Road evaluation with ground penetrating radar

Timo Saarenketo a, *, Tom Scullion b,1

a Roadscanners Oy, P.O.Box 2219, FIN-96201 Rovaniemi, Finland
b Texas Transportation Institute, Texas A & M University System, College Station, TX, 77843-3135, USA

Received 9 March 1999; received in revised form 8 June 1999; accepted 10 June 1999

Abstract

This paper provides a status report of the Ground Penetrating Radar (GPR) highway applications based on studies conducted in both Scandinavia and the USA. After several years of research local transportation agencies are now beginning to implement GPR technology for both network and project level surveys. This paper summarizes the principles of operation of both ground-coupled and air-launched GPR systems together with a discussion of both signal processing and data interpretation techniques. In the area of subgrade soil evaluation GPR techniques have been used to nondestructively identify soil type, to estimate the thickness of overburden and to evaluate the compressibility and frost susceptibility of subgrade soil. In road structure surveys, GPR has been used to measure layer thickness, to detect subsurface defects and to evaluate base course quality. In quality control surveys, GPR techniques have been used for thickness measurements, to estimate air void content of asphalt surfaces and to detect mix segregation. Future developments are described where the technique has great potential in assisting pavement engineers with their new pavement designs and in determining the optimal repair strategies for deteriorated roadways. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Ground penetrating radar; Road structure; Subgrade; Dielectric value

1. Introduction

In Scandinavia, the first Ground Penetrating Radar (GPR) tests with ground-coupled antennae were performed in early 1980s in Denmark (Berg, 1984) and in Sweden (Johansson, 1987), but the method did not gain general acceptance at that time. In Finland the first tests were made in 1986 (Saarenketo, 1992) and after the Road District of Lapland of the Finnish National Road Administration (Finnra) purchased its own unit in 1988, the method has been used as routine survey tool in various road design and rehabilitation projects in Finland (Saarenketo, 1992; Saarenketo and Majala, 1994; Saarenketo and Scullion, 1994). Most of the research and development works in highway applications in Finland has been performed with low frequency (100–500 MHz) ground-coupled antenna in order to evaluate subgrade soils and their interlayers, probe the depth of overburden and survey road structural layers. GPR technique was also applied in aggregate prospecting (Saarenketo and Majala, 1994). In early- and mid-1990s tests with high frequency 1.0–1.5 GHz air-coupled and ground-coupled antennae were started.
in bridge deck surveys (Saarenketo and Söderqvist, 1993; Maijala et al., 1994), and in pavement design and quality control (Saarenketo and Roimela, 1998; Scullion and Saarenketo, 1998; Saarenketo, 1999).

The history of GPR tests on road surveys in the USA relates to the mid-1970s, when according to Morey (1998), Federal Highway Administration tested the feasibility of radar in tunnel applications and later on bridge decks. The first vehicle mounted GPR system for highways was developed under a FHWA contract in 1985 (Morey, 1998). Since then, most applications have been focused on pavement thickness measurements (Maser, 1994), detecting voids under concrete slabs (Scullion et al., 1994) and detecting deteriorated areas in bridge decks (Alongi et al., 1992). These surveys have mainly been performed with high frequency (1.0 GHz) air-launched antennas (see Scullion et al., 1992).

A good description of the current practices of GPR applications in highway agencies in North America is given by Morey (1998). The result of the questionnaire sent to 50 states, Puerto Rico, the District of Columbia and 11 Canadian transportation agencies showed that 33 agencies of the 51 responses had experience with GPR. The most common GPR applications reported were pavement layer thickness (24 agencies), void detection (22 agencies) and bridge delamination (16 agencies); followed by delamination detection (11 agencies), depth to steel dowels (8 agencies), buried objects (8 agencies), depth to bedrock (8 agencies), asphalt stripping (7 agencies), and scour around bridge support (6 agencies). Of the various applications GPR seemed to be the most successful for pavement layer thickness measurements, while agencies report less satisfactory results with void detection and questionable results locating areas of asphalt stripping (Morey, 1998).

This paper gives a state-of-the-art review of GPR applications in road surveys in Scandinavia and in the USA. The testing of bridges with GPR will not be addressed in this review because this is a large area which needs a separate article. In other parts of the world GPR techniques have been used for road monitoring in more than 20 countries and according to the knowledge of the authors, GPR surveys on roads are widely used in Canada, France, Italy, Switzerland and the UK.

2. GPR hardware and software for roads

2.1. Hardware

Impulse Radar techniques are based on the measurement of travel time and reflection amplitude of a short electromagnetic pulse transmitted through a pavement and then partly reflected from electrical interfaces within the structure. Electrical interfaces occur at layer interfaces when the GPR wave encounters different materials or changes in either moisture content or density. GPR systems typically have the following three components: (1) a pulse generator which generates a single pulse of a given center frequency and power, (2) an antenna which transmits the pulses into the medium and captures the reflected signal, and (3) a sampler/recorder which samples the reflected signals and converts them into a form for computer storage. The radar antennae in common use fall into two broad categories: air-launched horn antennae and ground-coupled dipole antennae. A ground-coupled 500 MHz antenna mounted in front of a van is seen in Fig. 1.

