within the concrete and hence the signal velocity would vary within the section of interest. Any evaluation in the time domain of ε_r for concrete using a velocity approach and using a broadband radar signal can only yield a single value of ε_r. This value would be a mean one for the range of frequencies in the signal pulse and for the range of moisture levels encountered within the concrete element.

TRANSMISSION LINE MEASUREMENTS

A more promising technique is to use a coaxial transmission line approach to obtain the complex permittivity properties of a concrete specimen and to determine how these properties are dependent upon the frequency of measurement. This method enables a well-defined electromagnetic signal to propagate from one end of the transmission line to the other, with no signal attenuation due to spatial divergence. If measurements are taken in the frequency domain, by applying a steady-state sinusoidal excitation at a series of discrete frequencies, it is then possible to examine the relationship between the dielectric properties of the concrete and the frequency of measurement.

Transmission lines are traditionally used by electrical engineers for measuring the properties of material samples a few millimeters in size. When a civil engineering material such as concrete is to be measured, it is necessary to fabricate a coaxial fixture on a much larger scale. The University of Liverpool and Virginia Tech, in two independent research projects, have developed two coaxial transmission lines that both converged on very similar solutions although they were different in the design.

Transmission Line Development at The University of Liverpool

The coaxial transmission line system developed at Liverpool initially comprised a cylindrical concrete specimen cast onto a 44 mm-diameter brass core and surrounded by a 101 mm-diameter copper sleeve (Fig. 2). The concrete specimen thus
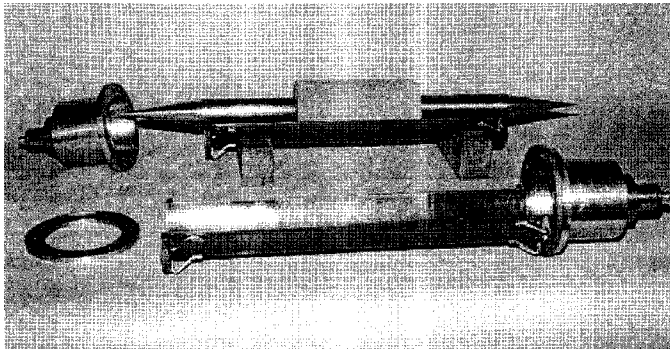
FIG. 2. The University of Liverpool 101 mm-Diameter Transmission Line

FIG. 4. Dimensions of The University of Liverpool 150 mm-Diameter Transmission Line

is an annulus with a thickness of 28.5 mm, enabling concrete-using aggregates of up to 10 mm in size to be studied.

The intrinsic impedance of a coaxial transmission line Z is given by

$$Z = \frac{60 \ln\left(\dfrac{b}{a}\right)}{\varepsilon_r^{1/2}} \qquad (6)$$

where a and b = respective radii of the inner and outer metallic conductors. Hence, when air-filled, the transmission line has an intrinsic impedance of 50 Ω.

The cylindrical parts of the coaxial transmission line were connected to standard N-type connectors without any sudden changes in impedance that could cause unwanted signal reflections. This was achieved by machining two conical sections, fitting to both ends of the inner and outer cylindrical sections of the transmission line. These cones maintained the ratio of a/b and hence gave no change in the impedance. Between the concentric conical end-pieces and the concrete specimens were two 200 mm air-filled coaxial sections (Fig. 3). The purpose of these air-filled end sections was to ensure that the signal remained in pure transverse electromagnetic mode when the signal encountered the surface of the concrete specimen, i.e., the vector direction of the electric field is normal to the inner and outer metallic surface at all points.

All transmission line measurements were carried out using a Hewlett Packard HP-8753B network analyzer with a 850044 A 50 Ω, 300 kHz to 3 GHz, S-parameter test set. A series of 201 measurements at frequencies from 1 MHz to 1 GHz were taken to give a series of S_{11}, S_{21}, S_{12}, and S_{22} scattering parameters at each frequency selected. $\mathbf{S}_{ij}$ denotes the vector ratio of the signal exiting port i to the signal entering port j. Hence when $i = j$, Sij denotes a reflection coefficient, and when $i \neq j$, Sij denotes a transmission coefficient. In practice, for a symmetric transmission line $S_{11} = S_{22}$ and $S_{21} = S_{12}$.

