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Robert Evans

Abstract

This paper reports on the ability of the ground penetrating radar (GPR) to identify and locate areas within asphalt (bitumen-bound) road pavements where moisture ingress has occurred. Bitumen-bound materials are susceptible to damage as a result of the presence of water, particularly as a result of the reduction in cohesion between bitumen and aggregate, which can lead to deterioration such as the stripping and de-bonding of pavement layers. The capability to identify areas of excessive moisture presence, or moisture ingress, is thus of great significance for the assessment and maintenance of asphalt pavements. This issue is especially relevant in regions where climatic records suggest trends of increasing the total rainfall and increasing the frequency of very wet weather. GPR is a non-invasive technique used routinely in several countries for pavement investigation, and has had various claims reported concerning its ability to locate the moisture within the pavements. This study uses a series of laboratory tests on a number of bituminous core samples taken from in-service roads, to establish the relationship between the amount of moisture present in the material and the materials ‘dielectric permittivity’ value determined from the GPR data. From the work conducted, it has been possible to observe and quantify the changes in the permittivity of asphalt as it changes as a result of changing moisture content. The findings of the paper can be applied to the GPR pavement moisture investigations in order to more accurately assess moisture amounts and to determine locations for possible moisture ingress within asphalt pavements.

Keywords: Asphalt, Bitumen, Ground penetrating radar (GPR), Moisture, Pavements.

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Introduction

Ground Penetrating Radar (GPR) for Pavement Assessment

The ground penetrating radar (GPR) has a number of applications in pavement investigation, including the determination of layer thicknesses, identification of construction changes, and the location of discrete objects such as voids and reinforcement. The presence of moisture affects the propagation of radar waves and so a further use is to identify areas of moisture within pavement materials (asphalt, sub-base, etc.). Saarenketo and Scullion (2000) and Evans et al. (2008a) provide overviews of established GPR pavement applications.

The use of GPR involves the non-destructive recording of reflections of electromagnetic waves transmitted into the pavement structure, and it is a relatively rapid method for data collection, when compared to other common pavement investigation techniques such as the falling weight deflectometer or the extraction of core samples. Several national documents, such as those by the Highways Agency (2008) & AASHTO (2009), include guidance for GPR use in pavement assessment and it is a well-established tool in a number of countries, in particular in Europe and North America.

Moisture in Pavements

Excessive moisture within asphalt pavements leads to deterioration mechanisms such as stripping (loss of adhesion between the bituminous binder and the aggregate), the loss of cohesion within the binder itself leading to a reduction in asphalt stiffness, and to the de-bonding of asphalt layers. In addition, once water enters the pavement it is prone to damage from freeze-thaw cycles (Willway et al., 2008). Any moisture related damage can also then increase the severity of pavement deterioration caused from vehicle loadings over time.

For typical asphalt mixes, a volumetric air void content of between 3-8% is recommended to provide the optimum pavement performance (Roberts et al., 1996). Usually at such air voids contents the voids are not fully inter-connected, but if it was possible for free water to enter all air voids then this would result in 'free' moisture contents of around 1.3 to 3.4%. As such, the amount of moisture that can potentially enter 'dry' asphalt is small when compared to moisture in soils, for example – but despite this the potential for damage from mechanisms outlined above is significant.

In the UK, there is evidence indicating a trend towards increased rainfall totals and an increase in the frequency of very wet weather, particularly over the last 40 years. Projections regarding the future effects of climate change indicate that different regions of the globe may undergo different effects, but for the UK reports such as Osborn and Maraun (2008) and The Met Office (2011) suggest that rainfall extremes are generally projected to increase, particularly during winter. Thus, the likelihood of moisture entering pavement structures, and the ability to detect such areas, may become increasingly important in the future.

Dielectric Permittivity and Moisture Content

The electromagnetic properties of a material influence the passage of radar (electromagnetic) waves through that material, and for GPR investigations on pavement materials it is the 'dielectric' properties that are of most importance (Daniels, 2004). The ability of a material to store an electric field that has been applied to it is known as its 'dielectric permittivity' (ε), and the measure of this property relative to that of a vacuum is reported as the relative dielectric permittivity (ε_r), sometimes also referred to as the 'dielectric constant'. This property is critical in the practical application of GPR, affecting the velocity of signals, governing how much energy from a transmitted wave is reflected back from a material interface, and also affecting the resolution of the data obtained.

