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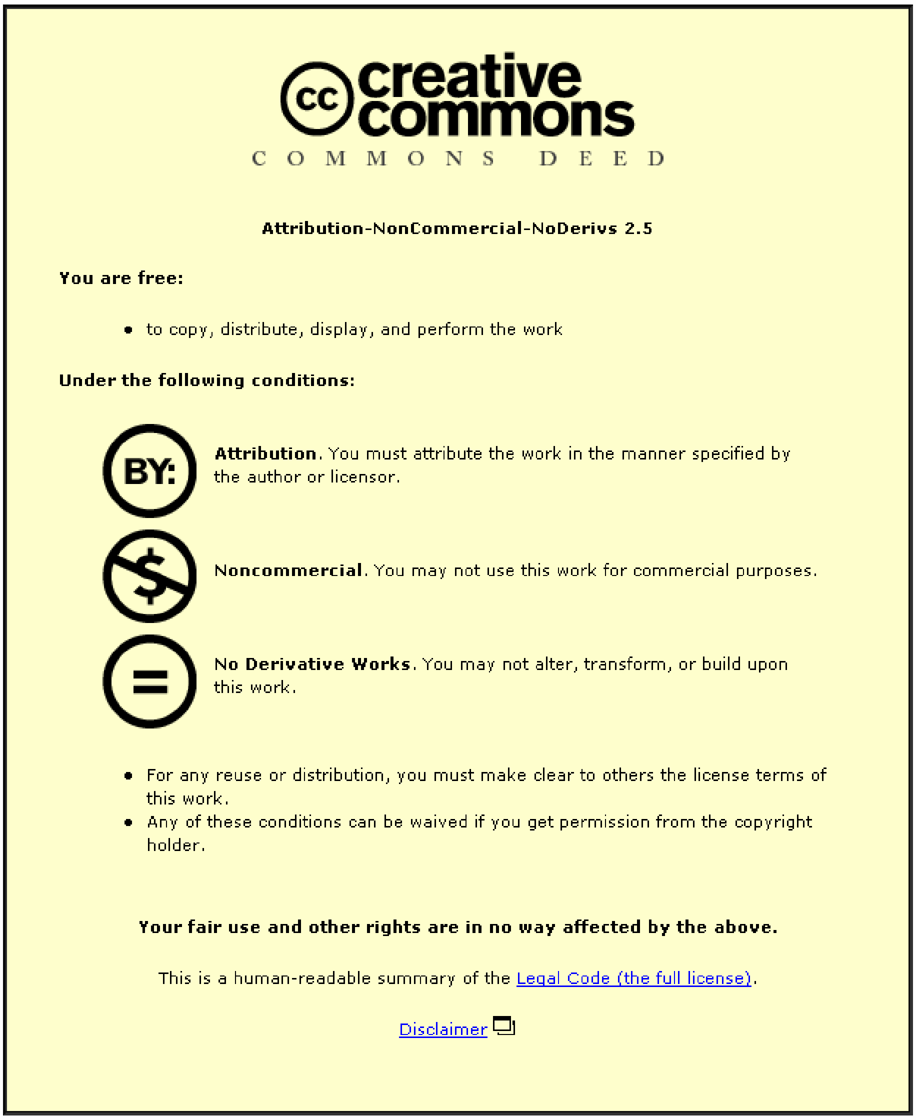

ASSESSMENT OF THE IN-SITU DIELECTRIC CONSTANT OF PAVEMENT MATERIALS

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ABSTRACT

The use of ground penetrating radar (GPR) for pavement investigation has rapidly developed over the past 20 years. The technique involves recording the passage of electromagnetic pulses transmitted into the pavement structure, and GPR has enhanced and improved the range and certainty of information that can be obtained from pavement investigations. Analysis of data can provide information on layer depths, material condition, moisture, voiding, reinforcement and location of other features.

The dielectric constant is a material property which affects the speed and reflection amplitude of electromagnetic GPR pulses. Accurate determination or estimation of the dielectric constant is required for accurate analysis of information from GPR, about the pavement materials. Typical pavement materials will have a ‘bulk’ dielectric constant, used in analysis which is the result of both the material constituents (binder, aggregate, etc) and condition (moisture content, amount of voiding, etc).

This paper aims to provide a review and assessment of in-situ dielectric constants of bituminous pavement materials, determined from analysis of GPR data. The results of a large number of in-situ pavement investigations, on a range of bituminous materials of varying condition, are reported. Dielectric constants from analysis of GPR investigations are determined and compared to existing data, and the effect of material condition and properties are discussed and assessed.

