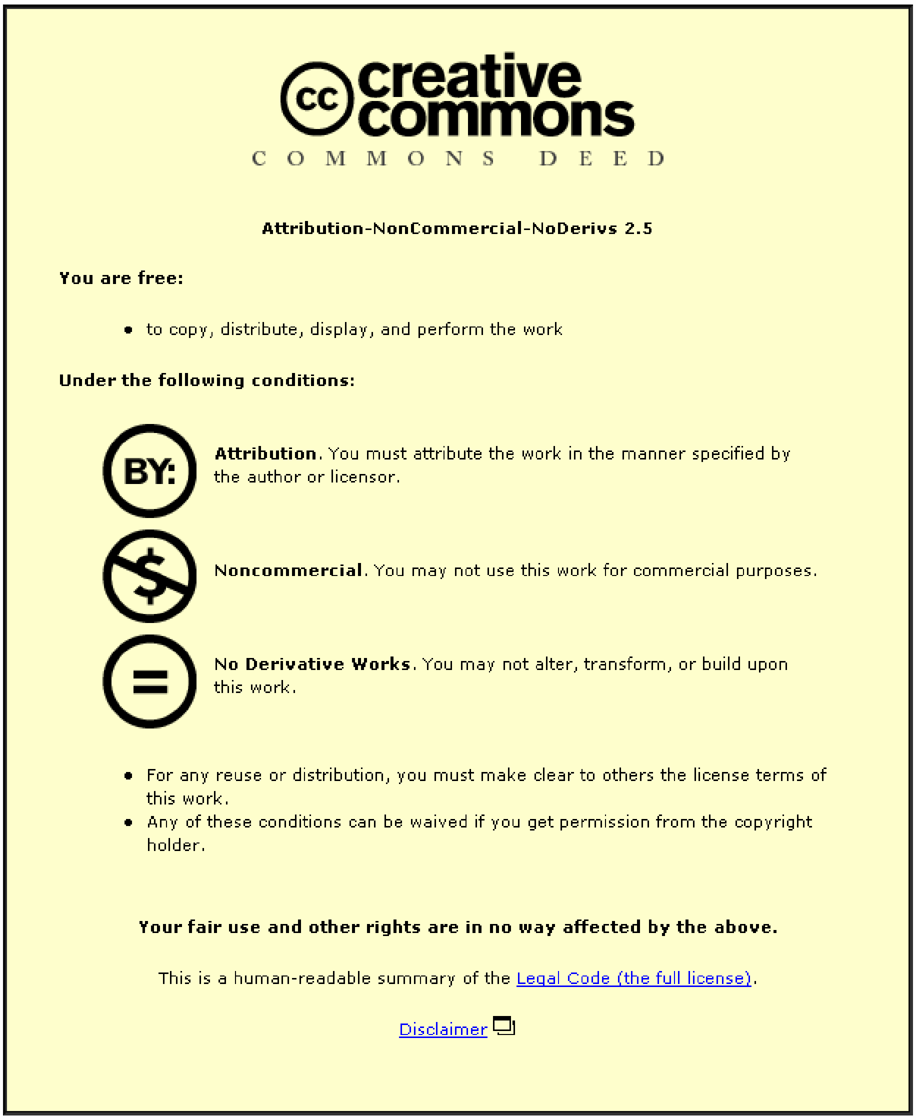

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A Review of Pavement Assessment Using Ground Penetrating Radar (GPR)

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Abstract - **The use of GPR to obtain information on pavement structures has greatly developed over the past 20 to 30 years. The early 1980's saw the first major developments of GPR for pavement applications and it is now an accepted technique for pavement investigation. GPR has a proven ability to obtain a variety of information on parameters relating to the structure and materials of the pavement. Despite this, several hindrances to wider use of the technique exist, and there is a requirement to address a number of both perceived and real limitations of GPR use for pavement investigation. This paper aims to provide an up to date discussion and summary of the current and developing uses of GPR for pavement investigation, through reference to previous work and ongoing research, including that conducted by the authors. This paper is intended for both GPR specialists and pavement engineers, and reports the ability of GPR to obtain good data for the various uses described, and discusses the applicability, limitations, and scope of GPR for further developments in pavement investigation.**

1. INTRODUCTION

1.1 Aims

This paper aims to provide a review of the established applications of GPR for the pavement engineer, and also to outline applications which are currently under development or are not yet adopted with sufficient confidence to be routinely applied, but which may provide useful information to the pavement engineer. For both current and developing applications the successes and limitations of the technique are highlighted. Key references are provided for the uses and issues described, and work conducted by the authors is also discussed to illustrate some of the recent and ongoing developments of the technique.