Several material properties influence dielectric permittivity, including temperature, moisture (and the nature of the pore fluids), density, mineralogy, and electrochemical interactions (Martinez et al., 2001; Jaselskis et al., 2003). As a result there will be a range of relative permittivity values that a given pavement material might possess, and for example Daniels (2004) reports that the approximate ranges of relative permittivity values for "dry asphalt" and "wet asphalt" are 2-4 and 6-10 respectively. The presence of air, which has a relative permittivity of 1, in voids within asphalt, will affect the overall 'bulk' permittivity of the asphalt. Water, with a relative permittivity of 81 however, has a much greater influence on materials overall bulk permittivity. The relationship between permittivity and moisture content is complex and influenced by a number of factors, but where materials have a degree of permeability and effective porosity (such as asphalt) there will be significantly different dielectric properties between wet and dry conditions.

It is possible to determine the relative permittivity of a material if the velocity of the radar wave through the material, and the thickness of the material (i.e. the distance that the wave travels) are known. For non-magnetic materials (where the magnetic permittivity of the material does not have an influence on the propagation of electromagnetic waves) the following relationship exists:

$$d = \frac{ct}{\left(\sqrt{\varepsilon_r}\right)} \qquad \text{Equation 1}$$

Where: d = distance;
c = velocity of light in free space (vacuum);
t = travel time of signal;
ε_r = relative dielectric permittivity.

Also, the permittivity of materials influences the amplitude of reflected waves from an interface (which could result from an interface between different materials or between 'wet' and 'dry' types of the same material). This can be quantified by the 'reflection coefficient':

$$\rho = \frac{\left(\sqrt{\varepsilon_1}\right) - \left(\sqrt{\varepsilon_2}\right)}{\left(\sqrt{\varepsilon_1}\right) + \left(\sqrt{\varepsilon_2}\right)} \qquad \text{Equation 2}$$

Where: ρ = reflection coefficient;
ε_1 = dielectric permittivity of the upper material;
ε_2 = dielectric permittivity of the lower material.

Thus, the greater contrast in the dielectric properties of materials, the larger the reflection of the amplitude. Previous works, using laboratory based GPR experiments, have demonstrated that drier asphalt materials have a lower dielectric permittivity that saturated asphalt samples (Evans et al., 2008b; Liu, 2007; Shang et al., 1999). For soil, an empirical relationship was suggested by Topp et al. (1980) relating permittivity to volumetric moisture content, and previous work has been conducted using GPR based determinations of moisture content and comparing these to other dielectric-based methods, showing some correlation of moisture values obtained by both methods (Benedetto et al., 2013). GPR determination of moisture content in pavement asphalt conducted by Plati and Loizos (2013) used an empirical relationship devised by Baran (1994) to show a correlation between measured values of ε_r and moisture content, but limitations exist in that the verification of the actual moisture content of the asphalt investigated is not possible, and thus results rely on the accuracy of the empirical moisture-permittivity relationship.

Although some guidance on GPR use in pavements is available (see subsection “Ground Penetrating Radar (GPR) for Pavement Assessment”) there is currently no generally accepted method specifically regarding the accurate determination of the presence of excessive moisture in bound pavement layers. The determination and quantification of precise moisture content values for materials can prove difficult and so investigations using GPR tend to be limited to relative indications of areas where moisture is ‘high’ or ‘low’.

Summary of Investigation

A series of laboratory based investigations, using GPR to collect data from asphalt core samples, was conducted. 10 asphalt core samples were used for the study, obtained from in-service pavements, and the GPR equipment used was that typically used for shallow pavement investigation. The relative permittivity for each of the core samples was determined from the radar pulse velocities, over a range of different moisture contents. The aim of the investigation was to quantitatively assess the relationship between the moisture content and the relative permittivity of the asphalt.

It is hoped that quantification of the permittivity changes caused by known changes in asphalt moisture will allow improved pavement investigations using GPR, by allowing the magnitude of variations in recorded permittivity of the asphalt, from in-situ GPR pavement investigation, to be related to the magnitude of variations in moisture content. The gravimetric moisture content of the asphalt in this study was directly determined through weighing of the asphalt samples, rather than by indirect means.

