Optimising Ground Penetrating Radar (GPR) to Assess Pavements

Robert D. Evans

Jacobs Engineering UK Ltd.
Cardinal Square
10 Nottingham Road
Derby
DE1 3QT

Centre for Innovative and Collaborative Engineering
Department of Civil & Building Engineering
Loughborough University
Loughborough
Leicestershire, LE11 3TU

Loughborough University

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OPTIMISING GROUND PENETRATING RADAR (GPR) TO ASSESS PAVEMENTS

By
Robert D. Evans

A dissertation thesis submitted in partial fulfilment of the requirements for the award of the degree Doctor of Engineering (EngD), at Loughborough University

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Jacobs Engineering UK Ltd.
Cardinal Square
10 Nottingham Road
Derby
DE1 3QT

Centre for Innovative and Collaborative Engineering
Department of Civil & Building Engineering
Loughborough University
Loughborough
Leicestershire, LE11 3TU

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Several aspects of the EngD research undertaken also required use of materials and test data obtained with the kind permission of clients of Jacobs, and this is gratefully acknowledged.

ABSTRACT

Ground penetrating radar (GPR) technology has existed for many decades, but it has only been in the last 20 to 30 years that it has undergone great development for use in near surface ground investigations. The early 1980's saw the first major developments in the application of GPR for pavements (i.e. engineered structures designed to carry traffic loads), and it is now an established investigation technique, with generic information included in several national standard guidance documents. Analysis of GPR data can provide information on layer depths, material condition, moisture, voiding, reinforcement and location of other features. Assessing the condition of pavements, in order to plan subsequent maintenance, is essential to allow the efficient long-term functioning of the structure and GPR has enhanced and improved the range and certainty of information that can be obtained from pavement investigations.

Despite the recent establishment of the technique in pavement investigation, the current situation is one in which GPR is used routinely for pavement projects in only a minority of countries, and the specialist nature of the technique and the sometimes variable results that are obtained can mean that there is both a lack of appreciation and a lack of awareness of the potential information that GPR can provide. The fact that GPR is still a developing technique, and that many aspects of its use are specialised in their nature, means that there are also several technical aspects of GPR pavement investigations which have not been fully researched, and knowledge of the response of GPR to some material conditions has not been fully established.

The overall aim of this EngD research project was to provide improved pavement investigation capabilities by enhancing the methodologies and procedures used to obtain information from GPR. Several discrete research topics were addressed through various research methods including a literature review, fieldwork investigations, experimental laboratory investigations and a review of previously collected data. The findings of the research allowed conclusions and recommendations to be made regarding improved fieldwork methodologies, enhancing information and determining material condition from previously collected GPR data, assessing the effect of pavement temperature and moisture condition on GPR data and also on managing errors and uncertainty in GPR data. During the EngD project, a number of documents and presentations have been made to publicise the findings both within the EngD sponsoring company (Jacobs) and externally, and an in-house GPR capability has been established within Jacobs as a direct result of the EngD project.

KEY WORDS

Ground penetrating radar (GPR), non-destructive testing (NDT), pavements, dielectric constant

PREFACE

The Engineering Doctorate (EngD) Scheme was established by the Engineering and Physical Sciences Research Council (EPSRC) in 1992. This doctorate-level scheme is aimed at providing engineers with an intensive, broadly based research programme, also incorporating a taught component, relevant to the needs of industry. The EngD scheme is intended to provide ambitious and able graduates with the ability to innovate and implement new ideas in practice, and enable them to reach senior positions in industry early in their careers.

The EPSRC provides the EngD candidate (the 'Research Engineer') with support for up to four years, and the EngD research and training programme is undertaken as a partnership between industry and academia. Each Research Engineer has both industrial and academic supervisors who oversee the project to ensure that the objectives are achieved.

The EngD scheme aims to:

- provide Research Engineers with experience of rigorous, leading edge research in a business context;
- develop competencies which equip Research Engineers for a range of roles in industry;
- provide a mechanism and framework for high quality collaboration between academic groups and a range of companies;
- contribute to the body of knowledge on a particular technical discipline, industrial sector or multi-disciplinary theme.

After completion of the taught component, consisting of a number of postgraduate modules, the EngD is assessed on the basis of a thesis that comprises of a discourse of about 20,000 words supported by at least three (but not more than five) research publications. The research papers of an EngD are produced during the course of the project, and must be read in conjunction with the discourse to allow the reader to have a better understanding of the research.

This thesis is a result of research conducted from 2004 to 2008 as part of an EngD project, in collaboration between the Centre for Innovative and Collaborative Engineering (CICE) at Loughborough University and Jacobs Engineering UK Ltd.

USED ACRONYMS / ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society of Testing and Materials
c	Velocity of light in free space (= 299,792,458ms^{-1})
CBM	Cement bound material
CEPT	European Conference of Postal and Telecommunications Administrations
CICE	Centre for Innovative and Collaborative Engineering
CW	Continuous wave
DBM	Dense bitumen macadam
DMRB	Design Manual for Roads and Bridges
ε_r	Dielectric constant (or relative permittivity)
EM	Electro-magnetic
ETS	Equivalent time sampling
ETSI	European Telecommunications Standards Institute
EngD	Engineering Doctorate
EPSRC	Engineering and Physical Sciences Research Council
EuroGPR	The European GPR Association
FCC	Federal Communications Commission
FWD	Falling weight deflectometer
GPR	Ground penetrating radar
GSSI	Geophysical Survey Systems Inc.
HA	Highways Agency
HBM	Hydraulically bound mixture
HMA	Hot mix asphalt
HRA	Hot rolled asphalt

JPM	Jacobs Pavement Management
NDT	Non-destructive testing
ns	Nanoseconds (10^{-9} seconds)
NSWT	Near side wheel track
OSWT	Off side wheel track
PQC	Pavement quality concrete
PRF	Pulse repetition frequency
PVM	Pavement Management team (Jacobs Derby office)
Radar	Radio detection and ranging
Rx	Receiving antenna
Tx	Transmitting antenna
UWB	Ultra-wide band

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LIST OF PAPERS

The following papers, included in the appendices, have been produced in partial fulfilment of the award requirements of the Engineering Doctorate during the course of the research, and are referred to throughout this thesis.

PAPER 1 (SEE APPENDIX A)

Evans, R., Frost, M., Stonecliffe-Jones, M. & Dixon, N. (2008).

A review of pavement assessment using ground penetrating radar (GPR).

Proceedings of the 12th International Conference on Ground Penetrating Radar, June 16th-19th 2008, Birmingham, UK.

PAPER 2 (SEE APPENDIX B)

Evans, R., Frost, M., Stonecliffe-Jones, M. & Dixon, N. (2006).

Ground penetrating radar investigations for urban roads.

Proceedings of the Institution of Civil Engineers - Municipal Engineer. Volume: 159, Issue 2, pp 105-111.

PAPER 3 (SEE APPENDIX C)

Evans, R., Frost, M., Stonecliffe-Jones, M. & Dixon, N. (2007).

Assessment of in situ dielectric constant of pavement materials.

Transportation Research Record: Journal of the Transportation Research Board, No. 2037, pp. 128–135.

PAPER 4 (SEE APPENDIX D)

Evans, R., Frost, M., Dixon, N. & Stonecliffe-Jones, M. (2008).

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

Advances in Transportation Geotechnics: Proceedings of the 1st International Conference on Transportation Geotechnics (Ellis, E., Yu, H.S., McDowell, G., Dawson, A. & Thom, N, eds), pp 713-718. Taylor & Francis Group, London ISBN 9789-0-415-47590-7

PAPER 5 (SEE APPENDIX E)

Evans, R., Frost, M., Stonecliffe-Jones, M. & Dixon, N. (2007).

Variation in information obtained from interpretation of ground penetrating radar (GPR) pavement investigation data.

Proceedings of the International Conference on Advanced Characterization of Pavement and Soil Engineering Materials (Loizos, A., Scarpas, T. & Al-Qadi, I.L., eds), pp 983-991. Taylor & Francis Group, London, ISBN 978-0-415-44882-6

1 INTRODUCTION

1.1 OVERVIEW

This chapter provides an introduction to the overall theme of this EngD project. It outlines the different topics which combine to form the overall subject matter, giving background information on both pavement structures and ground penetrating radar (GPR). The overall aim and the individual objectives of the project are described, and the scope and justification for the work are summarised. Also provided in this chapter is a summary of the papers published as a result of the EngD project, which should be read in conjunction with this thesis.

1.2 BACKGROUND TO THE RESEARCH

1.2.1 PAVEMENT STRUCTURES

A ‘pavement’ can be defined as an engineered structure designed to carry vehicle loads (distinct from a ‘footway’ which is designed for pedestrians only) and the importance of well built and maintained pavement structures has been recognised for many years. Some of the earliest examples of purpose built pavement structures include stone-paved streets in the Middle East and wooden log surfaced roads in England, both dating from around 4000 B.C., and brick paving used in India around 3000 B.C. (Lay, 1992). Historically, the most famous use of sound pavement engineering was by the Roman Empire, which contained a network of approximately 78,000km of paved roads at its peak (O’Flaherty, 2002), and whose practice of constructing roads on raised embankments (to allow a better view of the surrounding area) gave rise to the term “highway”.

Whilst the purpose of modern pavement structures is to carry vehicles, there are a number of different pavement types depending on their specific use. Roads are the most common type of pavement but others include airport runways, taxiways, ports and industrial flooring, and all of these pavement types are vital for the infrastructure, development and economy of countries around the globe. Modern pavement structures consist of several elements and Watson (1994) defines the functions of a pavement as being to provide a safe, stable and durable structure for a period of time whilst under the action of both the weather and the loading imposed by vehicles.

Generally, pavements consist of several layers of materials placed over the natural ground ('subgrade'), as illustrated in Figure 1.1. Above the subgrade is the 'sub-base' which is usually a layer of un-bound compacted aggregate to protect the subgrade from the action of cold weather and to provide a platform for construction of the upper pavement layers. (Sometimes a 'capping' layer is also included below the sub-base, consisting of lower grade compacted unbound aggregate). The sub-base, capping (if present) and subgrade are together considered to be the foundation of the pavement structure.

Above the sub-base the main structural layer of the pavement, known as the 'base' (or 'roadbase'), is constructed. This usually consists of a selected crushed rock material bound together with bitumen to form an asphalt layer, or cement to form a cement bound material (CBM) layer. The base layer is designed to withstand the loadings placed on the pavement by vehicles, and to distribute them so that the foundation materials do not become damaged. Above the base layer is the pavement surfacing, which is often provided in two bound material layers, known as the 'binder course' and the 'surface course'. The binder course is in effect an extension of the base layer and provides a regulating course, upon which the uppermost surface course layer is placed to provide a comfortable and safe surface for vehicles. When bitumen bound material (asphalt) only is used in the pavement, each layer consists of a slightly different mix of aggregate and bitumen best suited to perform the function required, but when the pavement is constructed from CBM only, the function of all the bound layers (surface course, binder course and base) is provided by a single concrete slab (which sometimes may contain steel reinforcement). The material used for high strength pavement slabs is often referred to as pavement quality concrete (PQC).

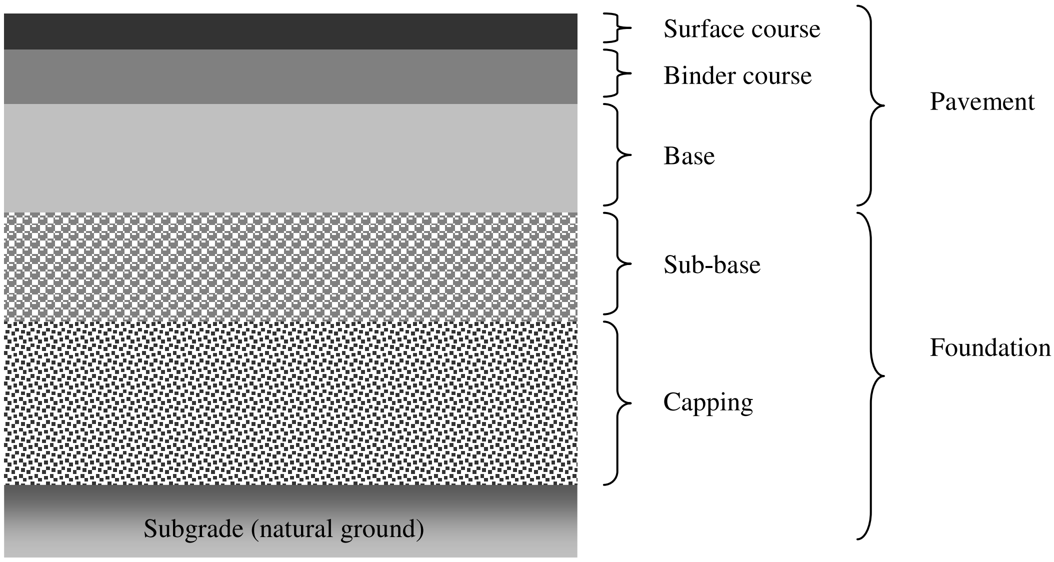


Figure 1.1 Typical layers in a pavement structure

Pavements which consist only of asphalt material are known as 'flexible' pavements, and those with CBM only are termed 'rigid' pavements. Also, some pavements are designed with a CBM base layer and asphalt surfacing, and these are termed 'composite' pavements. Although CBM is still a widely recognised description, recently the term 'hydraulically bound mixture' (HBM) has entered use, which is used as a generic term for pavement material consisting of aggregate bound with any binder which requires the presence of water (which includes cement, but also lime, slag, fly ash and others). Thus, as CBM is a type of HBM, the use of the term HBM to refer to cement bound materials is becoming more widespread (Highways Agency, 2008). The first two chapters of Thom (2008) provide an up to date overview of the different materials used for pavements, and the different properties and requirements of asphalt, HBM and un-bound (foundation) materials are discussed.

1.2.2 GROUND PENETRATING RADAR (GPR)

The use of radar (RAdio Detection And Ranging) for determining the distance of objects was initially developed in the first half of the 20th century, with arguably its most well known early use being the range finding of aircraft during World War 2. However, attempts had been made in the 1920's and 30's to use rudimentary radar technology to measure depths and thicknesses of ice sheets and glaciers. As electronics and technology developed, the use of radar technology for determining properties of other ground materials took place, but it was not until the 1960's that the technique began to gain use for relatively short distances in the ground and the first applications of what, by then, had become known as 'ground penetrating radar' on road structures took place in the 1970's and 80's.

The initial application of GPR to pavement structures focussed on determination of depths within the pavement, such as material layer thicknesses. However, as work developed, the use of GPR data to obtain information on other pavement properties began to develop. By further investigating the response of pavement materials to the passage of radar signals within pavement structures, other information regarding material properties such as the location of discrete features, and presence of water and air (voids) could also be determined and communicated to the pavement engineer.

Several GPR system types exist, each based on the same physical principles of electromagnetic (EM) wave propagation, but which employ different hardware, software 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, amplitude and phase of reflections of the pulse to return to the antenna. Impulse GPR surveys on pavements are usually conducted by collecting data along survey lines, which consist of a number of individual radar pulses recorded at a constant spacing along the length of the survey line.

1.2.3 PAVEMENT INVESTIGATION METHODS

The condition of a pavement will deteriorate over time, as a result of several factors. The main cause of deterioration is the effect of vehicle loadings, but other factors such as the action of weather and water can contribute to pavement deterioration, and poor design or construction can exacerbate the effects. Thus, it is important to be able to assess the condition of existing pavements, so that appropriate maintenance treatments can be planned. A number of techniques can be used to assess pavement condition, through the use of both 'routine' investigation methods, which are used to identify areas of pavement which are of concern, and 'detailed' investigations which provide information about the structural condition of the pavement which is then used to plan maintenance treatments.

A variety of different pavement properties can be investigated to assess pavement condition, and both non-intrusive (i.e. non-destructive testing, NDT) methods and intrusive (i.e. destructive) methods are commonly used. To obtain information on the pavements structural condition one of the most useful methods is the falling weight deflectometer (FWD), a device which measures the vertical deflection of the pavement under a simulated vehicle loading, and from which data can be used to determine the stiffness of the pavement layers. Intrusive methods can include obtaining core samples to confirm layer thicknesses and to retrieve material for further laboratory analysis. Whilst intrusive methods can provide extremely useful data on the pavement properties and condition, they have the disadvantage that it is time consuming to excavate material from a pavement, and that further time and costs are incurred to repair the pavement after testing. The use of non-intrusive methods, wherever possible, allows pavement properties to be assessed without damage to the structure and often provides a less time consuming approach than intrusive investigation. Comprehensive pavement investigations will employ the appropriate mix of relevant techniques to obtain the optimum amount of information.

The recent development of GPR for use in pavement investigation has provided a new non-intrusive technique from which data can be used to both directly determine pavement properties, and to confirm the findings and enhance the accuracy of other techniques.

1.2.4 MODERN USE OF GPR FOR PAVEMENT INVESTIGATION

1.2.4.1 Standards for use

For the initial applications of GPR on pavements, methodologies were often ad hoc and the main guidance for use of the equipment was that provided by the GPR manufacturer or based on the experience of the GPR operative in using the technique for other ground investigations. Since then there have been developments in both the production of guidelines for use and in the development of a regulatory framework for GPR.

In countries where GPR has gained most acceptance there are standard documents available providing generic guidance, and which are updated periodically to reflect on-going developments. These include Volume 7 of the UK Design Manual for Roads and Bridges (Highways Agency, 2008) and those produced by the American Association of State Highway and Transportation Officials (AASHTO, 2004) and the Finnish Roads Administration (Tiehallinto, 2004). Some published documents also provide standard test methods for specific applications of GPR on pavements such as that by the American Society of Testing and Materials (ASTM, 2006). However, the nature of GPR investigations means that such documents, whilst providing useful guidance, can not be used alone to plan and conduct GPR surveys and interpret the data. Unlike some ground and pavement investigation techniques, which can apply a standard investigation methodology to all sites investigated, GPR has a number of variables in hardware, software, data collection methods, data handling procedures and information presentation methods which can be adjusted and tailored to the specifics of the investigation at hand. Daniels (2004) and Saarenketo & Scullion (2000) highlight that it is a necessary aspect of GPR investigations that the GPR operative is sufficiently knowledgeable in the science and application of the technique, and also in the engineering aspects of the pavement under investigation, to be able to optimise the technique to the specifics of the investigation undertaken.

1.2.4.2 Regulatory framework

During the past 10 years, the development of a regulatory framework has taken place regarding the use and manufacture of GPR. This has not been a straightforward process, and Chignell & Lightfoot (2008) summarise some of the processes that have led to the current regulatory regime in Europe. Initially the use of GPR was unregulated but various factors have contributed to the development of the legislation which exists today, including the treatment by radio authorities of GPR as a radio transmitter, the increase in the use of ultra-wideband (UWB) electro-magnetic (EM) signals (of which GPR is a type) and the perception that GPR signals may interfere with other radio frequency signals. There has, however, been very little evidence to suggest that GPR may cause interference (Daniels, 2004, Chignell, 2004), and in the UK the lobbying and work of the European GPR Association, EuroGPR (www.eurogpr.org), on behalf of the GPR industry has influenced the current situation. Framework documents have been produced by the European Telecommunications Standards Institute (ETSI) against which GPR systems used in Europe should be manufactured and by the European Conference of Postal and Telecommunications Administrations (CEPT) whose procedures should be adhered to when operating a GPR system. Also, in the UK the Office of

Communications, the regulatory body for telecommunications including radio, issues licences (Ofcom, 2008) required for the legal operation of what are described as “wireless telegraphy” (i.e. a radio transmitter, which under the existing legislation GPR is classed as being) and a code of practice, developed by the European GPR Association (EuroGPR, 2008), has been adopted.

In North America, where the Federal Communications Commission (FCC) is the dominant licensing body, similar developments have taken place, but some of the regulations are more restrictive than in Europe. During the development of product standards for GPR in Europe, several national regulators indicated that GPR should be a licensed radio service, in order to permit the power limits widely used in Europe (which are higher than those allowed in the USA). This is one of the major differences between the current FCC regulations in the USA and those in use in Europe. For FCC regulations, every GPR system must be registered by the manufacturer, and then the user of the system must also separately register the system with the FCC. In both Europe and the Americas, the regulatory situation has been developing over the last decade and continues to do so, and so it is important that the GPR users and manufacturers keep up to date with developments to ensure that equipment and use is compliant with legislation.

1.3 THE INDUSTRIAL SPONSOR

Jacobs Engineering Group Inc is one of the world’s largest providers of technical, professional and construction services worldwide, currently with over 56,000 employees and over $10 billion in revenues. In August 2004, Jacobs acquired Babtie Group Ltd, a UK based engineering consultancy with over 50 offices worldwide and over 3500 staff. Babtie had been formed in 1895 and, since its conception, one the key areas of expertise was that of pavement engineering and management. The newly formed Jacobs-Babtie continued to operate in pavement engineering, and it was incorporated into the newly branded Jacobs Engineering UK Ltd in 2008.

Within Jacobs Engineering UK Ltd., the specialist area of pavement investigation and assessment is undertaken by Jacobs Pavement Management (JPM), and the EngD work reported in this thesis was conducted in collaboration with the Derby office of JPM. Prior to the commencement of the EngD in October 2004 the Derby office was responsible for pavement structural investigation and assessment, and was thus well placed to offer mutual benefits for the EngD project.

1.4 AIMS AND OBJECTIVES

The overall aim of this EngD research project was to provide improved pavement investigation capabilities by enhancing the methodologies and procedures used to obtain information from GPR.

The individual objectives required to achieve this aim included:

1. Devise improved procedures for conducting GPR investigations used to provide information for structural pavement assessment;
2. Develop methods for enhancing the amount of information that can be obtained from GPR pavement investigation data;
3. Establish the significance of material properties determined from GPR, and how they relate to the condition of the pavement;
4. Determine the factors which affect the accuracy of GPR pavement investigations and produce methods for managing them.

In addition to these four objectives, a further objective was to review previous GPR work conducted in pavement assessment and in associated topics. This review of other work was necessary to provide the background and context to the work conducted during the EngD project, and also to establish the current state of knowledge. This meant that it was necessary to conduct the review as an on-going process throughout the entire EngD project, in order to support, and emphasise the relevance of, the work conducted for the four EngD project objectives listed above.

The research methodologies used to address the four objectives listed above involved undertaking separate tasks investigating the way that GPR data is collected, assessing the amount and type of information that can be determined from GPR data and evaluating the accuracy and variability of information determined from GPR. Details of the research tasks and methodologies are given in Chapter 3.

In order to address the aim of this EngD project, there were also several themes that affected all of the objectives listed above, and which in particular affect the ability to relate the research undertaken to the application of GPR in a commercial industry-based context. These included ensuring that the results of the research undertaken could be applied in a practical way to GPR pavement investigations and that information from GPR could be efficiently integrated with that from other investigation techniques. Also important was the ability in GPR investigations to effectively communicate information to relevant parties, especially the end-users of information obtained.

1.5 JUSTIFICATION AND SCOPE

This project is concerned with investigating an existing, although developing, technology (GPR) and providing methodologies to both enhance the information that can be obtained from data, and to optimise the way that the technique is used, in a well established engineering field. Despite the relatively complex physics that forms the technical basis of the technique, the use of GPR equipment can be fairly straightforward. However, it is very important that the technique is not seen as a ‘black-box technology’, where information is obtained with little appreciation of the processes involved. An understanding of what is being measured, the processes employed to measure it, and what engineering properties the data can be related to are essential if the optimum benefit is to be obtained from the technique.

Despite the existence of standard guidance documents, and a history of use for pavement investigation in Europe and North America of well over 20 years, the current situation is one of a variable level of acceptance of the technique across the globe, and GPR remains a technique which is used routinely for road (pavement) projects in only a minority of countries in Europe (Saarenketo, 2006). Despite the use of GPR being common in some counties, others have very little or no experience of the technique, and even in areas where guidelines exist, the specialist nature of the technique and the sometimes variable results that are obtained can mean that there is both a lack of appreciation and a lack of awareness of the potential information that GPR can provide.

GPR is a technique which does not lend itself well to a ‘standard’ method of application for a number of reasons. These include the number of different objectives which can be intended for a GPR investigation, the number of options for data collection, processing and analysis methodologies, and the existence of several different GPR manufacturers who produce systems with slightly different hardware and software options. Use of the technique without careful and measured consideration of the specifics of the individual project job will result in the technique not being applied in the optimum way.

This EngD project has been undertaken as the use of GPR is becoming more formalised and regulated, with much recent development in Europe and the Americas of legislation under which GPR falls. The regulatory framework, in addition to standard guidance documents where appropriate, should be used in conjunction with knowledge about what GPR can provide, obtained from research and experience conducted over the past few decades. The theme and activities of this EngD project involve the review and investigation into methods concerning how GPR data can be best obtained, used and provided.

1.6 STRUCTURE OF THESIS

This thesis comprises five main chapters.

Chapter 1 gives an overview of the topics that form the background to the research, and sets out the context and aim of the project.

Chapter 2 provides a background to the principles and technology of GPR and a summary of the established uses of GPR in pavement investigation. An explanation of the physics of GPR, including a discussion of the significance of the dielectric properties of materials, and an overview of modern GPR systems is provided. This chapter also outlines the relevance of the EngD research to other applications. EngD Paper 1 (Appendix A), providing a literature review of GPR for pavement applications, should be read in conjunction with Chapter 2.

Chapter 3 explains the research methodologies adopted to address the objectives of the EngD, and maps out the research activities.

Chapter 4 describes the details of the work conducted to determine methods for optimising the use of GPR, including the assessment and review of pavement investigation data collection methodologies, and the experimental research undertaken to investigate pavement material properties using GPR.

Chapter 5 details the key findings of the project and the implications on the sponsor and wider industry, as well as presenting a critical review of the work and recommendation for future research related to the theme of this EngD.

Appendices A to E contain the full contents of the five papers referred to throughout this thesis, which were published as a result of the work undertaken. These papers should be read in conjunction with the thesis so that the link can be established between the detailed research work of the EngD, and the overall EngD theme. Table 1.1 summarises the content of the published papers. In addition, **Appendix F** gives the full technical specification of the GPR systems used for data collection during the EngD work.

Table 1.1 Summary of published papers included in EngD thesis

Reference	Title	Publication	Status	Synopsis
Paper 1 Appendix A	A review of pavement assessment using ground penetrating radar (GPR)	12^{th} International Conference on Ground Penetrating Radar (Birmingham, UK)	Published (peer reviewed) conference proceedings	Review of the development and use of GPR for pavement investigation
Paper 2 Appendix B	Ground penetrating radar investigations for urban roads	Proceedings of the ICE: Municipal Engineer	Published (peer reviewed) journal	Guidance on methodology for use of GPR on urban road pavements
Paper 3 Appendix C	Assessment of in situ dielectric constant of pavement materials	Transportation Research Record: Journal of the Transportation Research Board	Published (peer reviewed) journal	Investigation into the effect of asphalt condition on dielectric constant, with methodology for determining potential for in-situ variation
Paper 4 Appendix D	The response of ground penetrating radar (GPR) to changes in temperature and moisture condition of pavement materials	1^{st} International Conference on Transportation Geotechnics (Nottingham, UK)	Published (peer reviewed) conference proceedings	Laboratory study of the effect on temperature and moisture on the dielectric properties of asphalt pavement core samples
Paper 5 Appendix E	Variation in information obtained from interpretation of ground penetrating radar (GPR) pavement investigation data	International Conference on Advanced Characterization of Pavement and Soil Engineering Materials (Athens, Greece)	Published (peer reviewed) conference proceedings	Discussion of the main sources of error and uncertainty in GPR data, and recommendations for managing and minimising them.

2 CURRENT PRACTICE AND RELATED WORK

2.1 OVERVIEW

This chapter provides a background to the technology and principles of GPR, including an explanation of the physics of electromagnetic (EM) wave propagation that governs the ability of GPR to provide data, and an overview of modern GPR systems. A summary of the established uses of GPR for pavement investigations is given and the relevance of the EngD research to other GPR applications is outlined. Throughout the EngD project, a review of existing literature and other research was undertaken, and EngD Paper 1 (Appendix A) should be read in conjunction with this chapter.

2.2 THE PHYSICS AND TECHNOLOGY OF GROUND PENETRATING RADAR

2.2.1 ELECTROMAGNETIC (EM) WAVES

2.2.1.1 General

The passage of radar signals through materials is governed by the physical laws concerning EM waves. EM waves are alternating electrical and magnetic fields that propagate out from an oscillating electrical charge, and there are many different types of EM wave that comprise the entire EM spectrum. The different types of EM wave are characterised by their frequency, which is measured by the number of cycles per second (hertz, Hz) of the electrical and magnetic fields. The frequency of the wave, together with the speed at which it travels through a material, determines its wavelength. The EM 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. Although the acronym ‘radar’ originally referred to radio frequency waves, modern GPR systems operate at the lower end of the microwave frequency range, with wavelengths of the order of a few cm.

A dielectric substance refers to one that does not conduct electricity well, but that does support electric fields, and the response of a material to an EM wave is a function of the materials dielectric properties, namely its electrical permittivity (ε), magnetic permeability (μ) and electrical conductivity (σ).

2.2.1.2 Electrical permittivity

The permittivity of a substance refers to its ability to store (i.e. ‘permit’) an electric field (i.e. EM energy) that has been applied to it, and can be described by a complex function having both real and imaginary parts:

$$\varepsilon = \varepsilon_r - i\varepsilon_r' \qquad (2.1)$$

where ε is the complex dielectric permittivity, ε_r is the real part of the complex permittivity, ε_r' is the imaginary part of the complex permittivity and $i = \sqrt{-1}$.

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 the ratio of the permittivity of the material to the permittivity of free space (a vacuum) and can be expressed as shown in Equation 2.2, below. It is known as the ‘relative permittivity’ or ‘dielectric constant’ of the material:

$$\varepsilon_r = \frac{\varepsilon_s}{\varepsilon_o} \qquad (2.2)$$

where ε_r is the dielectric constant, ε_s is the permittivity of the substance under investigation and ε_o is the permittivity of a vacuum.

The value of the dielectric constant is important because it relates to several parameters that are essential for the interpretation of GPR data. The velocity of the GPR signal through the material is related to the dielectric constant by the relationship shown in Equation 2.3, below:

$$v = \frac{c}{\sqrt{\mu_r \varepsilon_r}} \tag{2.3}$$

where v is the velocity of the GPR signal through the material, c is the velocity of light in free space (≈ 300,000kms^{-1}) and μ_r is the relative magnetic permittivity (= 1 for non-magnetic materials, discussed below). When determining depths from GPR data, the velocity of the signal through the material is required so that the two-way travel times (for the GPR signal 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:

$$d = v \times \frac{t}{2} \tag{2.4}$$

where d is the depth of the feature, and t is the two-way travel time of reflected signal recorded by the GPR system.

Reflections of GPR frequency EM waves occur when the wave meets a boundary between two materials with different dielectric constants. Some of the radar energy passing from one material into the other is reflected back from the material boundary to the antenna. For two adjacent materials with similar dielectric constants there may be little reflection of the EM wave occurring, and in such circumstances identification of material boundaries may be difficult. 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:

$$R = \frac{\left(\sqrt{\varepsilon_1}\right) - \left(\sqrt{\varepsilon_2}\right)}{\left(\sqrt{\varepsilon_1}\right) + \left(\sqrt{\varepsilon_2}\right)} \tag{2.5}$$

where R is the reflection coefficient and ε_1 and ε_2 are the dielectric constants of the adjacent materials.

Water has a very high dielectric constant (≈ 81) and air has a relatively low value (≈ 1), whilst most pavement materials have dielectric constants within the range 2 to 20, and most geological materials have values within the range 2 to 30 (Daniels, 2004). One of the fundamental principles of GPR, that of the ability to distinguish the boundary between different materials, relies on their being a contrast in the dielectric constant values of the materials.

The magnetic permeability (μ), as well as the electrical permittivity, affects the way EM energy is stored and released during the passage of an EM wave. It can be an important factor during GPR investigations, depending on the way the EM wave acts on the magnetic dipole moment of magnetic minerals and atoms in the material under investigation, and the magnetic permeability can influence both the velocity and attenuation of the EM wave. However, for non-magnetic materials the value of the relative (to a vacuum) magnetic permeability (μ_r) is 1. It is possible that badly deteriorated steelwork or materials containing high levels of magnetic minerals may affect the velocity and attenuation of GPR signals, but in practice the vast majority of pavement materials will have values of $\mu_r = 1$, resulting in no influence on the signal velocity and attenuation.

2.2.1.3 Electrical conductivity

The electrical conductivity (σ) of a material describes the flow of electrical charges during the passage of an EM wave, and can greatly affect the energy loss or attenuation of the EM signal. Conductivity, as well as signal frequency, is one of the main influences on signal attenuation, which in turn governs signal penetration depth, and a high conductivity will attenuate GPR signals rapidly. Factors that increase conductivity include a high amount of salts present in water in the material, and the presence of clay minerals because of the molecular ionic structure particular to clays that have high levels of exchangeable cations. Hence, the presence of water and clay minerals can reduce the effective penetration depth of a GPR survey.

Olhoeft (1998), Daniels (2004) and Cassidy (2008) provide further in depth discussions and details on the influence of the electrical and magnetic properties of materials on the propagation of EM waves and performance of GPR.

2.2.2 IMPULSE GPR

Although all GPR systems operate by the EM wave principles described above, there are different types of GPR system that exploit slightly different aspects of EM wave propagation and use different hardware and data processing procedures. 'Impulse' GPR systems are the most commercially available, and are by far the most commonly used. This type of GPR system was used for all investigations during this EngD project. Another type of GPR system is continuous wave (CW) GPR, and step-frequency (SF) GPR, an advanced form of CW-GPR, has been recently developed for pavement investigation although it is not currently widely used. The advantages and limitations of this type of GPR are outlined in Appendix A (EngD Paper 1).

The main components of an impulse GPR system (shown in Figure 2.1) consist of an antenna unit (with transmitter and receiver), control unit, data console/display and power unit. Impulse GPR systems operate by transmitting a very short EM burst or 'pulse' from a transmitter and recording the reflections of the pulse, arising from features or layers within the pavement, as they are returned to a receiver.

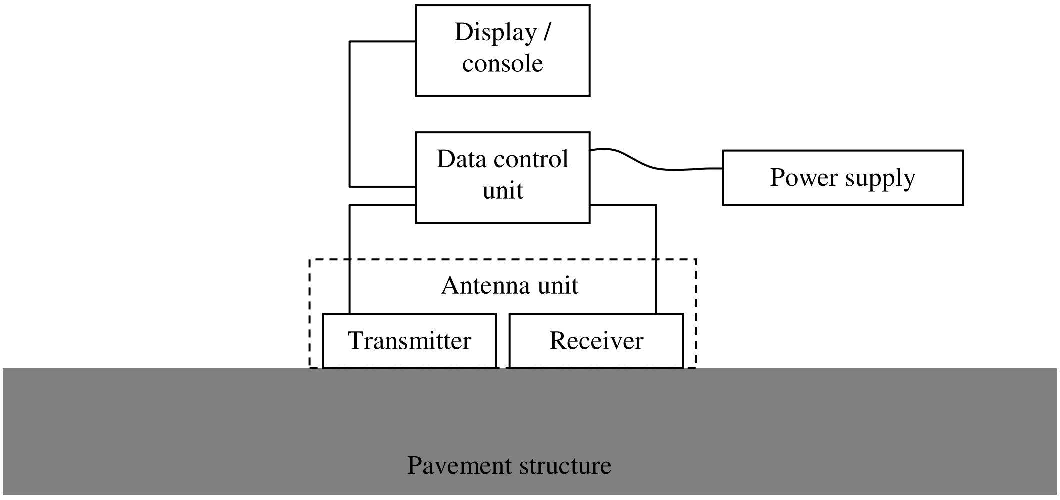


Figure 2.1 Main components of a typical impulse GPR system

Figure 2.2 shows a simplified representation of the passage of an EM pulse, from GPR, through a pavement structure. As the transmitted pulse travels down through the pavement structure, a portion of the pulse's EM energy is reflected whenever the pulse meets a boundary between contrasting material dielectric properties. Such contrasts are commonly caused by a change in layer materials or by the presence of a discrete feature such as a void or steelwork. The travel time, amplitude (i.e. strength) and phase of the pulse reflections are recorded, and this data can be used to determine pavement properties.