The paper concludes that more accurate values of in-situ dielectric constant could be used instead of bulk values in the analysis of radar data, if assessment of material condition is made when selecting the values used in the analysis.

INTRODUCTION

Ground penetration Radar (GPR) is a non invasive tool used to assess layer thickness as part of pavement investigations to calibrate other pavement investigation techniques. GPR works by measuring the reflection time and energy of electromagnetic pulses through the pavement structure, and to assess the material thickness a material constant called the dielectric constant must be known. Frequently lumped values of dielectric constants, from published data and standards are used in the analysis of layered structures. This can lead to inaccuracies in the predicted pavement thickness, which can have implications for the assessment of residual life and for the planning of appropriate maintenance.

Alternatively calibration of the dielectric constant can be assessed directly insitu from cores, however, often data from a single core is used for substantial lengths of road. In service pavements can have great variability, in both their material as constructed state (type, density, water content, etc) as well as in service structural condition (voiding, disintegration etc). Therefore this paper describes a methodology for determining the in-situ dielectric constant of pavement material, to analyze the potential degree of variability of dielectric constant, caused by variations in material condition. This provides information relating to the expected uncertainties and errors in reported depths from GPR.

A background in to pavement investigation and GPR is presented, as well as a review of previous work on the determination of dielectric constants of bituminous materials. The paper then describes investigations conducted into the dielectric properties of in-situ pavement materials, using a data collection methodology similar to that used for ‘standard’ GPR investigations. The values measured are then compared to the in-situ condition and nature of the materials which allows a determination of the potential variability of dielectric values used in pavement analysis which can then be considered when undertaking further pavement analysis and planning of maintenance.

BACKGROUND TO PAVEMENTS AND GROUND PENETRATING RADAR (GPR)

Pavement Materials

The structural layers of many highways use a bituminous binding material to form a solid, bound, upper pavement layer. Usually the upper pavement layer will itself consist of several individual layers of slightly different types of material, to provide good load-spreading, prevent ingress of water and give a smooth ride for vehicles.

In the USA ‘bitumen’ refers to the class of cementitious materials which includes tars and asphalts. ‘Asphalt concrete’ is a general term used for material formed from a mix of bituminous binder and aggregate, and then compacted into a mass (*1*), and are often given specific terms, depending on the specific preparation procedures, with ‘hot mix asphalt’ (HMA) being one of the most common.

In the UK ‘Hot rolled asphalt’ (HRA) is one of the most common types of UK ‘asphalt’ material. A ‘macadam’ describes a certain type of aggregate, and a ‘coated macadam’ is a material which, similarly to ‘asphalt’, is a mix of bituminous binder and aggregate, but in which the aggregate particles are coated with bituminous binder and the main structural strength of the mix results from aggregate interlock. ‘Dense bitumen macadam’ (DBM) is a common type of UK coated macadam. (This terminology will be referred back to later in the paper).

However, specific in-situ conditions of any bituminous material lead to variations in properties between materials that are nominally the same material. De-bonding of layers, stripping, material deterioration (e.g. disintegration caused by repeated vehicular loadings over time), ageing, variation in local aggregate used, compaction and resulting material density, moisture amounts and temperature of the material can all lead to variations in the material engineering properties. Therefore material described as a ‘HMA’, may have different properties to ‘HMA’ in a different location.

Pavement Investigation

Typically, modern pavements have design lives of 20 or 40 years, before any major maintenance or reconstruction is required, but pavement structures will deteriorate over time before this design life is reached. Deterioration can be caused by a number of factors, the main one being the number and magnitude of vehicle loadings to which the pavement is subjected. In order to maximize the functional life of a pavement it is essential to obtain information about its in-service condition, so that any deterioration can be identified or anticipated, and maintenance treatments can be planned.

Several techniques exist for assessing the structural integrity of pavements, and documents such as the AASHTO Guide (*2*), and the Design Manual for Roads and Bridges (*3*) in the UK, contain guidance on assessing the condition of roads. Once areas of a road have been identified as requiring detailed investigation there are several methods, both intrusive and non-intrusive, which can be used to assess the in-situ pavement condition (*4*).

Intrusive methods are those such as coring and trial pits (with associated testing within the pits). Data from intrusive investigations are useful (*5*), and used to calibrate non-intrusive investigations, but the more investigations that can be conducted non-intrusively the less the damage (and subsequent expense to repair) to the pavement structure. Ultimately, the information obtained from investigations is collated and used to assess the condition, and to plan treatments to optimize the performance to extend the life of the pavement structure.