Methodology

Asphalt Samples

The asphalt used in the study was obtained from the core samples taken from the A9, A90 and M90 trunk (major) roads in Scotland (see Figure 1). The use of asphalt taken from in-service pavements aligned with the intention of this investigation that the results would be relevant and applicable to GPR investigations of in-service pavements.

Figure 2. *Extraction of Asphalt Core Sample Used from Asphalt Pavement*

10 samples (each of 150mm diameter) were used in this study, consisting of hot rolled asphalt (HRA) or dense bitumen macadam (DBM) bitumen-bound layers, with full depths ranging from 200mm to 420mm. Figure 2 shows an example of one of the cores, containing DBM, used for testing.

Figure 2. *Example of Asphalt (Dense Bitumen Macadam) Core Sample*

Prior to using the cores, it was desirable that as much moisture was removed as possible so that they were in a 'dry' condition. Previous work conducted by the authors (Evans et al., 2008b) had shown that the bitumen of a similar asphalt material had undergone softening at 45^0C, causing the deformation of the material. As a result, once the cores were extracted from the pavement they were taken to the laboratory and stored in dry conditions at room temperature for a number of weeks and then at 35^0C for 48hrs to ensure that drying took place but that the material was not damaged.

Following drying, core samples were weighed to determine the 'dry' weight of each core (although it is noted that removal of all free water from the cores could not be ensured, and so the 'dry' weight was only an approximation). Each sample was then immersed in a water tank for 20 days to ensure the asphalt was 'saturated'. Upon removal from immersion, the 'saturated' weight of each sample was taken. The mass of moisture contained in the asphalt, compared to its 'dry' weight was then used to determine a moisture content for the asphalt (moisture content = mass of moisture/mass of dry material). Also, the density for each of the asphalt cores was determined in the 'dry' condition, with values ranging from 2.614 to 2.102 kg/m^3.

The GPR data collection (see subsection "Data Collection") was then conducted, and each sample was then allowed to dry (at room temperature) over several days. During this drying phase, periodic re-testing of the asphalt was conducted. For each re-testing cycle, as the asphalt dried and moisture content reduced, each sample was re-weighed and the changing moisture content could be recorded.

Data Collection

For engineering investigations, the GPR signal frequencies used are generally within the range 400MHz to 2GHz, with the higher frequencies used for relatively shallow investigations such as asphalt pavement layers (higher frequency of GPR signal give greater resolution of data, but less penetration depth). In this study a Geophysical Survey Systems Inc. dipole (ground coupled) antenna with a centre frequency of 1.6GHz was used.

The GPR data collection procedure for each core was to place the GPR antenna on the top of the core and then record the travel time for signals transmitted downwards into the top of the core to be reflected back from the lower end of the core (the ‘two-way’ travel time). For in-site pavements, reflections from the bottom of the asphalt layer would occur because of the contrast between asphalt and the underlying sub-base material, but for this study a metal plate was positioned at the base of the core to ensure a good reflecting surface (see Figure 3). The system used allowed GPR travel times to be recorded to a precision of 0.03ns (nanoseconds).

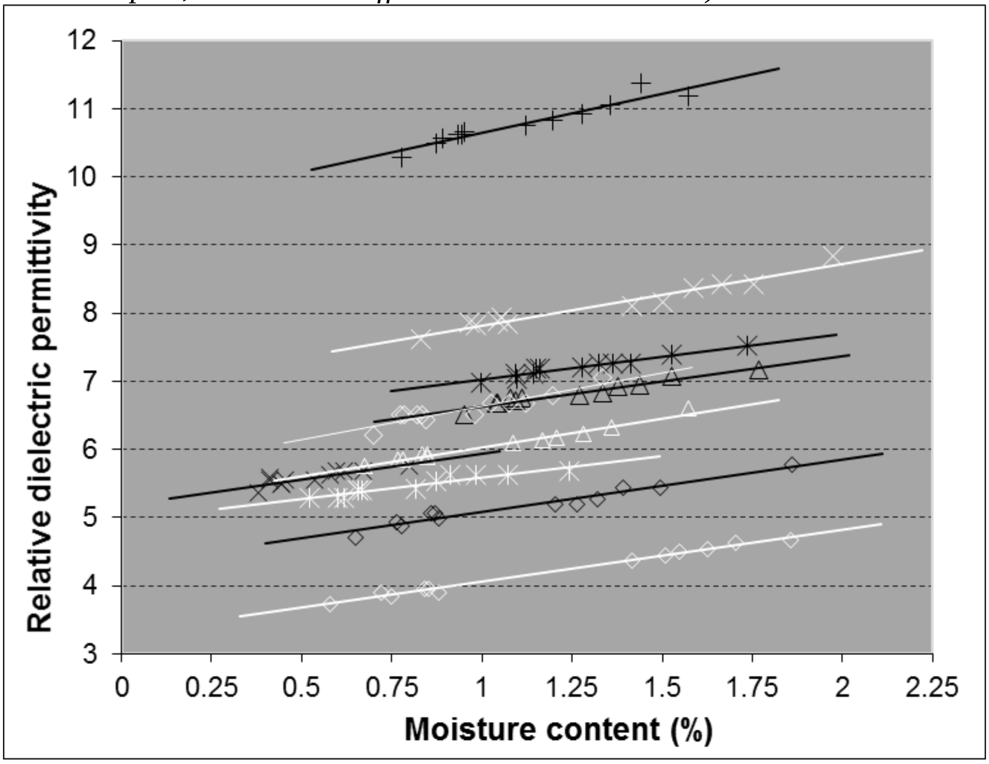
Figure 3. *GPR Data Collection from an Asphalt Core Sample (Showing GPR Antenna on Top of Core and Metal Plate at Base of Core)*

