Interpretation of Radar Test Results

by Stephen G. Millard, John H. Bungey,
Marcus R. Shaw, Cledwyn Thomas,
and Brian A. Austin

Synopsis: Experimental work has been undertaken in the laboratory and on site to assist understanding and interpretation of the results of radar testing of structural concrete. This has included the development and use of a large-scale emulsion simulation tank in which a very large range of reinforcing steel and void configurations have been examined with field testing apparatus for a range of simulated concrete properties. A library of characteristic responses as well as limits of size and spacing upon successful resolution have been obtained. A large diameter co-axial transmission line has also been designed, fabricated and used to determine the fundamental electrical properties of a range of concretes and moisture conditions at frequencies from 1MHz up to 1GHz.

Results have been compared with those for tests on larger concrete specimens with field testing apparatus and confirm the dominant influence of moisture compared with other aspects of the concrete composition. Frequency effects are quantified and related to characteristics of field antennas, and potential errors of using 'typical' values of concrete properties in interpretation and numerical modelling are identified. The test results from transmission line studies are compared with experimental and theoretical results from other research workers.

Keywords: concretes; conductivity; microwaves; nondestructive tests

Dr Stephen G Millard is a Senior Lecturer in the Civil Engineering Department at Liverpool University specialising in durability assessment of concrete, including reinforcement corrosion. He has worked on radar applications to concrete for over 5 years and has authored many papers on the subject.

Professor John H Bungey is head of the structures group in the Department of Civil Engineering at the University of Liverpool, UK. He specialises in non-destructive testing of concrete and has written numerous books and papers on this subject, serving on and chairing relevant committees in the UK and overseas. He is a consulting member of ACI 228 committee.

Dr Brian A Austin is a Senior Lecturer in the Department of Electrical Engineering and Electronics at Liverpool University specialising in antennas and electromagnetics.

Mr Cledwyn Thomas is a Research Associate in the Civil Engineering Department at Liverpool University working on radar testing of structures.

Dr Marcus Shaw is a Research Associate in the Civil Engineering Department at Liverpool University working on sub-surface radar.

INTRODUCTION

Subsurface radar has become well established as a non-destructive technique for inspection of structural concrete in a wide range of applications. The principles were outlined by Cantor (1) in 1984 and subsequent developments have more recently been reviewed by Clemena (2) as well as Bungey and Millard (3). Despite significant developments in commercially available equipment, the most successful applications currently involve interpretation procedures which are largely comparative in nature and based on pattern recognition. These include location of reinforcing steel and ducts, estimation of element thickness, identification of constructional details, location of voids and cracking as well as location of regions of saturated or salt contaminated concrete.

Specialised skills are required to interpret successfully the output data from radar surveys and numerical modelling techniques including ray-tracing, finite element and finite difference techniques have been employed to simulate the responses from particular configurations (4). Validation of such models requires comparison with results from known circumstances. The scope for the use of site results for this purpose is inevitably limited, thus laboratory studies are required and the Authors have developed a large scale simulation tank using an oil-water emulsion to permit a large number of known configurations to be systematically studied without the need for casting, curing and conditioning an impossibly large number of concrete specimens (5) . Numerical models, as well as quantitative interpretation procedures, also rely on a knowledge of the fundamental electrical properties of particular concretes at the test frequencies used. It is known that moisture is a key influencing factor and Halabe et al (6) have described theoretical models to predict variations of these properties from a knowledge of the constituents and their proportions also taking account of temperature effects. Similar attempts have been reported by Tsui and Matthews (7) incorporating geometrical pore shape effects. Validation of these theoretical predictions of electrical properties is not easy. Halabe et al (6) have used tests on sand, gravel, water and salt mixtures whilst Al-Qadi et al (8) and the Authors have developed electrical transmission line systems for testing concrete samples.

Key results obtained from simulation tank and transmission line studies in the Civil Engineering Department at the University of Liverpool supplemented by other laboratory and site tests, are presented in this paper. These provide information about the likely limits to the capabilities of radar techniques applied to reinforced and prestressed concrete as well as the scope for improvements to interpretation procedures.

