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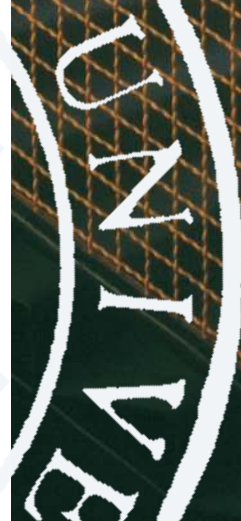
*Timo Saarenketo*

ELECTRICAL PROPERTIES  
OF ROAD MATERIALS AND  
SUBGRADE SOILS AND  
THE USE OF GROUND  
PENETRATING RADAR IN  
TRAFFIC INFRASTRUCTURE  
SURVEYS

FACULTY OF SCIENCE,  
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A

SCIENTIAE RERUM  
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*TIMO SAARENKETO*

**ELECTRICAL PROPERTIES OF ROAD  
MATERIALS AND SUBGRADE SOILS  
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INFRASTRUCTURE SURVEYS**

Academic dissertation to be presented, with the assent of  
the Faculty of Science of the University of Oulu, for public  
defence in Auditorium GO101, Linnanmaa, on November  
11th, 2006, at 12 noon

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# **Saarenketo, Timo, Electrical properties of road materials and subgrade soils and the use of Ground Penetrating Radar in traffic infrastructure surveys**

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## ***Abstract***

This PhD thesis is composed of a synopsis and five published papers that are focused on both the research results of studies on electrical properties of road materials and subgrade soils and their seasonal changes and the use of Ground Penetrating Radar technique in traffic infrastructure surveys. The data for this survey was collected mainly in Finland, Texas, Scotland and Sweden and thus presents many kinds of road materials, subgrade soils and climate conditions.

The synopsis of this work begins with a presentation of the theory and basic principles of GPR techniques. Special attention is given to the dielectric properties and seasonal changes of unbound road materials and subgrade soils. The synopsis also presents different kinds of GPR hardware systems as well as recommendations and experiences from different data collection, processing and interpretation techniques. Special attention is given to a method whereby GPR data is integrated with other road survey data and then analysed using a number of structural diagnostic methods. Finally, the synopsis provides an overview of the various GPR applications on roads and streets, bridges, railways and airports.

The laboratory test results presented in this work show that the relationship between dielectric value and increasing water content is not linear or exponential but more likely a series of logarithmic functions. Laboratory results also showed that dielectric dispersion, which can be related to poorly performing subgrade soils and road aggregates, takes place mainly in loosely bound adsorption water and capillary water layer. As such these moisture sensitive problem materials can also be identified during the dry summer seasons when they are stiff. Dielectric value and electrical conductivity can also be related to other technical properties of road materials and subgrade soils such as frost susceptibility, shear strength, plastic limit, compaction degree and voids content. Laboratory tests and field data collected using the Percostation technique also demonstrate that a knowledge of seasonal changes and thermodynamics is very important in understanding and modelling the mechanical behaviour of road structures. Finally, laboratory and field tests indicate that colloids have an important role in the failure mechanism of the road materials.

This research demonstrates that the GPR technique not only gives valuable structural information on the different types of structures and subgrade soils but it provides a wide range of information of the electrical properties of the materials under survey which can be further related to their mechanical performance. The best information will be gained if GPR data is analysed together with other non destructive testing data collected from the roads, railways and airports.

*Keywords:* airport, asphalt, bearing capacity, bridge, dielectric dispersion, dielectric value, electrical conductivity, freeze-thaw, Ground Penetrating Radar, pavement, percystation, permanent deformation, railway, road, road material, seasonal changes, soil



*“Water is the Earth’s Joker –  
it beats everything in the end.”*

Tuukka Saarenketo, 3 years

*To my family  
Merja, Jaakko, Ville, Matti and Tuukka  
and to my father  
Tapio*





## **Preface – Acknowledgements**

This research, which started more than 10 years ago, was first sponsored by the Lapland Road Region of the Finnish Road Administration and it never would have got started without the open-mindedness of the Region Chief Sauli Niku-Paavo and my superior Erkki Vuontisjärvi who believed in the technique even in the pioneering phase. In the early phase the excitement and commitment of the Lapland Road Region GPR crew to test and develop the technique was crucial for the successful results. An excellent example was foreman Paavo Naukkarinen who demonstrated that there was no need to have an academic background to become a GPR expert. At that time my long lasting co-operation with Pekka Majjala also began. Without Pekka's knowledge of the GPR technique and his data processing and programming skills many of the findings presented in the work could not have been made.

The greatest part of the laboratory data and key results of this PhD thesis have been collected and analysed during my visit to the Texas Transportation Institute in 1994–95. Tapani Pöyry, Region Chief of Finra Lapland Region, encouraged me with this thesis and provided all of the necessary help and support with the trip arrangements and research funding on the Finnish side. Tom Scullion, Program Manager at TTI, provided invaluable help with the research arrangements but also with the practical arrangements. The enthusiasm of Tom for our research and his guidance was a driving force for me to continue these surveys even in hard times. In the laboratory test and in the data analysis I got great help from Joel Calwel and Chun-Lok Lau. Special thanks also to Texas Transportation Institute and Texas Department of Transportation for all the help needed for the material collection and analysis. Finally I would like to thank the Jenny and Antti Wihuri Foundation and the Tauno Tönning Foundation for the economic support that made the research work in Texas possible.

After 1995 the major part of this work has been done in close cooperation with technical University of Tampere and the preliminary research results and ideas from the Texas test were verified by the laboratory and field tests made under the guidance of Professor Pauli Kolisoja and Nuutti Vuorimies. Special thanks to Pauli for an open minded attitude and technical support for my ideas but also keeping my feet on the ground. Thanks to Nuutti, the data quality has always been excellent. Special thanks can also be given to Tiit Plakk from Adek Ltd, Estonia. The major part of the work on laboratory and field testing

the dielectric properties of materials is based on the instruments designed and made by Tiit. From other organizations supporting this research I would like to acknowledge Hannu Peltoniemi from FRE and Kalevi Luiro from Finra. I would also like to acknowledge the Roadex projects, especially Row Munro, and all the excellent research teams and steering committees who allowed these ideas to be tested in practise in the Northern Periphery area.

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Finally this work would have never been finished without my supervisors at the University of Oulu, first Professor Risto Aario and during the last years Professor Vesa Peuraniemi have been pushing me in a positive way to finish this work.

Rovaniemi 06.06.2006

Timo Saarenketo

## Abbreviations

AASHO	American Association of State Highway Officials
ASTO	Finnish Asphalt Pavement Research Program 1987–1993
BCI	Base Curvature Index
CBR	California Bearing Ratio
CEC	Cation Exchange Capacity
CMP	Common Mid Point
DCP	Dynamic Cone Penetrometer
EM	Electromagnetic
FHWA	Federal Highway Administration (USA)
Finra	Finnish Road Administration (Finland)
FIR	Finite Impulse Filter
FWD	Falling Weight Deflectometer
GPR	Ground Penetrating Radar, Ground Probing Radar, Georadar
GPS	Global Positioning System
GSSI	Geophysical Survey Systems Inc.
HBD	Hemispheric Butterfly Dipole
HMA	Hot Mix Asphalt
HW	Highway
HWD	Heave Weight Deflectometer
IDS	Ingegneria dei Sistemi
IIR	Infinite Impulse Filter
MALA	Malå Geoscience
NDT	Non Destructive Testing
PC	Personal Computer
PCC	Portland Cement Concrete
PMS	Pavement Management System
QA	Quality Assurance
QC	Quality Control
SCI	Surface Curvature Index
SHRP	Strategic Highway Research Programme
TEM	Transverse Electromagnetic

TS test	Tube Suction Test
TTI	Texas Transportation Institute
TUT	Tampere University of Technology
UTSI	Utsi Electronics ltd
WARR	Wide Angle Reflection and Refraction

## List of original articles

- I Saarenketo T (1998) *Electrical Properties of Water in Clay and Silty Soils*. In: Sato M & Versteeg R (eds) *Ground penetrating radar (GPR '96)*. *Journal of Applied Geophysics* 40 (1–3): 73–88.
- II Saarenketo T (1999) *Road Analysis, an Advanced Integrated Survey Method for Road Condition Evaluation*. *Proceedings of an International Workshop on Modelling and Advanced Testing for Unbound and Granular Materials*, January 21–22. Ed A Gomes Correia. AA Balkema, Lisbon, Portugal, 125–133.
- III Saarenketo T & Scullion T (2000) *Road Evaluation with Ground Penetrating Radar*. *Journal of Applied Geophysics* 43: 119–138.
- IV Saarenketo T, Kolisoja P, Vuorimies N & Peltoniemi H (2002) *Effect of Seasonal Changes on Strength and Deformation Properties of Unbound and Bound Road Aggregates*. *Proceedings of BCRA 2002*, Lisbon, Portugal, 1059–1069.
- V Kolisoja P, Saarenketo T, Peltoniemi H & Vuorimies N (2002) *Laboratory Testing of Suction and Deformation Properties of Base Course Aggregates*. *Transportation Research Record* 1787. Paper No 02-3432, 83–89.



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# 1 Introduction

## 1.1 Background

The history of Ground Penetrating Radar (GPR) tests in traffic infrastructure surveys dates back to the early and mid 1970s when, according to Morey (1998), the Federal Highway Administration (FHWA) in the U.S.A. tested the feasibility of radar in tunnel applications and later on bridge decks. In the tests that followed Morey and Kovacs (1977) used it to detect moisture in construction materials, Cantor and Kneeter (1978) tested it for the inspection of bridge decks and More and Erhard (1978) employed it to detect voids under concrete highways. The first vehicle mounted GPR system for highways was developed under an FHWA contract in 1985 (Morey 1998). In the early 1980's, GPR surveys were also started in Canada (see Manning & Holt 1983, Carter *et al.* 1992). The other active area in the late 1970's and early 1980's was Scandinavia, where the first GPR tests with ground coupled antennas were performed in Sweden (Ulriksen 1982, Johansson 1987, Carlsten 1988) and in Denmark (Berg 1984), and although the results were promising the method did not receive general acceptance at that time. However, after the first tests were conducted in Finland in 1986 (Saarenketo 1992) the method rapidly became a routine survey tool in various road design and rehabilitation projects in Finland (Fig. 1) (Saarenketo 1992, Saarenketo & Maijala 1994, Saarenketo & Scullion 1994, Paper III) and later as a pavement quality control tool (Saarenketo & Roimela 1998, Scullion & Saarenketo 1998, Paper II, Pälli *et al.* 2005). During recent years the development work on GPR has been focused on different types of applications on low traffic volume roads, both paved and gravel roads (Saarenketo & Vesa 2000, Roadex 2001, Saarenketo 2001, Saarenketo *et al.* 2002b, Saarenketo & Aho 2005a), but research on how to use GPR on railways has also been done (Saarenketo *et al.* 2003, Silvast & Nurmikolu 2005). In 2004 (Tiehallinto 2004) Finra has published the first specifications concerning the use of GPR techniques in road rehabilitation projects. Research has also begun on the transfer and utilisation of GPR results by automated road construction machinery (Heikkilä *et al.* 2004).

In the late 1980's and early 1990's, most infrastructure applications in North America focused on pavement thickness measurements (Maser 1994), detecting voids under con-

crete slabs (Scullion *et al.* 1994) and detecting deteriorated areas in bridge decks (Alongi *et al.* 1992). These surveys were mainly conducted with high frequency (1.0 GHz) air-coupled antennas (see Scullion *et al.* 1992) but later ground coupled antennas also started to see use in road surveys (see Scullion *et al.* 1997). In the mid and late 1990's the most common applications of GPR by highway agencies were surveys to: measure pavement layer thickness, detect voids and bridge delamination; followed by measuring depth to steel dowels and depth to bedrock, detection of buried objects, asphalt stripping and scour around bridge support. 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).



**Fig. 1.** GPR surveys in mid and late 1980's by the Finnish National Road Administration, Lapland Road Region projects. Photo A is a site investigation for a new road surveys line on road 91 Ivalo-Rajajooseppi using Geo-Work Oy's GPR systems with an 80 MHz antenna. Photo B presents tests for measuring ice thickness of a winter road crossing the Kemijoki river in Sierilä, near Rovaniemi. Photo C presents the use of a GSSI SIR-8 system with a 100 MHz antenna for sand and gravel prospecting in North-Eastern Lapland and photo D presents bridge deck cross section data collection using a 1.5 GHz antenna on Kulpinputaa bridge on HW4 near Rovaniemi.

According to Hobbs *et al.* (1993) the first civil engineering tests with GPR in the U.K. were done in 1984. Since then the published GPR research has focused especially on concrete structures (see Millard *et al.* 1993) pavement testing (Ballard 1992, 1993, Daniels 1996) and, recently, railway surveys (see Clark *et al.* 2003a). In France, the main focus was on pavement testing (see Daniels 1996). In the Netherlands, the main application on roads has been layer thickness measurements (Hopman & Beuving 2002). In other parts of the world GPR techniques have been used for monitoring roads in more than 20 countries and according to the author's knowledge GPR surveys on roads are quite widely used in Australia, Canada, China, Estonia, Germany, Italy, Lithuania, New Zealand, Spain, Sweden, Switzerland and the U.K.

## 1.2 The goal of the work

Research on the dielectric properties of road materials and subgrade soils started in the late 1980's and early 1990's when the use of GPR in road rehabilitation projects was growing and there was an increasing need to develop a better fundamental understanding of the dielectric properties of road aggregates. (Ravaska *et al.* 1991, Lau *et al.* 1992, Saarenketo & Scullion 1994, Saarenketo 1995a). At the same time, the first results concerning the dielectric properties of subgrade soils were published (see Topp *et al.* 1980, Sutinen & Hänninen 1990, Sutinen 1992) and the first papers were also published where the dielectric properties of subgrade soils were related to their frost susceptibility (Saarenketo 1995b).

Another reason for these surveys was that GPR and FWD were increasingly being used in the same projects in Finland and an observation was made that there seemed to be a correlation between low bearing capacity during the spring thaw period and a certain type of reflection pattern in the GPR data. These relationships were noticed even during the dry summer months when the road was at its strongest and this "ringing" type of reflection pattern could not be explained by any other reason than changes in the dielectric properties of the base material (Saarenketo 1995a). At the same time Olhoeft and Capron (1994) reported that a change in signal shape is most often caused by frequency dependent properties of materials.

These observations and results suggested that there should be a good correlation between the dielectric properties and strength and deformation properties of all types of soils and aggregates, i.e. the higher the dielectric value the lower the bearing capacity will be (Saarenketo 1995a). The idea of this relationship was also presented earlier by Mitchell (1993) who wrote that "*As the strength of a soil depends in part of interparticle attractions, it would be expected that the strength would be also influenced by dielectric constant*".

The research series focusing on dielectric properties and strength and deformation properties of road materials started in 1994 at the Texas Transportation Institute, where dielectric properties of both good and problem quality Finnish and Texas aggregates were tested and new laboratory testing methods were developed (Saarenketo 1995a, Saarenketo & Scullion 1995, Saarenketo & Scullion 1996, Scullion & Saarenketo 1997, Syed *et al.* 2000, Guthrie *et al.* 2002). Since the late 1990's, research with unbound (uncrushed

gravel or crushed aggregate without any treatment agent) and bound (material that has been treated with binders such as bitumen or cement) base course materials has continued mainly in the Laboratory of Foundation and Earth Structures of the Tampere University of Technology (Saarenketo *et al.* 1998, Saarenketo *et al.* 2000a, Saarenketo *et al.* 2001). Field monitoring of the seasonal changes in the electrical properties of road materials and subgrade soils have also been conducted at the Koskenkylä Percostation site near Rovaniemi, Northern Finland (Saarenketo *et al.* 2002a, Vuorimies *et al.* 2002) and later at other sites in Finland, Sweden and Scotland (Vuorimies *et al.* 2004a,b, Saarenketo & Aho 2005a).

In recent years, the research has focused on gaining a more detailed understanding of the relationship between the dielectric properties and permanent deformation properties of unbound materials (Kolissoja & Vuorimies 2003, 2004, Schneider 2003, Dawson & Kolissoja 2005). New knowledge based on the measurements of the dielectric value and electrical conductivity in the laboratory has also played a key role in the development of new material testing and treatment techniques (Syed & Scullion 2001, Guthrie & Scullion 2003, Kolissoja & Vuorimies 2005, Vuorimies & Kolissoja 2005). The Roadex II project has also provided valuable information regarding how dielectric properties can be used to monitor seasonal changes and especially spring thaw weakening on low traffic volume roads and how to use this information in making load restriction policy (Saarenketo & Aho 2005a).

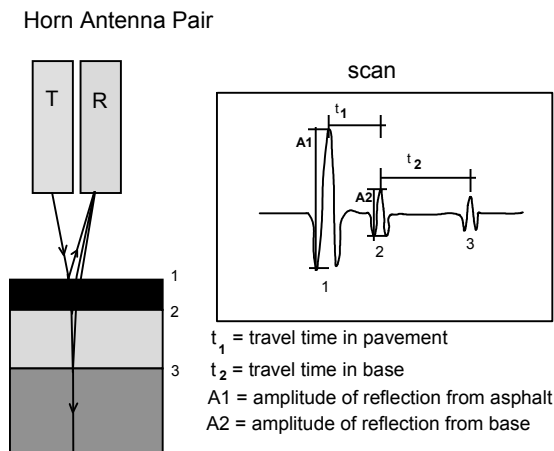
### **1.3 The structure of the synopsis**

This PhD thesis synopsis provides a summary of the research work and experiences concerning the use of Ground Penetrating Radar in traffic infrastructure surveys. The other part of this work presents research results regarding the factors affecting the electrical properties of road materials. These electrical properties then affect the GPR signal propagation. The thesis also presents the results of research on how measurement results of electrical conductivity, dielectric value and dielectric dispersion, which tells if the dielectric value of the material is frequency dependent, can provide information about the strength and deformation properties of road materials and subgrade soils and their seasonal changes.

## 2 GPR principles and pulse propagation

### 2.1 General

Ground Penetrating Radar systems use discrete pulses of radar energy with a central frequency varying from 10 MHz up to 2.5 GHz to resolve the locations and dimensions of electrically distinctive layers and objects in materials. Pulse radar systems transmit short electromagnetic pulses into a medium and when the pulse reaches an electric interface in the medium, some of the energy will be reflected back while the rest will proceed forwards (Fig. 2). The reflected energy is collected and displayed as a waveform showing amplitudes and time elapsed between wave transmission and reflection. When the measurements are repeated at herz frequencies (currently up to 1000 scans/second) and the antenna is moving, a continuous profile is obtained across the target. A good summary of the GPR technique in general and it applications is given by Daniels (1996).



**Fig. 2. Basic principle GPR technique with horn antenna for pavement examination. T represents the transmitting antenna and R the receiver antenna. Interface 1 presents the air-asphalt interface, 2 presents the asphalt-base course interface and 3 presents the base-sub base interface.**

The propagation and reflection of the radar pulses is controlled by the electrical properties of the materials, which comprise 1) magnetic susceptibility, i.e. magnetism of the material, 2) relative dielectric permittivity and 3) electrical conductivity.

The magnetic susceptibility of a soil or road material is regarded as equal to the value of the vacuum, and thus does not affect the GPR pulse propagation. Olhoeft and Capron (1994) and Goodman *et al.* (1994) have nevertheless reported cases in which magnetic susceptibility has affected the electrical properties of soils.

Electrical conductivity in a soil implies charge-carrier movement with free or limited dislocations, which may be caused by various phenomena. Most of the ionic or covalent bonded rock forming minerals, such as quartz, micas and feldspars, are non conductors, and when the surfaces of these minerals come into contact with liquid water, electrolytes are formed and ionic transmission, generated by the electrical field, causes electrical conduction. Ionic movement is proportional to the magnitude of the electric field, and is affected by temperature, ionic concentration and ionic size. The electrical conductivity of the medium contributes to the attenuation of the GPR wave and, to some extent, its reflection. The effect of the variations in electrical conductivity and magnetic susceptibility on the synthetic radargrams has been demonstrated by Lazaro-Mancilla and Gomez-Trevino (1996). In GPR surveys of roads and bridges in cold climate areas, the presence of deicing salts are a major factor affecting the electrical conductivity of the materials.

The most important electrical property affecting GPR survey results is dielectric permittivity and its' effect on the GPR signal velocity in the material and, as such, it is very important to know precisely how to calculate the correct depth of the target. Dielectric permittivity is a complex number and a function of frequency. Relative dielectric permittivity  $K^*(\omega)$  (also referred to as the dielectric value or dielectric constant) is a ratio of the complex dielectric permittivity ( $\epsilon$ ) to the dielectric permittivity of free space ( $\epsilon_0$ ).  $\omega$  refers to the angular frequency. The dielectric value can be expressed in the form:

$$(1) \quad K^*(\omega) = K'(\omega) - iK''(\omega),$$

where  $K'$  denotes the real part of the dielectric value and  $K''$  its imaginary part, i.e. the loss part (Hoekstra & Delaney 1974, Davis & Annan 1989). The relationship between electrical conductivity ( $\sigma$ ) and  $K''$  is

$$(2) \quad K''(\omega) = \sigma / \epsilon_0 \omega,$$

where  $\epsilon_0$  is dielectric permittivity of free space, equal to  $8.85 * 10^{-12}$  F/m.

The loss tangent, indicated by  $\tan \delta$ , is given by Hoekstra and Delaney (1974):

$$(3) \quad \tan \delta = K''(\omega) / K'(\omega)$$

## 2.2 Basic equations used in ground penetrating radar surveys

If magnetic susceptibility is neglected the following simple formulae can be used in practical Ground Penetrating Radar surveys (see Ground Penetrating Radar 1992):

$$(4) \quad v = c / \sqrt{K^*},$$

where  $v$  is wave propagation speed (m/ns),  $c$  is speed of light in a vacuum (0.3 m/ns) and  $K^*$  relative dielectric permittivity,

$$(5) \quad s = v t / 2,$$

where  $s$  is interface depth (m) from the surface of the medium and  $t$  is two-way travel time from surface of the medium to the interface depth ( $ns = 10^{-9}$ ),

$$(6) \quad k = (\sqrt{K^*_2} - \sqrt{K^*_1}) / (\sqrt{K^*_2} + \sqrt{K^*_1}),$$

where  $k$  is reflection coefficient,  $K^*_1$  is relative dielectric permittivity value of first layer and  $K^*_2$  is relative dielectric permittivity value of second layer,

$$(7) \quad R = 1 - k,$$

where  $R$  is penetration coefficient,

$$(8) \quad A = 1635 \sigma / K^*,$$

where  $A$  is attenuation in medium (dB/m) and  $\sigma$  is electrical (ohmic) conductivity of the medium (S/m) (Ground Penetrating Radar 1992)

$$(9) \quad I = 1000 c / (f \sqrt{K^*})$$

where  $I$  is wavelength, and  $f$  is frequency (MHz).

## **3 Dielectric properties and seasonal changes of unbound road materials and subgrade soils**

### **3.1 General**

As already mentioned in Chapter 1, when the use of GPR became more common there arose a need to understand the factors affecting the signal propagation and reflection in road, airport, railway and bridge structures better. Information detailing GPR signal velocity was needed to define a correct calibration factor to change the GPR signal time scale into depth scale. Since GPR is an all season tool and data can be collected throughout the year there was also an interest in collecting information concerning how signal velocities and in general electrical properties change during the different seasons. Later the research interest focused on whether GPR could be used to evaluate the moisture content of road materials and further how much information GPR data provides about the strength and deformation properties of materials that are used to build traffic infrastructures and the subgrade soils beneath these structures.

### **3.2 Thermodynamics and water**

Seasonal changes and freeze-thaw cycles and the damage they cause are the most significant factors affecting the road condition of northern cold climate road networks. In the USA, the AASHO research program studied the appearance of pavement distress during different seasons (White & Goree 1990, referred by Ehrola 1996) and, according to the results, 60 % of the distresses appeared during the springtime when the relative amount of traffic was 24 %. During the summer time the relative amount of new pavement damage was only 2 % when the relative traffic amount was 30 % .

In order to better understand the mechanisms behind seasonal changes and especially the spring thaw weakening process one must understand the basic principles of thermodynamics. In general, the road structure above the ground water table can be considered to be a thermodynamic system. This system along with its surroundings can change in terms



of both materials, mainly water, and energy. This system is thermodynamically balanced if its properties do not change over time. In order to be called thermodynamically balanced the system must have 1) temperature balance, 2) chemical balance and 3) mechanical balance. A road that is exposed to daily solar radiation, seasonal temperature changes, rainfall and snowfall and changes in the ground water level and is subject to dynamic load cycles caused by heavy vehicles cannot be considered to be thermodynamically balanced and that is why thermodynamics should always be considered when studying seasonal changes (Saarenketo & Aho 2005a).

The main transmitter element trying to balance the thermodynamic instability in a road structure is water and it plays a critical role in almost all road failures. 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 when making a preliminary estimation of the stability and compressibility of subgrade soils, when designing highways in areas with expansive clays and when evaluating the frost susceptibility or the permanent deformation properties of the materials. Water can have different forms and when evaluating these mechanical performance properties it is important to understand the amount and volume of bonded and free water as well as ice. The best way to do this is by measuring the dielectric properties of the materials.

Water content affects the pore water pressures that develop in soils. Both positive and negative pore-water pressures have a major effect on shear strength and volume change (Fredlund *et al.* 1995). Soil suction theory and principles of suction force have been used to explain the relationship between thermodynamic properties and the strength and deformational properties of road materials and subgrade soils. Soil suction describes the energy level, also known as Gibb's free energy; at which water is bonded to a particle surface and that which is needed to release bonded water molecules to free water (Edris & Lytton 1976, Fredlund & Rahardjo 1993).

The most important suction components affecting the mechanical performance of unbound road structures and subgrade soils are 1) matric suction, 2) osmotic suction and, in the cold climate areas, also 3) cryo suction. The sum of matric suction and osmotic suction is also called "total suction". Matric suction is mainly affected by void ratio, voids' size and the amount of fines in the material, while the amount of ionic compounds mainly affects the level of osmotic suction. Cryosuction is effective when the temperature in the soil or road materials drops below 0°C. In soils with low moisture contents, suction, which generates tension in the pore water between soil particles, can increase the stiffness of soils and unbound aggregates and lead to high modulus values, but when moisture content increases suction decreases (Fredlund & Rahardjo 1993). At high moisture content, positive pore water pressure under increased loads can reduce a material's resistance to permanent deformation.

### **3.3 Electrical properties of water in soils and aggregates**

All road materials and subgrade soils can be described as composite materials, where their dielectric values are a combination of the 1) individual dielectric constants of the components, 2) volume fractions of components, 3) geometrics of components, and 4) the

electrochemical interactions between the components (see Knoll & Knight 1994). In soils and unbound road materials these components are normally: air, water and/or ice, mineral aggregates and their weathering products, clays, colloidal particles, salts and organic compounds.

According to Olhoeft and Capron (1994) electrical loss mechanism, affecting the GPR signal performance, include 1) intrinsic conduction thermal loss, 2) orientation relaxation of water molecule mechanical loss, and 3) clay mineral electrochemical loss. The result of these phenomena is a complex frequency dependent dielectric permittivity.

The real part of the dielectric permittivity can vary in natural materials between 1 (air) and 81 (free polar water at 20 °C). The most important component affecting the dielectric permittivity of soils and unbound road materials is water which, to a greater or lesser extent, also affects their mechanical properties. However, the magnitude of these effects depends on the material properties, moisture content and even the saturation history of the layer (Saarenketo & Scullion 1995).

Water in soils and aggregates can be classified as: 1) adsorption water, also known as hygroscopic water; 2) viscous water, or capillary water; and 3) free water (see Paper I, Fig. 1). Meniscus can also have a great effect on the performance of the unbound materials. Paper I (1998) provides a detailed description of these different forms of water and, based on the tests with Texas soils, shows that hygroscopic and viscous water layers in soils with low cation exchange capacity (CEC) are arranged in an orderly manner throughout the whole layer, but that orderly arrangement decreases as the concentration of cations increases when hydrated cations disrupt the structure.

The dielectric permittivity of water in soils and aggregates depends on the degree of bonding of the water molecules around the soil particles such that the dielectric permittivity of tightly bound water near the mineral surface is close to the dielectric value of ice (3,5–3,8) (Dobson *et al.* 1985, Campbell 1990) even though the molecular structure of water is not the same.

The relationship between water content and dielectric permittivity has been discussed in several papers and mixture models that describe the mathematical relations of soil particles, water and air have been made (see Wobschall 1977, Topp *et al.* 1980, Ansoult *et al.* 1985, Dobson *et al.* 1985). Ulaby *et al.* (1986) present a good review of different mixture models of water in soils. Benedetto (2004) has used the current models to examine different subgrade soils from Italy and shows that each model has problems with moisture prediction in certain soil types. He suggests the use of a semi-empirical model for moisture prediction in subgrade soil after the model has been calibrated. Saarenketo (Paper I) suggests that the relationship between dielectric value and moisture content is a series of logarithmic functions rather than the exponential relationship that is used with dielectric mixture models (see Fig. 7, Paper I). This is due to the fact that the molecular structure of the water seems to be quite constant in each layer. The degree to which a soil has been compacted also has a considerable effect on its dielectric and electrical conductivity values (Paper I).

Dielectric dispersion, if it exists, occurs mainly in the loosely bound adsorption water layer and the outer capillary layer, both of which act as interface zones between a more tightly bound water molecular structure and a loose one (Paper I). Olhoeft and Capron (1994) suggest that dielectric dispersion can be measured when the imaginary part of

dielectric permittivity starts to rise. Paper I (1998) shows that the amount of dispersion correlates well with the cation exchange capacity (CEC) of clay soils.

Different magnitudes of dielectric dispersion could also be found when Finnish and Texas base course aggregates were investigated at the Texas Transportation Institute using a Surface Network Analyzer at a GPR frequency range of 30 MHz – 3 GHz and a Percometer at a frequency of 50 Mhz (Saarenketo & Scullion 1995, Saarenketo 1997). The highest dielectric dispersion in the fine material that had been allowed to adsorb water from air was measured from those aggregates which were known to be poor performers while for instance the Tohmo granite hard rock aggregate from Finland, known to be a good performer, hardly had any dielectric dispersion through the measured range (Fig. 3). This, together with other findings presented later, suggests that dielectric dispersion is one indicator that could be used to evaluate the performance properties of road materials and subgrade soils.

The results of tests with clay soils, published in Paper I, also showed that the dielectric value and electrical conductivity of a soil are very closely related to other technical properties of soils such as optimum compaction, moisture (Proctor) content and plastic limit. Sutinen (1992) found a good correlation between clay content and dielectric value for soils in Wisconsin.

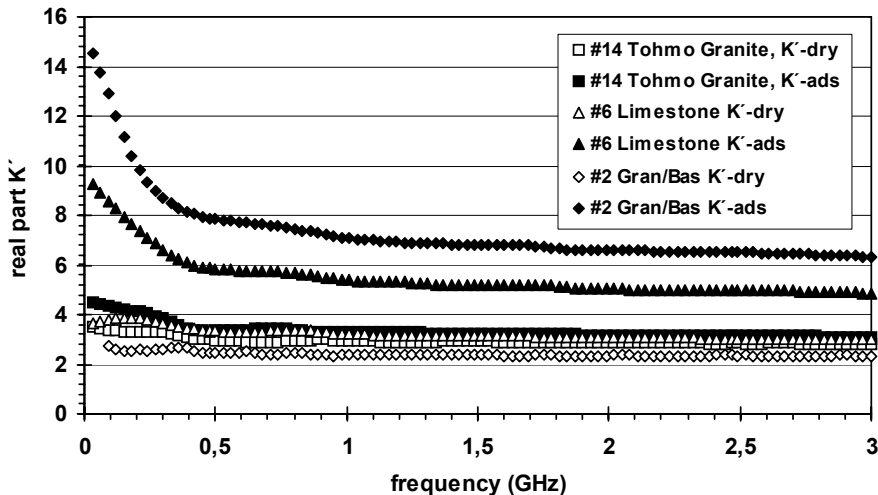


Fig. 3. Real part ( $K'$ ) of the dielectric value of the fines from three different types of base course aggregates between measurement frequencies of 30 MHz and 3 GHz. Measurements with Surface Network Analyser probe have been made from oven dried samples and samples balanced with 100 % relative air moisture at room temperature.

### 3.4 Laboratory research on dielectric properties and strength and deformation properties

#### 3.4.1 General

The following text will provide a chronological summary of the research done in the previously mentioned research projects directed towards understanding the relationship between electrical properties and strength and deformation properties of unbound road materials and subgrade soils and how seasonal changes affect these properties. A more detailed literature review and description of moisture content as it relates to bearing capacity is given in the Roadex report, “Drainage on low traffic volume roads” by Berntsen and Saarenketo (2005a, see also Berntsen & Saarenketo 2005b). A description of the permanent deformation properties of road materials is given by Kolisoja *et al.* (2004) and in the Roadex II report by Dawson and Kolisoja (2005, see also Dawson *et al.* 2005).