The paper focuses on the application of GPR to bound pavement layers, which have been laid over a foundation material. Whilst the specific application of GPR to bridge decks and to foundation materials covers a number of issues which are applicable to the testing of bound pavement material, bridge deck and foundation investigations also offer a number of specialist issues and to cover all of these sufficiently would require a separate paper. Therefore, where appropriate, GPR bridge deck and foundation applications are discussed, but a comprehensive review has not been attempted.

A brief history of the development of GPR for assessing pavements is given, followed by a section detailing the established uses of GPR and reference to documents which exist to aid the pavement engineer. GPR applications which are under development are then outlined, and recommendations for the use of GPR in pavement assessment are made. The experience of the authors during both 'routine' pavement investigations and in recent research activities are used to highlight and illustrate specific issues. It is hoped that an improved understanding of the applicability, limitations and scope for development of GPR pavement assessment is provided.

1.2 Pavement structures

A 'pavement' is an engineered structure designed to carry vehicle loads. There are many different types of pavement structure, including roads, aircraft runways and taxiways, factory floor slabs and any other surface intended for the passage of vehicles (but it should be noted that these structures are distinct from 'footways', which are designed for pedestrians only). Most modern pavements consist of a bound upper layer, over an un-bound granular 'sub-base' layer and a bottom 'subgrade' layer (which is often the natural ground). For some pavements the sub-base may also consist of bound material, but usually it is only the upper pavement structure which consists of bitumen-bound or cement-bound material. (NB, Sometimes cement-bound material is described as 'hydraulically-bound material', a description which includes both relatively fast setting cement based mixtures but also other slower setting mixtures which harden by hydraulic reaction). It the bound upper pavement material which provides the main structural strength and load spreading ability, reducing stresses imposed by vehicles to a level that can be sustained by the subgrade. Whilst cement bound layers can be treated as a single layer of material, the design of bitumen bound pavements requires individual layering of different mixes of bituminous materials (‘surface course’, ‘binder course’ and ‘base’, see Figure 1), each performing a different function within the overall bituminous-bound material layer.

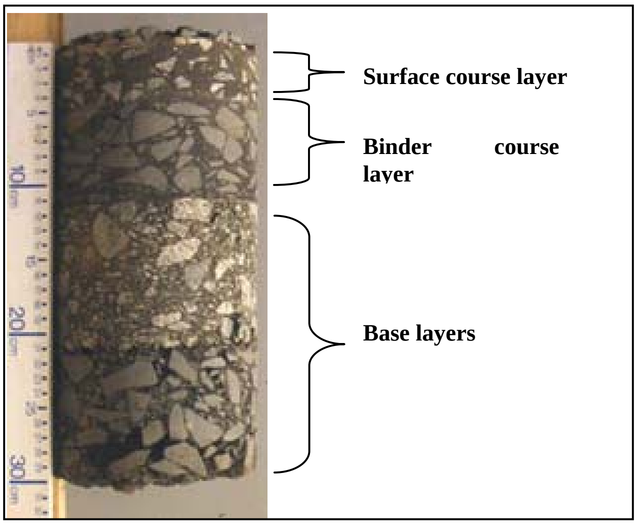

Figure 1. Core sample, showing layers in a typical bitumen-bound pavement. (Left hand depth scale in cm)

1.3 Pavement assessment

One of the main areas of work of a pavement engineer involves maintaining and improving existing pavement structures. This can be achieved by employing the appropriate investigation techniques, from a range of possible options including include GPR, to gain the optimum amount of information on the condition of the existing pavement. Once a pavement evaluation has been undertaken, appropriate maintenance work can be planned. Assessing the condition of the bound pavement material involves investigating the properties of the entire bound layer, those of the individual layers within the bound material and the bond integrity between the layers.

A recent study has suggested that, despite widespread use of a number of geophysical methods in transportation projects, “the majority of in-house geoscientists and engineers have insufficient knowledge regarding the advantages of geophysics” [41]. The main deterrents for using geophysical methods (of which GPR was found to be one of the most popular) were a lack of understanding, the non-uniqueness of results and a lack of confidence. Daniels [11] also highlighted similar issues, and emphasised that the physical principles behind GPR must be understood if the technique is to be properly applied. Also, despite the fact that GPR has proven to be a very useful tool for the highway engineer, several failures of GPR have also been reported and often this has been attributed to over-selling the technology by those who understand GPR but do not appreciate the complexity of pavement systems [38]. It has also been claimed that a factor in the limited use of GPR for pavement evaluation is the lack of reliable automated data analysis procedures, as well as the difficulty of manually interpreting the large amounts of GPR data collected during pavement surveys [26].

