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The response of ground penetrating radar (GPR) to changes in temperature and moisture condition of pavement materials

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ABSTRACT: The use of geophysical techniques to assess geotechnical and pavement structures can provide much useful information to the engineer. The development of ground penetrating radar (GPR) in recent years has led to its increasing use for pavement and geotechnical investigations, and the technique involves recording the amplitude and travel time of electromagnetic GPR signals reflected from features within the ground or structure of interest. Depths can be determined, and features of interest such as different layers, excess moisture, voids and changes in materials can be identified. The interpretation of GPR data depends largely on the 'dielectric constant' of the material(s), which governs the passage of GPR signals through a material and the amount of signal energy reflected from features within a structure.

This paper reports an investigation of pavement material samples, conducted under controlled conditions, using GPR. The effect of changes in material moisture and temperature on the dielectric constant, and hence the passage of GPR signals, was investigated. Core samples of bituminous material obtained from highway pavement sites were used to conduct a series of laboratory tests, in which the temperature of the material was controlled in the range from -5 to +45 degrees C, and the dielectric constant and GPR signal velocity were determined. Also, the materials dielectric constant and signal velocity were determined under dry and soaked moisture conditions.

The test programme allowed an assessment of the effect of changes in materials temperature and moisture condition to the response of data obtained during GPR investigations. The results of the testing showed that both moisture and temperature can have a significant effect on the data obtained from GPR surveys of pavement structures.

1 INTRODUCTION

1.1 *Ground penetrating radar (GPR) and dielectric permittivity*

One of the most useful techniques used for pavement investigation is ground penetrating radar (GPR), which involves recording reflections of electromagnetic waves transmitted into the pavement structure. GPR is completely non-destructive, and relatively quick to conduct compared to many other investigation techniques. The uses of GPR in pavement investigation include determination of layer thicknesses, location of construction changes, areas of high moisture, voids, reinforcement and other discrete objects.

The ability to use GPR data to assess pavement properties relies on the response of materials to the passage of electromagnetic waves transmitted from

the GPR antenna. There are a number of important processes that can affect the propagation of GPR signals, and Olhoeft (1998) describes the electrical, magnetic and geometrical properties that are of importance in determining the performance of GPR. Important factors in the response of a material are its electromagnetic properties, namely dielectric permittivity (ϵ), magnetic permeability (μ) and electrical conductivity (σ).

The dielectric properties of pavement materials are of great importance when conducting GPR investigations, and Daniels (2004) provides a good overview. Dielectric substances are those which are poor conductors of electricity, but support electrostatic fields well, 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.

Each material has a ‘dielectric constant’, which is a measure of its relative (to a vacuum) dielectric permittivity, and it is a critical parameter in the practical application of GPR data. The dielectric constant affects the velocity at which GPR signals will travel through the material, affects the ‘reflection coefficient’ (governing how much energy is reflected when there is a change in material), and also affects the resolution of data that is obtained. Therefore, understanding what factors affect the dielectric constant, and the degree to which they affect it, can assist in conducting GPR surveys and interpreting and understanding the data.

The measurement of the dielectric properties of asphalt materials can also be useful to assess density and provide information on compaction quality control. The presence of relatively low dielectricity air (in air voids) within materials will affect the overall dielectric properties of an asphalt mix, so it is possible to assess the compaction (i.e. density) of pavement material by measuring dielectric properties of the asphalt (as described by Saarenketo, 1997).

In GPR investigations, the dielectric constant can be determined by calculating the GPR signal velocity within the material. The velocity is related to the dielectric constant by the relationship shown in Equation 1, below:

$$v = \frac{c}{\left(\sqrt{\mu_r \epsilon_r} \right)} \quad (1)$$

Where v = velocity of electromagnetic (i.e. GPR) wave through the material; c = velocity of light in free space (vacuum) = approximately 300,000kms⁻¹; μ_r = relative magnetic permittivity (= 1 for non-magnetic materials); and ϵ_r = dielectric constant (relative permittivity).

Reflections of GPR signals occur when the materials in the pavement have contrasting dielectric 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 amount of radar energy reflected is indicated by the reflection coefficient (which depends on the contrast in dielectric properties of the materials) and is given by:

$$\rho = \frac{\left(\sqrt{\epsilon_1} \right) - \left(\sqrt{\epsilon_2} \right)}{\left(\sqrt{\epsilon_1} \right) + \left(\sqrt{\epsilon_2} \right)} \quad (2)$$

Where ρ = reflection coefficient; ϵ_1 = dielectric constant of the upper material; and ϵ_2 = dielectric constant of the lower material.