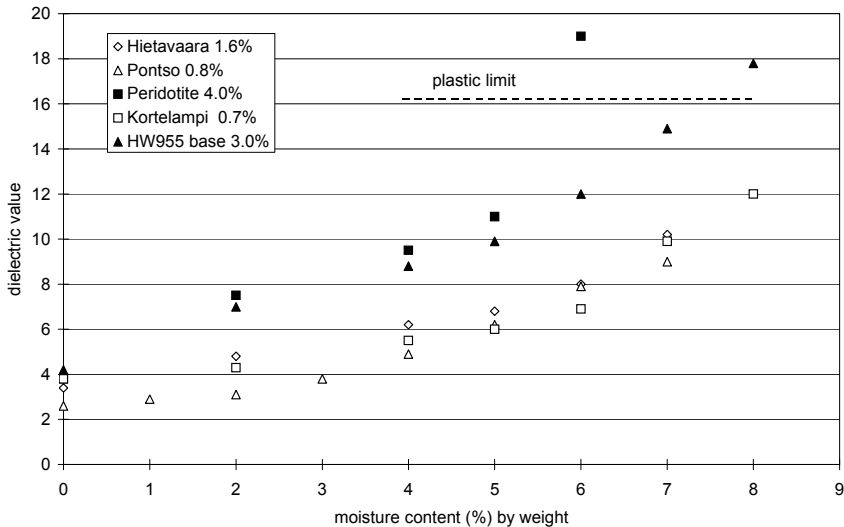
#### 3.4.2 Research done at Texas Transportation Institute in 1994–1995

In this research series, the correlation between dielectric properties and strength and deformation properties was first studied at the Texas Transportation Institute in a series of laboratory tests in 1995, where dielectric values and CBR values were measured using DCP tests (Fig. 4).



**Fig. 4.** DCP testing at the Texas Transportation Institute research laboratory. The aggregates were compacted at different moisture levels in the bucket. Dielectric value and electrical conductivity was measured from the DCP hole using a Percometer tube probe.

Eight Texas and 3 Finnish base course aggregates were tested at different water contents (Saarenketo 1995a, Saarenketo & Scullion 1995, 1996). Resilient moduli values were also measured from certain test specimens (Saarenketo & Scullion 1995, see also Titus-Glover & Fernando 1995). At the same time, the data collected from Finland (see Marjeta 1993) was further analysed and these results demonstrated a clear difference between the known good performing base course aggregates and the problem ones when the dielectric values of the materials were plotted with gravimetric moisture content (Fig. 5).



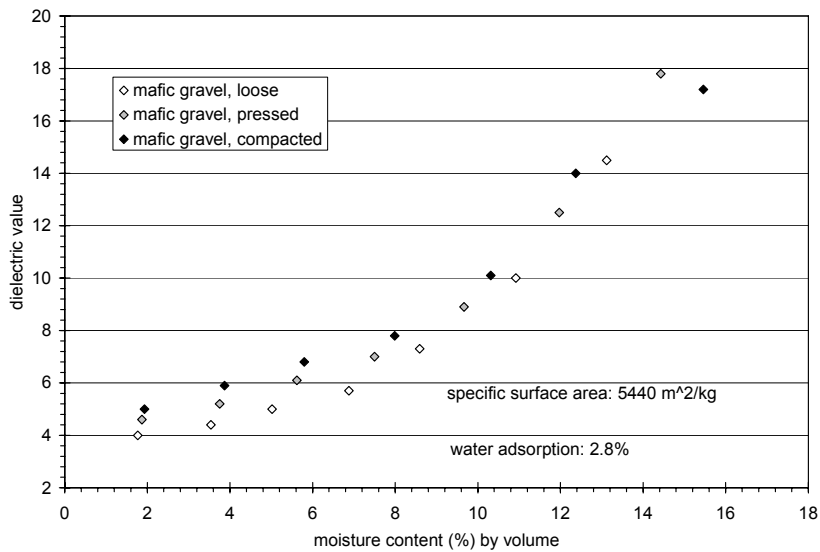
**Fig. 5. Dielectric value of Finnish base course aggregates at different gravimetric moisture contents. Measurement frequency was 50 MHz. Filled squares and triangles represent known moisture sensitive problem aggregates with high water adsorption values while the unfilled shapes represent known good performers (Figure modified from Saarenketo 1995a, see also Marjeta 1993). Legend also presents water adsorption values of the aggregate fines.**

The results of the DCP tests showed that aggregates with high water adsorption properties have higher tensile strength under traffic loads when they are dry and have lower dielectric values. Tests also showed that at higher water contents dielectric value correlates well with the CBR value which describes the shear strength of the material. This correlation is also much better than the correlation between the CBR value and water content. This can be explained in that dielectric value is mainly a measure of the amount of free water in the material and it is a critical component when positive pore water pressure develops.

This survey showed that most aggregates with a dielectric value higher than 16 became plastic in the DCP test and at the same time the resilient moduli values of Texas aggregates were also very low, even lower than 50 MPa (Saarenketo & Scullion 1995, see also Titus-Glover & Fernando 1995). The only exceptions were those aggregates that had a very open graded grain size distribution and could no longer hold water once they had reached dielectric values greater than 16 – such situations only exist in road structures below the ground water table.

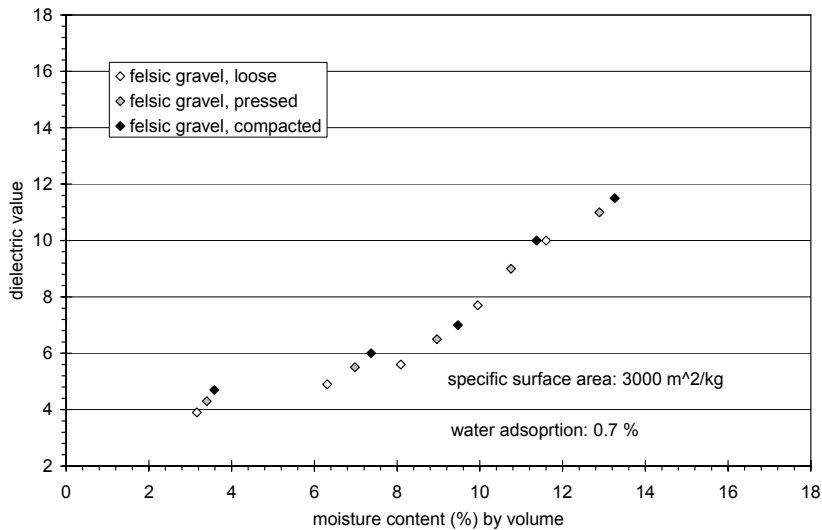
The electrical conductivity measurement results with the same materials also showed that the electrical conductivity value of materials had a high increase when the base course aggregates were failing. This indicates some kind of change in the electro-chemical properties of pore water in this phase. Most likely the phenomenon is caused by dissociation of ions and colloids from mineral surfaces to the pore water.

The compaction test results with different aggregate types at different moisture contents showed that the dielectric value is not directly a function of volumetric moisture content at different compaction levels and that dielectric value is slightly higher at higher compaction levels. The difference is bigger with known poorly performing aggregates as can be seen from Figures 6 and 7. This can be explained as a reduced amount of bound adsorption water with lower dielectric value when the material is compacted (Saarenketo & Scullion 1995).



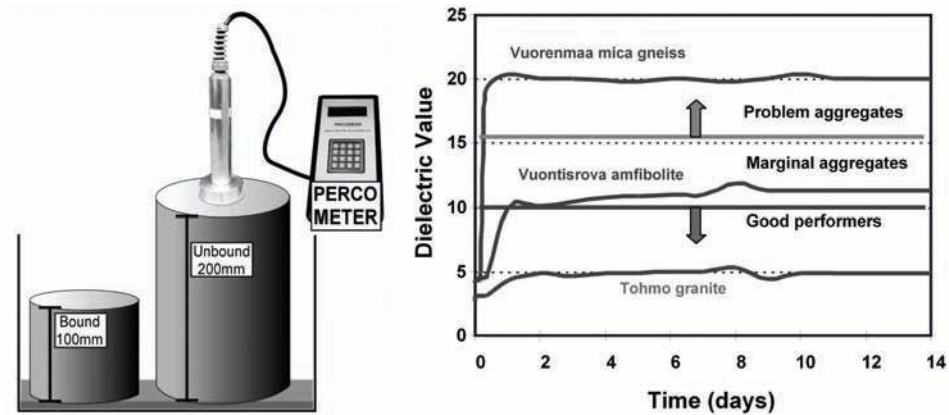
**Fig. 6. Correlation of dielectric value and volumetric moisture content of a Finnish mafic gravel aggregate known to be a poor performer (Figure modified from Saarenketo & Scullion 1995).**

The results of the wetting-drying tests demonstrated the effect of hysteresis (see Paper II, Fig. 2) and showed that dielectric values correlated surprisingly well with the known suction properties of the materials. Fredlund and Rahardjo (1993) have also shown that the suction force can vary with the same volumetric water content if the material is wetting or drying. Knight and Knoll (1990) have shown that the dielectric value is lower at the same moisture content when the material is drying. These findings can be explained by changes in molecular structure and shape of meniscus and also by the fact that the water molecules are better arranged during the drying phase compared with the wetting phase when new water molecules, colloidal particles and ions are entering the system. This explanation is also supported by the results of Knight (1991) who found that the electrical conductivity in sandstones is consistently higher during the wetting period compared with the same saturation level during the drying phase.



**Fig. 7. Correlation of dielectric value and volumetric moisture content of a Finnish felsic gravel aggregate known to be a good performer (Figure modified from Saarenketo & Scullion 1995).**

The results with some Texas base course aggregates, especially Iron Ore Gravel and Caliche Gravel indicated that the mechanical behaviour of a material immediately after the compaction does not necessarily represent the final behaviour of the material in a road base course. This is due to different chemical reactions occurring when particle contacts form covalent and other types of bonds during the drying phase after the first compaction. These findings indicate that in the future the laboratory analysis should be done on samples that, following compaction, have been allowed to dry to their normal level and then left to passively adsorb moisture in order to obtain a moisture balance. These findings at TTI along with an idea to simulate a thermodynamic environment in the road structures lead to a development of a special Tube Suction Test (Fig. 8) for unbound materials (Saarenketo & Scullion 1995, Scullion & Saarenketo 1997, Saarenketo *et al.* 2000b). This test is currently recommended in the USA for use when evaluating the frost susceptibility of aggregates (Saeed *et al.* 2003). Later, this test was also applied in testing of bound materials (Syed *et al.* 2000, Syed & Scullion 2001, Raitanen 2005, Vuorimies & Kolisoja 2005).



**Fig. 8. Principle of Tube Suction test for bound and unbound road materials. The samples dried at 40°C temperature are placed in a tank with about 10 mm of distilled or deionised water in the bottom. The adsorption of water through the sample is monitored on the samples surface by measuring dielectric value and electrical conductivity with a Percometer for 14 days. The limit values for good quality unbound aggregate (example Tohmo crushed granite aggregate) is dielectric value 9, for marginal aggregate 9–16 (example Vuontisrova amfibolite aggregate) and values of more than 16 indicate water susceptible aggregates (example Vuorenmaa mica gneiss aggregate).**

### ***3.4.3 Laboratory tests in Finland 1996–2000***

Since 1996 in Finland a series of different research projects, sponsored by the Finra Road Regions of Lapland and Vaasa, were initiated to share information and continue the research work on the strength and deformation properties of unbound base materials done by Kolisoja (1997). These projects also continued the research work that was started at the Texas Transportation Institute by Saarenketo and Scullion (1995). The initial results from this research cooperation were published by Saarenketo *et al.* (1998).

In the first phase of the project in 1996–97, selected crushed gravel and hard rock aggregates from Lapland and Vaasa districts were tested in Finra’s Lapland Regional laboratory, at the Oulu University, Department of Chemistry, and at the Tampere University of Technology. The selected test materials were those known to have performed well in road structures and those, which were known to have caused numerous problems. The aggregates were tested first with a Tube Suction test (Ylitapio 1997, Saarenketo 2000) using 200 mm high samples with different fines contents (Saarenketo *et al.* 2001). At the Oulu University Department of Chemistry, < 2 mm fractions of the aggregate samples were analysed to ascertain their chemical and mineral composition. In addition, cation concentration and the presence and classification of colloids in the aggregates were analysed from the extracted solutions (Yliheikkilä 1998, Saarenketo *et al.* 2001).

In the cyclic loading triaxial tests performed at the Tampere University of Technology in 1997, the aggregate samples’ resilient modulus values were examined using the SHRP P46 method (referred by Kolisoja 1997). These tests, followed the procedures for the



Tube Suction test, but using 400 mm high compacted samples, were performed after drying the samples for two weeks at 45° C, and then afterwards allowing them to absorb water through the bottom of the sample for one week. This method aimed at defining the minimum and maximum modulus values of the aggregates for summer and autumn seasons (Saarenketo *et al.* 2001).

In 1998, the test series continued at TUT and, at that time, a freeze-thaw cycle was added to the test procedures and frost heave was measured in the samples during the cycle. After thawing, a cyclic loading triaxial test was performed on the samples, as well as an additional  $10^5$  load pulse cyclic axial loading test series, which aimed at simulating the deformations which occur in the aggregate during the frost thawing phase. In the test series the fines content of these aggregates was varied (Saarenketo *et al.* 2001).

In a new test series in 1999–2000 the known problem aggregates were stabilized using different amounts of emulsified bitumen and then tested using the Tube Suction test and TUT test series. The target of the tests was to determine the amount of bitumen needed to prevent the problems previously observed in these aggregates. In addition, the test series of 1999–2000 aimed at examining the effect of axial stress level on the development of permanent deformations after a freeze-thaw cycle, as well as to study changes in the dielectric value of the material during deformation. All the test materials and methods are documented in detail in the TUT research reports (Saarenketo *et al.* 2000b).

The results of the TUT tests proved that the Tube Suction could be used for identifying moisture susceptible and frost susceptible aggregates. The suction properties of unbound aggregates are affected by the fines content of the aggregates (Fig. 3, Paper II), voids ratio and chemical properties of the unbound materials (Saarenketo *et al.* 2000b). The gravimetric water content after the TS test may vary approximately 2 % for samples with same fines content (Fig. 1, Paper V). The variation was especially high with crushed mica rich hard rock aggregates that adsorbed a great amount of water (Paper V).

The Tube Suction test results also showed that, with samples 0–20 mm grading, when the fines content was greater than 5 % then the dielectric value normally exceeded 9 which has been set as an upper limit for determining the quality of an aggregate. However, with the problem aggregates the critical fines content limit could be as low as 4 % (Fig. 2, Paper V). A fines content of 5% was also a threshold value which once exceeded frost heave could become measurable in the samples. When the fines content was higher than 5 %, a good correlation between the fines content and frost heave values could be made (Fig. 4 in Paper V).

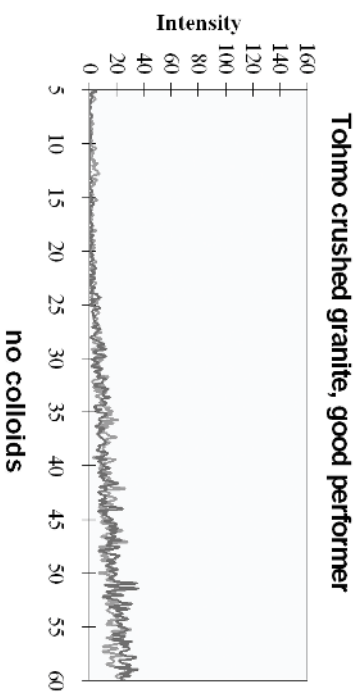
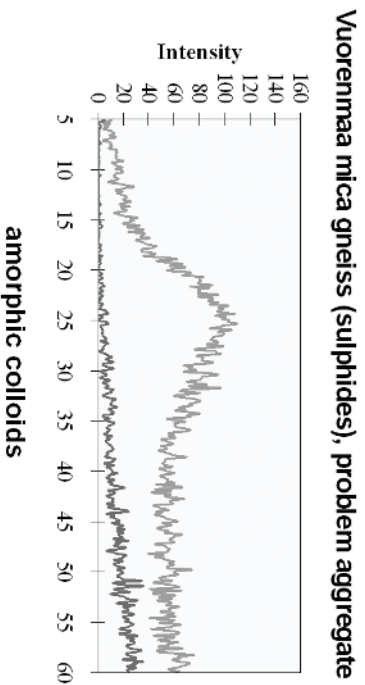
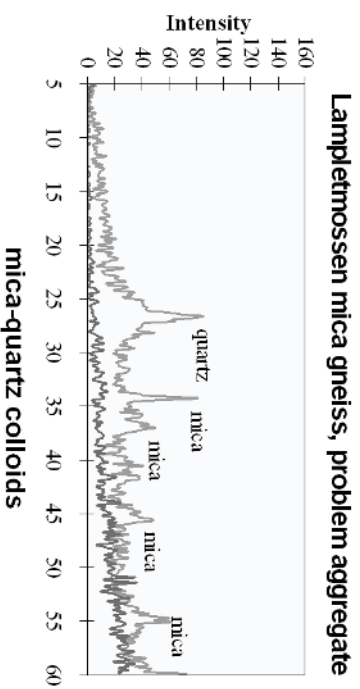
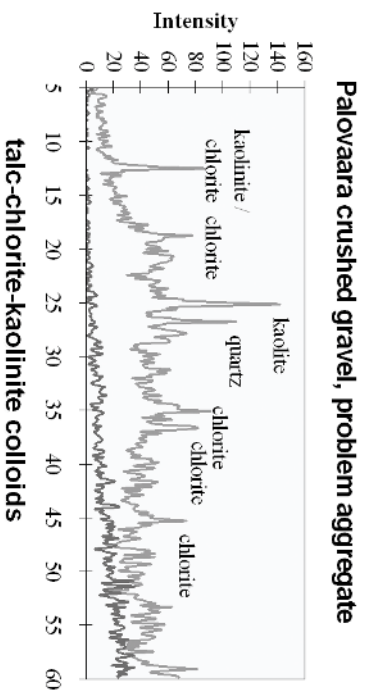
An interesting finding was made when the dielectric value following a Tube Suction test was compared with the calculated voids ratio of the aggregate samples (Fig. 3 in Paper V). The Figure shows that in compacted samples decreasing voids ratio increases dielectric value and volumetric water content but it also shows clear differences between gravel and hard rock aggregates. This can be explained in that hard rock aggregates with fresh mineral surfaces are more susceptible to reactions with water and increase osmotic suction in the sample (Paper V).

The Tube Suction test results also showed that even a small amount of bitumen could have a major impact in reducing the suction and frost heave properties of the unbound aggregates (Fig. 4 in Paper V).

The chemical tests done at the University of Oulu (Yliheikkilä 1998, Saarenketo *et al.* 2000b) showed that there were surprisingly large variations in the pH values of the pore

water of the aggregates. This could partly explain the different types of failure behaviour of the aggregates. For instance a low pH value of the pore water was measured from certain aggregates from the Vaasa District in Finland that had high dielectric value in the Tube Suction test but in the triaxial tests did not have highly reduced resilient modulus values when they were wet. Low pH increases tensile strength between the tip of mineral particles with a positive charge and other negatively charged mineral surfaces and, as such, the fine particles and colloidal particles will flocculate or stay flocculated on the mineral surfaces of coarser particles (see Mitchell 1993). As such with high pore water pH values these fine particles will become suspended in the pore water under dynamic loads and this increases pore water viscosity and pore water pressure. The amount of cations in the pore water following the chemical stress test provided another means of identifying problem aggregates (Yliheikkilä 1988).

Very interesting results were achieved when Yliheikkilä (1988) analysed the types of colloids present in the different aggregates. Her findings were then used to sort the aggregates into four categories. Three of the categories were based on the presence of the following: a) mica colloids, b) talc-chloride colloids and kaolinite colloids and c) amorphous colloids (Fig. 9). The fourth category, those aggregates in which colloids could not be found, contained the best performing aggregates, such as Tohmo granite from Kemijärvi (see also Fig. 3).



**Fig. 9.** Four diffraktograms from the colloidal particles found in four Finnish base course aggregates. Palovaara, Lampelmossen and Vuorenmaan present different types of problem aggregates while Tohmo granite presents a well performing aggregate. The upper line represents particles that penetrated through the filter paper and the lower and darker line represents a reference measurement from pure glass plate (Figure modified from Yliheikkilä 1998).

The results of the TUT triaxial tests showed that the resilient moduli values of the base course aggregates varied greatly when they were dry, when they were allowed to adsorb water and after the freeze-thaw cycles. The difference was growing as a function of the fines content of the aggregate (see Fig. 5 in Paper V). This can be explained through the matric suction properties of the materials. However, compared to the Texas results with Texas aggregates (see Chapter 3.3), the resilient moduli values of the Finnish aggregates were not critically low enough, even after the freeze-thaw cycle, to explain the road failures (Fig. 6, Paper V). This observation led to the study of the effect of repeated load pulses and high moisture content on the permanent deformation properties of the materials.

The TUT permanent deformation tests results correlated better with the known performance properties of the aggregates. However, if the fines content was high enough, permanent deformation could be measured in almost all of the samples (Fig. 8, Paper V). Another critical parameter for permanent deformation was found to be the axial stress level in the material after the freeze thaw cycle (see Fig. 8, Paper IV). These results bear witness to the importance of controlling axial loads on weak low volume roads during the spring thaw weakening periods (Dawson & Kolisoja 2005, Saarenketo & Aho 2005a,b).

Another interesting finding of the TUT laboratory tests was that the amount of frost heave in the base course does not directly correlate with the permanent deformations that take place during the cyclic loading test after the freeze-thaw cycle. A critical factor seems to be whether or not the excess pore water can freely leave the aggregate during the thawing phase. However, dielectric values measured with the Tube Suction test indicated well the potential permanent deformation problems of the materials after the freeze-thaw cycle. This demonstrates that GPR and other methods that can be used to measure dielectric properties of the road materials have great potential for use in evaluating the risk for permanent deformation in the roads.

During some permanent deformation tests at the TUT laboratory a short dielectric probe was also installed inside the sample. During the test, changes in dielectric values were followed by measuring changes in voltage in the capacitance sensor (Saarenketo *et al.* 2000b). Figure 10 presents the results of one test conducted with Vuorenmaa aggregates with a fines content of 7.6 %. Even though the amount of analysed test data was low (4) certain trends could be seen in all samples. When the cyclic loading started, dielectric value increased during the 10 first load cycles and deviation between the measurement results was great depending, most likely, on whether the voltage was measured during the loading phase or between them. This can be explained by that material is compacted due to loading and thus volumetric water content is slightly increasing. Once permanent deformation begins, the dielectric values in the sample quickly drop to levels even below that of the initial level. This can be explained by dilation during the plastic deformation phase which reduces pore water pressure creating a situation where water can “escape” from the material. During this phase, permanent deformation develops at a steady, but slow, rate and dielectric value remains at the same level. After this phase, dielectric value starts to rise relatively quickly which can possibly be explained as an event triggered by the suspension of ions and/or colloidal particles in the pore water. When the dielectric value drops after this peak a phase of steady plastic permanent deformation begins and dielectric values directly reflect this change (Saarenketo *et al.* 2000b). The three phases of the plastic deformation found in these tests have also been described by Ullditz (1998).

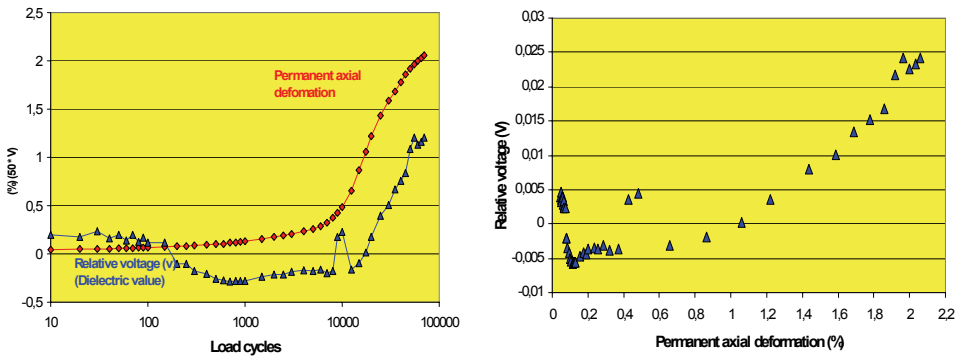


Fig. 10. Permanent deformation and changes in the dielectric values of Vuorenmaa aggregate during the repeated loading test done after a freeze-thaw cycle. The left graph present these changes as a function of the number of load pulses and the right graph presents changes in dielectric value (voltage) as a function of permanent deformation. Axial load pulse pressure was 250 KPa and cell pressure 50 KPa. The initial dielectric value was approximately 15.5 when the loading started.

### 3.4.4 Laboratory tests 2000–2005

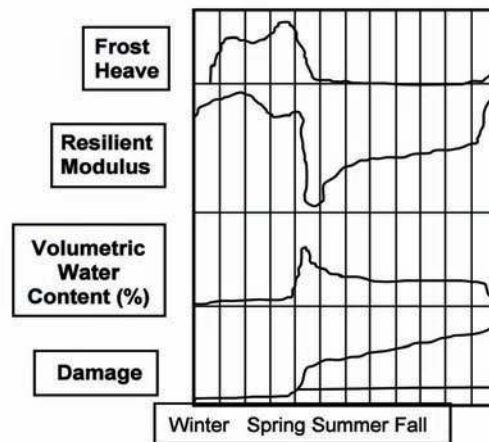
After 2000, the laboratory research at the Tampere University of Technology, run by Pauli Kolisoja and Nuutti Vuorimies, has focused mainly on gaining a greater understanding of the factors affecting the permanent deformation properties of road materials, how problem materials can be identified and the testing of different treatment agents (Kolisoja & Vuorimies 2003, Schneider 2003, Kolisoja & Vuorimies 2004, Kolisoja *et al.* 2004, Vuorimies *et al.* 2004a,b, Raitanen 2005, Vuorimies *et al.* 2005, Vuorimies & Kolisoja 2005). In the years from 2002 to 2005, research at the Tampere University of Technology was also done in cooperation with the University Nottingham under the Roadex II project (Dawson & Kolisoja 2005).

As a result of these surveys, it was suggested that in the future road materials' sensitivity to permanent deformation should be evaluated using the Tube Suction test. If the dielectric values, measured during this type of test, are found to be at a critical level then the strength of the aggregate should be assessed during the critical period (spring thaw) and the stress ratio between deviator stress ( $q$ ) and hydrostatic stress ( $p$ ) evaluated. If the voids ratio of problem material itself is not improved by adding coarse aggregates (Dawson & Kolisoja 2005) or if the material is not treated (see Kolisoja & Vuorimies 2005) the new pavement structure should be designed so that the ratio  $q/p$  of the material is not greater than 0.55 in areas where freeze-thaw cycles occur and not more than 0.7 in other areas (Kolisoja *et al.* 2004, Dawson & Kolisoja 2005).

### 3.5 Monitoring seasonal changes in the field

#### 3.5.1 General

Changes in water content as well as the form that water takes in different seasons are the main parameters affecting the physical processes that occur in road structures and sub-grade soils. The water content of the materials is affected by the properties of the materials, precipitation, drainage system of the structure, traffic loads (pumping) and in cold climate areas freeze-thaw processes. Figure 11 modified from Kestler (2003) demonstrates well the relationship between frost heave, resilient modulus, volumetric water content and cumulative increase of damage on the road over the year. It shows that the most critical time affecting the lifetime of the pavement during the year is a relatively short period during the spring thaw phase (see also Saarenketo & Aho 2005a). Even in areas considered to be warm, such as West Texas, major failures can occur in structures after a few freeze-thaw cycles, if water is present in the road structures, (see Carpenter & Lytton 1977). During this most critical period deformations can be caused by a fairly low number of load repetitions, in fact, less than 10 passing heavy vehicles could cause permanent deformation (Paper IV),



**Fig. 11. A schematic graph of the seasonal variations in different parameters that influence the cumulative damage of a pavement structure. Figure is modified after Kestler (2003).**

However, even though water content and seasonal changes have proven to be so crucial with regard to pavement lifetime little research has been done on this topic. Berntsen and Saarenketo (2005a) provide a summary of various published reports concerning seasonal changes in water content and related measurement techniques and Saarenketo and Aho (2005a) have summarized the latest published research concerning freeze-thaw cycles and spring-thaw weakening.

This research project has utilised the Percostation technique which has been developed to assist road officials with tracking real-time moisture levels, depth of the frost and

especially the risk for permanent deformations in the road structure during the spring thaw season (Paper IV). But at the same time Percostations have provided valuable information for GPR users about the changes in dielectric properties over the year. The following text provides a summary of the research done in this field.

### ***3.5.2 Freeze-thaw process***

In the fall when the temperature of the mineral aggregate or soil goes below 0°C, free water freezes forming hexagonal crystals and thus increases its volume (Tsytoich 1975). During the freezing process water molecules freeze one-by-one attaching themselves to the growing number of ice crystals and although they are joined by the ice at the same time they are separated from the mineral surface by a thin film (Anderson 1989). This frozen fringe is a relatively narrow zone below ice lenses (Ladanayi & Chen 1989). At the same time negative pore water pressure and cryo suction causes water molecules to flow towards ice lenses (see Carpenter & Lytton 1977, Konrad & Morgenstern 1980).

According to Kujala (1991) the amount of unfrozen water is the most important factor enabling the growth of segregation ice (ice lenses). Tice *et al.* (1978) have shown that the amount of unfrozen water also increases beneath the freezing front even in so called non-frost susceptible soils if the water content is high enough.

The amount of unfrozen water in the soils and aggregates is affected by their mineralogical properties, grain size distribution, specific surface area of soil particles and surface tension. Anderson (1989) reported that the amount of unfrozen water in tested soil was 12 % of the total volume of water at an air temperature of -5°C. Tsytoich (1975) suggests that amount of unfrozen water at an air temperature of -10°C in Russian soils were 0.0 % for quartz sand, 3.5 % for silty sand and 15.3 % for montmorillonite clay.

According to Kujala (1991) the frost susceptibility of subgrade soil is also affected by volumetric water content, specific surface area, cation exchange capacity and capillary rise. All of these parameters can somehow be related to dielectric properties of materials.

When monitoring seasonal changes electrical conductivity should also be measured because the freezing process is also influenced by dissolved salts, colloidal particles and hydrolysis reaction products all of which reduce the amount of free energy and thus freezing temperature (see Carpenter & Lytton 1977, Kujala 1991, Saarenketo & Aho 2005a). According to Hudec and Achampong (1994) the fine grained aggregates consisting of limestones, vulcanites, sandstones and cherts have been found to degrade rapidly during drying-wetting and freeze-thaw cycles especially if deicing salts have been used abundantly. The extensive use of chlorides have also been reported to cause pavement failures (Dore *et al.* 1997, Saarenketo & Riihiniemi 2002).

### ***3.5.3 Percostation technique and test sites***

The Percostation measuring technique used in these tests is based on dielectric value and electrical conductivity measuring techniques developed by the Estonian company Adek

Ltd. In road surveys the Percometer technique was first used to estimate the frost susceptibility of roads' subgrade soils (Saarenketo 1995b) and later to measure the water susceptibility of base aggregates (Saarenketo 1995a, Saarenketo & Scullion 1996). Currently, the Percometer is most commonly used for taking measurements in the previously mentioned Tube Suction test (TS test), used to measure the water susceptibility of aggregates and bound materials (see Chapter 3.4.2). However, it has also been successfully used in the classification of forests soils for forest regeneration research (see Hänninen 1997) as well as for assessing moisture damage in buildings and the moisture content of snow.

A Percometer or Percostation sensor can be used to measure the dielectric value, electrical conductivity and temperature of a material. In dielectric measurements, the Percometer measures the real part of the relative dielectric permittivity. The measurement is based on the change in capacitance caused by the material at the tip of the probe. The capacitance measuring frequency is in the range of 40–50 MHz. Conductivity is measured with a dual electrode system using an alternating current of 1–2 kHz. The Percometer measures the resistivity between the two electrodes and calculates a specific conductivity value. The measurement is calibrated against standard conductivity solutions. Electrical conductivity is mainly a function of water content, mineral quality, ion content and amount of colloids in the pore water but also temperature. Dielectric measurements, using a tube probe, are reliable when the conductivity of the material being measured is  $< 1000 \mu\text{S}/\text{cm}$  (Saarenketo & Aho 2005a).

The Percostation differs from the Percometer, in that it presents the option of measuring the dielectric value, electrical conductivity and temperature through a maximum of eight channels. The measurements are normally repeated at 2 hour intervals and the results are saved in the station's memory where they can be read via wireless modem. Normally the Percostation uses solar panels to supply power (Fig. 12).

The first Percostation was installed in road 9421 in Koskenkylä, near Rovaniemi during autumn 1999. This road is used especially by heavy trucks hauling aggregate to Rovaniemi (Paper IV). The structure of the road and material properties are described by Paper IV. Since spring 2000 the dielectric values and electrical conductivity values and later also temperatures have been monitored from the key layers in the road structure.

The other test site where seasonal changes were monitored using the Percostation technique was located in Säijä near Tampere, Finland. The unit was owned and the research work was done by Tampere University of Technology (see Vuorimies *et al.* 2004a). After the Roadex II project started, new stations have been installed on gravel roads in Kemi-järvi and Kuorevesi in Finland, on a gravel road in Ängesby near Boden in Northern Sweden and on a paved road in Garvault in Sutherland, Northern Scotland (Fig. 12). A detailed description of these sites is given by Saarenketo and Aho (2005a).





**Fig. 12. Percystation test site in B871 at Garvault, Sutherland, Scotland.**

### ***3.5.4 Field test results***

Monitoring results from different Percastations have provided, among other things, basic information with regard to selecting proper dielectric values that should be used in GPR data interpretations during different seasons. Figure 1 from Paper IV provides a typical case of the changes in dielectric values during the thawing period in spring 2000 from Koskenkylä Percystation. The dielectric values of the aggregates, when frozen, are typically between 3 and 5, which support the practise of using an average value of 4 or 5 when calculating road structure thicknesses from the GPR data measured during the winter time. When each unbound layer starts to thaw a typical higher dielectric value peak can be measured and this can be explained in that thawing ice lenses and thaw settlement as well as loading of this structure pushes water upwards from the thawing front (see also Saarenketo & Aho 2005a). After the thawing of ice lenses the road structures and subgrade soils begin the slow process of drying and dielectric values settle to their normal value usually by the end of June and in deeper structures by the end of July.