It is apparent that, despite successful use of GPR by pavement engineers, several issues exist which require addressing. These include gaining a better understanding of how the electrical properties measured by GPR can relate to engineering properties of pavement materials, developing the ability to successfully integrate GPR data with other pavement investigation data and providing appropriate training to both those who are responsible for GPR surveys and those who use the GPR data. The pavement engineer can benefit greatly by having an understanding of the principles and applications of GPR, but the GPR specialist can equally benefit by gaining an understanding of the issues relating to pavement structures and materials.

2. HISTORY & DEVELOPMENT

Experiments exploiting the ability of radio waves to pass through ice were first conducted in the late 1920’s and 1930’s, and further work in this field continued intermittently over the next few decades [10, 44]. It was not until the 1960’s, however, that development of the technique for other ground materials began to gain pace [10, 29].

GPR was first applied to roads in the 1970’s, initially for tunnel and bridge deck investigations [33], and during the early to mid 1980’s several investigations were undertaken on the use of GPR for locating voids beneath bound pavement layers, with varying degrees of success [24, 32, 42, 43]. North America and Scandinavia were main areas for development, with the first vehicle mounted GPR system for use on roads being developed by the US Federal Highways Administration in 1985 [33], and in Scandinavia by the late 1980’s ground-coupled GPR had become a routine tool in road maintenance projects [38]. In the UK, by 1990, a number of successful GPR pavement surveys had been conducted, although the experience was “fragmented” [47].

Large technological advances in the design of GPR hardware and software took place in the 1990’s, and development has included features such as greater processing power, smaller size of components, simpler and more user-friendly software and the ability to perform vehicle-towed surveys. Also, work on the ability of GPR to provide ‘network level’ pavement surveys (aimed at obtaining data to provide an overview of large sections of the entire road network), and to provide layer thicknesses for integration with other data such as from the falling weight deflectometer (FWD) led to GPR applications becoming well established [12, 18, 27, 31, 37].

In 1998 Morey [33] reported that 33 of 51 North American highway and transportation agencies had used GPR (mainly for layer thicknesses, void detection and bridge deck de-lamination, but also including several other applications), indicating that whilst the technique was gaining much use, there was still a large section of the industry that was not fully utilising the potential of GPR. The publication of a number of documents by US state and national transportation organizations during the mid 2000's, detailing the applications and feasibility of GPR for pavement investigations indicates that whilst the technique is becoming more widely used, the education of engineers to the usefulness and applicability of GPR is still ongoing [21, 29, 46].

3. MODERN APPLICATION OF THE TECHNIQUE

3.1 General

The main guidance documents produced by national highway authorities in North America and Europe on the specific use of GPR for pavement investigation [1, 6, 13] have been periodically updated to reflect ongoing developments. Also, to assist the engineer in appreciating what information may be obtainable, and in selecting appropriate techniques and applications, several publications exist in which a general overview of GPR (and other geophysical techniques) is given [9, 46].

There is a range of information which can be obtained by GPR depending on how the technique is applied. Once the engineer has decided which pavement features are of interest, and what information is required, the GPR specialist should (after gaining as much information about the specific site conditions as possible) decide on the methodologies employed for data collection and analysis, so that the optimum amount of information can be obtained. Although using GPR alone can provide useful information, pavement investigations will often involve utilising several techniques, such as the FWD or coring of the pavement, and so a dialogue between the engineer and GPR specialist will ensure that GPR information can be obtained and presented to best compliment other investigation data.

3.2 Position location

The ability to accurately record and report the location of GPR data is of paramount importance in any GPR (or other) pavement investigation. Often, a road or airport site will have a pre-defined distance ('chainage') system in place which defines the longitudinal location along the pavement, and commonly the pavement chainage and the transverse offset across the pavement (which for roads will often be one the near-side or off-side wheel track, and for runways is often a transverse distance from the centre-line) are used to define locations.