Fig. 1. Finnish National Road Administration (Finnra) GPR survey van with GSSI 500 MHz ground-coupled antenna.
Ground-coupled antennae operate in a wide range of central frequencies from 80 to 1500 MHz. The clear advantage of ground-coupled systems is their depth of penetration compared with air-launched systems, while the surface coupling and antenna ringing present problems, which make it difficult to obtain any quantitative information from the near surface without signal processing. Data collection speed with ground-coupled systems is normally 5–15 km/h. The leading manufacturer of ground-coupled systems is GSSI of New Hampshire, USA, other manufacturers include Sensors and Software from Canada and MALÅ from Sweden.

Air-launched systems operate in the range of 500 MHz–2.5 GHz, the most common central frequency being 1.0 GHz. Their depth penetration is typically 0.5–0.9 m. During the data acquisition these antennae are suspended 0.3–0.5 m above the pavement surface. The data collection speed can be up to 100 scans/s which allows GPR survey velocities up to 100 km/h. Currently three vendors from the USA manufacture and sell air-launched systems: GSSI of New Hampshire, Penetradar of New York, and Pulse Radar of Texas. Fig. 2 presents TTI Penetradar air-launched horn antenna.

In order to promote efforts for better GPR hardware systems, Scullion et al. (1996) have proposed test protocol and performance specifications for the air-launched antennae and ground-coupled antennae with higher frequencies than 500 MHz.

In the future, the road GPR hardware development will go towards smaller non-contact antennae and multichannel data collection systems, which allow tomographic images from the road. One example of these systems is the 64-channel HERMES bridge inspector under development by the Lawrence Livermore National Laboratory (Davidson and Chase, 1998).

2.2. Software

The GPR software available for road surveys can be classified into four groups: (1) GPR data acquisition software, (2) GPR data processing software, (3) interpretation and visualization software, and (4) software for integrated road analysis and design.

Most of the GPR data acquisition software has been developed by the GPR systems manufacturers. However, custom built data collection and quality control software packages are now being developed. Improved packages are needed when air-launched horn antenna systems are used for pavement quality control purposes, where measurements have to be repeatable and where the GPR results will be used determine bonuses and penalties on newly completed projects.

A very important feature in data acquisition software is the linkage to the positioning systems, such as GPS, because modern pavement management systems (PMS) pavement design software need information to be attached to $x, y, z$ coordinates. Currently, most systems are using a distance based data acquisition control. In the next few years exact positioning and linking of GPR data to other pavement survey data is one key research area.

GPR manufacturers also provide GPR data processing systems, but most of the software has been written in order to process ground-coupled data collected for geological surveys. Air-launched GPR systems produce relatively clean and repeatable signals, therefore the processing...
requires only basic signal filtering and background removal algorithms. A challenge in the future in data processing software is to infer some quantitative information on electrical properties of the pavement layers and subgrade. Spagnolini (Spagnolini, 1996; Spagnolini, 1997; Agosti et al., 1998) has approached this problem by investigating promising techniques to resolve some of the essential problems in road structure evaluation, i.e., inversion technique to gain information about vertical distribution of dielectric value in road structures and layer stripping technique to define the exact location of the reflections when overlapping each other.

GPR data interpretation and visualization software for roads are used for detecting layer interfaces and individual objects from the GPR data and transforming the GPR data time scale into depth scale. Many efforts, including the use of neural networks, have been made in order to develop automatic interpretation software for roads and bridges. However, the results of these development projects have not been encouraging and have caused confusion among highway engineers. The reason for automatic interpretation software packages will most likely never work is that the roads are mostly historical structures with “accumulation and deteriorated structures” and discontinuities in longitudinal, vertical, and transverse directions. That is why semiautomatic interpretation software used by well trained and experienced interpreting staff together with limited coring or other reference survey results has proved to be the only working solution in road surveys. The user must also ensure that the echoes are from real interfaces and not the result of multiple reflections between strong reflectors by comparing the echo profiles of the interface in question with those nearby. The only cases where automatic interpretation seems to calculate right thickness and dielectric values are surveys on new and defect free pavements. More discussion on this will be given in Section 5.

A new generation among GPR software are the integrated road analysis and design software packages, which are designed for the combined analysis of GPR data with other road survey data, with the ability to calculate parameters which describe the condition of the old road, and parameters needed for a new road structure or rehabilitation design (Saarenketo, 1999). In road surveys GPR data output are presented in numeric format or they are visualized in longitudinal profiles or GIS maps. In many cases the actual GPR data is not presented, only the results are visualized. When combined with other data types such as longitudinal profile, the GPR is used to identify the potential cause of surface defects.