Due to cryosuction, the dielectric values and electrical conductivity values of road materials and subgrade soils are at a higher level during the spring than they were before freezing in the fall. Figure 13 presents values measured by the Koskenkylä Percystation from fall 2000 to early summer 2001. Normal late summer dielectric values measured from the base course have varied been 6 and 8 at the 50 MHz frequency, which corre-

sponds to a dielectric value of 5–7 at the frequencies used in GPR measurements assuming that the materials have slight dielectric dispersion. The dielectric value of problem sub base in the fall is normally 16–18 while during the spring thaw periods it varies between 20–25 depending on the spring. Also the electrical conductivity values of the base and sub base were higher in the spring but the changes do not correlate directly with the changes in the corresponding dielectric value. The changes in dielectric values and electrical conductivity of the filter sand (0.80 m) and sandy subgrade containing some silty layers (1.1 m) in fall and spring were not significant. In the winter time all the measured dielectric values were about 5 and in February 2001 during the coldest season around 4.

Figure 14 provides interesting information about the daily changes in dielectric value and also about thermodynamics during the spring 2001. The dielectric value of the base course at a depth of 0.15 m starts to decrease when the pavement surface starts to warm around 9 AM in the morning and decreases due to evaporation until around 9 PM when the air again cools. At that time the increased suction causes pore water to flow from the depth of 0.30 and dielectric values start to increase again. This “pumping” effect is mirrored by the dielectric values at a depth of 0.30 m verifying the water flow upwards through the pavement. The daily changes of dielectric value in the spring were about two units in the base surface and sub base. Another interesting observation was that the dielectric values inside the base course could differ by as much as four units in the late afternoon while in the early morning the values were relatively close. The daily changes during the spring thaw period could be measured down to 0.55 m but not too much at a depth of 0.8 m. During the summer and fall these changes were very small. In other Percostation sites, the changes were much smaller when the probes were installed in places where the pavement did not have any cracking showing that cracking can speed up drying of the pavement structure during the spring thaw (see also Berntsen & Saarenketo 2005).

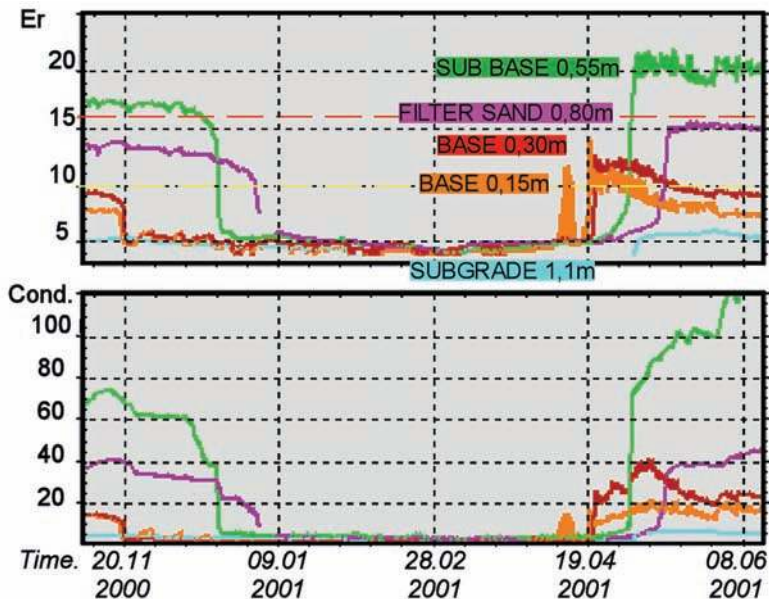


Fig. 13. Dielectric value and electrical conductivity of road structures and subgrade soils measured at Koskenkylä Percostation over the winter 2000–2001.

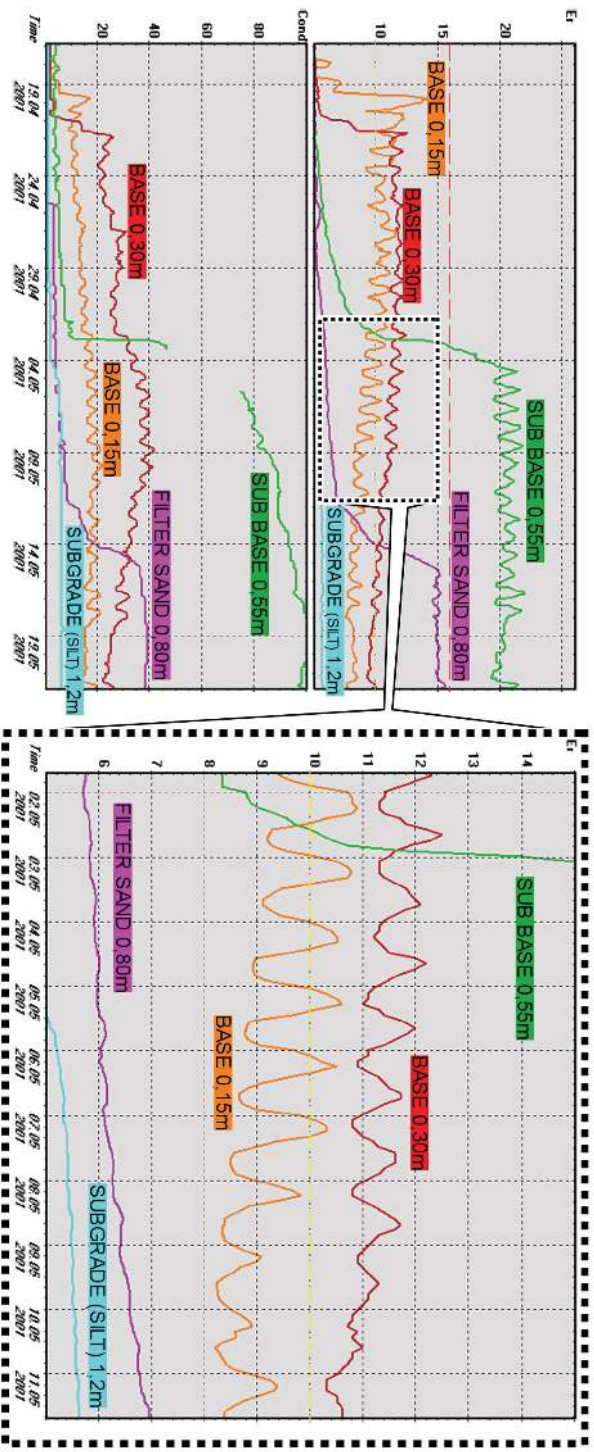
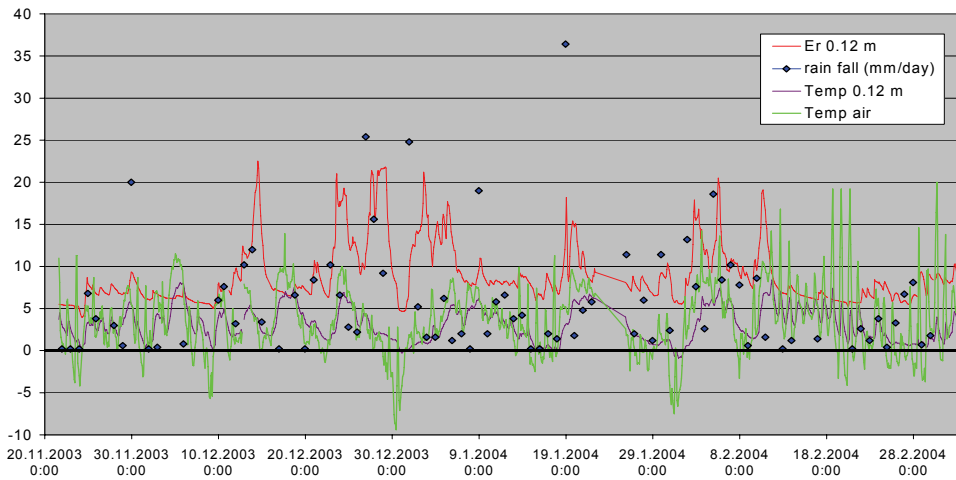
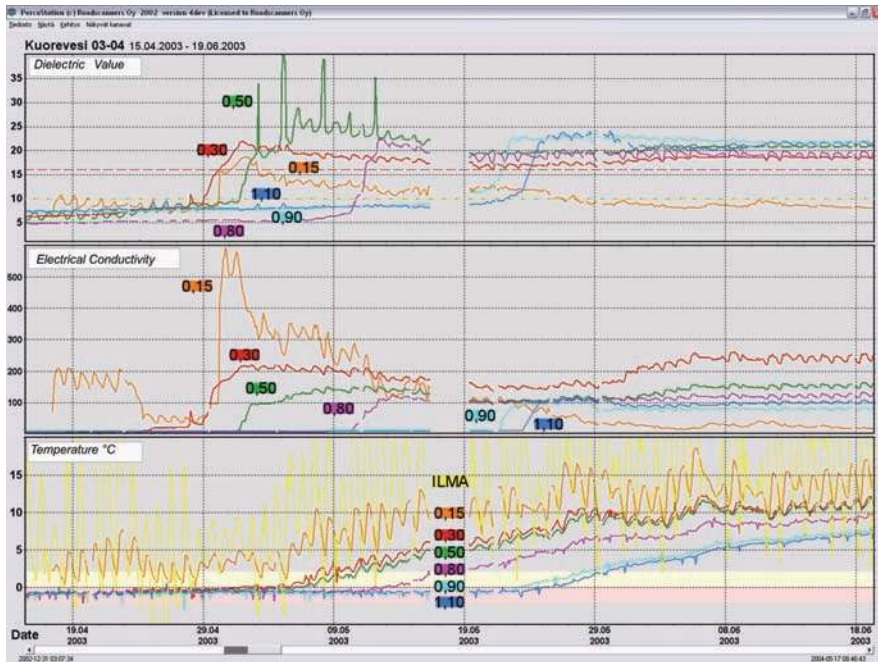


Fig. 14. Dielectric values and electrical conductivity measurement results from Koskenkylä Percostation during the spring thaw period in 2001 (left) and measurement results of dielectric value of base course during a ten day period in early May 2001 (right). The measurements were made at two hours intervals. Notice the slightly increased electrical conductivity values of the 0.3 m probe immediately after the sub base thawed.



**Fig. 15.** Dielectric value and temperature of the base course at a depth of 0.12 m presented together with the air temperature and daily rainfall at the Garvauld Percostation in winter 2003–2004. Dielectric values higher than 16 are critical for base course (Saarenketo & Aho 2005a). During this time the road was closed from the heavy timber haulage.



**Fig. 16.** Monitoring results from the Kuorevesi Percostation during the spring thaw period in 2003. Each colour represents a sensor reading from different depths (Figure from Saarenketo & Aho 2005a).

Falling Weight Deflectometer (FWD) surveys have also been made at the Koskenkylä Percostation site. Figure 2 from Paper IV shows that dielectric value measured from the sub base at Koskenkylä Percostation correlates quite well with the Surface Curvature Index (SCI,  $D_0$ – $D_{200}$  mm). This is because the biggest problems at this site are related to the sub base layer (Paper IV). The highest dielectric values were measured during the spring thaw at the same time as the highest SCI values illustrating the effect of moisture content on the stiffness of the road structure (Paper IV).

Full scale loading tests have been performed at some of the Percostation test sites in order to monitor the effect of dynamic axle loads on the electrical properties of road materials. Figures 3 and 4 in Paper IV present the effect that a 60-ton aggregate truck has on voltage which is a function of the dielectric value of base course and sub base materials at a depth of 0.15 and 0.55 m. The results show that the dynamic load response for the materials with low dielectric values can be considered as “elastic” while the response in the sub base layer with high dielectric values is different and can be classified as “visco-elastic” (Paper IV). The recovery time, seen in Figure 4 (Paper IV), has also been monitored at other test sites and is discussed by Saarenketo and Aho (2005a).

The Roadex II monitoring results 2002–2004 (Saarenketo & Aho 2005a,b) from the Percostation test sites in Finland, Sweden and Scotland have also provided new information about spring thaw weakening and about dielectric properties and strength and deformation properties of road materials. Percostation results from Garvault demonstrated the roles that both freeze-thaw cycles and heavy rains can have in increasing water content in the base course below the pavement (Fig. 15). A third factor affecting the dielectric value in the unbound layers, that could be seen in Garvault, was pumping caused by heavy vehicles.

The Percostation results from the gravel road sections in Ängesby, Kuorevesi and Kemijärvi in combination with observations of the surface condition showed that the surface thaw weakening phase, when the road surface becomes plastic, can be characterized by highly increased electrical conductivity (see Fig. 16). The temporary rise in electrical conductivity can be explained as being caused by the release and suspension of colloidal particles and ions from the clay particle surfaces into the pore water due to dynamic load cycles. The electrical conductivity results from the full scale loading tests made during the spring thaw phase (Vuorimies *et al.* 2002) support this theory (Fig. 17). The results from monitoring electrical conductivity during the fall at the Koskenkylä Percostation result also show that after a freeze-thaw cycle the electrical conductivity value does not return to the level at which they were at before the freeze-thaw cycle, especially if the amount of heavy traffic is low.

After the surface thaw period the next critical period, according to the Percostation data, was when moisture susceptible road structures with a high moisture content (high dielectric value) started to thaw (Fig. 16). In this phase, permanent deformation of the structures, evident as fast rutting or alligator cracking, could be observed on roads that heavy vehicles were using.

Percostation data has also provided information about the correlation between dielectric value and the temperature of road structures and subgrade soils. The monitoring results (Fig. 18) from the Koskenkylä Percostation site show that when road structure and subgrade soil freeze unfrozen water is still present in materials between 0°C and -2 °C and after that changes in dielectric values are quite small but are still a function of tem-



perature. The laboratory test results published by Ravaska *et al.* 1991 and Saarenketo and Scullion 1995 show that still at  $-5\text{ }^{\circ}\text{C}$  the dielectric value of frozen road aggregates is still slightly higher with those aggregates that have high dielectric value when they are unfrozen. This is further supported by results from monitoring the forest soils below the unpacked snow cover, published by Hänninen (1977), which show that dielectric values higher than 9 only decrease slightly during the winter.

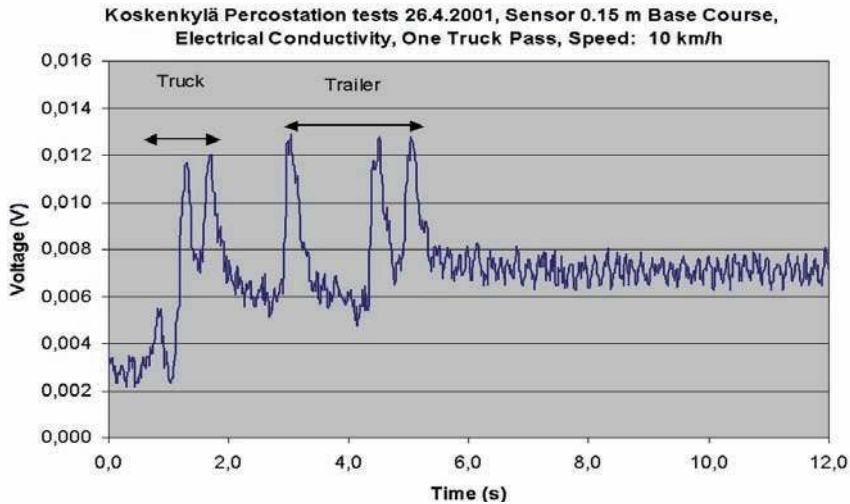


Fig. 17. Effect of a 60 ton truck and trailer combination on the electrical conductivity of a base course immediately after it has thawed on 26.04.2001 (Figure modified after Vuorimies *et al.* 2002).

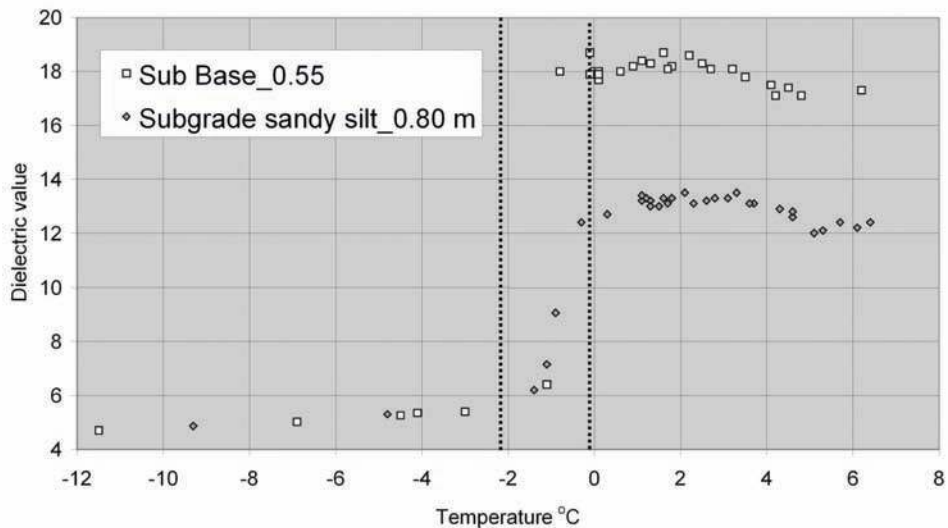


Fig. 18. Dielectric values vs. temperature profiles measured at the Koskenkylä Percostation during the freezing period in winter 2000–2001. Unfrozen water is present between  $0^{\circ}\text{C}$  and  $-2^{\circ}\text{C}$  (Saarenketo *et al.* 2002a).

## 3.6 Dielectric properties of bound road materials

### 3.6.1 General

The term “bound road material” is normally understood to mean materials that have been treated with a binder like bitumen or cement. The following text will provide a short literature review of the factors affecting the electrical properties of bound road materials and it also summarises the research results done in 1994–1995 at Texas Transportation Institute which have not yet been published. One special material used in roads that has been found to have a great effect on the electrical properties and also on GPR signal attenuation is steel slag. The experiences from the GPR field surveys in Finland has shown that the presence of steel slag in the base course causes high signal attenuation and if steel slag has been used in asphalt concrete or recycled asphalt the dielectric value is so high that the normal mixture model used to calculate air voids content (see Paper III) is no longer applicable.

### 3.6.2 Bitumen Bound Materials

Bitumen bound layers like asphalt are composed of aggregate, bitumen binders and air and in special structures, like emulsion, water. Asphalt used in pavement structures can be divided into three groups (Roberts *et al.* 1991) 1. asphalt cements, 2. emulsified asphalts and 3. cutback asphalts. Asphalt cement is obtained by distilling crude petroleum through different refining techniques. Emulsified asphalt, or emulsion, is a mixture of asphalt cement, water and an emulsifying agent. Cutback asphalts are like liquid asphalts in that they are manufactured by adding petroleum solvent to asphalt cements. Since the 1990's, mainly due to environmental reasons, emulsified asphalts have increasingly been substituted for cutback asphalts. Based on its composition, asphalt cement can be divided into asphaltens and maltens, which can be further divided into resins and oils (Roberts *et al.* 1991).

Most organic molecules have structural asymmetry and thus have dipole moment as a result of permanent separation of positive and negative charges within the molecule. A chemical model of asphalts describes polar materials dispersed in non polar materials so that polars form a continuous three dimensional mixture. The close proximity of polars allows for the formation of hydrogen bonds which with other weaker bonds, like dipole forces and van der Waals forces, control the physical properties of asphalt (Bishara & Reynolds 1995, Roberts *et al.* 1991).

The most polar components in bitumen are asphaltens, ketons and karboxyl acids. Karboxyl acids have a greater ability to bond with a mineral surface, but they are easily replaced by water. The greatest resistance against water impact had ketons and fenols (Petersen *et al.* 1982).

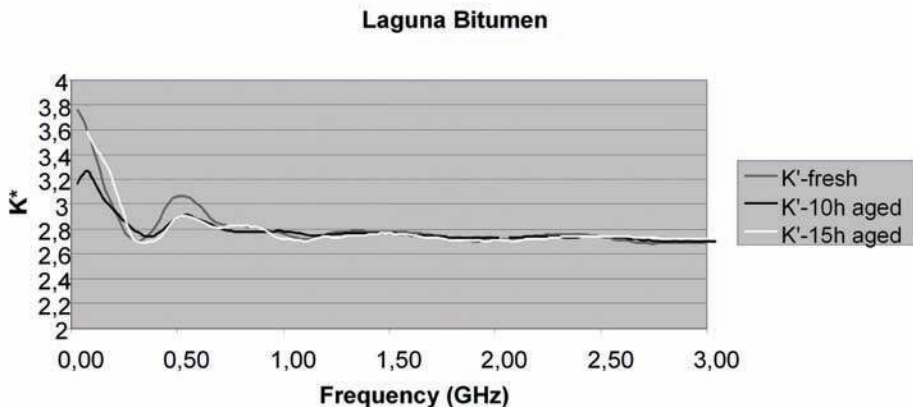
The Finnish ASTO project measured the effect of the polarity of bitumen by measuring the dielectric values, with 120 Hz, 1 kHz and 10 kHz frequencies, of bitumen in ben-

zene solutions. The results showed that there were no major changes in polarity between the tested bitumens (Pylkkänen & Kuula-Väisänen 1990).

The components of hot mix asphalt were examined at the Texas Transportation Institute by the author in 1994–1995 (Saarenketo 1997). The results showed that the dielectric values of absolutely dry aggregates vary between 4.5 and 6.5, carbonate rich rock types, such as limestone, had higher values. These materials are not dielectrically dispersive when absolutely dry (see Fig. 3). Network analyzer tests at TTI also showed that there were no remarkable fluctuations in the dielectric values of various types of bitumen or for different bitumen viscosities, the values have usually remained at a level of 2.6–2.8 (Fig. 19). The measured dielectric values were at the same level as those published by Bishara and McReynolds (1995). The TTI tests also indicated that ageing of the bitumen using thin film oven test (Fig. 19) or keeping samples in the sun for 6 months had no appreciable effect on dielectric values.

Since the electrical properties of the components of the asphalt were known, mixture models for new asphalts could be made. The basic assumption was that the dielectric value of a dry asphalt core is a function of the volumetric ratios of asphalt, air and rock and their individual dielectric values (2.5, 1, and 5.5 respectively). When material is compacted the volumetric proportion of air, which has a low dielectric value, is squeezed out of the mixture and thus the dielectric value of the asphalt mixture increases. The effect of the changes on bitumen content was also studied and small changes in the values did not affect the dielectric value of the mixture.

The values recorded for the imaginary part of the asphalt components in the case of new and dry asphalt were measured as being very close to the value of 0 at the frequencies GPR uses. This means that dielectric losses do not have to be taken into consideration when analyzing the results from new hot mix asphalt surfaces.



**Fig. 19.** Real part of the dielectric permittivity of both fresh and aged, using Thin Film Oven test, Laguna bitumen through a frequency range of 50 MHz to 3.0 GHz. Measurements were done using a Surface Network Analyzer (see Paper I).

The research concerning the relationship between dielectric value and air voids content of asphalt continued in Finland in the mid and late 1990's (Saarenketo 1997, Roimela 1998, 1999, Saarenketo & Roimela 1998). Based on the laboratory tests a model for the correlation between dielectric value and air voids content was made (see Fig. 12, Paper III).



Recently Yamamoto *et al.* (2004) have used numerical modelling and field tests where they used different pulse lengths of 0.67 ns and 1.33 ns to determine the degree of compaction on asphalt pavements.

The effect of water has also been examined, in the laboratory and in the field, due to the fact that water is present in emulsion pavements. Thus far there has not been any evidence to indicate that water has an effect on the results of quality control surveys on new asphalt pavements.

### 3.6.3 Cement bound materials

Cement bound base course is a material made of sand and coarse aggregate mixture, cement and water. When these components are mixed reactions take place between the cement and the water, referred to as cement paste, and this compound binds aggregates together in the form of a hardened concrete. According to O'Flaherty (1974), even though the reactions are not fully known, the first component that will hydrate very rapidly is tricalcium aluminate which has its most active period during the first day. Tricalcium silicate has its most active period on the 2nd and 7th days, forming tricalcium disilicate hydrate  $3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O}$ . Its contribution to the final strength of concrete is great. A similar compound is also formed when Dicalcium silicate is hydrated slowly from the 7th day onwards.

Unlike asphalt, there have been some experimental and theoretical studies done concerning the dielectric properties of concrete. Bell *et al.* (1963) showed that there is a dependence of dielectric properties and moisture content in hardened concrete. Morey and Kovacs (1977) used a GPR signal reflection technique to monitor the hardening of concrete. Wittman and Schlude (1975) have tested the properties of hardened cement paste with a water/cement ratio range of 0.3 to 0.6, moisture contents of 0 to 25%, curing time of 1 to 31 days, frequencies of 8.5 to 12.3 GHz and a temperature range of  $-10^\circ\text{C}$  to  $+20^\circ\text{C}$ . Lau *et al.* (1992) reported six times higher values of the imaginary value of Portland Cement Concrete (PCC) compared with asphalt concrete and suggest that this explains the higher GPR signal attenuation in PCC.

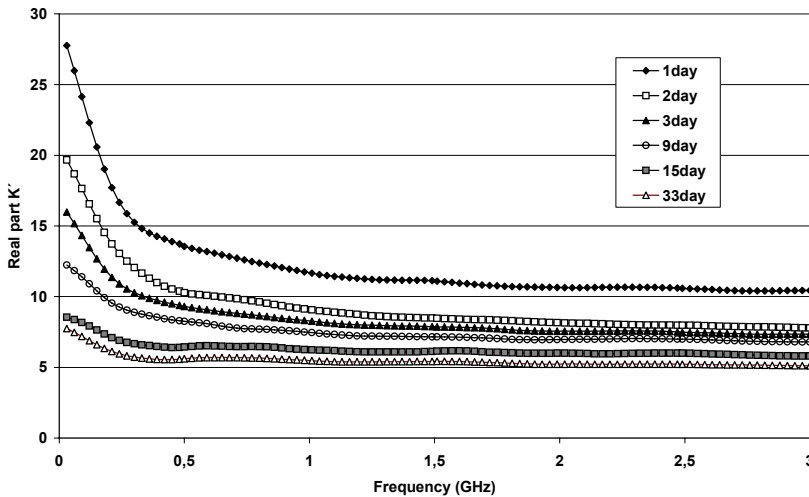
Mayhan and Bailey (1975) measured dielectric permittivity values of a concrete roadway under dry and wet conditions using frequencies slightly below the traditional GPR frequencies (Table 1). The results show that concrete is only slightly dispersive when it's in dry condition but remarkably dispersive in moist conditions.

Table 1. Dielectric values of concrete road under dry and wet conditions (Mayhan & Bailey 1975).

Frequency	K' (dry)	K' (wet)
470 KHz	8.5	27.5
3.85 MHz	6.5	19.0
9.50 MHz	5.8	13.5

Halabe *et al.* (1993) report that the salinity of pore water in concrete has a negligible effect on the real part of complex concrete dielectric permittivity, but has a large effect on the loss factor and attenuation coefficient. The real part of concrete was dispersive at low GPR frequencies, but was not sensitive in the frequency range from 0.6 GHz to 3.0 GHz.

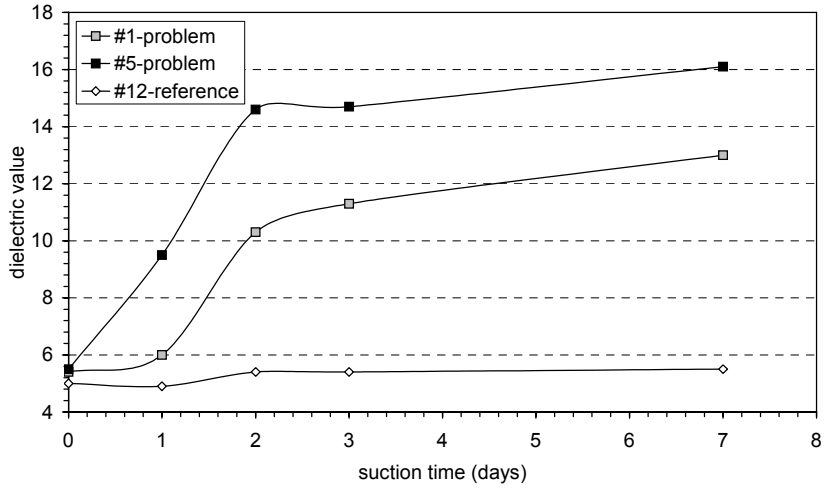
The change in the dielectric value during the concrete curing time was also measured by the author at the TTI laboratory using a surface network analyser and Fig. 20 provides a summary of the results. The Figure shows that the biggest change in the dielectric value happens during the first day of the curing when tricalcium aluminate is forming. The amount of dispersion also decreases when the concrete is becoming harder during the formation of tricalcium disilicate hydrate. This indicates that dielectric dispersion could be used in monitoring the hardening of the concrete. Dielectric properties of PCC through the GPR frequency range and using a capacitor probe have also been studied by Alzaabi (2000).



**Fig. 20.** Real part ( $K'$ ) of dielectric value of a concrete sample during the curing process. Measurements with a Surface Network Analyser probe have been made at measurement frequencies of 30 MHz and 3 GHz.

At the TTI laboratory, the Tube Suction test was also used to test some known well performing and problem cement stabilized base course samples. Figure 21 presents the results from one of the first tests, which show that water penetrates through the problem aggregates quickly increasing dielectric value in the sample surface, while there were hardly any changes in the dielectric value of the sample taken from the well performing road. Since these tests, numerous other tests have been done to verify these results (see Syed & Scullion 2002).

## Cement Bound Base Suction Test



**Fig. 21. Tube Suction test results of cement stabilized Texas base course aggregates.**

## 4 GPR hardware and accessories

### 4.1 General

The GPR systems used thus far in road surveys have mainly been impulse radars, but recently stepped frequency radar systems have also been tested in road surveys (Huston *et al.* 2000, Derobert *et al.* 2001, Derobert *et al.* 2002a, Eide 2002). The GPR hardware, mounted on a survey van and used in traffic infrastructure surveys normally have the following components: 1) ground coupled and/or air coupled antennas with transmitter/receiver electronics 2) cables 3) GPR control unit 4) pulse encoder and other positioning units and 5) accessory equipment. Normally a GPR road survey unit has an additional control unit, normally a PC, to facilitate the combined use of GPR and accessory equipment or make log files that allow subsequent linking of the data sets to one another (Fig.22).

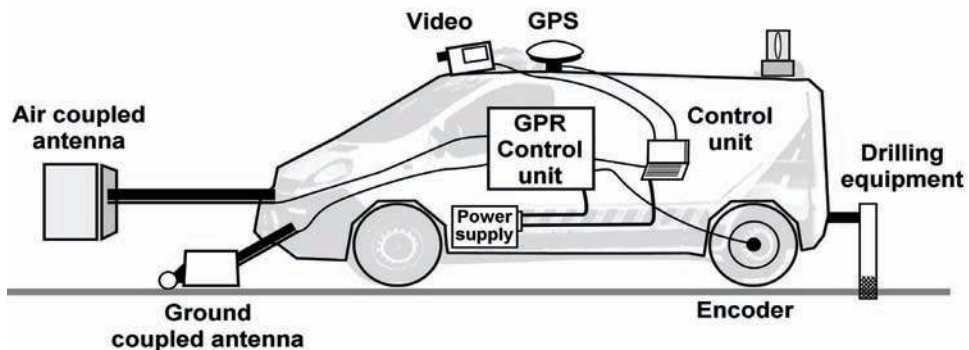


Fig. 22. A GPR system for road surveys. Antennas are normally mounted in front of the car, which allows the driver to control and manoeuvre the antennas and add markers precisely when the antenna passes reference points. Antennas are also better protected from collisions when mounted in front.

## 4.2 Air coupled systems

The air coupled GPR systems are increasingly being used to evaluate the upper part of the pavement structure. They produce relatively clean signals and can operate at close to highway speed. Furthermore, with defect free pavements the signals can be processed to compute both layer thickness and layer dielectrics (Paper III). Air coupled antenna systems are pulse radar systems and they generally operate in the range from 500 MHz to 2.5 GHz, the most common central frequency being 1.0 GHz. Their depth penetration is typically 0.5–0.9 m. During data acquisition these antennas are suspended 0.3–0.5 meters above the pavement surface. Most air coupled antenna types are TEM horn antennas but hemispherical butterfly dipole (HBD) types have also been used in road surveys.

The greatest advantage of air coupled systems is their repeatability because antenna coupling does not change with the changes in pavement properties. This allows them to be used for measuring changes in material properties for instance in asphalt quality control surveys (Saarenketo 1997). Another advantage is, because they are mounted above the pavement, data collection can be done at full speed (up to 100 km/h) without interfering with traffic. That is why air coupled systems are recommended for use in network level PMS surveys in Germany (Golgowsky 2003). Currently, horn antenna type air coupled systems are manufactured by GSSI, Penetradar; Pulse Radar and Wavebounce, all from USA, and butterfly dipole systems by Radar Team Sweden Ab. Euradar air-coupled GPR systems have also been used in pavement surveys in the Netherlands (Hopman and Beuving 2002).

The Texas Transportation Institute has conducted a large amount of research and development work both in improving air coupled system performance and specifications as well as developing new pavement testing applications (see Lau *et al.* 1992, Scullion *et al.* 1992, Scullion *et al.* 1994, Scullion *et al.* 1997, Scullion 2001).

## 4.3 Ground coupled systems

Ground coupled antennas operate in a wide range of central frequencies from 80 MHz to 1500 MHz and the signal penetration in traffic infrastructure surveys can be up to 20–30 m. During data acquisition these antennas maintain contact with pavement or they are suspended just above it. If they are not in contact, the distance to structure surface must be kept constant because the coupling changes as a function of distance. The clear advantage of ground coupled systems is the better signal penetration compared to air coupled systems, although surface coupling and antenna ringing present problems which make it difficult to obtain any quantitative information from the near surface without signal processing. Another advantage is better vertical resolution, compared to air coupled antenna systems, which allows these antennas to be used, for example, to detect pavement cracks, cables and reinforcement bars in concrete structures. Data collection speed with ground-coupled systems is normally 5–30 km/h.