The use of global positioning systems (GPS) to locate GPR pavement data is often not specifically required, but can prove extremely useful, especially for accurate integration of other data and for surveys where longitudinal data is less dominant. Several commercial software systems currently exist which allow GPS co-ordinates to be collected with GPR data, but important issues also exist concerning the use of GPS referenced data [40] and ultimately the decision on what location referencing procedure to use should be based on which system ensures the optimum accuracy and also ease of reference for the information user.

3.3 GPR types

Several GPR system types exist, each based on the same physical principles of electromagnetic wave propagation, but which employ different hardware and data processing procedures. 'Impulse' GPR systems, which are the most commercially available and the most commonly used, transmit a short pulse of electromagnetic energy and record the time taken for reflections of the pulse to return to a receiver. Other system types less commonly used in pavement investigation, but which also have engineering applications, are discussed later.

Several types of antenna exist for GPR, and the most commonly used for impulse systems are "dipole", requiring contact with the pavement surface (ground coupled) and "horn", which are able to operate whilst suspended a short distance above the pavement surface (air coupled). Ground coupled dipole antennas provide greater depth penetration (for a given signal frequency), but air coupled horn antennas provide higher data acquisition rates and thus facilitate higher speed surveys. For a given signal frequency, horn antennas may prove the most appropriate when the upper layers of a pavement are of most interest, and dipole antennas may be more suitable where thicker pavements are encountered (e.g. airports) or where information about the pavement foundation is also required.

The penetration depths GPR signals of a given frequency are greatly affected by site material conditions, but the experience of the authors in conducting various road and airport pavement investigations has shown that a ground-coupled 1.5GHz antenna can be generally expected to obtain good data identifying individual bituminous layers down to 300-400mm depth in sound material. The vast majority of roads investigated by the authors in the UK, including trunk roads and motorways, have been investigated to their full bound material depth with a ground coupled 900MHz antenna. Thick types of bound pavement (including runways) have often required a lower frequency signal (e.g. 400MHz), but it should be noted that each pavement structure has its own specific dielectric conductivity and signal attenuation properties which will effect the penetration depth and signal resolution.

3.4 Dielectric properties of pavement materials

The dielectric properties of a pavement material can be determined directly from GPR data alone (such as by the calculation of the surface material dielectric properties by analysis of reflected signal amplitudes from air-coupled horn antennae) or indirectly by correlation with other data (such as calibration with core samples). Whilst an engineer may not be interested in the value of the dielectric constant itself, the dielectric properties of the material largely governs the amount of useful information that a GPR specialist can provide the engineer.

The dielectric constant of a material determines the velocity at which the radar pulse will travel, so by recording times for reflections to be received, a depth can be estimated. Investigations by the authors has previously shown that 2 separate locations on an in-service road can have dielectric constant values that differ by over 13%, despite having the same material type, because of differences in the material condition. A review of reported dielectric constant values for nominally similar “bituminously bound” pavement materials also showed that values ranging from 2 to 12 have been determined, which highlights the need to accurately determine the dielectric properties of materials at each site investigated [16].

3.5 Limitations

As with every investigation technique, limitations exist to aspects of GPR, and these can be diverse in their nature. As outlined in Section 1, some of the limitations of GPR arise not because of the technique itself, but due to perceptions of the technique, and lack of appreciation or expertise. Difficulties encountered during data interpretation (i.e. lack of expert knowledge) have also been suggested as one of the main reasons why GPR is not specified routinely by the US Department of Transportation [5]. Other sources for uncertainty or variation have previously been categorised by the authors into three areas [15]:

- Technological and scientific issues
- In-situ investigation methodology
- Data analysis methodology

The physical laws which govern the principles of electromagnetic radar wave propagation are unchanging, and therefore there are some areas where it may not be able to significantly improve the limitations of the technique. However, some recent developments are able to augment the already established uses of GPR. The use of GPR to directly determine dielectric properties of pavement materials, the level of accuracy achievable for GPR thickness evaluation, the optimum use of different types of antenna, improvements in computing and processing technology, and the process of integrating GPR data with other pavement investigation techniques are some of the areas which pavement engineers may gain benefit.