3. Road subgrade surveys

3.1. General

Subgrade surveys and site investigations with GPR has been classified into the following three categories (Saarenketo and Scullion, 1994): (1) new road alignment and site investigations, (2) strengthening and widening of an existing road, and (3) using the existing road as an information source for the design of a new roadway alongside the existing road. In each case the basic problem is similar, but the way the GPR techniques are applied varies.

In subgrade surveys for a new road alignment, GPR can be used to determine the soil types and their boundaries, estimating the depth of bedrock, and evaluating the ground water level and frost susceptibility (Saarenketo, 1992). GPR data can be used also for guidance of conventional site investigations such as drilling and, in places which cover the variety of geological conditions, to optimize the use of these traditional methods. Low frequency ground-coupled systems are used for this application.

In highway bridge site investigations, GPR has been used to monitor the bottom topography of rivers and lakes to map the quality of underwater sediments. In the USA and Finland, GPR
techniques have been used also for detecting scours around bridge piers (Haeni et al., 1992).

In road rehabilitation projects and when designing a new road alignment alongside the old roadway, most of the previously mentioned information is collected from the subgrade under the existing road. These subgrade data, combined with other GPR data collected from the existing road layers, provide valuable information that can be used for predicting the performance of the new road.

3.2. Subgrade soil evaluation

It is often quite easy to identify coarse grained gravel, sand and glacial till soils from GPR data and GPR works well with organic peat soils (Ulriksen, 1982; Doolittle and Rebertus, 1988; Ground Penetrating Radar, 1992; Saarenketo et al., 1992). GPR signals have relatively good signal penetration in most silty soils, but problems arise when surveys are carried out in clay soils. In Scandinavia, GPR signal penetration in clay soil areas is normally about 2 m, which is adequate for the cable and pipeline surveys but not for the highway design purposes. In such cases other geophysical methods, such as electrical resistivity profiling methods, have been applied.

In the USA, the penetration depth depends on the mineralogy and clay content of clay soils. A penetration depth of 5 m has been achieved in areas of Site Oxidic soils, while radar signals penetrate only 0.15 m in Vaiden type Montmorillonitic soils (Doolittle and Rebertus, 1988). According to Doolittle (1987) the best areas in the USA for radar in soil surveys are eastern and western states, while the greatest problems occur in the Mississippi–Missouri drainage basin area in the central states.

In many cases the soil type can be determined from the GPR data, because every soil has its own geological structure, dielectric, and electrical conductivity properties (see Saarenketo, 1998a); these properties cause a special “finger print texture” in a GPR profile. In Finland, for instance, soils that have dielectric dispersion tend to have a special “ringing” GPR reflection pattern whereas soils with no dispersive fine grained materials do not have this phenomenon. This knowledge has been applied especially when doing sand and gravel aggregate prospecting (Saarenketo, 1992). Soil type evaluations always need some ground truth data to confirm the GPR interpretation. A very helpful technique for interpreters is to attach drill core information to the GPR profile, which helps to select the right reflection interfaces for the final interpretation, as shown in the case study conducted in TH 28 Burtrum in Minnesota (Saarenketo, 1998b) (Fig. 3). In this figure strong reflectors between 300–370 m and 410–480 m present old road surface levels that have settled due to highly compressive peat subgrade. Excellent supporting information can also be gained from the Falling Weight Deflectometer (FWD) survey data.

3.3. Depth to bedrock and bedrock quality

In road surveys GPR information of the depth of overburden and location of the bedrock is used in the design of grade lines, or in design against uneven frost heave and other specific technical problems such as in backcalculation of pavement layer moduli. GPR allows also observation of bedrock stratification and major fracture zones when evaluating the stability of highway cutting walls (Saarenketo, 1992). Similar information can also be obtained in highway tunnel surveys where both ground-coupled and drill-hole antennae have been used (Westerdahl et al., 1992).

Identification of bedrock is often difficult, and it is impossible if the radar signal does not penetrate the overburden soil. However, if even weak reflections can be recorded, there are several interpretation techniques that can be used to confirm the bedrock interface. If the dielectric properties of bedrock and subgrade soil road structure are very close, the reflected signal amplitude from the interface will be weak. Also,
if the bedrock has been blasted under the road to a certain level, the transition zone from bedrock to road structures may be wide and no clear discrete interface reflection can be observed in the radar trace (Saarenketo and Scullion, 1994). That is also the case in areas of weathering crust over bedrock. In all of these cases, the estimation of bedrock interface has to be done by identification of the zone in the radar profile where the bedrock structure starts.

In highway engineering the bedrock is defined as a stiff material that cannot be excavated without blasting. Because GPR gives structural information, the survey data always needs some supporting information and reference data, such as drilling, excavation pits or seismic survey data. A very promising and economical technique in road surveys has been the analysis of the GPR data together with the FWD data (Saarenketo, 1999; Scullion and Saarenketo, 1999). If the bedrock is close to the surface it can be seen in the FWD deflection bowl data. The depth can be confirmed by using FWD backcalculation algorithms. Once the depth to the stiff layer has been calculated from the FWD measurement point, the surface of the bedrock between the FWD measurement points can be defined from the GPR data as done in Rd 17469 in Kuortane, Western Finland (Fig. 4). If GPR surveys are performed in the wintertime, the areas of the bedrock closer to the surface than the frost level are easy to identify because the frost line reflection in the bedrock cannot be seen from the radar profile (Fig. 4).