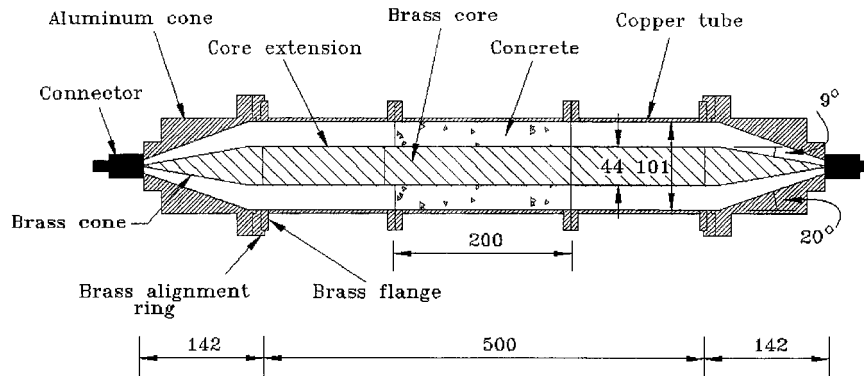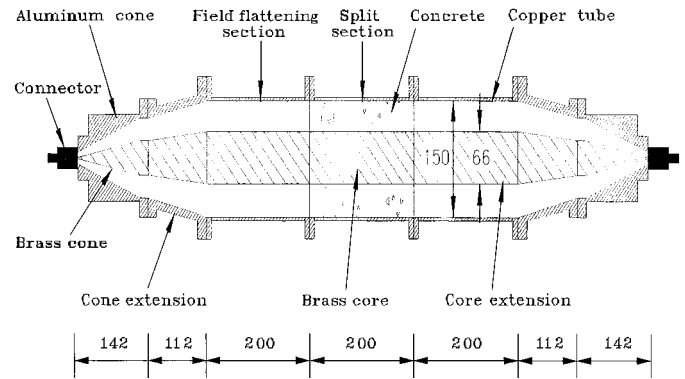The network analyzer calibration procedure using open circuit, short circuit, and 50 Ω terminators ensures that the effects of signal losses and phase changes within the connection cables are removed, and hence the measurement planes are taken at the connectors at each end of the transmission line.

Before use on concrete specimens, correct functioning of the transmission line was validated by taking measurements with no concrete specimen inside the center section. To support the central brass conductor, a hollow cylinder of expanded polystyrene was used, having dielectric properties very close to those of air. In addition, the transmission line was tested with a center section of distilled water held between two 5 mm-thick Perspex plates. Once the effects of the plates themselves had been eliminated, a relative permittivity of 81 for water was obtained through the frequency range of 1 MHz to 1 GHz. This was the expected result and served as an additional calibration for the system.

In addition to the development of a 101 mm-diameter transmission line, a second coaxial transmission line with an outer diameter of 150 mm and an inner diameter of 66 mm was developed (Fig. 4). This transmission line also had intrinsic impedance of 50 Ω throughout its length. The increased diameter enabled concrete with a maximum aggregate size of 20 mm to be studied. The sheer size and weight of this larger transmission line, however, made handling quite difficult, and hence only a relatively small number of 150 mm-diameter concrete specimens were investigated.

Each concrete specimen was cast within the center section of the transmission line. This section was split longitudinally (Fig. 3), enabling repeatable measurements of each specimen to be made. Alternatively, measurements of several specimens could be conducted within a short period of time by making use of this split facility. Each specimen could be tested during and after full hydration has occurred in a water-saturated condition.

FIG. 3. Dimensions of The University of Liverpool 101 mm-Diameter Transmission Line

Transmission Line Development at Virginia Tech

At the same time that the above studies were taking place at The University of Liverpool, independent research at Virginia Tech also led to the development of a similar transmission line fixture. This transmission line was designed to measure the dielectric properties of concrete within the frequency range of 100 MHz to 1 GHz. At lower frequencies (0.1–40.1 MHz), a parallel plate capacitor was developed and used to determine dielectric properties and at higher frequencies, a horn antenna system (0.5–10 GHz) was developed (Al-Qadi and Riad 1996).

The transmission line comprised a coaxial cylindrical center section with internal and external diameters of 25.4 and 154 mm, respectively, and a pseudo conical section at each end to allow connection to a standard SMA 50 Ω connector. The pseudo conical sections were not as smooth (from inside) as with the Liverpool transmission line, but comprised a series of four discrete steps (Fig. 5). From (6) it is seen that the central section, when air-filled, has intrinsic impedance of 107.5 Ω. Each concrete specimen was 150 mm in length and in diameter and was cast onto a central metal core of 25.4 mm diameter (the inner conductor used in the fixture), which is temporary connected to a specially designed mold during casting and curing. As with The University of Liverpool transmission line arrangement, the Virginia Tech system was longitudinally split to enable placement and removal of the concrete specimens. However, in the Virginia Tech coaxial transmission line, concrete is cast separately in a special mold and not in the concrete housing chamber of the line, as is the case in the Liverpool transmission line. Reference to the development details can be found in Al-Qadi et al. (1994, 1997).