4. EXISTING USES OF GPR

4.1 Main applications

The latest versions of the main guidance documents for pavement engineers [1, 13] cover the appropriate use of GPR for paved roads, and much of the information can also be applied also to other paved structures including airports, ports, industrial flooring, etc. Although the uses for which GPR is considered a reliable technique vary slightly between the existing guidance documents, and will change as documents are periodically updated, GPR applications which are generally considered as established include:

- Determination of layer thicknesses and location of construction changes (including use of GPR data for FWD analysis)
- Location of voids and excessive moisture beneath bound layers (including seasonal variations in sub-base moisture content)
- Determination of depth and alignment of steelwork
- Quality control of pavements (which can include thickness determination, but also air void content and density determinations)
- Detection of stripping in bituminous material

Some of the above applications concern features which affect both the bound material layers and the foundation material, but applications which are mainly concerned with the foundation layers are not covered in detail in this paper.

4.2 Thickness

Determination of layer thicknesses is one of the most common uses of GPR in pavement engineering. A contrast in the dielectric properties at material interfaces allows GPR to identify different layers. The experience of the authors is that the bottom of bituminous (asphalt) pavements are generally more easily identified than for rigid (concrete) pavements, where the dielectric properties of the cement bound material can sometimes be similar to underlying granular sub-base material.

Much work has been undertaken to determine the accuracy and resolution to which GPR can resolve layer thicknesses, and various claims have been made. The finite resolution of GPR signals means that depth resolution is more difficult in thinner layers, and deterioration of material often means that accurate depth determination is more difficult in older structures. In 2006, a review of published data (mainly from horn antennas) on pavement thickness accuracy reported that “The studies have generally compared the GPR results to cores, and have shown differences that range from 2-10%. The lower differences (2-5%) are generally associated with newly constructed pavements, while the bigger differences are generally associated with older pavements.” [21]. This is comparable to the UK DMRB [13] which states that a 6-10 % level of accuracy, depending on layer thickness. ASTM guidance [6] states that a typical GPR system “usually has a resolution sufficient to determine a minimum layer thickness of 40 mm to an accuracy of 5 mm.”

One of the main factors in accurate depth determination is the accurate calibration of GPR data. Several calibration options are available, depending on the GPR system hardware used, and the availability of data from other investigation techniques. Loizos & Plati [30] conducted an evaluation of calibration methods using core calibration, reflection amplitude calibration (i.e. using GPR data only) and laboratory determination of dielectric constants and found that whilst all three methods were sufficiently accurate for pavement evaluation purposes, “The travel time–core thickness procedure seems to provide the minimum error for the estimated AC [asphaltic concrete] thicknesses”.

When considering the reported accuracy that GPR is claimed to achieve compared to cores, it is also important to note that it is common for the base of bound pavement material to carry an unevenness of +/- 2.5cm or more [16], and it has been reported that an error of approximately 2.7% is comparable to the error obtained by direct thickness measurements on a core [4].

4.3 Integration of GPR and FWD data

The main non destructive device for testing pavement structural capacity is the falling weight deflectometer (FWD), which loads the pavement surface, simulating the effect of a moving heavy goods vehicle, and records the deflection of the pavement surface under this load. Back-calculation of material stiffness is then undertaken using the deflection data and layer thickness values. The stiffness values determined can be used to predict the ‘residual life’ of the pavement at each test point, hence providing the engineer with information to plan maintenance and rehabilitation work.

Traditionally, core samples were used to determine layer depths, but this has the limitations of both time and expense, and also that the data obtained is point specific and so the layer thickness for significant lengths of pavement often has to be interpolated or estimated. Procedures for the use of GPR layer thickness data with FWD can be found in official guidance documents but a number of other publications also provide methodologies for efficiently integrating data from the two techniques [39] and also with other pavement investigation data from a PMS [34].

4.4 Voids

Despite void detection being one of the earliest applications of GPR for pavements, unsatisfactory results have often been reported [33], and the latest version of the UK DMRB [13] recommends that GPR alone should not be used as justification for treatment. Also, the presence of reinforcement can affect the ability of GPR to successfully identify voiding below it. Despite this, GPR still offers a useful tool for void detection, and a recent study has shown the potential of a ground coupled, relatively low frequency (400MHz) antenna GPR to locate voids as small as 50mm in depth, and locate other voids beneath reinforcement [8], although drilling and coring were recommended to determine the extent and depth of the void.

4.5 Moisture

The dielectric constant of water is approximately 80, which provides a large contrast to that of pavement materials (which are in the range approximately 2 to 12), and so the ability of GPR to detect areas of excessive moisture is good. Accepted applications include detection of water in voids, and foundation material moisture. The use of GPR for assessing bound material moisture properties is not as well established, and work in this area is discussed in Section 5.