The leading commercial manufacturers of ground coupled antennas used in road, airport and railway surveys are GSSI (USA), IDS (Italy), MALA (Sweden), Penetradar (USA), Sensors and Software (Canada) and UTSI Electronics (U.K.).

#### 4.4 Antenna configurations

Most GPR antennas used in traffic infrastructure surveys are bistatic even though the antenna elements are mainly installed in the same antenna box with transmitter and receiver electronics. Bistatic antennas in different boxes have the advantage in that they can be used for determining the dielectric properties of the pavement structure using e.g. Wide Angle Reflection and Refraction (WARR) or Common Mid Point (CMP) sounding techniques (Maijala 1994), but these sounding techniques can also be used with multi-channel GPR systems.

Due to the rapid development of data processors and data storage capabilities, multi-channel systems are more and more popular in road surveys. There are several advantages gained when data is collected using several antennas simultaneously: 1) high frequency antennas with good resolution near the pavement surface and lower frequency antennas with greater signal penetration can be used at the same time (see Fig. 22), 2) multiple channels allow the use of antenna array techniques to determine signal velocities (Davis *et al.* 1994, Mesher *et al.* 1995, Emilsson *et al.* 2002,) and 3) multichannel systems allow data collection using many antennas with same frequency to collect several survey lines simultaneously which facilitates the preparation of a 3D model of the surveyed structures (Davidson & Chase 1998, Manacorda *et al.* 2002), or the configuration can be a combination of any of these three. Figure 23 presents different GPR antenna systems used in road surveys.



**Fig. 23. Different GPR systems and antenna configurations used in road surveys. Photo (A) presents a multichannel stepped frequency radar by 3-D Radar from Norway, photo (B) presents a 100 MHz GSSI ground coupled antenna and a 1.0 GHz Pulse Radar antenna used by the Texas Transportation Institute (TTI), photo (C) presents a Canadian Road Radar system, that has a horn antenna system and a multichannel ground coupled antenna array (see Davis *et al.* 1994), and photo (D) presents a multichannel air coupled horn antenna system by Penetradar (photo Penetradar).**

### 4.5 Antenna and GPR system testing

One problem with GPR hardware systems is that all the systems are unique and in the early 1990's especially there were major differences when different systems using the same model of antenna were compared on the same test track. The other problem was that the antennas' performance was changing over time and GPR users had difficulty testing if their older GPR systems were still functioning accurately in the field. The accuracy of GPR is especially important in asphalt quality control surveys because large fines can be imposed on asphalt contractors based on the GPR survey results.

In order to compare the performance of different GPR systems the Texas Department of Transportation (TxDOT) requested that the Texas Transportation Institute develop a series of performance specifications for 1.0 GHz air coupled systems (Scullion *et al.* 1996). The proposed tests were:

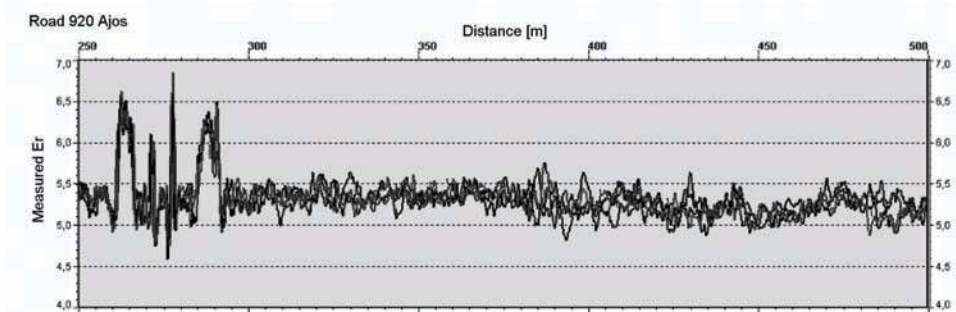
- Noise to Signal ratio (N/S ratio)
- Signal stability (amplitude and time jitters)
- Travel-Time linearity
- Long-term stability (time widow shifting and amplitude stability)
- Penetration depth

All of these tests, except the penetration depth test, have become common methods for testing air coupled antenna systems (Fig. 24) these tests can also be performed on ground coupled systems.



**Fig. 24. GPR system testing with a 1.0 GHz horn antenna at the Rovaniemi Polytechnic laboratory which has been authorized to perform these tests in Finland. All of the GPR systems used in asphalt quality control measurements in Finland must pass these tests annually (photo Manu Marttinen).**

Different GPR systems, or a single system, can also be tested in the field by using a simple repeatability test where the same road section is measured several times. Figure 25 presents the results of repeatability test of a 2,2 GSSI horn antenna done in summer 2005 (Saarenketo & Kantia 2005). The advantage of these tests is that they also provide information about the measurement skills of the GPR data collection crew.



**Fig. 25. Repeatability test results showing asphalt surface dielectric values measured using a GSSI 2,2 GHz horn antenna system. (Figure modified from Saarenketo & Kantia 2005.)**

## 4.6 Accessory equipment

There are many different accessories that can be used with GPR systems in traffic infrastructure surveys, but the two most popular systems, used on most survey vehicles, are digital video systems and GPS (Fig. 26). A third recommended accessory is a drilling system for taking reference samples.

Digital video allows the interpreter to see the antenna's surroundings during data collection, which further helps in comprehension of the GPR signal which in turn leads to more accurate interpretations of the structure or individual reflectors such as a culvert. Video is especially useful in pavement rehabilitation projects or forensic surveys where it is important to correctly diagnose the reasons for a defect. Infrared thermography cameras have also been used together with the collection of GPR data especially on bridge decks and concrete runways (Manning & Holt 1986, Maser & Roddis 1990, Weil 1992). Recently, infrared thermal cameras and temperature sensors have been used together with GPR in asphalt quality control (Sebesta & Scullion 2002a,b) and on railways (Clark *et al.* 2004).

Another, almost compulsory, system in traffic infrastructure surveys is a Global Positioning System (GPS) because, in most cases, the survey results need to be projected onto a survey line. This line is mainly a road register address that is calculated to the road centre because when data is collected from the outer lane or even the outer wheelpath in two-lane roads there are distance shifts on curves. Good quality GPS data permits distance data corrections and comparison of data collected from different lanes. Also, a GPS system with accurate z-coordinates helps interpreters and pavement engineers to better understand the GPR data (see Fig. 37). A GPS or tachymeter system is also very useful when data is collected from wide areas with no specific visual position referencing such



as airport runways and taxiways. Normally GPS coordinates are linked with GPR scan numbers and data processing software is used to make distance corrections.

There are also many types of road survey vans that have integrated different measurement devices into the same vehicle. Profilometers and pavement distress mapping systems especially have been instrumented together with GPR into the same van. Recently some attempts have also been made to integrate a GPR system into an FWD vehicle.



**Fig. 26.** A GPS and video system installed on the roof of a GPR car (photo Saara Aho).

## 5 GPR data collection

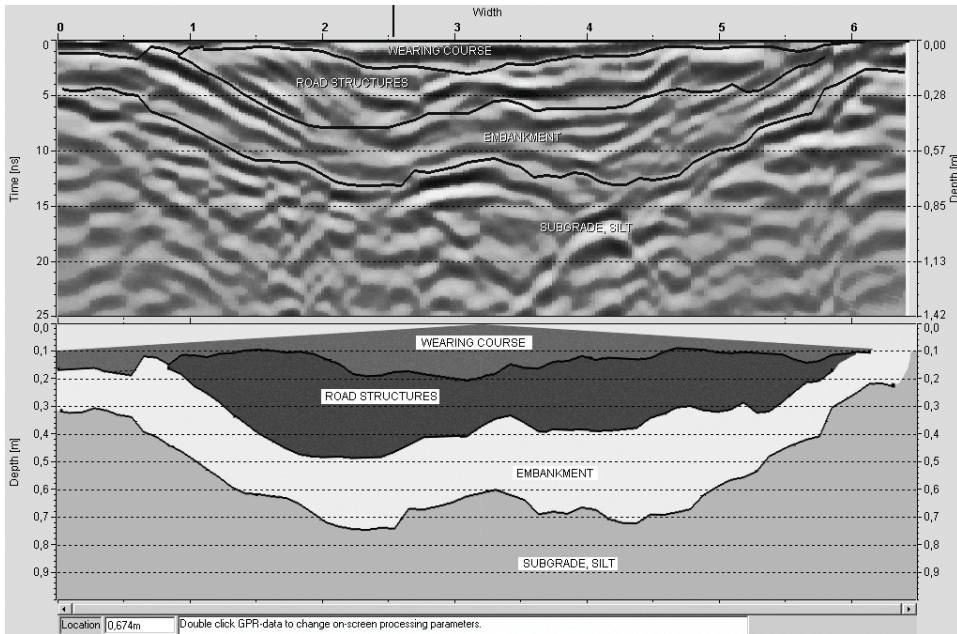
### 5.1 General

Ground Penetrating Radar survey design is a process where close co-operation between the customer and GPR survey contractor is strongly recommended. If the customer manages the project through a competition between different GPR contractors, then detailed project descriptions and GPR specification documents are necessary in the tender documents (see Golkowski 2003).

The key issue in the project description is a detailed outline of the nature of the problem with which the survey is concerned. The textbook “Ground Penetrating Radar” (1992) provides a checklist of points that customers and GPR consultants should resolve before the survey contract is signed.

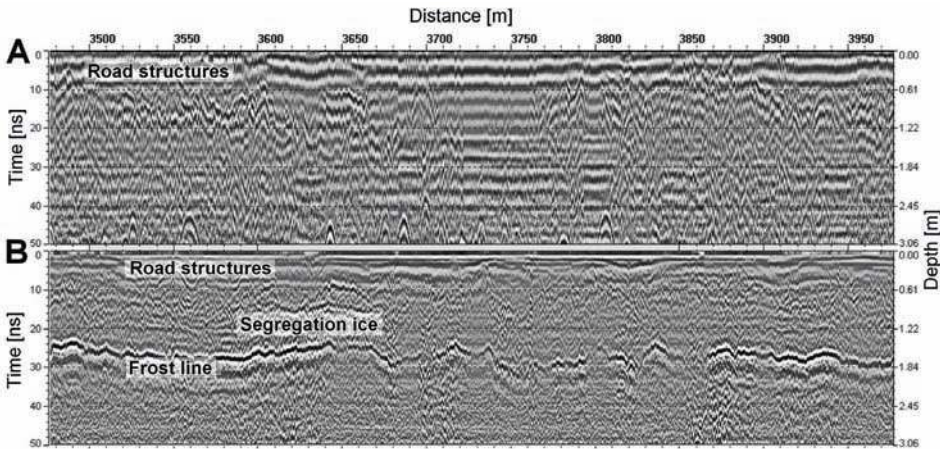
In planning a GPR survey, the number of survey lines should be defined. In routine road surveys, one longitudinal survey line is made and most commonly, in two-lane roads, the right wheelpath of the right lane (increasing road data bank distance) is used. However, recent results suggest that in asphalt quality control surveys utilising a horn antenna data should be collected from between the wheelpaths due to the effects of compaction on the wheelpaths caused by heavy traffic (Saarenketo & Kantia 2005). If a two antenna system with one air coupled and one ground coupled antenna is used (see Fig. 22), they can be placed in a line or beside each other in which case the ground coupled antenna should be placed to measure between the wheelpaths. In railway surveys, if only one line is to be measured, it should be done between the rails, but in many surveys data is also collected from both sides of the rails. In bridge deck surveys the recommended interval between survey lines is not more than 0.5 m.

Cross sections always provide very useful information concerning the road structures and help with the understanding of road failure mechanisms (Fig. 27, see also Roadex 2001) but on highly trafficked roads data collection is especially difficult and dangerous and, as such, special safety arrangements are a requirement. With new 3d GPR techniques, analysing road structures through a cross sections will become much easier.



**Fig. 27. A 400 MHz GPR cross section over a gravel road in a Roadex II test section in Tohmo, Kemijärvi presenting severe permanent deformation problems during spring thaw.**

Collection of GPR data does have some weather restrictions. Collecting data during a rainfall or when the pavement is wet is not recommended. When collecting the data with air coupled antenna systems the pavement must be dry with no visual moist spots and the pavement temperature should be above  $0^{\circ}\text{C}$  if dielectric information is to be used in the analysis. On the other hand, GPR data collection with ground coupled antennas during the winter can provide even better results especially on gravel roads, when a frozen wearing course with dust binding chlorides will not cause so much attenuation (Fig. 28). On high traffic volume roads, airports and busy railways data is often collected during the night. This does not pose any problems other than not being able to collect video data at the same time.



**Fig. 28.** A gravel road section from the Vaasa area in Finland measured using a 400 MHz ground coupled antenna in summer (A) and in winter during the time of maximum frost depth (B). The GPR data collected during the winter shows 0.5 m thick road structures while it is quite impossible to define them in the summer data. Winter data also presents, very clearly, the frost line as well as the presence of segregation ice (ice lenses) that cause differential frost heave and spring thaw weakening problems in the road.

In order to collect good quality data, the collection speed should be kept as slow as possible without interfering too much with traffic. There has been discussion among GPR users about the effect of data collection speed on the accuracy of a survey. The results of the tests carried out by the Texas Transportation Institute over a large aluminium reflector at different speeds up to 70 km/h showed that speed had no major influence on the amplitude reflection (Scullion *et al.* 1992). Hopman and Beuwing (2002) have compared GPR data collected by Dutch GPR contractors at different speeds with the drill core data and according to the results mean error at low speed was 5 % while at a speed of 80 km/h the error was 9 %.

The influence of surface roughness has also been discussed in some papers. Davis *et al.* (1994) suggest that roughness decreases the amplitude of the reflected signal from the pavement. Spagnolini (1997) discusses the scattering of the electromagnetic waves on rough surfaces but concludes that the phenomenon can be taken into account during the data processing.

## 5.2 Data collection setups and files

Data collection setups can be site and problem specific, for instance the number of scans/m used for surveying bridges is much higher than required for roads. However, the following setups have proven to provide good quality GPR data.

When measuring longitudinal sections on roads, railways and airports a good sampling density is 10 scan/m for both air coupled and ground coupled systems. This sampling

density provides information about cracks and crack propagation in pavement (Scullion & Saarenketo 1995) and segregation and enables detection of point like objects such as cables and pipes. When measuring cross sections on roads or conducting bridge deck surveys the recommended sampling density is 40 scan/m.

The gain setting on air-coupled systems should be one point gain (flat gain) because amplitude parameters are used in GPR analysis. The metal plate reflection sets a limit for the maximum gain with air-coupled antennas. With ground coupled systems, gain with several gain points can be used but the gain curve should be smooth. The recommended interval between gain points is 20 ns. The most common mistake during data collection on roads is that too much gain has been used and there is clipping of the GPR signal. Most GPR data collection software packages have an “autogain”, but this feature should not be used in road surveys. The optimal gain settings for each pavement type or bridge deck can be determined through testing, once defined these settings should be stored in the memory of the control unit. During data collection it may appear that the gain is not high enough but when the data density is 16 bit these problems can be handled with post processing software packages. New GPR control units have high data storage capacity and thus 8 bit sampling is no longer recommended. The recommended sample/scan density is 512 in most traffic infrastructure surveys.

During the data collection it is recommended that certain filters, to remove noise and ringing from the data, be used. However, this filtering should be very light so that actual structural or point-like object reflections are not removed. It should also be kept in mind that filtering can be done afterwards and many GPR systems, such as MALA, record only raw data during the data collection. However, if the filtering is done the following filter settings have proven to work well:

*Ground coupled antennas:* IIR filters with high pass filter 1/5 of the central frequency and low pass filter 5x central frequency (i.e. with 400 MHz antenna HP 80 MHz and LP 2500 MHz)

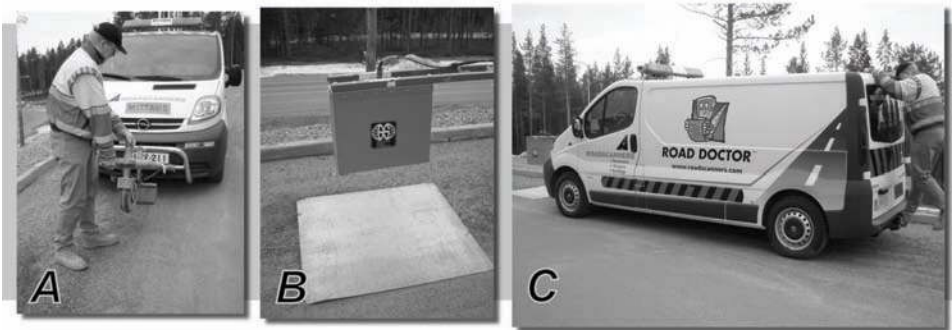
*Air coupled antennas:* FIR filters with high pass filter 1/2 of the central frequency and low pass filters 3x central frequency (i.e. with 1.0 GHz antenna HP 500 MHz and LP 3.0 GHz)

Each GPR manufacturer has its own recommendations regarding filter settings.

The measurement time depends on the target under examination, but normally a 20 ns time range has been used with high frequency pavement radar systems, where at least a 12 ns time window is collected below the pavement structure. With 400–600 MHz ground coupled systems normally a time window of 60 or 80 ns is used. With lower frequency antennas the time window should be defined based on the target depth of the survey so that the window should be about 1/3 longer than the maximum calculated depth.

When defining the position of a time window it is important that with air coupled systems' the direct pulse from transmitter to receiver is collected (see Fig. 30) because this pulse is used as a reference pulse in most post processing software packages. When selecting a time window with ground coupled systems it must be ensured that the surface reflection is within the window. This can be checked with an antenna lifting test (Figs 29 and 31) which should be done after each survey session. Due to coupling it is difficult to define the correct surface reflection in the data processing phase and the lifting test provides a solution to this problem.

When collecting air coupled data a static metal plate reflection should always be collected (Fig. 29b). In this survey a metal plate (about 100 \* 100 cm) is placed under the antenna and 100–200 scans are collected. It is highly recommended that this be done before and after the survey, but at the very least after the survey. Depending on the antenna quality, the so called “air pulse” can also be collected. To do this, the antenna is pointed upwards or sideways and a GPR signal without any reflections in the time window is collected. A third data file requiring collection is a height calibration file, which is used to correct the fact that the reflection amplitude is a function of the antenna’s height above the ground. Placing a metal plate under the antenna at different depths is one method of preparing a height calibration file. Calibration can also be done using the so called “bouncing test” whereby the road survey vehicle is bounced while the metal plate reflection is collected (Fig. 28).



**Fig. 29. GPR antenna calibration tests before or after data collection: photo A. presents the lifting test for a ground coupled antenna, photo B. the metal plate test for a horn antenna and photo C. the antenna bouncing test for a horn antenna.**

Before starting the data collection with many antennas, especially with air coupled antennas, it is important to allow an antenna to warm up at least 15–20 minutes in order to avoid amplitude and time drift of the GPR signal during data collection.

### 5.3 Positioning

Accurate positioning of the GPR data is the most important thing in the data collection process. Data with incorrect referencing is worthless to the customer and damaging for the GPR industry. A great number of GPR tests on roads have been classified as failures when the GPR data was compared to the ground truth data, many of these failures have originated from false positioning – of either the GPR data or the reference sampling.

Positioning can be done 1) using encoders that control the sampling interval, 2) adding markers to the GPR data at known reference points and 3) using GPS techniques. Digital video linked to GPR scan numbers also helps to ensure correct positioning. The best way is to use all of these methods in combination. Encoders should be installed on vehicle wheels (Fig. 22) or distance measurement instruments. The so called fifth wheel systems

have proven to be unreliable due to bouncing or movement in sharp curves. Markers should be inserted in the data at known reference points, such as culverts, bridge joints, access road intersections etc. The starting and ending place of a survey should be always marked on the road with road paint. On a short special survey section, such as a bridge deck or a forensic survey, it is recommended that reference points be painted on the pavement at 20–100 m intervals and markers be inserted at these points. In routine road surveys it is recommended that surveys be started and ended at known road registry referencing points.

Especially in bridge deck surveys accurate positioning in the transverse direction is also extremely critical and to do this different kinds of aiming systems, such as painted marks, lasers or video cameras have been used successfully.

## **5.4 Reference sampling**

In many projects, collecting reference samples at the same time as the GPR data is recommended, and if this is not possible it is recommended that the GPR crew marks the points for reference sampling on the road. The problem with this technique is, however, that preliminary data processing has to be carried out in the field.

In network level surveys and rehabilitation projects the points for reference samples should be selected from sections that present typical structures in the survey project. These points should be selected from sections where there are no changes in structure thickness at least +/- 10 m around the point. This ensures that there will be no errors in backcalculating dielectric values for each layer. Other points for reference sampling are anomalous areas indicating possible structural problems. Samples taken from these areas are used to verify the problem and its severity.

## **6 Data processing and interpretation**

### **6.1 General**

GPR data preprocessing, 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. Summaries about the GPR data processing techniques and algorithms are given by Maijala (1994), Daniels (1996) and Conyers and Goodman (1997).

Despite the facts that computer processors are becoming more efficient and GPR software packages are becoming more user friendly, the processing and interpretation of the GPR data from roads, railways and airports is still the most time consuming phase and an interpreter's skills play a key role in the success of a GPR project. GPR data processing can be divided into four phases: a) preprocessing, b) data processing, c) interpretation and visualization and d) reporting. During recent years, many software packages have developed new features allowing integration and viewing of other road survey data and video and also facilitate road analysis (Roimela *et al.* 2000) and integrated rehabilitation design (Saarenketo 2001). Many of the previously mentioned GPR manufacturers are also producing software packages or modules for road and bridge surveys, but there are also special commercial packages that have specifically been developed for use in road surveys, such as Road Doctor™ or "Haescan Pro A" by Roadscanners (Finland) or "Reflex" by Carl Sandmayer (Germany). In addition, many universities and road research laboratories have developed their own software packages.

### **6.2 GPR data preprocessing**

In the preprocessing phase GPR data is edited in such a way that the raw data itself will not be changed. In this phase the GPR data editing features normally used are: file reversal (allows comparison of data collected from right and left lane in two-lane roads or bridges), cutting and combining, scaling and linking data to GPS coordinates or to differ-



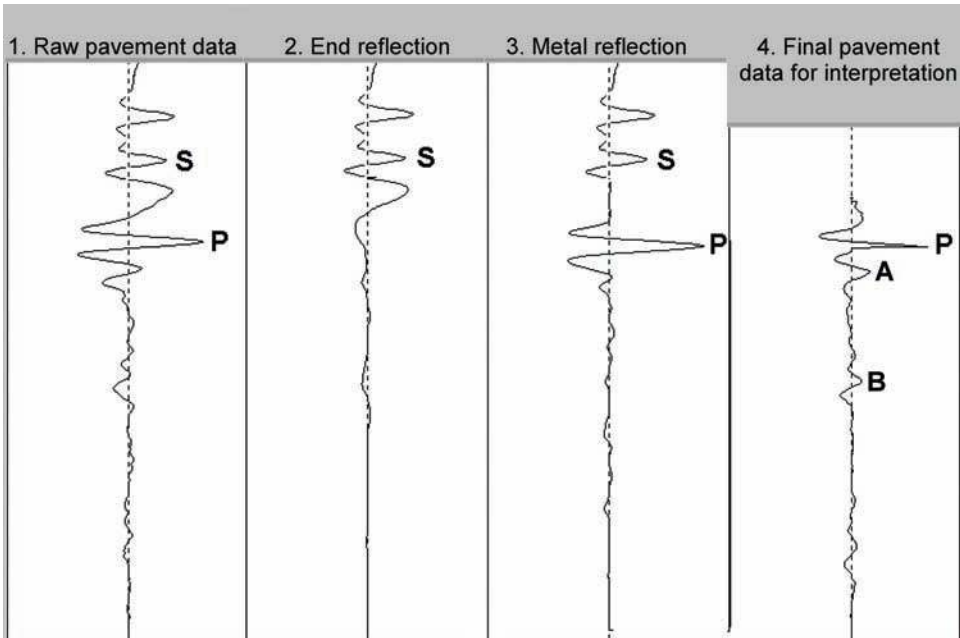
ent road address data bases. In the distance scaling phase it is important to check that markers match with known landmarks – this can be done using video and maps, for example. Most of the new GPR software packages for road data analysis now have project options that allow the interpreter to link several GPR survey lines to the same project. Useful project handling features often include processing templates to be used with every data file. In the preprocessing phase other road survey data and ground truth data, such as drill core data, should also be linked to the project.

Distance scaling is, at its simplest, a phase in which the starting and ending points and the distance between these points is calculated and the software scales all the scans between these two points using a constant scale parameter (scan/m). The problem with this scaling method is the distance errors caused by curves, which can be solved by using the previously mentioned markers technique and/or using GPS data linked to scan numbers. Major changes in z-coordinates (height) can also cause problems in scaling. GPR data preprocessing software can calculate the real x,y,z coordinates and distance from starting or reference point to each scan.

In GPR data preprocessing it should be ensured that GPR signal polarity and colour scales follow certain rules that were agreed upon by GPR consultants in the early 1990's. In a measured pulse from a metal plate in a single scan mode the maximum peak (see Fig. 30) should always point to the right and it should be referred to as the "positive reflection" (even though it is not necessarily positive) and in a line scan format using a grey scale it should be white and in a blue/red colour scale format it should appear as red. The two smaller peaks around the "positive" peaks are called negative peaks and in a grey scale they should be black and in a colour scale they should be blue. The same rule also corresponds for ground coupled systems so that positive (white) reflections are registered when the lower layer has higher dielectric value and negative (black) reflections appear when the lower layer has lower dielectric value than the upper layer (see also Fig. 30). If the polarity is reversed during data collection, this can be changed by multiplying the GPR signals by a factor of -1. These basic rules allow engineers to read and compare the data collected from the traffic infrastructure consistently and helps with observation of changes in moisture content in different layers or if the voids are filled with air or water.

### **6.3 Air coupled antenna data processing**

The different GPR signals needed in each phase of air coupled data processing are presented in Figure 30 and signal processing is described in detail in different software manuals. In the first phase a template subtraction is made, i.e. air pulse is removed from the metal plate file and from the raw data. It is only necessary to do this if the direct wave has clutter below the pavement surface level. If the air coupled antenna signal quality is good and the pulse shape is straight above the pavement surface reflection this process is not needed and the processing will be done using only the metal plate reflection.



**Fig. 30. Different air coupled antenna signals during the antenna processing. Signal 1. presents raw GPR data collected from the road, S is a direct signal from transmitter to receiver and P presents a surface reflection. Signal 2 presents an end reflection, where the antenna is pointed upwards or downwards from a dock, for instance, with no reflectors below. Signal 3 presents a metal reflection signal where the end reflection has been subtracted after the direct wave (see the straight signal above the surface reflection). Signal 4 presents processed GPR data ready for interpretation. where P represents the pavement surface, A presents a reflection from pavement bottom and B presents a reflector from the bottom of the base course.**

After the metal plate reflection is defined, the software flattens the changes in the surface reflection caused by bouncing of the survey vehicle and calculates the dielectric value of the road surface. The height of the antenna has an effect on the reflection amplitude (Scullion *et al.* 1992) and on the antenna near field effect (see Spagnolini 1997).

A height calibration test has been developed to control this effect (Scullion *et al.* 1992). In this test a metal reflection is measured with at specific distance intervals from the horn antenna. The travel time ( $D_t$ ) from the direct wave from transmitter antenna to the receiver antenna (bistatic systems) or from the end reflection (monostatic systems) to the metal plate is measured and a corresponding amplitude adjustment factor is calculated. This factor is used to adjust the input metal plate file in the layer thickness calculation. According to Scullion *et al.* (1992) the relationship between amplitude A and  $D_t$  is of the form:

$$(10) \quad A = b / (a + D_t).$$

The constants a (1.4678) and b (43.832), which have been measured with a Penetradar 1.0 GHz horn antenna height calibration test (see Scullion *et al.* 1992 p.22) match surprisingly well with the height calibration data of other air coupled horn antenna systems.

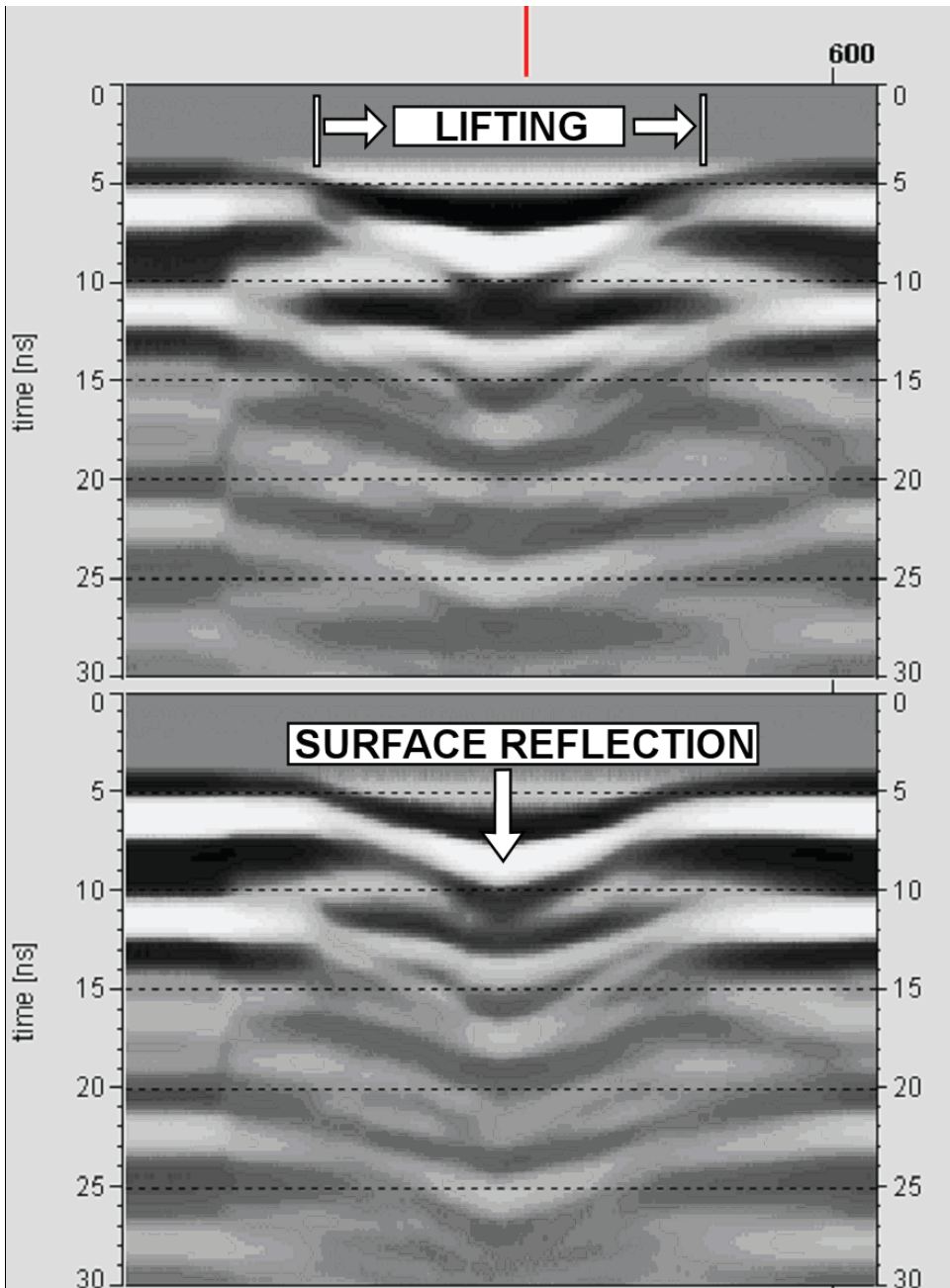
Many software packages also improve the surface resolution in this phase by using different algorithms.

Data filtering should also be done in this processing phase. Different filter setting can be tested to see if they improve the data quality. After the metal plate calibration and template subtraction other filters can be used. A special “background removal” filter described by Maijala *et al.* (1994) has also proven to improve the data quality. However, the background signal, which is to be removed from the data, has to be calculated from a road section where structure thickness changes, otherwise structural data can also be removed. Background removal cannot be used when the dielectric values of lower layers are calculated using the reflection technique.

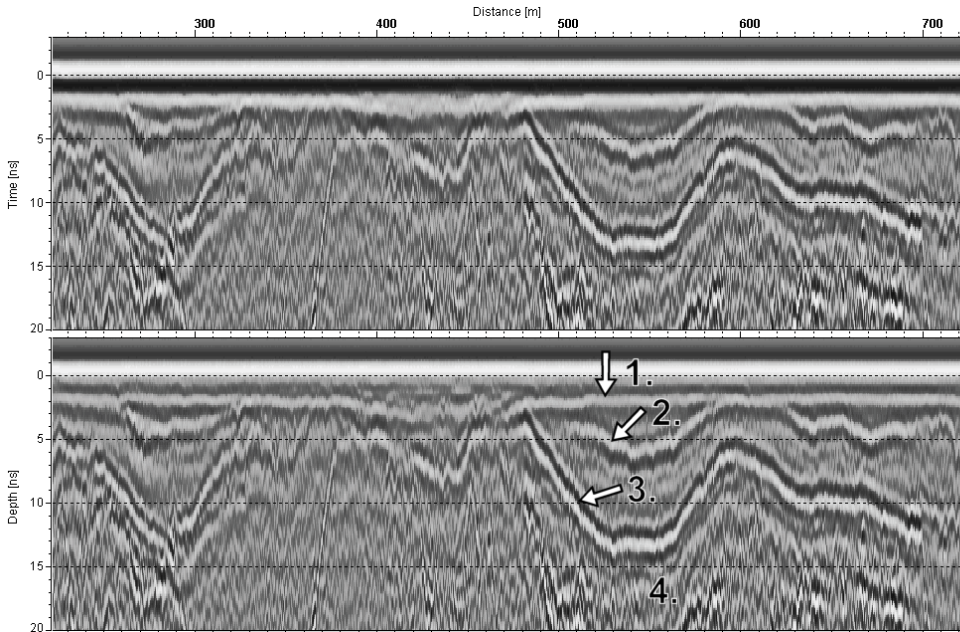
## 6.4 Ground coupled data processing

The basic processing of ground coupled data in traffic infrastructure surveys normally has only two steps: a) defining the pavement surface level in the data and b) background removal filtering. The pavement surface level can be defined by using the lifting test data. In this process the background is removed from the lifting file leaving only the position of the surface reflection (Fig. 31). There are also other techniques to detect this level, also known as the zero level, and Yelf (2004) provides a good description and test results of different ways to detect the true time zero level. Surface coupling also causes problems in the detection of structural layers near the road surface. A background removal filter is a good solution to this problem (Fig. 32). Another processing technique that can be useful in road survey data analysis is viewing the data in the frequency domain by using a Fourier transformation, which provides information regarding changes in electrical properties in structural layers and subgrade soils. Migration has been used occasionally in bridge deck surveys to filter the hyperbolas caused by the reinforcements. Migration is also needed when making time slices of the 3d GPR data.