The four small steps in the tapered end sections of the transmission line resulted in small discontinuities in impedance but the local reflections caused by these steps tended to be dampened out by the air-filled cylindrical sections on each side of the concrete specimen. For the coaxial transmission line, the dominant mode of wave propagation was in the transverse electromagnetic mode. When air-filled, the cutoff frequencies for TM and TE modes were 2.4 GHz and 1.1 GHz, respectively.

At Virginia Tech, measurements were taken on transmission line specimens in the frequency domain and in the time domain. Frequency domain measurements were taken using a Hewlett Packard 8510 network analyzer to obtain the four S-parameters (S_{11}, S_{21}, S_{12}, and S_{22}), as previously described. Measurements were conducted using a two-port measurement method. The thru, reflection, and line method was used for calibration purposes. Thru standard was realized by directly connecting the two buffer sections. The short standard was provide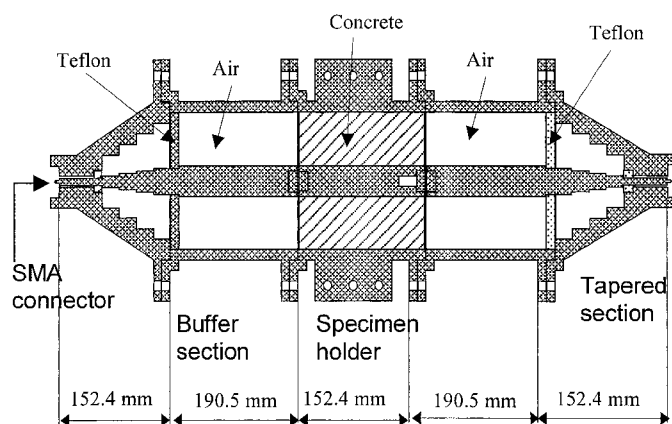d by placing a circular brass plate at the end of the buffer section while the line standard was achieved by using an empty specimen holder.

Time domain measurements were taken using a pulse generator and a Tektronix 11801 digital sampling oscilloscope and a one-port arrangement (Fig. 6). A pulse with approximately 200 ps rise time was used as a source excitation. By appropriate time gating of the signal response, it was possible to eliminate spurious reflections and to obtain a reflection simply from the first air-concrete interface, effectively simulating a semiinfinite length transmission line. Two waveforms were recorded for each measurement. The first waveform was obtained by placing a circular brass plate at the end of the buffer section (with no specimen inside the fixture). This waveform was flipped to generate the incident waveform $v_i(t)$. The reflected waveform $v_r(t)$ was obtained after placing the specimen inside the specimen holder. A solid Teflon specimen was used to calibrate the Virginia Tech transmission line fixture. Teflon is known to be nonlossy and to have a real part of the relative permittivity of 2.0 over the frequency range of 100 MHz to 1 GHz. Using a 3 ns time window to exclude spurious reflections, the results as seen in Fig. 7 validated the accuracy of the transmission line method. The slight increase in the real part of the relative permittivity at a frequency of about 500 MHz may be attributed to the effects of the small stop in the conical end sections and was not thought to be significant.
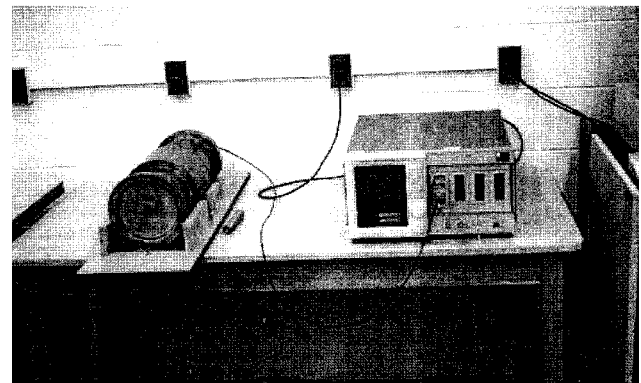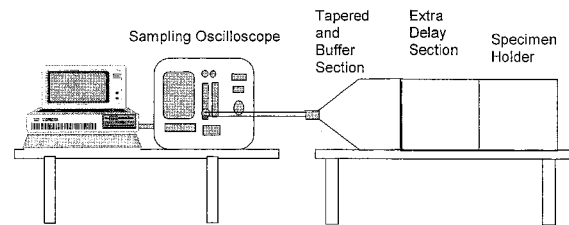