4.6 Steelwork

Of the various types of materials that may be found within pavement structures, metals provide the largest contrast in dielectric properties compared to other pavement materials. Hence, the ability to locate steelwork is a well established one. Recommended uses in reinforced pavements include determination of re-bar depths and checking of mis-alignments of dowel bars [13].

4.7 Quality control

Applications of GPR for quality control of pavements can involve determination of layer thicknesses, but more recent developments also offer the ability to assess air-void content (i.e. the amount of air contained within the material mix), segregation (localized areas of low density material, which can result from poor mixing or construction practices) and density of bound materials. The air void content will affect the density and compaction of bituminous material, and so it is a very important factor affecting a pavements life and deformation properties.

Measuring the air voids content by determining dielectric properties is based on the fact that the dielectric value of bituminous material is a result of the volumetric proportions of the dielectric values of its constituents, and hence more low-dielectric air will result in a lower overall ‘bulk’ dielectric value for the entire mix. Work on this topic resulted in GPR being adopted as a quality control tool (alongside other pavement density measurement techniques) for new pavement construction in Finland [38].

4.8 Stripping

Questionable results have been reported by several organisations using GPR for detection of stripping [33] (where the bond between bitumen and aggregate is broken, primarily through the action of moisture). Rmelie & Scullion [36] reported that GPR “appeared to work well in detecting the location and extent of subsurface stripping” but noted that the stripping detected was at a relatively advanced stage. Its use for detection of stripping is still recommended, but as results have been variable, it should be used in conjunction with other methods.

5. DEVELOPMENT OF GPR

5.1 General

Some areas for development of GPR in pavement investigation involve using new hardware, so that the data collected is different from what would be obtained from 'established' applications. Other areas for development are exploited by adapting existing systems to obtain more information from the data being collected. Three broad categories for new development are given in Sections 5.2 to 5.4.

5.2 Development of systems

Antenna development and design is seen by some as the most significant area for GPR development [28, 48]. Recent developments in impulse GPR hardware have resulted in a greater range of frequencies of antenna becoming commercially available, and the development of GPR systems which utilise arrays of multiple antennas (e.g. the GSSI Terravision array using 14 ground coupled antennas simultaneously to collect data).

Another significant antenna development for pavements involves the use of different antenna types. Step-frequency (SF) GPR transmits radar signals in a different manner to impulse systems and offer several advantages for pavement investigation [45]. SF-GPR antennas can transmit signals at different discrete frequencies (whereas impulse systems transmit at a range of frequencies, around a fixed 'centre frequency'). Signals are transmitted for a given time (the 'dwell' time) and then transmitted at another discrete frequency, and so on. In this way, a range of depth penetration and signal resolution can be achieved from a single antenna, overcoming one of the main disadvantages of impulse antennas. The disadvantages of SF-GPR are that data collection time is generally increased and the physical size of the antenna is large. The technique has been shown to be successful at resolving layer thickness to a better resolution than commercially available impulse systems, particularly for thin pavements [14], and although SF-GPR is not widely used in pavement investigation, SF-GPR systems are commercially available.

5.3 Development of methodologies

Developments in both the methodologies used for collection of data in-situ, and the methodologies and processes used in the analysis of the data, can offer improvements in the amount and accuracy of information provided by GPR.

The use of different methods for calibration of GPR data is an area where much work has been conducted. Rather than using core calibration, horn antenna can be calibrated by determining a value for the surface dielectric by comparison of the amplitudes of surface and reflected pulses, and dipole antennas can use common mid-point (CMP) calibration, where antenna transmitter and receiver are separated over a common mid-point and signal travel times are recorded, and also by wide angle reflection and refraction (WARR) in which in which the transmitter is kept fixed while the receiver antenna is moved away. These methods, though less common, are accepted calibration techniques. Another possibility is to fit scattering hyperbolae from rebars, or discrete features, and Al-Qadi & Lahouar [3] describe a study using this method where, following detection of re-bar, the reflected parabolic shape was fitted to a theoretical reflection model to estimate the pavement's dielectric constant and the re-bar depth. The technique showed an average error of 2.6% on the calculated re-bar cover depth.

Section 4.3 highlighted the role of integrating GPR and FWD data. In the USA, GSSI Ltd and Foundation Mechanics have recently developed a single vehicle GPR & FWD system using an air launched 2GHz antenna and software specifically developed to integrate the data [22, 35]. Also, in the UK Jacobs have developed a methodology used routinely for pavement investigations, in which data from a FWD and from ground coupled 1.5GHz and 900MHz antennae are collected simultaneously from a single vehicle (see Figure 2).