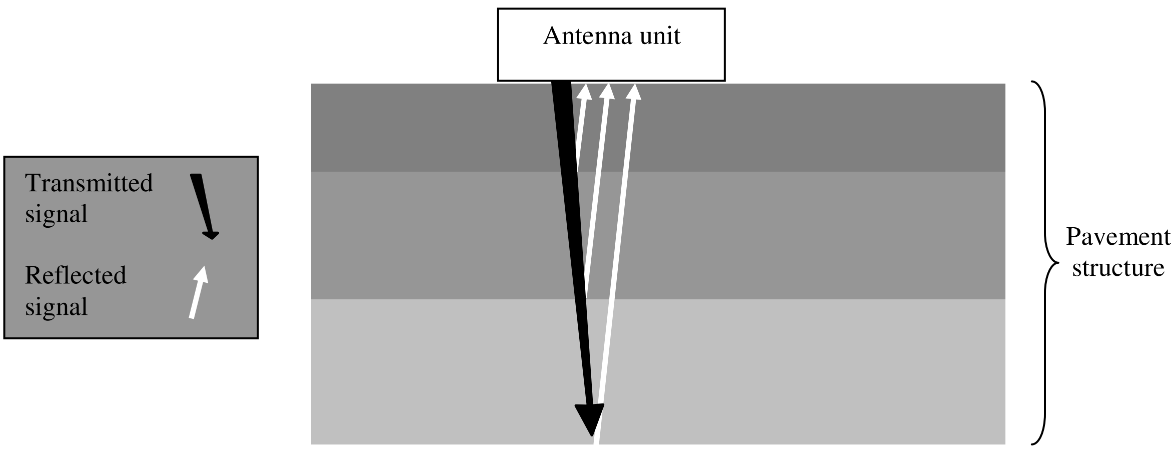


Figure 2.2 Simplified representation of the passage of a GPR pulse within a pavement

For most pavement investigations the antenna unit is moved along the length of the pavement as a series of pulses are transmitted, with a survey wheel linked to the data control unit, and the rate at which data is collected (the 'scan rate') is controlled so that GPR scans are collected at equally spaced intervals (e.g. a scan every 0.05m) along the length of the survey run. Depending on the GPR system specifications and antenna configuration, there will be a limit on the maximum scan rate possible and this will govern the maximum speed at which the antenna can be moved along the survey line. For example, if the system specifications allowed a maximum scan rate of 78 scans per second and GPR scans are planned for every 0.05m along the survey line, then the maximum speed possible would be 0.05m x $78s^{-1}$ = $3.9ms^{-1}$ or approximately $14kmh^{-1}$.

There are a number of manufacturers of commercial impulse GPR systems, including Geophysical Survey Systems Inc (GSSI), Sensors & Software, MALA Geoscience, ERA Technology, Utsi Electronics and others. Each of the GPR systems produced by the various manufacturers has slightly different system features, hardware and software, but all systems follow the principles outlined above. The appearance of the individual features of GPR systems varies between manufacturer and model, but each consists of the main components shown in Figure 2.1. An example of a GPR data control unit and console/display (from a GSSI 'SIR-20' GPR system) is shown in Figure 2.3, and antennas are discussed in Section 2.2.3.

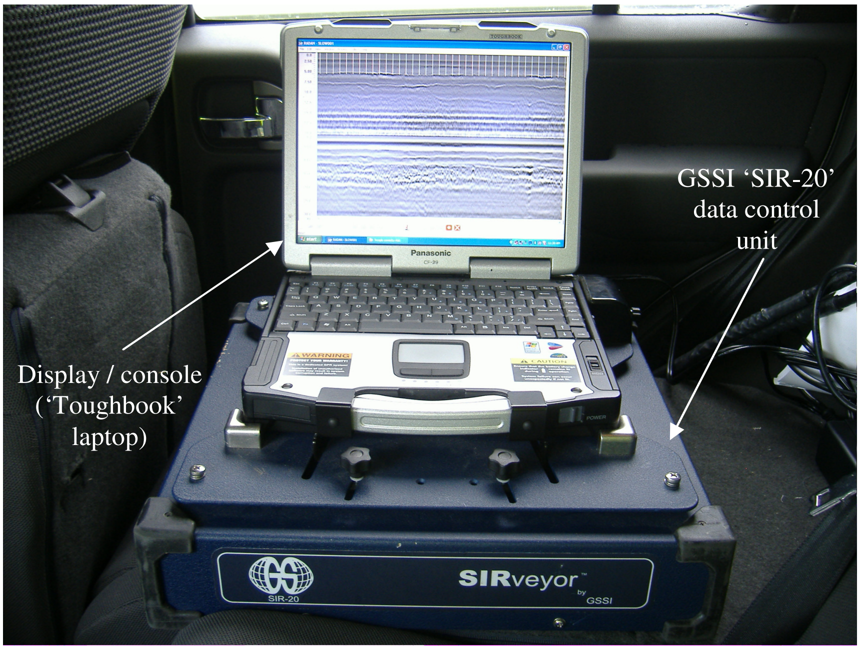


Figure 2.3 GPR data control unit and display / console (for 'SIR-20' GPR system)

2.2.3 ANTENNAS

2.2.3.1 Types

EM antennas are the devices which allow GPR to transmit and receive EM waves by converting EM waves into current and vice versa, and the amplitude (strength) of a GPR signal can be measured by recording the voltage associated with the current. It is possible to both transmit and receive signals from a single antenna, but the technical requirements of GPR would require an ultra-fast transmit-receive switch that has several technical difficulties associated with it, and so for modern GPR systems separate transmitting (Tx) and receiving (Rx) antennas are used. Often the Tx and Rx antennas are housed within the same unit and the entire unit is considered to be a 'mono-static' antenna. (NB. The true definition of a mono-static antenna, however, is one which uses the same antenna to both transmit and receive signals, whereas units that have a separate transmitting antenna and receiving antenna are correctly termed bi-static).

Several types of antenna exist for GPR, and the most commonly used for impulse systems are ‘dipole’ or ‘bow-tie’, requiring contact with the pavement surface (known as ground coupling) to be most effective and ‘horn’, which are able to operate whilst suspended a short distance above the pavement surface (air coupled). Examples of ground coupled and air coupled antennas are shown in Figures 2.4 and 2.5 respectively, and further information on GPR antenna concepts and design can be found in Daniels (2004) and de Jongh et al. (1998).

Figure 2.4 GSSI ground coupled 900 MHz bow-tie antenna

Ground coupled antennas provide greater depth penetration (for a given signal frequency) and are physically smaller in size, but air coupled horn antennas allow higher scan and data acquisition rates and thus facilitate higher speed surveys. For a given signal frequency, air coupled horn antennas may prove the most appropriate when the upper layers of a pavement are of most interest, and ground coupled antennas may be more suitable where thicker pavements are encountered (e.g. airports) or where information about the pavement foundation is also required.

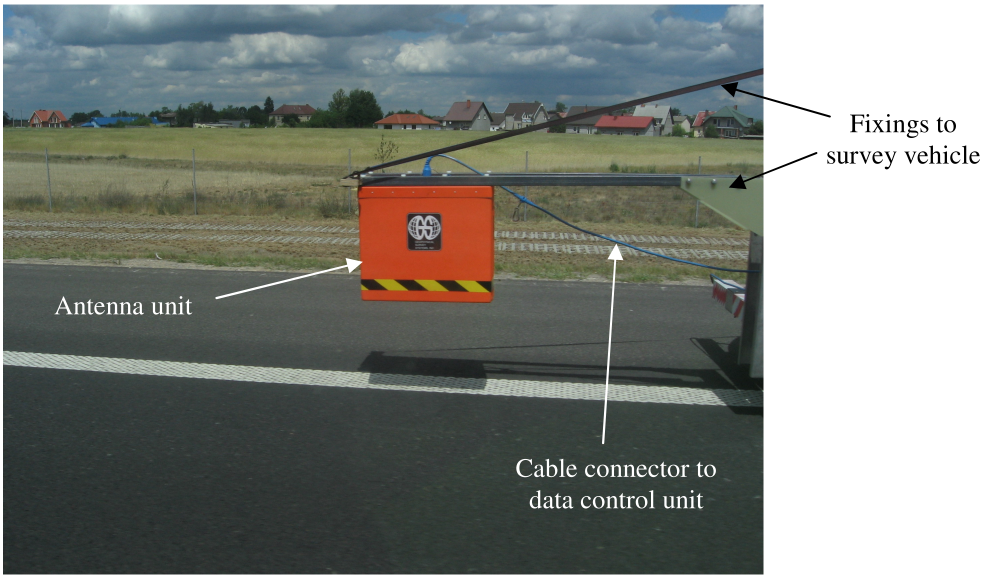


Figure 2.5 GSSI air coupled 1000 MHz horn antenna, during data collection

2.2.3.2 Signal frequencies

The EM signal transmitted by a GPR antenna covers a large range, or bandwidth, of frequencies (GPR antennas are defined as 'ultra-wide band' (UWB) transmitters), allowing more information to be obtained than for narrow bandwidth signals, and GPR antennas are defined by the centre frequency of that range. For pavement and shallow engineering investigations, centre frequencies of about 400 MHz to 2 GHz (2000 MHz) are typically used. High frequency GPR signals are subject to greater attenuation, and so pulses from lower frequency antennas will be able to penetrate deeper into the pavement structure than higher frequency signals. However, for higher frequency signals the vertical resolution (i.e. the ability to distinguish individual reflections from 2 vertically separated features) and the precision to which depths can be determined is greater. Thus, when conducting GPR investigations, the choice of antenna frequency is a trade off between depth penetration and data resolution / precision.

When considering the penetration depth achievable by GPR it should also be noted, as discussed in section 2.2.1.4, that highly conductive materials will also increase attenuation and hence limit the penetration depth.

2.2.3.3 GPR pulses

Transmitted pulses from an antenna have a certain polarity and this would ideally consist of a positive peak followed by a negative peak, as shown in Figure 2.6. In reality, GPR antennas often transmit pulses that are positive-negative-positive (GSSI, 2006).

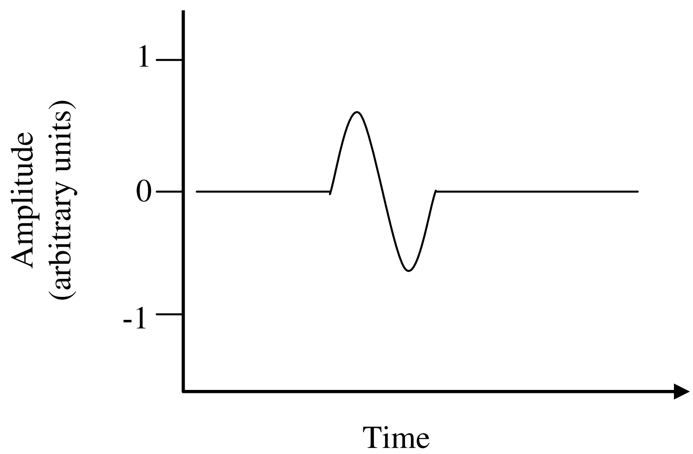


Figure 2.6 General idealised GPR transmit pulse

The transmitted pulse from a GPR antenna is typically the order of a nanosecond, ns (10^{-9} or one billionth of a second), in duration depending on the signal frequency. Under the ideal conditions shown in Figure 2.6, this ‘pulse duration’ could be measured from the moment the pulse amplitude changes from zero to the moment it returns back to zero at the end of the entire pulse. However, in real EM pulse measurements, precise location of the ‘zero’ reading before and after the pulse is difficult to pinpoint, and so usually the pulse duration is taken as being the time from when the pulse amplitude reaches 50% of its maximum value to when it returns to 50% of its minimum value. The pulse duration quoted by GSSI for their ground coupled 900 MHz and 400 MHz antennas are 1.1ns and 2.5ns respectively (GSSI, 2005). As well as providing a wide bandwidth (see 2.2.3.2), short pulses allow better resolution and also mean that the power required to generate each pulse is low.

For current GSSI ground coupled antennas that are commonly used for pavement investigation, the number of pulses transmitted per second (the pulse repetition frequency, PRF), is 100 kHz. A high PRF means that, for a survey where the antenna is moving along the pavement, the antenna only moves a very short distance between pulses. This is important because of the way that reflections of the pulses received at the Rx antenna are recorded. The technique used to digitally record data is known as equivalent time sampling (ETS), which avoids recording the entire received signal from every single pulse transmitted (which would require extremely fast analogue to digital converters and require huge amounts of memory space). Each transmitted pulse creates a received signal at the Rx antenna. The ETS technique takes a number of consecutive received signals (each created by consecutive transmitted pulses), and uses a single data point (a ‘sample’) taken from each of the received signals to build a composite digital representation of the received signal. This recorded received signal is known as a ‘scan’, and the PRF and the number of samples used to create each scan will govern the maximum number of scans per second that can be recorded. This in turn will govern the minimum scan spacing possible when the antenna is moved along the pavement during a mobile GPR investigation. Various values can be selected on modern GPR systems, but commonly 512 samples per scan are used.

2.2.4 VERTICAL AND HORIZONTAL RESOLUTION

For situations where there are two vertically separated features, the reflected signal from one interface can become obscured and combined with the reflected signal from the second interface. The vertical resolution (i.e. the minimum distance between 2 vertically separated features) that GPR can achieve is largely influenced by the signal wavelength (which in turn is affected by the materials dielectric properties), with higher frequency signals having better resolution. The vertical resolution achievable by GPR is generally taken to be between one half to one quarter of the signal wavelength (Daniels, 2004, GSSI, 2006, and Martinez & Byrnes, 2001).

The horizontal resolution is the minimum distance that GPR can identify two features (at the same depth) that are separated horizontally. When two features are spaced closer than the horizontal resolution, they appear on GPR data as one single feature. The horizontal resolution of GPR depends on several factors including the number of traces (and number of scans) per metre, and the geometry of the EM radiation pattern (which results in the size of the 'Fresnel zone' or antenna 'footprint' at a given depth). The number of scans per metre can be adjusted and controlled by the GPR operator, but the area covered by the antenna footprint depends on the antenna and material properties and so the horizontal resolution achieved by a system can be site specific. Rial et al. (2007) list several commonly used equations that can be used to approximate the area of the footprint, and experimentally test the accuracy of each approximation. Smaller signal wavelength (i.e. higher signal frequency), shallower depth of features, higher material dielectric constant and increased signal attenuation have all been shown to increase horizontal resolution.

2.2.5 DATA DISPLAY

The recorded scans can be displayed in several ways. A single scan displayed as a 'wiggle', showing the amplitude of the received signal against the time taken for the signal to arrive at the Rx antenna, is known as an A-scan and is shown in Figure 2.7. This display is similar to the way seismic data (which has a number of data recording and processing techniques similar to GPR) is commonly displayed.

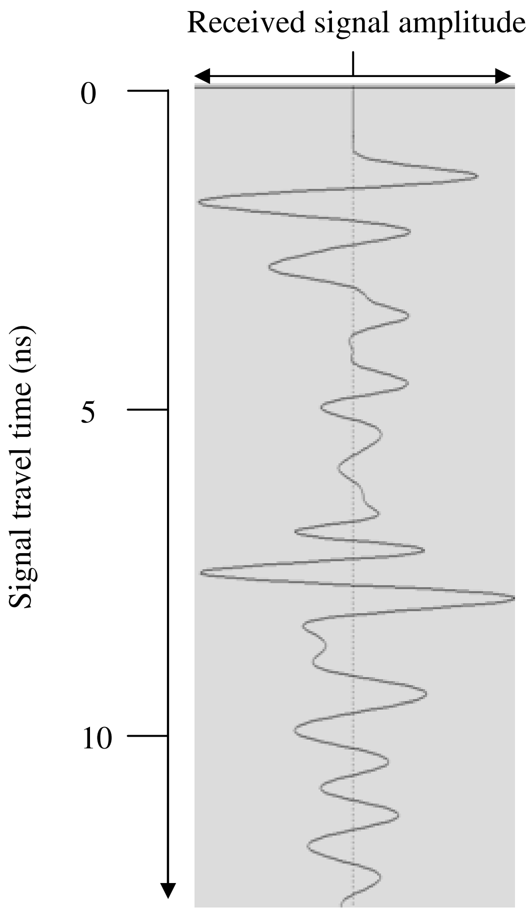


Figure 2.7 'A-scan' wiggle display of a single GPR scan

When analysing individual GPR scans, the A-scan wiggle display can be the most useful representation of data, but where several GPR scans have been obtained along a length of pavement (as for most pavement investigations) a colour- or grey-scale representation is used. For this type of display, the reflection amplitude recorded in an individual scan (wiggle) is represented by colours, and the data from each successive scan is presented so that the data has an appearance like a cross-section through the pavement. This display is known as a B-scan. It should be noted, however, that because the data is recorded as amplitude against signal travel time, and not depth, it is not a true cross-section (and hence is sometimes referred to as a 'pseudo-section').

If the GPR pulse velocity is known within the pavement material, depths can be determined from the recorded signal travel times. Figure 2.8 shows simplified representations of B-scans in both wiggle and grey-scale format of the same GPR data, where a scan has been recorded and displayed at regular distances along the pavement. B-scan displays are the most common way of displaying data from a single GPR survey line, and they are sometimes also known by several other names including profiles, sections, radargrams or linescans.

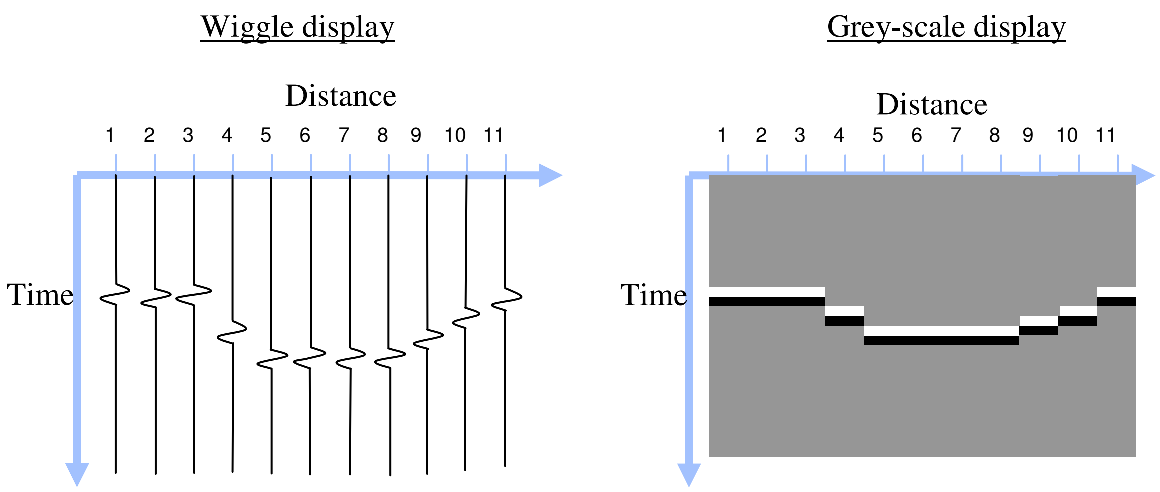


Figure 2.8 Illustrations of 'B-scan' wiggle and grey-scale displays of GPR data

The raw data recorded on site by a GPR system can be used to provide information, although processing is usually conducted to improve interpretation. A number of different processing steps can be conducted by modern GPR software packages, but typical procedures include static correction (to place the pavement surface accurately at the zero time position on the data record), background removal (which assists in removing noise from the data), and conversion of travel times to depths (which requires knowledge of the velocity of the GPR pulse through the pavement material, and is discussed in EngD Paper 1 in Appendix A). An example of GPR data collected at a scan spacing of 0.04m along a bridge deck and pavement are shown in grey-scale in Figure 2.9. The features and interfaces shown in the data are a result of the bridge deck and pavement properties.

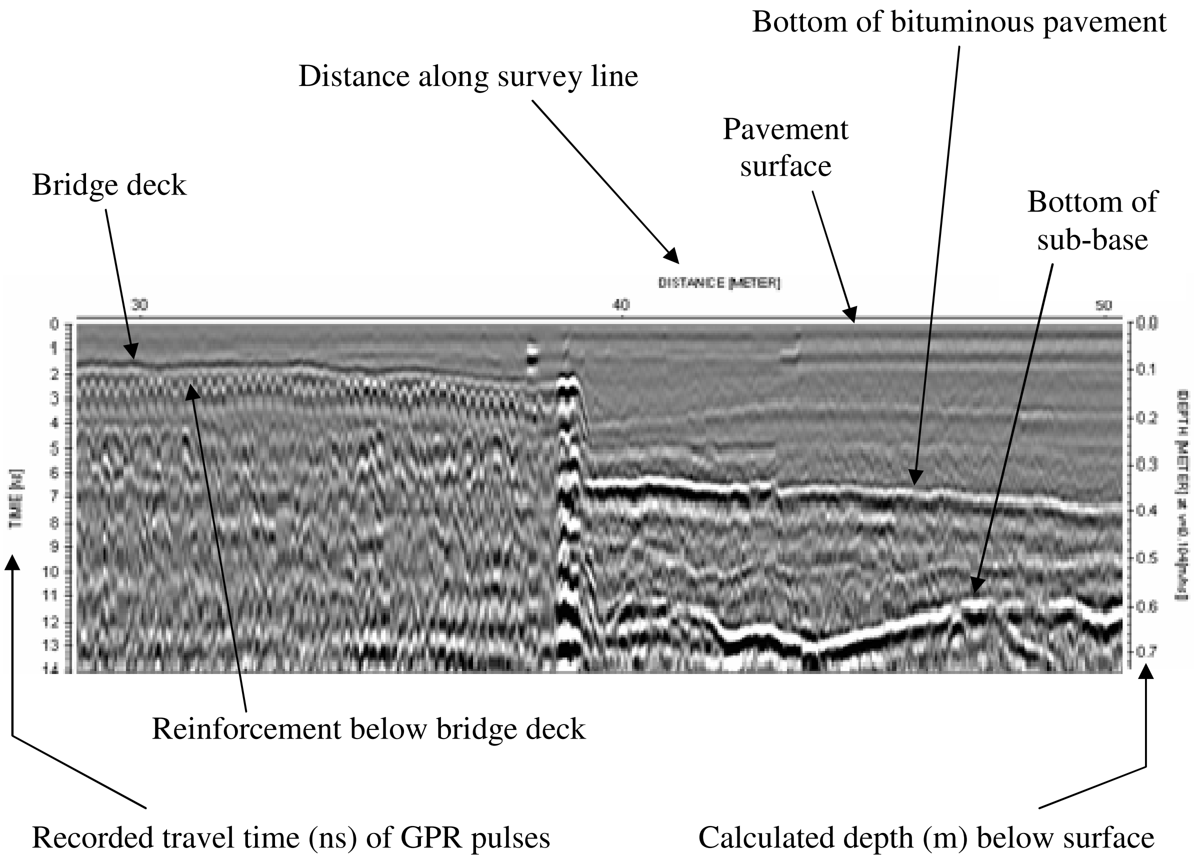


Figure 2.9 Display (B-scan) of processed GPR data from a pavement survey

Annan (2002) discusses the presentation of GPR data and reports that much of the GPR practitioner community uses GPR cross sections (B-scans) to present information but also points out that for some applications the display of information interpreted from the data, rather than direct display of GPR sections, can offer a clearer representation of information. Whilst some representations of information derived from GPR data can be relatively simple (for example, charts of pavement layer depths) other applications of GPR may require the use of more sophisticated representations (for example, presentations of dielectric constant values to infer material moisture condition) and some of the work conducted during this EngD project addressed aspects of the data presentation issue (see Chapter 5).

2.3 LITERATURE REVIEW

2.3.1 INTRODUCTION

A review of literature relating to the general subject area of geophysical and non-destructive testing of pavement structures was initially undertaken in the first year of the EngD project. The aim of this review was to establish the current state of practice in the UK (and overseas) for structurally assessing pavements using geophysical and non-destructive methods. It focused on two of the most useful methods for providing information used in structural assessment of pavements – deflection testing (especially the falling weight deflectometer, FWD) and GPR. This initial review was written up and submitted as part of the postgraduate module 'Research, Innovation and Communication' (at Loughborough University Civil and Building Engineering Department) completed as one of the taught component requirements in the first year of the EngD.

Subsequently, and throughout the research period of the EngD project, further review of literature was conducted to build on the initial review described above, including liaison with industry and the research community. This on-going work was focussed on both the objectives of the project and the specific use of GPR on pavement structures and materials and was updated and reviewed continuously throughout the EngD project.

The entire review process was used to produce EngD Paper 1 (Appendix A), which aimed 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, current practice and ongoing research. The paper was 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.

2.3.2 STRUCTURAL PAVEMENT INVESTIGATION TECHNIQUES

The development and use of appropriate methods for assessing the structural performance of pavements is governed by the issues of how best to quantify the deterioration of in-service pavement structures, and how this information can then be used to determine suitable maintenance treatments required for the pavement. Each pavement structure has specific maintenance requirements depending on its nature (materials, size, imposed loadings, design life) which in turn leads to the use of specific techniques and analysis procedures to address the maintenance requirements.

There are different types of pavement structure including roads, airports, ports and industrial floors slabs, but most structural pavement assessment methods are applicable to all pavement types. Current UK practice for road pavement maintenance has developed from a range of research, trials and practical experience and has resulted in Volume 7 of the DMRB, used for the design and maintenance of trunk road (including motorway) pavements. Section 3, Volume 7 of the DMRB provides guidance on the current required practice in the UK for structural pavement maintenance, including documents HD29/08 ('Data for Pavement Assessment') and HD30/08 ('Maintenance Assessment Procedure') both of which were updated in 2008. Other pavement types also have appropriate guidance documents, such as the 'Guide to airfield pavement design and evaluation' (Defence Estates, 2006).

Similar documents to the DMRB are also produced in other countries. However, often there are different statutory implementation procedures than those existing in the UK. The Highways Agency (HA) requires implementation of the DMRB guidelines for trunk roads in England and Wales (as does the Scottish Executive in Scotland). In the USA, however, whilst

AASHTO and ASTM publish several documents on pavement assessment techniques and procedures, similar to those in the DMRB, the specific implementation of methods and procedures is overseen at the state, rather than national, highway authority level.

A range of techniques can be used to determine information about the pavements condition, but those techniques which can obtain information without damaging the pavement (non-destructive testing, NDT) have a distinct advantage, and wherever possible tend to be favoured for pavement investigations. The main methods for structural assessment of pavement materials include the FWD, GPR, coring of the pavement material, excavation of test pits (also known as 'trial pits') and laboratory testing of core or trial pit samples. Of these options, FWD and GPR offer particular advantages to pavement maintenance engineers in that they are both NDT methods.

Obtaining measurements of the deflections of road pavements under loads, such as with the FWD, is currently one of the main criteria for assessing the long-term performance of pavements. TRL Report LR 833 (Kennedy and Lister, 1978) details the relationship between deflection and predicted future pavement performance, where measured deflections and known traffic loading of a pavement can be used to give a prediction of how long the pavement will take (the 'residual life') to reach the point at which strengthening will be required to prolong its useful life.

Various deflection testing devices exist, and the FWD is one of the more sophisticated methods used today, for detailed structural assessments. The FWD applies a load of typically 50-75kN, by dropping a mass onto a plate placed on the pavement surface. By measuring the deflection of the pavement beneath the load, and also at locations radially away from the load (up to approximately 2m), the shape and magnitude of the deflection 'bowl' along the pavement surface is measured, and information can then be obtained about individual layer stiffnesses of the pavement.

There have been other recent developments in deflection testing such as the Traffic Speed Deflectometer, TSD, (Rasmussen et al., 2008) which to date is undergoing final stages of development. Also, there has been development and use of light-weight deflectometers (LWD's), which provide a more portable though less sophisticated and lower load level deflection assessment, and recently such devices have become incorporated into the DMRB guidance and ASTM standards (ASTM, 2007).

In order to fully analyse FWD data, knowledge of the layer thicknesses is required and the use of GPR to determine continuous layer thickness profiles (as well as indicating other relevant features such including voids, excessive moisture and construction changes) allows greatly improved stiffness analysis from FWD data. The alternative for thickness information is the use of less effective methods such as core data (for which thickness values have to be interpolated between core locations) or construction records (which can often be inaccurate or incomplete).

2.3.3 USES OF GPR FOR PAVEMENT INVESTIGATION

EngD Paper 1 (Appendix A) details how 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 established technique in many countries. The early development of GPR for pavements took place particularly in North America and Scandinavia, including the first development of a vehicle mounted GPR system for road investigation, by the US Federal Highways Administration, in 1985. GPR has been used successfully for a number of purposes in pavement investigation, and also currently has the potential to be developed further to obtain other pavement information.

GPR pavement investigations can provide information on several different pavement properties and features. EngD Paper 1 (Appendix A) describes the proven ability of GPR to obtain a variety of information on parameters relating to the structure and materials of the pavement.

The methods used for specific GPR pavement applications can vary, depending on the nature of the information required, but a number of applications can be considered as 'established', where there is a history of successful use often with published guidelines or case studies indicating the reliability of the technique. Other applications of GPR do not have a long history of successful use, or may not have fully proven capability, and such application are often referred to as 'developing' or 'research' applications. The uses for which GPR is considered an established and reliable technique vary slightly between the existing guidance documents, and will change as research and development continues. The uses of GPR currently generally considered as established and listed in EngD Paper 1 (Appendix A) are:

- 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).
- Location of steelwork.
- Quality control of pavements (which can include thickness determination, but also air void content and density determinations).
- Detection of stripping (loss of adhesion between bitumen and aggregate) in asphalt material.

Further discussion of each application is given in EngD Paper 1 (Appendix A).

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. EngD Paper 1 (Appendix A) aimed 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 (and as the paper was published toward the end of the EngD project, reference to work conducted during the project was made).

EngD paper 1 (Appendix A) highlighted three key areas for the continued success and future development of the technique for pavement investigations:

- Continued 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.

These three areas relate to both the limitations of GPR, discussed in Section 2.3.4, and to the justification of the work undertaken for the EngD project, discussed in Section 2.4.1.

2.3.4 LIMITATIONS OF GPR

As with every pavement investigation technique limitations exist to aspects of GPR, and these are outlined in EngD Paper 1 (Appendix A). Within the specific context of investigating the errors and uncertainties that can exist in the information derived from GPR data, EngD Paper 5 (Appendix E) discussed the limitations of GPR further and classifies them into three source areas:

- Technological and scientific issues;

- In-situ investigation methodology;
- Data analysis methodology.

The physical laws which govern the principles of electromagnetic wave propagation are unchanging, and therefore there are some areas of GPR use where it may not be possible to significantly improve the limitations of the technique. Therefore, the three areas listed above provide the clearest areas to address when attempting to reduce errors or uncertainty in GPR investigations.

However the literature review revealed that some of the limitations of GPR arise because of factors not included in the three areas listed above, which relate to the technique itself, but due to lack of appreciation or expertise. EngD Paper 1 (Appendix A) reports how difficulties encountered during data interpretation (i.e. lack of expert knowledge) have been suggested as one of the main reasons why GPR is not specified routinely by the US Department of Transportation. The education and awareness of both the GPR specialist and the pavement engineer can be improved to counter some of the issues highlighted during the literature review, including lack of appreciation or lack of understanding (from both parties).

A further factor highlighted during both the overall literature review process, and during the gathering of background information relating to specific EngD research tasks (Chapter 4), was that much previous research and development of GPR has been conducted under 'ideal' conditions, rather than conditions that are encountered during real GPR investigations. Sometimes the laboratory environment necessary to provide the controlled conditions used to investigate the accuracy or applicability of GPR to a certain issue may not fully take account of or reflect the circumstances under which the technique is used for pavement investigations. Hence, the ability to apply research findings and recommendations to genuine pavement investigations is of great importance.

2.4 SUMMARY

2.4.1 JUSTIFICATION OF ENGD WORK

The optimum use of GPR requires a wide-ranging approach including an understanding of the physics of the technique, of the hardware and software options available, of the methodologies for data collection and analysis and also an understanding of pavement structures and engineering. Despite having a history of use dating back to the early 1980's, GPR investigation of pavement structures is less well known and exploited than some other pavement investigation techniques such as deflection testing. However, the potential benefits of fully utilising GPR are large, and there also exists the potential to further develop the technique and improve and enhance the use of GPR.

There are four areas of GPR use, each of which is addressed by a specific EngD objective (see Section 1.4), that have been highlighted in this chapter as topics which provide an opportunity to optimise the use of GPR in pavement investigation:

- The investigation methodology used to collect GPR data at a pavement site;
- The amount and type of pavement information that can be obtained from GPR data;
- The significance and effect of the pavements condition and material properties on collected GPR data;
- The uncertainties and accuracy of information determined from GPR data.

Several documents exist to offer guidance on investigation or data analysis methodologies (see Section 1.2.4.1) but by their nature, and the nature of GPR investigation, such guidance can only be generic. To optimise GPR investigations, each site has to be treated separately, and whilst general procedures and approaches can provide a useful staring point for planning the investigation, the optimum in-situ methodology for a specific site may involve a data collection approach which is not covered by standard guidance. This is where experience and competence of GPR operator becomes especially significant. The in-situ data collection methodology is an area which may sometimes not be given appropriate importance (especially by GPR non-specialists specifying inappropriate methodologies or uses, or through under-appreciation that specific GPR investigations can require different in-situ data collection methodologies). Hence, optimising the data collection and handling methods for specific investigation types is an important area to address.

Often a single calibration value (for determining material properties such as depth) is used for large amounts of collected GPR data, but currently there is usually very little analysis of how the calibration may be affected by variation in material properties within a pavement investigation site. The nature of materials at a site can be variable or may change, and in such circumstances it may mean that data calibration procedures need to be altered to maintain the robustness of the information determined from GPR data. This issue not only relates to the effect of the material properties on the GPR data collected but also to the ability to quantify the levels of uncertainty or error in reported information.

GPR data can be affected by changes in material type, environmental factors (moisture, temperature) and also by the effect of deteriorated material (common when assessing pavements targeted for maintenance treatments). Such factors can affect the information obtained from GPR data, and the change in the nature of GPR data collected has the potential to be used as an indicator of what material conditions are causing the GPR data to change. Issues such as the effect of moisture and temperature of pavement materials is an area where much potential exists. The detection or mapping of areas of suspected high moisture in pavements has been conducted previously, but it is not currently a widely used or well-established technique. Moisture is, however, known to affect the dielectric constant of pavement materials and so an improved understanding of how moisture in asphalt can effect GPR data will lead to further and more accurate application of GPR for this purpose.