3.4. Soil moisture and frost susceptibility

Moisture content has a great effect on the strength and deformation properties of the road structure and subgrade soils. Information about the subgrade soil moisture content is needed in estimating stability and compressibility of the subgrade soils, when designing highways on areas with expansive clays and when evaluating frost susceptibility of soils.

Both positive and negative pore water pressure in soil have major effect on shear strength and volume change of the soil. In unsaturated
soils and unbound road structures the term “suction” is used for the thermodynamic quantity, Gibbs free energy, which generates tension in the pore water between soil particles. The total suction is composed of two components: (1) matric suction and (2) osmotic suction (Fredlund and Rahardjo, 1993). The magnitude of the matric suction is mostly affected by the amount of fines in soils, while cation exchange capacity (CEC) and salt content affect the osmotic suction.

In low moisture contents, suction can increase the stiffness of soils and unbound aggregates and they have high modulus values, but when moisture content increases, suction decreases (Fredlund and Rahardjo, 1993). At high moisture content, positive pore water pressure can decrease the material resistance to permanent deformation.

In the case of widening and/or strengthening an existing highway, or when constructing new lanes, the best information about the changes in compressibility of the subgrade soil can be obtained directly by surveying the existing road with GPR. This technique is especially useful when estimating the amount of settlements in new road and when designing preloading embankments over clay, silt or peat subgrade (Saarenketo et al., 1992). A good example illustrating the information obtained from an old road is the case study conducted on HW 170 near Helsinki, Finland (Fig. 5).

Frost action, which appears in areas where frost susceptible soils have a great effect upon the fatigue of the road, can be seen as permanent deformation of road structures taking place during the spring frost thawing period. Another typical frost damage is uneven frost heave re-
lated to subgrade soil and moisture transition areas, or to the presence of bedrock or boulders. Structural elements in the road body, such as culverts, have also caused surface damage if the transition wedges are not properly constructed.

Frost susceptibility is also closely related to the moisture content and drainage characteristics of the subgrade, which can be estimated with GPR and other dielectric measurement devices, such as the Percometer technique. Saarenketo (1995) has proposed a frost susceptibility and compressibility classification for the subgrade soils in Finland, which is based on in situ measurements of dielectric value and electrical conductivity.

A tentative quality assessment of the strength and deformation properties of soils and unbound road materials based on the dielectric properties is presented in Table 1 (see also Hänninen and Sutinen, 1994; Hänninen, 1997).

The evaluation of potential frost action areas and presence of segregation ice using GPR can

<table>
<thead>
<tr>
<th>Dielectric value</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>4–9</td>
<td>Dry and non-frost susceptible soil, in most cases good bearing capacity (excluding some sands)</td>
</tr>
<tr>
<td>9–16</td>
<td>Moist and slightly frost susceptible soil, reduced but in most cases adequate bearing capacity</td>
</tr>
<tr>
<td>16–28</td>
<td>Highly frost susceptible and water susceptible soil, low bearing capacity, under repeated dynamic load positive pore water pressure causes permanent deformation</td>
</tr>
<tr>
<td>28–</td>
<td>Plastic and unstable soil</td>
</tr>
</tbody>
</table>
also be performed in winter time when frost has penetrated into the subgrade soil and when the dielectric value of frozen soils is closer to the relative dielectric value of frozen water (3.6–4.0). When analyzing the GPR data the interpreter has to pay attention to the following phenomena: (1) the appearance of the frozen/non-frozen soil interface reflection, (2) the depth of frost table and clarity of the reflection, and (3) the effect of the frost action upon the road structures (Saarenketo, 1995, 1999; Saarenketo and Scullion, 1994).

If the frost level cannot be identified from the radar data, then the subgrade soils have a low dielectric value and thus are non-frost susceptible. If the frost level reflection is very clear in the GPR data, then the frost has penetrated the subgrade without forming segregation ice lenses that cause frost heave. High and uneven frost heave can be found in areas where the frost level comes close to the surface. Here the segregation ice containing unfrozen water can be seen in the GPR data above the frost level as in the case from HW 322 Skalstugavägen in Western Central Sweden (Fig. 6).