BASIC PRINCIPLES OF RADAR APPLIED TO CONCRETE

A diverging beam of electromagnetic radiation is directed into the concrete from a transmitting antenna scanned across the surface. Reflections from buried interfaces are detected by a receiving antenna which is usually located adjacent to the transmitter. The propagation velocity of the signal is determined predominantly by the relative permittivity of the concrete whilst the attenuation and hence effective penetration depth is related to the electrical conductivity. The strengths of reflections are governed by the contrast in relative permittivity and conductivity at an interface, whilst some energy will pass through the interface by refraction and may be reflected from deeper features.

The pattern developed during a scan will be influenced by the beam divergence angle, the shape and orientation of the reflective surface, and the scan speed. Interpretation may also involve a study of the polarity changes which may occur in reflected signals. Conductive materials such as steel reinforcing bars will provide a very strong response and are thus relatively easy to identify but no signal will pass through to greater depths.

Beam spread and penetration capabilities are also influenced by the antenna characteristics as well as the concrete properties, with lower frequencies generally providing greater penetration but lower resolution than higher frequencies. This has been discussed in detail by Padaratz and Forde (9), and most radar testing of concrete lies in the 500MHz to 2.4GHz frequency range. Hand held 900MHz or 1GHz apparatus is most popular for structural investigations with effective penetration typically up to 300 mm in saturated concrete.

Fundamental theory is highly complex and beyond the scope of this paper although key features have been summarised by Halabe et al (6). Other aspects of the principles, apparatus, interpretation and signal processing procedures have been reviewed elsewhere (1, 2, 3, 10).

SIMULATION TANK STUDIES

A 1250mm x 1100mm x 450mm deep all-timber tank was fabricated to simulate a concrete slab with dimensions likely to provide a central zone free of edge effects. This was located with an 770mm air gap above the laboratory floor to minimise interference reflections from the floor. The tank was filled to an appropriate depth with an oil-water emulsion. Reinforcing bars were supported within the emulsion on dowelled wooden boards fitted within the longer sides of the tank, and adjustable runners set to the top surface level of the fluid facilitated surface contact scanning as illustrated in figure 1 where a 1GHz antenna is being used. Voids formed by expanded polystyrene or plastic boxes were similarly supported by small diameter timber dowelling.

Emulsions of rape-seed oil and water with appropriate sodium chloride additions have been successfully developed to model concretes ranging from saturated to air-dry conditions (5). Values of relative permittivity were adjusted by varying the oil and water proportions, whilst signal attenuation characteristics were matched to those obtained on similar sized concrete slabs tested with field apparatus by adjustment of salt concentration of the water component. Trials were undertaken on a range of emulsion mixtures in a small perspex tank using 1GHz centre frequency field testing apparatus to develop a relationship between emulsion proportions and relative permittivity and were supplemented by results obtained using a version of the transmission line system described below. The rape-seed oil alone had a measured relative permittivity of approximately 3. By adding up to 30% water by weight, the relative permittivity could be increased to approximately 12. However, the relationship between the relative permittivity and the water content of the emulsion is not linear. There is a marked transition between the region of 8% water and 12% water where the emulsion changes from being a water-in-oil emulsion to an oil-in-water emulsion. This transition causes a very marked change in the physical appearance of the emulsion and a sharp increase in the measured value of the relative permittivity from 4 to 6. On the basis of these results emulsions with 12.5% and 29% water contents by weight, with relative permittivities of 6.2 and 10.6 respectively, were used to simulate dry and wet concretes. Corresponding salt contents of 0.05% and 0.14% by weight of water yielded d.c. conductivities of 15×10^{-3} and $46 \times 10^{-3}\ \Omega^{-1}\ m^{-1}$ respectively.

Results obtained with this facility were validated by comparison with specially fabricated laboratory concrete samples and by site tests on members of known construction details. This is illustrated by figure 2 which compares scan results obtained on a 1m square 200mm thick concrete slab containing a rectangular 100mm x 50mm air void and two single reinforcing bars (25mm and 8mm) set at mid depth. These are black and white versions of colour plots, but the general similarity between these two scans 2(b) and 2(c) is apparent. There is a general tendency for the simulation tank material to give a 'cleaner' response as might be expected due to its greater homogeneity than concrete containing discrete aggregate particles which are likely to cause some scattering and 'noise' on the reflected signals. Results nevertheless provide useful 'best case' reference data and are compared in figure 2(d) with predictions obtained by ray-trace numerical modelling using appropriate materials parameters.