1.2 Temperature and moisture effects on dielectric properties

Measurements of the dielectric properties of various types of materials can prove useful. The dielectric properties of wood can be used to determine density and moisture content non-destructively, and Kabir et al (2001) showed that the dielectric constant of wood increases with increased temperature. Previous work has also shown that, at GPR frequencies, both temperature and moisture affects the dielectric properties of pavement materials. Jaselskis et al (2003) investigated the dielectric properties of a number of asphalt samples in the frequency range from 100Hz to 12GHz, whilst researching the use of a microwave pavement density sensor. It was observed that the dielectric constant of asphalt samples slightly increased with temperature, and also increased with moisture (greatly at low frequencies and slightly at higher GPR frequencies).

An overview of the work conducted on the effect of moisture content on the dielectric constant of materials at GPR frequencies is given by Daniels (2004). Water has a dielectric constant of approximately 80, so a relatively small increase in moisture content can cause the bulk dielectric constant of asphalt materials (with dielectric constant of approximately 2-12) to be greatly altered. Methods such as time domain reflectometry (TDR) rely on this moisture-dielectric relationship to assess soil moisture content from dielectric constant measurements.

Shang et al (1999) conducted a series of tests using an electromagnetic wave apparatus to assess the dielectric constant of a number of laboratory prepared asphalt samples in dry and ‘soaked’ (up to 1.25% moisture content) conditions. It was found that moisture content was a dominant factor, with the dielectric constant of samples increasing linearly by 0.62 for each 1% increase in moisture content. Further work by Shang & Umana (1999) indicated that beyond a moisture content of 1.2%, the effect on dielectric constant was greater and non-linear.

1.3 Investigation synopsis

A series of laboratory tests were conducted, so that the dielectric constant could be calculated for bitumen bound pavement material at a range of temperatures (with constant moisture content), and also for material in soaked and dry conditions (at constant temperature). The test methodology employed was to use material taken from in-service pavements and use GPR equipment and analysis procedures in a similar manner to that employed during in situ pavement investigations, so that it would be possible to best relate the findings of the study in a practical engineering context.

For testing at various temperatures, it was important to use material samples that were dry, as any

removal of moisture from the material (as temperatures were increased) would affect results. Also, for the testing at different moisture conditions it was important to test dry and soaked material at the same temperature to avoid any influence temperature may have on the results.

2 METHODOLOGY

2.1 Materials

One of the underlying themes of the work was to be able to apply the results as well as possible to in-service materials and conditions. Therefore, the pavement material used in the study was obtained from cores taken from in-service trunk road pavements in the UK. A total of 20 core samples (each of 150mm diameter) were obtained from bituminous bound pavements, consisting of various thicknesses of hot rolled asphalt (HRA) and dense bitumen macadam (DBM) layers. The core samples ranged from approximately 220mm to 420mm in depth, and were typical of trunk road bituminous pavement constructions existing in the UK.

2.2 Laboratory preparation of samples

2.2.1 Temperature

10 core samples were selected for testing at different temperatures. The dielectric constant was determined for each core sample at seven discrete temperatures, ranging from -5 to +45 degrees centigrade, chosen to give a typical range of potential temperatures a pavement may be subjected to in the UK. The presence of water in the samples would have an affect on the test results, so it was essential that the material was dry during testing at different temperatures. Initially, the cores were dried for 48 hours in a climate chamber, to ensure that any free water in the material had been removed. After the drying period, each core was conditioned at the desired temperature (starting with the highest) for 48 hours in the climate chamber, before being removed from the chamber and immediately tested using GPR. Once the testing at the desired temperature had been completed, the core was placed back into the chamber and conditioning at the next temperature was undertaken.

2.2.2 Moisture content

Prior to the temperature testing, all 20 of the core samples were tested under differing moisture conditions. When the cores had initially been extracted from the in-service pavements, they had been stored (at room temperature) for a number of weeks. This led to the core materials being in a 'dry' condition,

although no attempt had been made to remove all free moisture from the material by deliberate drying. The cores were initially tested in this 'dry' condition, at room temperature. Following 'dry' testing, the cores were submerged in a water filled tank for 48 hours, and re-tested in this 'soaked' condition (at room temperature).

2.3 GPR test procedures

A GPR system operating a dipole antenna at a centre frequency of 1.5GHz was used to collect test data. The GPR recorded the travel time of signals transmitted into the top of the core samples and reflected back from their base.

Following conditioning at the required temperature or moisture condition, the core samples were placed upright, with a metal plate placed at the base. The metal plate provided a perfect reflector for GPR signals to ensure easy identification of the base of the core sample. GPR pulses were emitted from the antenna transmitter downwards into each sample, travelling along its full depth before being reflected back to the antenna receiver from the metal plate at the base of the core. For each GPR pulse the travel time of the reflected signal were recorded to within 0.03ns (nanoseconds).