3.5. Other subgrade related surveys

GPR techniques have also been used when locating sinkholes under the road (Saarenketo and Scullion, 1994; Casas et al., 1996). Adams et al. (1998) have reported surveys results where GPR has been used to detect the washout of sandy material beneath the pavement in IS 44, Springfield, MO. After locating the area of voids, GPR has also been used to monitor the grout injection into the voids (see also Ballard, 1992). Another GPR application related to the subgrade surveys is the location of underground utilities under the existing road (Bae et al., 1996). Numerous authors have also had success with detecting buried tanks close to the edge of

![Fig. 6. 500 MHz ground-coupled data collected in March 1998 from HW322 Skalstugavägen, Sweden presented together with IRI (International Roughness Index) data. Clear reflection at the level of 1.4–2.0 m present frost line. The GPR data at the road section with severe damages between 5720 and 5820 m, shows strong reflection above frost line indicating the presence of segregation ice. Uneven section at 5875 m is caused by settlement in transition zone from till subgrade to peat subgrade.](image-url)
the existing pavement structure prior to widening of the highway.

4. Road structure evaluation

4.1. General

In highway engineering a potential major growth area for GPR applications will be in the evaluation of existing road structures. This is because the basic road network in the industrialized world is now almost complete and the activities of national road authorities will be increasingly focused on maintaining and improving the service standards of their current road network. At the same time national road administrations have faced the fact that public funding has decreased markedly. That is why new maintenance strategies and rehabilitation techniques are needed to optimally allocate the shrinking available funds. GPR can certainly play an important role in this area, it is the only technology that can be used at highway speed to provide subsurface information about the pavement structure. Combining GPR with other non-destructive road survey techniques provides a powerful tool for diagnosing current pavement problems and selecting the optimum repair technique (Saarenketo, 1999).

In pavement structure evaluation, both ground-coupled and air-coupled antennae systems are used. Most of the ground-coupled antennae surveys are conducted using 400–500 MHz antennae in order to get information from the whole pavement structure up to 3 m, but high frequency 1.5 GHz ground-coupled antennae have been used to locate stripping and other defects in pavement (Saarenketo, 1998c).

The air-launched GPR systems are increasingly being used for evaluation of the upper part of the pavement structure. They produce relatively clean signals and can operate at close to highway speed. Furthermore, on defect free pavements the signals can be processed to compute both layer thicknesses and layer dielectrics. This is demonstrated in the following, with reference to Fig. 7 which shows a GPR reflection from a homogeneous newly constructed flexible pavement. The reflections $A_1$, $A_2$ and $A_3$ are reflections from the surface, the top of granular base and the top of subgrade, respectively. The principles of using GPR reflections to compute layer properties has been given by Maser and Scullion (1991). By automatically monitoring the amplitudes and time delays between peaks, it is possible to calculate both layer dielectrics and thicknesses. These equations are summarized below:

$$
\varepsilon_a = \left[ \frac{1 + A_1/A_m}{1 - A_1/A_m} \right]^2,
$$

where, $\varepsilon_a$ = the dielectric value of the asphalt surfacing layer; $A_1$ = the amplitude of the reflection from the surface in volts (peak $A_1$ in Fig. 7); $A_m$ = the amplitude of the reflection from a large metal plate in volts (this represents the 100% reflection case).

$$
h_1 = \frac{c \times \Delta t_1}{\sqrt{\varepsilon_a}},
$$

where, $h_1$ = the thickness of top layer; $c$ = the speed of the GPR wave in air as measured by

![Fig. 7. GPR trace from a new pavement measured with a 1.0 GHz horn antenna and after background removal. Peaks $A_1$, $A_2$, and $A_3$ are reflections from road surface, base and subgrade.](image-url)
the system; \( \Delta t = \) the time delay between peaks \( A_1 \) and \( A_2 \) of Fig. 7

\[
\sqrt{\varepsilon_b} = \sqrt{\varepsilon_a} \left[ 1 - \frac{A_1^2}{A_m^2} + \frac{A_2}{A_m} \right],
\]

where, \( \varepsilon_b = \) the dielectric of the base layer; \( A_2 = \) the amplitude of reflection from the top of the base layer in volts.

These simple equations have been proven to work well for flexible pavements over granular bases. They assume that no attenuation of the GPR signal occurs in the surface layer. This assumption appears to be reasonable for asphalt pavements and also gives reasonable dielectric values for base layer, if the asphalt is thicker than 60 mm and there are no also thin layers on the top of the base. However, the computations become less reliable for concrete pavements and for computing subgrade dielectrics beneath granular base layers. Current research activities are aimed at incorporating signal attenuation into the calculation process.

For new or defect free pavements, the surface and base dielectrics together with the surface thickness can be easily calculated. Current work in Texas and Finland is aimed at performing these calculations in real-time primarily for quality control purposes. The results for a section of highway are often displayed as shown in Fig. 8. It is the magnitude and variation of both the surface and base dielectric which yields substantial information about subsurface conditions. The factors which primarily impacts the surface dielectric is the density of the asphalt layer, the factor impacting the base dielectric is the volumetric moisture content of the base. The GPR reflections can also be used to judge the homogeneity of the pavement layers. The reflections shown in Fig. 7 are from a defect free homogeneous pavement structure. As can be seen from this figure there are no reflections

![Fig. 8. Basic processing of GPR data. The actual traces are shown in upper left box. The computed layer thickness and dielectrics are shown in other boxes.](image)
between the reflections from the top of the surface and base. If the layer contained a defect at middepth such as stripping or trapped moisture then additional reflections would occur between peaks $A_1$ and $A_2$.