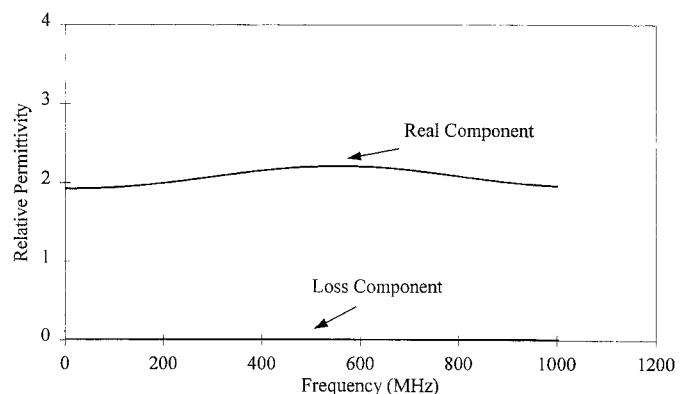**FIG. 6.** Time Domain Coaxial Transmission Line Setup

FIG. 5. Cross-Sectional View of Virginia Tech Transmission Line

FIG. 7. Relative Permittivity Plots for Teflon (Using Coaxial Transmission Line Fixture)
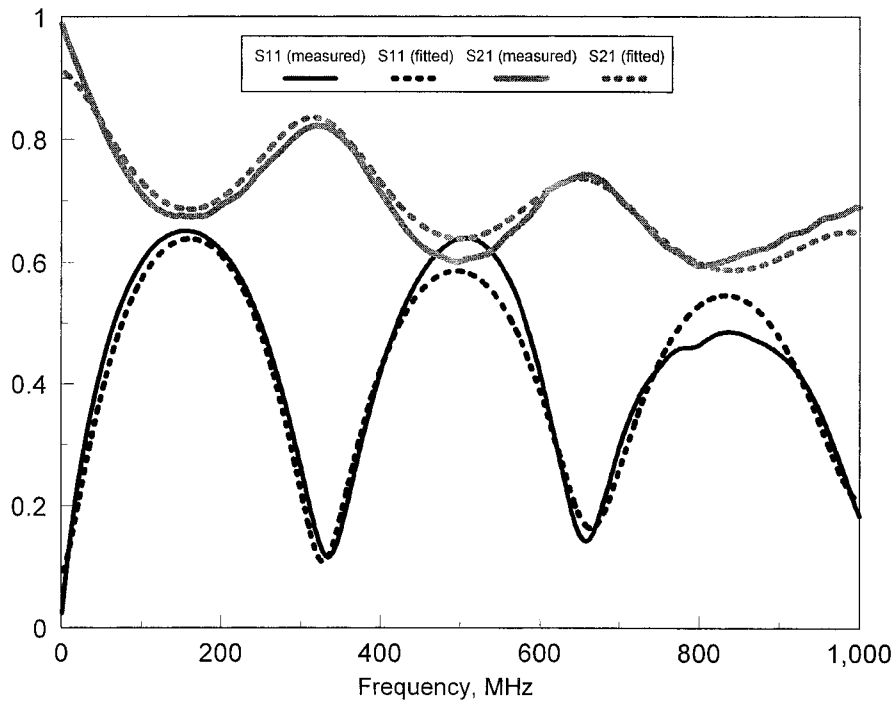
FIG. 8. Matching Measured and Theoretical *S*-Parameters

Current research at Virginia Tech suggests that a 1 ns time window converges to better results.

DATA PROCESSING OF TRANSMISSION LINES

In order to make a direct comparison between the results of transmission line measurements on concrete specimens carried out in the frequency domain at The University of Liverpool and Virginia Tech, it was necessary to establish that the procedures adopted for processing the raw *S*-parameter measurements were comparable. As the respective procedures adopted were quite dissimilar, these will first be reviewed and then compared.