Tests with Reinforcing Bars

Reinforcing bars were placed across the width of the tank, perpendicular to the direction of scan, which provides the optimum orientation of the polarisation plane of the antenna for bar detection when orientated as shown in figure 1. Bar sizes ranged from 6mm to 32mm diameter set at covers between 12mm and 250mm and with spacings down to 50mm centre to centre. More than 300 different configurations have been systematically studied for emulsions designed to simulate typical air-dry and saturated concretes. Detailed results (11) have shown that whilst the clear characteristic hyperbolic response pattern will be obtained by a scan across an isolated reinforcing bar which is located (for 1GHz centre frequency) more than about 100mm below the concrete surface as shown in figure 3(a), bars at more common cover depths will produce a response which merges with the surface reflection as shown in figure 3(b). A pattern obtained by Finite Element Analysis for a simulated bar at depth is also shown in figure 3(c) for comparison. Whilst the top of the bar signal is relatively clear when at depth, this is less clearly defined when close to the surface thus making depth estimation, which is based on the return signal time between the concrete surface and the bar, more difficult. Depth estimations must thus be treated with caution, and are further complicated by uncertainties about the relative permittivity and hence signal velocity. Confidence limits of up to +45% to -30% have been suggested (11) using assumed values of concrete relative permittivity for bars at small covers unless calibration drilling is undertaken.

As bars become more closely spaced, the reflected responses will tend to overlap as shown in figure 4 and there is a limiting spacing below which it is not possible to resolve individual bars. This limiting spacing will be influenced by cover, bar size and concrete properties although these latter effects have been found to be relatively minor. Figure 5(a) suggests effective limits for 1GHz apparatus irrespective of bar diameter or concrete condition although there is a general tendency for wet concrete (with higher attenuation) to yield greater resolution for bars which are near to the surface. The shaded area represents a zone in which individual bars may or may not be detectable, and it will be seen that at 50mm cover it may be possible to identify bars at 100mm centres whilst it may not be possible at spacings below 150mm. Closely spaced bars will also effectively screen out deeper features due to a 'Faraday Cage' effect. This critical spacing will be related to the signal wavelength ($\approx$ 100mm at 1GHz) and experimental results in figure 5(b) illustrate the effect of bar diameter and spacing for a mesh at between 25 and 50mm cover. It can be seen that for large diameter bars, the effective limiting spacing may be as high as 200mm at 1GHz test frequency, compared with the value of 100mm often quoted in the literature. This limiting spacing may be expected to increase as frequency decreases and the size of the target bar below the mesh was found to have relatively little effect upon the ability to detect it although 'weaker' features such as air voids will be more difficult to identify. The identification of deeper reinforcing bars or meshes will thus be difficult especially if bars are located directly beneath those in the surface layer.

Changing the transducer orientation by 90° to that shown in figure 1 will significantly reduce the response obtained from transverse bars and is recommended if their effect is to be minimised when seeking other, deeper, features. Bars running parallel to the scan direction have also been demonstrated to have a constant and minor affect upon the ability to detect transverse bars even when directly under the antennas unless their diameter exceeds that of the transverse bars being sought. It is nevertheless recommended that scan lines should be located midway between bars if possible.

Accuracy of estimation of the lateral positioning of bars will depend upon the consistency of scan speed, reference grids and location marker inputs but ± 10mm should be possible. The method is thus particularly valuable in this respect offering improved clarity of practical data and greater depth range compared with conventional covermeters. It can be seen from figure 2 that it is possible to differentiate comparatively between large and small diameter reinforcing bars. Detailed analysis of a wide range of results, including study of individual reflected waveforms, leads however to the conclusion that quantitative bar size estimation is not realistically possible from simple examination of the results of a single scan.