### 4.2. Pavement thickness

The GPR pavement thickness data has been collected for: (a) network level surveys where thickness is required for PMS data bases (Fernando et al., 1994), (b) to supplement FWD data in calculation of layer moduli (Briggs et al., 1991), (c) pavement design purposes, e.g., to check if the pavement is thick enough for recycling milling, and (d) for quality control purposes (Saarenketo and Roimela, 1998; Scullion and Saarenketo, 1998).

Using the techniques described above for new pavements the accuracy of GPR thickness predictions has been around 3–5%, without taking a validation core. For the base layer, the accuracies have been reported to be close to 8–10%. For older pavement, validation cores are recommended (Maser and Scullion, 1991; see also Morey, 1998).

### 4.3. Pavement defects

Even though a greatest part of the defects observed on asphalt pavements are related to material problems of the layers beneath the pavement, there are also some pavement damages caused by deterioration problems inside the pavement. The most common asphalt pavement damage is stripping, which is a moisture related mechanism where the bond between asphalt and aggregate is broken leaving an unstable low density layer in the asphalt. Stripped layers should always be detected and removed before placing a new overlay. That is why engineers responsible for in-pavement design should know if stripping is present or not, how deep and how widespread it is.

GPR technique has been widely used to detect stripping with varying success (see Morey, 1998). Stripping can be seen in most cases as an additional positive or negative (reversed reflection polarity) reflection in the pavement. However, similar reflection can be received from an internal asphalt layer with different electrical properties, which is why reference data, such as drill cores and FWD data should always be used to confirm the interpretation. Fig. 9 presents a case from Willmar, Minnesota, where 1.5 GHz ground-coupled and FWD data were used to evaluate stripping (Saarenketo, 1998c).

Another major cause of surface distress is moisture becoming trapped within the surface layer. This happens when impermeable fabrics or chip seals are placed between asphalt layers or when the existing surface is milled and replaced with a less dense layer. GPR signals are highly sensitive to variations in both moisture and density. In a recent study in Texas, five types of reflections were identified from within asphalt surfacing. These are shown schematically in Fig. 10. The “ideal” trace with little contrast between the new and old Hot Mix Asphalt (HMA) is defined as a Case 1 reflection in Fig. 10, a small reflection $B_i$ is proposed from the interface between the new and old HMA layers.

GPR reflections from existing highways can be complex particularly if the old HMA layer contains numerous thin layers constructed with different aggregates compacted to different densities. Moisture barriers within the layer and collecting data shortly after significant rain can also complicate the analysis. Fig. 10 was developed to aid in signal interpretation.

Other asphalt defects include cracking (Saarenketo and Scullion, 1994), thermal cracking and debonding, which takes place when the bonding between separate asphalt layers comes loose.

The major defects in concrete pavement have been reported as voids beneath the joints, cracking and delamination of the concrete pavement. The formation of voids beneath concrete pavements is a serious problem, which is particularly noted on jointed concrete pavements built with
Fig. 9. 1.5 GHz ground-coupled antenna data collected from TH71 Willmar, Minnesota presented with FWD data. The road section with severe stripping on the bottom of the asphalt between 900 and 990 m can be seen both with GPR and FWD data.

stabilized bases (Saarenketo and Scullion, 1994). Over time, bases erode and supporting material is frequently pumped out under the action of truck loads.

The problem when using GPR to detect the voids beneath concrete slabs is the moisture content of the voids, i.e., depending on whether the voids are dry, semidry or saturated, in each case the GPR reflection pattern looks different. The size of the voids has to be big enough; GPR can detect only voids bigger than 15 mm (Saarenketo and Scullion, 1994).

4.4. Base course and unbound road structures

Base course layer made of unbound aggregates which supports asphalt or concrete pavement is one of the most critical layer in road structure. A series of research projects have been carried out in Finland and Texas where the relationship of dielectric properties of Finnish and Texas base materials to their water content and to their strength and deformation properties were studied with a DCP (Dynamic Cone Penetration) test and dynamic triaxial tests (Saarenketo and Scullion, 1995, 1996; Saarenketo et al., 1998). A special Tube Suction laboratory test based on the dielectric measurements of the material at its moisture equilibrium level has also been developed in order to test the moisture susceptibility of road materials (Saarenketo and Scullion, 1995; Scullion and Saarenketo, 1997).

Results of the surveys conducted have shown that the dielectric value, which is a measure of how well the water molecules are arranged around and between the aggregate mineral surfaces and how much free water or "loosely
bound water” exists in materials, is a much better indicator of the strength and deformation properties of road aggregates than the moisture content. Each aggregate type has a unique relationship between material dielectric and moisture content. As shown in Eq. (3), the amplitude of the GPR reflection from the top of the granular layer is used to calculate the dielectric of that layer. Furthermore, high dielectric values (>16), calculated from the GPR data, for example, are good indicators for potential problems in the layer (Saarenketo et al., 1998).