Section 2.3.3, and EngD Paper 1 (Appendix A), list the main established uses of GPR in pavement investigation. However, it has also been highlighted that GPR is a developing technique, and as research continues and the technique develops it is possible to use GPR data to obtain further information about pavements than can currently be obtained. The ability to enhance the information obtained from data collected allows an improved understanding of the nature of the materials investigated. It may be possible to re-use existing GPR data to determine pavement properties that previously were unknown, or to obtain more information from GPR data without greatly altering existing investigation methodologies. Hence the benefit of obtaining GPR data can be enhanced, as the type and scope of information obtained from an investigation is enhanced.

Very little quantitative assessment of errors and uncertainty is undertaken during most pavement investigations, and although it is a very important issue, relatively little research has been conducted to find methods for quantifying GPR information uncertainty at the project level. Quantifying uncertainties in GPR data and information is an area which requires clarification and education amongst both GPR specialists and pavement engineers. Although there have been many publications and investigations examining GPR data limitations or accuracies, such work mainly reports solely on technical limitations of the GPR technique rather than those which can be influenced by human input or by factors relating to incorporation of other data. The analysis of GPR data requires much human input, especially in the interpretation of data and identification of features. Also, one of the main uses of GPR data in pavement structural investigations is to integrate it with other data (such as core calibration, or use in material stiffness analysis with FWD deflection data). Thus it is an important aspect in optimising the use of GPR to investigate the uncertainties and inaccuracies from such sources, especially as a lack of understanding of the uncertainties and errors in GPR data has been cited as a main reason for the under-use of the technique.

An overall requirement which can be lacking in some research and development work, but which forms part of the essence of the EngD programme and was at the forefront of all the work conducted during this project, was the ability to apply research findings and recommendations to genuine pavement investigations.

2.4.2 RELEVANCE OF RESEARCH TO OTHER APPLICATIONS

There are a number of non-pavement uses that exist for GPR, and Daniels (2004) provides an extensive list of applications for which GPR has been successfully used. The range of topics covered at events such as the International Conference on Ground Penetrating Radar (which began in 1986) and the International Workshop on Advanced Ground Penetrating Radar (first held in 2001), both of which have been bi-annual events since their inauguration, also serve to illustrate the diverse range of applications possible with GPR. In addition to pavement investigation, other applications for GPR have included those with similarities in purpose or materials, such as engineering investigations on bridge decks, tunnels, building structures, railways and utilities, but also more diverse applications such as geotechnical, geological and archaeological site investigations, land mine detection, planetary investigations, and forensic, river bed, snow and glacier investigations. Such applications range from established to experimental uses, and various aspects of this EngD research work are applicable to several of these.

The EngD work relating to specific properties of bituminous materials is relatively specialist in its nature, although aspects of the work relating to the general theme of how the condition and nature of an engineering material can have important implications on the recorded GPR data can apply to a range of GPR applications, particularly in engineering investigations. Some aspects of the EngD work conducted on GPR methodology, and several issues covered concerning the assessment and management of errors and uncertainties in GPR investigation, are relevant to many other applications of GPR. Whilst pavement materials and properties are the focus of this EngD project, it is hoped that GPR providers and end-users for other GPR applications will also find benefit from the research undertaken.

3 RESEARCH METHODOLOGY

3.1 OVERVIEW

The purpose of this chapter is to provide an overview of the approach chosen to undertake the research, including a discussion of the research topics addressed during the EngD project and a description of the methods used to conduct the research.

A brief review is given of both the considerations required to develop a research methodology (i.e. the overall manner in which research is conducted), and of the different appropriate research methods available (i.e. the specific techniques and investigation tools used to undertake research work), including an illustration of the main research topics and methods used to address the EngD project objectives. Also, a review and discussion is given of the methods used to conduct previous research on GPR in related areas and their relevance to the work covered in this EngD project.

The selection of the methods used in this project is summarised and justified, and a research map is presented to illustrate how the current situation within the EngD theme links to the research tasks conducted, and how these tasks relate to each other and contribute to the project outputs.

3.2 METHODOLOGICAL CONSIDERATIONS

3.2.1 GENERAL

Within this thesis the ‘research methodology’ is the term used to describe the overall approach required to conduct the entire EngD project, incorporating all of the various stages and activities from the projects inception to the production of deliverables and implementation of new knowledge. The research methodology refers to the overall principles and procedures of the research undertaken. This differs from a ‘research method’ which is a specific technique used to undertake a task during the research, such as a literature review or a laboratory test. Each of the project objectives relate to research ‘topics’ (which refer to the specific areas of subject matter under question, such as pavement material properties or data processing procedures) and a research ‘task’ is a specific package of work focussed on answering a specific question or addressing an objective (e.g. devising improved procedures for conducting GPR investigations). The research methods utilised are selected on the basis of the research task, and the objective associated with the task.

Neumann (1997) states that most research follows seven typical steps, shown in a simplified form in Figure 3.1. In practice, research is usually a more interactive process, with aspects of various stages often combining together, and feedback from different activities resulting in an overall process that is not linear. Also, an individual stage of research, or an overall research process, can often stimulate new ideas or lead to further research questions.

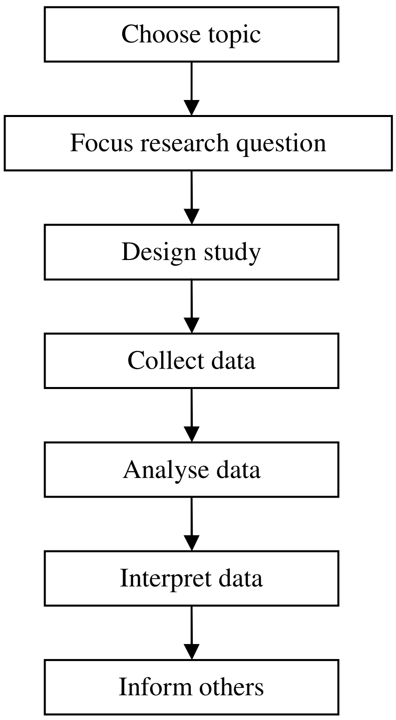


Figure 3.1 Typical simplified approach to research (after Neuman, 1997)

There are various methods which can be employed to conduct research. The methods chosen for the various activities during a research project depend on several factors which Yin (2003) summarises as including the research question (relating to the type of research area and topic), the extent of control the researcher has over the events being researched and whether the focus is on contemporary or past events (i.e. obtaining new information or reviewing existing information). Table 3.1 summarises the general situations used for each research method.

Table 3.1 Situations for different research methods (after Yin, 2003)

Method	Research question	Requires control over events?	Focuses on contemporary events?
Experiment	How, why	Yes	Yes
Survey	Who, what, where, how many, how much	No	Yes
Archival analysis	Who, what, where, how many, how much	No	Yes/no
History	How, why	No	No
Case study	How, why	No	Yes

The EngD project, and the research activities within the project, require customised planning, but the general issues outlined in Figure 3.1 and Table 3.1 give an indication of some of the typical main considerations required to devise the research methodology and to select the appropriate research methods.

Research methods can be classified as 'quantitative' or 'qualitative' depending on their nature. Quantitative methods involve collecting factual data in order to investigate how relationships between facts agree with theories or build on previous work. Typically, research involves devising a hypothesis which is then tested by the research undertaken, and where a great degree of control over the variables is possible. The results of the research are subjected to testing and validation in order to determine to what extent the objectives of the work have been achieved. In Table 3.1, 'experiment' would be a typical quantitative method.

Qualitative methods involve a lower degree of control over variables, and often there is no control at all. A qualitative investigation is normally undertaken in order to gain enough understanding so that theories will emerge, and is not one which tests or validates previously conceived theories. Qualitative methods tend to be used to produce descriptive data and are often used in the social sciences, depending on the task at hand, involving methods such as questionnaires, surveys or case studies.

3.2.2 METHODS USED IN PREVIOUS AND RELATED WORK

A variety of individual topics have been addressed by previous research undertaken in the subject area of pavement investigation with GPR. The drivers behind such work have originated from a number of sources, including the desire to commercially exploit GPR, the technical improvement of GPR practices, the incorporation of new hardware and software developments into GPR technology and to improve the understanding of how the physics of GPR can be used to determine useful engineering properties of pavements.

Reviewing the methods used for previous GPR research work in related areas shows that the nature of the methods chosen depends on the objectives and purpose of the work undertaken. Literature reviews, by their nature, are largely based on the requirement to gather, collate and report historical information, and the review of road evaluation using GPR by Saarenketo & Scullion (2000) uses this approach to achieve its aim. Sirles (2006) and Morey (1998) use both historical information and also surveys of engineering professionals to provide reviews and establish the state-of-practice for geophysical and GPR techniques in North America. Collation of previously published data from a number of sources has also been used as a method to provide information, in a general feasibility study on the use of GPR for pavements (Infrasense, 2006).

A large proportion of published research work on GPR has required research methods involving experimental investigation, to establish the relationships between facts. A variety of different types of experimental work has been conducted, including both closely controlled laboratory investigations and experimental fieldwork studies, investigating a variety of topics including the dielectric properties of materials (such as those by Al-Qadi et al., 2005, Jaselskis et al., 2003, and Shang et al., 1999), the accuracy of GPR data (e.g. Loizos & Plati, 2007, Willet & Rister, 2002 and Davis et al., 1994) and the feasibility of fieldwork methods (e.g. Noureldin et al., 2003).

Although experimental work has been used in a number of studies relating to the accuracy or error in data for a specific aspect of GPR use, there have been few studies providing an overview of procedures and methodologies, to provide generic information on the process of managing uncertainties in data as a whole (which in itself is one of the justifications for some of the work conducted in this EngD project, see Section 2.4.1). Where such type of work has been undertaken in the past, as by Olhoeft (2000) providing a study on maximising the amount of information obtained from GPR data, and Martinez & Byrnes (2001) providing advice and information to aid in data interpretation, historical data has been gathered and archival analysis of previously collected data has been required.

Case studies have also been used as a method for helping to establish how and why GPR can be successful for certain applications, especially where procedures without a long history of use have been employed (e.g. Maser and Scullion, 1992 and Fernando et al., 1994).

The end-use of GPR data relies on processes that have both 'science' and 'art', the interpretation of information in both quantitative and a qualitative ways. Some processes for handling and analysing GPR data can use automated processes, which involve mathematical manipulation of the data in a very controlled manner. Also, some processes require a much more subjective approach, where the input of the individual is required, and there is more scope for uncontrolled or biased procedures depending on the specific analyst's personal preferences or opinions. This use of both quantitative and qualitative procedures to obtain information from collected GPR data is reflected in the need to use both procedures to fully research the topics of this EngD project.

3.2.3 RESEARCH TASKS

The overall aim of this EngD research project was to provide improved pavement investigation capabilities by enhancing the methodologies and procedures used to obtain information from GPR. There were also four specific objectives to address (see Section 1.4), and one of the first steps to establish the appropriate approach to the EngD work was to break down the overall project into a number of research areas and topics associated with each objective. These research areas formed the basis for deciding the individual tasks required to address each of the EngD project objectives, and although each research task involved specific research activities, there was a degree of overlap between tasks.

Figure 3.2 shows an overview of how the specific project objectives led to the development of different research areas and topics, and the main methods used to conduct the required research. (There was, however, a degree of overlap between research areas and methods used to produce the publications, so that several publications utilised findings from more than one research area).

The EngD objectives were addressed by planning a research task based around each area of research required. Each of the research tasks then formed a separate work package within its own right. In addition to the general process indicated in Figure 3.2, where four research tasks were produced from the four specific project objectives, a literature review (see Section 2.3) was also conducted as a separate, but ongoing, project activity. The literature review was used as a foundation and frame of reference for the entire project and established the current practice, helped focus the project objectives and provided a background for the project (as well as being the main input used to produce EngD paper 1).

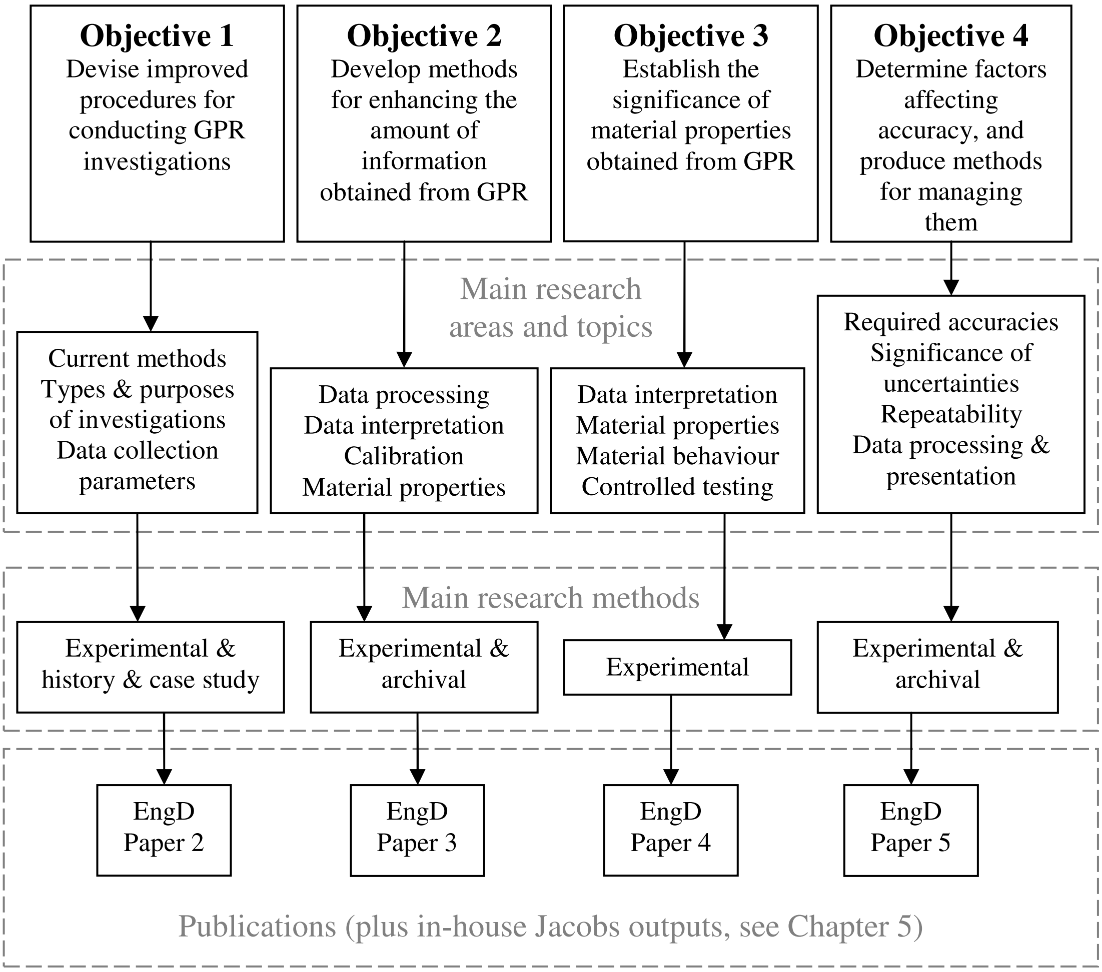


Figure 3.2 Research areas and methods directly linked to project objectives

The main research methods used included a number of experimental activities, which included both laboratory work where conditions could be controlled whilst investigations were undertaken, and also fieldwork investigations where conditions were less controllable. The use of both laboratory and field experimental work allowed the development of established relationships from laboratory work to be examined under field testing conditions, to allow an examination of the practical application of some of the project findings, and provide a way of allowing feedback between both types of experimental work.

During the course of the EngD project, in addition to the specifically planned tasks, there were occasions where either the research being conducted or the commercial needs of Jacobs led to further research areas or new research questions arising. In such cases, additional work to a task was conducted, or a new task was planned to address the research area (see Sections 4.3 to 4.6).

3.3 ADOPTED METHODOLOGY

3.3.1 SUMMARY OF METHODS USED

The overall methodology required to address the project aims and objectives requires a co-ordinated, structured but also diverse number of individual research tasks to be conducted, using several appropriate research methods. The literature review required the use of historical information, but the use of archival information and the examination of case studies also both contributed to the on-going literature review process conducted during the EngD.

Experimental investigations were required for all research topics, resulting in each research task conducted (see Chapter 4) involving an element of experimental work to establish relationships between facts. This included both laboratory and field investigations, where varying degrees of control were possible over the factors which influenced relationships. Other methods were also required during the research, and as can be seen from Figure 3.2, research of historical facts, review and re-analysis of archival data and presentation of a case study were all also used during the project to address research questions.

One of the important themes that underpinned all of the research objectives was the ability to relate the research undertaken to the application of GPR in a commercial industry-based context. This included ensuring that the results of the research undertaken could be applied in a practical way to GPR pavement investigations. With this in mind, although some of the work required that artificial conditions were created for certain aspects of the investigation, wherever feasible, all research methods used data and material from actual pavements so that the research findings could be related to real pavements as easily and practicably as possible.

3.3.2 SUMMARY OF PROJECT METHODOLOGY

Describing the overall project methodology involves including not only the research methods used, but the overall procedure applied to the research project. The approach to the research undertaken was to first establish the background to the work theme through literature review. Then, using the established situation as a frame of reference for subsequent work, the main research areas and topics were identified for each of the individual objectives. An assessment of research methods then identified which methods would be most appropriate to address the identified research topics, and the topics and methods were used to form individual work tasks intended to address each of the project objectives. Outputs (EngD publications) from each of the work tasks and from the literature review were then planned. This process formed the framework for the EngD project methodology.

In addition to the methodology described above, there were occasions where the EngD work or the business needs of Jacobs resulted in new or additional research topics to be addressed, which had not been considered as part of the main research methodology planning. Such tasks were conducted in parallel with the overall EngD research methodology and these were used with knowledge gained directly from the EngD outputs to develop and lead commercial project work, capability development and produce work protocols for Jacobs commercial business (see Chapter 5). Also, in addition to the planned EngD outputs (publications in peer reviewed journal and conference proceedings), further dissemination was conducted through a number of presentations on research findings, in-house reports for Jacobs and development of a number of procedural guidelines and investigation methodologies for GPR (detailed in Chapter 5).

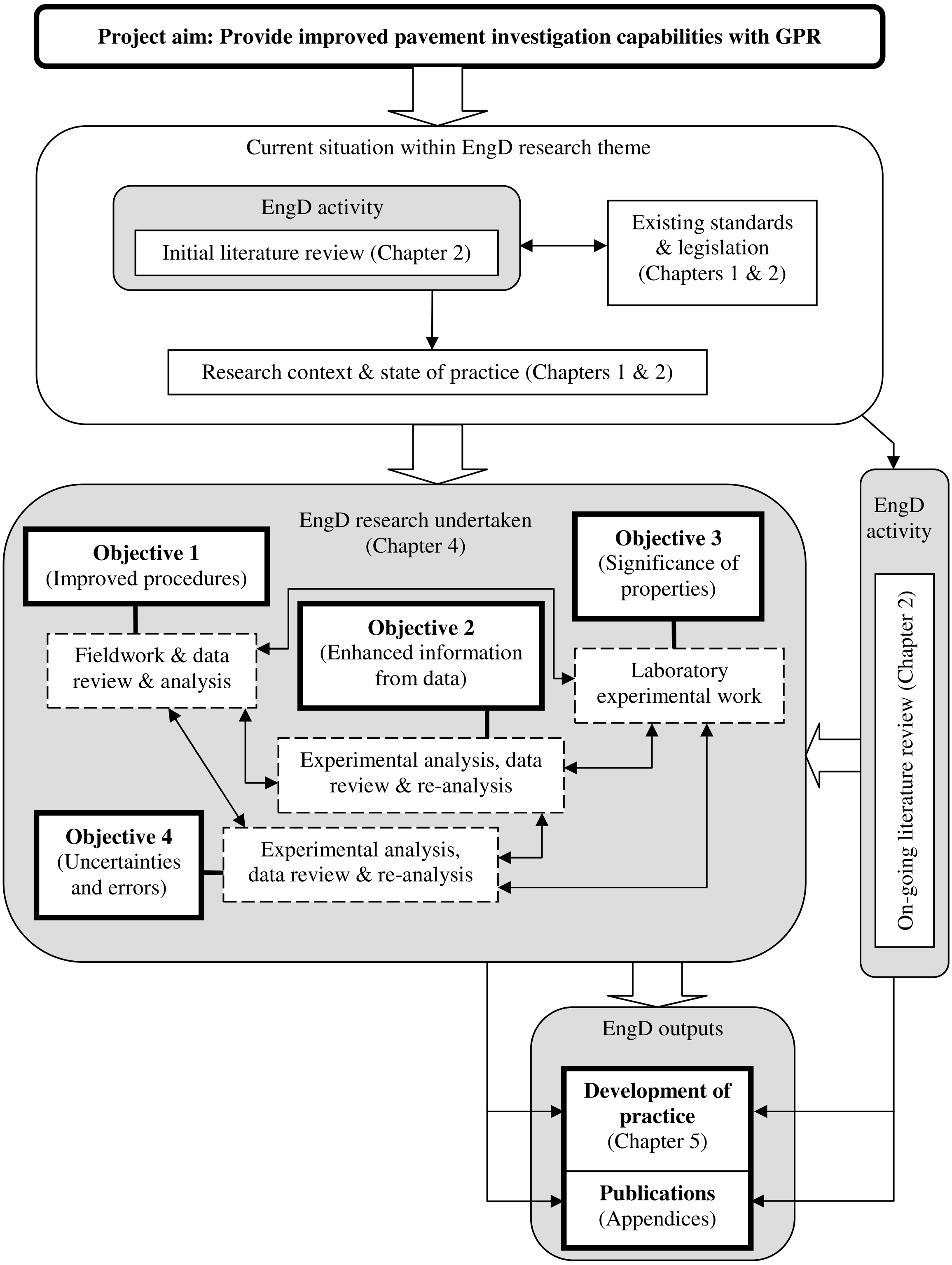


Figure 3.3 Research map of EngD project activities

Figure 3.3 summarises the various stages of the entire EngD project, and shows the links between the activities undertaken. The overall project aim is shown at the top, with the project outputs shown at the bottom, and the research methodology chosen and undertaken has allowed the work described in Chapters 1, 2 and 4 to progress and successfully address the project aim and the individual objectives.

As there were several areas of overlap between work tasks, there were a number of activities where work conducted was relevant to more than one objective. Results from methods used could often be of significance to other research tasks and methods. Also, during the research work the on-going literature review fed into the investigations being undertaken, and for each of the EngD outputs it was possible to keep up to date with the state-of-practice of GPR and provide a context to the research topic.

The tasks, methods and overall methodology described in this chapter form the basis from which the EngD research was undertaken. The detailed research activities described in Chapter 4 and the EngD published papers (Appendices A to E), conducted to address the project aim and objectives, provide a description of the research undertaken following the formulation and consideration of the research methodology described in the chapter.

4 THE RESEARCH UNDERTAKEN

4.1 OVERVIEW

This chapter details the research work and key findings of the EngD project. Distinct research tasks focussed on specific EngD objectives (see Section 1.4) are described, although the themes and issues of the different research tasks are often inter-related. The details given for the activities undertaken within each research task are intended to provide confidence in the results produced and conclusion drawn from the EngD project, and this chapter should be read in conjunction with the EngD published papers included in Appendices A to E, in order to give a complete description of the EngD research undertaken.

4.2 GENERAL

The use of GPR for both research and established applications involves a wide range of considerations, depending on the focus of the work. Figure 4.1 provides an overview of the main considerations, several of which overlap and others which can be treated exclusively.

The requirement that the EngD research be applicable directly to industry, and the commercial requirement for Jacobs to develop as rapidly as possible a competent GPR capability, led to the decision to use a commercially available, proven GPR system for the research undertaken. GSSI GPR systems were selected for use for all EngD project activities, and this choice was driven by several factors, including their known user-friendly and robust nature, as well as the ability to collect data from a multiple GPR antennas if required. Initially a GSSI SIR-10H system was hired for use, but the on-going development of the Jacobs GPR capability, through the EngD project, demonstrated its commercial feasibility and market, leading to the purchase of a GSSI SIR-20 GPR system by Jacobs in 2006.

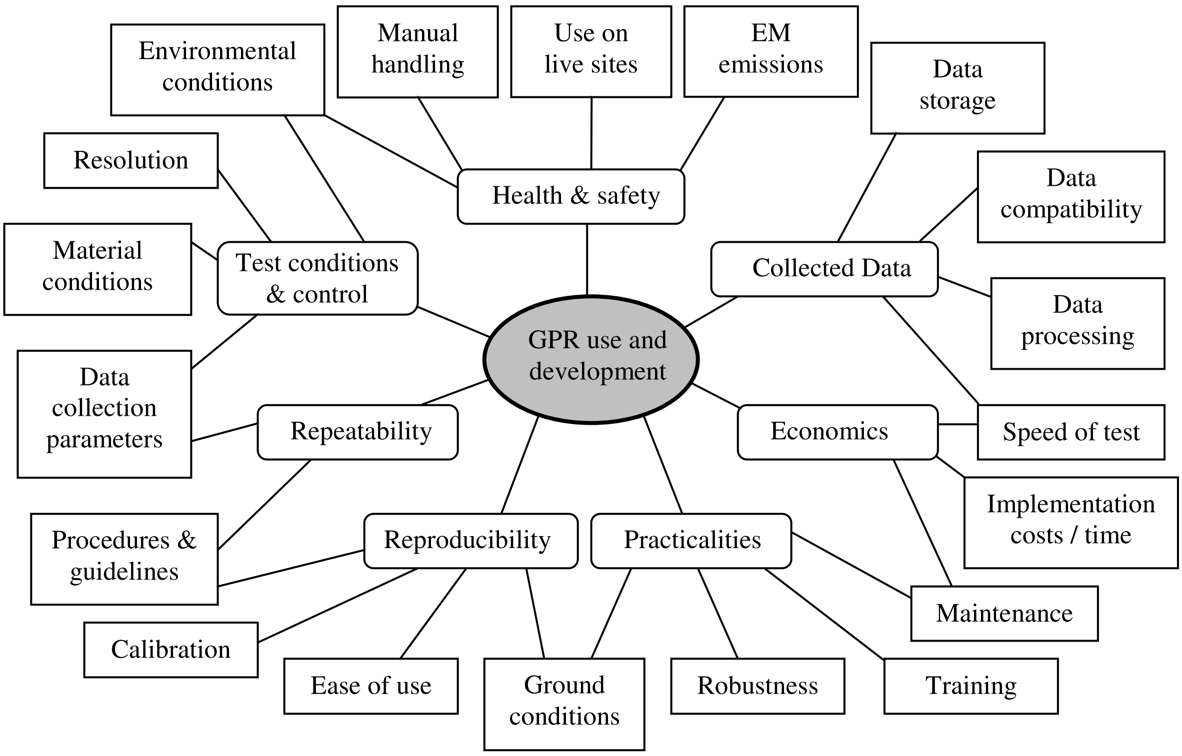


Figure 4.1 Main considerations and requirements for GPR research and development

The SIR-20 is the next generation of GSSI GPR system from the SIR-10H, and operates the same models of GSSI antenna and obtains the same type of data, but has greater electronic processing capability allowing faster data collection, smaller size of system components, a laptop and windows-based user interface rather than a system dedicated DOS-based interface, a much improved and faster data download ability and the SIR-20 also offered an improved ability to review and process data collected on site almost immediately.

The SIR-10H has the one advantage that it can operate up to 4 antennas at the same time (should this be required), whereas the SIR-20 can operate only 2. For research tasks involving use of data collected from in-service pavements (see research tasks described in Sections 4.3, 4.4 and 4.6), data was often collected using several antennas simultaneously, and where investigations were conducted using 2 antennas with the SIR-20, this proved a sufficient maximum number. The GSSI system specifications for the SIR-20 are given in Appendix F.

For data processing and analysis of data, the need for direct applicability to industry required the use of commercially available software, and the widely used and proven REFLEXW package was selected for use. The ability and processes for different GPR software packages are generally similar, and no specific programs are recommended in GPR guidance documents. REFLEXW was an appropriate choice of GPR processing and analysis software for this project, not only because it is a popular and well established GPR package used by several GPR operators, providing the ability to conduct all the necessary and commonly used processing options, but also because it has the ability, should it be required, to import and analyse data collected from almost all the different commercially available GPR systems (rather than being a system specific GPR software package).

Typically, the data processing stages used for each GPR raw data file before analysis was undertaken included static correction and background removal, although this depended on the nature of the analysis being undertaken. Static correction positions the zero time, on the travel time y-axis, at the pavement surface thus meaning that when travel times are converted to depths during the calibration process, the pavement surface is at the zero depth mark. Background removal is a processing stage that removes noise from the raw data, allowing a clearer presentation of data recorded from reflections within the structure.

The use of data collected with either SIR-10H or SIR-20 GPR systems, and data processed and analysed with REFLEXW, was conducted throughout all of the EngD research tasks and activities described in Sections 4.3 to 4.6. Also, the majority of road pavements in the UK are asphalt (rather than concrete), and currently no new road designs are made in the UK for concrete pavements (unless as part of a flexible-composite construction), so it was decided that the most appropriate pavement materials to focus the EngD work on were asphalt materials.

4.3 ASSESSING EFFECTIVENESS OF FIELDWORK METHODOLOGIES

4.3.1 BACKGROUND & RESEARCH CONSIDERATIONS

Objective 1 of the EngD project was to devise improved procedures for conducting GPR investigations used to provide information for structural pavement assessment. EngD Paper 1 (Appendix A) describes the development of the use of GPR on pavements which has led to the publication of a number of guidance documents. In the UK, the DMRB (Highways Agency, 2008) provides mandatory procedures for roads belonging to the HA network (motorways and trunk roads), but it is not intended for, and does not provide any specific guidance for, non-trunk roads.

Non-trunk road types, and particularly those in urban areas, form a significant part of the UK road network, and in Great Britain there are several thousand km of urban roads, the large majority of which are unclassified roads (see Table 4.1). Non-trunk roads (including ‘evolved’ roads) often contain specific features and construction which are more variable than major roads (see Section 3 of EngD Paper 2, Appendix B), and as such they often require a specific set of considerations when conducting a GPR investigation.

Road type	Length (km)
Urban trunk	590
Urban Principal	10,548
Urban B road	5538
Urban C road	10,859
Urban unclassified	113,520
Total urban	141,055

Table 4.1 Lengths of urban roads in Great Britian in 2004 (Dept. for Transport, 2005)

In 2005, information was required on the internal structure of a single carriageway two-lane urban ‘evolved’ road, in Coventry, UK, approximately 500m long. Section 5 of EngD Paper 2 (Appendix B) describes the information on the pavement condition initially gathered by the local highway authority, and the considerations for maintenance treatments.

Jacobs were commissioned to undertake the detailed pavement investigation on the road, and this allowed the opportunity to devise and trial a GPR fieldwork methodology aimed at addressing the specific issues encountered in such a non-standard pavement construction. No specific guidance exists for evolved or non-trunk roads, and a GPR investigation which used DMRB guidance alone, and employed a similar methodology to that of a ‘network level’ trunk road investigation, would not provide sufficient information to address the specific nature of the urban road.

The research activities included devising a GPR field investigation methodology for use at the site, which could provide sufficient information to be able to adequately plan the necessary maintenance treatment, and then also to review and assess the success of the GPR investigation with a view to employing similar investigation methodologies for other similar urban road sites.

The main requirements for this research task were to:

1. Establish the current methodology for GPR investigation based on existing guidance documents and standards;
2. Devise and implement revised GPR investigation methodology for urban road site;
3. Review findings of revised site investigation methodology;
4. Provide recommendations for a detailed site investigation methodology for use at urban or variable pavement sites.

The research work conducted was published in the Proceedings of the Institution of Civil Engineers: Municipal Engineer journal in 2006 (EngD Paper 2, Appendix B), and also published at the 10th International Congress of the International Association of Engineering Geology (Evans et al., 2006).

4.3.2 RESEARCH DETAILS

4.3.2.1 Establishing current investigation guidelines

Section 1.2.4.1 and EngD Paper 1 (Appendix A) summarise the reviews of literature conducted throughout the EngD, highlighting the fact that there is little specific guidance for highly variable non-trunk pavements, and although information from documents such as the DMRB can be useful for generic guidance it is difficult to provide specific guidance for all situations. Daniels (2004) and Saarenketo & Scullion (2000) highlight that it is necessary to consider both the science of the technique and the engineering aspects of the particular pavement under investigation, and hence it is important that hardware, software and data collection methods are tailored to the specifics of the investigation required.

The current DMRB document covering GPR use (on trunk roads and motorways), HD 29/08 ‘Data for pavement assessment’, reflects the fact that a single approach is not applicable to all GPR investigations, and the details of the in-situ field investigation are left to the discretion of the GPR operative. The DMRB guidance provides a useful starting point when considering GPR investigations on non-trunk roads, but the main factors which required specific consideration for the EngD investigation included:

- Location referencing accuracy
- Antenna type
- Antenna signal frequency

- Scan rate
- Data calibration
- Choice of tracks / survey runs surveyed

The considerations required to address these issues are discussed in Section 4.3.2.2.

4.3.2.2 Devising a methodology for urban roads

The first stage of devising the GPR methodology was to gather and review existing information from the road. The site used for the research task was local high street, with an evolved pavement construction, and work undertaken by Jacobs prior to the GPR investigation of the road, described in detail in EngD Paper 2 (Appendix B), indicated the general construction as summarised in Figure 4.2.

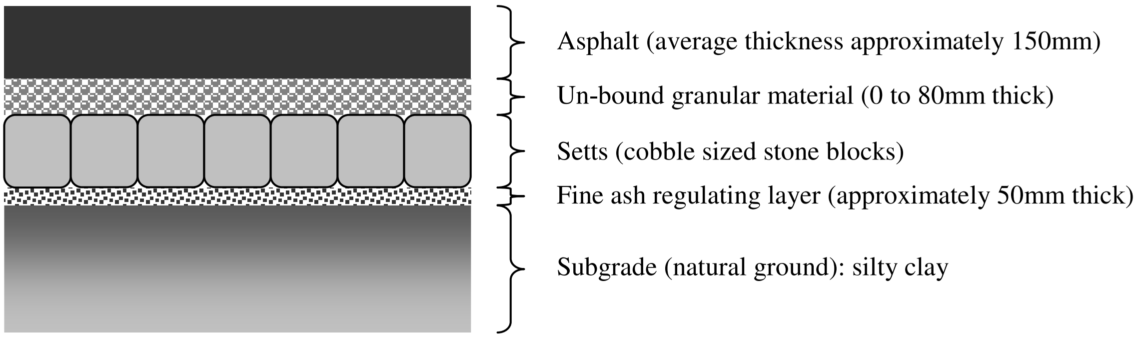


Figure 4.2 General pavement construction indicated by trial pits

Gathered information indicated that the road had evolved over time, resulting in a construction that differed significantly from that of a typical pavement design (as described in Chapter 1, Section 1.2.1). Whilst the existing asphalt layer was the main focus of the GPR investigation, information on lower layers would also provide information which could assist in planning of maintenance treatments, and the key issues that were addressed to devise the fieldwork methodology are shown below.

Location referencing accuracy

The DMRB specifies that "all GPR surveys carried out on the HA network must be referenced against network sections to an accuracy of better than ± 5m". However, the initial information gathered had indicated a potentially highly variable construction and condition, which may require localised treatments on short sections of pavement, and so the location accuracy of GPR investigation was required in greater detail than 'network' level surveys.

Consideration was given to the use of global positioning systems (GPS), but its use raised several issues. Some GPR manufacturers only tentatively recommend use of GPS, and GSSI (2005) qualify their advice on the incorporation of GPS into GPR surveys by stating that for applications where a survey wheel is used and the start and end locations are noted, GPS is not needed. Sensors & Software (2008) provide a review of various GPS options, from differential GPS alone which may only give accuracy of +/-10m, to differential GPS systems with post-processing using a local reference station and real-time kinematic (RTK) systems, which may give accuracies up to +/-2cm (and which are relatively expensive). GPS can sometimes be affected when used in close proximity to buildings or other structures, and whilst the use of GPS may provide some safeguards against location errors, the practicality of using expensive high accuracy GPS is not always possible.