Dielectric dispersion is significant and has to be taken into account when GPR surveys are carried out in wet soil conditions (see Goodman *et al.* 1994 and Paper I). In wet soils this usually results in the higher frequency components of pulse attenuating and propagating faster than the lower frequency components resulting in pulse broadening (Olhoeft & Capron 1994). This causes problems in deconvolution and migration of the data because the pulse is not in same shape and phase everywhere. In dry soils there is very little loss and dispersion of the electrical properties, but losses and dispersion increase rapidly with increasing water content (Goodman *et al.* 1994, Saarenketo 1996).



**Fig. 31.** Defining the pavement surface reflection position using the lifting test. This data was produced using a 200 MHz ground coupled antenna lifted from the pavement surface. In cases where there is an air gap between the antenna and pavement the difference would have been greater.



**Fig. 32.** An example of the effect of background removal in improving the 400 MHz ground coupled data quality. The top profile is raw data and below is the same data after background subtraction. The pavement bottom reflection (1.) can easily be defined from the filtered data, whereas this cannot be done in the raw data. The figure also illustrates how the polarity of the reflections provides information on the dielectric properties (and moisture) of the road structures. Positive (white in the middle) reflectors 1 and 2 reveal that the dielectric value of the base course, below the pavement, and sub base, below the base course, is higher than the dielectric value of the layers above. However, reflection 3 has negative polarity (black in the middle) and this shows that layer 4, which is sandy gravel, has a lower dielectric value and lower moisture content than the sub base layer.

## 6.5 Determining dielectric values or signal velocities

An accurate estimation of layer dielectric values or signal velocities is a key issue in successful traffic infrastructure GPR data processing. An interpreter, analysing traffic infrastructure data, needs information concerning the dielectric properties of structures and subgrade soils in order to a) calculate the correct layer thickness of structural layers and subgrade soil layers, b) calculate the moisture content, c) calculate the asphalt air voids content, d) estimate the moisture susceptibility and sensitivity which is directly related to permanent deformation of unbound materials, e) estimate the frost susceptibility of subgrade soils, f) estimate the compressibility of subgrade soils, g) estimate the homogeneity and fatigue of bound layers. In many surveys, especially in QC / QA (quality control / quality assurance) projects, there are major economic factors attached to the surveys results and as such there is a requirement for high quality data.

The traditional method for determining the dielectric value of pavement is backcalculating the value using reference drill cores. This method is still the most common especially when using ground coupled systems. The other very popular method is the surface reflection method (Maser & Scullion 1991), which can be used with air coupled antenna systems. In this method the reflection amplitude from the pavement surface is compared with the metal plate reflection representing a total reflector. By calculating the amplitudes, it is possible to calculate the dielectrics of both layers. Equation 10 presents the algorithm for the surface dielectric value calculation and equation 11 for second layer (base course) surface dielectric value.

$$(10) \quad \mathcal{E}_a = \left[ \frac{1 + A_1/A_m}{1 - A_1/A_m} \right]^2, \text{ where}$$

$\mathcal{E}_a$  = the dielectric value of the asphalt surfacing layer

$A_1$  = the amplitude of the reflection from the surface

$A_m$  = the amplitude of the reflection from a large metal plate (100% reflection case)

$$(11) \quad \sqrt{\mathcal{E}_b} = \sqrt{\mathcal{E}_a} \left[ \frac{1 - \left[ \frac{A_1}{A_m} \right]^2 + \left[ \frac{A_2}{A_m} \right]}{1 - \left[ \frac{A_1}{A_m} \right]^2 - \left[ \frac{A_2}{A_m} \right]} \right], \text{ where}$$

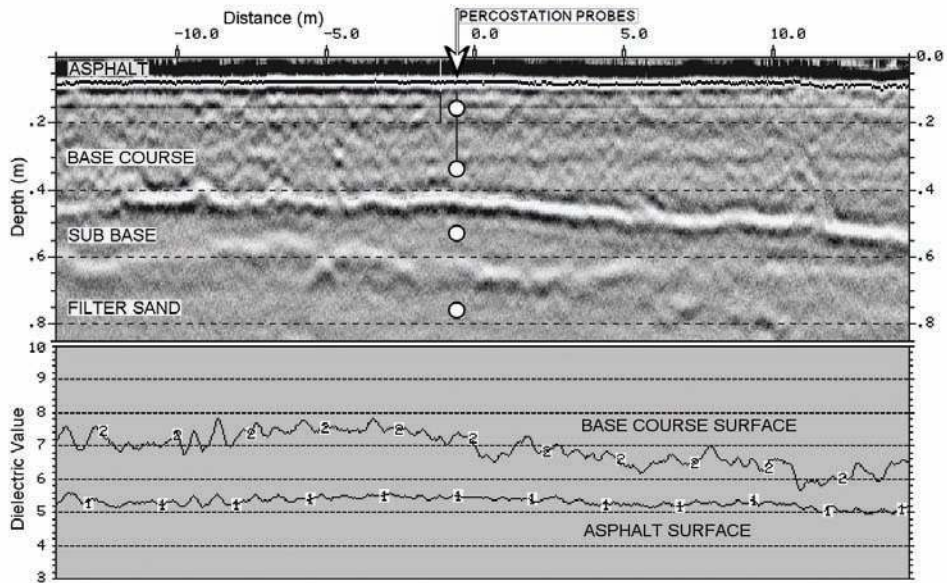
$\mathcal{E}_b$  = the dielectric of the layer 2 (base layer)

$A_2$  = the amplitude of reflection from the top of layer 2

These equations have proven to work well for estimating dielectric values for the first layer in homogenous asphalt pavement and most concrete pavements. Equation 11 assumes that no attenuation of the GPR signal occurs in the surface layer. This assumption appears to be reasonable for asphalt pavements and also provides reasonable dielectric values for the base layer, if the asphalt is thicker than 60 mm and there are no thin layers with different dielectric properties on the bottom of the asphalt on top of the base as can be seen in Figure 33 measured at the Koskenkylä Percostation site in 2001. However, the computations are less reliable for certain concrete pavements. In order to improve this method in the future, signal attenuation has to be incorporated into the calculation process.

For new or defect free pavements, the surface and base dielectrics together with the surface thickness can be calculated easily. The main factor affecting the surface dielectric is the density of the asphalt layer while base dielectric is primarily influenced by the volumetric moisture content of the layer. The GPR reflections can also be used to judge the homogeneity of the pavement layers.

Another method used in estimating the dielectric values of road structures is the CMP (common middle point) method (Maser 2002a, Al-Qadi *et al.* 2002). According to Fauchard *et al.* (2003) this method provides sufficient accuracy of dielectric values for first two or three layers in road structures. Dielectric values have also been measured using different antenna array techniques (Hänninen 1997, Davis *et al.* 1994, Emilsson *et al.* 2002).



**Fig. 33.** GPR 1.0 GHz horn antenna profile measured at the Koskenkylä Percostation site (Paper III, see also Chapter 3.5.4). The measured dielectric values from the base surface (2) are lower where the base course above the sub base with a high moisture content is thicker which demonstrates the effect of capillary rise. According to measurements from the Percostation the dielectric values of the base course at the time of the GPR measurements were about 7–8 and the dielectric value of sub base was 16–18. The depth scale of the GPR data has been calculated using a dielectric value of 6.

If reference data is not available for the layer thickness calculations then general dielectric values can be used as they can provide reasonable thickness estimates. Table 2 presents the dielectric values of air, water and different road materials and subgrade soils which, based on experience, are known to work reasonably well when making calculations for GPR road surveys in Scandinavia.

*Table 2. Dielectric values air, water, ice and different subgrade soils and road materials that are normally used in the GPR data interpretation in Scandinavia. Road materials and subgrade soil values, except peat, are those used above ground water table.*

Material	Dielectric value
Air	1
Water (fresh)	81
Ice	4
Bedrock (granite)	5–7
Peat (natural)	60
Peat (under road)	40
Clay	25–40
Silt	16–30

*Table 2. Continued*

Silty sand	7–10
Sand	4–6
Gravel	4–7
Glacial till (moraine)	8–18
Asphalt / other bituminous pavements	4–8 (if slag present 8–15)
Concrete	8–10
Gravel road wearing course	12–14
Crushed base	6–8
Bitumen bound base	6–7
Cement bound base	8–10
Insulation boards (new)	2–2.5
Road structures in average (new/dry)	5
Road structures in average (normal)	6
Road structures in average (wet/old)	7–8
Gravel road structures in average	7–9
Frozen road structures (normal)	5
Frozen road structures (wet/old)	6

## 6.6 Interpretation – automated vs. user controlled systems

Many efforts, including the use of neural networks, have been made to develop automatic interpretation software for roads and bridges. However, the results of these development projects have not been encouraging and have also resulted in confusion amongst highway engineers. The reason that automatic interpretation software packages will, most likely, never work on older roads, railways or airports is that these structures are typically historical structures with discontinuities in longitudinal, vertical, and transverse directions (see Paper III, Hugenschmidt 2003). Manually controlled semiautomatic interpretation software used by well trained and experienced interpretation staff and utilizing different kinds of reference survey results has proved to be the only reliable solution in traffic transport infrastructure surveys (Mesher *et al.* 1996, Roberts & Petroy 1996, Paper III). The only cases where automatic interpretation seems to calculate the correct thickness and dielectric values are surveys on new and defect free pavements (Paper III).

## 6.7 Interpretation of structures and other objects

The interpreter's knowledge of the road, bridge, railway and airport runway or taxiway structures and their damage mechanisms play a key role in the interpretation process. The GPR data is filled with information from reflectors, individual objects, amplitude anomalies (moisture, attenuation etc) and the interpreter has to select and report on those that are essential to the final report. Sometimes, reflections from lamp posts or guard rails can



be seen in the data, especially if the gain level is high, but due to their wide hyperbolas these reflections are easily detected and ignored. As such the interpreter should always, at least, interpret the key structures and, most importantly, the individual objects found in the data. Based on the goals of the project as determined in the project design phase it should be determined what other structures are to be reported.

In road, street and airport runway and taxiway surveys the key structures that should always be interpreted are a) bottom of the bound layers (pavement and bound base), b) bottom of unbound base, c) bottom of the entire pavement structure and d) bottom of the embankment, if the road is on an embankment. The layer thickness data is needed to backcalculate layer moduli values from FWD data (Fig. 34) and also for dimensioning a new pavement structure. In addition, in routine GPR surveys an estimate of subgrade soil quality should always be made. If bedrock is close to surface and it can be identified, it should also be interpreted. Additional information that should be reported is the location of culverts and bridges and damaged road sections and reasons for the damage. Cables and pipelines should be reported if this has been written in the contract. With regard to road structures usually the thickness of the subbase and filter course and the location of old road structures should also be reported.

In bridge deck surveys a standard interpretation includes identification of the following interfaces: a) pavement bottom, b) bottom of the protective concrete (if it exists), and c) the level of the top reinforcement of the bridge slab. In railway surveys the key structures are normally a) ballast, b) sub ballast, c) thickness of the whole structure and d) embankment, if it exists.

The exact location in the GPR signal where a layer interface is selected and followed varies. Most GPR consultants and software use the maximum amplitude of each reflection. This technique is the most accurate in measuring the thickness of different layers, but the interpreter must always be aware of changes in polarity (see Fig. 32). Another technique, still in use, is to define the layer interface according to the position where the signal passes the zero amplitude level after the first reflection peak of that layer. This technique is independent of the changes in signal polarity between each layer but, on the other hand, easily gives false thickness information if there are thin layer reflectors near the key interfaces causing overlapping reflections.

Interpretation of a layer interface in new structures is generally a straightforward process as they are quite easy to identify. Problems, however, can occur when dealing with older fatigued structures. Frost action and heavy traffic especially can cause mixing in the layers such that the layer interfaces are very hard to define precisely. However, in rehabilitation design surveys it is very important that these layers are interpreted and usually it is important to report that there might be an important layer or an object, such as bedrock or old frost insulation board, that the design engineer should be aware of. Finnish GPR users have agreed on a technique to distinguish the degree of certainty regarding an interpreted layer (Ground Penetrating Radar 1992). With this system GPR consultants can illustrate the reliability of an interpretation. This classification has three classes (Table 3).

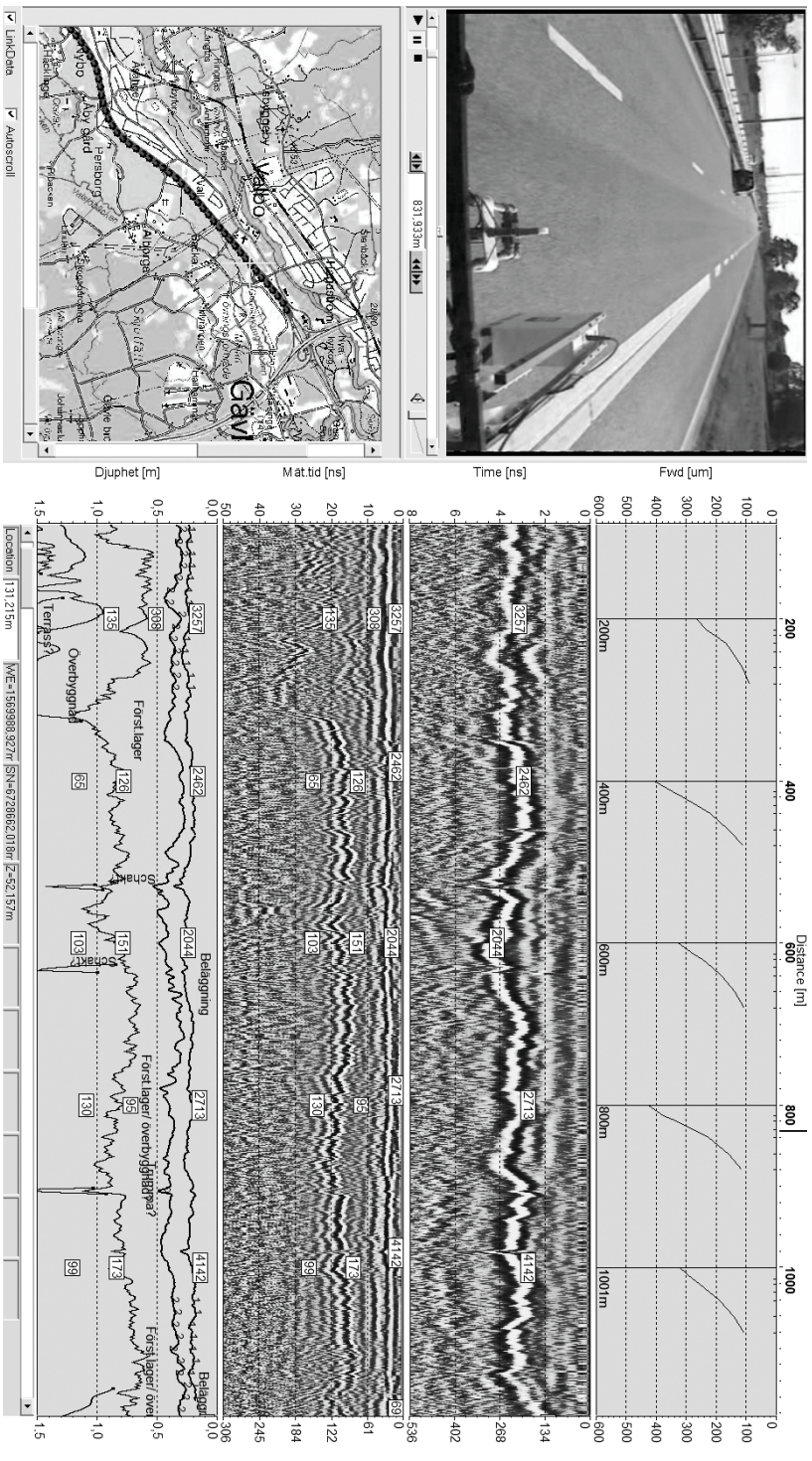


Fig. 34. An example of FWD data, GPR data and backcalculated moduli results using Elmod 5.0 software and presented in Road Doctor™ software together with digital video and a map. The top frame presents FWD deflection bowls measured from the road. Two GPR profiles in the middle represent 1.0 GHz horn antenna data (upper) and 400 MHz ground coupled data (lower). The lowest profile presents road structure thicknesses that were calculated from the GPR data. Small boxes present moduli values from each layer.

*Table 3. Layer interface identification class according to Finnish Ground Penetrating Radar text book (Ground Penetrating Radar1992).*

Degree of distinction	Symbol	explanation
a. obvious interface	—————	continuous line
b. distinguishable interface	-----	lines longer than spaces
c. possible interface	- - - - -	spaces longer than lines

Individual objects about which the interpreter is uncertain are marked with a question mark (?) after the object description. During the interpretation the layer thickness should always be verified with drilling and sampling data and crosschecked with the GPR data to see if the interpreted layers match with the ground truth thickness information.

The easiest option with difficult GPR data cases, such as fuzzy layer interfaces, is to leave them uninterpreted. However, the professional skill of an interpreter is reflected in how well one can identify these layers and in Finland, according to Finnish GPR specifications, it is required that all of the layers be interpreted (Tiehallinto 2004).

## **7 Integrated GPR data analysis with other road survey data**

### **7.1 General**

As with many other geophysical applications GPR survey results become much easier to understand and results are more reliable if there is other supporting data available when analyzing the radar data. Roads can be surveyed using several other non-destructive techniques such as falling weight deflectometers, and profilometers. The combination of GPR with other non-destructive road survey techniques provides a powerful tool for diagnosing current pavement problems and selecting the optimum repair technique (Paper II, Roimela *et al.* 2000, Saarenketo 2001, Johansson *et al.* 2005). Integrated analysis has also been used in estimating the need for load restrictions on low volume roads (see Mohajeri 2002, Saarenketo & Aho 2005a, Saarenketo 2005). Figure 35 presents an example of a integrated data view from Road Doctor<sup>®</sup> software used in a network level bearing capacity survey in Region Mitt in Sweden (Johansson *et al.* 2005).

### **7.2 GPR and FWD**

Of all the integrated road survey techniques the combined use of GPR and FWD data has been the most popular among road engineers. Saeed and Hall (2002) compared several testing methods for characterizing the in situ properties of pavement materials. The best combination was FWD and GPR. Noureldin *et al.* (2003) also recommend that FWD and GPR should be used as part of the Indiana Department of Transportation's pavement management system. The integrated analysis of GPR and FWD data, used in support of one another, offers many advantages for pavement evaluation. Especially FWD data backcalculations require the kind of accurate pavement structure thickness information that GPR can provide (Lenngren *et al.* 2000, Al-Qadi *et al.* 2003a, Noureldin *et al.* 2003) and changes in the thickness of asphalt pavement and bound layers are a major source of errors when the results from Falling Weight Deflectometer (FWD) measurements are being calculated into the pavement layer moduli values. This is especially so with thin pavements (Irwin *et al.* 1989). According to Jooste *et al.* (1998) thin, stiff layers such as a stabilized subbase were found to be the most sensitive to layer thickness fluctuations.

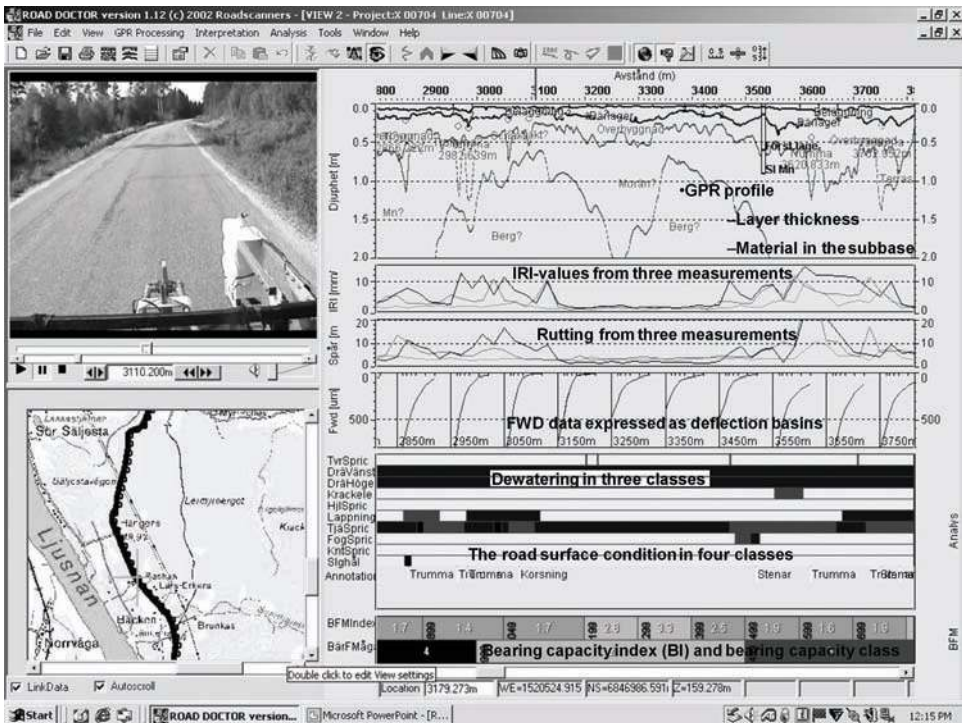


Fig. 35. An example view of integrated road surveys data when analysing road condition. The top graph on the right presents interpreted GPR data from 1.0 GHz and 400 MHz antennas. The two lower graphs present profilometer history data (IRI and rutting). FWD deflection bowls are presented in the middle and beneath that pavement distress analysis information and drainage condition information is presented. The lowest graph presents the results from Swedish Bearing Capacity Indexes calculations (see Johansson *et al.* 2005). Bedrock is close to the surface at 3100 m and 3350 m.

Using moduli values backcalculated from the FWD data and GPR thickness data it is also possible to check the quality of the GPR interpretation and, based on the GPR profile, ignore those FWD data points that were collected from points that do not represent the structure well. In pavement condition evaluation the FWD data helps to verify disintegration in the pavement layers and/or check if the problems are related to the base course or sub-base (Saarenketo *et al.* 2000a, see also Fig. 9 in Paper III). GPR data can be used to locate water susceptible base course sections where the FWD data, collected during dry summer months, would not indicate any problems.

The FWD data provides valuable information for GPR analysis about the subgrade soil type. In addition, the shape of the deflection bowl in combination with the GPR data indicates immediately if bedrock is present and close to the surface (Fig. 35, see also Fig. 4 in Paper III) or if the road has been constructed over peat. Using FWD backcalculation software or by using other subgrade moduli calculation methods it is also possible to estimate with GPR data where the road has been constructed on peat, silt or clay or sand and gravel (Saarenketo 2001).

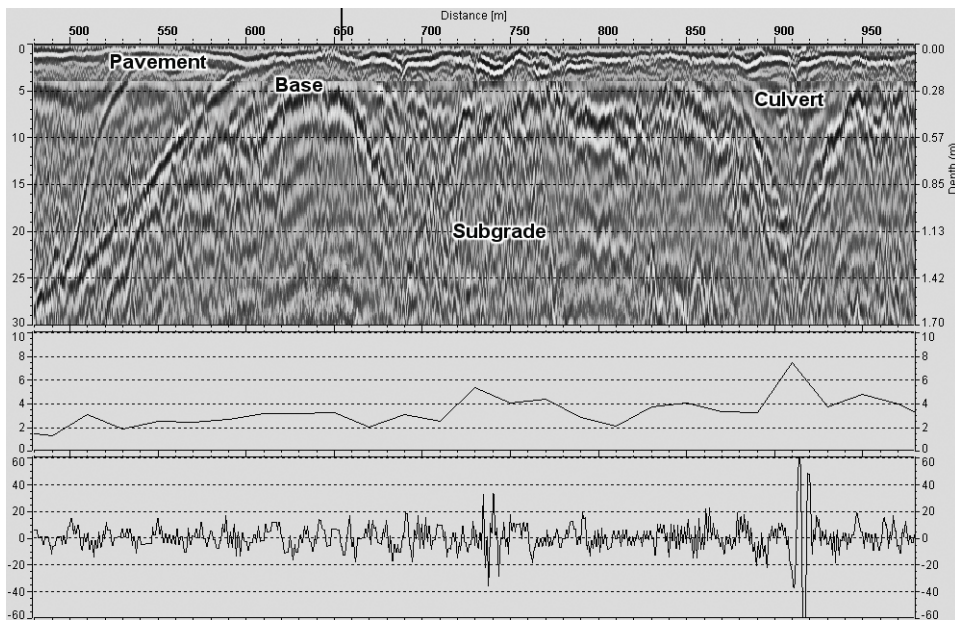


### 7.3 Profilometer data

Road profilometers are used to measure parameters, which describe longitudinal and transverse evenness and the cross fall of a road surface (Sayers & Karamihas 1997). The most common parameter used to describe longitudinal evenness is called IRI (International Roughness Index) and transverse evenness is described with different rut depth parameters. Analysing GPR data in combination with profilometer data helps interpretation personnel to locate problem areas and identify the reason for the problems, for example, whether problems are due to differential frost heave or settlements or caused by permanent deformation due to moisture susceptible road materials.

If profilometer data is not available and information on the unevenness of the road is needed a good indicator for sections with unevenness problems is the air coupled antenna height file, which can be calculated from the raw data. The data from this file presents the height of the air coupled antenna from the pavement surface and changes in this height demonstrate areas where the survey vehicle has been driving over uneven spots in the pavement (Fig. 36).

In the future, profilometers or road surface scanners will be used with multichannel GPR systems to prepare 3D models of roads, railways and airports.

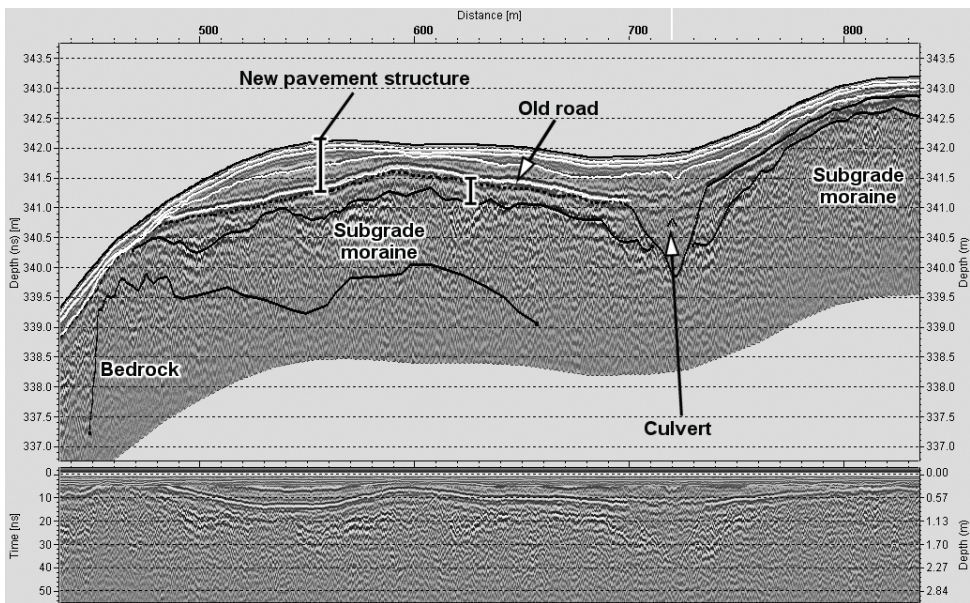


**Fig. 36.** Integration of GPR data, profilometer data and air coupled antenna height data, Road 752, Sweden. The first 4 ns in the GPR profile is 1.0 GHz horn antenna data and 4–30 ns is 400 Mhz ground coupled data. The profile in the centre is IRI (International Roughness Index) presented at 10 m intervals. The data in the bottom frame presents the distance from the horn antenna to the pavement surface. The biggest differential frost heave sections can be related to section 700–770 m where frost fatigue has also mixed the layer interfaces in the GPR data and to 900–920, where the uneven frost bump can be related to a culvert.

## 7.4 GPS, digital video and photos

GPS data is mainly used to position the measurements correctly but it also helps with interpretation. If the correct GPS z-coordinates are available and the software has a topography correction feature, this helps an interpreter to check that the interpretation is logical (Fig. 37). If the GPR data is linked with GPS coordinates the GPR survey line can be linked to geological maps, like soil maps, and this helps with verification of the subgrade soil quality.

As previously mentioned, having video with the GPR data is a “must” for most organizations performing GPR surveys on roads, railways and airports. Since, without digital video, it is very difficult to know whether the structures are on an embankment or a road cut. Video also helps to identify problems related to drainage and the presence of bedrock. Video shows the pavement damage and helps the interpreter to make a correct diagnosis of the problems. Video can be viewed from a separate video player but the best option is when digital video is linked with the GPR data.



**Fig. 37.** 400 MHz ground coupled and 1.0 GHz air coupled data (first 5 ns) from HWY 21 in Finland presented as uninterpreted data (bottom) and height corrected and interpreted data (top). The height corrected profile demonstrates well how the vertical geometry of the road has been improved during the last strengthening project.

Digital photos are also useful during interpretation. Detailed photos of the drill cores have been especially useful during the interpretation.

## 7.5 Other data

Road, railway and airport authorities have many kinds of databases and this data is often very useful in GPR data analysis. An interpretation can be greatly improved if an interpreter has access to pavement distress and condition databases, paving history and thickness databases.

In special projects it is worthwhile collecting other geophysical data to support the GPR data interpretation (see Wilson & Garman 2002). Electrical resistivity sounding or profiling data support the GPR analysis if the GPR signal has penetration problems due to high conductivity of the subgrade soils. Resistivity profiles help with identification of soil types and their moisture contents. Soil type and moisture content can also be verified through measurement of soil dielectric value and electrical conductivity data collected using a dielectric probe, such as a Percometer (Saarenketo 1995b, 2001). Electromagnetic (EM) measurements have aided in the identification of cables and other objects under the pavement.



## **8 GPR applications on roads and streets**

### **8.1 General**

GPR applications on roads and streets can be divided roughly into four main categories: a) surveys carried out in design of a new road, b) surveys needed for the rehabilitation design of an existing road, c) quality control or quality assurance surveys on a road project and d) surveys for pavement management systems and similar purposes (see Saarenketo 1992, Fernando *et al.* 1994, Hugenschmidt *et al.* 1996, Scullion & Saarenketo 1998, Paper III, Saarenketo 2001, Scullion 2001, Maser 2002a,b, Al-Qadi *et al.* 2003c, Ahmed *et al.* 2003, Johansson *et al.* 2005). GPR can provide different types of information regarding the bound and unbound pavement structures, subgrade soils, moisture contents and other features of interest to these projects. A general description of each application is given in the following sections.

### **8.2 Subgrade surveys, site investigations**

Subgrade surveys and site investigations with GPR have been classified into the following three categories (Saarenketo & 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 in which the GPR techniques are applied varies.

#### ***8.2.1 Subgrade quality and presence of bedrock***

When evaluating the subgrade soil type in road projects it is usually quite easy to identify coarse grained gravel, sand and glacial till soils from the GPR data. GPR also works

well for identifying most organic peat soils (Ulriksen 1982, Doolittle & Repertus 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 on clay soils. In Scandinavia, GPR signal penetration in clay soil areas is normally about 2 m, which is adequate for cable and pipeline surveys but not for highway design purposes. In the USA, penetration depth depends on the mineralogy and clay content of the soils. According to Doolittle and Rupertus (1988) 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.

In many cases the soil type can be determined from the GPR data, because each soil has its own specific geological structure, dielectric, and electrical conductivity properties (see Paper I, Benedetto & Benedetto 2002); these properties produce a special "fingerprint texture" in a GPR profile. Soil type evaluations always require some ground truth data to confirm the GPR interpretation. Excellent supporting information can also be obtained from the Falling Weight Deflectometer (FWD) survey data.

In road surveys GPR information concerning the depth of overburden and location of bedrock is used in the design of grade lines, or in design against uneven frost heave and other specific technical problems (Paper III, Fish 2002). If the bedrock is close to the surface the GPR interpretation can be confirmed with the FWD deflection bowl shape (Fig. 35, see also Fig. 5 in Paper II) and FWD backcalculation algorithms (Scullion & Saarenketo 1999, Paper III). If GPR surveys are performed in the wintertime, the areas of bedrock closer to the surface than the frost level are easy to identify because there are no frost line reflections in the bedrock in the radar profile. GPR also allows observation of bedrock stratification and major fracture zones when evaluating the stability of highway cutting walls (Saarenketo 1992, Fish 2002). Similar information can also be obtained in highway tunnel surveys where both ground coupled and drill-hole antennas have been used (Westerdahl *et al.* 1992).

When calculating the thickness of subgrade soil layers it should be kept in mind that the dielectric properties of soil correlate highly with water content and type of water in the soils. This is especially important if the subgrade beneath the road is peat (see Saarenketo *et al.* 1992). In soil surveys dielectric dispersion is quite significant and different dielectric values will be obtained if the measurements are performed with 400 MHz and 1.5 GHz antennas (Paper I, Benedetto & Benedetto 2002).