Data Processing Procedure Developed at The University of Liverpool

Measurements of the scalar magnitude of both S_{11} and S_{21} against frequency showed that results were cyclic in nature as the frequency was increased (Fig. 8). This was attributed to constructive and destructive interference of signals reflected from the near and far concrete-air interfaces. As the transmission line geometry is well known, it is easy to determine the theoretical values for S_{11} and S_{21} that would be expected at any frequency for given values of relative permittivity and conductivity. A numerical procedure was developed in which the values used as input to determine the theoretical S_{11} and S_{21} at the highest and lowest frequencies of interest were iteratively adjusted so as to optimize a least-squares fit with the experimentally measured S_{11} and S_{21} values. A simplex minimization routine from the NAG library was used that systematically adjusted the input relative permittivity and the conductivity at the highest and lowest frequencies until the best fit was obtained. These input values were then considered to match those of the concrete specimen being studied. The conductivity at intermediate frequencies was then found by linear interpolation while the relative permittivity at intermediate frequencies was assumed to vary exponentially with frequency. These assumed relationships matched the experimentally observed behavior of similar materials measured by Wensink (1993) and were therefore considered reasonable. Electrical
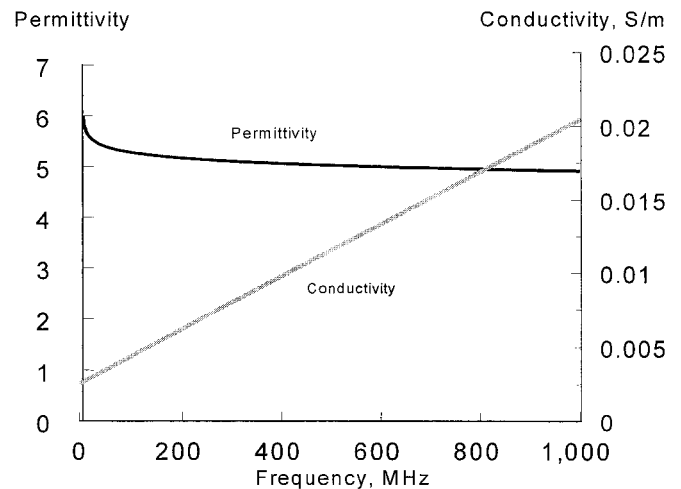

FIG. 9. Electrical Material Properties Derived from Fig. 8

material properties derived from the *S*-parameter results seen in Fig. 8 are presented in Fig. 9.

Data Processing Procedures Used at Virginia Tech

A different approach was used by Virginia Tech to process the *S*-parameter obtained from the frequency domain. Values for S_{11} and S_{21} were obtained as described previously and symmetric values were assumed for S_{22} and S_{12}. S_{11} and S_{21} can be expressed in terms of the complex reflection coefficient ρ and a propagation term τ, where

$$\rho = \frac{Z - Z_o}{Z + Z_o} = \frac{(\mu_r/\varepsilon_r)^{1/2} - 1}{(\mu_r/\varepsilon_r)^{1/2} + 1} \tag{7}$$

$$\tau = \exp[-iw(\mu_r\varepsilon_r)^{1/2d/c}] \tag{8}$$

Thus

$$S_{11} = \frac{\rho(1 - \tau^2)}{1 - \rho^2\tau^2} \tag{9}$$

$$S_{21} = \frac{\tau - \rho^2 \tau}{1 - \rho^2 \tau^2} \qquad (10)$$

Solving these equations in terms of ρ and τ gives

$$\rho = \left[\frac{1 - (S_{21}^2 - S_{11}^2)}{2S_{11}} \right] \pm \left\{ \left[\frac{1 - (S_{21}^2 - S_{11}^2)}{2S_{11}} \right]^2 - 1 \right\}^{1/2} \qquad (11)$$

$$\tau = \frac{(S_{21} + S_{11}) - \rho}{1 - (S_{21} + S_{11})\rho} \qquad (12)$$

where the $\pm$ sign is selected so that $|\rho| \leq 1.0$.

These equations are solved used the technique presented by Nicolson and Ross (1970) to give the complex relative permittivity ε_r^* and the complex relative magnetic permeability μ_r^*

$$\varepsilon_r = \frac{1 - \rho}{1 + \rho} \cdot \frac{i \ln(1/\tau)c}{\omega d} \qquad (13)$$

$$\mu_r = \frac{1 + \rho}{1 - \rho} \cdot \frac{i \ln(1/\tau)c}{\omega d} \qquad (14)$$

Thus over a particular frequency range, measurements of S_{11} and S_{21} would lead to the determination of ε_r and μ_r.