The average velocity of the GPR signal within each of the core samples was the distance travelled divided by the time taken. The length of each core was measured, and the travel time of the signal was determined from the data recorded by the GPR system. Hence, the dielectric constant of the material can be determined by substituting into Equation 1, giving:

$$d = \frac{ct}{\left(\sqrt{\epsilon_r}\right)} \quad (3)$$

Where d = depth (i.e. length) of core sample; t = one-way travel time of reflected signal. μ_r (in Equation 1) can be taken as being = 1 for bituminous pavement materials. For each core (at each temperature or moisture condition) the travel time of reflected signals was recorded and the dielectric constant calculated.

3 RESULTS

3.1 Dielectric constant variation with temperature

10 individual core samples of bituminous pavement material (referenced Core 1 to Core 10) were scheduled for testing at -5, zero, 5, 15, 25, 35 and 45 degrees centigrade. During the conditioning of the samples at the highest temperature the bituminous binder of the material of Cores 5 and 7 softened to the point where the material suffered partial col-

lapse. Hence, Cores 5 and 7 were not used during the test programme.

Figure 1 shows the results of the testing, and it can be seen that for each individual core material sample there was an overall increase in dielectric constant as the temperature of the material increased.

Figure 1. Dielectric constant of bituminous core samples determined at 1.5GHz in temperature range -5°C to 45°C. (Core samples 5 and 7 damaged during testing).

The rate of increase in dielectric constant varied between specific material samples but most showed a similar trend. The size of the increases in the calculated dielectric constant values over the temperature range from -5 to +45 degrees centigrade were between 7.3% and 20.2%. The average rates of increase in dielectric constant (for the whole temperature range) were between 0.14% and 0.40% per degree centigrade increase in temperature. However, some of the results indicate that there may be a non-linear trend, as several (although not all) of the samples showed larger than average rates of increase for the dielectric constant between 35 and 45 degrees centigrade.

From the collected data it can also be observed that for the 8 samples tested there was a large range of values of dielectric constant determined at each temperature. At 15 degrees centigrade, for example, the dielectric constant of the core samples ranged between 6.1 and 9.3, showing that generically similar materials at the same moisture and temperature

condition could possess quite different dielectric properties.

3.2 Dielectric constant variation with moisture

The results of the tests conducted on the core samples at different moisture contents are shown in Figure 2. The dielectric constant was determined for 20 individual samples, in both the 'dry' and 'soaked' conditions (see Section 2.2.2) at room temperature.

The data shows that for each individual sample, the dielectric constant was greatest when the material was in the 'soaked' condition. However, the magnitude of the increase in dielectric constant varied greatly between samples, from the smallest increase of 3% (Sample 11) to the greatest increase of 39% (Sample 18).

The average dielectric constant of the material samples when dry was 8.0, and when soaked was 9.3 (a difference of 16%) which corresponds to a decrease in signal velocity from approximately

0.106m/ns to 0.098m/ns (see Equation 1).

Figure 2. Dielectric constant of bituminous material samples, in 'dry' and 'soaked' condition, determined at 1.5GHz.

4 DISCUSSION

4.1 Temperature

The data from the temperature testing shows that there is a relationship between the dielectric constant of bitumen bound pavement materials and temperature, under the conditions tested. The data collected, however, is limited in its scope and so further investigation is also needed to more comprehensively assess this relationship.

The results plotted in Figure 1 indicate that there is a general trend, with an average increase in dielectric constant of 0.27% per degree centigrade increase in temperature, but the specific trend for each individual material was over a range of values and requires further investigation.

The mechanism for the increase in dielectric constant with temperature has been previously investigated in relation to non-pavement materials. Studies such as Hrubesh & Buckley (1997) and Satish et al (2002) have investigated the effect of temperature on the dielectric properties of silica aerogels (for use as a low dielectric material in electronics) and ceramic-polymer composites. In these studies the dielectric constant was observed to increase with temperature, and it was concluded that the cause was the greater mobility of molecules within the material (caused by the elevated temperatures) allowing dipoles to re-orient more readily, and thus causing an increase in the ability of the material to support electromagnetic fields. In practical terms, this means the increasing temperatures facilitated a mechanism that increases the dielectric constant. It is thought that this process is also occurring within the asphalt material investigated in this study.

The data shows that, for the material samples at the same condition (temperature) there is a range of dielectric constant values. This agrees with much previous work, including that of Evans et al (2007), which shows that generically similar asphalt materials, in similar conditions, can have different dielectric constant values.