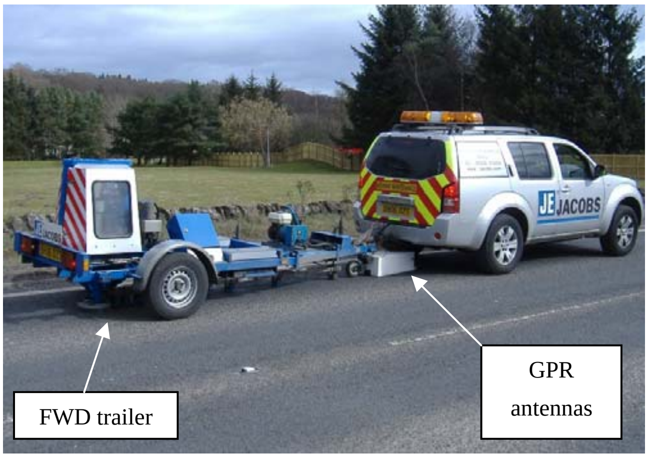

Figure 2. GPR and FWD data collection simultaneously from a single vehicle

Data integration software, designed for the combined analysis or presentation of results of GPR data with other road survey data, such as FWD, video surveys or surface conditions is an area of development that has much potential for further uptake. Commercially available software packages such as Road Doctor are available, which can perform such functions, but they are not routinely used by either pavement engineers or GPR specialists.

A number of studies have also investigated the development of software for automatic processing and interpretation of data. Automated processes tend to be more successful for new or defect free pavements, where interfaces and more easily observed and the pavement structure is generally less complex. An iterative data processing approach using least-squares fitting, on data collected with a 1GHz air-coupled antenna has been described [26], involving several stages of data processing. Reported results were promising and thickness errors (when compared to cores) of 2.5% were reported. It has also been shown that improved data analysis techniques for signal processing can improve thickness accuracies, by a modified 'deconvolution' algorithm, which improved the error in average thickness determination of HMA pavement at 19 different locations from 12% to 3%, when compared to core data [2].

The evolution of a pavement over time, through deterioration and maintenance processes means that fully automatic interpretation software packages will most likely not be able to process and analyse all types of in-service pavement, but the use of semi-automatic interpretation software can prove extremely useful when used by competent interpreters together with limited coring or other reference survey results [38].

5.4 Development of applications

There are some pavement features which GPR may be able to determine for which the technique is under development, and which may gain widespread acceptance in the future.

Cracking which originates at pavement the surface can lead to structural problems, especially if water is allowed to penetrate. Thus, the ability to accurately map the depth of any surface cracking is a useful one. Work by Utsi Electronics & TRL has reported promising results for a GPR system, using a cross-polarised antenna configuration with frequencies between 700MHz to 2.5GHz, for detecting the bottom of cracks in bituminously bound pavements. It was reported that cracks between 50mm to 160mm could be detected by the prototype system used in the study [19], and further development in ongoing.

The presence of moisture within pavements can lead to many problems, including loss of structural strength and deterioration of materials, and although GPR has an established application in monitoring sub-base moisture levels, the ability of GPR to determine moisture in bound materials is less developed. Some work, however, has reported the ability of GPR to classify and interpret different subsurface reflections from asphalt layers containing a buried moisture barrier, depending on the presence of moisture within individual layers [38].

The determination of dielectric properties of pavement materials (for which moisture has a large influence) is a developing field, and the influence of external factors on the dielectric constant of a material is an important area for research. The effect of moisture in increasing the dielectric constant of bituminous materials has been investigated in a study by the authors [17], with pavement material specimens having dielectric constants an average of 16% greater when 'soaked', compared to 'dry'. The same study also highlighted the influence of temperature, with a rise in bitumen bound pavement core material temperature (within a range reasonable for in-service pavements) observed to cause an increase in dielectric constant (see Figure 3).