Tests with Voids

Large voids were formed by a 100mm x 100mm x 50mm plastic box which could be air - or water - filled, whilst smaller air voids were formed by expanded polystyrene cut to cubic or spherical shapes ranging from 20mm to 100mm in size. Tests have also included reinforcing bars and voids in combination as well as both steel and plastic 100mm diameter post-tensioning ducts in grouted and ungrouted conditions.

Results have clearly demonstrated that a water-filled void provides a stronger response with increased likelihood of secondary reflections due to reverberations of the reflected signal between the void and concrete surface than a comparable air-filled void. This is to be expected due to the increased contrast in dielectric properties between the void and the surrounding concrete. Void shape similarly has a significant effect, since a sphere will inherently reflect a smaller proportion of the signal back to the concrete surface but this will commence when the antenna is at a greater distance away from the centreline of the void than for a cubic void with one face parallel to the surface. This effect, leading to a flatter response for a spherical void is illustrated in figure 6 which compares voids of similar size and depth with identical apparatus settings. The difficulties in estimating both shape and depth of the void are readily apparent. It is sometimes suggested that the smallest non-metallic feature that can be detected will have a plan dimension of about 1 wavelength. For concrete tested at 1GHz, this typically corresponds to about 80mm to 120mm. Tests have shown however that an air-void at 150mm cover could be readily detected down to 50mm in diameter but not at smaller sizes. Careful adjustment of apparatus controls permitted cubic voids as small as 20mm to just be detected (12) without the need for signal processing, but this was only possible because of the known target depth. These sizes are also significantly smaller than that suggested as the minimum detectable using a Freznel Zone approach (9). Adjustment of gain settings has thus been shown to be crucial in the ability to locate small voids, as demonstrated by figure 7, and in reality they are likely to be missed if their size is less than 50mm. Operator skill and experience is thus crucial if features are to be reliably detected. The presence of a layer of surface zone reinforcing steel will further hinder the ability to detect small voids. As with reinforcing bars, the centre position of a void can be defined reasonably accurately but the actual dimensions are hard to estimate due to the unknown variables such as beam divergence angle, scan speed and void shape.

Tests on prestressing ducts, as expected, confirmed that the interior condition of a metallic duct cannot be differentiated although the duct position can be clearly defined. For plastic ducts it was found that it was possible to distinguish between those containing prestressing strand and which were either fully grouted or ungrouted. This is best achieved by comparison of individual reflected waveforms, and has subsequently been confirmed by tests on similar ducts cast into concrete and by finite element modelling. The ability to detect discrete voids within grouted ducts remains to be investigated.

TRANSMISSION LINE STUDIES

Initial attempts by the Authors to assess changes in relative permittivity due to moisture changes in laboratory concrete slab specimens (10) using field testing apparatus illustrated the difficulties associated with this approach. It was thus decided that a 'transmission line' approach was the only viable way to examine accurately a range of concrete samples under controlled moisture conditions over a sensible frequency range and to yield conductivity data as well as relative permittivity.

System and Measurement Details

For the frequency range of primary interest it was concluded that the best form would be a coaxial system comprising a cylindrical concrete sample cast on a metallic inner core and surrounded by an outer conductive casing as shown in figures 8 and 9. The detailed development of this system and the relevant theory is described elsewhere by the Authors (13) whilst Al-Qadi (8) has also more recently provided details of a similar approach. Dimensional details are determined by the need to satisfy electrical parameters, and the system shown in figures 8 and 9 is 101mm in diameter which can accommodate concretes with approximately 10mm maximum aggregate size. This has a 50 Ω intrinsic impedance and is used in conjunction with a Hewlett-Packard 8753b Network Analyser. The transmission line was designed so that it could serve as a mould for the cylindrical concrete specimens which could subsequently be dismantled to permit specimens to be removed for curing and conditioning prior to, and between, measurements. The version illustrated represents a modification of the original prototype in which the sample length has been reduced to 200mm. The introduction of an air gap at each end of the specimen improves field uniformity and reduces losses in the specimen due to its shorter length.

Both ends of the cylindrical section of the transmission line are connected to a network analyser using concentric metal conical sections. A signal is input to the transmission line from one end. The ratio of the input signal to the signal reflected back from the concrete specimen can be measured. Alternatively the signal transmitted through the concrete to the far end can be measured.