A tentative quality assessment scale for unstabilized flexible base is proposed in Table 2.

4.5. Project level surveys and road analysis

One of the best fields for the applications of GPR technology is in the project level testing for pavement management purposes. Identifying the cause of existing problems and defining the optimal rehabilitation strategy is an area of critical importance. GPR alone can provide only a part of the answer, but it becomes more powerful when combined with other geophysical and non-destructive pavement testing methods. In Texas, GPR data has been analyzed together with FWD structural data, pavement distress data from the video image and drill core data (Scullion and Saarenketo, 1999). Integrated analysis techniques has also been applied in airports where GPR data has been analyzed together with infrared thermography, magnetometer and pachometer measurement data (Weil, 1998). Case studies of GPR in project level surveys has been published by Hugenschmidt et al. (1996) and Wimsatt et al. (1998) (see also Morey, 1998).

In Finland, a comprehensive Road Analysis package has been developed by Roadsammers Oy in cooperation with Finnra. It includes an evaluation of: (1) overall pavement condition, (2) condition assessment of the unbound pavement structure, (3) subgrade damage related to frost fatigue, (4) drainage condition, and (5) local damage of the surveyed road. The analysis is based on measurements conducted with GPR, with the support of drill core samples, roughness and rutting measurements with 5 or 10 m mean value (5 m-IRI), FWD measurements, and visual observations of pavement surface condition.

A key tool in Road Analysis is the Road Doctor software developed by Roadsammers Oy, which is used for the integrated analysis of the

<table>
<thead>
<tr>
<th>Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality criteria for unstabilized base material</td>
</tr>
<tr>
<td>Dielectric</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>5–10</td>
</tr>
<tr>
<td>10–16</td>
</tr>
<tr>
<td>&gt; 16</td>
</tr>
</tbody>
</table>
pavement structure. In the first phase, Road Doctor processes the ground-coupled and air-coupled GPR data and the thickness of the asphalt and other structural layers are calculated. In the next phase, FWD rutting and roughness survey data are imported to the Road Doctor database together with other reference data such as drill core information (Fig. 11). If $x, y, z$ information of the road under survey is available, the GPR data can be viewed with topography information and all the layer interface information can be transferred to a road CAD systems together with the coordinates. In the Road Analysis, the road is divided into homogenous sections and classified according to the subgrade soil quality and effect of the freeze–thaw process to the road structures. Also structural course thickness and material properties are evaluated. As a result of a detailed Road Analysis of the road structure, the quality and extent of the damages in road structures are reported to the pavement engineer in order to provide reliable information to support rehabilitation design decisions.

5. Quality control of a new structure

5.1. General

Nondestructive pavement testing methods, such as GPR, have gained increasing popularity in quality control surveys of new road structures. The greatest advantages of GPR methods

Fig. 11. Road Analysis profile over section 2200–2600 m of HW930 in Ylitornio, Finnish Lapland.
are that they are not destructive when compared to the traditional drill core methods, they are low cost methods and GPR surveys can also be performed from a moving vehicle reducing safety hazards to highway personnel. GPR allows for the possibility for continuous data collection and thus a 100% coverage can be acquired from the new road structure under inspection. Drill core methods provide point specific information and they cannot be reliably used to find defect areas in new pavements.

The GPR applications in quality control surveys include thickness verification of the road structures. This technique has been discussed earlier in Section 4.2. GPR has also been used to check if the soil replacement and transition wedges are constructed according to instructions and if dowel bars between concrete slabs have been installed properly. New GPR quality control applications include measuring the air voids content of asphalt and detecting segregation in asphalt.

5.2. Asphalt air void content

Asphalt air void content, i.e., the amount of air incorporated into the material or its function asphalt density, is one of the most important factors affecting the life span and deformation properties of pavements. This parameter has earlier been estimated by means of drilled sample analysis or radioactive methods, but after 3 years of testing the GPR surface reflection technique, it has also been accepted as official quality control method in Finland (Saarenketo, 1997; Saarenketo and Roimela, 1998; Roimela, 1998, 1999).

Measuring voids content using its dielectric value relies on the fact that the dielectric value of the asphalt pavement is a function of volumetric proportions of the dielectric values of its components. Compaction of the asphalt reduces the proportion of low-dielectric value air in the asphalt mixture and increases the volumetric proportions of bitumen and rock and thus results in higher dielectric values of asphalt. The relationship between dielectric value of asphalt and air voids content measured in the laboratory is presented in Fig. 12.