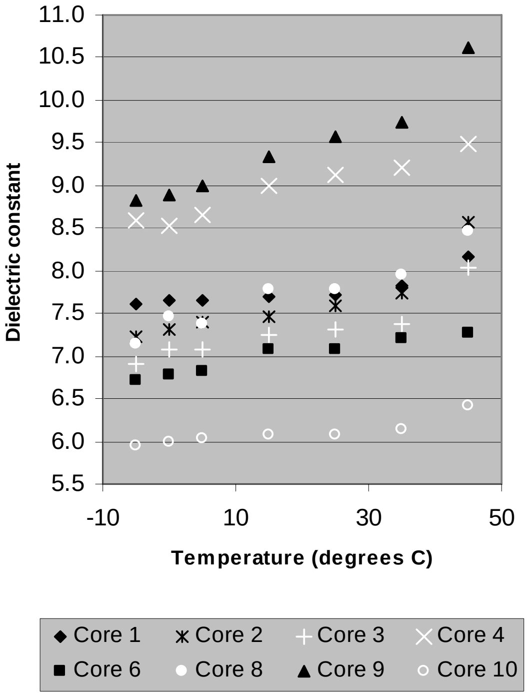

Figure 3. Dielectric constant of bituminous core samples determined at 1.5GHz

The lack of bond between pavement layers is also a very significant feature for pavement engineers to be able to determine. Khweir and Fordyce [23] report that "Bond failure at one interface can cause a predicted loss of two-fifths to five sixths, to as low as one sixth of the potential life of the pavement". Infrared thermography has been successfully used to locate de-bonding and delaminations in bridge decks and concrete pavements [20], but Kruntcheva et al [25] report that although work has been conducted using several different techniques to detect de-bonded or non-bonded layers, there is no accepted non-destructive test method for reliable detection of poor bonding.

A number of GPR providers claim detection of layer debonding as one of the applications of GPR, but results from some published studies (mainly concerning bridge decks) have been variable [7, 21] and it remains an area for further development. Research is currently being undertaken by the authors, aimed at quantifying the effect of moisture on the ability of GPR to detect the de-bonded layers.

6. DISCUSSION & CONCLUSIONS

Morey [33] highlighted the fact that engineers often view the non-uniqueness of GPR results as a factor in deterring their use, and previous work by the authors [15] has discussed the variations and uncertainties that can occur from

GPR pavement investigations. There can be a tendency in engineering to attach more credence to test results obtained from mechanistic methods (such as a core thickness, or a pavement deflection reading) despite the inherent uncertainties associated with such methods, than for the results of GPR. The "lack of understanding" cited by engineers [41] can lead to geophysical methods being treated as 'black box' technology.

Whilst developments continue, the ability to address the uncertainties arising from the above sources is essential so that the engineer can fully gain the benefit of developments in the application of GPR. Many of the developments discussed in Section 5 relate to the technical aspects of GPR, but a number of other factors to enhance the applications and improve confidence in GPR data can be undertaken. For example, when presenting information, it is possible to give an indication of the level of confidence in the results, which will provide the engineer with the capability to use the GPR information appropriately.

The engineer is often most interested in the condition of the pavement at its worst location (so that maintenance can be appropriately targeted and planned), so the collection of data from wheel-paths (where the most trafficking of the structure occurs) should be the default choice when conducting longitudinal GPR survey runs. Accurate positioning of such data is extremely important and can sometimes be overlooked. Despite much development in ensuring data locations can be precisely recorded, multiple operatives and sub-contractors collecting data from a pavement scheme over a period of time will seldom use a single location referencing methodology. The use of GPS can offer some solutions to this problem, but a comprehensive standardisation of techniques does not currently exist, and even when GPS is used problems can exist. Both the GPR specialist and the engineer should give as much consideration to accurate positioning of data as is given to more technical issues such as choice of signal frequency or data processing procedures used.

The education and awareness of both the GPR specialist and the pavement engineer can be improved to counter some of the issues raised above, including lack of appreciation or lack of understanding (from both parties). It can be the case that GPR surveys are specified by clients without a full appreciation of what can be obtained from the investigation and there is a responsibility which rests with the GPR specialist to appropriately advise the client. Often aims and objectives of surveys are not clearly specified by clients and when GPR surveys are not appropriately structured or do not have specific information objectives (e.g. layer depths, moisture, steelwork, etc) then the use of GPR will not be optimised, and hence the uncertainty in results is increased, which can lead to disappointment.

GPR offers arguably the most flexible technique, and the ability to provide the most diverse range of information, to the pavement engineer, but three key issues exist for the continued success and future development of the technique for pavement investigations;

- Continuing development, in applications, technology and methodologies, enhancing the ability of GPR to obtain useful information on pavement properties.
- Successful integration of GPR data with other pavement investigation data.
- Increased education and appreciation by both GPR information users and GPR information providers, of the application of GPR to pavements.

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