The length of each core was measured and thus recorded signal travel times could then be used to determine the relative permittivity values using Equation 1.

Results

Figure 4 shows the results of the laboratory investigations, with relative permittivity being determined for each of the 10 asphalt cores at 12 different moisture contents. For all of the 10 samples, under the test conditions that existed, there was a generally linear relationship between the measured moisture content and relative permittivity, with higher values of permittivity calculated when the moisture content was higher. This was apparent in the data collected by the GPR system used, as there was a decrease in the two-way travel time of the signals reflected from the base of the samples as the moisture content decreased in the asphalt. This reduction in travel time was a result of increased GPR signal velocity, which in turn is a result of the lower proportions of water present in the material giving a lower overall ‘bulk’ permittivity vale for the asphalt. The average increase in relative permittivity per 1% increase in moisture content (i.e. the average gradient of the trend lines plotted in Figure 3) was 0.82.

Figure 4. *Relative Permittivity against Moisture Content (for 10 Asphalt Core Samples, Each at 12 Different Moisture Contents)*



Analysis & Discussion

Test Results

Previous work by the authors (Evans et al., 2008a) showed that the reflection amplitude from an interface between 'dry' asphalt and 'wet' asphalt (at average moisture content of 1.16%) was 22% greater than the reflection amplitude from a completely 'dry' interface. The increased reflection amplitude from this wet interface could be clearly seen in the GPR data collected. This previous work supports the evidence gathered in this study that, despite only small changes in the moisture content being possible in asphalt (under 2% in this study) which causes small changes in permittivity (of 0.82 per 1% increase in 'free' moisture content), the magnitude of permittivity increases caused by such small asphalt moisture content increases is detectable by GPR investigation.

The amount of interconnected air voids within the asphalt determines the amount of moisture absorbed during the soaking process and the average difference in the gravimetric moisture content for the asphalt samples when fully 'soaked' compared to 'dry' was 1.43%. This reflects the low porosity of the material, as would be expected from the asphalt. However, the high relative permittivity of water (ε_r = 81) means that when low permittivity air (ε_r = 1) is replaced by water within the asphalt (typically ε_r = 3 to 12) the overall change in the 'bulk' permittivity of the asphalt is detectable.

The average ‘dry’ permittivity value of the asphalt in this study was 6.25, increasing to an average of 7.02 when soaked (a difference of 12.3%), which was a measurable increase using the analysis of GPR signal travel times. Although the actual permittivity value for each sample was different (for example, the ‘soaked’ asphalt samples had values ranging between 4.66 and 11.18), the overall trend for the change in permittivity with a 1% change in moisture was similar for each sample (the average of 0.82 had a standard deviation of 0.16, although it is noted that this is from a small data set of 10 samples).

This result for the relationship between permittivity values and moisture content indicates not only the magnitude of permittivity change that might be expected when the moisture content changes, but also indicates that different samples of the same asphalt material (DBM) show very similar behaviour regarding the amount of variation in permittivity that could be expected when moisture content changes. GPR practitioners undertaking asphalt moisture investigations may be able to relate the results they obtain to the quantified measurements made in this study.