4.2 Moisture

The entire range of dielectric constants during the testing process was 5.6 to 11.6, which gives an indication of the potential range of variation in dielectric properties that may be present in typical bituminous pavement materials, depending on their temperature and moisture condition.

Greater dielectric constants (i.e. lower signal propagation velocities) were recorded for each material when the material was soaked. Low dielectricity air ($\epsilon_r \sim 1$) in voids present in materials are replaced within the material matrix by relatively high dielectricity water ($\epsilon_r \sim 80$), causing the overall bulk dielectric constant of the material to increase.

The individual nature of the core sample materials will have had a great effect on the change in dielectric constant. The amount of moisture present in the 'soaked' samples compared to the 'dry' samples will affect the magnitude of the difference in dielectric constant between these two states. The amount of interconnected air voiding within the materials will govern the amount of moisture that the samples could absorb during the soaking process, so it is likely that the % increase in dielectric constant between dry and soaked states is an indicator of the amount of voiding present in the material.

Moisture testing showed large range (3% to 39%) of dielectric constant increase when material was soaked. From a qualitative view, the core logs for the materials which tended to have lower increases in dielectric constant appeared to be slightly more voided, but as no quantitative assessment of voiding has yet been undertaken, no firm conclusions can be drawn. Core logs showed varying degrees of voiding within materials, but further testing (which is planned) will establish the actual amount of voiding present within the material samples.

4.3 General

The dielectric constant of material can vary depending on signal frequency (although only by a small amount within the GPR signal frequency range), but it should be noted that the results in this study are related to a specific signal frequency (1.5GHz).

The nature of the materials used in this study means that it is not possible to provide specific conclusions to some aspects of the work, because the precise mixes and materials used in each core sample were different. The material samples obtained were nominally similar (i.e. HRA surface course with DBM binder course and base), but each individual sample was taken from a different site on the UK trunk road network. Although every sample used can be described as a bitumen bound asphalt material, the individual nature of the aggregates and bitumen binder used has meant that there is a range of dielectric properties present in the materials tested.

Although the use of samples taken from different sites allows less control over the specific nature of the material used in the study, the use of such material, however, means that the results obtained can be taken to be more representative of the degree of variability likely for in-situ bituminous materials, than might be otherwise obtained from laboratory prepared samples.

Within the results obtained, there will be certain uncertainties and potential errors. Experimental work and analysis was conducted to minimise these as much as possible. This included repeat testing of several of the material samples (which re-produced test results to an acceptably high degree), but factors remain which, given the methodology employed, can not be influenced. For example, the GPR equipment used is capable of measuring signal travel times to within 0.03ns. This precision could lead to an error in individual dielectric constant calculation of approximately 0.07. Whilst it is important to note such potential for error, the level of uncertainty in the results of this study is not considered to have significantly affected the data or the conclusions drawn.

The use of unmodified GPR equipment, and the use of material samples obtained from in-service pavements, allows the study data to realistically rep-

resent the degree of accuracy that may be obtained from in-situ GPR pavement investigations, and shows that practical application of the results is possible.

Whilst the effect of moisture on dielectric constant has been widely investigated (and is used by some methods to assess material moisture content) the effect of temperature variation on asphalt materials is less researched. It is hoped to build further on the initial investigations described in this paper to more fully investigate the changes in dielectric properties with both temperature and moisture.

5 CONCLUSIONS

Within the range of conditions investigated, the results from the study show that:

- The dielectric constant of asphalt materials increases with temperature.
- The mechanism for the increase in dielectric constant with temperature is likely to be the increased re-orientation ability of dipoles, resulting from the increase in thermal energy.
- The dielectric constant of asphalt materials increases with moisture.
- The response of an asphalt material to wetting, and the resulting effect on its dielectric constant, is likely to be governed by the amount of air voids initially present in the material matrix.
- The dielectric properties are material specific, and generically similar bituminous materials do not necessarily have the same dielectric constant.
- Bearing the previous point in mind, the calibration of GPR data to the correct signal velocity (which is governed by the dielectric constant) is required on a site specific basis, to ensure the accuracy of data analysis and interpretation of in-situ GPR pavement investigation data.
- The work conducted for this paper is limited in some aspects, and further work is required and planned to address these issues.

The use of GPR for investigation of bituminous pavement material relies on the dielectric properties of the material. The specific type of material and the condition it is in have an effect on the dielectric properties. A wider understanding of the dielectric response of bituminous materials, under conditions which might be expected in-situ, allows a more comprehensive understanding of the significance of data obtained by GPR.

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