The use of GPS during this research was ruled out mainly due to high cost, and so the calibrated GPR survey wheel was used to measure distances along each survey run. The investigation required a slow speed for each GPR survey run (see 'Scan rate' section, below), and so during the work it was planned to reference important features (in particular core locations for depth calibration of GPR data) by pausing the GPR survey run at the location of interest to ensure that its location could be electronically marked onto the GPR data with high accuracy. The recording of fixed feature positions also allowed referencing and checking of location accuracy for the data.

Antenna type

The information in the DMRB outlines the advantages and limitations of ground-coupled and air-coupled antennas (see Chapter 2, Section 2.2.3.1), and provides some general guidance on their suitability and performance for certain applications. There is not, however, any rigid specification of antenna type and the choice is left to the GPR operative.

As it was intended to obtain data from layers below the asphalt surfacing, ground coupled antennas offered the best option because of their greater depth penetration than horn (air-coupled) antennas. The use of horn antennas is also a less flexible approach because they require specialised fixings to survey vehicles (as shown in Chapter 2, Figure 2.5) and are less suitable to conducting transverse survey runs (see 'Survey runs / tracks' section, below).

Antenna signal frequency

The importance of signal frequency is described in Chapter 2 (Section 2.2.3.2), and the DMRB offers information on the typical penetration depths and resolution that can be obtained for GPR operating at several discrete frequencies, although the actual values obtained depend on specific in-situ conditions and hence the information can only be taken as a general guide.

The benefits of using multi-channel GPR systems (allowing data to be collected from several antennas simultaneously) are briefly mentioned in the DMRB, but the selection of specific numbers of antennas and signal frequencies is not stated. The use of several antennas of different frequency is mentioned, but only in the context of being "useful for network level surveys where data is only gathered from one line (generally the nearside wheeltrack)".

From previous experience it was known that, typically, antennas of lower frequency than 400MHz did not provide sufficient resolution, and penetrated (dependent on material type and condition) to depths deeper than were necessary for pavement investigation work. The available antennas for the SIR-10H system used for the work included 1.5Ghz (the highest available), 900MHz and 400MHz, and so it was decided to use these three antennas simultaneously for data collection, as described in Section 5.1 of EngD Paper 2 (Appendix B). An antenna housing was constructed for the work, to be towed behind the survey vehicle (see Figure 4.3, and also Figure 5 in EngD Paper 2, Appendix B) allowing the three antennas to run along the same survey line.

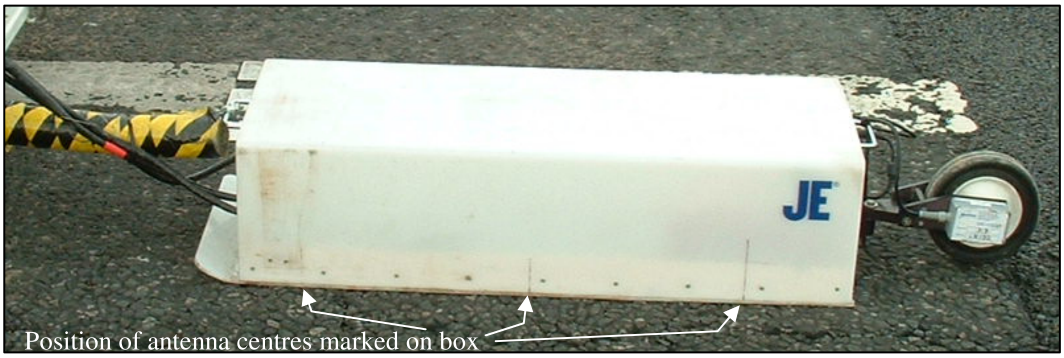


Figure 4.3 Housing 'box' for multiple antenna data collection

Scan rate

The distance along the pavement between successive GPR scans has a great effect on the amount of detail that can be obtained from the data, including the size (length) of objects that can be resolved and the precision to which distances along the pavement can be reported. As trunk roads tend to be relatively homogenous in construction, radar scans every 0.5m along such survey lines is not uncommon.

Chapter 2 (Section 2.2.2) describes some of the important aspects of a selected scan rate, and how a higher scan rate results in a lower possible survey speed along the pavement. The

DMRB highlights these factors but does not recommend or specify specific scan rates for certain applications other than providing general guidance on surveys being conducted at "low speed, typically between 0.5 and 20 km/h, or at traffic speed, typically between 50 and 80 km/h" for certain applications. As with other GPR survey parameters mentioned above, the specific system setting is left to the discretion of the GPR operator.

For the site investigated, a high scan rate (per metre) had to be selected in order to provide detailed data of the features of interest. However, a compromise had to be made so that the survey run speed was not limited to the extent that data collection would take an un-practically long time. The GPR system parameters used are described in Section 5.1 of EngD Paper 2 (Appendix B), with a scan every 0.04m along each survey line. Chapter 2, Section 2.2.4, outlines how the geometry of the EM radiation pattern from a GPR pulse effects the size of the antenna 'footprint' at a given depth, and the antenna frequency, antenna type and the material properties will affect this. Each GPR scan covers an area (rather than just providing data from a narrow beam), and so all the features in the pavement between scans are not missed.

Another factor to consider when selecting the scan (per metre) rate was that the greater number of scans per metre, the larger the data file size for a given distance, and so managing data files to a size where data storage and handling was not a concern was also a consideration.

Data calibration

The DMRB mentions the different calibration methods which can be used to convert signal travel times into depths, and recommends the use of the core calibration method (a detailed description of which is given in Section 4.4.1). Previous work has also reported core calibration as the most accurate method (Loizos & Plati, 2007). The DMRB requires that core locations should be "located on the radar data to an accuracy better than a metre", but for potentially highly variable urban pavement structures, where layer depths may vary significantly within a metre, a better accuracy is required. Modern GPR systems can allow marking of locations directly onto the GPR data, as described in 4.3.2.2.1, and as data collection was not at high speed the core locations can be marked with high accuracy.

Accurate depth information was one of the main requirements of the pavement investigation, and Section 5.1 of EngD Paper 2 (Appendix B) provides details of the core calibration conducted for the investigation. Cores were extracted as part of the commissioned Jacobs investigation, the locations of which were selected by examining the raw data on site and identifying areas of both homogenous construction and also where construction data was difficult to determine. Thus it was possible to use core data to both calibrate depths where layers could be easily identified in the GPR data and also to assist in interpretation in locations where the GPR data was less certain. The high number of cores for the length of pavement investigated allowed an assessment of the necessity of coring for GPR calibration on highly variable pavement construction (see Section 4.3.2.4).

Survey runs / tracks

The location of GPR survey runs for network level surveys is stated in the DMRB as generally being along the near side wheel track (NSWT). Conducting several parallel survey runs is mentioned only in the context of "where large areas need to be surveyed in detail", but there is no further discussion or explanation. It is inferred that if multiple survey runs are conducted they are also longitudinal runs along the length of the pavement, with the lane(s) and track required to be reported for each GPR survey run, i.e. NSWT, off side wheel track (OSWT) or between wheel tracks. As is the case for much of the GPR guidance, decisions on the specific detail of the investigation methodology are left to the GPR operative.

The visual condition of the road had indicated that there may be significant variability transversely as well as longitudinally in the pavement, and so the planned methodology was to conduct GPR survey runs in both the NSWT and OSWT in each lane (see Figure 6 in EngD Paper 2, Appendix B), and also to conduct a number of transverse runs by dragging the antenna housing by hand (see Figure 7 in EngD Paper 2, Appendix B), thus allowing significant features occurring across each lane to be more easily identified.

4.3.2.3 Review findings from pavement GPR investigation

The GPR methodology used on site was conducted as described above, and is also summarised in Section 5.1 of EngD Paper 2 (Appendix B). Following data collection, the GPR raw data files were processed and analysed using the REFLEXW v3.5 program. Figure 4.4 shows an example of the raw data collected at the site (and which could be seen in real time during data collection). Some features, such as the variation in the depth of the setts layer, can be seen in the raw data but other features require some data processing before confident information could be determined. Figure 3 in EngD Paper 2 (Appendix B) summarises the stages undertaken in the processing and presentation of data.

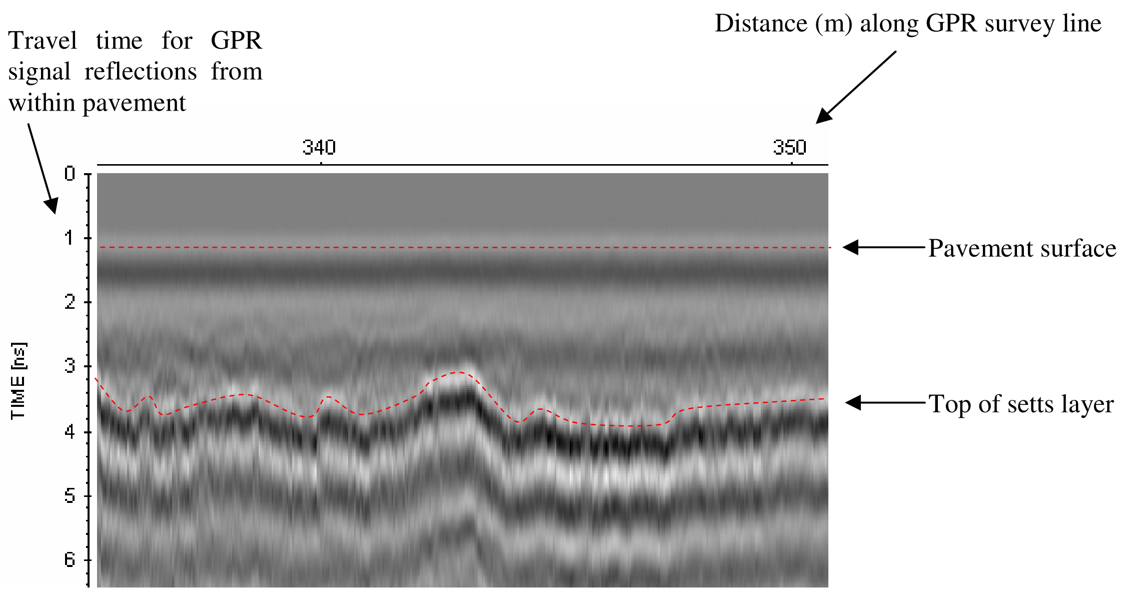


Figure 4.4 Raw GPR data, as displayed during data collection

In much of the raw data, as shown in Figure 4.4, identification of a sub-base layer was difficult. However, following data processing and adjustment of the data amplitude plot-scale (which enhances the contrast displayed between different reflected signal amplitudes) it was possible to identify the relatively weak interface reflections resulting from the un-bound sub-base above the setts layer.

The main findings of the GPR investigation are summarised in Section 5.2 of EngD Paper 2 (Appendix B), including the identification of three distinct construction sections, determination of layer depths within those sections, determination of much of the pavement to be in a poor condition including several areas of wet material, and identification of high variability in the transverse profile of the pavement layers.

Figure 4.5 shows a presentation of processed GPR data from three different transverse GPR survey runs (each across one lane) taken at different locations along the site, showing two runs with different sub-base thickness and one run with no distinct sub-base present.

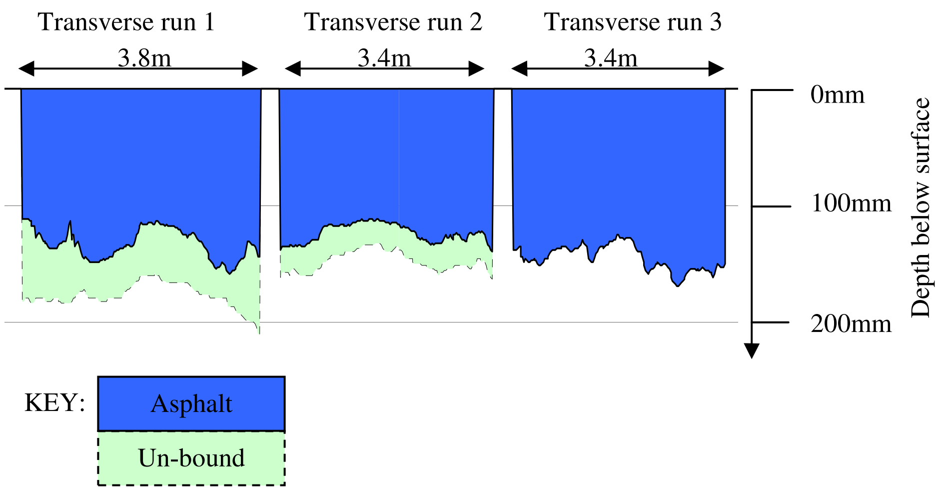


Figure 4.5 Presentation of results from three transverse GPR runs across road

The transversely variable thickness of the asphalt, and variable thickness and presence of the sub-base, above the setts layer would have proved difficult to determine without transverse GPR survey runs.

4.3.2.4 Recommendations for site investigation methodology

The field investigation undertaken provided a basis to evaluate the effectiveness of the various aspects discussed in Section 4.3.2.2, and the lessons learnt allowed a set of main considerations to be produced for GPR investigations on non-standard pavements where high detail is required or where a highly variable structure is expected. These key recommendations are given and discussed in Section 6 of EngD Paper 2 (Appendix B).

Also, as a result of this work a set of generic considerations was formed, based on the key recommendations, to be used within Jacobs prior to conducting pavement investigations with GPR. Appendix F shows a generic proforma which includes these main considerations, and which can be used as a basis for discussing and subsequently deciding appropriate aspects of fieldwork methodology, prior to commencement of a GPR pavement investigation project.

The data collected during this study showed that the variability of the layer depth was as much as 50mm (in an approximately 150mm thick layer) within a 0.5m length of survey run. Data collected with a more ‘standard’ approach used for network level investigations would not have provided the detail obtained by the survey undertaken. Precise detection of small or localised features such as high layer depth variation, re-bars, small voids or areas of moisture can not be confidently reported with traffic speed surveys, and several survey parameters such as the use of a single antenna alone, the collection of data only along longitudinal survey runs, or the use of core calibration data which was not highly accurately located would have resulted in the full details of the highly variable pavement structure not being obtained.

It is difficult to provide a general recommendation for the number of cores required to ensure adequate GPR data calibration. The variability or homogeneity of the pavement will determine the core sampling density (i.e. number of cores per km of pavement length) required for adequate calibration, but the variability of the pavement is often not revealed until the GPR investigation has taken place. As such, where possible, it is advantageous for the core investigation to be determined from the findings of the GPR survey. For relatively homogenous trunk roads with minimal construction and condition variability, cores every several hundred metres (or possibly several km) may be appropriate. However, for pavements where variable construction is expected, such as that encountered during the field investigation described in this section, at least one core per construction section would be required. Where little information is known about an expectedly highly variable pavement, as many cores as is practicable should be taken, which may result in a core density of greater than one per 200m length of pavement.

The recommendations and general methodology outlined in EngD Paper 2 (Appendix B) has been adopted by Jacobs as the default approach for detailed investigations using GPR because of the benefits, and reduction in uncertainty and risk, provided by adopting that methodology. Appendix G shows the pro-forma used, by Jacobs, as a tool to discuss and decide on the main factors for optimum fieldwork methodology for detailed GPR investigations.

4.4 ENHANCING INFORMATION OBTAINED FROM GPR DATA

4.4.1 BACKGROUND & RESEARCH CONSIDERATIONS

Objective 2 of the EngD (see Secion 1.4) was to develop methods for enhancing the amount of information that can be obtained from GPR pavement investigation data. Chapter 2 (Section 2.2.1) and Sections 4.5 and 4.7 of EngD Paper 1 (Appendix A) describe the types of information that can be determined from study of the dielectric properties and determination of the dielectric constant of materials. Where the dielectric constant values are not directly determined, analysis of GPR data still relies on the fact that materials with different dielectric properties will give different responses to GPR signals, and this contrast forms the basis of all GPR investigations.

To determine the depths of features it is necessary to convert the recorded pulse travel times into depths within the pavement, and Section 2.4 of EngD Paper 3 (Appendix C) provides an overview and discussion, including the limitations, of the calibration procedure, with Section 3.2 of EngD Paper 3 (Appendix C) providing a review of the significance of the dielectric properties of pavement materials.

As discussed previously, core calibration is a well established method for determining GPR pulse velocity values, where material layers and depths identified by the core are compared to the layers apparent in the GPR data at the core location. Re-arranging Equation 2.4 (see Chapter 2), the velocity of a GPR pulse in a pavement can be determined:

$$v = \frac{2d}{t} \qquad (4.1)$$

where d is the depth of the layer (i.e. depth of the core), t is the two-way GPR signal travel time from the layer and v is the pulse velocity.

For the example of core and GPR data shown in Figure 4.6, the asphalt core depth is 300mm (0.300m), and the time for the GPR pulse to be reflected from the bottom of the asphalt is 5.0ns. Using Equation 4.1, this would produce a pulse velocity of:

$$v = \frac{2 \times 0.300m}{5.0ns} = 0.12\text{mns}^{-1}$$

The velocity can then be used to convert travel times to depths for all recorded GPR data. Although it is not necessary to directly determine the dielectric constant of a material in order to use it for depth calibration (as can be seen from the variables required in Equation 4.1), it is the dielectric properties of a material that determine the velocity of a GPR pulse through the material, and the relationship between the dielectric constant and the signal velocity is described by Equation 2.3, and discussed in Chapter 2.

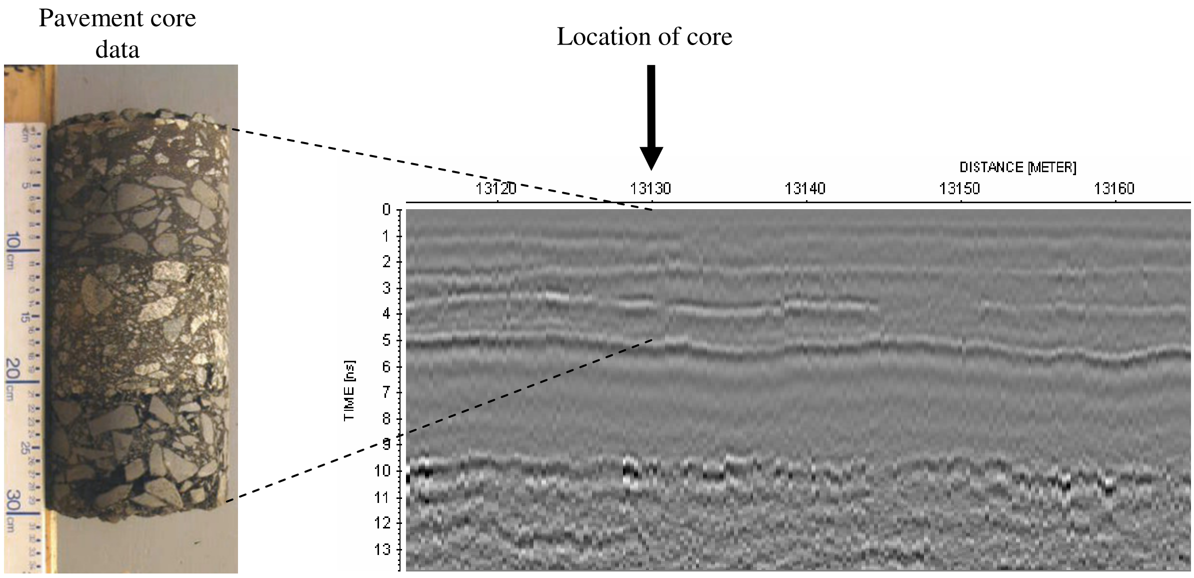


Figure 4.6 Use of core data to calibrate GPR data

The use of core samples has been shown to be the most accurate calibration method (see Section 4.2 of EngD Paper 1, Appendix A), there are some limitations. Firstly, the method assumes that core locations are accurately recorded on the GPR data (discussed further in Section 4.3 and in EngD Paper 5, Appendix E). Secondly, although the calibration velocity determined from a core is often, in practice, used to convert travel times to depths for substantial lengths of pavement, variations in material type and condition may cause variability in dielectric properties (and thus GPR pulse velocity) along the pavement length. Further discussion of methods for depth calibration is given in Section 2.4 of EngD Paper 3 (Appendix C).

The issues described above led to the design of a research task focussed on the feasibility of using a core calibration based procedure to assess whether the dielectric constant could be used to infer in-situ material condition, and thus provide enhanced information without altering data collection methodology. In addition, the study would also give an indication of the variability of dielectric properties of pavement materials which would in turn provide information concerning the variability and uncertainty in depths, and also quantify some of the limitations in the practical applications of the core calibration method.

The requirements for this research task included the ability to:

1. Use previously collected GPR and core data, from ‘standard’ pavement investigations, as the input data for the research task;
2. Re-analyse the GPR data to determine the dielectric constant of the in-situ core material;
3. Establish the relationship between the in-situ material dielectric constant and the in-situ material condition;
4. Provide new or enhanced information from GPR data, without the need for modification of in-situ data collection procedures.

The methodology employed was to use data previously obtained from standard pavement investigations, so that it would be possible to relate the findings of the study in a practical way to commercial Jacobs pavement investigation work, and Section 4.4.2 provides a detailed description of the research undertaken. The work was presented at the 86th Annual Meeting of the Transportation Research Board in Washington DC in January 2007 and published in the Transportation Research Record: Journal of the Transportation Research Board in December 2007 (EngD Paper 3, Appendix C).

4.4.2 RESEARCH DETAILS

4.4.2.1 Pavement data

Throughout the course of the EngD project Jacobs has had an on-going commercial contract, as part of the BEAR consortium which maintains Scotland's trunk road network, to conduct detailed pavement investigations on a number of roads. Each detailed pavement investigation includes GPR, FWD and coring investigations of the pavement, and the main purpose of the GPR data is to provide pavement material layer depths, which are then used during FWD data analysis to determine material layer stiffnesses.

The GPR and core data used for this research task were taken from 3 separate BEAR pavement investigation sites (known as 'schemes'): The A96 Auldern by-pass (pavement investigation data originally collected in 2005), the A90 Stonehaven by-pass (data collected in 2005) and the M90 near Perth (data collected in 2006, see Figure 4.7).

Figure 4.7 M90 near Perth, Scotland, used for collection of pavement data

At the time of data collection it was not known that the data would be used for EngD research and so no special consideration was given to obtaining data for any purpose other than for the work being undertaken for the BEAR contract. This was an important issue for this research task, so that it could be determined what enhanced information could be obtained without having to alter the existing on-site procedures for data collection.

Details of the GPR and coring investigations undertaken are given in Section 4.2 of EngD Paper 3 (Appendix C), involving collection of all data from the same wheel track of the lane being investigated. Core data included 14 cores taken at the A96 scheme, 29 cores from the A90 and 13 cores from the M90, with asphalt material ranging from approximately 90 to 215mm thick, and consisting of both hot rolled asphalt (HRA) and dense bitumen macadam (DBM).

In addition to providing information on asphalt material type and thickness, the core logs also classified the material as ‘sound’, ‘voided’ or ‘disintegrating’. Some cores contained entirely sound material and some contained material which was voided or disintegrating in one or more layers, and so it was possible to classify the cores depending on their material layers and condition and thus compare materials of different condition within a scheme, and also to compare similar materials between schemes.

4.4.2.2 Data re-analysis procedures

The data was reviewed and the bottom of the asphalt core material was identified in the GPR data at each core location (as shown in Figure 4.6). Combining and re-arranging equations 2.3 and 2.4 (see Chapter 2) provides equation 5 in EngD Paper 3 (Appendix C), which can be used to determine the dielectric constant of the core material as described in Section 4.3 of EngD Paper 3 (Appendix C).

As the signal travel time information for the bottom of the asphalt is taken from the GPR data collected in-situ (and the depth given in the core log provides the depth of the in-situ asphalt), the dielectric constant determined is that for the material in its in-situ condition. Thus values for the 'bulk' dielectric constant, as a function of the properties of the entire asphalt layer at the core locations, could be calculated, and Section 4.3 of EngD Paper 3 (Appendix C) provides further details on the data analysis. For the determination of dielectric constants, there are several factors for which uncertainty exists, which may lead to errors in calculated results. These are discussed further in Section 4.4.2.4.

4.4.2.3 In-situ material properties

The main results from the data analysis, given in Section 5 and Table 2 of EngD Paper 3 (Appendix C), showed a range of values for the in-situ dielectric constant values. Within each of the schemes sound material had the highest dielectric constant values, with voided (compared to sound) material showing a lower average dielectric constant value, and the results are discussed in detail in Section 5.2 of EngD Paper 3 (Appendix C).

The results allowed several relationships to be investigated, including the dielectric constant in relation to the condition of the asphalt material, the amount of air in the material mixture (resulting from poor compaction during construction, or deterioration of material over time caused by vehicle loadings) and also the variation of dielectric values between similar material in the same condition at different schemes. These issues are discussed in detail in Sections 5 and 6 of EngD Paper 3 (Appendix C).

4.4.2.4 Enhanced information

The work described in Sections 4.4.2.1 to 4.4.2.3 and in EngD Paper 3 (Appendix C) provides a method which can be used to obtain more pavement condition information, and also to assess the variability and uncertainty in the information gathered from a pavement investigation than would otherwise be possible.

By comparing materials of the same type from within each scheme, but which have different condition, the results indicated that determination of the dielectric constant as described in Section 4.4.2.2 could provide a distinction between sound and deteriorated material of the same type. Also, by comparison of results from different schemes (i.e. where generically the material is similar, but there are variations in specific material type) the results emphasised the variation between dielectric constant that can occur in generically similar materials. These findings emphasise the issue that reporting GPR results that have used published dielectric constant reference values, rather than data calibration for the specific site materials, has a higher potential for error and this fact should be communicated to the end user of the information.

Although the results indicate some promising results there are several factors concerning the accuracy and uncertainty in the data that should be taken into account concerning material condition determined from the above method. It is important to note that the uncertainty in the results determined for dielectric constant values is affected by the accuracy of the input values, of time and depth, used in the calculations described in Section 4.4.2.2. Firstly, there is limited accuracy associated with depth data from core logs. Work described in Section 4.5 involved measurement of core depths, and suggested that, because of the uneven nature of the bottom of most core samples, reporting depths more precisely than to the nearest 5mm would be unrealistic. (The depths recorded on the core logs used in this research task were to the nearest 5mm). A second factor which also affected the accuracy of the results was the precision to which the signal travel time could be measured (which was to the nearest 0.03ns).

For the range of asphalt depths used in this research task, the uncertainties in the variables used in calculations could lead to errors in dielectric constant determination of approximately 3.8 to 8.8%, with the larger errors associated with shallower depths. For depths of 300-350mm, generally typical of asphalt pavement trunk roads in the UK, errors in dielectric constant determination using the described method could be expected to be approximately 2.4 to 2.8%.

Whilst the uncertainty in travel time determination is mainly a factor of the electronics of the GPR system, and remains constant for each measurement taken, the accuracy of depth determination is more subjective as it involves the input of the materials engineer tasked with logging core information. Regarding the data set of results from this research task, if uncertainties in depth values were introduced of the region of 10 to 20mm for the shallower cores used (approximately 100mm thickness), the degree of uncertainty in dielectric constant values would be approximately the same magnitude as any of the changes observed as a result of material condition. All cores will carry a certain amount of unevenness along their bottom, but for particularly uneven cores, the uncertainty in both determining an accurate depth for the core, and also in determining an accurate value for the first arrival of reflected GPR signals (to determine the travel time) would be difficult. Bearing in mind the typical depth accuracy measurable from cores, the use of the method described in this research task should not be applied with confidence to cores shorter than approximately 100mm.

4.5 LABORATORY TESTING OF MATERIAL PROPERTIES UNDER CONTROLLED CONDITIONS

4.5.1 RESEARCH CONSIDERATIONS

Although it is possible to utilise GPR for several applications without direct determination of the dielectric constant values of materials, the ability to determine useful information from all GPR applications relies on the dielectric response of the materials, as described in Section 4.4, Chapter 2 (Section 2.2.1) and Sections 4.5 and 4.7 of EngD Paper 1 (Appendix A).

The type and condition of a material has an effect on its dielectric properties, and during the early stages of the EngD project it was thought that Objective 3 (see Section 1.4) may lead to an investigation of the relationship between GPR data and asphalt properties such as density or stiffness. However, during background work and literature review activities, it was found that one of the most significant and relevant properties to influence GPR data, in relation to pavement assessment, is the amount of moisture in the material, and that possibly the most neglected factor which can influence GPR data is the temperature of the material. Section 1.2 of EngD Paper 4 (Appendix D) provides a discussion of the significance of moisture and temperature on pavement materials. Relatively small increases in moisture content can cause significant changes in the dielectric constant of asphalt materials, and using GPR to determine the spatial variation in dielectric constant within a pavement can be used to identify locations where there may be variations in moisture content. The temperature of pavement material also has an effect on its dielectric constant, and so for GPR applications where properties are determined from dielectric constant values (such as the presence of moisture or air voids), pavement material temperature is an important issue to take into account during analysis of GPR data.

A wider understanding of the dielectric response of bituminous materials, under different moisture and temperature conditions, allows a more comprehensive understanding of the significance of data obtained by GPR. EngD objective 3 (see Section 1.4) was to establish the significance of material properties determined from GPR and how they relate to the condition of the pavement, and was the driver behind the research task described in this section. The requirements for the research task included the ability to:

1. Use test samples representative of in-situ, in-service pavement material;
2. Control and alter the temperature and moisture condition of the material;
3. Obtain GPR data from the material in a known condition;
4. Determine values for the dielectric constant from the GPR data obtained;
5. Establish the relationship between the dielectric constant, and the temperature and moisture condition of the pavement material.

A series of laboratory tests were conducted to address this research task, and Section 4.5.2 provides a detailed description of the research undertaken. The work was presented and published at the 1st International Conference on Transportation Geotechnics, in Nottingham, UK, in August 2008 (EngD Paper 4, Appendix D).

4.5.2 RESEARCH DETAILS

4.5.2.1 Pavement material

One of the underlying themes of the EngD programme is that the research work has real relevance to the sponsoring company and to wider industry in general. During this research task, this was reflected through the intention to be able to relate the results to in-service materials and conditions. With this consideration in mind, the research tasks utilised pavement materials exclusively obtained from live roads in the UK.

Figure 4.8 Extracting pavement cores from the A9, near Perth, subsequently used in EngD research

Section 4.4.2.1 outlines the commercial pavement investigation work conducted by Jacobs throughout the EngD research period for the BEAR consortium. As part of the BEAR 2007 schemes, pavement investigations were undertaken at several trunk roads, including the A9, A90, A92 and M90, and asphalt pavement cores taken from these schemes (see Figure 4.8) were made available for use for this EngD research task.

A total of 20 asphalt core samples (see Section 2.1 of EngD Paper 4, Appendix D for a summary description) were selected, and assigned numbers 1 to 20 for reference during testing. Figure 4.9 shows core sample 6 (288mm in length) and core sample 7 (280mm in length). A main factor influencing the number of samples chosen for testing was the amount of time required to prepare and conduct each series of tests on the material, so that the research task did not take up an excessive proportion of the entire EngD research period.

Figure 4.9 Examples of pavement cores used in EngD research

The selection criteria for the cores included several practical considerations, including selecting cores without excessively deteriorated layers, ensuring any de-bonds between layers did not include material disintegration, and not selecting cores with excessively uneven bottom faces, all of which would have made testing of the cores, from a practical point of view, more difficult (further details given in Section 4.5.2.3).

4.5.2.2 Control of material condition

The laboratory testing regime involved 2 separate programmes, one for GPR testing of cores at controlled moisture conditions and one at controlled temperature conditions, and Section 2.2 of EngD Paper 4 (Appendix D) provides a summary of the laboratory preparation of the cores, with further details given below. All testing was conducted in the Civil and Building Engineering Department laboratories of Loughborough University.

Moisture

It was decided that the study would initially assess the dielectric constant of each core sample in 2 different extreme moisture conditions, to establish the significance of the effect of such moisture conditions on dielectric properties, with the results obtained to be used to plan further testing if required.

When the cores had initially been extracted from the in-service pavements, they were dried (see Section 2.2 of EngD Paper 4, Appendix D), and following testing in the ‘dry’ condition they were then submerged in a water filled tank (normally used for curing of concrete specimens) for 48 hours, to prepare for testing in a ‘soaked’ condition. The facilities at the laboratory were sufficient to allow all cores to be submerged at the same time, in a number of identical curing tanks, so that all testing could be conducted at the same time in one batch.

It was important to test all core samples at the same temperature, to avoid any influence this may have on the results. The air temperature and the water temperature were monitored during the testing programme, and the water in each of the curing tanks was approximately 1^0C lower than air temperature during testing. Any effect on GPR test results caused by the air / water temperature difference of 1^0C was negligible, as shown by the results of the temperature testing (see Section 4.5.2.5).

After soaking, each core was removed from the tank and as soon as excess water had been allowed to run off (which usually took approximately 10-20 seconds) it was tested in this ‘soaked’ condition (at room temperature). The testing of the cores in this way allowed a comparison of ‘dry’ and ‘soaked’ condition, although no measurements were made to quantify the moisture content. The results, relating to the effect of moisture on dielectric constant, from this study were used to plan and commence a further research project involving quantification of the moisture content and testing at a greater number of moisture conditions (see Section 4.5.2.5).

Temperature

The temperature of the cores was controlled through use of a Fisons Environmental Cabinet, (see Figure 4.10) which allowed conditioning at manually selected air temperatures. Testing was conducted after conditioning at temperatures of 45^0C, 35^0C, 25^0C, 15^0C, 5^0C, 0^0C and -

5^0C, chosen to give a range which included typical temperatures a pavement may be subjected to in the UK.

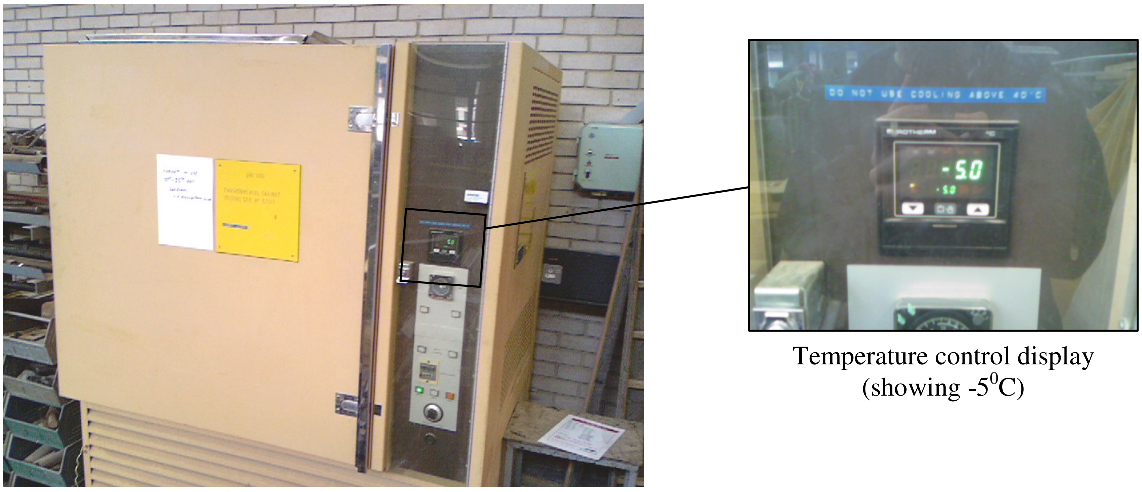


Figure 4.10 Environmental cabinet used for temperature conditioning of cores

Inside the cabinet it was possible to comfortably fit a maximum of 10 core samples, and so to allow conditioning and testing of samples at the same time, it was decided to limit the temperature testing to 10 of the 20 core samples. This also meant that GPR testing was conducted in one batch for each discrete temperature, ensuring the testing did not require conditioning of several batches, which would have added excessively to the time required to complete testing.