Despite the relationships mentioned in subsection “Dielectric Permittivity and Moisture Content” it can be difficult to quantitatively relate the value of permittivity to the actual asphalt moisture content, and it is the authors experience that often the approach used during pavement moisture investigations is to use spatial variations in asphalt permittivity to indicate potential variations in relative moisture content, rather than reporting the actual moisture content. This study indicates that each area of distinct pavement asphalt, even if of the same generic type, may possess significantly different permittivity values. (The range of relative permittivity values during the entire testing process was 3.72 to 11.18, indicating the range of permittivity values that might exist in DBM asphalt pavement, depending on the moisture condition).

However, the study also shows that small variations in the moisture content of a distinct type of asphalt can produce measurable variations in bulk asphalt permittivity. The detection of such variations can be used to indicate areas where moisture may lead to problems with material integrity.

Limitations and Uncertainties

Despite procedures being used during this study with the aim of minimising potential errors and uncertainties, including conducting repeat testing of several samples, some factors remain that introduced uncertainty.

One of the technological limitations of the GPR equipment used was that it is capable of measuring signal travel times to a precision of 0.03ns. This degree of precision could introduce a potential error of approximately 0.07 during the calculation of individual relative permittivity vales. It is important to note the potential for such an error, but the level of uncertainty that this attached to the results is not considered to significantly affect the data or the conclusions. Also, standard unmodified GPR equipment was used for this study thus reflecting the type of data and degree of accuracy that would be obtained from state-of-practice GPR pavement investigations.

An issue to note, in particular if applying the results to a wider context of permittivity and moisture outside of ground radar and engineering scenarios, is that the permittivity of a material is affected by electromagnetic signal frequency (although only by a small amount within the GPR signal frequency range). The results in this study are specific to the 1.6GHz GPR signal frequency used during data collection.

As mentioned previously, each asphalt sample used was of a generically similar type (DBM) but as each sample was taken from different pavement locations slight differences in mix proportions and material properties resulted, which in turn gave a range of dielectric properties for the 10 samples used. Although the use of samples from ‘in-service’ pavements at different sites allows less control over exact material properties it has the advantage that results are representative of the variability likely for in-situ asphalt pavements, rather than by preparing ‘artificial’ pavement asphalt under laboratory conditions.

One assumption made during the GPR assessment of moisture is that the variations in moisture are the dominating factor causing changes in permittivity of the asphalt. There are several material properties that can affect the results (see subsection “Dielectric Permittivity and Moisture Content”) but the use of the laboratory controlled experiments in this study ensured that only the moisture content of each individual asphalt sample was altered during testing. It should be noted, however, that other factors may influence dielectric properties (e.g. variations in air void content, density, material types, mix proportions), in particular during in-situ investigations. Therefore, if the results of this study are applied to the GPR assessments of other in-service pavements, it is important that supporting information should also be used to compliment findings from the GPR investigation (which, in itself, is good practice for any GPR investigation).

Conclusions

For the range of material and test conditions investigated, the results showed that:

- On average, the relative permittivity of asphalt changed by 0.82 for each 1% change in gravimetric moisture content.
- The changes observed in permittivity, caused by changes in moisture content, were detectable using the analysis of the GPR travel time data.
- There was a general correlation between the rate of change in permittivity with changing moisture content, for all material tested, but the absolute values of permittivity were different for each individual asphalt sample.
- With reference to the previous point, the calibration of in-situ GPR pavement investigation data should be undertaken for each specific site and each specific material to ensure optimum interpretation of GPR data.

- The mechanism for the increase in permittivity with increase in moisture is the replacement of low permittivity air (ε_r = 1) with relatively high permittivity water (ε_r = 81) within the voids of the asphalt.
- This study is limited in some aspects, and therefore any reference of the results from this study to practical applications of GPR should make note of the limitations described above.

This study provides information which may be used to improve the assessment of asphalt pavement moisture from the GPR data. The recording of GPR signal travel times has been shown to be a viable method for assessing changes in asphalt permittivity caused by changes in the moisture content of the asphalt. Also, the amount of permittivity change caused by moisture changes has been quantified and it is hoped that such information can be used to assist in the assessment of the significance of measured permittivity changes for in-situ pavements.

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