Use of Ground Penetrating Radar (GPR) for Pavement Evaluation

In modern pavement engineering, one of the most useful non-intrusive methods is ground penetrating radar (GPR), which transmits and records the passage of electromagnetic waves through the pavement structure. The primary use of GPR is usually is to determine layer thicknesses, and locate construction changes, areas of high moisture, voids, reinforcements and other discrete objects, and when used to assess the structural capacity of the pavement it should be integrated with other structural pavement investigation methods, such as the falling weight deflectometer (FWD) and coring (*6, 7, 8*). GPR allows much larger amounts of data to be collected and longer lengths of pavement to be investigated for a given time and cost. GPR is one of the more recently developed pavement investigation methods, and it remains a developing technique today.

It is only in the past 15 years or so that the use of GPR has become more widespread for the structural assessment of pavements. It is one of the few techniques that allows collection of an almost continuous record of data along the entire pavement length (rather than data from discrete points). GPR is an accepted method for ground investigations, and Daniels (*9*) gives a comprehensive overview of radar technology for sub-surface applications. Despite recent developments, there are several issues to consider when using GPR. A number of studies have been published on various aspects of the accuracy and applicability of GPR for pavement and ground investigations (*10, 11, 12*).

GPR operates over a range of signal frequencies, typically 2000MHz (2GHz) to 400MHz are used for engineering and 'shallow' investigations. Generally a higher frequency gives better resolution (i.e. more precise indication of depth), but a lower penetration depth. Another consideration is the type of radar antenna to use, the most common being dipole and horn antennae. Dipole antennae require close proximity to the ground ('ground-coupling') for the best results, and for a given frequency, the physical size of the antenna is relatively small and the depth of penetration tends to be greater. Horn antennae, (which are air-coupled), have the advantages that they tend to have higher measurement rates and better resolution. The choice of antennae depends on the specific requirements of the project, but generally air-coupled (horn) antennae tend to be used more often in North America, and dipole antennae tend to be used more in the UK.

Determination of Pavement Dielectric Constant

GPR operates by transmitting a radar pulse from an antenna into the ground and then recording properties of the reflections of this pulse, such as time taken for the reflected signal to return to the antenna, and the amplitude and phase of the reflected signal. The passage of the radar pulse through the material is dependent on the material type, condition, moisture content and pore fluid content. These material properties have an affect on what is called the 'dielectric constant' of the material, which governs how fast electromagnetic signals travel through the material.

To convert raw data into useful pavement data, information concerning the dielectric constant of the material is required for analysis. (The nature of the propagation of electromagnetic waves and dielectric conductivity is discussed in more detail below.)

Dielectric constant values can be obtained in a number of ways. Published values with a data range are available from various sources, and are frequently used (Table 1). Using such generic values is possibly the most inaccurate method because of the variable nature of pavement materials, and the fact that many published values are taken from laboratory or artificially prepared samples and do not take into account factors which may affect the in-situ condition of the material.

An accurate way of determining the constant, (and a method which is commonly used to calibrate pavement GPR data), is to correlate the GPR data with core samples at known points. When travel times and depths to interfaces are matched, the radar signal velocity, and subsequently the dielectric constant, of the pavement material can be back-analyzed. This method can provide a very accurate determination of dielectric constant at core locations. Once core calibration has been undertaken it is possible to convert GPR signal travel times to depths for the pavement sections of similar construction adjacent to the core. Errors can occur, however, when core locations are not accurately matched to the corresponding GPR data location. Another perceived disadvantage is that this requires relatively expensive and time consuming intrusive coring of the pavement (although often coring will have to be undertaken as a requirement of the overall pavement investigation).

For air coupled (horn) antennae, the dielectric constant of the surface layers can be determined by compares the amplitude of a reflected signal from the pavement surface to the amplitude of a signal reflected from a copper plate (a perfect electromagnetic reflector) placed on the pavement surface. However, only upper layers of the pavement are investigated, and the presence of different layers of various age or composition can lead to errors (*13*). The method only applies for air-launched antennae because for ground-coupled antennae it is difficult to distinguish between surface reflected and direct (transmitter to receiver) waves (*14*).

The common mid-point (CMP) technique is another way of determining the in-situ dielectric constant, involving the separation of the transmitter and receiver parts of the antenna, or by separation of two antennae, at each location where the dielectric constant is to be determined. This is not always possible within the restrictions of in-situ pavement investigations. Lahouar et al (*15*) describe a modified CMP method using both air and ground-coupled antennae, to determine the dielectric constant of the whole bituminous pavement layer, rather than just the surface layer, and the method described is based upon the two-way travel times of the reflections rather than their amplitudes, with reported accuracies comparable to other calibration methods.