There were no specific criteria used to select which 10 cores were used for temperature testing, and so for ease of reference cores numbered 1 to 10 were selected. It was initially planned that if results from the testing led to further questions or issues, cores 11 to 20 could also be tested (see Section 4.5.2.5 for further discussion) to obtain further data.

Prior to initial testing, the cores were dried (see Section 2.2 of EngD Paper 4, Appendix D). In most engineering materials, including asphalt, part of the water content of the material exists as bound or adsorbed water while part may be free water. For asphalt core samples, there would still be moisture present within the material matrix even if drying were continued until no weight (water) loss can be measured between successive periods of drying. Therefore, the drying process was to remove free water, although adsorbed water would still be present, and hence the material would not be truly ‘dry’ material.

During the conditioning at 45^0C, core samples number 5 and number 7 (obtained from different sections of the A92) suffered partial collapse caused by softening of the bitumen binder, resulting in only 8 cores being used for the temperature testing.

4.5.2.3 Data collection

GPR data collected was conducted using a SIR-20 GPR system. To obtain GPR data from each core it was necessary to obtain a scan whilst the antenna is in a fixed position at one end of the core, and reflections from the bottom of the core were recorded. To conduct such data collection several important considerations were required for the design and conduct of the experimental work, which are described below and in Section 2.3 of EngD Paper 4 (Appendix D).

The data collection parameters of the SIR-20 had to be configured so that the GPR antenna collected data in the ‘free run’ mode (i.e. without the need for a moving survey wheel to drive the data collection, as is the case for a normal pavement investigation as described in Section 2.2.2, and for the GPR data used for other research tasks). In the free run mode, GPR scans were collected at fixed time intervals (at a fixed rate of 50 scans per second) and the antenna was held stationary during data collection. Scans were recorded for a few seconds for each test, resulting in collection of several hundred scans per test which allowed a validation check on the repeatability of the data, but also allowed the ability to view data in a grey-scale B-scan format, rather than just the A-scan format allowed by a single scan (see Section 2.2.5), which can assist with data interpretation.

A slight concern was that internal reflections of the GPR pulses from the sides of the core may cause significant noise in the received signal (because the propagation of GPR signals from an antenna is not in a single narrow beam, but in a cone shaped envelope). This was, however, a minor concern as the most direct portion of the signal (i.e. the first to cause reflections to be received back at the antenna) would be that portion of the EM wave-front travelling directly down the core and back again from the bottom. Hence any noise caused by internal reflections should be received after the reflection from the core bottom and thus would not interfere with determination of reflection travel time.

The issue of the antenna frequency used for data collection also required consideration, as it was important to collect data with an antenna which provided the best resolution for the depths of penetration encountered. Experience during commercial pavement investigations for Jacobs had shown that, although depth penetration was affected by specific material type and condition, a 1.5GHz dipole (ground coupled) antenna could often provide useful information for depths in asphalt of up to 400-500mm. As the longest core used for testing was 420mm, a 1.5GHz antenna was selected to use for data collection.

All of the test protocol issues were fully assessed by conducting a feasibility trial of GPR test procedures before commencement of the experimental testing. Using the data collection and system parameters outlined above, the test procedures and quality of data obtained were assessed on asphalt core samples up to 420mm long. The trial proved successful, and the same test procedure was then used for experimental data collection on the cores at Loughborough University.

Following conditioning of the cores at the desired moisture or temperature condition, as described in Section 4.5.2.2, the GPR data collection was conducted, with core samples placed upright on the metal base plate, and the antenna placed on top of the core, as shown in Figure 4.11.

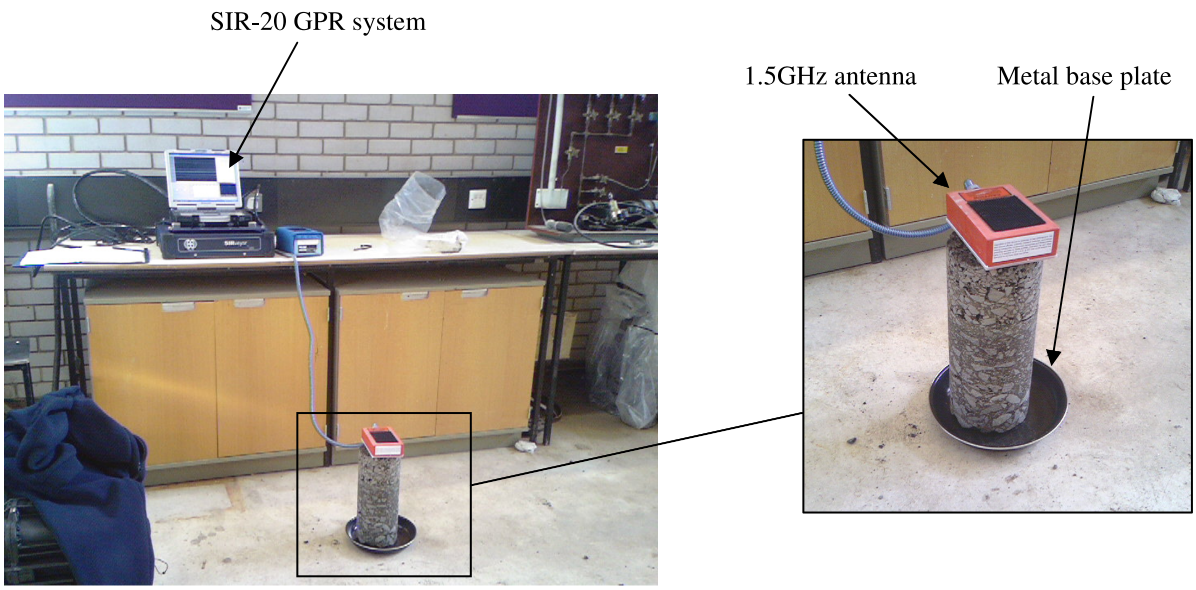


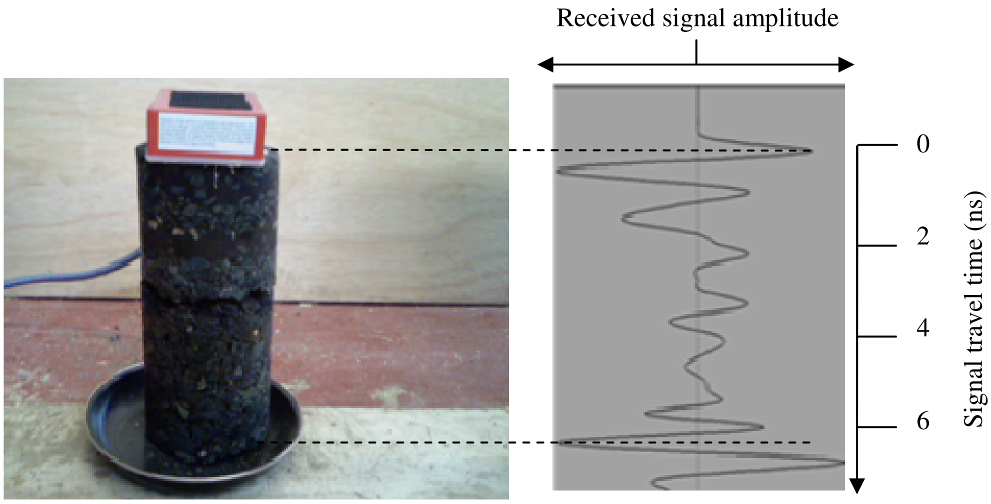
Figure 4.11 Experimental GPR data collection

The time required from removal of the core from the cabinet or tank to completion of the data collection, was approximately 1 minute. For the temperature testing, the core material would cool slightly whilst it was out of the chamber, but the thermal properties of asphalt and the short time required for data collection meant that any temperature drop would be negligible and would not significantly affect the experimental data.

Immediately after each of the temperature tests, the core was weighed in order to assess if there had been any changes in moisture content (which would be indicated by a weight change in the core between tests). During the testing programme, no significant weight changes were recorded.

4.5.2.4 Determination of dielectric constant values

In order to determine the dielectric constant of each core under each test condition, the procedure described in Section 2.3 of EngD Paper 4 (Appendix D) was used. Some of the core faces were slightly uneven and so the depth of each core (d) was determined by measurement of the core length 3 times and determining an average. Concerns that the core length may be altered during conditioning (especially when at higher temperatures, through thermal expansion) were addressed by test measurements of the length of some of the cores at higher temperatures, and it was found that no measurable difference between room temperature length and high temperature length could be determined.



(a) GPR core test apparatus **(b) Recorded GPR data**

Figure 4.12 Example of GPR data (A-scan) collected from core

For each test conducted, GPR pulse travel time data was recorded to within 0.03ns, and A-scan displays of travel time against reflected signal amplitude were used to determine the locations of the upper and lower faces of the core (see Figure 4.12). This data was then used in Equation 3 in EngD Paper 4 (Appendix D) to calculate the dielectric constant for the core material, in the condition tested.

4.5.2.5 Research results

The findings of the research are presented and discussed in detail in Sections 3 and 4 of EngD Paper 4 (Appendix D). Figure 1 from EngD Paper 4 (Appendix D) shows the full results for the temperature testing, where a general trend can be seen that, for each individual core tested, the calculated dielectric constant increases as the test temperature increases. The mechanism causing the increase in dielectric constant with temperature is discussed in Section 4.1 of EngD Paper 4 (Appendix D).

After the temperature test programme had been conducted, 3 cores were selected for re-testing to assess the reproducibility of the test results, at temperatures of -5^{0}C, 15^{0}C and 45^{0}C. The temperature re-tests showed the same general trend apparent in the original testing, and showed individual dielectric constant results which varied from original results by an average of approximately 1.5% (i.e. a difference in the dielectric constant value of approximately 0.12 between original tests and re-tests of the same core at the same condition).

Comparing results from the re-testing to the original tests, the possible uncertainty in overall trends in the temperature testing results, presented in Section 3.1 of EngD Paper 4 (Appendix D), could be expressed as:

- Average increase in dielectric constant value (between -5^{0}C to 45^{0}C) = 13.5% +/- 3.5%;
- Average dielectric constant increase per degree C increase in temperature = 0.27% +/- 0.07%.

The results from the moisture testing on all 20 cores are shown in Figure 2 in EngD Paper 4 (Appendix D), and for each core a clear increase in dielectric constant can be seen from 'dry' to 'soaked' conditions (with an average increase of approximately 16%). The mechanism for the increased dielectric constant with increased moisture results is discussed in Section 4.2 of EngD Paper 4 (Appendix D).

Re-testing of 3 cores at 'dry' and 'soaked' moisture conditions to determine the reproducibility of moisture results showed a similar degree of variation between original and re-test dielectric constant values as shown in the temperature re-testing (approximately 1.5%

difference). The results of the original testing and re-testing indicated that the average increase of dielectric constant from ‘dry’ to ‘soaked’ conditions should be expressed as 15.6% +/- 2.4%.

Whilst the moisture testing at ‘dry’ and ‘soaked’ conditions allowed an overall relationship to be confirmed, further questions arose as to the precise relationship between moisture content and dielectric constant, and with this in mind an undergraduate student research project was planned and undertaken to follow on from the moisture work described above. Using the procedures and methodology designed for this research task, a new set of core testing was conducted under close guidance and supervision, and results showed the same general relationship between moisture and dielectric constant but allowed a greater degree of quantification of the relationship, by testing of cores at a range of moisture contents. It is hoped that results from this new study will be combined with the other work conducted in this area and published in the future.

Towards the end of the EngD project research period, in 2008, the knowledge and capability gained, relating to the effect of moisture on the dielectric properties of pavement materials, allowed Jacobs to act as a supervising engineer to direct an investigation in Poland using GPR to determine areas of excess moisture within the base course of a motorway pavement (see Chapter 5).

4.6 REVIEWING AND INVESTIGATING ERRORS AND UNCERTAINTY IN GPR DATA

4.6.1 RESEARCH CONSIDERATIONS

Whilst pavement investigation data of all types contains a degree of error and uncertainty, it is not uncommon for data to be used with little detailed consideration for their presence or significance. The relatively short history of GPR in pavement investigation and the specialised nature of GPR theory and equipment can often lead to a lack of appreciation of both the applicability of the technique and of the usefulness of the results, and so it is important that both the data provider (a GPR specialist) and the data user (often a pavement specialist) understand and appreciate the limitations and applicability of the technique, and are aware of what is expected from the GPR investigation.

Geophysical surveys, such as GPR, which do not meet the expectations of the end-user are a significant issue within civil engineering, and a variety of causes including insufficient knowledge of the physical principles, lack of confidence in the technique and over-selling of the technology have contributed to this, as discussed in EngD Paper 1 (Appendix A), Daniels (2004), Saarenketo & Scullion (2000) and Sirles (2006).

EngD objective 4 (see Section 1.4) was to determine the factors which affect the accuracy of GPR pavement investigations and to produce methods for managing those factors. This objective was the driver behind the research task described in this section, and several research activities were conducted:

1. Review previous work relating to accuracy of GPR investigations;
2. Identify main areas for error or uncertainty in GPR investigations;
3. Investigate the significance of typical errors in GPR data;

4. Consider and provide practical methods for managing errors and uncertainties associated with GPR investigations.

The overall subject area of errors and uncertainty in GPR is a very large one, and whilst it would be unrealistic to address every single topic related to error or uncertainty, this research task was intended to consider the main factors and to provide an insight into some of the approaches that could be used to manage or minimise them.

The previously described EngD research tasks (Sections 4.3 to 4.5) involved consideration of information determined from specific activities which, although often inter-linked, can be adequately described by discrete packages of work. However, much of this research task involved consideration of information from activities which were not conducted specifically to address the objective of this research task, including information obtained from other research conducted during the EngD project and from commercial GPR investigation projects for Jacobs. In addition to this, re-analysis of previously collected data and experimental analysis of data analysis procedures were conducted for this research task.

An overview of the work conducted was presented and published at the International Conference on Advanced Characterization of Pavement and Soil Engineering Materials, in Athens in 2007 (EngD Paper 5, Appendix E), summarising the main considerations undertaken during the research task. Section 4.6.2 expands on the summary provided in the paper and also provides a description of specific topics not covered in detail.

4.6.2 RESEARCH DETAILS

4.6.2.1 Review of previous work

The literature reviews (see Section 2.3) revealed some general information concerning typical depth accuracies that can be obtained from GPR data. Building on these reviews, a focussed review of previous work was then undertaken for this research task, in which the accuracy of depths determined from GPR data was investigated in more detail. The findings of several studies into the accuracy of GPR thickness determination are described in Section 2 of EngD Paper 5 (Appendix E), and Section 4.2 of EngD Paper 1 (Appendix A).

As highlighted in EngD Paper 5 (Appendix E), the review of previous work highlighted that many published studies on GPR accuracy are the result of research undertaken under closely controlled conditions which, although may be necessary for some studies (such as with the research described in Section 4.5), may not fully reflect the accuracy of GPR when used in practice. The work described in Section 4.4 also shows that a straightforward measure of depth accuracy for GPR data may not indicate the full nature of uncertainties and variation that can exist in reported information.

It can be difficult to state a quantitative value for some of the uncertainties in data that arise from sources such as data collection, analysis or processing procedures, but it is important to be aware of their sources and understand their significance so that their impact on the quality of output from a GPR investigation can be appreciated.

4.6.2.2 Identification of main sources of error

In addition to specific literature review investigations, much of the work undertaken during other stages and research tasks of the EngD project allowed knowledge to be gained which could also be used to identify the main sources of error in GPR investigations. There are a number of inherent limitations in capabilities of GPR, as a result of the physics and technology of the technique, and Section 2.2 provides a review of these. Section 4.3 describes the work undertaken to assess the effectiveness of fieldwork methodologies, and during this research task much knowledge was gained concerning ineffective, or limitations arising from, data collection procedures. Also, GPR data analysis activities conducted over the course of the EngD project and during commercial Jacobs GPR work provided the opportunity to assess and consider a range of issues associated with errors incorporated during the handling of GPR data.

The overall consideration of all of the above allowed an assessment to be made of the main sources of error or uncertainty in GPR investigations, and these were broadly categorised into three areas, stated in Section 2.3.4, and also discussed in EngD Paper 5 (Appendix E):

- Technological and scientific
    - Limitations in the science (physics)
    - Limitations of the hardware
- In-situ investigation methodology
    - For GPR data collection
    - For collection and incorporation of other pavement data
- Data analysis procedures
    - Data processing and analysis (including analyst interpretation)
    - Presentation methods

Several issues associated with the categories above can be easily controlled and altered to optimise the investigation, but other factors (especially those such as physical limitations in the science of GPR) are less controllable. There are also some issues which require more holistic consideration, and which span more than just one of the three broad categories listed above.

Technological and scientific issues

A background to the science of EM wave propagation, including an overview of the limitations, is given in Section 2.2. Also, in each of the EngD papers (Appendices A to E) brief summaries are given of the scientific limitations relating to GPR, including the importance of the dielectric properties of the materials under investigations, the significance of the reflection coefficient and the influence of antenna signal frequency on depth penetration and data resolution.

Scientific constraints of the technique have several other important limitations. In particular, situations can occur where the type or condition of the pavement materials affects their dielectric properties which in turn impacts on the effectiveness of GPR, and these are summarised in Section 2.3 of EngD Paper 5 (Appendix E).

The distinction between precision and accuracy is an important one and had to be considered throughout the reporting of GPR data during the EngD work. It is common for GPR processing software, including that used during the EngD, to report depth values to the nearest mm. Whist this is a highly precise value, if the true depth is several hundred mm different from the reported value it is also highly inaccurate. Data presented to a high precision can give a misleading impression of accuracy, and the accuracy of the information is a function of the entire investigation methodology used including factors such as efficient data collection, accurate calibration and competent interpretation of data.

The precision to which signal travel times (and hence depths) can be determined is a function of the frequency of the GPR signal, but is also greatly influenced by GPR system parameters such as the number of samples per scan (see Section 2.2.3.3). Each recorded GPR scan (i.e. the record of received signal amplitude during the selected recording time window, at a distinct location) is digitised, and 512 samples per scan (i.e. 512 individual recordings of signal amplitude along the length of the scan) are typical for GPR data recording. Greater samples per scan increase the detail recorded of the scan, but also increase the data file size and slows the data collection speed possible, and so a reasonable compromise has to be made.

Typically for the data collected during this EngD, and also reasonable for typical expected thicknesses of bound pavement material layers, a time window of approximately 10-20ns was generally used for recording of GPR scans. At 512 samples per scan this gives a sample approximately every 0.02-0.04ns along the length of the scan. Depending on the signal velocity, these data collection parameters correspond to a data point (sample) at approximately every 2-4mm along the depth of the pavement material, and Figure 4.13 illustrates the process used during pavement data analysis. On the data shown, an interface between material layers has been identified, and marked on each individual GPR scan, as seen in Figures 4.13(a) and 4.13(b). Using GPR processing software (in this case REFLEXW) the location of the interface can be picked manually (or where data is of sufficient quality semi-automatic processes can be used). Figure 4.13(c) shows the wiggle display of an individual GPR scan (with 512 samples) and how this corresponds to both the grey-scale display used for data analysis, and to the chosen location of the identified interface in Figure 4.13(d).

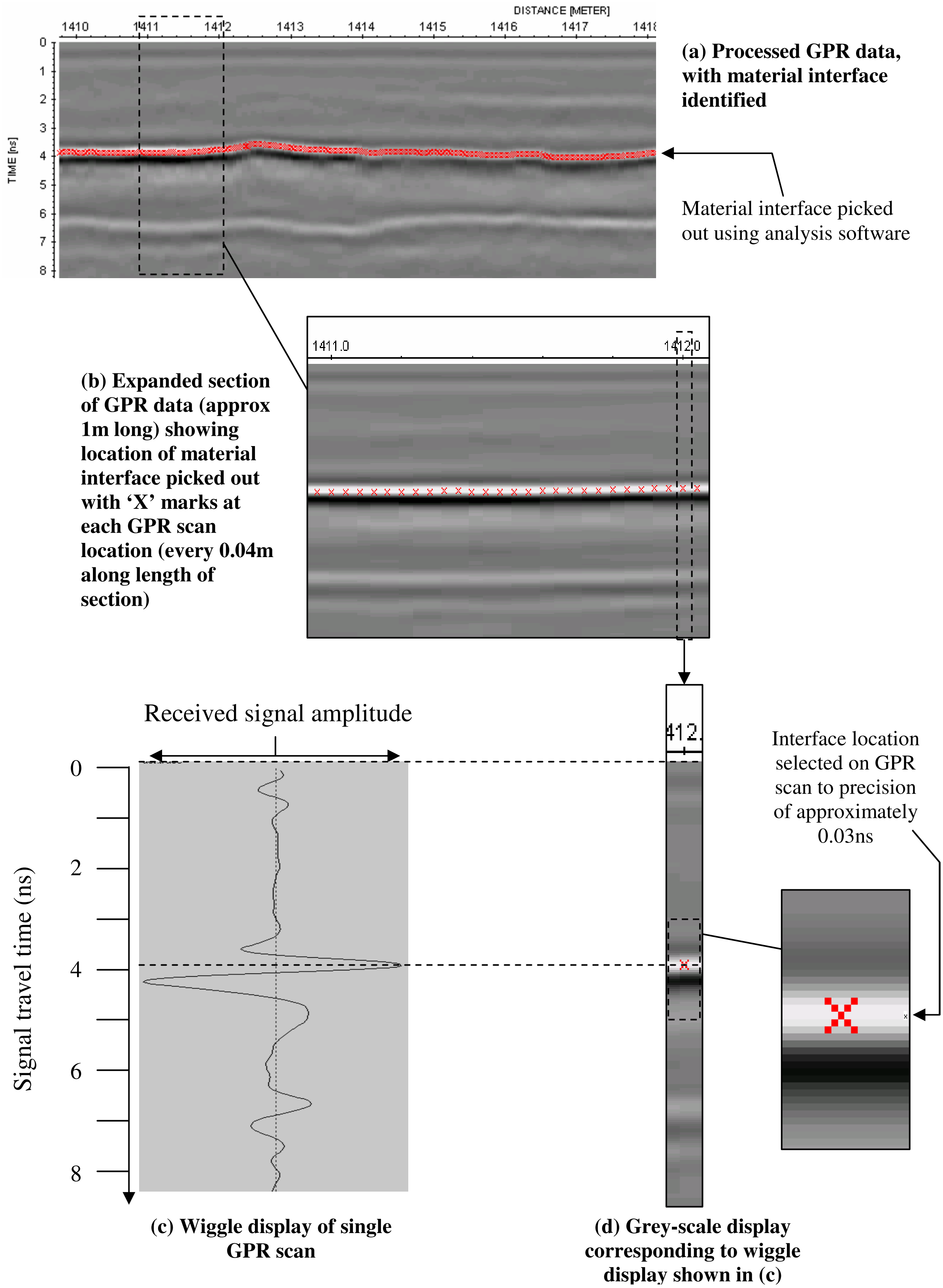


Figure 4.13 Use of analysis software to locate interface in GPR data

Another important factor to consider during analysis of data in the EngD work was the ability to distinguish 2 vertically separated features. Vertical data resolution (i.e. the minimum distance that can exist between two vertically separated features, for them to be individually recognisable in GPR data) is discussed in Section 2.2.4, and can be estimated from Equation 4.2, below.

$$Rv = \frac{1}{4}\lambda \qquad (4.2)$$

where Rv = vertical resolution, λ = wavelength of the GPR signal and:

$$\lambda = \frac{V}{f} \qquad (4.3)$$

where V = velocity of radar wave through the material, and f = signal frequency.

Equations 2.3 (see Section 2.2.1.2), 4.2 and 4.3 describe how the signal frequency (and thus wavelength) and the dielectric constant (and thus signal velocity) affect the vertical resolution. Signal frequency can be selected for each GPR investigation, but the dielectric constant of the material(s) under investigation cannot, and so each site or material and each specific GPR system configuration will have slightly different data resolution.

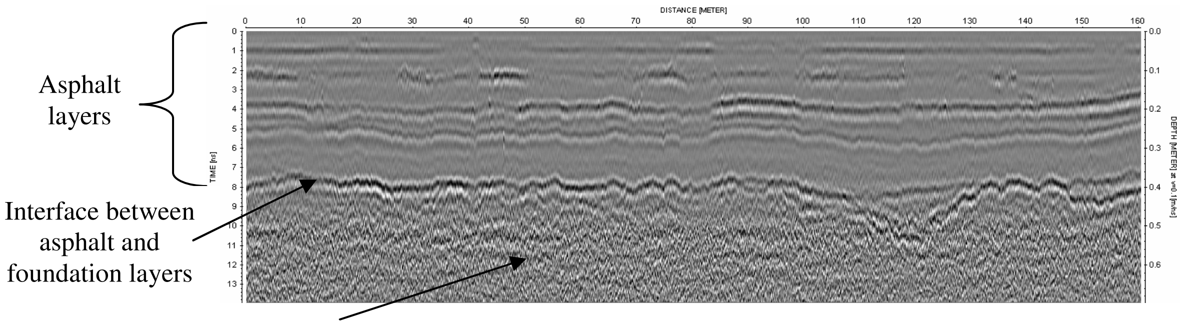
Antennas of 1.5GHz, 900MHz and 400MHz frequencies were used to collected data during the EngD research, but where depth penetration was sufficient, the higher resolution 1.5GHz data was used for analysis. The choice of antenna frequency has large implications for precision and uncertainty in the data. Using the previous equations, and using GPR system parameters and material properties typical of those in this EngD project, Table 4.2 shows typical values for expected vertical resolution. Examples of data collected using both 1.5GHz and 900Mhz antennas on the same section of pavement are shown in Figure 4.14(a) and 4.14(b), where differences in depth penetration and data resolution can be seen.

Table 4.2 Vertical resolution and depth penetration possible with typical GPR parameters used

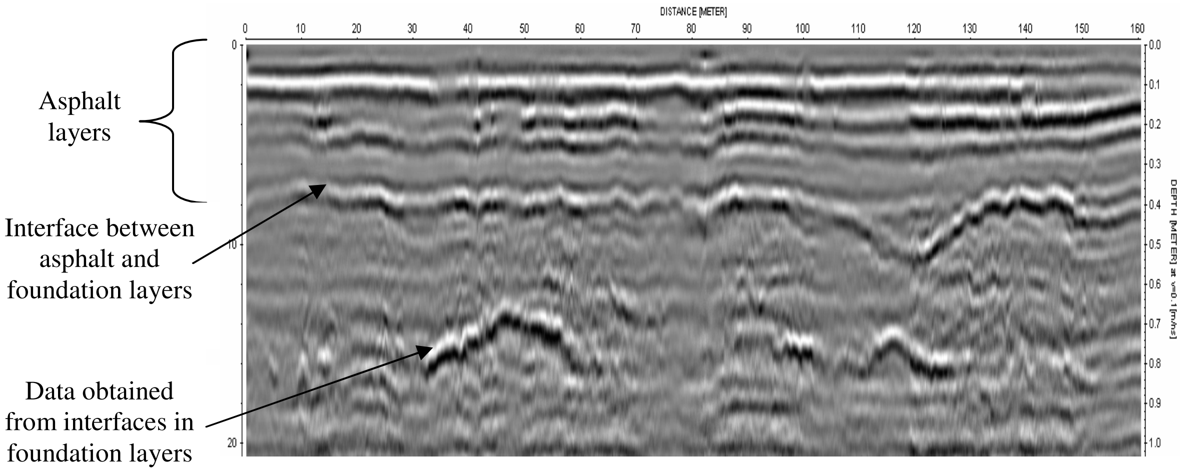
Antenna frequency[a], f (Hz)	Wavelength[b], λ (m)	Signal velocity[c] in material (m/ns)	Vertical resolution[d], Rv (m)	Example of data obtained with given system and site parameters	Typical approximate signal depth penetration in asphalt material[e] (m)
1.5GHz	0.067	0.1*	0.017	See Figure 4.14(a)	0.5
900MHz	0.111	0.1*	0.028	See Figure 4.14(b)	0.9

[a] Selected by GPR operator.
[b] Function of antenna frequency and signal velocity (see Equation 4.2).
[c] Function of pavement material properties relating to the materials dielectric constant (see Equation 2.3).
[d] Function of antenna frequency (selected by GPR operator) and signal velocity (property of material).
[e] Function of antenna frequency (selected by GPR operator) and signal attenuation in material (property of material).
*Actual signal velocity would be determined by calibration, but approximately 0.1m/ns is typical for asphalt material studied during the project.

Table 4.2 provides an illustration of the limitations of collecting data with only one antenna. Whilst the limitations of individual antennas cannot be overcome, the selection of appropriate antenna frequency is an example of managing the data collection methodology to address limitations in the science of the technique. The research task described in Section 4.3 also involved investigation and optimisation of this and other aspects the data collection methodology to, in part, address scientific GPR limitations.



(a) GPR data from 1.5GHz antenna



(b) GPR data from 900MHz antenna

Figure 4.14 1.5GHz and 900MHz GPR data collected from the same section of pavement

Data collection methodology

EngD Paper 2 (Appendix B) and Section 2.3 of EngD Paper 5 (Appendix E) describe several choices that can be made in GPR data collection methodology to minimise uncertainty or error in collected data, including consideration of the antenna frequency, the number and location of survey lines and the number of scans per metre taken along the survey line. The commercial GPR work conducted by Jacobs also highlighted the importance of accurately recording locations during data collection, and also accurately correlating GPR locations to other data locations, such as FWD test points or core locations (especially when these may be recorded on different dates by different contractors, often using different location methods). Jacobs experience has shown that one of the main sources of uncertainty or error in pavement investigation data is from poorly recorded or uncertain location information.

When referencing the location of GPR survey runs, commonly the distance from a fixed point is measured by the GPR system survey wheel, and this approach was undertaken for both EngD and Jacobs commercial pavement investigation work. Placing digital markers directly onto the GPR data as it is recorded and marking fixed site features such as core locations (as described in Section 4.4.2.1) allows locations to be checked and re-located along the survey profile during data processing, to address the issue that survey wheels and other distance measuring instruments (DMI's) are not 100% accurate. This procedure can be less suitable for high speed surveys however, and another option to address location errors is the use of global positioning systems (GPS), as discussed in Section 4.3.2.2.

Incorrect location information can have a significant affect on the accuracy of core calibration of GPR data, and Table 4.3 provides an example of the error in depth information introduced solely from inaccurate location information. For the data shown in Figure 4.14(a), a core at chainage 100m showed an asphalt depth of 395mm. However, if the location of the core was taken to be 99m (i.e. an error of 1m from the true location of the core), a 4% error is introduced to the calibration velocity, which would then propagate through to errors in the depth information provided from the GPR data.

Table 4.3 Error in core calibration value caused by inaccurate core location

	Recorded two way signal travel time	**Depth of asphalt [a]**	**Calculated Signal velocity**	**Error in signal velocity**
Calibration[a] values using GPR data at chainage 100m[b]	7.88ns	395mm	0.100m/ns	None
Calibration[a] values using GPR data at chainage 99m[c]	7.56ns	395mm	0.104m/ns	4%

[a] Using core data showing asphalt thickness = 395mm.
[b] Correct core location.
[c] Error in core location of 1m.

It may also be possible that variations in pavement material type or condition could result in different calibration velocities for different cores taken along the same GPR survey line. This issue is discussed and addressed in EngD Paper 3 (Appendix C). For all situations where other data is incorporated with findings from GPR, the quality of the data should be noted. The accuracy of information reported from GPR surveys can be heavily reliant on calibration or correlation with other data and so projects where it has been reported that the GPR investigation has not met expectations may not have been a result of poor GPR work, but of poor incorporation of other data, or incorporation of poor data.

Data analysis and presentation

During the processing and analysis of GPR data conducted throughout the EngD project, various processing and analytical procedures were used, depending on the purpose of the work. As stated in Section 4.2, typically raw GPR data was subjected to static correction and background removal before analysis was undertaken. Such common processing procedures have a relatively small impact on the potential for introducing errors into data analysis. However, the subjective nature of GPR data analysis can result in situations where different analysts can produce different interpretations of the same data set, as illustrated in Figure 1 in EngD Paper 5 (Appendix E). Figure 4.14 shows the first 160m of data from the 400m GPR survey shown in Figure 1 of EngD Paper 5, where the uncertainty in the layer data between approximately 100 and 130m can be seen. Such situations highlight that the input of the analyst should not be a case of producing the information (e.g. depth) alone, but also in communicating the uncertainties or confidence level in the information.

The appropriate consideration of the final presentation of results is important and can sometimes be overlooked. A well conducted investigation can be severely diminished by presenting results in a format which does not efficiently communicate the appropriate information, and the objective of the investigation must be considered during the results presentation stage. Experience gained during commercial GPR investigation work for Jacobs has shown that it can sometimes be easy for the GPR specialist to overlook the fact that the information user may be unused to, or inexperienced at, handling GPR information and presentation of information which appears uncomplicated to the specialist may be confusing to the non-specialist. The distinction between 'knowledge', which is the intended outcome for the end user, 'information' which is the interpretation of pavement properties provided by the GPR operative, and 'data', which has little use to the non-specialist, is important. Data only becomes information through efficient analysis, and information only becomes knowledge when the presentation and communication is effective.

4.6.2.3 Investigation of the significance of errors

One of the most common uses of GPR is to provide pavement layer thickness values (Al-Qadi & Lahouar, 2005 and Infrasense, 2006), and it is this use of GPR that forms a large proportion of the commercial GPR work conducted by Jacobs, especially for the determination of pavement layer stiffness values from falling weight deflectometer (FWD) data (see Sections 2.3.2 and 2.3.3). The use of GPR allows a much more confident model of the pavement structure to be determined than by use of layer thicknesses from coring alone, and hence provides improved determination of layer stiffness and thus of pavement maintenance requirements. Consequently, one of the most relevant and important areas of concern for Jacobs is to assess the effect of errors in GPR layer thicknesses data used during the calculation of material stiffnesses from FWD data.

To investigate the effect of using inaccurate thickness values in the back analysis of stiffness values, an investigation was undertaken where the assessment of pavement layer stiffness was conducted using different thickness values for input into the layer stiffness analysis. FWD deflection data was collected along a 1km section of a newly constructed section of the A66 trunk road in Cumbria, northern England, consisting of an asphalt pavement over a granular sub-base. For data collection an improved methodology involving the use of both FWD and GPR simultaneously from the same vehicle was trialled (see Figure 4.15), that was in part a development undertaken from the findings of the research described in Section 4.3, and which has since gone on to become the routine data collection methodology for Jacobs pavement investigation projects (described further in Section 5.2).