### ***8.2.2 Soil moisture and frost susceptibility***

The GPR technique has been used to locate road sections with excess moisture in the subgrade and help pavement engineers to design proper drainage (Wimsatt *et al.* 1998). There are also a few cases reported for using GPR in embankment stability surveys especially with roads located on sloping ground (see Roadex 2001, Ékes & Friele 2004).

GPR can also be used to monitor settlements in roads by comparing the changes in pavement and/or road structure total thickness with road surface level information (Paper III, Jung *et al.* 2004). In the case of widening and/or strengthening an existing highway, or when constructing new lanes, the best information regarding changes in the compressibil-

ity of the subgrade soil can be obtained directly by surveying the existing road with GPR (Fig. 5 in Paper III, see also Fig. 40). This technique is especially useful when estimating the extent of settlements in a new road and when designing preloading embankments over clay, silt or peat subgrade (Saarenketo *et al.* 1992).

A GPR profile can present areas, where frost action has caused damage to the road. The damage, or early phase frost fatigue can be observed as permanent deformation of road structures taking place during the spring frost thawing period or in the form of an uneven frost heave related 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 have not been properly constructed (Paper III) (see Fig. 36).

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. Saarenketo (1995b) 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 (Saarenketo 1995b). However, later tests have shown that especially electrical conductivity limits can vary significantly based on the area and soil type. The evaluation of potential frost action areas and presence of segregation ice using GPR can be performed in winter when the frost has penetrated 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 the frost table and clarity of the reflection, and 3) the effect of the frost action upon the road structures (see Saarenketo & Scullion 1994, Saarenketo 1995b, Paper II). 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 reflection from the frost level 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 (see Fig. 28, see also Fig. 6, Paper III).

Paper II and Paper III propose a quality assessment of the strength and deformation and frost susceptibility properties of soils based on their dielectric properties, which is presented in the Table 4. (see also Hänninen & Sutinen 1994, Hänninen 1997).

*Table 4. Quality assessment of mineral soils and unbound road materials above the ground water level according to their dielectric properties (dielectric value for plastic limit with clays can be higher than 28, see Paper I).*

Dielectric value	Interpretation
4–9	Dry and non-frost susceptible soils, in most cases good bearing capacity (excluding some sands)
9–16	Moist and slightly frost susceptible soil, reduced but in most cases adequate bearing capacity
16–28	Highly frost susceptible and water susceptible soil, low bearing capacity, under repeated dynamic load and high stress level positive water pressure causes permanent deformation
28–	Wet, plastic and unstable mineral soil

### 8.2.3 Other subgrade applications

GPR has great potential for aggregate prospecting (Saarenketo & Maijala 1994, Cardimona & Newton 2002). Ground Penetrating Radar techniques have also been used to locate sinkholes (Beck & Ronen 1994, Saarenketo & Scullion 1994, Casas *et al.* 1996, Geraads & Omnes 2002, Wilson & Garman 2002) and washouts under the road (Adams *et al.* 1998, Lewis *et al.* 2002). After locating the areas of voids, GPR has also been used to monitor the injection of grout into the voids (Ballard 1992). Another GPR application related to subgrade surveys is locating underground utilities under an existing road (Bae *et al.* 1996). Several authors have also had success with detecting buried tanks or other objects close to the edge of existing pavement structures prior to widening of the highway.

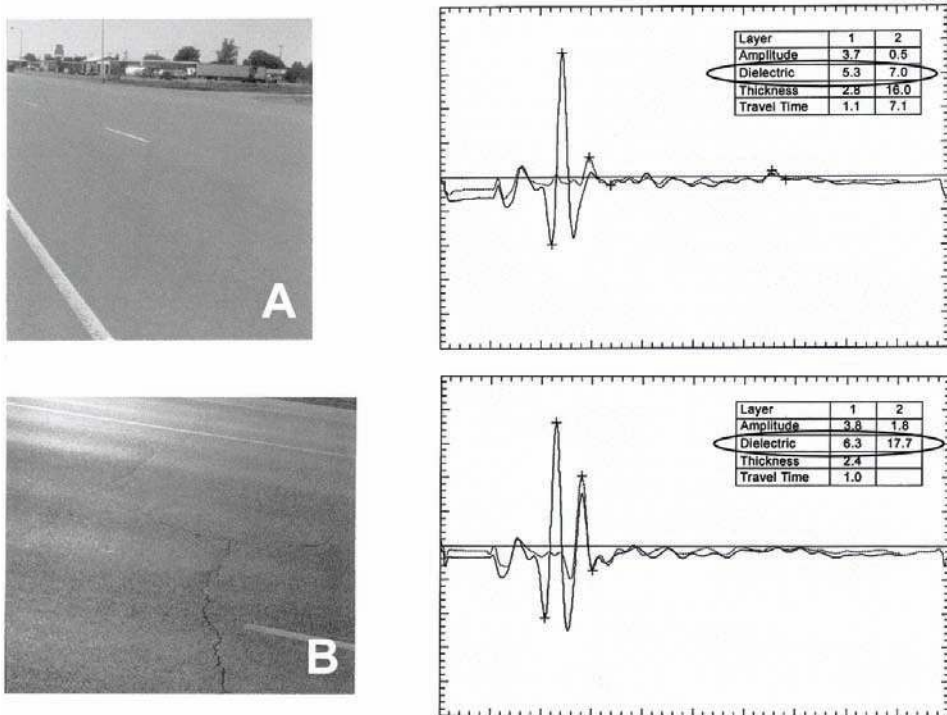
## 8.3 Unbound pavement structures

Unbound pavement structures are situated between the subgrade soil and top bound layers. Unbound pavement structure is normally made of crushed gravel, crushed hard rock, ballast or macadam and non-frost susceptible and non-water susceptible natural soils, such as gravel and sand, good for construction purposes. The key road structures in which these materials are used are presented in Chapter 6.7. The base course layer, made of unbound aggregates, which supports asphalt or concrete pavement is one of the most critical layers in a road structure. The accuracy of base layer thickness measurements using GPR have been reported to be close to 8–12 % (Al-Qadi *et al.* 2002, Maser 2002b).

The results from the laboratory and field tests surveys, mentioned in Chapter 3, 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. Furthermore, high dielectric values of the base course (9–16, >16), calculated from the GPR data are always good indicators for existing or potential problems in the layer (Saarenketo *et al.* 1998, Paper III, Scullion 2001, Scullion & Saarenketo 2002). Figure 38 modified from Scullion and Saarenketo (2002) presents a typical case where the dielectric value of an unbound base, measured by using both GPR and the Tube Suction test in the laboratory, indicate well the problems with the road.

Also too low dielectric values in unbound layers can indicate potential road problems. In this case, the base course material grading is too “open” and under compaction is susceptible to permanent deformation (Wimsatt *et al.* 1998, see also Yan & Nazarian 2003).

Table 5 modified from Papers II and III presents a classification of unbound base materials based on their dielectric properties.



**Fig. 38.** Examples of the relationship of GPR value measured with GPR and pavement lifetime. Upper graph A presents a four year old base course material made from gravel on SH136 that has had good field performance. The dielectric value of asphalt was 5.3 and base course 7.0 and this material also passed the Tube Suction test criteria. The lower photo and graph B is from a section from the same road that has been made from Caliche gravel and that already has moderate cracking. The dielectric value of asphalt measured with GPR was 6.3 and base course 17.7. Based on the Tube Suction test criteria, this material has also failed (Figure modified from Scullion & Saarenketo 2002).

*Table 5. Classification of base course materials according to their dielectric properties. The limit value for problem base in the USA is 10, while in Finland it has been 9.*

Dielectric value	Interpretation
< 5	Dry and open graded base course material with low water adsorption and large voids ratio. Low tensile strength, might be sensitive to permanent deformation
5–9 (10)	Dry base with low water adsorption properties, optimum dry strength properties, non frost susceptible, non water sensitive
9 (10)–16	Moist base course, still high shear strength due to suction, hysteresis has great effect on strength value, frost susceptible especially if drainage is not working, sensitive to permanent deformation on higher stress levels especially after freeze-thaw cycles
> 16	Wet or almost water saturated base course, low shear strength above the ground water table, sensitive to plastic deformation under dynamic load, extremely frost susceptible

## 8.4 Bound pavement structures and wearing courses

The top part of the pavement structure of roads and airfields is mainly made of so called bound materials. These bound layers can be bound base course, pavement and wearing course – or only one of them. The most common binding agents in road pavements are bitumen (asphalt) and cement (concrete), but other agents have also been used marginally. Gravel road wearing course is defined as an “unbound” layer, or “water bound” layer but related GPR applications are also described in this chapter.

### 8.4.1 Bituminous pavement thickness and moisture content

The GPR pavement thickness data has been collected for: a) network level surveys where thickness is required for Pavement Management System (PMS) data bases, b) to supplement FWD data in calculation of layer moduli, c) pavement design purposes, e.g. divide road into homogenous sub sections, or to check if the pavement is thick enough for recycling milling and d) for quality control purposes (see Fernando *et al.* 1994, Saarenketo 1997, Saarenketo & Roimela 1998, Scullion & Saarenketo 1998, Berthelot *et al.* 2001, Maser 2002b, Sebesta & Scullion 2002a,b, Saeed & Hall 2002, Noureldin *et al.* 2003, Hugenschmidt 2003).

Using the techniques for new pavements described earlier the accuracy of GPR thickness predictions has been around 3–5 %, without taking a validation core. The highest accuracy has been reported by Maser *et al.* (2003), who tested both the horn antenna technique and ground coupled antenna with CMP (common mid point) technique in quality assurance of new asphalt pavements and reported an accuracy of 2.5 mm. The problem with older pavement, when using the surface reflection technique, is that the surface dielectric value of the pavement is estimated from the asphalt surface and this can some times lead to overestimation of asphalt thickness (see Al-Qadi *et al.* 2002). As such validation cores are recommended for older pavements (see Maser & Scullion 1991, Morey 1998, Paper III, Maser 2002b) with the accuracy then varying between 5–10 %. The thinnest pavement layers that can be detected with the newest 2.2 GHz GPR antennas and good processing software are less than 20 mm. Dérobert *et al.* (2002a) have been developing a stepped frequency radar with an ultra wide band Vivaldi antenna to detect the thickness of very thin pavements.

GPR has also been used to monitor changes in the moisture content of asphalt pavement (Liu 2003). In these surveys the changes in signal velocities are so small (3–5 %) that it corresponds to only 2–3 samples in one scan (Liu 2003).

### 8.4.2 Defect in bituminous pavements

In bituminous pavements GPR techniques have been used to detect different kinds of defects, such as segregation, stripping, crack detection and moisture barriers (Saarenketo

& Scullion 1995, Paper III, Sebesta & Scullion 2002a,b). The following provides a brief description of these problems.

Segregation manifests itself as localized periodic small areas of low-density material in the compacted surfacing layer (Paper III). Upon close inspection of these small, localized areas an excess of coarse aggregates will be found. The causes are often traced to improper handling or construction techniques. If an asphalt surface is uniformly compacted, the surface dielectric should be constant, however, if an area of low permeability has excessive air voids this will be observable in the surface dielectric plot as a decrease in measured dielectric value (Sebesta & Scullion 2002a,b) as seen in Figure 39. An example of the use of 3d radar technique to detect segregation is presented later in Figure 47.

### GPR Detection of HMA Segregation Surface Dielectric Plots

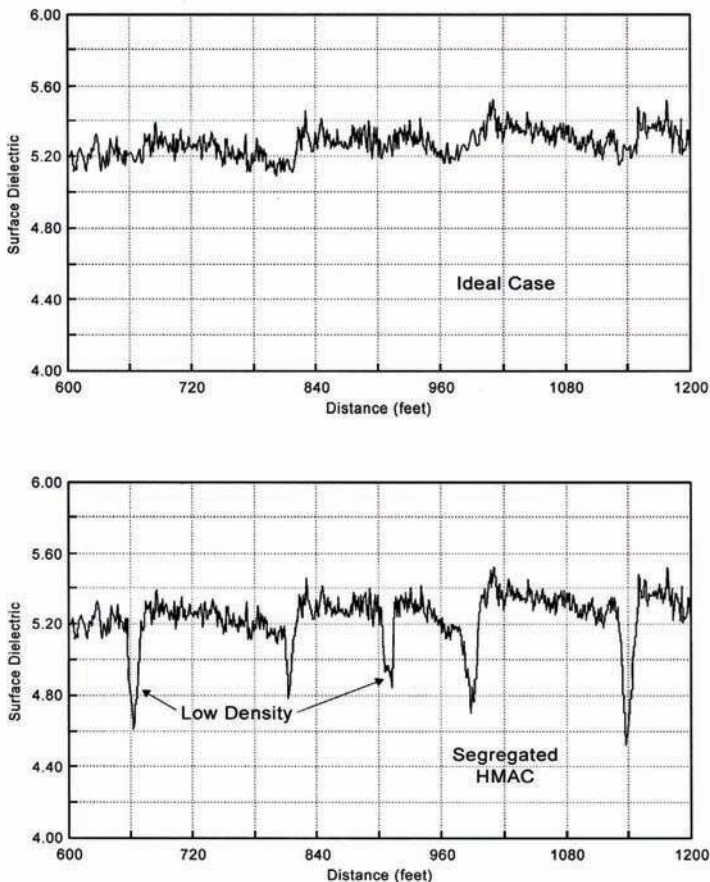


Fig. 39. Hot Mix Asphalt (HMA) surface dielectric values from new pavements from US 79, Texas, USA. The upper profile presents an ideal case with homogenous asphalt density. The lower profile presents segregation problems and a low density asphalt surface (from Sebesta & Scullion 2002b).

The most common asphalt pavement damage inside the pavement 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. The GPR technique has been widely used to detect stripping with varying success (see Rmeili & Scullion 1997, Morey 1998, Paper III, Saarenketo *et al.* 2000b, Cardimona *et al.* 2003). Stripping can be seen, in most cases, as an additional positive or negative (reversed reflection polarity) reflection in the pavement. However, similar reflections can also 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 (Saarenketo *et al.* 2000b).

Another major cause of surface distress is moisture becoming trapped within the surface layer. This happens when impermeable fabrics or chip seals or surface dressing 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. GPR reflections from existing highways can be complex particularly if the old Hot Mix Asphalt (HMA) layer contains numerous thin layers constructed with different aggregates compacted to different densities. Moisture barriers within the layer and collecting data shortly after a significant rainfall can also complicate the analysis (Paper III). One such moisture barrier which has caused problems for road performance is old bituminous layers left inside the old unbound base course. If they are closer than 0.4 m from the current pavement surface, the interpreter should identify it in the GPR data.

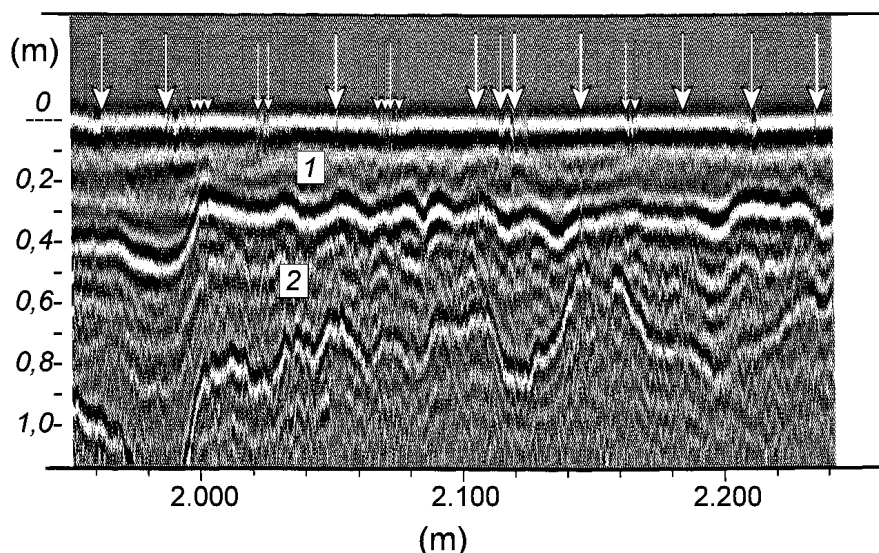


Fig. 40. Example of using GPR in determining the causes of transverse cracks, HW 4 in Rovaniemi. The antenna used was a GSSI 1,5 GHz ground coupled antenna. Layer 1 presents asphalt and bound bases and layer 2 unbound road structures (unbound base and sub base). Cracks reaching the surface are marked with arrows. The data shows that the location of the transverse cracks can, in most cases, be related to a rapid change in the thickness of pavement or unbound layer. These changes can be related to differential settlements of the road structures during (unbound layers) and after the construction (bituminous layers).



Other asphalt defects include cracking, thermal cracking and debonding, which takes place when the bonding between separate asphalt layers becomes loose. Of these defects, GPR has proven to be useful in detecting transverse cracking (Saarenketo & Scullion 1994). Figure 40 presents one case from HW 4 in Rovaniemi, where the location of transverse cracks can be related to locations where the thickness of both bound and unbound layers change quickly. In the UK, Forest and Utsi (2004) have introduced a Non Destructive Crack Depth Detector, based on slow speed GPR, to detect the depth of top down cracks in asphalt pavements.

### 8.4.3 Concrete pavements

The major defects in concrete pavement have been reported as being voids beneath the joints, cracking and delamination of the concrete pavement. The formation of voids beneath concrete pavements is a serious problem, which has been particularly noted on jointed concrete pavements built with stabilized bases (Saarenketo & Scullion 1994). Over time the bases erode and the supporting material is frequently pumped out under the action of truckloads.

GPR was first reported to be in use on concrete pavements to locate voids under concrete pavement (Kovacs & Morey 1983, Clemena *et al.* 1987). However, the problem has been in detecting small voids with several failures having been reported (see Morey 1998, Al-Qadi *et al.* 2002). Glover (1992) reports that the smallest voids detectable with ground coupled antennas are with a diameter of 0.25 m. Air coupled GPR systems can detect voids larger than 15 mm (Saarenketo & Scullion 1994). The problem with void detection is knowing whether the voids are air voids, water filled or partly water filled, in each case the GPR reflection pattern looks different (Paper III).

Another GPR application on concrete pavements has been detecting and locating dowels and anchors around the concrete slab joints (Maierhofer & Kind 2002). Huston *et al.* (2000) have tested stepped frequency radar using 0.5 to 6.0 GHz air coupled waves to detect delamination in concrete roads.

Concrete thickness measurements have caused problems sometimes, because detecting the reflection from the concrete/base interface can be difficult (Cardimona *et al.* 2003). The reason for this difficulty has been attributed to the similar properties of concrete pavement and base course. Higher signal attenuation in the concrete can also be another reason for this problem. Other reasons include using the wrong antenna type and improper data processing. Clark & Crabb (2003) have been able to measure changes in sub base moisture content under the concrete pavement using 450 MHz and 900 MHz ground coupled antennas. Often, the dielectric value of concrete (normally around 9) is higher than the base course (normally 6–7) and thus negative reflections can be obtained from the concrete – base interface (Saarenketo *et al.* 2000b).

In many cases, concrete pavements have asphalt overlay and in rehabilitation projects GPR has been used to measure the overlay thickness and indicate areas with a likelihood of deterioration in the underlying concrete (Maser 2002b).

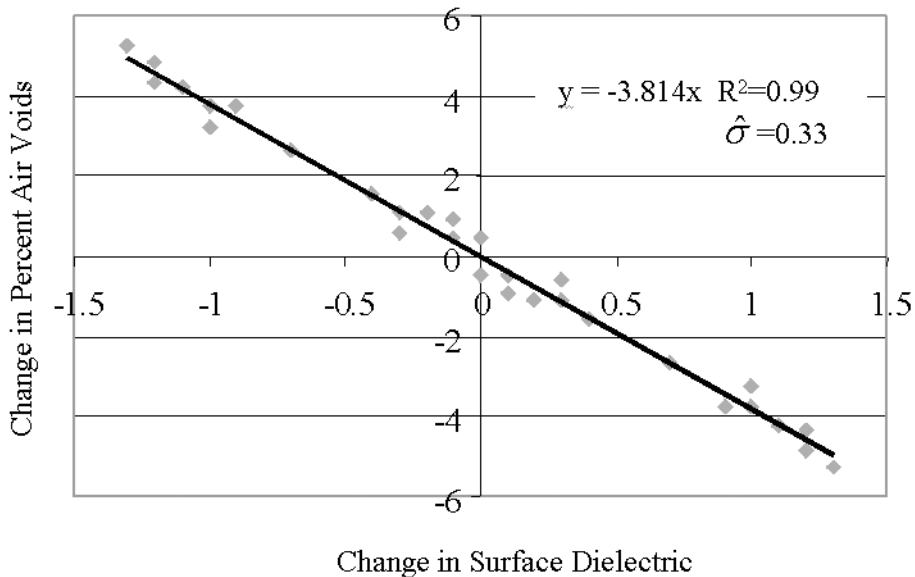
#### ***8.4.4 Gravel road wearing course***

Gravel surfacing is still widely used on low volume public roads around the world. The maintenance actions on these roads focus mainly on wearing course. The wearing course should have a proper thickness and the material should have special suction properties to prevent dusting but at the same time not become plastic under wheel loads in wet conditions. Saarenketo and Vesa (2000) present a technique for classifying gravel road wearing courses based on surface dielectric value and wearing course thickness. Because wearing course thickness has great variation in the transverse direction of the road, the accuracy of GPR measurements in wearing course surveys is 25 mm. The optimum range of dielectric value for a 100 mm thick gravel road wearing course is 12–16 (Saarenketo & Vesa 2000). Tests performed on gravel roads in Finland in 2004–2005 have shown that the new 2.2 GHz horn antenna works better when measuring wearing course thickness compared with the “traditional” 1.0 GHz antenna.

### **8.5 GPR in QC / QA**

Since the late 1990's GPR has gained increasing popularity in quality control surveys of new road structures. The traditional application of GPR in quality control surveys has only been road structure thickness verification (Al-Qadi 2003b). New GPR quality control applications include measuring the air voids content of asphalt and detecting segregation in asphalt (Paper III). The greatest advantages of GPR methods are that they are not destructive in comparison to the traditional drill core methods, costs are low and GPR surveys can be performed from a moving vehicle reducing safety hazards for highway personnel. The GPR method also presents the possibility of continuous linear data collection and thus 100 % coverage of a new road structure under inspection can be achieved. Drill core methods only provide point specific information and thus they cannot reliably be used to find defective areas in new pavements (Scullion & Saarenketo 2002).

Asphalt air voids 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. 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 (see Chapter 3.6). 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 (see Fig. 12 in Paper III) (Saarenketo 1997, Saarenketo & Roimela 1998, Scullion & Saarenketo 2002). The relationship between dielectric value and air voids content has been logarithmic (see Fig. 12 in Paper III) but as seen in Figure 41 very good linear relationships have also been measured in Texas (Sebesta & Scullion 2002b).

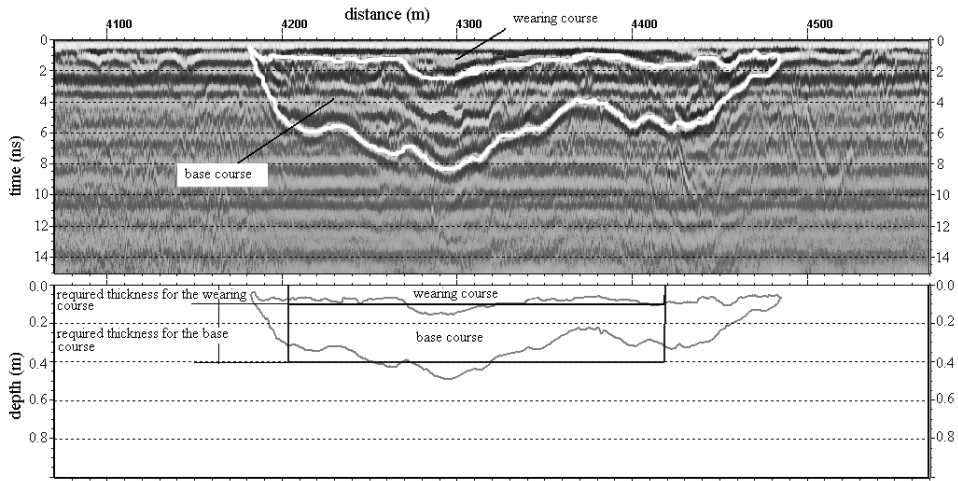


**Fig. 41. Correlation between changes in the surface dielectric value (x-axis) and changes in the percentage of air voids (y-axis) on US 79, Texas, U.S.A. (from Sebesta & Scullion 2002b).**

The GPR measurements in the field are performed using a 1.0 GHz horn antenna and at that frequency the thickness range of measured density is normally 0–30 mm. Higher frequency (2.2 GHz) antennas can and should be used to measure the density of thinner overlays and according to preliminary tests they seem to work better especially with remix pavements (Saarenketo & Kantia 2005). On the other hand they are also more sensitive to variations in asphalt surface texture and are also more sensitive to external noise. Dielectric values of asphalt surfacing are calculated by using the surface reflection techniques described earlier. Following the GPR field evaluation one or two calibration cores are taken and these cores are returned to the laboratory for traditional void content determination. For each type of aggregate and mix design, similarly shaped relationships have been developed (Saarenketo & Roimela 1998). The calibration cores are used to establish the link for each specific project. In 1999 GPR was accepted for use as a quality control tool, among other pavement density measurement techniques, on all new surfacing projects in Finland and since 2004 it is the only method allowed on high traffic volume roads because it does not obstruct traffic.

Asphalt quality control must always be conducted in dry conditions and not when the pavement is wet or frozen (see Saarenketo & Roimela 1998, Liu & Guo 2002).

In addition to quality control or quality assurance surveys of new asphalt pavement GPR has, during the last few years, been applied increasingly in quality control surveys of other road structures (Pälli *et al.* 2005). Figure 42 from Pälli *et al.* (2005) presents the use of GPR in quality control of a road rehabilitation project.



**Fig. 42.** An example of quality assurance data from a rehabilitated gravel road section using a 1.0 GHz horn antenna. The GPR data with the interpretation is shown above and the true layer thickness compared to the required layer thickness below. Figure shows clearly where the repaired base course layer is not thick enough (Pälli *et al.* 2005).

## 8.6 Special applications

Ground Penetrating Radar has been used for tunnel inspection in both roadway and railway tunnels. The focus of these surveys has been to detect fracture zones (Davis & Annan 1992) and measuring concrete wall thickness, locating rebar or detecting voids between the concrete and bedrock, detecting water leakage and other defects (Uomoto & Misra 1993, Daniels 1996 Hugenschmidt 2003) as well as testing grouting behind the lining of the shield tunnels (Xie *et al.* 2004).

## 9 Bridges

### 9.1 General

GPR was first used in bridge deck surveys in the U.S.A. and Canada since the early 1980's (Cantor & Kneeter 1982, Manning & Holt 1983, Clemena 1983). Quite soon the research was focused on developing automated or semiautomated GPR data analysis (Maijala *et al.* 1994, Mesher *et al.* 1996). In the late 1990's, research and development work was done especially in developing a multi channel GPR system for mapping bridge deck deterioration (Azevedo *et al.* 1996) but the methods did not become popular. During recent years the focus has been on collecting reflection amplitude data from bridge decks and preparing maps that present damaged areas in the bridge structures (Romero & Roberts 2004). Further there have been development projects for multichannel high frequency GPR systems (Washer 2003) and for high frequency (0.5–6 GHz) GPR systems to detect subsurface delamination (Huston *et al.* 2002).

GPR applications related to bridge surveys can be divided roughly into a) bridge foundations surveys related to problems such as site investigations and detecting scours around bridge piers (Haeni *et al.* 1992, Forde *et al.* 1999, Fish 2002, Inchan *et al.* 2004), b) bridge decks and bridge beams surveys (Romero & Roberts 2004, Hugenschmidt 2004) and c) other surveys such as surveys on approaching slabs, bridge abutments etc. (Lewis *et al.* 2002, Hugenschmidt 2003).

A majority of the reported GPR bridge surveys have been done on concrete bridges but there has also been some testing done on masonry bridges (Clark *et al.* 2003b) and wood bridges (Muller 2003).

### 9.2 Bridge deck surveys

A bridge deck can be examined in many ways and Hugenschmidt (2004) lists the following issues that can be addressed using GPR:

- Pavement thickness
- Thickness of single pavement layer

- Pavement damage
- Concrete cover of top layer of reinforcement
- Spacing between rebars (reinforcement bars)
- Position of tendons or tendon ducts
- Concrete damage
- Concrete and pavement properties

Parry and Davis (1992) have compiled a test parameter matrix for bridge decks, where they prioritised the different types of survey parameters that can be identified by measuring dielectric contrast, signal velocity (dielectric value), reflection coefficient and attenuation estimate. Highest priority, class 1, parameters were: asphalt/pavement thickness, rebar covering, debonding, delamination and scaling. Priority 2 parameters were: chloride content, moisture content (free moisture), moisture content (bound in concrete) and the lowest class 5 parameters were: cracking (surface) and cracking (subsurface).

In general, the primary cause of deterioration in bridge decks in North America is corrosion of the steel reinforcements which induces concrete cracking, which frequently results in delamination. This corrosion is caused mainly by deicing salts and when the reinforcements corrode they expand and a horizontal crack is formed in the reinforcement level. Another primary cause of deterioration in cold climate areas is freeze-thaw cycles in chloride contaminated concrete (Saarenketo & Söderqvist 1993). This deterioration, also called scaling, normally starts at the concrete surface and progresses downwards. According to Manning and Holt (1983) deterioration can be rapid if the cover layer over the top reinforcements is too thin. A third damage type found on bridges is debonding which takes place when asphalt or concrete overlay debonds from the concrete bridge deck.

Both high frequency ground coupled and air coupled antennas can be used in bridge deck surveys. Ground coupled systems can provide very detailed information about the bridge deck's structures and reinforcement bars. The major problems are the slow speed of data collection and that bridge lanes have to be closed during the data collection. As such, the use of air coupled antenna systems, which can perform data collection without causing major traffic problems, is highly recommended especially on high traffic volume roads.

Bridge deck deterioration mapping using the reflection amplitude from layer interfaces and especially the reflection amplitude from the top rebar as a measure of deterioration has become a very popular method in deck condition assessment. Romero and Roberts (2002, 2004) have introduced a special dual polarization horn antenna setup (Fig. 43) and processing technique that can be used to eliminate the effect of longitudinal reinforcement bars, which has been the problem when collecting data with air coupled antennas. Shin and Grivas (2003) used statistical methods for evaluating the accuracy of GPR results on bridge decks. The results showed that rebar reflection data detects defects at 75 % true detection rate with a 15 % false detection rate. Surface dielectric value failed to discriminate defects from the decks. There is still a fair amount of controversy over publications and research reports concerning the reliability of GPR especially in detecting delamination in bridge decks (see Morey 1998). Some research has attributed this difficulty to GPR resolution problems (Rhazi *et al.* 2003, Washer 2003) and that is why higher frequency antennas have been tested and recommended for use in these surveys (Huston *et al.* 2002).



**Fig. 43. Dual polarization configuration of horn antennas for high-speed, high-resolution bridge deck surveys (photo Francisco Romero).**

Due to the nature of the problems in bridge deck surveys, GPR alone cannot provide reliable enough information on the damage in the deck but it is an excellent tool for the initial mapping and specifying of locations where other non-destructive evaluation methods and limited ground truth (sampling) testing can be used to verify the problems. GPR is sensitive to electrical and chemical changes that are present in early phase corrosion and concrete disintegration. Often, anomalies detected by GPR cannot be verified visually from drill cores but only by using thin section or chemical analysis (Fig. 44).

GPR can also be used as an evaluation tool for quality assurance regarding placement, density and pattern of steel reinforcement. This can be done quite precisely and Hugen-schmidt (2003) reported a mean error of 3 and 17 mm for concrete cover.

Another promising application of GPR on bridges is detecting voids in post tensioned concrete beams. Giannopoulos *et al.* (2002) suggest that the optimum orientation of GPR antennas is perpendicular to the long axis of the ducts containing the post-tensioning tendons. Dérobert *et al.* (2002b) have tested several NDT methods in testing post-tensioned bridge beams and suggest that the best combination of current techniques is GPR before gammagraphy.