For all of the methods described above a common problem is that when dielectric constants are used to analyze GPR data, only a few values are obtained along the length of pavement of interest. Often, a single GPR data file is collected for a length of pavement, and this data is calibrated to just one dielectric constant value (which is a ‘best fit’ value for the entire data file). In reality, there will be variations in the dielectric properties along the length of the pavement, caused by variations in material types, condition and moisture content, and this will lead to uncertainties and errors in the depths reported for locations that are not directly at calibration points.

Some factors affecting accuracy relate to the technological and scientific limitations of GPR, but it is important to note that inaccuracies can arise from both the way in which the technology is used and the way in which data is analyzed and reported. For the core calibration method, an important factor that can introduce uncertainty or error into the calculations are uncertainties in the reported core depth. Core depth values are taken from core logs. The uneven nature of the base of pavement core samples means that quoting depths to the nearest mm is an unrealistic level of precision, and is misleading as the actual pavement depth (that is revealed by a 150mm diameter core, that will provide an interface for the GPR signal footprint to reflect from) will vary slightly across its width. The amount of unevenness at the base of a core sample will vary from core to core, but depths reported to the nearest 5mm (i.e. effectively a maximum uncertainty of +/- 2.5mm), are often common. This serves as a mechanism to allow for the variable depth of materials along the uneven base of a core. Such a level of uncertainty in depth could produce an uncertainty of the order of approximately 3 - 4% in dielectric constant for core calibrated GPR data.

DIELECTRIC PROPERTIES OF MATERIALS

Electromagnetism and Dielectric Permittivity

Electromagnetic Waves

The passage of a radar signal pulse, from a GPR system through pavement material, is governed by the physical laws concerning electromagnetic waves. Electromagnetic waves are a result of a disturbance propagating out from an oscillating electrical charge in the form of vibrating electrical and magnetic fields, and there are many different types of electromagnetic wave, with radar waves being one.

The different types of electromagnetic waves are characterized by their frequency, and the frequency and speed of the waves will determine their wavelength. The electromagnetic wave spectrum includes, at the highest frequency, gamma waves with wavelengths of the order of 0.01nm (0.01 x 10^{-9}m), down to radio waves at the lowest frequency with wavelengths of the order of 1km. Modern GPR systems operate at the lower end of the microwave frequency range, with wavelengths of the order of a few cm.

Significance of the Dielectric Constant

The response of a material to an electromagnetic wave is a function of the materials electromagnetic properties, namely dielectric permittivity (ε), magnetic permeability (μ) and electrical conductivity (σ). It is the dielectric properties of a material which are of most interest to the GPR specialist.

A 'dielectric' substance refers to one which is a poor conductor of electricity but a good supporter of electrostatic fields, and the dielectric permittivity of a substance refers to its ability to store (i.e. 'permit') an electric field which has been applied to it. The permittivity of a material is a complex function having both real and imaginary parts:

$$\varepsilon_r^* = \varepsilon_r - i\varepsilon_r' \qquad (1)$$

where ε_r^*= complex dielectric permittivity
ε_r =real part of the complex permittivity
ε_r' = imaginary part of the complex permittivity
$i = \sqrt{-1}$

The parameter ε_r' is sometimes called the 'loss factor' and relates to the energy losses associated with attenuation and dispersion of the radar signal. The parameter ε_r is called the 'relative permittivity', because it can be expressed as the ratio of the permittivity of the material to the permittivity of free space (i.e. a vacuum). This 'relative permittivity' is also known as the 'dielectric constant' of the material and can be defined as:

$$\varepsilon_r = \varepsilon / \varepsilon_o \qquad (2)$$

where ε_r = dielectric constant (or relative permittivity)
ε = permittivity of the material
ε_o = permittivity of free space (vacuum)

The value of the dielectric constant is important because it relates to several parameters which are essential for the interpretation of GPR data, for example the velocity at which the radar) waves will travel through the materials is related to the dielectric constant.

$$v = c / \sqrt{\varepsilon_r} \qquad (3)$$

where v = velocity of electromagnetic (i.e. radar) wave through the material
c = velocity of light in free space (vacuum) = approximately 300,000kms^{-1}

When determining layer or feature depths from GPR data, the velocity of the wave through the material is required, so that the two-way travel times (for the pulse to travel from the antenna into the pavement structure, and back, having been reflected from a feature) recorded by the GPR system can be converted into depth values:

$$d = v \times t \qquad (4)$$

where d = depth of feature
v = velocity of signal = $c / \sqrt{\varepsilon_r}$
t = two-way travel time of reflected signal