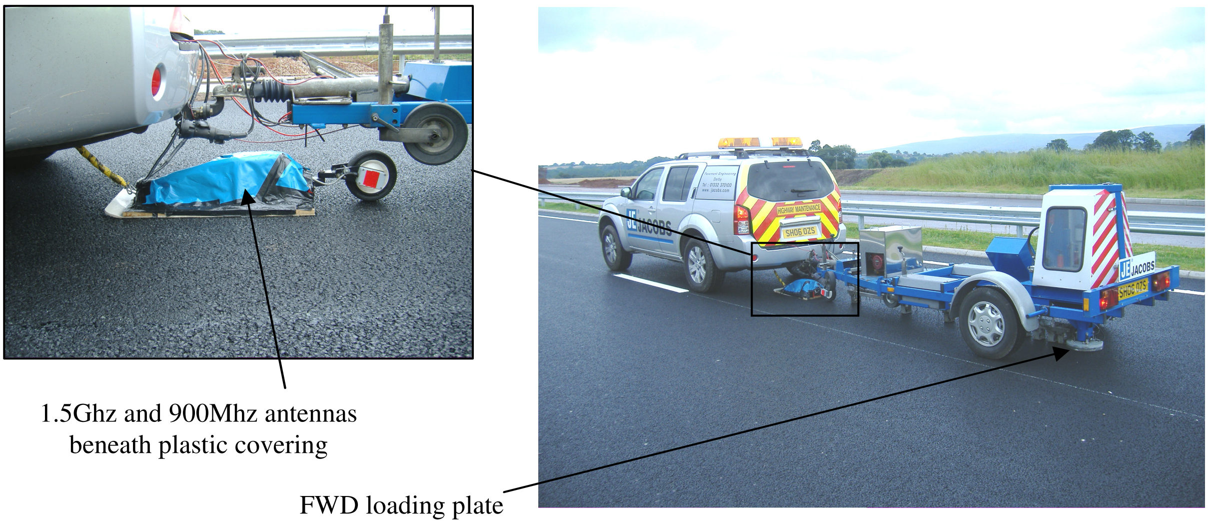


Figure 4.15 FWD and GPR data collection on a new build section of the A66, Cumbria

Data was collected from 1.5GHz and 900MHz antennas during a slow speed survey (GPR scans at 0.04m spacings) along the same wheel-path as the FWD testing, and the signal penetration and quality of the 1.5GHz data was sufficient to be able to identify pavement layers down to the bottom granular sub-base (see Figure 2.9 for an example of data obtained at the A66 site). The GPR data was calibrated with as-built and intrusive data supplied by the pavement construction contractor, and for the 1km section investigated the asphalt pavement had an average thickness of 320mm.

The FWD tests, at 50kN loads, were conducted at 20m intervals along the pavement with pavement deflections measured at 9 geophone locations, from beneath the loading plate to up to 2.1m away. The deflection and layer thicknesses data was then modelled using ELMOD software, one of several available programs which uses the DMRB recommended method of linear elastic multi-layered analysis for calculating layer stiffness. The pavement models created in ELMOD were used to determine the asphalt and sub-base layer stiffness at each of the FWD test locations, using a 3 layer model (asphalt and sub-base over a nominal 100MPa lower foundation). The layer stiffness analysis was then re-run several more times with the same parameters and 3 layer model, but with asphalt thickness data altered by various amounts up to +20% and -20% from the original values. Figure 4.16 shows the results of the study, in which the average asphalt stiffness for the pavement was calculated to be approximately 8300MPa when modelled with the correct asphalt layer thickness of 320mm.

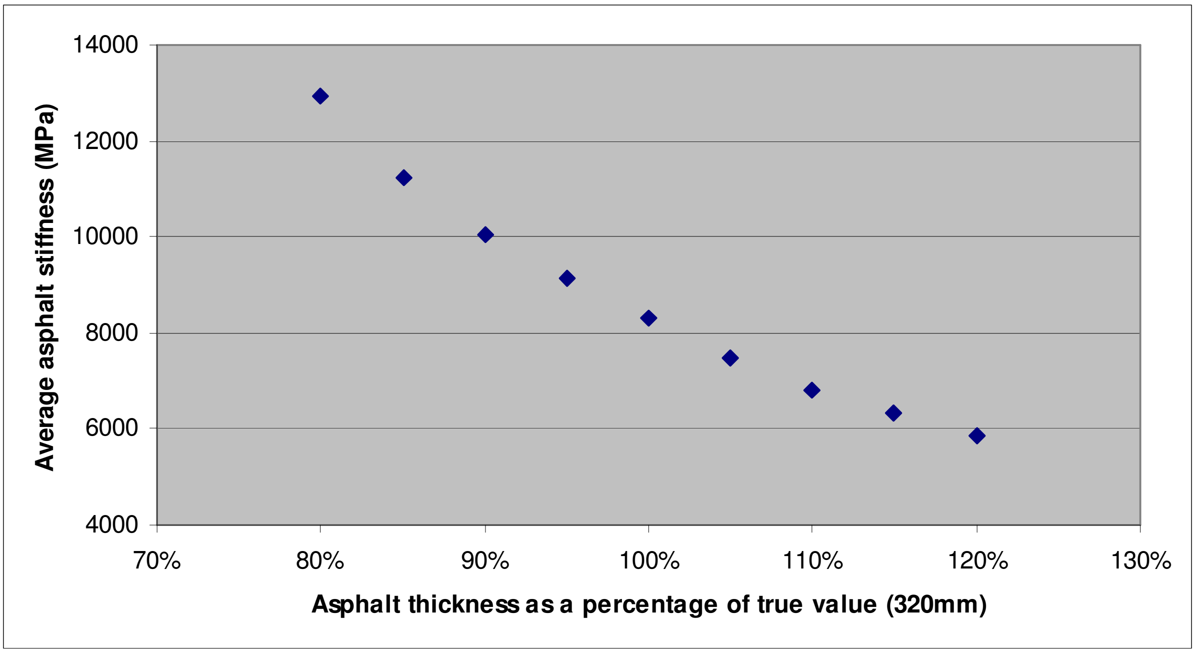


Figure 4.16 Variation in calculated pavement stiffness values caused by use of inaccurate depth data.

When the modelled asphalt layer thickness values were altered by 5%, the calculated average asphalt stiffness altered by approximately 10% compared to the initial calculations using correct data. Changes in asphalt thickness of +20% and -20% produced -29% and +55% changes in stiffness values respectively. Changes in the calculated average sub-base stiffness were also produced (of -8% to +19% respectively, for +20% to -20% changes in asphalt thickness), even though the modelled sub-base thickness remained constant. Such pavement material stiffness errors could lead to significant over-design or under-design of maintenance treatments.

The DMRB states that when determining layer thicknesses “for the accurate interpretation of Falling Weight Deflectometer results accuracies of ±6 per cent or better are required. GPR trials have shown that at slow speed (<25km/h), GPR could determine the combined bound layer thickness with an accuracy of approximately 5 per cent of the real thickness. However, at traffic speed (70km/h) the error could increase to approximately 9 per cent”. Using the information from the study described above, this would result in an error in calculated asphalt stiffness when using layer thickness from slow speed GPR of up to approximately 10%, and when using high speed survey data of up to 20%.

The potential for error shown by the study highlights the importance of the use of accurate thickness data during calculation of stiffness values from FWD deflection data, but all other applications of GPR investigations (see EngD Paper 1, Appendix A) also carry their own risks which are increased if the uncertainty in GPR data is not managed correctly.

4.6.2.4 Methods for management of errors

The aim of the EngD was to provide improved pavement investigation capabilities by enhancing the methodologies and procedures used to obtain information from GPR. This aim has resulted in a common theme in each of the research tasks (see Sections 4.3 to 4.5), in which their findings have included methods which suggest ways to improve the application of GPR. EngD Paper 2 (Appendix B) provides recommendations for a data collection methodology, EngD Paper 3 (Appendix C) includes details of a method for quantifying the amount in-situ variation in properties of pavement materials and EngD Paper 4 (Appendix D) describes the effects of changes on the pavement material condition on the response of GPR. All of these investigations, at least in part, contribute information to the objective of this research task, which was to determine factors which affect the accuracy of GPR pavement investigations and produce methods for managing them.

In addition to the findings from other research tasks, to fully address the objective of this research task several research activities were undertaken, from which a number of practical measures to limit and manage the main sources of error discussed above were considered. Whilst it would be impractical, not to say impossible, to address every issue in full within the scope of an EngD study, EngD Paper 5 (Appendix E) provides an overview of some of the main factors which can lead to errors in GPR data, and an investigation and appreciation of other significant issues has been given in this section.

Many of the factors investigated rely heavily on the competency of the GPR operative or analyst, and their actions, resulting from a combination of the individual's skill, training, experience and knowledge of both ground radar and pavements, can greatly influence the information output from GPR. Indications of GPR operative competence can be provided in the form of examples of previous work and experience, or possibly through relevant qualifications in engineering or geophysics, but currently there is no formal system or accreditation in place for GPR providers. Membership of organisations such as EuroGPR (see Section 1.2.4.2) may provide an indication, and recently EuroGPR has proposed to introduce a voluntary training-based course, which may provide an indication (although not a guarantee) of competency. In the UK, the HA have also proposed to introduce an assessment of ability and accreditation scheme for potential GPR contractors for HA projects (Lagarde-Forest et al., 2008), although it is important that any such accreditation scheme should be both appropriate and workable for there to be any added benefit from their introduction.

The success or failure of an investigation ultimately rests with the level of knowledge which is imparted to the end user. For all individual issues requiring consideration, the overall objectives of the survey should remain in focus, and a holistic approach both to the GPR work and to other data which compliments the GPR investigation, should be maintained at all times. Both the GPR operatives and the information end-user have to be aware of what is expected from the GPR data collected. If the (often non-specialist) end user is educated concerning the relevant issues and applicability of GPR then their expectations are realistically set. Problems can arise where the GPR operative over sells the capability of the GPR, leading to unrealistic expectations, or where the end user does not appreciate the information that they are being provided with. However, it is important for users of GPR information to appreciate that there may be some situations where the physical site conditions mean that, even if every other aspect of the GPR investigation is conducted to the highest standard, the GPR data acquired will not adequately identify features, and Section 3 of EngD Paper 5 (Appendix E) discusses the importance of communicating the accuracy or quality of information presented.

5 CONCLUSIONS

5.1 OVERVIEW

This chapter provides a summary of the key findings of the research, and aims to highlight the innovative aspects of the work and the contribution to existing GPR practice. A description is given of the impacts of the research that have directly benefited Jacobs, and also those issues that are of relevance and importance to the wider industry concerned with GPR and pavement investigation. This chapter also includes a critical evaluation of the research undertaken, and recommendations for industry and further research in this subject area.

5.2 THE KEY FINDINGS OF THE RESEARCH

5.2.1 INTRODUCTION

This EngD project involved several research tasks, each consisting of a discrete package of work, as described in Chapter 4. The research tasks, along with the literature review undertaken during the EngD, were used as the main source for the five EngD publications (Appendices A to E). Table 5.1 summarises the main focus for each of the published papers.

Discussion of the results from the work are included within each of the published papers, but the key findings arising from the research tasks described in Sections 4.3 to 4.6 are summarised in Sections 5.2.2 to 5.2.5 respectively.

Table 5.1 Main topics addressed in each published EngD paper

EngD publication	Objective 1[a]	Objective 2[b]	Objective 3[c]	Objective 4[d]
Paper 1, Appendix A: A review of pavement assessment using ground penetrating radar (GPR)	Background for all project objectives			
Paper 2, Appendix B: Ground penetrating radar investigations for urban roads	Main focus			Part focus
Paper 3, Appendix C: Assessment of in situ dielectric constant of pavement materials		Main focus		Part focus
Paper 4, Appendix D: The response of ground penetrating radar (GPR) to changes in temperature and moisture condition of pavement materials			Main focus	Part focus
Paper 5, Appendix E: Variation in information obtained from interpretation of ground penetrating radar (GPR) pavement investigation data				Main focus

[a] Objective 1: Devise improved procedures for conducting GPR investigations used to provide information for structural pavement assessment.
[b] Objective 2: Develop methods for enhancing the amount of information that can be obtained from GPR pavement investigation data.
[c] Objective 3: Establish the significance of material properties determined from GPR, and how they relate to the condition of the pavement.
[d] Objective 4: Determine the factors which affect the accuracy of GPR pavement investigations and produce methods for managing them.

5.2.2 EFFECTIVE FIELDWORK METHODOLOGY

The work described in Section 4.3 produced recommendations for fieldwork methodology for detailed GPR investigation of variable pavements structures, often encountered in urban roads, for which there does not currently exist any specific guidance or standard documentation. The key findings of the work are:

- Data collection using several antennas, of different frequencies, should be conducted to provide the optimum coverage of depth of penetration and data resolution.
- Survey runs should be conducted along a number of parallel longitudinal and transverse profiles along and across the pavement, to ensure that variations in layer depths and the horizontal extent of features are fully investigated.

- Despite the disadvantages of slow speed surveys (increased time to conduct data collection and the need for traffic management), they are required for detailed surveys so that a high scan rate can be achieved, to provide adequate data coverage for identification of all relevant features in the pavement. Data from high speed surveys should only be used as an overview, and not to plan maintenance treatments.

The findings from this work have shown the benefit of collecting information at slow speed and using transverse survey runs, which in turn necessitates the use of traffic management and/or slow moving survey vehicles. Hence, this methodology creates associated safety issues which will require adequate consideration, but the use of such investigation methodology must be considered if the optimum amount of pavement data is to be obtained.

5.2.3 ENHANCED INFORMATION FROM GPR DATA

The work described in Section 4.4 provided a method for assessment of the in-situ dielectric constant of asphalt pavement material, without modification to established pavement investigation methodology, in order to assess material condition properties and variability. The key findings of the work included:

- Variations of the in-situ condition of a specific asphalt material mix can cause the dielectric constant to vary by over 10%. Air voids within the asphalt, and disintegration of material, decreases the dielectric constant. Hence, lower dielectric constant values are produced by material of poorer condition, and thus may indicate material of lower stiffness.
- Generically similar asphalt materials of a similar condition can have in-situ dielectric constant values that vary by over 20% from site to site, which emphasizes the need for accurate calibration of data on a site specific basis.

- 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, in order to produce accurate depth values from the GPR data.

5.2.4 TEMPERATURE AND MOISTURE EFFECTS ON ASPHALT PROPERTIES

The work described in Section 4.5 consisted of laboratory testing under controlled conditions of the changes in asphalt dielectric constant, determined by GPR, caused by variations in temperature and moisture condition of the material. The research established a relationship between both the temperature and moisture content of asphalt samples and their dielectric constant, which has great significance for the use of GPR for applications where dielectric constant is directly calculated during analysis of the pavement. Key findings from the work included:

- The dielectric constant of asphalt materials increases with temperature, and the mechanism for this is likely to be the increased re-orientation ability of dipoles, resulting from the increase in thermal energy.
- The dielectric constant of asphalt material increases with moisture, as a result of the relatively high dielectric constant of water (compared to asphalt) increasing the overall bulk dielectric constant value of the material mix. The change in the dielectric constant of asphalt material as a result of wetting is likely to be greatly influenced by the amount of deterioration and air voids present in the material matrix.
- The dielectric properties are material specific, and generically similar bituminous materials do not necessarily have the same dielectric constant. As with findings highlighted in Section 5.2.3, this point reinforces the issue that 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 significant effect of temperature on dielectric properties of asphalt means that when a GPR investigation is conducted to obtain information on pavement material condition through assessment of the materials dielectric properties, the temperature of the pavement layers should also be obtained. The temperature of the pavement material is particularly significant for temporal or seasonal GPR surveys where changes in material dielectric properties (caused by moisture changes, or material deterioration) are monitored over time.

5.2.5 REVIEWING AND INVESTIGATING ERRORS AND UNCERTAINTY IN GPR DATA

The work described in Section 4.6 consisted of a focussed review of literature, a review of information obtained from the other research tasks (Sections 4.3 to 4.5), and also a number of studies focussed at addressing specific research topics. The key findings of the work included:

- The main sources of error and uncertainty can be categorised into three broad areas:
    - Technological and scientific issues (including limitations in the science and the hardware/software);
    - In-situ investigation methodology (including that for GPR data collection and that for collection and incorporation of other pavement data);
    - Data analysis procedures (including data processing, analysis and presentation methods).

- Although pavement layer thicknesses derived from calibrated GPR data are more applicable than data obtained from coring alone, the use of GPR thickness data in determination of asphalt layer stiffness from FWD data may introduce errors in calculated stiffness values of up to approximately 10% when using layer thickness from slow speed GPR, and of up to 20% when using high speed survey data.
- The education of current and potential users of GPR information is an extremely important issue, as many of the perceived and actual failures of GPR investigations to deliver expected results has arisen because of lack of knowledge and understanding of the technique. The responsibility for this education is largely that of the GPR industry.
- The subjective nature of some aspects of GPR data analysis and interpretation will inevitably result in a degree of uncertainty in information produced from GPR investigations, and this is affected by the GPR analyst's competence.
- Reporting an overall expected uncertainty level, or an indication of confidence in the information reported, is recommended for all results determined from GPR survey data. Sometimes this can take the form of quantified values in potential errors, and other times this can be a more qualitative indication of the quality of information interpreted from GPR. The success or failure of any investigation will ultimately rest with the level of understanding or knowledge that is imparted to the end user.

5.2.6 SUMMARY

In addition to the above, several key findings also overlapped different research tasks, and similar conclusions could be drawn from separate investigations conducted. The key findings which encompassed the entire project and were not limited to specific individual research tasks were:

- Users and clients for GPR information should be made aware of the various uses and limitations of the GPR data, and the fact that different applications of GPR often require very different investigation and analysis methodologies, depending on the site specific conditions and the purpose of the GPR work.
- When GPR is used as part of a larger pavement investigation, involving other techniques, to provide the optimum output from GPR a conscious effort should be made to integrate survey techniques. Dialogue should be ongoing between the different members of the investigation team, including the GPR survey team, other survey teams, engineers, project managers, client, etc, before, during and after data collection, to provide a co-ordinated approach to the investigation.
- For a GPR pavement investigation, accurate locations for fixed features, including any core locations used for calibration, is of utmost importance and inaccurate location data is one of the main sources of error in reported information.
- Calibration of GPR data is required to determine accurate depths from GPR pavement investigation data, and intrusive surveys (usually in the form of cores) provide the most accurate options for calibration.

The issues requiring consideration to optimise GPR pavement investigations include the uncertainty in data, the adequate representation of complex structures and materials, and the optimum role and responsibilities of the information provider and information user. For all individual issues requiring consideration, the overall objectives of a GPR survey should remain in focus, and a holistic approach both to the GPR work and to other data which compliments the GPR investigation, should be maintained at all times.

5.3 IMPLICATIONS AND IMPACT ON THE SPONSOR

Prior to commencement of the EngD project in October 2004, Jacobs did not have an in-house GPR capability of any kind, and had required the use of GPR contractors to obtain data during several pavement investigation projects. As a direct result of the EngD project Jacobs developed an in-house capability, which has had both financial and technical benefits, with the first GPR data collection work (using a hired SIR-10H system) commencing in January 2005. Success of GPR work led to the purchase of a SIR-20 system in October 2006, which has been used to date for numerous commercial projects, as well as for EngD research work.

The GPR capability now offered by Jacobs (in the Pavement Management team, based in Derby, UK) comprises the first GPR system to be owned and operated by Jacobs, and staff are sufficiently trained and experienced in data collection, analysis and reporting so that GPR has become a standard tool of Jacobs pavement investigation process. Commercial GPR work has averaged at approximately 100 on-site data collection shifts per year in 2007 and 2008, and in 2009 the use of GPR has expanded with some projects also involving hire of a SIR-3000 GPR system (specifically adapted to detailed surveys by hand) in addition to ongoing use of the existing SIR-20 system.

The findings of the EngD research have allowed Jacobs to develop knowledge applicable to the close integration of data collection, analysis and interpretation with that of other data. Prior to commencement of the EngD, the main pavement investigation equipment operated from the Jacobs Derby office was the FWD, and the integration of GPR and FWD data and technologies was both a research and commercial theme during the period of the EngD work. Jacobs improved capability, as a result of the EngD project, includes operation of both FWD and GPR from the same vehicle during data collection. The introduction of GPR as a routine technique for use alongside Jacobs other pavement investigation methods has resulted in an integrated approach to pavement investigation projects, and has produced the resulting pavement assessments and pavement maintenance treatments with reduced levels of uncertainty and risk.

The main area of commercial development that has resulted since the establishment of an in-house GPR capability has been structural road pavement investigation. However, there has also been a wide range of other commercial GPR investigation projects that have been possible since the start of the EngD work. These have included pavement and non-pavement related projects in the UK and Europe, including investigation of road pavement moisture, airport pavements, embankments, dock flooring, location of cellars, industrial floor slab investigations and utility location. All of this work, and all of the technical GPR capability currently offered by Jacobs, is a product of this EngD project.

5.4 IMPLICATIONS AND IMPACT ON WIDER INDUSTRY

The work conducted on the optimisation of GPR use for pavement assessment, has raised several issues for the GPR and pavement engineering industry. A clear and critical finding has been to highlight the site and material specific nature of the dielectric properties of asphalt materials, and to quantify some of the changes in those properties that can occur as a result of changes in the condition of the asphalt. This site specific nature of asphalt pavement material properties has stressed the importance of calibration of GPR data, in order to provide the optimum data from GPR surveys, and the importance of calibrating data on a site specific basis in order to produce accurate depth information, through the use of coring or other intrusive data, has been shown.

The methodology used to collect GPR data during pavement investigations has been shown to be optimised when it is conducted using GPR data as one of several integral data collection techniques, to be used in a co-ordinated overall survey methodology, rather than through use of 'stand-alone' investigations which attempt to combine data after the fact. Also, the integration of FWD and GPR technologies during data collection, by use of both techniques from the same data collection vehicle, has demonstrated the advantages of this approach from both financial and technical viewpoints.

It can often be the case that traffic speed surveys using GPR are specified by clients, because of their advantages of less disruption to traffic and less time to conduct surveys of a given length. However, these are only useful for an overview of pavement condition or properties, and it is important to appreciate that detailed information can only be collected with relatively slow speed surveys.

Various potential sources of uncertainty and error have been highlighted during this project, and a number of practical measures to limit uncertainties have been recommended. Incorporation of confidence or uncertainty levels within presented data should always be considered and communicated to the information user, if GPR data is to be used in the optimum manner.

During the course of this EngD project, in addition to the published papers (Appendices A to E) work from the research tasks, and also from Jacobs projects which have incorporated findings from the EngD work, have been publicised at a number of events, listed in Table 5.2.

The various events listed in Table 5.2, and the papers published during the EngD project have allowed the findings to be released to the wider GPR and pavement industry. As a result of this publicity, interest has been generated both in the UK and internationally, and enquiries have been received by Jacobs from a number of countries in addition to the UK, including Poland, New Zealand and the USA.

Table 5.2 Events publicising EngD findings to industry

Title	Date	Event
Integration of FWD and GPR	May 2006	Presentation at Institute of Asphalt Technology Annual Training Day, Blackpool, UK
Optimising the use of ground penetrating radar (GPR) for urban road investigations[1]	September 2006	Paper in Proceedings of the 10th IAEG International Congress, Nottingham, UK
Assessment of the in-situ dielectric constant of pavement materials[2]	January 2007	Presentation at TRB 86th Annual Meeting, Washington DC, USA
Variation in information obtained from interpretation of ground penetrating radar (GPR) pavement investigation data[2]	June 2007	Presentation at 'Advanced characterization of pavement and soil engineering materials' conference, Athens, Greece
Use of ground penetrating radar by Jacobs	October 2007	Presentation at EuroGPR Annual General Meeting, High Wycombe, UK
Assessing dielectric properties of road structures	February 2008	Article in Innovation & Research Focus, Issue No.72, Institution of Civil Engineers
Ground penetrating radar (GPR) use for pavement investigation	May 2008	Presentation at Postgraduate Research Seminar, Loughborough University, UK
A review of pavement assessment using ground penetrating radar[2]	June 2008	Poster display at the 12th International Conference on Ground Penetrating Radar, Birmingham, UK
The response of ground penetrating radar (GPR) to changes in temperature and moisture condition of pavement materials[2]	August 2008	Presentation at 1st International Conference on Transportation Geotechnics conference, Nottingham, UK
Pavement investigation, A2 motorway	September 2008	Presentation for GDDKiA (Polish Department of Transport), Poznań, Poland
Introduction to ground penetrating radar and analysis	November 2008	Presentation for Jacobs Pavement Management, Derby, UK
Pavement investigation	November 2008	Presentation for BEAR, Perth, Scotland, UK
Ground penetrating radar equipment and analysis	January 2009	Presentation for Transport for London (TfL) and Jacobs Ringway, TfL, London, UK
Falling weight deflectometer and ground penetrating radar interactive surveys	April 2009	Presentation at 'Impulsive Matters 2009' conference, Warrington, UK

[1] See Evans et al. (2006)
[2] Associated with EngD published paper

5.5 CRITICAL EVALUATION OF THE RESEARCH

The research was undertaken within the context of using GPR for pavement assessment, and as such the sponsoring company approached the topics from the viewpoint of pavement engineering, and how GPR can improve and assist in the understanding of structural condition and behaviour. Thus, it was necessary that the focus of the work was on the application of results mainly from the pavement engineer's perspective, and whilst this was extremely useful to focus the objective of the work on the application of GPR, there was little input into aspects where hardware or software development of GPR could have benefited the work. The work conducted used commercially available 'off the shelf' GPR systems, and whilst this was a result of the Jacobs need to establish a commercial GPR capability as rapidly as possible, it meant that no attempt was made to address technical GPR issues through development of hardware or software.

Also, further dialogue and discussion with the GPR specialist industry would have been useful, for example with members of EuroGPR and other GPR operators, to provide a forum for various wider technical GPR issues raised during the research. The requirement of Jacobs to implement and commercially exploit the research findings meant that an open discussion of many of the technical issues covered during the development of methodologies and procedures, before the full GPR capability was established within Jacobs, was difficult.

The assessment of in-situ dielectric properties of asphalt (Section 4.4) and the laboratory testing undertaken to investigate the effects of temperature and moisture on asphalt dielectric properties (Section 4.5) required a number of individual assessments to be made on individual asphalt samples taken from in service pavements. Both research tasks were limited in their nature, and although clear relationships could be established, both sets of findings could have been enhanced by larger testing programmes involving a larger data-set and also involving a greater range of validation testing, through repeat tests, which would have produced a more comprehensive analysis of relationships and greater confidence in results.

5.6 RECOMMENDATIONS FOR INDUSTRY AND FURTHER RESEARCH

Discussions with delegates at conferences attended as part of the EngD project, and correspondence received as a result of interest in published papers, has indicated that two of the main areas of concern for pavement assessment, and where full understanding is limited, are detection of layer de-bonding and moisture within pavements. Both of these areas are good candidates for further research, and investigation of the capability of GPR to successfully detect de-bonding, and the effect that moisture at the de-bond interface may have on the success of the technique, would prove useful for future application of GPR in this area.

Detection of the presence of moisture within pavement materials is an application for which GPR has been used, and research conducted in this EngD project addressed some issues and led to a further student project attempting to quantify the relationships between moisture content and dielectric response. Also, one of the commercial projects for which the Jacobs GPR capability, established as a result of the EngD project, was used for was to act as supervising engineers for an asphalt moisture detection project on a new build motorway in Poland. However, relatively few applications and case studies of GPR for this purpose have been published. Further work on the use of GPR to investigate moisture within pavements, especially on in-service pavement or full scale trial pavements, would help to quantify relationships and further validate and establish GPR for this purpose.

During the course of this EngD, dialogue with pavement engineers and GPR information users has raised many questions and queries about its capabilities, but the single most often asked question is “How deep can GPR see?”, the response to which is “It depends…”. This apparently simple question reflects much of the difficulty in education and awareness of GPR capabilities, in as much as information users want clear, precise answers that can be applied to all situations, but the nature of GPR is that it is often a site and situation specific technique, and whilst capabilities can be estimated before a job is undertaken, each project has to be assessed, planned, undertaken and reported whilst taking into account its own particular issues, materials, properties and purpose.

In order for the benefits of GPR to be fully exploited in pavement investigation, increased awareness must be generated of the both the benefits and limitations of GPR, amongst the users of pavement condition information. Much of this responsibility lies with the GPR industry, to educate current and potential users of GPR. This is not an easy task, and there is always the very real risk of over selling its capabilities, which can lead to inappropriate specification and application of the technique. The potential users of GPR for pavement information also have the responsibility to appreciate that whilst GPR will not provide all answers for all situations, the efficient application of GPR provides one of the most useful and versatile sources of structural pavement information, in a rapid and non-destructive manner.

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APPENDIX A PAPER 1

Full Reference

Evans, R., Frost, M., Stonecliffe-Jones, M. & Dixon, N. (2008).

A review of pavement assessment using ground penetrating radar (GPR).

Proceedings of the 12th International Conference on Ground Penetrating Radar, June 16th-19th 2008, Birmingham, UK.

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.

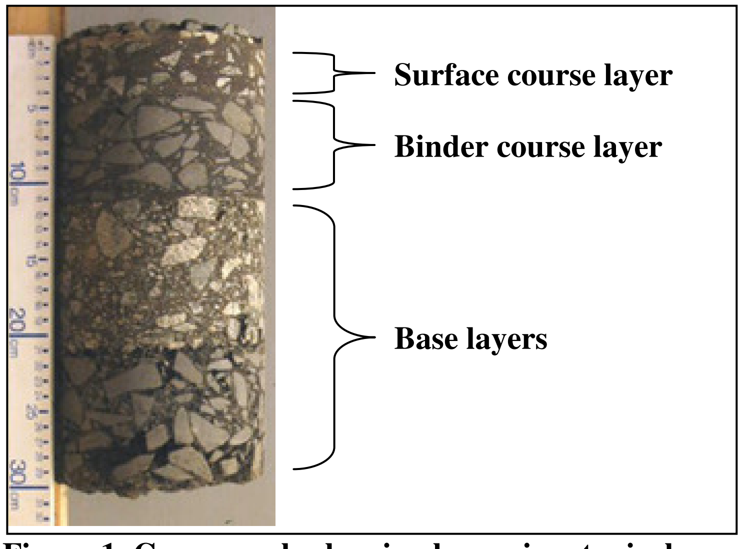

Figure 1. Core sample showing layers in a typical bitumen-bound pavement. (Left hand depth scale in cm)

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 antenna can use common mid-point (CMP) calibration, where antenna transmitted 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 re-bars, 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).

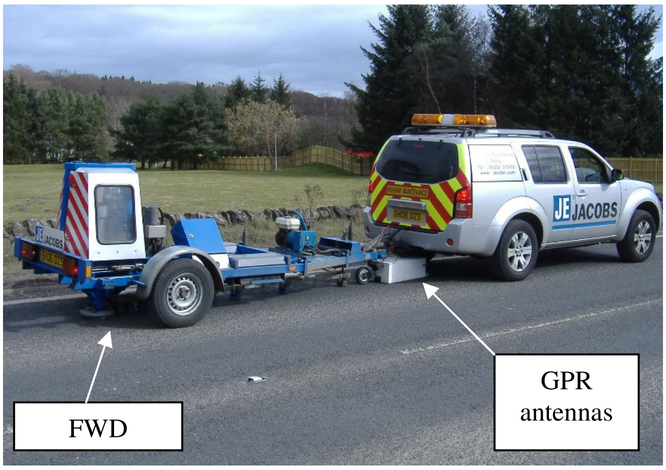

Figure 2. GPR and FWD data collection simultaneously from a single vehicle

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).

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 de-bonding 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.

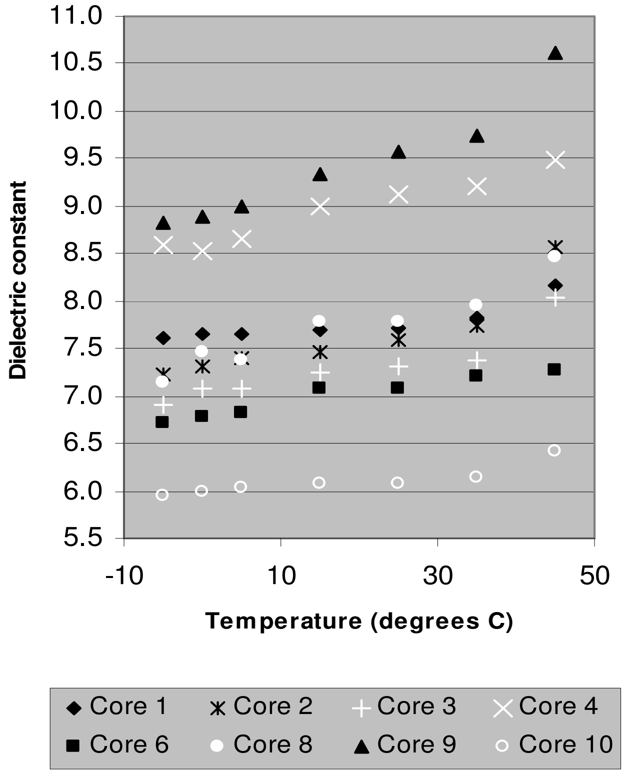

Figure 3. Dielectric constant of bituminous core samples determined at 1.5GHz

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.

7 ACKNOWLEDGMENTS

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APPENDIX B PAPER 2

Full Reference

Evans, R., Frost, M., Stonecliffe-Jones, M. & Dixon, N. (2006).

Ground penetrating radar investigations for urban roads.

Proceedings of the Institution of Civil Engineers - Municipal Engineer. Volume: 159, Issue 2, pp 105-111.

Abstract

Although Ground Penetrating Radar (GPR) technology has existed for many decades, it has only been in the last 15 - 20 years that it has undergone great development and is now a commonly used non-destructive technique for assessing layer thicknesses and material condition of trunk road pavement structures. Intrusive investigations provide vital additional information, but are often costly and time consuming, and have the limitation that only data at discrete points is obtained.

The nature of urban sites means that ground conditions are highly variable, and urban pavements have often been subject to much maintenance and re-construction. This can result in roads containing several pavement types or layers of materials of different age and condition, often overlying discrete buried objects, services or structures. Other site specific factors also affect the quality of data obtained. However it is possible to tailor a GPR survey to optimise data by adjusting the investigation methodology. Using an example of a recent urban pavement investigation, this paper shows how the use of detailed and extensive GPR data collection can be used to target concurrent invasive investigations to optimise analysis of variable urban pavement structures, and hence focus maintenance treatments and methodologies.

1 INTRODUCTION

Assessing the condition of urban pavement structures to plan maintenance is essential to allow the efficient long-term functioning of the highway network. Optimising the methods used for such assessment will lead to better information being obtained about the pavement condition. The condition assessment of urban pavements will be affected by a number of factors, including the properties of the pavement, the supporting sub-base and subgrade (natural ground), and the ability to obtain good information about the entire area of the road.

Several non-destructive methods are available to investigate pavements, with minimal damage or disturbance to the structure. It is common practice to implement routine investigations of pavement structures, and use this information to target more detailed investigations. Ground Penetrating Radar (GPR) is one of the main tools to provide information of road condition, particularly on the main truck road network. The use of GPR for urban pavement investigation merits special consideration due to the often highly variable and complex nature of the road structure and underlying ground encountered in urban environments. Pavements, sub-bases and the subgrade often contain different materials and pavement types with different properties in relatively close proximity.