In the time domain technique, MATLAB was used to process the recorded waveforms and to calculate the complex dielectric constant. A fast Fourier transform was used on $v_i(t)$ and $v_r(t)$, which were in turn used to compute S_{11} as a function of frequency (Loulizi et al. 1999). Thus

$$S_{11}(i\omega) = \frac{F[v_r(t)]}{F[v_i(t)]} \qquad (15)$$

where F denotes the fast Fourier transform operation. The relative permittivity can then be obtained from

$$\varepsilon_r = \left(\frac{1 - S_{11}}{1 + S_{11}} \right)^2 \qquad (16)$$

Comparison of Data Processing Procedures

Prior to performing any comparison between the electrical properties found by both The University of Liverpool and Virginia Tech for a range of different concrete types and moisture levels, it is essential to ascertain that the different data processing procedures are compatible. To achieve this, a typical set of experimentally measured Liverpool S-parameters were selected for one concrete specimen and the Virginia Tech processing procedures were used to obtain a complex ε_r varying with frequency. The complex ε_r was then transformed into a relative permittivity real part (ε') and a conductivity (σ) using (3)–(5). The result is shown in Fig. 10. It can be seen that a very good agreement is found for the real part of the relative permittivity ε_r' from 100 MHz to 1 GHz. From a comparison of the processed conductivity results, it can be seen that the overall trends of the two curves are very similar. The discrepancies are thought to be due to errors in the collection of the raw data, using a curve fitting approach by Liverpool and fast Fourier transform by Virginia Tech, but these differences are not thought to be significant. The results from measurements on a range of concrete specimens in the United Kingdom and the United States to examine the influence of the concrete mix parameters on its complex dielectric constant is the subject of a subsequent paper.

CONCLUSIONS

The timely coincidence of two research projects, working independently on a common problem, has given a rare opportunity both for a corroboration of the respective measurement
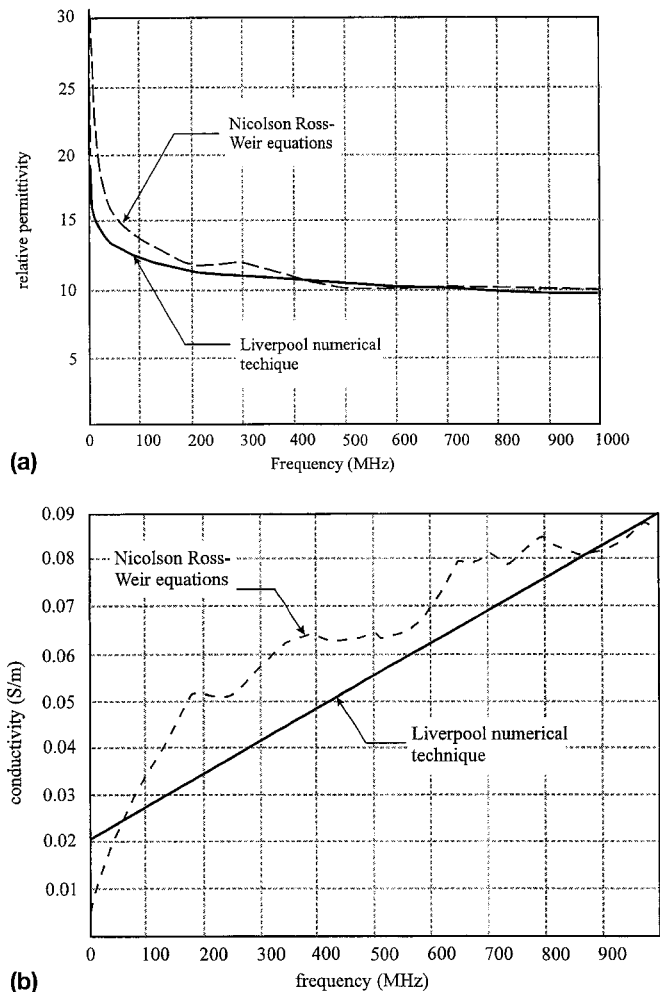

(a)

(b)

FIG. 10. Comparison of Transmission Line Data Processing Techniques: (a) Real Part of Relative Permittivity ε_r'; (b) Electrical Conductivity σ

techniques used for assessing the electrical properties of concrete at radar frequencies and for a comparison of the results found for United Kingdom and United States concrete. Although there were differences in the detail of the experimental arrangements and in the data processing procedures, a comparison of the same set of raw data processed both ways has shown that the techniques are essentially the same. In addition, this paper concludes that coaxial transmission line technique can be used to measure the dielectric properties of concrete. Measuring dielectric properties of concrete at this frequency range is critically needed for accurate interpretation of ground-penetrating radar data.

ACKNOWLEDGMENTS

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