If the two-way travel time is recorded during a survey, and if the dielectric constant of the material is known then by substituting in equation 4 the depth to features can be determined:

$$d = ct / \sqrt{\varepsilon_r} \qquad (5)$$

Reflections occur when the materials in two layers in the ground have contrasting properties. In this scenario some of the radar energy passing from one material to the other is reflected back from the material boundary to the antenna. The key to this process is for the materials to have different dielectric constants, and in practice most (although not all) pavement materials do. A (dielectric) contrast between different materials is required for resolution of layer interfaces, because a low reflection coefficient may mean that resolution of material boundaries is not possible. The amount of radar energy reflected depends on the 'reflection coefficient' (which in turn depends on the contrast in dielectric properties of the materials) and is given by:

$$RC = [(\sqrt{\varepsilon_1}) - (\sqrt{\varepsilon_2})] / [(\sqrt{\varepsilon_1}) + (\sqrt{\varepsilon_2})] \qquad (6)$$

where RC = reflection coefficient
ε_1 = dielectric constant of the upper material
ε_2 = is the dielectric constant of the lower material

Equations 5 and 6 form the basis of most GPR pavement investigations, respectively allowing determination of depths to layers or features (from travel times), and govern how distinct a material interface appears. Equation 6 can also be used to provide an indication of areas where excessive moisture exists, because water has a very high dielectric constant ($\varepsilon_{water} \approx 81$) compared to most pavement materials ($\varepsilon \approx 3\text{-}12$, see Table 1), so the presence of water produces a high reflection coefficient.

It can be seen from the above that the dielectric constant of pavement materials, and the ability to use accurate values for data analysis, are very important factors for the interpretation of GPR data into useful information for the pavement engineer.

Bituminous Materials

From the above it can be seen that the properties of a material affecting the propagation of electromagnetic waves (dielectric permittivity, magnetic permeability and electric conductivity) are dependent on the frequency of the electromagnetic wave, with the general trend that as the frequency increases the dielectric constant generally decreases and the conductivity and dielectric loss increases. However, the frequency dependence of the dielectric constant value has been reported as not being significant over the typical range of frequencies used by GPR antennae (*15, 16, 17*).

Properties of materials shown to influence the dielectric constant include the temperature, moisture, pore fluids, porosity, density, mineralogy, geometries, and electrochemical interactions. (*16, 18*). Often, investigations of dielectric properties have been conducted under artificial or laboratory conditions, where control of the material and its condition is easier, but it should be noted that published values for dielectric constant of materials may not match the field conditions of the in-situ materials, and it is the in-situ condition of the material that is of interest to the pavement engineer.

For an in-situ material, such as HMA, its dielectric constant will be an overall 'bulk' value for the entire material mix. However, even if it were possible to maintain the material proportions precisely consistent (e.g. bituminous binder, aggregate consistency and amount), then variations in other factors such as the air or water content in the material will lead to variations in the bulk dielectric constant. Table 1 shows a number of previously determined dielectric constants.

Table 1 Examples of Published Values for Dielectric Constant of Bituminously Bound Pavement Materials

Material	**Dielectric constant, ε**	**Frequency (Hz)**	**Reference**	**Notes**
"Bituminous bound"	4 - 10	-	(3)	"Typical" values given in UK Design Manual for Roads and Bridges
"Dry asphalt"	2 - 4	100MHz	(*9*)	"Typical range of dielectric characteristics" given in leading GPR reference text
"Wet asphalt"	6 - 12			
"Asphalt"	3 - 6	-	(*22*)	Kentucky Transportation Center GPR guidance document
HMA (various mixes)	3.5 - 10	-	(*23*)	Field study using GPR data from Finland, USA and Canada
HMA (various mixes)	4.0 - 4.9	500-2000MHz	(*21*)	Field study, with copper plates installed in pavement: reflection coefficient used to calculate ε
"Asphalt" (4% binder with sand aggregate)	3.8 - 4.4	11GHz	(*18*)	Laboratory study, ε values measured with (non-GPR) microwave sensor apparatus