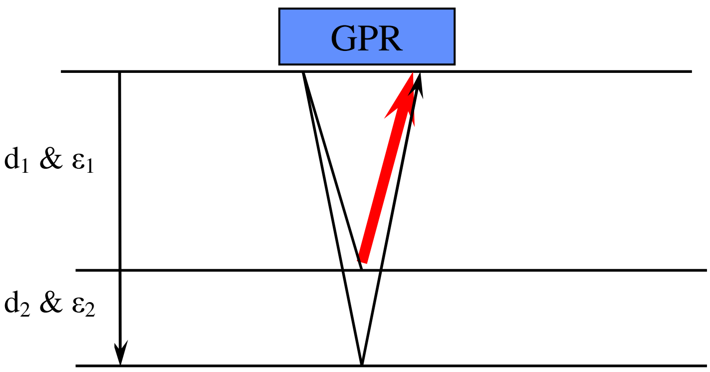
This paper outlines the principles of GPR investigation in urban roads, the nature of non-trunk urban roads and the specific issues related to their in-situ investigation. It then goes on to detail how on-site methodology for GPR surveys can be optimised for (non-trunk) urban roads, using examples of successes and limitations of an actual investigation to illustrate key points. The whole investigation process for the road structure (i.e. pavement, sub-base and subgrade) is considered, from the planning stage through to presentation of information to the end-user.

2 THE USE OF GROUND PENETRATING RADAR (GPR) IN PAVEMENT EVALUATION

In order to assess the condition of a road, information on its internal structure is required. Core samples or trial pits are often taken to confirm material type, condition and thickness. Whilst providing vital data, it is costly and time consuming to take invasive samples, and only data from the points where cores or trial pits are taken is obtained, and data for the sections of road between the samples has to be interpolated. GPR (which transmits and records the passage of electromagnetic waves through media) has become a widespread non-destructive pavement evaluation tool. Intrusive pavement investigations are still required [1], and are used for calibration of GPR data (further discussed below), but the amount of intrusive investigations (and time taken for surveys) can be reduced, whilst the amount of information obtained increased, by the use of GPR.

2.1 PRINCIPLES OF GPR

GPR systems operate by transmitting a radar pulse from an antenna into the ground, and recording the time taken for reflections of this pulse to be returned to the antenna. The passage of radar waves through a material is dependent on the materials type, condition, water content and pore fluid content. These properties affect the 'dielectric constant' of the material (which governs the radar signal speed through a material). When two material layers have contrasting properties, some of the radar energy is reflected back from the material boundary (Figure 1). The key to this process is for the materials to have different dielectric constants, and in practice the majority of in-service road materials (bituminous, cement bound, un-bound aggregates, different soil types, etc) have this contrast. The amount of radar energy reflected will depend on the 'reflection coefficient'; which in turn depends on the contrast in dielectric properties of the materials.



$$v = c / \sqrt{\varepsilon_r} \quad \& \quad d = v \times t/2$$

where:
v = velocity of radar signal
c = speed of light
ε_r = dielectric constant of material
d = depth
t = travel time for reflected signal

Figure 1. Calculation of radar pulse velocity, dielectric constant and depth

GPR operates over a range of signal frequencies, but typically systems that operate between 400MHz and 2GHz are used for engineering and ‘shallow’ investigations. Generally a higher signal frequency gives better resolution (i.e. more precise indication of depth), but lower penetration (i.e. shallower investigation depth). Conversely, lower frequencies provide less interface resolution, but deeper signal penetration, (Figure 2).

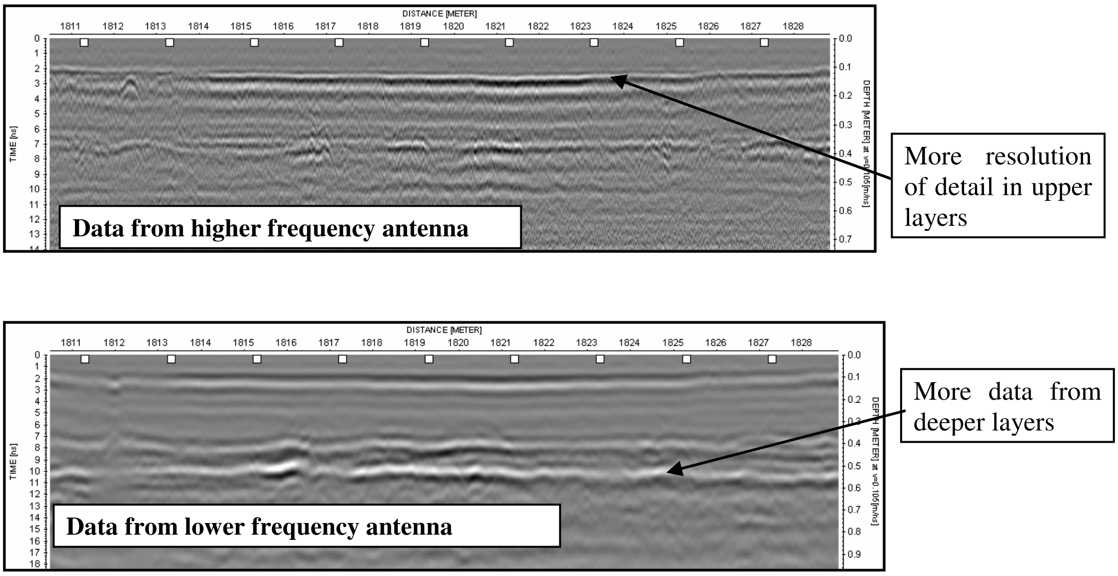


Figure 2. Contrast in resolution and depth of signal penetration for two different frequency antennae, along the same section of road.

Data from GPR survey lines are typically plotted as a ‘pseudo-section’, of signal travel time (which may be converted to depth) against chainage, with the amplitude of the reflected signal plotted in colour or greyscale. Figure 3 shows greyscale plots, with white and black indicating a strong signal reflection (i.e. a material interface), from which the layer interface can be picked out.

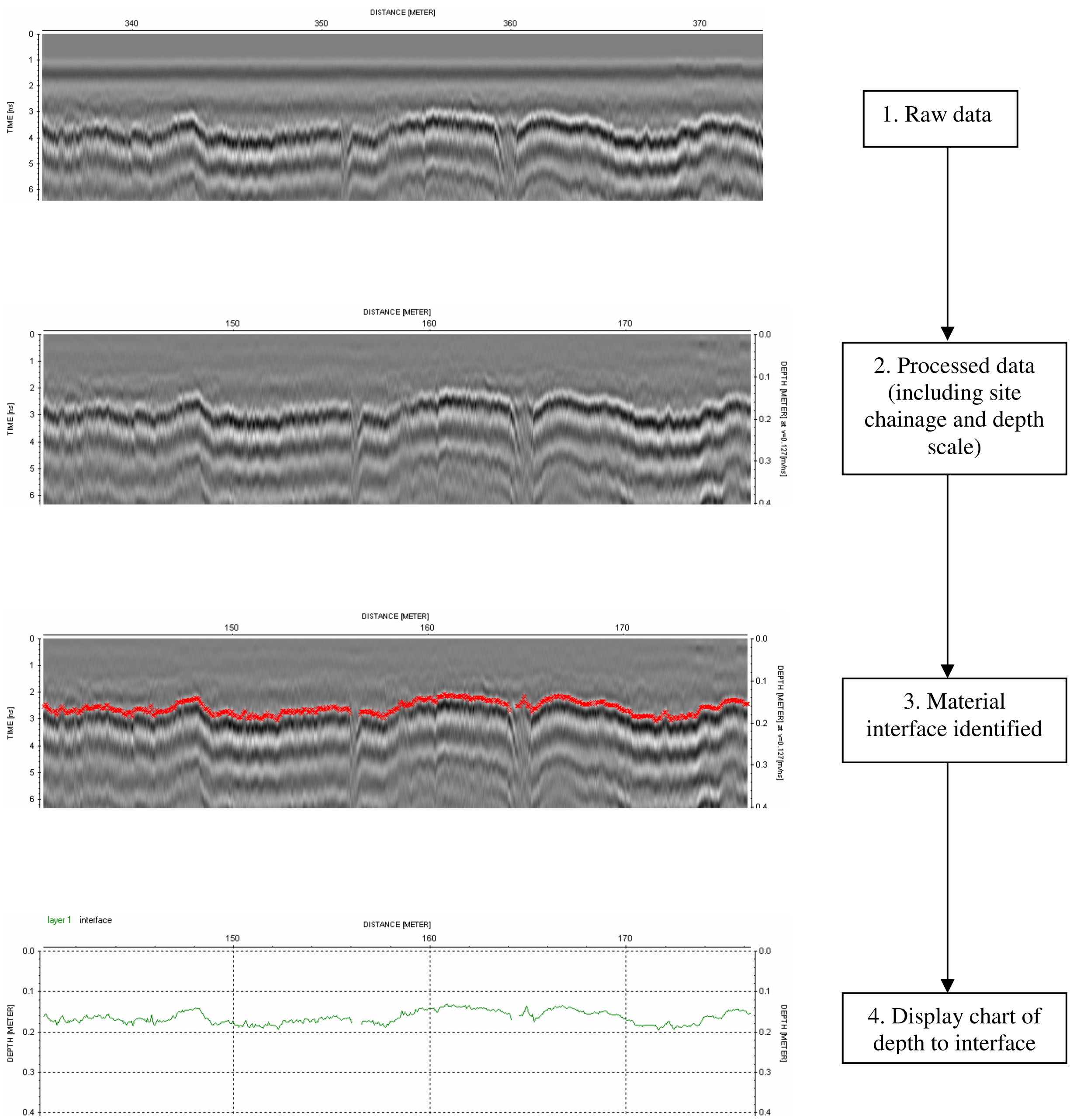


Figure 3. Typical stages in GPR data processing and presentation

2.2 DEVELOPMENT OF GPR

GPR is an accepted method for ground investigations of all kinds, and the reader is directed to the following three papers which provide useful overviews of the technology and use of GPR in sub-surface evaluation, [2, 3, 4]. For pavements, developments in the use of radar, including technological advances in the design of GPR hardware and software, have mainly taken place since the 1990's. The development of greater processing power, smaller component size, user-friendly software and the ability to perform vehicle-towed surveys have contributed to the increased use of GPR on trunk roads and its inclusion in the UK Design Manual for Roads and Bridges (DMRB) [5]. However, GPR often perhaps remains under-utilised and its potential is not fully realised in many engineering and geological applications, such as in urban road investigations where conditions are more variable.

Despite these recent developments, there are several issues that must be considered when planing the use of GPR. Certain pavement and soil conditions can have an affect on the quality of GPR data, such as high material water contents, high material conductivity, and pavement reinforcement masking deeper features. However, when such conditions are expected and recognised in surveys, GPR data can still provide an accurate and applicable tool for urban pavement investigation [6].

2.3 LIMITATIONS OF GPR

The quality of GPR data obtained from a survey is a function of several factors, including material properties and conditions (detailed above), and the GPR system used, (antennae type, power, the signal gain settings used and survey methodology). The amount of information obtained is affected by the processing and analysis procedure used (software, procedures performed, data presentation, etc, see Figure 3). The competence of the GPR operator and data analyst can also affect the results obtained. Many of these factors can be addressed to optimise data and information quality, however some are less controllable. Generally, in-service materials have a range of values for their dielectric constant, so a (dielectric) contrast between different materials will not always be apparent, and the resulting low reflection coefficient may mean that resolution of material boundaries is difficult. Also, wet materials tend to absorb and attenuate GPR signals, meaning less energy is reflected, resulting in greater difficulty in resolving layers from GPR data. Disintegrated material boundaries can also prove difficult to accurately map on pseudo-sections. These factors can cause uncertainty in the identification of distinct boundaries between materials. There will always be some situations where the site properties mean that, even if every other aspect of the investigation is conducted to the highest standard, the GPR data can not adequately identify relevant features.

3 URBAN ROADS

A large range of road types exist in UK urban areas, from low volume local estate roads, through to major access roads and urban motorways. Many urban roads have ‘evolved’ and may have been subject to periodic overlaying or re-construction as traffic and the loading imposed has increased over many years or even centuries. Therefore it is not uncommon for roads in long established towns and cities to have developed from a track into a paved road and finally into a ‘modern’ layout. Such roads frequently have highly variable ‘non-standard’ construction, particularly in the lower layers, where new materials may have been placed over the original structure. In such situations, the ability to undertake efficient site investigation of the pavement structure to determine the thickness, variability and nature of the materials is particularly important to target remedial measure and construction methodologies.

3.1 USE OF GPR ON URBAN ROADS

The main use of GPR proposed in the DMRB [5] is to establish layer thickness for integration with falling weight deflectometer (FWD) data to allow detailed stiffness assessment of pavement layers. Other uses include the detection of construction changes, location of voids and wet patches (indicating poor support), location of reinforcing bars and location of excess sub-base moisture (indicating poor drainage). These all relate to the reflection of energy caused by changes in the materials within the pavement structure.

In the 1990's the use of GPR to provide 'network level' surveys was established. More recent work integrates the routine use of GPR, FWD data and information from other pavement condition assessment within pavement management systems [7]. Despite the development of 'routine' GPR investigations, the often variable nature of urban pavements and urban geology means that using standard GPR investigation methodologies (devised for trunk roads) on urban sites will frequently obtain inadequate information.

3.2 VARIABILITY OF GPR RESULTS

As described above, in situ materials generally have a range of dielectric constant rather than a specific value. Asphalt pavement materials have been shown to have constants in the range of 3.5-10 (corresponding to velocities of 95-160 mm / ns) suggesting that the range of radar propagation velocity for in-service pavements could be large [8]. Therefore it is important when conducting GPR surveys on pavements that actual layer depths are obtained (usually by coring), in order to calibrate the GPR, to ensure accuracy of the data. This becomes especially critical in urban locations where the nature of both the road pavement and the underlying ground tends to be highly variable.

The reported level of accuracy achievable for layer thickness evaluation is varied, and it must be noted that site specific conditions will play a part in this, as well as the GPR data collection parameters used. The guidance in DMRB [5] states that "10 % level of accuracy can generally be achieved for layers greater than 75mm thick" and that "6 % level of accuracy can be achieved for layers greater than 125mm thick". In the large majority of cases GPR is a useful non-invasive tool for the engineer, providing valuable information, increasing the understanding of the condition and features and variability of the pavement and ground, providing longer-term cost and time savings.

4 CONDITION INVESTIGATION OF URBAN ROADS

Visual surveys are a common technique for routine inspection of UK urban road condition and are used to target further detailed investigation, often the first indication that maintenance may be required is noted by the appearance of cracking or rutting of the road surface.

The DMRB [5] contains guidance on techniques for assessing the condition of trunk roads and these methods are also used for the detailed investigation of urban roads. These investigations are then used to plan maintenance treatments. However, as described above, the variable nature of many urban roads present a more variable and challenging assessment environment than that encountered in trunk road or motorway investigations, where pavement structures tend to be more consistent and homogeneous. A good overview of the in-situ assessment of pavement structural conditions, from a UK perspective, is given by Rockliff (2000) [9].

5 A GPR INVESTIGATION OF AN URBAN ROAD

In 2005, information was required on the internal structure of an urban 'evolved' road, in the West Midlands. The road was a local high street with both residential and commercial properties nearby. From visual inspections, the surface of the road was showing signs of severe structural damage. The bituminous road pavement was generally in a poor condition and had undergone several maintenance / re-surfacing treatments over a number of years, but its was thought the pavement foundations had remained un-treated. Ruts and cracks could clearly be observed on both repaired and un-repaired areas, and planing off the bituminous layers and replacing them with new material was being considered.

The construction details of the road were known to be non standard and variable and although little detailed information existed, it was thought to be one of a number of similar road structures in the region. Information on the depth of the various layers in the road, especially to the bottom of the bituminous layer along the length of the site and identification of the presence and thickness of sub-base, had to be determined before planing could be planned.

A site investigation was therefore planned, aimed at determining whether GPR could provide adequate information to assist in the detailed planning of the maintenance work, and also to optimise a GPR methodology to provide a basis for detailed routine investigations on other similarly variable pavements. The GPR investigation of the site was combined with intrusive evaluation.

Initially a desk study of available pavement data was performed and two initial trial pits were excavated to aid planning of further evaluation. These pits showed the subgrade to be a silty clay, overlain by a 50mm fine ash layer, acting as a bed for stone blocks or cobble stones (locally know as ‘pitchings’), which formed the original pavement for which there was no foundation as such (Figure 4). The current bituminous pavement had then been constructed over the top of the pitchings. It was originally thought there was a granular sub-base acting as a regulating layer above the pitchings along the entire road, but initial investigations indicated that the sub-base layer was highly variable, ranging from 80mm thick in some places, to zero (no sub-base) in others.

Figure 4. Trial pit showing bituminous road pavement, pitchings and silty clay subgrade

5.1 SITE INVESTIGATION

The GPR unit used for the investigation had 3 antennae operating at frequencies of 1.5Ghz, 900MHz and 400MHz. This meant that for each survey line three GPR data sets were obtained, one at each frequency, to maximise the information available, and accommodating the resolution / depth / frequency relationship of GPR. Using three antennae had no operational effect on the investigations, as a purpose built antennae housing was towed behind the survey vehicle (Figures 5 and 6). The antennae were linked to a data collection unit inside the vehicle, displaying real time raw data (pseudo-section) profiles of the radar travel time. The raw data gives an initial indication of the layers and interfaces on site, however further post survey data analysis is required.

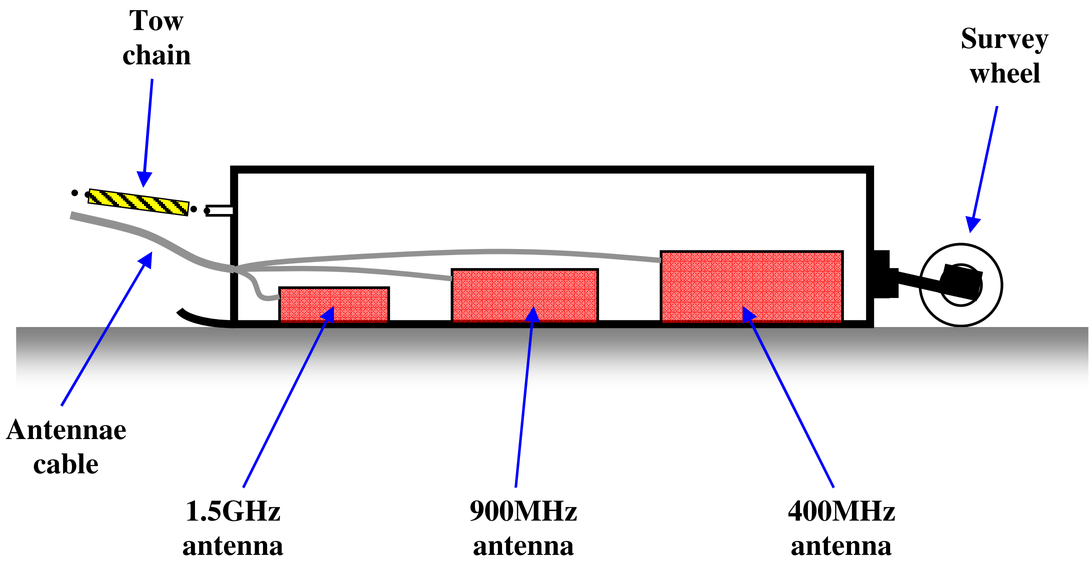


Figure 5. Schematic diagram of a pavement GPR

Figure 6. GPR survey vehicle, with antennae housing in towing position

A survey wheel was connected to the antennae, and the rate of radar pulses (scans) transmitted (i.e. the number of pulses per second) was driven by the movement of the wheel. When connected to a survey wheel, different GPR systems have different maximum scan rates, and this along with the speed at which the antennae move along the ground determines the scan spacing (i.e. data points over a given distance). GPR network level surveys can be conducted at high speeds (40 km/h or above). However, the faster the speed the less scans per metre. As network survey roads tend to be relatively homogenous in construction, radar scans every 0.5m along a survey line is acceptable and not uncommon.

Slower surveys speeds will increase the survey time, but for variable urban sites, a more detailed picture of construction and material features is required. A relatively high speed survey may miss details or features of interest. The GPR system parameters were set so that a scan was taken approximately every 0.04m along each survey line, requiring a vehicle speed of approximately 3km / h.

It is common to only collect GPR data in one wheel-path per lane. After consideration of the existing information indicating the variable nature of pavement at the site, and the cracking and ruts on the road, it was felt that surveys in one wheel-path would miss important features of the pavement structure. Therefore, GPR survey runs were taken in both the near-side and off-side wheel-paths in each lane, and a number of transverse runs were also taken (pushed by hand within the confines of site traffic management, see Figure 7). This approach, whilst adding to the time taken for the investigation meant that a comprehensive picture of the road structure could be collected, and pavement features and properties could be observed which would have been missed if a 'standard' survey approach had been taken.

Figure 7. Transverse survey across road. (The GPR display is visible inside the survey vehicle)

GPR data were referenced to local site chainages, which were marked from fixed features which could be easily found if the site was re-visited (such as centre lines of road junctions).

The importance of accurate site chainages is often overlooked, but is particularly important where features occur and data is collected at relatively close spacing.

Invasive samples previously taken from the site, had their positions recorded directly onto the GPR raw data as the antennae passed the locations. New core locations undertaken concurrently during the work, targeted by the GPR team from the raw data to optimise their value, were also plotted.

Post survey analysis in conjunction with other site data was undertaken to give a more comprehensive and accurate determination of layer and feature depths, an indication of material type and integrity and identification of homogenous and anomalous lengths of pavement construction. Core information was used to re-calibrate the GPR data, by correlating the material depths from the cores to radar travel times from GPR signals at the exact core locations. A velocity for the radar signal through the material could be calculated and then used to determine depths within the road structure for the lengths of the GPR survey between core locations, thereby giving the most accurate calibration of the GPR data. In total, 13 cores (old and new) were taken, and approximately 2000m of GPR survey lines were obtained. The rate of cores per GPR survey length is high compared to many investigations but the trial nature of the work and existence of previous core data, facilitated this. Obviously the number of cores required for adequate calibration of data for a given survey depends on the homogeneity of the site materials encountered, and will vary from site to site.

The data was processed and filtered to include corrections for the fact that the GPR antennae were not flush with the road surface, background noise removal and conversion of signal travel times to pavement depth. During the site investigation the methodology employed was reviewed and revised, with the aim of optimising the GPR survey procedure and information obtained.

5.2 FINDINGS FROM THE SURVEY

The GPR data identified that there were actually three distinct longitudinal pavement sections, rather than one as originally thought. These consisted of a short section of surfaced reinforced concrete pavement (300mm thick, Figure 8), a section of poor condition bituminous pavement (150mm thick), and a section of sounder slightly thicker bituminous pavement (180mm). The thickness changes were easily identifiable and the condition of the material was assessed based on correlations with the intrusive investigations. Much of the pavement appeared to be in a poor condition, with areas of sound and partially deteriorated pavement materials overlying areas of badly disintegrated material, sub-base and/or pitchings (Figure 9). The nature of these disintegrated materials meant that identifying discrete GPR layer boundaries in places was difficult because of the mix of materials present, although the presence of these areas could be established. The inability to determine precise layer thicknesses was not just limited to the GPR data - there would also be uncertainty in reporting layer thickness from intrusive investigations in these areas. The GPR data showed several areas of the road to contain wet material, and further trial pits confirmed this. This meant that the amount of radar energy penetrating deeper in the road structure was reduced, leading to difficulty in identifying the exact top of the pitchings in some areas.

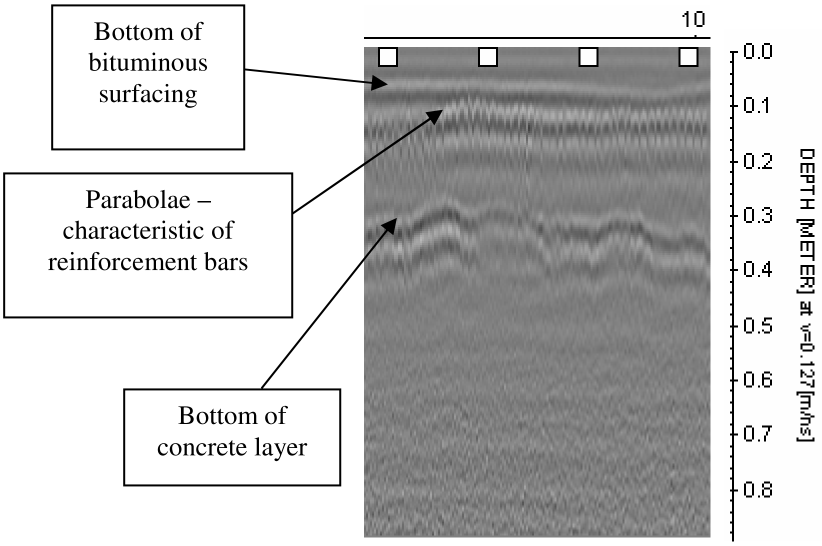


Figure 8. GPR Profile of thin bituminious surface over reinforced concrete slab

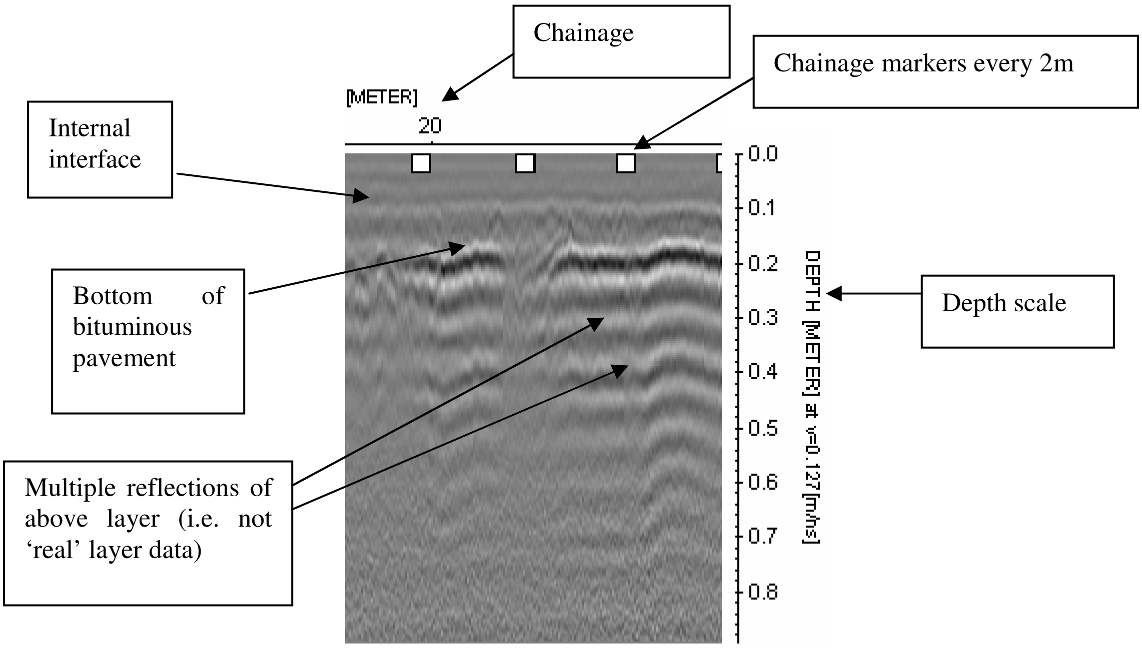


Figure 9. GPR Profile of bituminous pavement over hand pitchings (note loss of resolution in pitchings layer)

Data from transverse GPR surveys proved very useful, since material thickness in the upper bituminous pavement tended to be greater in the wheel-paths than in the lane centre (possibly because of previous overlaying of rutted pavement). Without the transverse surveys, this information would not have been discovered. Differences of up to 50mm in pavement depths below the road surface to top of pitchings were discovered, with some sharp variations in short distances. Considering the intended maintenance treatment of planing away existing material these thickness differences and variations between lane centre and wheel-path were important discoveries. The indication from intrusive investigations that the sub-base layer present in the road was not constant throughout the entire site was confirmed by the GPR data and consolidated throughout the survey area.

From the survey, it can be determined that an attempt to plane material to the depth of the pitching would be difficult, and planing to the base of the bituminous layers (identified by the GPR data) would be more appropriate. Due to the transverse variation in pavement depth, planing of material in three distinct runs per lane was proposed.

6 DISCUSSION & RECOMMENDATIONS

6.1 DISCUSSION OF FINDINGS FROM SITE INVESTIGATION

The investigation was successful in identifying a ‘safe’ planing depth to which material could be removed. Identification of the bottom of the bituminous pavement was successful, but identification of lower layers (sub-base and top of pitchings) could only be indicated. It is likely that at other similar sites with deteriorated and variable thin materials in poor condition, the confidence in reporting individual layers could also be variable.

Several factors which affect the level of information obtained from this investigation, existed during each stage of the process (planning, investigation, processing and reporting). Technical and scientific issues relating to the materials and nature of the site, and to the GPR technology used, were not necessarily the most influential factors. The physical laws governing radar wave propagation mean that a change in GPR equipment would be unlikely to alter the information obtained. The trial nature of the site allowed the flexibility for the on-site data collection methodology to be adapted to site specific situations. It is unlikely that changes to the processing procedure would alter the level of information obtained. A key issue to obtaining the best results in such challenging pavement scenarios is for the data provided by each member of the investigation team to be integrated in an optimum way. A close working relationship for the team is therefore essential, if the most benefit is to be obtained from the investigation. Concurrent discussion and feedback of information from the various teams involved in the investigation, (including the coring and GPR crews, the laboratory staff, engineering geophysicist, pavement engineers, and the client) is essential for the optimum information to be obtained. Ultimately the end user has to receive information in a form that will prove most useful for the purpose for which it is required (e.g., the planning and selection of maintenance).

6.2 RECOMMENDATIONS FOR URBAN ROAD GPR INVESTIGATION

It is essential for urban sites that a sufficient amount of information is obtained to allow a full assessment of the condition of the pavement, in order to plan the most appropriate maintenance treatment. If ‘high speed’ GPR methodologies often used for trunk roads are employed, information can easily be missed. Time spent on the in-situ investigation can lead to much larger time savings, by provision of sufficient information to allow the most appropriate treatment works to be conducted. Clearly, judgement is required on the benefits of certain aspects of the GPR methodology, such as taking multiple survey lines and transverse survey lines, which add time but increase the amount of information provided, and these factors will be site specific. However time and money saved in the evaluation stage by performing a less than adequate investigation may result in much greater costs during the maintenance stage due to inappropriate construction techniques being selected, maintenance requirements not being fully assessed, or treatments not addressing the full nature of the problem.

When conducting GPR investigations of urban sites, as much information as possible should be obtained about the site before any investigation is planned. Information on the nature of the site – age of the road, 'modern' or evolved construction, variable materials or homogenous construction, subgrade information, etc – will affect the methodology used for the in-situ investigation.

Where urban roads are thought to be of highly variable nature, or there is little information available, it is recommended that the following points are considered:

- Several antennae, providing a range of radar frequencies, should be used to provide the best coverage of depth of penetration and resolution.
- Using slow speed surveys (i.e. giving a high number of radar pulses per distance travelled) are recommended for sites with highly variable construction, so that relevant features in the road structure are not missed.
- Along with longitudinal survey profiles in both wheel-paths, transverse surveys across the road are recommended.
- Intrusive surveys (usually in the form of cores, but also trial pits) are necessary to calibrate GPR data to a suitable level of accuracy. The number of intrusive investigations will depend on the nature of the site.
- Special attention should be paid to a sensible and easy to follow site chainage system, marked from fixed locations on site.
- All core locations should be marked directly on the GPR pseudo-section to provide the accurate correlation of core locations with GPR survey data.
- Additional cores should be identified, and excavated during the same work period as the GPR survey.
- Discussions should be ongoing between the different members of the investigation team (coring crew, GPR survey team, engineers, project managers, client, etc), to provide a co-ordinated approach to the investigation.
- Team members, especially the end users of the information, should be also made aware of the various uses and limitations of the GPR data.

7 ACKNOWLEDGEMENTS

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APPENDIX C PAPER 3

Full Reference

Evans, R., Frost, M., Stonecliffe-Jones, M. & Dixon, N. (2007).

Assessment of in situ dielectric constant of pavement materials.

Transportation Research Record: Journal of the Transportation Research Board, No. 2037, pp. 128–135.

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 pavement material information from GPR data. 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 improved assessment of in-situ dielectric constant can be conducted, providing enhanced information from radar data analysis, if consideration of material condition is made when selecting the values used in the analysis.

1 INTRODUCTION

Ground penetrating radar (GPR) is a non invasive tool often used in pavement investigations to assess layer thicknesses, material condition, moisture, voiding, reinforcement and location of other features, and to compliment other pavement investigation techniques. GPR systems measure the travel time and amplitude of reflections of electromagnetic pulses transmitted through the pavement structure, and in order to accurately assess pavement features and thicknesses a material property called the dielectric constant must be known.

Average dielectric constant values, or ranges of typical values, can be obtained from published data and standards. However the site specific nature and variability of in-situ pavement dielectric constant values means that if published values are used it can lead to inaccuracies in the calculated pavement thickness, which can in turn 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 in-situ from cores, or by other point calibration methods. Often, however, data from a single calibration point is used for substantial lengths of road, but the actual dielectric constant of an in service pavement may have great variability along its length as a result of variations in both its as-constructed material state (type, density, water content, etc) and its 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 can then be used to provide information relating to the expected uncertainties and errors in reported depths from GPR.

A background into 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 the dielectric values used in pavement analysis. This variability can then be considered when undertaking further pavement analysis and planning of maintenance.

2 BACKGROUND TO PAVEMENTS AND GROUND PENETRATING RADAR (GPR)

2.1 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 ability, 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 asphalt concrete materials 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 ‘asphalt’ material. A ‘macadam’ describes a certain type of aggregate, and a ‘coated macadam’ is a material which, similar 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, the specific in-situ conditions of a bituminous material lead to variations in properties between materials that are nominally the same. 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.

2.2 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 investigation is collated, and used to assess the condition and to plan treatments to optimize the performance and extend the life of the pavement structure.

2.3 USE OF GROUND PENETRATING RADAR (GPR) FOR PAVEMENT EVALUATION

In modern pavement engineering, one of the most useful non-intrusive methods is GPR, which transmits and records the passage of electromagnetic waves through the pavement structure. The primary use of GPR is usually to determine layer thicknesses, and locate construction changes, areas of high moisture, voids, reinforcement 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 large amounts of data to be collected and long 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, and 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 antennae 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.

2.4 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 effect on 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 often referred to (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.

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	Not stated	(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	Not stated	(*22*)	Kentucky Transportation Center GPR guidance document
HMA (various mixes)	3.5 - 10	Not stated	(*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			

An accurate way of determining the dielectric 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 determined. 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).

A method, applicable only for air coupled (horn) antennae, to determine the dielectric constant of the surface layers is to compare 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 the 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 (revealed by a 150mm diameter core, which provides 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 an 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.

3 DIELECTRIC PROPERTIES OF MATERIALS

3.1 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). The ‘relative permittivity’ is also known as the ‘dielectric constant’ of the material (mentioned above) 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, such as the velocity at which the radar waves will travel through the materials.

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

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 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:

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

where d = depth of feature

v = velocity of signal = $c / \sqrt{\varepsilon_r}$

t = one-way travel time of reflected signal

If the travel time is recorded and the dielectric constant of the material is known then by substituting in equation 4, the depth to features can be determined:

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

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 is indicated by the reflection coefficient (which depends on the contrast in dielectric properties of the materials) and is given by:

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

where RC = reflection coefficient

ε_1 = dielectric constant of the upper material

ε_2 = 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 governing 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 ($\varepsilon \approx$ 3-12, 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.

3.2 BITUMINOUS MATERIALS

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.

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 values (*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.

4 IN-SITU DETERMINATION OF DIELECTRIC CONSTANT

4.1 INVESTIGATION RATIONALE

As discussed above, using published values of dielectric constants (such as those in Table 1) for analysis of GPR data 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.

4.2 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 project sites (schemes) 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 amplitudes of reflected signals were 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 conducted 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.