Measurements can be taken in the time domain, where the velocity of propagation and the attenuation of a transient pulse is measured and used to determine the relative permittivity and electrical conductivity of the concrete specimen. Alternatively measurements can be taken in the frequency domain, where the steady state response to a continuous sinusoidal signal is measured over the range of frequencies of interest. Each technique has its own merits but measurements taken in the frequency domain can be converted into the time domain and vice versa using appropriate Fourier Transform functions. Detailed theory (13) of the transmission line system is beyond the scope of this paper.

The dielectric properties of a material are often complex with measurements involving real and imaginary components. When a material's properties are expressed as relative permittivity and electrical conductivity, the real part of the complex permittivity is seen as the relative permittivity whilst the electrical conductivity is determined from both the real and imaginary components. An alternative way of expressing the way in which a material attenuates a radar signal is to use the ratio of imaginary and real parts of the complex permittivity which is known as $\tan\delta$, where δ is called the 'loss angle'. An understanding of these relationships will assist comparisons of reports from different sources.

This system has successfully enabled measurements of both relative permittivity and conductivity in wet concretes at discrete frequencies up to 1GHz. A larger 150mm diameter version has also been commissioned for concretes using coarse aggregate size up to 20mm but whilst this has been used successfully, the increased bulk and weight diminish ease of handling. Krause et al (14) have recently demonstrated that aggregate size ranging between 8mm and 32mm has no measurable effect when using a 900MHz antenna and this has been confirmed over a wide frequency range in the present study for gravels from 10mm to 20mm, thus the use of this larger version may not be advantageous.

Test Programme

A total of fourteen 101mm diameter and six 150mm diameter specimens have been cast in the present study and tested at a range of moisture contents (typically 3 to 5 tests per specimen) over a period of several months of natural air drying in laboratory conditions. This was assisted by controlled oven drying at the later stages, eventually to a fully oven-dry condition, with moisture contents calculated from weighings at each stage. Measurements only commenced at an age of approximately 28 days due to the high attenuation characteristics of recently cast hydrating and immature concrete (13). Interpretation of the transmission line results involves the use of computer based curve fitting processes to match established logarithmic profiles for permittivity and linear profiles for conductivity with varying frequency over the range covered. Considerable effort was required to refine these procedures to yield information successfully relating to the higher end of the frequency range.

Gravel concrete samples encompassed 28 day cube strengths from approximately 17N/mm^2 to 60N/mm^2 whilst other specimens incorporated either Pulverised Fuel Ash or Ground Granulated Blast Furnace Slag as partial cement replacements over a range of proportions. Other specimens included lightweight coarse aggregates with either natural sand or lightweight fines. Typical results for a particular concrete mix are as shown in Figure 10, from which the significant effect of moisture can be seen upon both relative permittivity and conductivity.

Discussion and Analysis of Results

For comparison of different mixes, results relating to a specific 1GHz frequency are plotted in Figure 11. These demonstrate the major differences in response between lightweight and 60N/mm^2 gravel concretes for which the mean line and range of results on 3 replicate specimens are plotted. Although not plotted, results for lightweight concrete with natural sand fines lay between these two curves as might be expected, whilst mixes containing pfa or ggbfs lay close to the 60N/mm^2 gravel concrete curve for both permittivity and conductivity. Gravel concretes of much lower strength similarly lay very close to the higher strength results for conductivity but with a small reduction in relative permittivity at very low moisture levels (oven drying) as indicated. At low moisture levels it can be seen that relative permittivities all tend towards a value of about 5.0 which is that associated with the aggregate material. The use of alternative natural coarse aggregates (granite and limestone) was found to have only a relatively minor effect in relation to gravel concretes compared with the major influence of moisture, although limestone did yield a small increase in relative permittivity which is consistent with its greater water absorption characteristics.

Earlier studies of concrete properties at radar frequencies using the initial prototype transmission line (13) used frequency domain results over the entire range of 1MHz to 1GHz to produce a simulated broadband time domain pulse. From the velocity of this pulse through the transmission line, the relative permittivity could be determined. It was found that the relative permittivities