"Asphalt" (8.4% binder with sand aggregate)	4.75			
"Asphalt" (4% binder with crushed rock aggregate)	6.5 - 6.7			
"Asphalt" (8.5% binder with crushed rock aggregate)	5.7 - 6.3			
"Dry asphalt"	6.0 +/- 0.15	8-900MHz	(*19*)	Laboratory study. Moisture dominant factor in affecting ε.
"Soaked asphalt" (0.25 to 1.25% moisture content)	6.52 +/- 0.99			
"Dry asphalt"	5.5 - 6.1	100 MHz	(*20*)	Laboratory study, ε values measured with custom designed measurement apparatus
"Wet asphalt"	6.1 - 6.8			

Guidance and reference documents commonly provide a range of values, giving an indication of the order of magnitude of dielectric values (references *3*, *9* and *22* in Table 1). This is necessary because of the variation in the generic materials, due to differences in specific composition and condition, as shown in a previous study of in-situ generic HMA material at a number of sites (*23*). Errors of approximately 5-10% in calculated depths may result from errors of up to 1 in the value of the dielectric constant (*16*), so using such ranges of values for data analysis gives huge uncertainty in depth values. Thus to use values which match specific materials of interest, more precise information and guidance is required.

Field investigation of specific mixes of HMA has provided precise values for individual bituminous material mixes (*21*), but the results are site specific. If such values are used to analyze GPR data from other sites, there is no guarantee that the values quoted will apply to the materials in question, in both terms of the mix constituents, and condition.

Laboratory studies have been used to obtain valuable information on dielectric properties. Controlling the constituent amounts in a material mix has been investigated, and increasing the density of the mix has been shown to increase the dielectric constant (*18*). Also, control of the amount of water in the material mix has shown that increasing moisture increases dielectric constant (*19* and *20*).

Despite such useful information, matching dielectric constant values from previous published work to those studied during an in-situ investigation could lead to significant uncertainty in reported information.

IN-SITU DETERMINATION OF DIELECTRIC CONSTANT

Investigation Rationale

As discussed above, using lumped published dielectric constants (such as those in Table 1) can lead to large uncertainty in depth determinations. The most accurate method for calibrating depths from GPR data is to use cores, but there can again also be uncertainties arising during data analysis (as described above). Therefore, the investigations described below were conducted to address the question of whether refinement of such calibration can be undertaken to assess the degree of variability and uncertainty in GPR data, and hence provide improved information.

Data Collection and Enhanced Data Presentation

The data used in this study was collected with a Geophysical Survey Systems Inc. (GSSI) SIR-10H GPR system via a ground coupled 1.5GHz dipole antenna, towed behind a survey vehicle. GPR data was collected from three different project sites in the UK, each of which had a bituminously bound pavement construction typical of UK major road bituminous pavement construction. The pavements at the Scheme 1and Scheme 2 sites consisted of a HRA surface course layer (with a nominal 14mm sized aggregate) above 2 layers of DBM (with nominal aggregate size of 20mm). Scheme 3 consisted of a thin surface dressing over 2 HRA layers, with some sections also having a lower layer of DBM.

As the survey vehicle traveled along the road, radar scans were taken every 0.04m along the length of the pavement, in survey lines of various lengths from a few hundred meters to several km. The amplitude of reflected signals was recorded against the two way travel time for that signal. A total of 56 individual core samples were taken and as the GPR antenna passed over each core location its position was marked accurately onto the GPR data record by reducing the survey vehicle speed as it passed the core location. (Often one of the main sources of error in GPR pavement assessment using cores for calibration is inaccurate core location.)

The field data collection was using a methodology similar to that of a 'standard' GPR survey (*3*). As such, it is possible to use the analysis and assessment method described in this paper for GPR data obtained from 'standard' GPR investigations.

Following the determination of accurate dielectric constants at each of the core locations, and their direct comparison with core log information, it was possible to provide an assessment of degree of variation of dielectric constant between a number of samples of similar in-situ material, along the same length of pavement. This provided an indication of the possible errors in depth determination reported from GPR surveys that can be expected for nominally 'homogenous' bituminous pavements. The uncertainties or errors in GPR data could be quantified, allowing use of the GPR to be optimized by incorporating the potential uncertainty into any assessment of pavement condition or planning of maintenance treatments.

Determination of Dielectric Constant

For each GPR pulse, the amplitude and travel time of the reflected signal were recorded to within 0.03ns (nanoseconds). Large amplitude reflections indicated the presence of interfaces or features within the pavement. The travel time for the reflected signals depended on the depth of the interface, and the material which the radar pulse traveled through, but during the study typical two-way travel times for bituminous pavement around 200mm thick were of the order of 4 or 5ns.

For each of the schemes, the bituminous pavement overlaid either a granular sub-base, or a concrete base layer. These materials have a dielectric contrast with bituminous materials, and hence create a reflection coefficient large enough for the interface between the bituminous pavement layer and the underlying material to be easily distinguished from the GPR data.