4.3 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 in the GPR data.

The core samples taken showed that each pavement was comprised of several individual layers of material (see Figure 1). 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 the pavement at the core locations, 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.

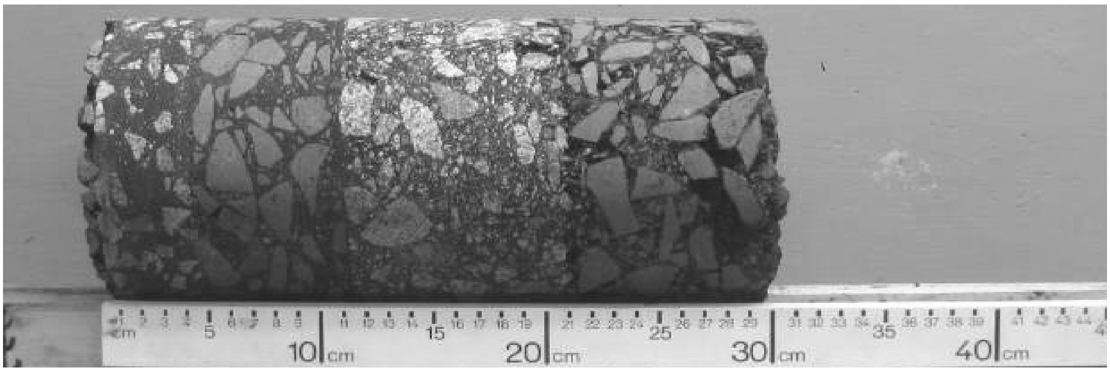

Figure 1. Example of core sample from Scheme 3, showing different layers within the bituminous pavement.

5 RESULTS & DISCUSSION

5.1 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 the material. For example, values of 4.0 - 4.9 are quoted in Table 1 for in-situ HMA. 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. For 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 the values of 4.0 - 4.9 reported for a similar material 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

5.2 DISCUSSION

Within the three pavement schemes used for data collection, a range of values existed for the bulk dielectric constant of nominally consistent material: 6.77 to 6.99; 7.03 to 7.45, and; 7.62 to 8.80, 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 reported GPR data should be quoted. Often a ‘best fit’ dielectric constant is used to determine depths from a GPR investigation, with emphasis on core calibration of sound material, and the potential variation in dielectric properties for sections which contain material of variable condition are sometimes not taken into account. If we consider the variation in the dielectric values that have been determined in this study, the possible resulting variations in reported depths (which would have been caused by simply using a ‘best fit’ dielectric value in equation 5) 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 calculations of depths in those areas. 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 have a large affect on its dielectric constant, and the direct comparison of values between different sites should be undertaken with caution, because local moisture conditions will vary from site to site.

6 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 routine pavement investigation data collection is conducted by ground coupled GPR because of the 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 is 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 the in-situ dielectric constant, relatively lower values compared to similar material may indicate that material is in a poorer condition. Lower dielectric constant values determined in this study were produced by material of poorer condition, and thus lower dielectric values may indicate material of lower stiffness, which may have implications for planning of maintenance work.

7 ACKNOWLEDGEMENTS

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APPENDIX D PAPER 4

Full Reference

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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:

$$v = \frac{c}{\left(\sqrt{\mu_r \varepsilon_r}\right)} \qquad (1)$$

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:

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

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

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.

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:

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

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 collapse. 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.

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.

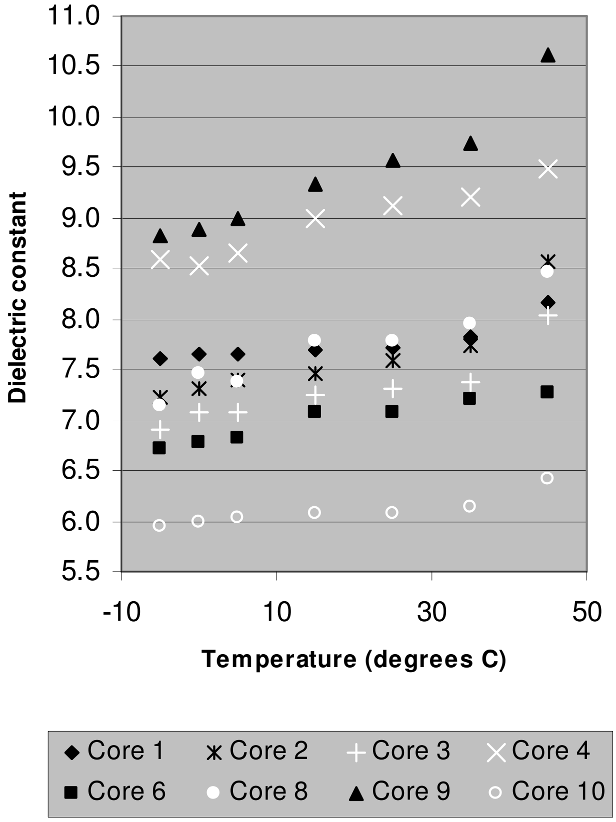

Figure 1. Dielectric constant of bituminous core samples determined at 1.5GHz in temperature range -5^{0}C to 45^{0}C. (Core samples 5 and 7 damaged during testing).

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).

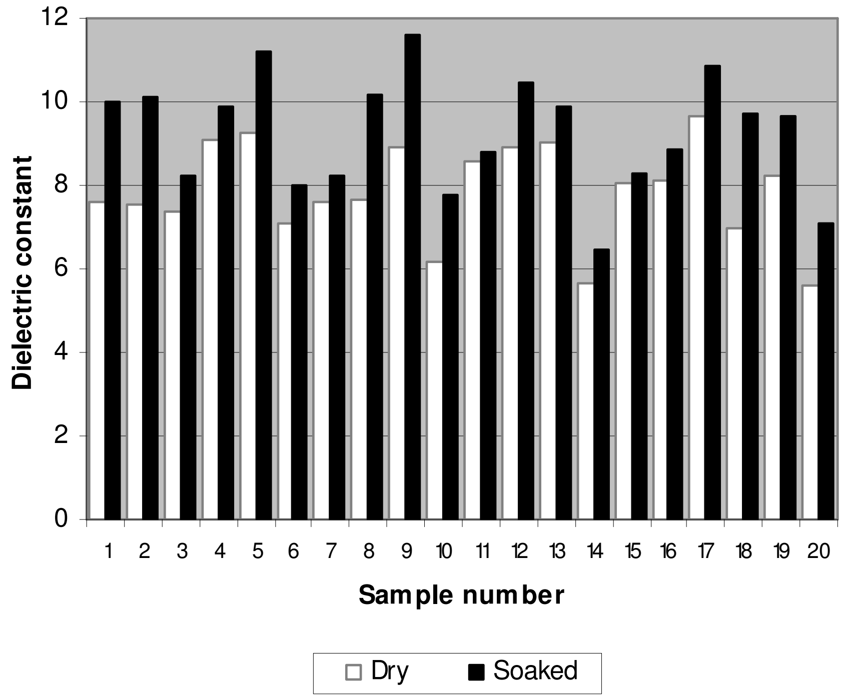

Figure 2. Dielectric constant of bituminous material samples, in 'dry' and 'soaked' condition, determined at 1.5GHz.

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 asses 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 (ε_r ~ 1) in voids present in materials are replaced within the material matrix by relatively high dielectricity water (ε_r ~ 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 represent 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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APPENDIX E PAPER 5

Full Reference

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Variation in information obtained from interpretation of ground penetrating radar (GPR) pavement investigation data.

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Abstract

Ground penetrating radar (GPR) data can be used to provide useful information about pavement structures. However, some limitations exist relating to GPR technology, and various limitations and uncertainties can exist in the reported information depending on the investigation methodology and the data analysis procedure used. The combination of all these factors results in a significant potential for uncertainty or variations in the analyzed data, and therefore consideration is required if the optimum amount of information from a GPR investigation is to be obtained. This paper discusses the possible errors and uncertainties that can arise from GPR investigations, and GPR pavement data is used to illustrate issues that can arise during data analysis and interpretation. Ways of minimizing and managing variations and uncertainties are discussed, and the use of appropriate data collection and analysis procedures are highlighted, so that the use of information from GPR can be optimized.

1 INTRODUCTION

1.1 GROUND PENETRATING RADAR (GPR)

Development

The use of radio waves to indicate the presence of objects was initially developed in the first half of the 20th century, and by the early 1940's the now well-known acronym of "radar" (RAdio Detection And Ranging) was being used to describe the technique. However, despite some early ground penetrating applications, radar was predominantly used for airborne transmission and the first commercial systems for ground penetrating applications were not manufactured until the 1970's. Since these early ground penetrating radar (GPR) systems were manufactured, large developments in the use of radar for ground investigations have taken place, especially since the 1990's, including technological advances in the design of GPR hardware and software. Matthews (1998) summarises the use of radar for subsurface investigation and Olhoeft (2000) discusses the kind of information that can be obtained from GPR studies. The development of systems with greater processing power, smaller size of components, more user-friendly software and the ability to perform vehicle-towed surveys have contributed to the increased use of GPR in near surface ground investigations. Today, GPR is an accepted method for ground investigations of many kinds, and Daniels (2004) gives a comprehensive overview of the key elements of radar technology for ground investigation applications.

The developments of GPR technology have resulted in its adoption for road investigations. However, despite the increase in its use for this purpose over the past couple of decades, GPR (as with many other geophysical techniques) often remains under-utilised and its potential is often not fully realized. Some of the criticisms often directed at GPR investigations are that they don't provide either the accuracy of results hoped for or the type of information required. Reasons for this criticism can sometimes be related to an under-appreciation of exactly what GPR is capable of providing, but also the fact that several aspects of the GPR survey process contain the potential for uncertainties or variation. There is a tendency to attach more credence to investigation results obtained from more mechanistic testing methods (such as a core thickness, or a dynamic cone penetrometer test) despite the inherent uncertainties associated with such methods, than there is to have confidence in the results of GPR which is seen by many as a 'black box' technology. GPR investigations have a number of potential sources for uncertainty (as do all other ground investigation techniques), but a competently conducted GPR investigation can provide invaluable information to an engineer. By appreciating how and where uncertainties may arise, how these can be addressed, it is possible to obtain a fuller understanding of how GPR information can be used.

Principles

For most ground investigations, GPR systems operate by transmitting a radar pulse from an antenna into the ground, and recording the time taken for, and amplitude of, reflections of this pulse to be returned back to the antenna. The passage of radar waves through a material is dependent on the material type, condition, moisture content and pore fluid content. These material properties have an affect on what is known as the 'dielectric constant' of the material. The value of the dielectric constant is important because it relates to several parameters which are essential for the interpretation of GPR data, such as the velocity at which the radar waves will travel through the materials:

$$V = \frac{c}{\sqrt{\varepsilon_r}} \qquad (1)$$

where V = velocity of radar wave through the material; c = velocity of light in free space (vacuum); and ε_r = dielectric constant.

When the materials in two layers in the ground have contrasting properties, 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 different road materials (bituminous, cement bound, un-bound aggregates, different soil types, etc) will have this contrast, although it should be noted that not all materials do. The amount of radar energy reflected will depend on the 'reflection coefficient' (which in turn depends on the contrast in dielectric properties of the materials) and is given by:

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

where ρ is the reflection coefficient, ε_1 is the dielectric constant of the upper material and ε_2 is the dielectric constant of the lower material.

GPR operates over a range of signal frequencies, but typically systems that operate between about 2000MHz (2GHz) at the highest, and about 400MHz at the lowest frequency, are used for engineering and 'shallow' investigations. As a general rule, a higher frequency of signal will give better resolution (i.e. more precise indication of depth), but a lower penetration (i.e. shallower maximum penetration depth). Conversely, a lower frequency will provide less precise depth resolution, but deeper depth penetration into the pavement.

Data from GPR survey lines are typically displayed as a 'pseudo-section', with distance along the horizontal axis and signal travel time (which may be converted to depth) on the vertical axis. The amplitude of the reflected signal (which indicates the presence of features and layers) is usually represented by a color- or grey-scale display.

1.2 USE OF GPR IN PAVEMENT INVESTIGATION

In order to fully assess the condition of a road, information on its internal structure is required. Core samples or trial pits are often taken to obtain such information, and to confirm material types, condition and thickness. Whilst providing vital data, it is costly and time consuming to take cores (or excavate trial pits), and also has a further drawback that only data from the points where cores or trial pits are taken is obtained. Data for the sections of road between data points has to be interpolated.

The use of GPR allows information to be obtained concerning layer thicknesses, and other established uses include detection of construction changes, location of voids and wet patches (possible indications of poor support), location of reinforcement bars, location of excess sub-base moisture (indicating poor drainage), location of pipes and services and for indicating general material condition. All of these uses relate to the reflection of radar energy back to the antenna receiver, caused by a change in the nature of the material within the pavement structure. Whilst intrusive pavement investigations are still extremely useful (Mooney *et al* 2000) and are required for calibration of GPR data, the use of GPR allows the amount of intrusive investigations and amount of time taken for surveys to be reduced, and the amount of information obtained about the pavement to be increased.

Using the data from a GPR investigation allows a continuous record of data to be collected along the entire pavement length, reducing the overall risk and uncertainty which can result from the use of pavement investigation techniques which obtain data only at discrete points. GPR data can be analyzed in several ways to obtain information about several parameters, and guidelines on its use pavement investigation have been incorporated into several 'official' documents such as the UK Design Manual for Roads and Bridges (DMRB). One of the main uses described in the DMRB, and possibly the most common use of GPR when planning maintenance of roads, is to provide pavement layer thickness values. Such values can be used as part of the back-calculation of stiffness values from falling weight deflectometer (FWD) surveys. The FWD measures deflections caused by impact loading of the pavements surface, and these data can be used to calculate the stiffness of pavement layers – as long as the thickness of the layers is known. Traditionally coring at discrete points would be used, but the use of GPR to determine thickness allows more accurate and confident determination of layer thicknesses values, allowing a more confident prediction of layer stiffness which in turn provides improved assessment of the maintenance requirements for the pavement.

2 LIMITATIONS AND UNCERTAINITES

2.1 INTRODUCTION

All pavement investigation methods will carry certain limitations and uncertainties, from various sources, in the information that can be obtained. The sources of uncertainty or limitation that effect GPR information can be categorized into three areas:

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

Sources of potential uncertainty are identified and outlined below, particularly those arising during the analysis of GPR data. Through identification, investigation and discussion of the factors which may result in uncertainty and variation in GPR data interpretation, it is hoped that the effect of such factors can be understood, managed and minimized.

Work has been previously conducted to try and assess the certainty to which GPR can provide data and information, and various quantifications on the levels of accuracy that can be achieved have been reported. Saarenketo & Scullion (2000) summarize a series of investigations which reported depth accuracies of 3-5% from GPR data which had not been calibrated with cores (which is the least accurate way of estimating depths) and Willet & Rister (2002) report some instances of depth errors of core calibrated GPR data of less than 1%. However, determination of uncertainty or error in GPR depths may often be undertaken under ‘ideal’ or artificial conditions, which sometimes may not take into account non-technical factors. Generally the actual uncertainty in GPR depths may be affected by more parameters than are taken into consideration during research studies.

Guidance in DMRB states that “10 % level of accuracy can generally be achieved for layers greater than 75mm thick” and that “6 % level of accuracy can be achieved for layers greater than 125mm thick”. However, this should not be taken as an absolute guide to the accuracy that GPR can determine layer thicknesses. The DMRB values give an indication of overall accuracy, but the sources for potential inaccuracies are many and varied, and each source of potential error has to be considered and managed in order to produce the most useful and appropriate information for the pavement engineer.

Studies reporting the values for the accuracy of GPR determined layer thicknesses are useful, but such values are often determined by a quantification of the agreement between GPR data and ground truth data. Not only does this assume that the locations of ground truth data has been precisely and accurately recorded onto the GPR data record (something which may not always be the case during a pavement investigation) but it also only provides a determination of one aspect of the overall uncertainty which may be present, and which is largely based on the scientific limitations of radar technology. It can be more difficult to determine a value of error or uncertainty which may have arisen from sources such as the data collection methodology or from the data analysis and processing procedures. Whilst it is sometimes difficult to state a quantitative value for some of the uncertainties in data, it is important to be aware of their sources and understand their significance so that their impact on the quality of output from a GPR investigation can be minimized.

2.2 SIGNIFICANCE OF VARIATION IN GPR INFORMATION

Variation or uncertainties in GPR information results in a degree of risk to the pavement engineer using the information for design or planning. As mentioned above, there are a number of features and properties of pavement that can be identified by GPR, but one of the main uses of GPR data in pavement engineering is to determine layer thicknesses and identify changes in construction, for input into analysis of pavement condition for maintenance assessment. Such analysis typically takes the form of inputting GPR determined layer thickness values into the back-analysis of FWD data, and the use of GPR in this way is becoming a more common practice. When used effectively it can achieve a higher level of accuracy than with the use of coring information alone, but if used incorrectly it is possible that the GPR data will be less accurate and in the worst cases, may even provide an incorrect interpretation of the pavement condition.

The level of accuracy for GPR in determining layer thicknesses has been investigated by a number of previous studies, and a value of 6% (stated above, from the DMRB) is reasonable for routine or non-research investigations. Other research, also mentioned in the DMRB, has found that an under-estimation of 15% in thickness can lead to an over-estimation of 50% in layer stiffness. So, the implication is that the back-calculated stiffness may often be up to 20% out from the true value. Pavement material stiffness errors of this degree could lead to over- or under-design of maintenance treatments, and consequently incur un-necessary associated costs. Hence, the ability to reduce and minimize errors and uncertainties in layer thickness information is of great importance to the pavement engineer.

Due to the increased confidence in core location referencing that is achieved during slower speed surveys (discussed below), performing GPR investigations in this way may be the most appropriate method for use where data is used for pavement stiffness analysis. Clearly a requirement is that adequate core information is also needed to achieve this. Also, some back-analysis software packages are able to use individual construction thicknesses for each FWD test point, which can dramatically increase the level of accuracy. Again, there is a proviso that accurate locational referencing is used and that each thickness used is representative of the actual depth present.

The importance of accurate GPR determined thickness data, for use in back-calculation of stiffness values, has been discussed above because it is probably the most common current use of routine GPR pavement investigation data. However, it is not of course only when GPR information is used for this purpose that minimizing uncertainty or variation is important. All other applications of GPR investigations (mentioned in Section 1.2) all carry their own risks which are increased if the uncertainty in GPR data is not managed correctly.

2.3 SOURCES OF VARIATION IN GPR INFORMATION

Overview

For a given pavement structure, there can be variations in information obtained depending on how a GPR investigation is conducted, and how the GPR data is analyzed. Also, there are some known limitations relating to GPR technology that need to be managed, regardless of how the investigation is conducted and how the data is analyzed. The following summarizes the potential sources of errors in reported information from GPR investigations.

The quality of GPR data obtained from a survey is a function of several factors, including the dielectric properties of the materials and other site specific material conditions as discussed below. Also, the GPR system used on site (antennae type and power, gains used for data collection, survey methodology) will affect the data quality. The amount of information which can be obtained from the data is affected by the processing and analysis procedure used (software, processing procedures performed, data presentation method, etc). The competence of the GPR operator and data analyst can also affect the results obtained. Many of these factors can be addressed to optimize data and information quality, but it should be noted that some factors are less controllable.

Technological limitations of radar

Many of the limitations of early GPR systems, such as low sampling rates and poor memory capacity have been overcome with developments in electronic and computing technology. However, there are several issues which are not so easily overcome. The passage of a radar signal pulse is governed by the physical laws concerning electromagnetic waves, and the use of GPR data relies on recording the reflections of electromagnetic waves transmitted into the pavement structure. The different types of electromagnetic wave are characterized by their frequency. The frequency and speed of the waves will determine their wavelength, and the wavelength of the material will have a large effect on both the penetration depth of the signal, and the resolution (or precision) to which depths can be determined. This phenomenon, where higher frequency signals have greater resolution but lower penetration than lower frequency signals, is a physical limitation of GPR technology, and has to be taken into account when planning the GPR collection methodology (see 2.3.2).

There are also certain pavement and soil conditions that can have an affect on the quality of GPR data which can be obtained, such as materials with high moisture contents (although the ability of GPR to determine areas of higher moisture is, in itself, a useful ability), highly conductive materials (which attenuate the radar signal), and reinforcement in pavement layers masking deeper features. Therefore, the presence of such features in a pavement sometimes may limit the information that can be obtained. However, when the presence of such conditions are expected and recognized in survey results, GPR can still provide useful pavement investigation data (Barnes & Trottier, 2002).

Sometimes, features of the pavement will affect the efficiency of GPR in distinguishing details. For example, signal reflections from disintegrated material boundaries can prove difficult to accurately map on a GPR pseudo-section, causing uncertainty in the identification of distinct boundaries between materials. However, this problem is not just restricted to GPR data – core and other intrusive data are also liable to uncertainty when identifying depths of disintegrated material. The ability of the GPR data analyst can sometimes assist in data interpretation in such cases (see 2.3.3).

As stated in Section 1.1.2, the dielectric constant of a material is of great importance in GPR work. Several properties of materials have been shown to influence the dielectric constant including the temperature, moisture, pore fluids, porosity, density, mineralogy, geometries, and electrochemical interactions (Martinez et al, 2001 & Jaselskis et al, 2003). Generally, a given pavement material will have a range of values for its dielectric constant, because of such variations in the specific properties of that material. For example, Daniels (2004) reports the typical ranges of dielectric constant values for “dry asphalt” to be 2-4, “wet asphalt” to be 6-10, “dry concrete” to be 4-10 and “wet concrete” to be 10-20. Hence, a (dielectric) contrast between different materials may not always be the case, and the resulting low reflection coefficient may mean that resolution of material boundaries is not possible. Again, these physical limitations of GPR technology can sometimes be countered by employing the appropriate on-site data collection methodology (see 2.3.2). However, there will always be some situations where the physical site conditions mean that, even if every other aspect of the GPR investigation is conducted to the highest standard, the GPR data acquired can not adequately identify features or resolve layer boundaries.

In-situ investigation procedures

The methodology used to collect GPR data should be tailored to the specific site under investigation. It is not possible to provide a single methodology which will always provide the optimum data collection procedures at all sites. However, it is possible to outline general guidelines to minimize the limitations and uncertainties which may arise from the way data is collected and from the specific nature of the site. Also it is possible to use the data collection methodology to address some of the issues arising from the nature of GPR technology (see above).

Consideration of the site materials and depth of interest should be made so that the appropriate antenna(e) frequency can be used. Often the use of several antennae, providing a range of radar frequencies, provides the best coverage of depth penetration and resolution. Another factor, which can be addressed with appropriate on-site methodology, is to ensure that a sufficient density of data is obtained along the survey profile. Where detailed information is required a sufficiently high number of pulses (samples) per meter should be taken along the survey line, which may require a slow speed survey along the highway. This increases the time taken for the survey, but reduces the risk of obtaining insufficient density of data for the interpretation required. In locations where less detail is needed, less pulses per meter can be taken allowing a higher speed survey to be performed. A similar issue is the consideration of how many survey runs to perform. Depending on the requirements of a project, a single run along the pavement surface may be sufficient, but sometimes several runs along the pavement (e.g. in both wheel-tracks of a highway lane), or the inclusion of transverse runs may be required to minimize the risk of missing significant features.

There are several ways to calibrate GPR data (i.e. convert the signal reflection travel times recorded on site into depths, during analysis), but the most accurate method is to correlate the data with intrusive surveys. Intrusive surveys (usually in the form of cores, but also trial pits) are used to calibrate GPR data to a suitable level of accuracy, and the number of intrusive investigations will depend on the nature and homogeneity of the site materials. Targeting core locations after or during the GPR survey can assist with this process, and it is imperative that accurate marking of site locations in relation to GPR data points is conducted, not only to reduce uncertainty in core calibrations but also to ensure accurate reporting of the GPR data at the correct location on the site. Most GPR systems allow core locations to be marked directly on the GPR data pseudo-section, but in any case special attention should be paid to a sensible and easy to follow site chainage system, marked from fixed locations on site.

All of the above should be considered individually bearing in mind the specific nature of the site under investigations, and a dialogue between all members of the investigations team should be maintained to focus the information provided by the investigation on the needs of the end user.

Analysis procedures

GPR data processing and interpretation is not a fixed process, and there is a large range of processing steps that can be applied in order to obtain useful information from the data. The nature of the site, the quality of data obtained, and the required use of the data will effect which specific processing steps are required. Some stages of GPR data processing and interpretation have little potential to create variation between different analysts, as they are stages which apply procedures (for example, background noise filtering) to the entire GPR data set. However, one analyst may have a different preference or opinion on which of the various available procedures are relevant. For pavement investigations which focus mainly on layer depth determination, it is the processing stages which depend more on the experience, competency and preferences of the analyst which will have the greater effect on information variation between different analysts.

When core calibration is performed, often several cores are used within the same GPR data file (i.e. within the same survey run) for calibration. The use of several cores can result in different calibration velocities for each core. Where this is the case, sometimes an average velocity is used to convert signal travel times to depths, and other times it may be possible that, for example, several cores produce very similar velocities and a single core is in disagreement with the others. Also there can be instances where a core sample shows signs of deterioration or uncertainty in depth values for some reason, and the confidence attached to that core my be lower than other cores. Slight changes in materials can also affect velocities calculated from generically similar core materials. In such situations, the analyst has the main input into what value of calibration velocity is actually used. Variations in expertise, background and experience mean that, as with many engineering issues, there can be differences in professional judgment.

It is more difficult to quantitatively assess the uncertainties that may arise from the input of the data analyst, than those from technological or methodological issues. Ultimately the data analyst responsible for processing and analysis of the GPR data, in conjunction with other pavement data, provides the interpretation of what the GPR data shows, and it is this interpretation which is passed on to the end-user of the information (client, engineer, planner, etc).

As mentioned above, the production of useful pavement information, such as layer depths or areas of excess moisture, from GPR data requires a number of data processing and analysis stages. Some of these stages require the input of the analysts own geophysical and engineering knowledge in a qualitative way, as features within the GPR data are identified and reported to the end-user who is not likely to be a GPR specialist. A discussion of issues relating to the provision of useful information through analysis and interpretation of investigation data is given by Evans (2003).

Figure 1 shows processed GPR pavement investigation from a 400m length of motorway, in the UK. The white, black and grey lines indicate the depth to the bottom of the bituminous pavement layer, each line having been determined by a different analyst from the same initial raw data-set. The information presented (depth to the bottom of the bituminous material) is just one set of information that GPR data can be used to provide, and the data used was of good quality and had confident core calibration. As can be seen in Figure 1, the three interpretations of the same set of raw GPR data are broadly in agreement. However, despite the high quality raw data used, there are still several places where the analysts individual judgment and input have affected the analysis procedure and resulted in variations in interpretation (e.g. at distances of approximately 120m and 280m).

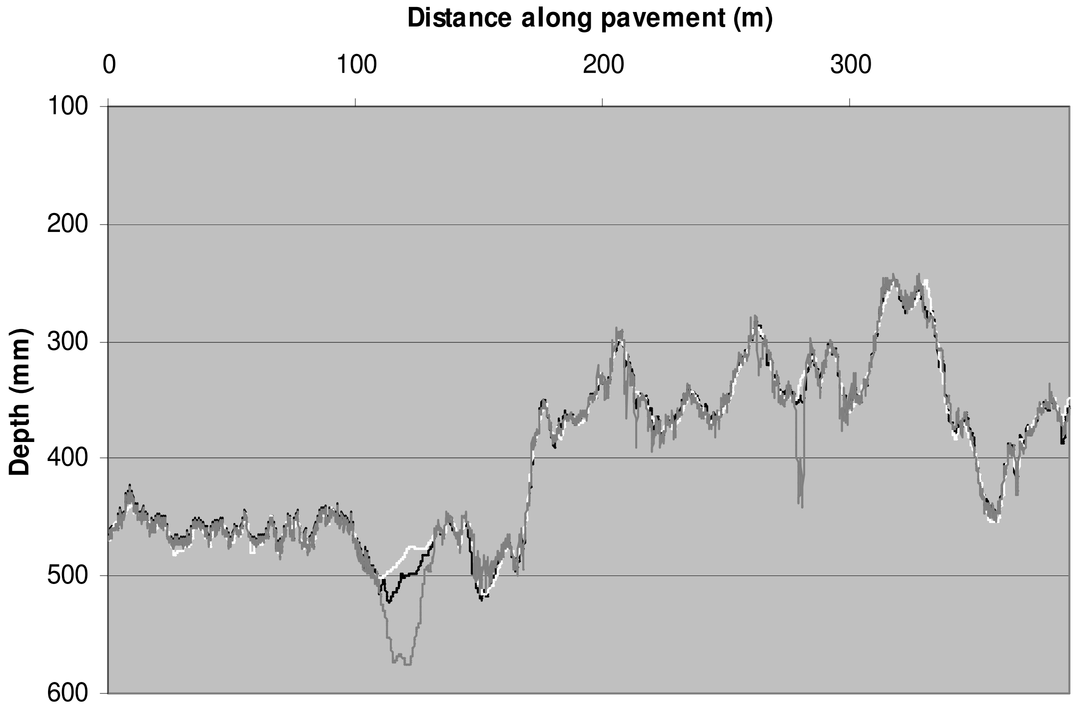

Figure 1. GPR data showing depth to bottom of bituminous pavement layer: three interpretations of the same raw data-set.

When considering variations from analyst input, unless the entire pavement under investigation is excavated and carefully measured, there can be no confirmation of ‘right’ and ‘wrong’ answers. However, the ability of an analyst to accurately interpret data will be enhanced and the risk of misinterpretation reduced through adequate training and experience in aspects of pavement engineering and GPR principles and technology.

3 CONCLUSIONS

GPR provides one of the most useful tools available to the pavement engineer. Information on a variety of parameters can be obtained, including layer depths, construction changes, material condition, location of features such as steel-work and pipes/services, areas of excess moisture and voiding. However, despite much recent development over the past few years, the various uncertainties that are associated with GPR investigation data have often resulted in its under use and under appreciation as a pavement investigation technique.

If the various uncertainties and sources of variability in GPR data are considered, it may be possible to indicate a ‘confidence level’ or other quantification of accuracy in the reported information (particularly for the less qualitative factors). Such a quantification of the quality of information is often not performed for some pavement investigation techniques. This can lead to a misconception that precise values reported for some investigations (for example, a thickness measurement from a core log, a stiffness value derived from an FWD test or a density value from a laboratory test), given without any quantification of accuracy or uncertainty, reflect high accuracy in the data. However, each individual pavement investigation method will have its own uncertainty or degree of variability associated with the data. The accuracy and confidence from GPR data can often be greater than that obtained from other investigations, especially when the technology and procedures used during GPR investigations is understood and appreciated.

GPR relies on both science and 'art', the interpretation of information in both quantitative and a qualitative ways. The optimization of on site data collection methodology can be used to address several technological issues, and the methodology employed will have a large influence over the overall ability to extract useful engineering information from GPR data. Also, individual analyst opinion or preference can influence the information output that results from processing and analysis of GPR data (as with other pavement investigation techniques). Whilst some GPR data processing options are fixed in their nature, some of the input of a GPR data analyst is qualitative and based on a combination of the individuals skill, training, experience and knowledge of both ground radar and pavements.

This paper has outlined the sources of GPR data uncertainty and variation, and described how these issues can be addressed and managed. Such sources can include technological limitations, uncertainties associated with the data collection methodology and variations arising from the procedures used to analyze data. By discussing and outlining the issues relating to these three areas of potential uncertainty and variation, it is hoped that both practitioner and engineers will have an enhanced understanding of how best to obtain and use information from GPR.

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APPENDIX F SYSTEM SPECIFICATIONS FOR GSSI SIR-20 GPR

SIR-20 System Specifications - For International Sales

System

Antennas: Records data from 1 or 2 hardware channels simultaneously; 1 to 4 data channels, selectable.
Data Storage, Standard (internal): 60 GB
Data Storage, Optional (external): Any standard PC peripheral using the PC parallel port, USB port or PCMCIA port
Display Modes: Linescan and Oscilloscope. In linescan display, 256 color bins are used to represent the amplitude and polarity of the signal.

Data Acquisition

Automatic System Setups: Storage of an unlimited number of system setup files for different survey conditions and/or antenna deployment configurations.[1]
Operating Modes: Free run, survey wheel, point mode.
Range Gain: Manual adjustment from -20 to +100 dB. Number of segments in gain curve is user-selectable from 1 to 8.
Vertical Filters: Individually filter the scans in the time domain. Low and High Pass, Infinite Impulse Response (IIR), Finite Impulse Response (FIR), Boxcar and Triangular filter types are available.

- IIR
  - Low Pass: 2 poles
  - High Pass: 2 poles
- FIR, Boxcar and Triangle
  - Low Pass: up to ½ scan length
  - High Pass: up to ½ scan length

Horizontal Filters:

- IIR
  - Stacking : 1 to 16384 scans
  - Background Removal: 1 to 16384 scans
- Static
  - Stacking: 2 to 32768 scans
  - Background Removal

Output Data Format: 8- or 16-bit, selectable.

Operating

Operating Temperature: -10°C to 40°C external.
Relative Humidity: <95% non-condensing.
Storage Temperature: -40°C to 60°C.

Rates @ 500 KHz PRF		
	Max Rate (scans/sec)	
Sample	**1 ch**	**2 ch**
128	980	700
256	725	475
512	570	290
1025	340	190
2048	190	105

Rates @ 100 KHz PRF		
	Max Rate (scans/sec)	
Sample	**1 ch**	**2 ch**
128	450	255
256	265	135
512	153	78
1025	78	39
2048	39	19

Radar System Connectors

- (2) Antenna inputs
- (1) 12 VDC input power
- (1) Survey wheel or DMI input
- (1) Marker input

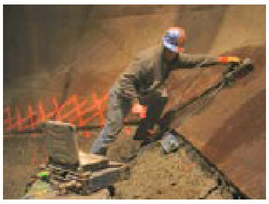
Electrical

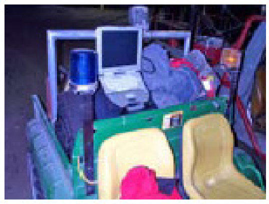
Antennas: Operates with any GSSI model antenna and can handle up to 2 antenna inputs simultaneously.
Resolution: 5 picoseconds.
Range: 2-8,000 nanoseconds full scale, selectable.
Input Power: 12 volts, DC nominal with operating range of 11-15 volts, 60 watts.

Radar System Parameters2

- Signal to noise ratio: > 110 dB
- Dynamic range: > 110 dB
- Time base accuracy: .02%

[1]Limited only by computer hard disk capacity
[2]Does not include antenna figures





APPENDIX G GPR PAVEMENT INVESTIGATION – BUSINESS PROCESS PROFORMA

GPR pavement investigation: methodology checklist To be completed prior to commencement of fieldwork			
Project		**Job number**	
Road ID		**Length**	
Date		**Staff**	

Consideration	**Methods / requirements**	**Comments (i.e. chosen methodology)**
Information required	Layer depths, rebar, moisture, voiding, etc.	
Depth penetration required	Antenna frequency	
Pavement details required (course, fine)	Survey speed / scan rate	
Survey run locations required (i.e. scope of information)	Number of longitudinal / transverse survey runs	
Calibration method	Core / as-builts / etc	
Is coring required / planned? If so: core spacing / density?	Approx number of cores required for survey length	
TM required?	Closure, mobile, stop-go, none	
Is there a site referencing system?	Specify chainage system	
Outputs required	Layer depth charts, moisture maps, CAD drawings, etc	