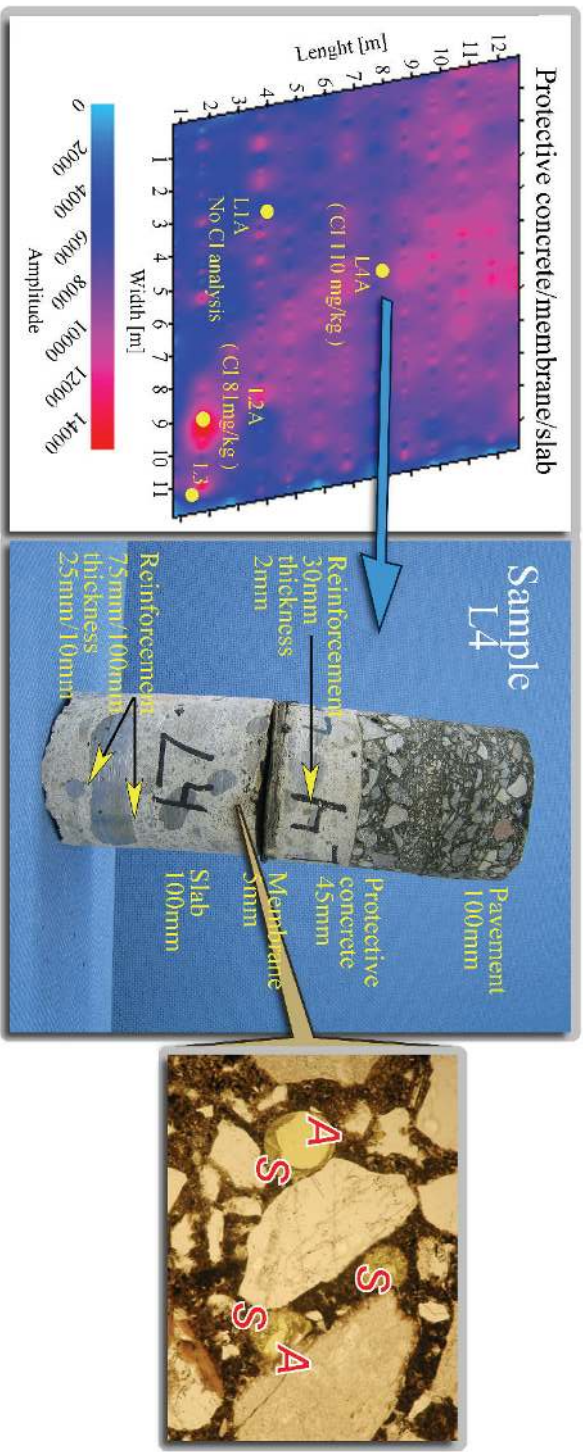


Fig. 44. Case from the Långsvedjan bridge in Sweden presents an example of how GPR can be used to predict problems, in the early phase, in bridge decks. The bridge structure has asphalt on the top, protective concrete in the middle and then a slab. The contour maps on the left present reflection amplitude from the protective concrete / slab interface, where a 5 mm membrane is also located. The contour maps on the left present core with no visual defects in any layer. The photo on the right is taken from a thin section taken from the slab below the membrane. This thin section shows the first indicators of deterioration where secondary weathering products (S) have started to fill air pores (A) which appear as yellowish material in the photo. Chloride content of the concrete in this place was also high, 110 mg/kg (Figure modified from Silvast & Johansson 2003).



### 9.3 Other bridge applications

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 (Ground Penetrating Radar 1992). Another application that has been tested in various projects has been detecting scours around bridge piers or abutments caused by the water flow erosion of a riverbed (Haeni *et al.* 1992, Forde *et al.* 1999, Fish 2002, Webb *et al.* 2002). These scours have been tested using low frequency antennas mounted in plastic or rubber boats or antennas have been moved over the river hanging from a cable. In Finland, these surveys have mainly been done in the wintertime when the river is frozen. The best results are obtained if the conductivity of the river water is less than 1000  $\mu\text{S}/\text{cm}$  (see Forde *et al.* 1999).

## 10 Railways

### 10.1 General

With regard to traffic infrastructure, GPR applications in railway surveys have had the fastest growth in recent years. In Finland, GPR was tested on railways in the mid 1980's but the results were not encouraging mainly due to problems with data collection and processing. In Germany, the GPR was first used to measure ballast thickness and to locate mudholes and ballast pockets and define the subgrade soils boundaries (Göbel *et al.* 1994).

GPR started to become more widely accepted among railway engineers in the mid 1990's. The first reports of successful track inspection tests were reported by Hugenschmidt in Switzerland (1998, 2000) and by Gallagher *et al.* in the U.K. (1998). Since 1998, a number of publications have been made regarding different GPR applications on railways. The system has been used in North America (Olhoeft & Selig 2002, Sussman *et al.* 2002) and in Europe, more specifically, in U.K. (Clark *et al.* 2003a,b,c, Brightwell & Thomas 2003), Germany (Manacorda *et al.* 2002), Austria, Switzerland, France, the Netherlands, Slovenia (see Staccone & de Haan 2003), Sweden (Smekal *et al.* 2003, Berggren *et al.* 2006) and Finland (Saarenketo *et al.* 2003, Silvast *et al.* 2006).

GPR applications on railways can be classified as a) ballast surveys (Clark *et al.* 2001, Sussman *et al.* 2002, Clark *et al.* 2003c, Silvast & Nurmikolu 2005) b) geotechnical investigations (Saarenketo *et al.* 2003, Sussman *et al.* 2003, Carpenter *et al.* 2004) and c) structural quality assurance of new non-ballasted railway trackbeds (Maierhofer & Kind 2002, Gardei *et al.* 2003). GPR has also been used in railway bridge and tunnel surveys.

### 10.2 Data collection from railways structures

Compared with pavement surveys, there are many more complications with obtaining a good quality GPR signal from railways. GPR operators have to struggle with interference from the rails and sleepers, especially concrete sleepers. Electrical wires have also

created interference in the GPR data especially when unshielded (air coupled) antennas are used. Researchers have solved these problems by using different kinds of antenna configurations (Fig. 45). Another problem has been the data collection speed. Railway surveys require high sampling density (scans/m) and thus the data collection speed, with many systems, has been slow and have caused problems with scheduling traffic. However, new GPR systems with fast processors allow high speed data collection with no problems with scheduling surveys (Clark *et al.* 2004).



**Fig. 45. Different GPR antennas used in railway surveys. Photo (A) presents a Swedish Mala ground coupled antenna (photo by Mala Geoscience), photo (B) presents a multichannel GSSI air coupled system (from Olhoeft *et al.* 2004), photo (C) presents a GSSI 400 MHz ground coupled antenna and photo (D) presents Radar Team Sweden 350 MHz 1.2 GHz Sub-Echo HBD antennas (photo Mika Silvast).**

The optimum antenna for use in railway surveys varies. In North America many successful tests have been carried out using 1.0 GHz horn antennas (Olhoeft *et al.* 2004), while in the U.K (Clark *et al.* 2003c) and Finland (Saarenketo *et al.* 2003) the best quality data in railway structure thickness measurements was collected using low frequency 400 & 500 MHz antennas. There have been some problems using high frequency air coupled antennas to measure ballast thickness but the antennas were good for detecting frost insulation boards (Saarenketo *et al.* 2003). Higher frequency antenna pulses with shorter wavelength are scattered in ballast with stones larger than 50 mm in diameter (see Clark *et al.* 2001). In railway surveys antennas have to be kept relatively high above the sur-

face level and as such antenna central frequencies are also slightly higher compared to when they are in contact with the surface (Clark *et al.* 2003c).

Also in railway surveys, the best results have been achieved when GPR results are combined with the results from other NDT methods. In the U.K., good results have been obtained from the integrated analysis of GPR and Infrared thermography (Clark *et al.* 2003c, 2004). Smekal *et al.* (2003) have tested GPR and a Track Loading Vehicle on the Swedish Western Main Line with a focus on sections with excessive settlements, slides and environmental vibration problems. In these surveys they used a 100 MHz ground coupled antenna in monostatic and array mode and 500 MHz antennas in bistatic mode. However, they did not find any correlation between vertical track stiffness and the average amplitude of radar. Later the integrated analysis of the GPR data and track stiffness data has given more promising results (Berggren *et al.* 2006). Grainger and Armitage (2002, referred by Clark *et al.* 2003) also report the combined use of GPR, an automated ballast sampler and a falling weight deflectometer (FWD) in railway trackbed evaluation.

### 10.3 Ballast surveys

Railway ballast thickness measurements and quality evaluations are the main applications of GPR on railways. Ballast is made of crushed hard rock or, sometimes, crushed gravel material, where smaller mineral particles have been sieved away. The ballast of a railway line must perform many different functions some of which are (Clark *et al.* 2001): reduce stresses applied to weaker interfaces, resist vertical, lateral and longitudinal forces applied to sleepers to maintain track position; and to provide drainage for water from the track structure. Ballast quality surveys focus on locating sections of clean and spent ballast. Spent ballast normally has a higher amount of fine particles than is allowed and can no longer fulfil the requirements for which it is being used (Clark *et al.* 2001). Fines are mainly formed through the mechanical wear, imposed by vibrations and loads from passing trains, and chemical wear caused by pollution and the effects of weather erosion on the larger particles (Clark *et al.* 2001). According to Nurmikolu (2005), mechanical wear is the most important factor increasing the fines content in ballast in Finland but organic material from external sources also has an important role in increasing water adsorption properties of ballast. However, in some countries coal dust from cargo trains has been the main source of fines in ballast. GPR can also detect, very reliably, if subgrade soil material has penetrated or mixed with the ballast (Hugenschmidt 2000, Brightwell & Thomas 2003).

Dielectric value is a good indicator of ballast quality. The dielectric properties of ballast materials have been surveyed by Clark *et al.* (2001) and Sussman *et al.* (2002). The main parameters affecting the dielectric properties are moisture content and the level of fouling (Sussman *et al.* 2002). Clark *et al.* (2003a) have presented the dielectric values of good and poor quality ballast materials that have been compared in dry, moist and wet conditions (Table 6).

Table 6. Published dielectric values of ballast (prepared by Clark *et al.* 2003a).

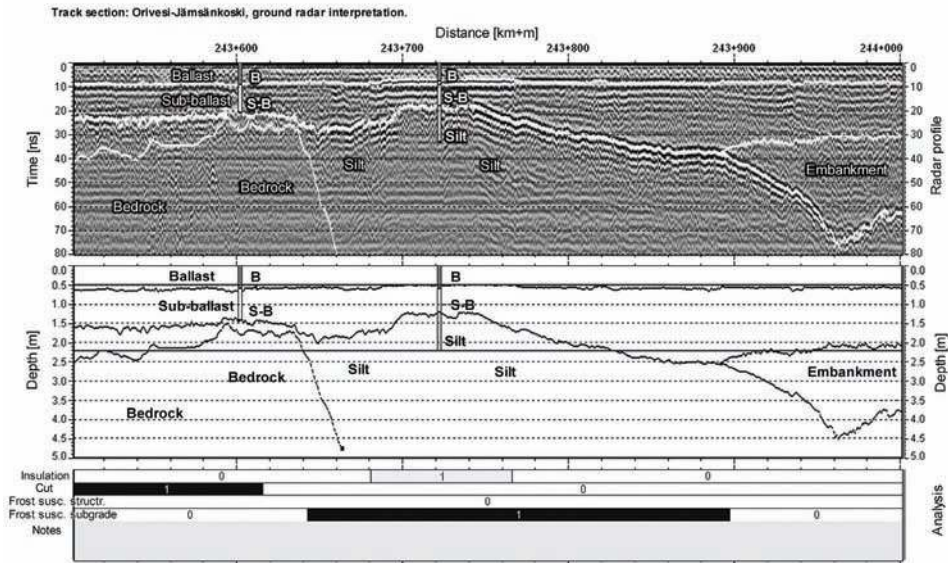
Material	Dielectric value:	Dielectric value of granite ballasts: Sussmann <i>et al.</i> (2002)
Dry Clean Ballast	3	3.6
Moist Clean Ballast	3.5	4
Dry Spent Ballast	4.3	3.7
Moist Spent Ballast	7.8	5.1
Wet Spent Ballast	38.5	7.2

The above Table also shows that in ballast thickness and quality surveys it is important to know the dielectric value of the material. Since the surface reflection technique cannot be used the options for determining the dielectric value are mainly the CMP or WARR methods. Al-Nuaimy *et al.* (2004) have used neural networks to discriminate between clean, mixed and spent ballast. In Finland, if the only goal is to determine ballast thickness, then the potential error caused by changes in dielectric values are eliminated by measuring the ballast thickness when it is frozen (Saarenketo *et al.* 2003).

#### 10.4 Subgrade surveys, site investigations

GPR can be used to detect problems related to embankment instability with a risk for track settlement (Sussman *et al.* 2003). Olhoeft and Selig (2002) have collected data from the railway substructure using 1.0 GHz horn antennas. Data was collected from the centreline and both sides of the rails and then compared. If the data is similar then all is well but when they differ dramatically, that should cause concern for track stability. In construction of new railways, Carpenter *et al.* (2004) have reported the use of a specialized geosynthetic, detectable with radar, in railway structures, which enables the use of GPR to monitor track stability in high-risk areas with karstic landscapes or old mine-workings for instance.

In addition to the risk of settlement, differential frost heave also causes problems in cold climate areas. Saarenketo *et al.* (2003) have tested different antenna types and frequencies for obtaining information from railway ballast and substructures up to maximum frost penetration depth of 3 & 4 m (Fig. 46). Tests showed that GPR can be used to detect frost susceptible areas and structures (see also Paper III).



**Fig. 46.** A GPR profile of a railway section from Jämsä to Orivesi in Finland. The profile on the top presents interpreted 400 MHz ground coupled GPR data with ground truth information. The profile in the middle presents thickness interpretation together with ground truth data. The top horizontal line presents the minimum ballast thickness level and the lower line the minimum total thickness of the whole structure against frost heave, if frost insulation is not used. The colour bars in the bottom frame present the location of frost insulation, the location of frost susceptible ballast and sub ballast structures and the location of frost susceptible subgrade.

## 11 Airfields

There are not many published records available about the application of GPR on airfields even though the system has been widely used in different airfield related surveys. Beck and Ronen (1994) have tested 1.0 GHz ground coupled antennas for runway substructure stratigraphic mapping and lateral variation estimations used in the planning of a reconstructed runway. Malvar and Cline (2002) have tested GPR together with other NDT methods in detecting voids under airfield pavements. In these projects GPR was useful in 25–75 % of the cases, but on the other hand the advantage of the GPR resides in the ability to process a large amount of data quickly and its ability to pinpoint drainpipe locations (Malvar & Cline 2002). Szykiewicz and Grabowski (2004) have used GPR and Heavy Weight Deflectometer (HWD) on airfields in Poland to map different pavement structures and their condition and to locate damages and their causes.

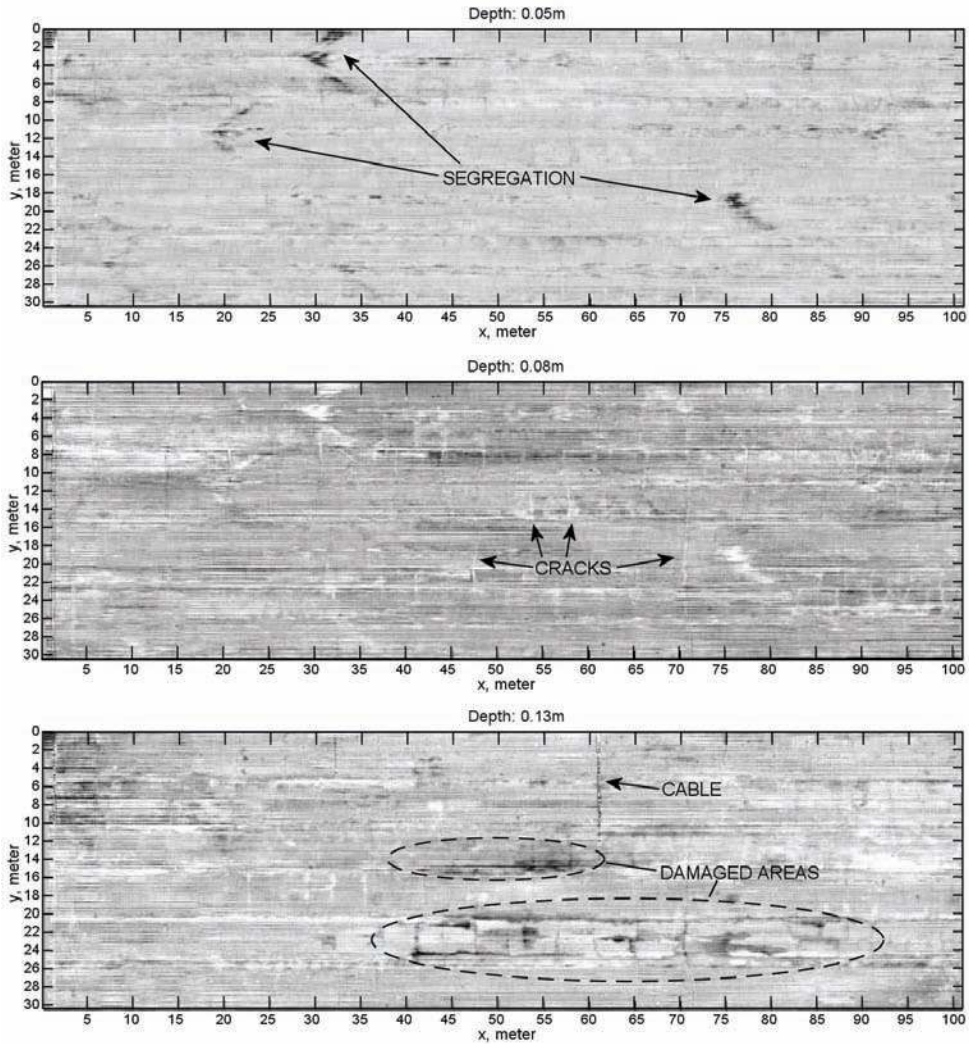
According to Weil (1992, 1998) the two prime NDT techniques in airfields are GPR and/or Infrared Thermography. He presents a list of applications in which these techniques can be used individually or to complement each other (Weil 1998):

- locating voids within, and below, concrete runways and taxiways
- locating moisture trails within and below concrete runways and taxiways
- locating post tensioning cables, in concrete garages, bridges and buildings
- locating voids and delaminations caused by corrosion or poor mixing of concrete roofs
- locating cables, conduits and reinforcing steel in concrete floors to assist in equipment placement
- locating underground storage tanks below concrete and asphalt pavements
- locating sewer, water, gasoline, jet fuel, natural gas, glycol, steam and chemical buried pipelines and leaks in those lines.

GPR has also been used in airport QC/QA surveys (Scullion & Saarenketo 2002). Because the depth of interest under airfield pavements can vary up to 3 meters, use of two antenna systems, where one is high and the other a low frequency antenna, is recommended (see Malvar & Cline 2002).

A very good new tool for airfield surveys is the multichannel 3d GPR technique which enables quick and economical coverage of the wide areas of runways and taxiways. Figure 47 presents an example of a runway pavement condition test survey done in Finland,

where time slices from three asphalt layers show different types of defects. The time slice from the depth of 130 mm clearly shows a problem zone in the third asphalt layer which can, in the long term, cause reflection cracking problems even in the pavement surface. The lowest maps also clearly show the location of a cable in the pavement.



**Fig. 47.** A 3d radar time slice from three asphalt layers of an airport runway in Finland. The first time slice calculated from a depth of 40 & 50 mm from the new asphalt overlay presents segregation in three places. Transverse cracks can be seen in the second time slice from 70 & 80 mm. The third time slice from 120 & 130 mm presents areas of cracking with moisture problems highlighted with the circles. A cable installed in the asphalt can also be seen in the lowest time slice.



## 12 Conclusions

The history of Ground Penetrating Radar in traffic infrastructure surveys is slightly longer than two decades and over this period the technique has grown from an “eccentric” geophysical technique to a more and more routine survey tool when detailed information about roads, streets, railways, runways or bridge structures or subgrade soils and their properties is needed. According to Anderson and Ismael (2002) among the geophysical engineering tools that provide information about the physical properties of a site which in turn can be related to highway problems GPR has the greatest number of applications. In traffic infrastructure surveys the major advantages of GPR techniques are continuous profile, speed and accuracy. According to Hall *et al.* (2002) it continues to be the only technology that can provide meaningful subsurface information at close to highway speed. Its disadvantages include the complexity of the GPR techniques, GPR data and, as such, more education and good software products are needed in order to make the GPR signals meaningful to engineers. Specifications and standards for the GPR equipment, data collection, processing and interpretation as well as output formats are also needed to ensure the high quality of the surveys results.

This work has tried to give an overview of the research and development work done by the author together with his colleagues and other researchers in this field but it also reviews basic theory and applications as well provides recommendations and check lists to ensure good results. The results and applications presented demonstrate the great potential that GPR technology can today provide to engineers and other specialists managing traffic infrastructure assets.

The future looks even more promising. The GPR technology so far has gone through two generations in the development of GPR systems; first generation was analogue GPR systems and the second generation started when the first digital systems came to the market in mid 1980's. Currently the third generation 3D GPR systems are entering the market with multiple antennas, faster processors and larger data storage capabilities. This opens a whole new range of applications in which structures and other objects and their properties can be analysed in a three dimensional format. However, GPR techniques alone cannot make traffic infrastructure management more economical if the management process does not find ways to make good use of the results. That is why GPR surveys need to be more closely integrated to entire rehabilitation process starting from data collection during the

monitoring phase and ending with the downloading of results to automated road construction or rehabilitation machinery.

This work shows that the benefit of Ground Penetrating Radar is not only the structural thickness information it can provide but also the knowledge and information of the electrical properties of road materials and subgrade soil can be very useful. Many countries only use GPR on main roads but this information can be especially meaningful in low volume roads, where the structures are inhomogeneous both in longitudinal and transverse directions, materials are often of poor quality and road owners have limited resources for their repair.

Water has a key role when discussing the lifetime of any traffic infrastructure. GPR is very sensitive to minor changes in water content in the structures and a fact, known for centuries, is that as long as road structures and subgrade soil do not have excess water the road works fine. This work provides evidence that in the very early phase of deterioration of the materials the imaginary part of the dielectric value starts to rise due to chemical or mechanical weathering processes. This imaginary part of the dielectric value of road materials is very difficult to measure but its increase can also be seen as increased dielectric dispersion of the material. This is especially the case below frequencies of 400 MHz. In GPR data collected using lower frequency antennas this can be seen as broader pulses, which was the initial observation that launched the whole study (see Chapter 1), and can be analysed using a Fourier analysis.

In order to understand GPR data when diagnosing failures or designing rehabilitation measures, the basic principles of thermodynamics must also be understood. As Mitchell (1993) writes, fluids, electricity, chemicals and heat are always flowing through the soils but also through man made structures. This work shows that the suction process and suction properties of materials should be known when evaluating the strength and deformation properties of road materials during different seasons. On roads with unbound materials with high fines content, matric suction mainly explains why these materials have a high bearing capacity when they are dry but lose their strength when they become wet. Osmotic suction theory explains, among other things, why chlorides work well as dust binders on gravel road wearing course if the fines content is not high enough. Cryo suction is a force that makes water molecules flow from the surroundings to the frozen fringe under the ice lenses, which as a result grow and cause frost heave in the road or soil surface.

The results of the laboratory tests done in this survey have shown that the biggest problem with the base course aggregates in Finland and other cold climate areas, especially on low volume roads, is not their resilient deformation properties but the permanent deformation that develops in the base course during the spring thaw period. Increasing pore water pressure can reduce effective stresses between soil particles and lead to plastic deformation after only a few axle load cycles. However, globally these problems cannot be related exclusively to spring thaw problems, as the Percostation test results from Scotland as well as monitoring results from Texas demonstrate. Critical dielectric values ( $> 9$ ) in the base course and permanent deformation problems can be measured even after a single freeze-thaw cycle especially if it is followed by heavy rains. Further, in warmer climate areas permanent deformation problems can be detected in roads where the dielectric value in the base course is higher than 16, if the level of shear stress is high enough. The results from the laboratory tests and field observations from Percostation field test sites

suggest that in the future, at least on low volume roads, the pavement design should not be made only by using elastic models but viscoelastic or viscoplastic behaviour should also be taken into consideration.

The test results have demonstrated that the Tube Suction test, developed during the laboratory work for this thesis, works well in identifying problematic unbound aggregates and determining whether the aggregates need to be stabilized. The test can also be used to estimate the effectiveness of a treatment agent and the amount of the agent required. Tube Suction tests have also showed a clear difference in the material properties between crushed gravel and hard rock aggregates because of newly exposed mineral surfaces of hard rock aggregates are more susceptible to reactions with water.

An interesting observations was that colloids could not be found in any of those aggregates that have performed well and those same aggregates hardly had any dielectric dispersion. This leads to the idea that colloidal particles might have an important role in the failure mechanism of unbound road aggregates and further research should be made on this topic.

Dielectric losses and the frequencies at which they occur are dependent on the intermolecular bond types and strengths (Mitchell 1993) and this provides a great opportunity to measure the complex strength properties of aggregates and subgrade soils through measuring their dielectric properties. The results of several studies reviewed in this thesis have verified the initial assumption that there is a relationship between the mechanical properties and electrical properties of unbound road materials and subgrade soils. Dielectric properties are perhaps the best possible indicators of the forces in soil or aggregate-water-air systems. In the future, measuring/monitoring changes in dielectric properties, especially by measuring the imaginary part or dielectric dispersion could be used to detect early phase deterioration of bound structures, such as pavements and bridges, and this information can be used in planning preventative maintenance actions to prolong the lifetime of these structures. Because GPR techniques also provide the exact location of the problem areas this allows the focus to be on the problem spots and thus substantially reduce the life cycle costs of traffic infrastructure. In the future it will be one of the key tools used in sustainable asset management of roads, streets, bridges, railways and airports.

## References

- Adams G, Anderson N, Baker J, Shoemaker M & Hatheway A (1998) Ground-Penetrating Radar Study of Subsidence along U.S. Interstate 44, Springfield, Missouri. In: Proceedings of the Seventh International Conference on Ground Penetrating Radar. May 27–30, Lawrence, Kansas, USA, 619–623.
- Ahmed Z, Helali K, Jumikis AA & Khan RA (2003) Enhancing the Pavement Management Systems Database Through Incorporation of GPR and Core Data. *Transportation Research Records*, 20 p.
- Al-Nuaimy W, Eriksen A & Gasgoyne J (2004) Train-Mounted GPR for High-Speed Rail Trackbed Inspection. In: Slob, Yarovov & Rhebergen (eds) *Proceedings of the Tenth International Conference on Ground Penetrating Radar*, Vol II, 631–634.
- Alongi T, Clemena GG & Cady PD (1992) Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Volume 3, SHRP Report SHRP-S/FR-92-105, Washington D.C.
- Al-Qadi IL, Lahouar S & Loulizi A (2002) Ground Penetrating Radar Evaluation for Flexible Pavement Thickness Estimation. In: IL Al-Qadi & Trenton MC (eds) *Proceedings of the Pavement Evaluation Conference 2002*, October 21–25, Roanoke, VA, USA, 15 p.
- Al-Qadi IL, Clark TM, Lee DT, Lahouar S & Loulizi A (2003a) Combining Traditional and Non-Traditional NDT Techniques to Evaluate Virginia's Interstate 81. *Transportation Research Board Paper 03-4214*, 17 p.
- Al-Qadi I, Lahouar S & Loulizi A (2003b) Successful Application of GPR for Quality Assurance/Quality Control of New Pavements. *Transportation Research Board Paper 03-3512*, 21 p.
- Al-Qadi IL, Lahouar S & Loulizi A (2003c) GPR: From the State-Of-the-Art to the State-Of-the-Practice. *Proceedings of International Symposium on Non-Destructive Testing in Civil Engineering (NDT-CE)*, September 16–19, 2003 Berlin, Germany (CD-rom).
- Alzaabi AA (2000) Capacitor Probe Calibration and Optimization for NDE Application to Portland Cement Concrete. PhD Thesis, Virginia Polytechnic Institute and State University, 187 p.
- Anderson TM (1989) Frost Heave Properties of Soils. In: Hans Rathmayer (ed) *Frost in Geotechnical Engineering*, Vol. 1. International Symposium, Saariselkä, Finland, 13–15 March 1989, 105–125.
- Anderson N & Ismael A (2002) A Protocol for Selecting Appropriate Geophysical Surveying Tools Based on Engineering Objectives and Site Characterization. In: *Proceedings of the 2<sup>nd</sup> Annual Conference on the Application of Geophysical and NDT Methodologies and NDT Methodologies to Transportation Facilities and Infrastructure*. April 15–19, California, USA, FHWA-WCR-02-001, 16 p.
- Ansoult M, De Backer LW & Delercq M (1985) Statistical Relationship between Apparent Dielectric Constant and Water Content in Porous Media. *Soil Science Society America Journal*, Vol 49: 47–50.

- Azevedo SG, Mast JE, Nelson SD, Rosenbury ET, Jones HE, McEwan TE, Mullenhof DJ, Hugenberg RE, Stever RD, Warhus JP & Wieting MG (1996) HERMES, A High-Speed Radar Imaging System for Inspection of Bridge Decks. *Nondestructive Evaluation Techniques for Aging Infrastructure and Manufacturing*, SPIE Vol. 2946: 195–204.
- Bae SH, Kim HS & Yoon WS (1996) Cases Studies on the Application of Ground Penetrating Technology in Detection of Underground Utilities and Structure Safety Diagnosis. In: *Proceedings of the Sixth International Conference on Ground Penetrating Radar*. September 30–October 3, Sendai, Japan, 467–472.
- Ballard G (1992) Under the Skin. *World Highways/Routes du Monde*. Jan/Feb 1992, 37–39.
- Ballard G (1993) Non Destructive Assessment of Pavement Design & New Build Quality. In: J. Bungey (ed) *Proceedings of Conference on Non-Destructive Testing in Civil Engineering*, 14–16 April, Liverpool, U.K., 391–404.
- Beck A & Ronen A (1994) The Application of Ground Penetrating Radar in Israel: Selected Case Histories. *Proceeding of the Fifth International Conference on Ground Penetrating Radar*, June 12–16, Kitchener, Ontario, Canada. Vol 3 of 3, 1101–1106.
- Bell JR, Leonards GA & Dolch WA (1963) Determination of Moisture Content of Hardened Concrete by its Dielectric Properties. *AST Proceedings*, V.63: 996–1007.
- Benedetto A & Benedetto F (2002) GPR Experimental Evaluation of Subgrade Soil Characteristics for Rehabilitation of Roads. *Proceedings of the Ninth International Conference on Ground Penetrating Radar*, April 29–May 2, 2002, Santa Barbara, California. Editors S Koppenjan & H Lee. *Proc of SPIE*, Vol 4758: 708–714.
- Benedetto A (2004) Theoretical Approach to Electromagnetic Monitoring of Road Pavement – Applied Geophysics and Stochastic Model. *Proceedings of the Tenth International Conference on Ground Penetrating Radar*, Vol II, Slob, Yarovov & Rhebergen (eds), 623–626.
- Berg F (1984) Ikke Destrøktiv Måling af Lagstykker I Vejbefæstelser. *Vejdirektoratet, Statens Vejlaboratorium, Notat 157*. Denmark.
- Berggren EG, Smekal A & Silvast M (2006) Monitoring and Substructure Condition Assessment of Existing Railway Lines for Upgrading to Higher Axle Loads and Speeds. *Proceeding of 7th World Congress on Railway Research June 4–8, 2006, Montréal, Canada* (in print).
- Berntsen G & Saarenketo T (2005a) Drainage on Low Traffic Volume Roads. Task 2.1 Report of the Roadex II project, 124 p. ([www.roadex.org](http://www.roadex.org))
- Berntsen G & Saarenketo T (2005b) Typical Drainage Problems in Northern Europe and Effect of Improving Drainage. *Proceeding of the Seventh International Conference on Bearing Capacity of Roads, Railways and Airfields, Trondheim, Norway* (CR-rom) 10 p.
- Berthelot C, Scullion T, Gerbrandt R & Safronetz L (2001) Application of Ground Penetrating Radar for Cold In-Place Recycled Road Systems. *Journal of Transportation Engineering*. American Society of Civil Engineers, Vol. 127, No 4.
- Bishara SW & McReynolds RL (1995) Effect of Microwave Energy on the Properties of Asphalt, and its Use as an Aging Tool. *Transportation Research Board Paper 950178*. Washington D.C. 40 p.
- Brightwell S & Thomas M (2003) Geophysical Assessment of Railway Assets – a Practical View. In: *Proceedings of 6<sup>th</sup> International Conference on Railway Engineering*, April 30– May 1, London, U.K. 8 p.
- Campbell JE (1990) Dielectric Properties and Influence of Conductivity in Soils at One to Fifty Megahertz. *Soil Science Society of America Journal* 54: 332–341.
- Cantor T & Kneeter C (1978) Radar and Acoustic Emission Applied to Study of Bridge Deck, Suspension Cables and Masonry Tunnel. *Transportation Research Record 676*, Washington D.C, 37–42.
- Cantor TR & Kneeter CP (1982) Radars as Applied to Evaluation of Bridge Decks. *Transportation Research Record*, 853: 37–42.