The core samples taken showed each pavement to comprise of several individual layers of material (Figure 1). For the study, the overall bituminous thickness of the pavement was considered, and the information provided in each core log was compared to the reflection amplitudes from the GPR data, and matches could be made between core depths and GPR signal travel times. These data provided values for variables 'd' and 't' (equation 5), and thus a value for the 'bulk' dielectric constant of pavement at the point, as a function of the properties of the entire bituminous pavement thickness, could be calculated. Using this procedure, it was possible to build up a database of dielectric constant values for bituminous materials of known in-situ composition and condition.

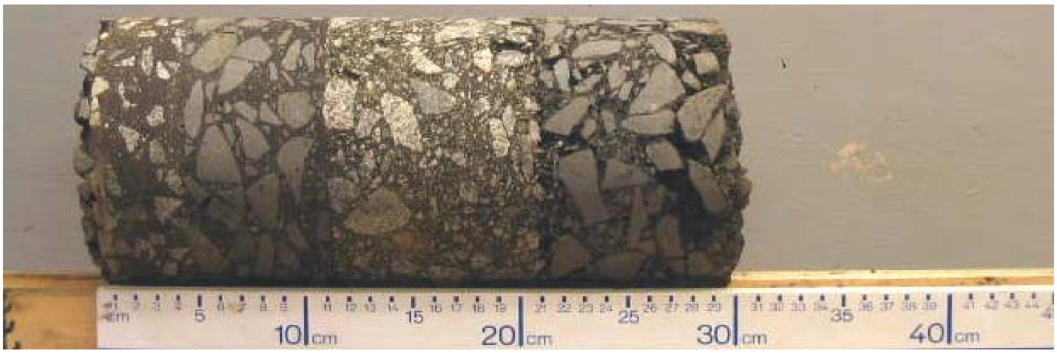

Figure 1 Example of core sample from Scheme 3, showing different layers within the bituminous pavement.

RESULTS & DISCUSSION

Results

The materials investigated at the three schemes would generically be termed as HMA in the USA. If published data were used for the dielectric constant, it would be possible to justify a number of values. For example, values of 4.0 - 4.9 are quoted in Table 1. Also, it is known that moisture increases dielectric constant values, and as the fieldwork was conducted during winter it could be argued that a value of 6.52, is valid (for "soaked asphalt"). Also the range of values for "wet asphalt" is 6 - 12, so the choice of a specific dielectric value from published data becomes very subjective.

Table 2 shows the results of the data analysis. Considering the locations where pavement material was sound, values of 6.99, 7.45 and 8.80 were determined for the three schemes. Despite nominally similar material composition, it can be seen that there is a relatively large variation between values, highlighting the site specific nature of data. The potential for error in using published data is also apparent by comparison with Table 1, where for a similar in-situ material (HMA), values of 4.0 - 4.9 are reported, which are only approximately 40 - 55% of the actual values reported in Table 2. Also the effect of material condition (voiding or disintegration) within a pavement can be seen to affect the values, with a variation of up to 13% caused by voiding within pavement material (Scheme 3). Quantifying such variation into values selected from published data would prove difficult.

Table 2 Dielectric constant values for in-situ pavement materials, at 1.5GHz

Scheme	Material layers	Bulk dielectric constant, ε		Notes
		Value	Std. dev	
1	HRA / DBM / DBM	6.99	0.59	Sound material
1	HRA / DBM / DBM	6.77	0.38	Both layers of DBM voided
2	HRA / DBM / DBM	7.45	0.47	Sound material
2	HRA / DBM / DBM	7.39	0.42	One layer of DBM voided
2	HRA / DBM / DBM	7.03	0.48	Both layers of DBM voided
2	HRA / DBM / DBM	7.08	0.46	Disintegrating DBM material
3	HRA / HRA / DBM	8.80	0.83	Sound material
3	HRA / HRA / DBM	7.62	0.46	DBM layer voided
3	HRA / HRA	8.72	0.99	Sound material

Discussion

Within the three pavement schemes used for data collection, a range of values existed for the bulk dielectric constant of nominally consistent material: 6.99 to 6.77; 7.45 to 7.03 and; 8.80 to 7.62, respectively. The values reported in Table 2 are the mean values from several core calibrations for each material listed, and so a standard deviation is also reported for each value (giving an indication of the variation in datasets for each specific material investigated). The GPR processing software used for the data analysis allowed reflection travel times to be selected for each 0.03ns of the time record. For this level of precision in travel times, uncertainties of approximately 0.1 could be expected in dielectric constant calculations (which would produce depth uncertainties of the order of approximately 1%).