The GPR measurements in the field are performed using a 1.0 GHz horn antenna. Dielectric values of HMA surfacing are calculated by using the surface reflection techniques described earlier. Following the GPR field evaluation one or two calibration cores are taken. These cores are returned to the laboratory for traditional void content determination. Long term studies in Finland have concluded that an exponential relationship exists between surface dielectric and air void content. For each type of aggregate and mix design, similarly shaped relationships have been developed. The calibration cores are used to establish the link for each specific project. The correlation between air void content measured with GPR technique and air void content using laboratory results is presented in Fig. 13. These results are obtained from a comprehensive series of field surveys conducted in Finland in 1997 (Saarenketo and Roimela, 1998). These results and additional survey results (Roimela, 1998, 1999) have convinced Finnra that GPR is a viable tool for monitoring the quality of new HMA surfacing. In 1999, GPR can be used as a quality control tool among other pavement density measurement techniques on all new surfacing projects in Finland.

Fig. 12. Results of the Finnra laboratory tests 1996, dielectric values versus void content.
5.3. Segregation

One of the major functions of Hot Mix Surfacing on highways is to provide waterproofing for the underlying structural base layers. If excessive moisture can enter the base layer, then rapid load and environmental damage will occur. The surfacing layer will only function as intended if it is compacted to optimum density, it does not contain any defects such as areas of segregation, and if the longitudinal construction joints are waterproof. Segregation manifests itself as localized periodic small areas of low density material in the compacted surfacing layer. Upon close inspection in these small localized areas, an excess of coarse aggregates is found. The causes are often traced to improper handling or construction techniques. During construction, the segregated areas are often impossible to detect visually; they only become apparent after 1 or 2 months in service. However, these areas often have a major impact on long term pavement performance. The segregated areas are often sources for moisture to enter the lower pavement layers. The asphalt industry is well aware of the segregation problem and in the past decade, several new construction techniques have been implemented including the use of Materials Transfer Vehicles as part of the paving train. Despite progress in this area, segregation is still a major concern and at the present time, there are no ways of detecting these problems during construction. A second problem area is that of the permeability of longitudinal joints.

GPR offers tremendous potential to assist in monitoring the quality of the completed surfacing layer. The GPR parameter which can detect these problem areas is the surface dielectric. GPR traces can be collected at closely spaced intervals, and with minimal data processing, a plot of surface dielectric versus distance can be produced. The dielectric of the surface layer is a function of the dielectric of the component materials (aggregate, air and asphalt) and their volumetric ratios. If an asphalt surface is uniformly compacted, the surface dielectric should be constant; however, if a low permeability area has excessive air voids, this will be observed in the surface dielectric plot as a decrease in measured dielectric.

The first use of GPR technology to monitor the quality control of pavements was reported by Saarenketo (1997). Large changes in the surface dielectric were attributed to the use of an experimental paver. Fig. 14 shows surface dielectric plots taken over longitudinal construction joints in Texas. The vehicle was travelling along the highway and made three transitions over the longitudinal joint between the lanes. As can be seen further away from the joint, the surface dielectric is relatively constant at around
5.5, whereas over the joint, the value is closer to 4.5. Research studies are underway in both Texas and Finland to relate the change in surface dielectric to changes in both air voids and mix permeability.

6. Future developments

Even though the history of the GPR applications in roads and highways is relatively short, the method has proven to be a very useful tool to solve various kinds of highway engineering problems. The life cycle of the GPR applications on roads are still on the introduction phase in most of the highway agencies. Awareness and education are still needed to get diffusion and adoption for the method.

A very important factor in the future of GPR in road surveys is to establish the technique in routine road analysis and pavement rehabilitation and design procedures. The status of radar as an interesting but obscure method for specific pavement survey projects should be changed to a routine road survey tool that is used among other survey techniques. For that to occur, certain standards and specifications for GPR equipment, data acquisition and interpretation techniques will be needed.

Even though this paper has described the GPR technique on roads and presents some successful cases, there are unfortunately several failures that have been reported around the world. These are usually attributed to over-selling the technology by vendors who understand GPR but do not appreciate the complexity of the pavement systems. The best hope for the future involves three critical steps: (1) developing user-friendly software packages in order to convert the GPR data with other road survey data into information which is meaningful to pavement engineers, (2) gaining an understanding of the electrical properties of road materials and subgrade soils and their relation to the moisture and strength and deformation properties, and (3) provide training for highway agencies and other customers who are using the GPR data and for the staff who are responsible for GPR surveys. When these steps have been accomplished, GPR techniques and applications will have huge markets in road design, construction and maintenance industry.

References


Briggs, R.C., Scullion, T., Maser, K., 1991. Asphalt thickness variation an effect on backcalculation. 2nd International Conference on Backcalculation, Nashville, USA.


Saarenketo, T., Scullion, T., 1994. Ground penetrating
radar applications on roads and highways. Research Report 1923-2F, Texas Transportation Institute, College Station, Texas, 36 pp.

Saarenketo, Scullion, 1995. Using electrical properties to classify the strength properties of base course aggregates. Research Report 1341-2, Texas Transportation Institute, College Station, TX.

Saarenketo, T., Scullion, T., 1996. Laboratory and GPR tests to evaluate electrical and mechanical properties of Texas and Finnish base course aggregates. Proceedings of the Sixth International Conference on Ground Penetrating Radar, September 30–October 3, Sendai, Japan, pp. 477–482.