For all schemes, the lowest value of dielectric constant resulted from voided material and the highest from sound material. This is consistent with a scenario where the greater the amount of low-dielectricity air there is in a material, the lower the dielectric constant. This phenomenon is discussed in previous work which uses the dielectric properties of asphalt to predict air voids content and can be used to give an indication of the density of the material (*24*). The effect of voided (compared to sound) material shows decreases of 3.1%, 5.6% and 13.4% in the dielectric constant values for Schemes 1, 2 and 3 respectively. These magnitudes indicate that variation caused by material condition could be significant.

Such results show that even when cores are used for calibration of depth values, the reported "calibrated" depth values may incur inaccuracies on sections distant from the calibration points. This will be one of the contributing factors to GPR depth inaccuracies, and wherever possible, the potential amount of depth uncertainty in reporting of GPR data should be quoted. Often a 'best fit' dielectric constant is used to determine depths from a GPR investigation, and the potential variation in dielectric properties for sections which contain material of variable condition are sometimes not taken into account. Using the variation in the dielectric values determined from this study, possible variations in reported depths (caused by using a 'best fit' dielectric value in equation 5, and not taking into account variable condition material) would be approximately 2%, 3% and 8% respectively for the three Schemes. For core correlated GPR data, it is possible to calculate the dielectric constants as described in this study, and thus report the potential uncertainty in reported depths.

The one dataset of cores which contained disintegrated material (from Scheme 2) showed a significant effect on dielectric properties. A disintegrating DBM layer caused a reduction of 5.0% in dielectric constant compared to sound material. However, the results indicate that the effect of disintegrating material may be much larger than voiding, because disintegrated material present in one DBM layer had a similar magnitude of effect as voiding in two layers of DBM (5.6% reduction). Only one dataset from Scheme 2 had a single layer of voided material present, and the reduction in dielectric constant was much less (approximately 0.8%). The implication is that for pavements which have core/depth calibrations conducted in areas of sound material, then sections of partly disintegrated material or sections of poorly compacted material may have similar detrimental effects on the accuracy of reported depths. However, the relatively few data from disintegrated material in this study means that further investigation should be conducted.

The data collected in this study generally has shown slightly higher dielectric constants than for previous work, which is understandable because (whilst noting that other factors will affect the values) much of the work quoted in Table 1 involves study of material in a dryer condition that would be found in-situ. The moisture condition of the material will also have a large affect on its dielectric constant, and the comparison of values between different sites should be undertaken with caution, because local moisture conditions will vary from site to site.

CONCLUSIONS

The pavements at each of the schemes consisted of similar, although slightly different, mixes of bituminous material. For all materials, in all conditions, the range of values for in-situ pavement was 6.77 – 8.80.

Much of routine pavement investigation data collection is conducted by ground coupled GPR because of their advantages discussed earlier, and the data is largely used for depth determination, so the usefulness of dielectric constant determination from ground coupled investigations is apparent. The methodology described in this paper allows a determination of dielectric properties without the need for modification of 'standard' GPR pavement investigation methodology. GPR data from routinely conducted investigations can be used to both indicate the condition of the pavement and also to provide an indication of the degree of error likely in reported depths.

The dielectric constant of material investigated varied by up to 13% for a given material within a given pavement scheme, depending on the condition of the material. The dielectric constant will be lowered by increased air voids (possibly caused by poor compaction of material during construction), or by disintegration of material (possibly caused by vehicle loadings over time).

For the three pavement schemes investigated, dielectric properties of similar bituminous material mixes, in similar condition, varied by over 1.8 (over 20%) between schemes. Voiding of material within a given scheme caused decreases in dielectric constant of just over 0.2, just over 0.4 and almost 1.2, respectively. The data obtained in this study indicated that such variations may lead to depth uncertainties of approximately 2-8%.

Published values of dielectric properties should only be used as an indication of the order of magnitude of dielectric constant values, and direct determination of values should be undertaken at each site investigated. If sound core material is used for calibration of depth values for GPR data, areas of voided and deteriorated material will result in material of a reduced dielectric constant, when compared to the calibrated values. Also when using GPR data to calculate in-situ dielectric constant, relatively lower values compared to similar material may indicate that material is in a poorer condition. Lower dielectric constant values are produced by material of poorer condition, and thus lower dielectric values may indicate material of lower stiffness, which may have implications for planning maintenance work.

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