- Cardimona S & Newton T (2002) Evaluation of GPR as a Tool for Determination of Granular Material Deposit Volumes. In: Proceedings of the 2<sup>nd</sup> Annual Conference on the Application of Geophysical and NDT Methodologies and NDT Methodologies to Transportation Facilities and Infrastructure. April 15–19, California, USA, FHWA-WCR-02-001, 10 p.
- Cardimona S, Willeford B, Webb D, Hickman S, Wenzlick J & Anderson N (2003) Automated Pavement Analysis in Missouri Using Ground Penetrating Radar. In: Proceedings of the 2<sup>nd</sup> Annual Conference on the Application of Geophysical and NDT Methodologies to Transportation Facilities and Infrastructure. April 15–19, California, USA, FHWA-WCR-02-001, 10 p.
- Carlsten P (1988) Peat, Geotechnical Properties and Up-to-Date Methods of Design and Construction. *Varia* 215. Statens geotekniska institut, Linköping, Sweden. 35 p.
- Carpenter SH & Lytton RL (1977) Thermal Pavement Cracking in West Texas. TTI Research Report 18-4F, Study 2-8-73-18. Texas A&M University, College Station, Texas, 232 p.
- Carpenter D, Jackson J & Jay A (2004) Enhancement of the GPR Method of Railway Trackbed Investigation by Installation of Radar Detectable Geosynthetics. *NDT and E International*, Vol. 37, Issue 2: 95–103.
- Carter CR, Chung T, Masliwec T & Manning DG (1992) Analysis of Radar Reflections from Asphalt Covered Bridge Deck Structures. In: J Pilon (ed) *Ground Penetrating Radar*, Geological Survey of Canada Paper 90-4: 33–40.
- Casas A, Lazaro R & Vilas M (1996) Detecting Karstic Cavities with Ground Penetrating Radar at Different Geological Environment in Spain. In: Proceedings of the Sixth International Conference on Ground Penetrating Radar. September 30–October 3, Sendai, Japan, 455–460.
- Clark MR, Gillespie R, Kemp T, McCann DM & Forde MC (2001) Electromagnetic Properties of Railway Ballast. *NDT&E International* 34 (2001) pp. 305–311.
- Clark MR, Gordon MO, Giannopoulos A & Forde MC (2003a) Experimental and Computer Modelling of GPR to Characterize Trackbed Ballast. In: proceedings of World Congress on Railway Research, Scotland, 16 p.
- Clark MR, Parsons P, Hull T & Forde MC (2003b) Case Study of Radar Laboratory Work on the Masonry Arch Bridge. In: Proceedings of 10<sup>th</sup> International Conference on Structural Faults and Repair, Engineering Technics Press, London 2003, 12 p.
- Clark MR, McCann DM & Forde MC (2003c) GPR as a Tool for the Characterization of Ballast. In: Proceedings of 6<sup>th</sup> International Conference on Railway Engineering, April 30–May 1, London, U.K. 9 p.
- Clark MR & Crabb G (2003) Detection of Water Movement Below a Concrete Road Using Ground Penetrating Radar. In: Proceedings of 10<sup>th</sup> International Conference on Structural Faults and Repair 2003, Engineering Tech Press, London 2003 (CD-rom).
- Clark M, Gordon M & Forde MC (2004) Issues over High-Speed Non-Invasive Monitoring of Railway Trackbed. *NDT&E International* 37, 131–139.
- Clemena G (1983) Nondestructive Inspection of Overlaid Bridge Decks with Ground Penetrating Radar. *Transportation Research Record*, 899: 31–37.
- Clemena G, Sprinkel M & Long RJ Jr (1987) Use of Ground Penetrating Radar for Detecting Voids Under a Jointed Concrete Pavement. *Transportation Research Record*, 1109: 1–10.
- Conyers LB & Goodman D (1997) *Ground-Penetrating Radar, An Introduction for Archaeologists*. Altamara Press, 232 p.
- Daniels DJ (1996) *Surface Penetrating Radar*. Institution of Electrical Engineers, U.K. 300 p.
- Davidson NC & Chase SB (1998) Radar Systems for Topographic Bridge Deck Inspection. Proceeding of the Seventh International Conference on Ground Penetrating Radar, May 27–30, 1998, Lawrence Kansas. Volume 2: 747–751.
- Davis JL & Annan AP (1989) Ground-Penetrating Radar for High Resolution Mapping of Soil and Rock Stratigraphy. *Geophysical Prospecting* 37: 531–551.

- Davis JL & Annan AP (1992) Applications of Ground Penetrating Radar to Mining, Ground Water and Geotechnical Projects: Selected Case Histories. In: J Pilon (ed) *Ground Penetrating Radar*, Geological Survey of Canada, Paper 90-4: 49–55.
- Davis JL, Rossiter JR, Mesher DE & Dawley CB (1994) Quantitative Measurement of Pavement Structures Using Radar. *Proceedings of 5<sup>th</sup> International Conference on Ground Penetrating Radar*, Kitchener, Ontario, Canada, 319–334.
- Dawson A & Kolisoja P (2005) Permanent Deformation. Task 2.1 Report of the Roadex II project, 48 p. ([www.roadex.org](http://www.roadex.org))
- Dawson A, Kolisoja P & Vuorimies N (2005) Permanent Deformation Behaviour of Low Volume Roads in the Northern Periphery. *Proceeding the of the Seventh International Conference on Bearing Capacity of Roads, Railways and Airfields*, Trondheim, Norway (CR-rom) 9 p.
- Dérobot X, Fauchard C, Cote Ph, Le Brusca E, Guillanton E, Dauvignac JY & Pichot Ch (2001) Stepped-Frequency Radar Applied on Thin Road Layers. *Journal of Applied Geophysics*, Vol. 47, Issues 3-4: 317–325.
- Dérobot X, Simonin JM & Laguerre L (2002a) Step-Frequency Radar Applied on Thin Pavement. In: *Proceedings of the Ninth International Conference on Asphalt Pavements*, August 17–22, Copenhagen, Denmark, 16 p.
- Dérobot X, Abraham O & Aubagnac C (2002b) Review of NDT Methods on a Weak Post-Tensioned Beam Before Autopsy. *Proceedings of the Ninth International Conference on Ground Penetrating Radar*, April 29–May 2, 2002, Santa Barbara, California. Editors S. Koppenjan and H. Lee. *Proc. of SPIE*, Vol. 4758: 365–370.
- Dobson MC, Ulaby FT, Hallikainen MT & El-Rayes MA (1985) Microwave Dielectric Behaviour of Wet Soil – Part II: Dielectric Mixing Models. *IEE Transaction on Geoscience and Remote Sensing GE-s3* (1): 35–46.
- Doolittle JA & Rebertus RA (1988) Ground-Penetrating Radar as Means of Quality Control for Soil Surveys. *Transportation Research Record* 1192.
- Dore G, Konrad J-M & Marius R (1997) The Role of Deicing Salt in Pavement Deterioration by Frost Action. *TRB Paper* 970598.
- Edris EV & Lytton RL (1976) Dynamic Properties of Subgrade Soils Including Environmental Effects. *Research Report* 164–3. Texas Transportation Institute, Texas A&M University, College Station Texas.
- Ehrola E (1996) *Liikenneväylien Rakennesuunnittelun Perusteet*. Tampere, Rakennustieto Oy. 365 p (in Finnish).
- Eide E (2002) Ultra-wideband 3d-Imaging Ground Penetrating Radar Using Synthetic Waveforms. In: *Proceedings of 32<sup>nd</sup> European Microwave Conference*, September 6–26, Milan, Italy, 4 p.
- Ékes C & Friele, P (2004) Ground Penetrating Radar and its Use in Forest Road Stability Analysis. *Proceedings of the Tenth International Conference on Ground Penetrating Radar*, Vol II, Slob, Yarovov & Rhebergen (eds), 639–642.
- Emilsson J, Englund P & Friborg J (2002) A Simple Method for Estimation of Water Content of Roadbeds Using Multi-Offset GPR. *Proceedings of the Ninth International Conference on Ground Penetrating Radar*, April 29–May 2, 2002, Santa Barbara, California. Eds S Koppenjan & H Lee. *Proc. of SPIE*, Vol 4758: 422–426.
- Fauchard C, Xerobert X, Cariou J & Cote Ph (2003) GPR Performance for Thickness Calibration on Road Test Sites. *NDT and E International*, Vol 36, Vol 36, Issue 2: 67–75.
- Fernando EG, Maser KR & Dietrich B (1994) Implementation of Ground Penetrating Radar of Network Level Pavement Evaluation in Florida. *Proceedings of the Fifth International Conference on Ground Penetrating Radar*, June 12–16, Kitchener, Ontario, Canada, Vol 1 of 3: 351–365.

- Fish M (2002) Enhancing Geotechnical Information with Ground Penetrating Radar. In: Proceedings of the 2<sup>nd</sup> Annual Conference on the Application of Geophysical and NDT Methodologies and NDT Methodologies to Transportation Facilities and Infrastructure. April 15–19, California, USA, FHWA-WCR-02-001, 15 p.
- Forde MC, McCann DM, Clark MR, Broughton KJ, Fenning PJ & Brown A (1999) Radar Measurement of Bridge Scour. *NDT&E International* 32: 481–492.
- Forest R & Utsi V (2004) Non Destructive Crack Depth Measurements with Ground Penetrating Radar. Proceedings of the Tenth International Conference on Ground Penetrating Radar, Vol II, Slob, Yarovov & Rhebergen (eds), 799–802.
- Fredlund DG & Rahardjo H (1993) *Soil Mechanics for Unsaturated Soils*, John Wiley & Sons, New York. 517 p.
- Fredlund DG, Gan JK-M & Gallen P (1995). Suction Measurements on Compacted Till Specimens and Indirect Filter Calibration Technique. Transportation Research Board Paper 950891.
- Galagher GP, Leiper Q, Williamson R, Clark MR & Forde MC (1998) Application of Ground Penetrating Radar in the Railway Industry. In: Proceedings of the 1<sup>st</sup> International Conference Railway Engineering -98. Technical Press, London 1999: 33–36.
- Gardei A, Mittag K, Wiggensauser H, Ripke B & Jovanovic M (2003) Inspection of Concrete-Embedded Tracks Process Development for the Quality Assurance of Concrete-Embedded Tracks Using Non-Destructive Testing Methods. Proceedings of International Symposium on Non-Destructive Testing in Civil Engineering (NDT-CE), September 16–19, 2003 Berlin, Germany (CD-rom).
- Geraads S & Omnes G (2002) Imaging Karstic Structures with GPR along a Motorway Under Construction. Proceedings of the Ninth International Conference on Ground Penetrating Radar, April 29–May 2, 2002, Santa Barbara, California. S Koppenjan & H Lee (Eds) Proc. of SPIE, Vol. 4758: 493–495.
- Glover JM (1992) Void Detection Using Standing Wave Analysis. In: *Ground Penetrating Radar*, ed. J.Pilon Geological Survey of Canada, Paper 90-4: 55–73.
- Giannopoulos A, MacIntyre P, Rodgers S & Forde MC (2002) GPR Detection of Voids in Post Tensioned Concrete Bridge Beams. Proceedings of the Ninth International Conference on Ground Penetrating Radar, April 29–May 2, 2002, Santa Barbara, California. S Koppenjan & H Lee (Eds) Proc. of SPIE, Vol 4758: 376–381.
- Göbel C, Hellman R & Petzold H (1994) Georadar – Model and In-Situ Investigations for Inspection of Railway Tracks. Proceeding of the Fifth International Conference on Ground Penetrating Radar, June 12–16, Kitchener, Ontario, Canada. Vol. 3 of 3, 1101–1106.
- Golgowski G (2003) Arbeitsanleitung für den Einsatz des Georadars zur Gewinnung von Bestandsdaten des Fahrbahnaufbaues. Berichte der Bundesanstalt für Straßenwesen (BAST), Straßenbau, Heft S 31. 22 p.
- Goodman D, Nishimura Y & Tobita K (1994) GPRSIM Forward Modelling Software and Time Slices in Ground Penetrating Radar Simulations. Proceedings of the Fifth International Conference on Ground Penetrating Radar, Kitchener, Ontario, Publ. Waterloo Centre of Groundwater Research, Waterloo, 31–43.
- Grainger PS & Armitage RJ (2002) Trackbed Investigation and Interpretation in Practice. In: Proceeding of the Railway Technology Conference, NEC, Birmingham, 26–28 November (CD-rom).
- Ground Penetrating Radar (1992) *Geophysical Survey Methods*, The Finnish Geotechnical Society and The Finnish Building Centre Ltd. Finland 64 p.
- Guthrie WS, Sebesta SD & Scullion T (2002) Selecting Optimum Cement Contents for Stabilizing Aggregate Base Materials, Technical Report 7-4920-2. Texas Transportation Institute, College Station, TX. February 2002.



- Guthrie WS & Scullion T (2003) Interlaboratory Study of the Tube Suction Test, Research Report 0-4114-2. Texas Transportation Institute, College Station, TX.
- Haeni FP, Placzek G & Trent RE (1992) Use of Ground Penetrating Radar to Investigate Refilled Scour Holes at Bridge Foundations. Geological Survey of Finland, Special Paper 16, 285–292.
- Halabe UB, Sotoodehnia A, Maser KR & Kausel EA (1993) Modelling the Electromagnetic Properties of Concrete. *ACI Materials Journal*, Vol. 90, No. 6, 552–563.
- Hall KT, Correa CE, Carpenter SH & Elliot RP (2002) Guidelines for Evaluation of Highway Pavements for Rehabilitation. In: IL Al-Qadi & TM Clark (eds) *Proceedings of the Pavement Evaluation 2002 Conference*, October 21–25, Roanoke, VA, USA, 23 p.
- Hänninen P (1997) Dielectric Coefficient Surveying for Overburden Classification. Geological Survey of Finland, Bulletin 396. Helsinki. 72 p.
- Hänninen P & Sutinen R (1994) Dielectric Prediction of Landslide Susceptibility: A Model Applied to Recent Sediment Flow Deposits. *Proceedings of VII IAEG*, Lisboa, 1: 137–144.
- Heikkilä R, Jaakkola M, Saarenketo T & Malaguti F (2004) Modelling Information Flows for Automated Road Rehabilitation Process. *ISARC'2004*, 21st International Symposium on Automation and Robotics in Construction, 21–25 September 2004. Jeju, Korea, 85–93.
- Hoekstra P & Delaney A (1974) Dielectric Properties of Soils at UHF and Microwave Frequencies. *Journal of Geophysical Research*, V.79, No.11: 1699–1708.
- Hobbs CP, Temple JAG & Hillier MJ (1993) Radar Inspection of Civil Engineering Structures. In: J. Bungey (ed) *Proceedings of Conference on Non-Destructive Testing in Civil Engineering*, 14–16 April, Liverpool, U.K., 79–96.
- Hopman V & Beuving E (2002) Repeatability, Reproducibility and Accuracy of GPR Measurements. In: *Proceedings of the 6<sup>th</sup> International Conference on the Bearing Capacity of Roads, Railways and Airfields*, Lisbon, Portugal, 24–26 June, 2002: 637–645.
- Hudec PP & Anchampong F (1994) Improving Aggregate Quality by Chemical Treatment. In: GW Luttig, *Proceeding of the 2<sup>nd</sup> International Aggregates Symposium*, Erlangen, Germany, October 22–27, 1990, ed, 135–146.
- Hugenschmidt J, Partl MM & de Witte H (1996) GPR Inspection of a Mountain Motorway – a Case Study. *Proceedings of the Sixth International Conference on Ground Penetrating Radar*. September 30–October 3, Sendai, Japan, 365–370.
- Hugenschmidt J (1998) Railway Track Inspection Using GPR – Some Examples from Switzerland. In: *Proceeding of Seventh International Conference on Ground Penetrating Radar*, May 27–30, Lawrence, Kansas, USA, Vol 1 of 2: 197–202.
- Hugenschmidt J (2000) Railway Track Inspection Using GPR. *Journal of Applied Geophysics* 43, 147–155.
- Hugenschmidt J (2003) Non-Destructive-Testing of Traffic-Infrastructure Using GPR. *Proceedings of International Symposium on Non-Destructive Testing in Civil Engineering (NDT-CE)*, September 16–19, 2003 Berlin, Germany (CD-rom).
- Hugenschmidt J (2004) Accuracy and Reliability of Radar Results on Bridge Decks. In: Slob, Yarovov & Rhebergen (eds) *Proceedings of the Tenth International Conference on Ground Penetrating Radar*, Vol I, 371–374.
- Huston D, Pelczarski N, Esser B & Maser K (2000) Damage Detection in Roadways with Ground Penetrating Radar. In: David A Noon, Glen F Stickley & Dennis Longstaff (Eds) *Proceeding of Eight International Conference on Ground Penetrating Radar*, May 23–26, 2000, Gold Coast Australia. SPIE Vol. 4084: 91–94.
- Huston D, Fuhr P, Maser K & Weedon W (2002) Nondestructive Testing of Reinforced Concrete Bridges Using Radar Imaging Techniques. *The New England Transportation Consortium Report* 94–2. 182 p.

- Inchan P, Joengwoo L & Woncheol C (2004) Assessment of Bridge Scour and Riverbed Variation by a Ground Penetrating Radar. In: Slob, Yarovov & Rhebergen (eds) Proceedings of the Tenth International Conference on Ground Penetrating Radar, Vol. I, 411–414.
- Irwin L, Yang WS & Substad RN (1989) Deflection Reading Accuracy and Layer Thickness Accuracy in Backcalculated Pavement Layer Moduli. ASTM, STP 1026. Bush AJ & Baladi GY (eds), Philadelphia, 224–229.
- Johansson HG (1987) Användning av Georadar I Olika Vägverksprojekt. Vägverket, Serviceavdelning Väg och Brokonstruktion, Sektionen för geoteknik, Publ 1987, 59. Sweden.
- Johansson S, Saarenketo T & Persson L (2005) Network and Project Level Bearing Capacity Surveys and Analysis Using Modern Techniques. Proceedings of the Seventh International Conference on Bearing Capacity of Roads, Railways and Airfields, Trondheim, Norway (CR-rom) 10 p.
- Jooste F, Kekwick SV & Muthen M (1998) Effect of Allowable Thickness Variation on Backcalculated Moduli. Transportation Research Record 1639, Paper No. 98-1134: 43–50.
- Jung G, Jung J & Cho S-M (2004) Evaluation of Road Settlements on Soft Ground from GPR Investigations. Proceedings of the Tenth International Conference on Ground Penetrating Radar, Vol II, Slob, Yarovov & Rhebergen (eds), 651–654.
- Kestler MA (2003) Techniques for Extending the Life of Low Volume Roads in Seasonal Frost Areas. Transportation Research Record 1819, Volume 2, 275–284.
- Knight RJ & Knoll M (1990) The Effect of Saturation History on Electrical Properties of the Unsaturated Zone, in Third International Conference on Ground Penetrating Radar, Abstracts of the Technical Meeting, Lakewood, Colorado, USA, 14–18 May 1990, JE Lucius, GR Olhoeft & SK Duke (eds), U.S.G.S. Open-File Report, 90–414.
- Knight R (1991) Hysteresis in the Electrical Resistivity of Partially Saturated Sandstones. Geophysics, vol. 56, No. 12: 2139–2147.
- Knoll MD & Knight R (1994) Relationship Between Dielectric and Hydrogeologic Properties of Sand-Clay Mixtures. In: Proceedings of the Fifth International Conference on Ground Penetrating Radar, June 12–16, Kitchener, Ontario, Canada, Vol 1 of 3, 45–61.
- Kolisoja P (1997) Resilient Deformation Characteristic of Granular Materials. PhD Thesis, Tampere University of Technology, Publications 223, 188 p.
- Kolisoja P, Saarenketo T, Peltoniemi H & Vuorimies N (2002) Laboratory Testing of Suction and Deformation Properties of Base Course Aggregates. Transportation Research Record 1787. Paper No. 02-3432. p. 83–89.
- Kolisoja P & Vuorimies N (2003) Susceptibility of Unbound Base Course Materials to Seasonal Variations. In: Proceedings of International Symposium on Testing, Evaluation and Design of Pavement Constructions. April 3–4, Dresden, Germany. 11 p. (CD-rom)
- Kolisoja P & Vuorimies N (2004) Impact of Moisture Condition and Fines Content on the Performance of Finnish Unbound Base Course Aggregates. Proceedings of 10<sup>th</sup> Nordic Aggregate Research Conference. Tampere. 4 p.
- Kolisoja P, Vuorimies N, Saarenketo T (2004) Assessment of the Effect of Seasonal Variations on the Unbound Materials of Low Volume Roads. Proceedings of UNBAR6, Nottingham 07/04, U.K. (CD-rom).
- Kolisoja P & Vuorimies N (2005) Material Treatment. Report on Task 2.2, Roadex II project. 34 p. ([www.roadex.org](http://www.roadex.org)).
- Konrad JM & Morgenstern NR (1980) A Mechanistic Theory of Ice Formation in Fine Grained Soils. Can Geotech Journal 17: 473–486.
- Kovacs A & Morey RM (1983) Detection of Cavities Under Concrete Pavement. US Army Corps of Engineers, Cold Region Research and Engineering Laboratory, Hanover, New Hampshire, CRREL Report No 83–18.
- Kujala K (1991) Factors Affecting Frost Susceptibility and Heaving Pressure in Soils. Acta Univ Ouluensis, C58, 99 p.

- Ladanyi B & Shen M (1989) Mechanics of Freezing and Thawing in Soils. In: Frost in Geotechnical Engineering, Vol. 1. International Symposium, Saariselkä, Finland, 13–15 March 1989, ed. Hans Rathmayer, 73–103.
- Lau C-L, Scullion T & Chan P (1992) Using Ground Penetrating Radar Technology for Pavement Evaluations in Texas, USA. Geological Survey of Finland, Special Paper 16: 277–283.
- Lázaro-Mancilla O & Gómez Treviño E (1996) Synthetic Radargrams from Electrical Conductivity and Magnetic Permeability Variations. *Journal of Applied Geophysics*, Vol. 34: 283–290.
- Lenngren CA, Bergström J & Ersson B (2000) Using Ground Penetrating Radar for Assessing Highway Pavement Thickness. *Proc. SPIE Vol. 4129*: 474–483.
- Lewis JS, Owen WP & Narwold C (2002) GPR as a Tool for Detecting Problems in Highway-Related Construction and Maintenance. In: *Proceedings of the 2<sup>nd</sup> Annual Conference on the Application of Geophysical and NDT Methodologies and NDT Methodologies to Transportation Facilities and Infrastructure*. April 15–19, California, USA, FHWA-WCR-02-001, 11 p.
- Liu L & Guo T (2002) Dielectric Property of Asphalt Pavement Specimens in Dry, Water-Saturated and Frozen Conditions. *Proceedings of the Ninth International Conference on Ground Penetrating Radar*, April 29–May 2, 2002, Santa Barbara, California. S Koppenjan & H Lee (Eds) *Proc. of SPIE*, Vol. 4758: 410–415.
- Liu L (2003) Ground Penetrating Radar: What Can It Tell about the Moisture Content of the Hot Mix Asphalt Pavement? *Transportation Research Board Paper*, 9 p.
- Lytton RL (1994) Prediction of Movement in Expansive Clays. *Geotechnical Special Publications No. 40*. “Vertical and Horizontal Deformations of Foundations and Embankments.” Ed A. Young, American Society of Civil Engineers.
- Maierhofer K & Kind Th (2002) Application of Impulse Radar for Non-Destructive Investigation of Concrete Structures. *Proceedings of the Ninth International Conference on Ground Penetrating Radar*, April 29–May 2, 2002, Santa Barbara, California. S Koppenjan & H Lee (Eds) *Proc. Of SPIE*, Vol. 4758: 382–387.
- Maijala P (1994) Ground Penetrating Radar and Related Data Processing Techniques. Report, University of Oulu, Department of Geophysics, 129 p.
- Maijala P, Saarenketo T & Valtanen P (1994) Correlation of Some Parameters in GPR Measurement Data with Quality Properties of Pavements and Concrete Bridge Decks. *Proceedings of the Fifth International Conference on Ground Penetrating Radar*, June 12–16, Kitchener, Ontario, Canada, Vol. 2 of 3, 393–406.
- Malvar LJ & Cline GD (2002) Void Detection Under Airfield Pavements. In: IL Al-Qadi & TM Clark (eds) *Proceedings of the Pavement Evaluation 2002 Conference*, October 21–25, Roanoke, VA, USA, 15 p.
- Manacorda G, Morandi D, Sparri A & Staccone G, (2002) A Customized GPR System for Railroad Tracks Verification. *Proceedings of the Ninth International Conference on Ground Penetrating Radar*, April 29– May 2, 2002, Santa Barbara, California. S Koppenjan & H Lee (Eds) *Proc. of SPIE*, Vol 4758: 719–723.
- Manning DG & Holt FB (1983) Detecting Deterioration in Asphalt Covered Bridge Decks. *Transportation Research Record*, 899: 10–19.
- Manning DG & Holt FB (1986) The Development of Deck Assessment by Radar and Thermography. *Transportation Research Record*, 1083: 13–20.
- Marjeta J (1993) Dielektrisyysmittarin Käyttö Murskeiden Kosteuden Mittaukseen ja Murskeiden Laadun Arviointiin. *Insinööriyö*, Rovaniemi Institute of Technology, Department of Construction Technology. English Abstrac: The Use of Dielectric Permittivity Meter in Moisture and Qualitative Determination of Crushed Gravel, 55 p.
- Maser KR & Roddis WMK (1990) Principles of Thermography and Radar for Bridge Deck Assessment. *Proceedings of the American Society of Civil Engineers, Journal of Transportation Engineering*, Vol. 116, No.5: 583–601.

- Maser KR & Scullion T (1991) Automated Detection of Pavement Layer Thicknesses and Subsurface Moisture Using Ground Penetrating Radar. Transportation Research Board Paper 1991.
- Maser KR (1994) Highway Speed Radar for Pavement Thickness Evaluation. Proceedings of the Fifth International Conference on Ground Penetrating Radar, June 12–16, Kitchener, Ontario, Canada, Vol 2 of 3, 423–432.
- Maser K (2002a) Non-Destructive Measurement of Layer Thickness of Newly Constructed Asphalt Pavement. In: Imad L Al-Qadi & Trenton M Clark (eds) Proceedings of the Pavement Evaluation 2002 Conference, October 21–25, Roanoke, VA, USA, 24 p.
- Maser K (2002b) Use of Ground Penetrating Radar Data for Rehabilitation of Composite Pavements on High-Volume Roads. Transportation Research Record (1808) pp. 122–126.
- Maser KR, Holland TJ, Roberts R & Popovics J (2003) Technology for Quality Assurance for New Pavement Thickness. Proceedings of International Symposium on Non-Destructive Testing in Civil Engineering (NDT-CE), September 16–19, 2003 Berlin, Germany.
- Mayhan R & Bailey R (1975) An Indirect Measurement of the Effect Dielectric Constant Tangent of Typical Concrete Roadways. IEEE Transaction on Antennas and Propagation, Vol 23, Issue 4: 565–569.
- Mesher DE, Dawley CB, Davies JL & Rossiter JR (1995) Evaluation of New Ground Penetrating Radar Technology to Quantify Pavement Structures. Transportation Research Record 1505: 17–26.
- Mesher DE, Dawley CB & Pulles PC (1996) A Comprehensive Radar Hardware, Interpretation Software and Survey Methodology Paradigm for Bridges Deck Assessment. Proceedings of the Sixth International Conference on Ground Penetrating Radar, September 30–October 3, Sendai, Japan: 353–358.
- Millard SG, Bungey JH & Shaw MR (1993) The Assessment of Concrete Quality Using Pulsed Radar. In: Proceeding of the Non-Destructive Testing in Civil Engineering, April 14–16 1993. The University of Liverpool, Vol 1 of 2: 161–186.
- Mitchell JK (1993) Fundamentals of Soil Behaviour. Second Edition. John Wiley & Sons, New York. 437 p.
- Mohajeri JH (2002) Loading Zoning Study, Elkhart County, Indiana. In: Proceedings of the Pavement Evaluation 2002 Conference, October 21–25, Roanoke, VA, USA, Imad L Al-Qadi & Trenton M Clark (Eds), 11 p.
- More JR & Erhard JD (1978) Radar Detection of Voids Under Concrete Highways. Georgia Institute of Technology, Atlanta.
- Morey RM & Kovacs A (1977) Detection of Moisture in Construction Materials. CRREL (Cold Region Research and Engineering Laboratory). Report 77–25. Hannover, New Hampshire, 9 p.
- Morey R (1998) Ground Penetrating Radar for Evaluating Subsurface Conditions for Transportation Facilities. Synthesis of Highway Practice 255, National Cooperative Highway Research Program, Transportation Research Board. National Academy Press.
- Muller W (2003) Timber Girder Inspection Using Ground Penetrating Radar. Proceedings of International Symposium on Non-Destructive Testing in Civil Engineering (NDT-CE), September 16–19, 2003 Berlin, Germany (CD-rom).
- Nourelidin A.S, Zhu K, Li S & Harris D (2003) Network Pavement Evaluation Using Falling Weight Deflectometer and Ground Penetrating Radar. Transportation Research Board Paper, 25 p.
- Nurmikolu A (2005) Degradation and Frost Susceptibility of Crushed Rock Aggregates Used in Structural Layers of Railway Track. PhD thesis. Tampere University of Technology, Publication 567. 235 p.
- O'Flaherty CA (1974) Highways, Volume 2. Highway Engineering. Second Edition. Edward Arnold, London. 457 p.

- Olhoeft GR & Capron DE (1994) Petrophysical Causes of Electromagnetic Dispersion. In: Proceedings of the Fifth International Conference on Ground Penetrating Radar, Kitchener, Ontario, publ. Waterloo Centre of Groundwater Research, Waterloo, vol 1 of 3: 145–152.
- Olhoeft GR & Selig ET (2002) Ground Penetrating Radar Evaluation of Railway Track Substructure Conditions. Proceedings of the Ninth International Conference on Ground Penetrating Radar, April 29– May 2, 2002, Santa Barbara, California. S Koppenjan & H Lee (Eds) Proc. SPIE, Vol 4758: 48–53.
- Olhoeft GR, Smith III S, Hyslip JP & Selig Jr, ET (2004) GPR in Railroad Investigations. In: Proceedings of 10<sup>th</sup> International Conference on Ground Penetrating Radar, 21–24 June 2004, Delft, The Netherlands, 635–638.
- Pälli A, Aho S & Pesonen E (2005) Ground Penetrating Radar as a Quality Assurance Method for Paved and Gravel Roads in Finland, Proceedings of the 3rd International Workshop on Advanced Ground Penetrating Radar, S Lambot & AG Gorriti (eds), May 2–3, 2005, Delft, The Netherlands
- Parry N & Davis JL (1992) GPR Systems for Roads and Bridges. Geological Survey of Finland, Special Paper 16: 247–257.
- Petersen JC, Plancher H, Ensley EK, Venable RL & Migake G (1982) Chemistry of Asphalt-Aggregate Interaction: Relationship with Pavement Moisture-Damage Prediction Test. Transportation Research Record 843. Washington, 95–104.
- Pylkkänen K & Kuula-Väisänen P (1990) Bitumin ja Kiviaineksen Välinen Tartunta Asfalttipäällysteessä, Osa I. Asfalttipäällysteiden Tutkimusohjelma ASTO 1987–1992, TR2 / 3. Valtion Teknillinen Tutkimuskeskus, Tie- ja liikennelaboratorio, no 776. English Abstract, Espoo. 106 p.
- Raitanen T (2005) Sitomattomien väylärakennemateriaalien uudet käsittelytekniikat. Diplomityö, Tampereen Teknillinen Yliopisto, Pohja- ja maarakenteet, Tutkimusraportti 57, 130 p + 3 app. (in Finnish)
- Ravaska O, Saarenketo T & Kerkelä S (1991) Ground Penetrating Radar for Quality Control in Road Structural Courses, Finland. Extended Abstract Volume of ISCORD '91, Edmonton Alberta, 84–85.
- Rhazi J, Dous O, Ballivy G, Laurens S & Balyssac J-P (2003) Non Destructive Health Evaluation of Concrete Bridge Decks by GPR and Half Cell Potential Techniques. Proceedings of International Symposium on Non-Destructive Testing in Civil Engineering (NDT-CE), September 16–19, 2003 Berlin, Germany (CD-rom).
- Rmeili E & Scullion T (1997) Detecting Stripping in Asphalt Concrete Layers Using Ground Penetrating Radar. Transportation Research Board Paper No 97-0508. 25 p.
- Roadex (2001) Roadex Project 1998–2001, Creating Effective Technical Exchange & Co-Operation Between Road Districts in the NP Region. CD-rom. ([www.roadex.org](http://www.roadex.org)).
- Roberts FL, Kandahl PS, Brown ER, Lee D-A & Kennedy TW (1991) Hot Mix Asphalt Materials, Mixture Design and Construction. NAPA Education Foundation, Lanham, 490 p.
- Roberts R & Petroy D (1996) Semi-Automatic Processing of GPR Data Collected Over Pavement. Proceedings of the Sixth International Conference on Ground Penetrating Radar, September 30–October 3, Sendai, Japan, 347–352.
- Roimela P (1998) Ground Penetrating Radar Surveys in Pavement Quality Control 1996–1997. Tielaitoksen selvityksiä 4/1998. Rovaniemi, Finland (English abstract), 55 p.
- Roimela P (1999) The Use of Pavement Radar in Quality Control of Bituminous Pavements. Tielaitos, Konsultointi. Tielaitoksen selvityksiä 6/1999. Rovaniemi, Finland (English abstrac), 33 p.
- Roimela P, Salmenkaita S, Majjala P & Saarenketo T (2000) Road analysis – a Tool for Cost Effective Rehabilitation Measures for Finnish Roads. GPR '2000, Proceeding of the Eighth International Conference on Ground Penetrating Radar. Gold Coast, Australia 23–36 May, 2000: 107–112.

- Romero FA & Roberts RL (2002) Mapping Concrete Deterioration: High Speed Ground Penetrating Radar Surveys on Bridge Decks Using New Analysis Method Based on Dual Polarization Deployment of Horn Antennae. Proceeding of International Bridge Conference, Pittsburgh, PA, USA, June 10–12, 2002. Paper IBC-02-12.
- Romero FA & Roberts RL (2004) Data Collection and Analysis Challenges – GPR Bridge Deck Deterioration Assessment of Two Unique Bridge Deck Systems. In: proceedings of SAGEEP 2004.
- Saarenketo T (1992) Ground Penetrating Radar Applications in Road Design and Construction in Finnish Lapland. Geological Survey of Finland, Special Paper 15: 161–167.
- Saarenketo T, Hietala K & Salmi T (1992) GPR Applications in Geotechnical Investigations of Peat for Road Survey Purposes. Geological Survey of Finland, Special Paper 16: 293–305.
- Saarenketo T & Söderqvist M-K (1993) GPR Applications for Bridge Deck Evaluations in Finland. Proceeding of the Non-Destructive Testing in Civil Engineering, April 14–16 1993. The University of Liverpool. Vol 1 of 2: 211–226.
- Saarenketo T & Majjala P (1994) Applications of Geophysical Methods to Sand, Gravel and Hard Rock Aggregate Prospecting in Northern Finland. In: Gerd W Luttig (ed) Aggregates – Raw Materials' Giant, Report on the 2<sup>nd</sup> International Aggregates Symposium, Erlangen, Germany October 22–27, 109–123.
- Saarenketo T & Scullion T (1994) Ground Penetrating Radar Applications on Roads and Highways. Research Report 1923-2F. Texas Transportation Institute, College Station, Texas. 36 p.
- Saarenketo T (1995a) Using Electrical Methods to Classify the Strength Properties of Texas and Finnish Base Course Aggregates. Center for Aggregates Research, 3<sup>rd</sup> Annual Symposium Proceedings, Austin, Texas, 19 p.
- Saarenketo T (1995b) The Use of Dielectric and Electrical Conductivity Measurement and Ground Penetrating Radar for Frost Susceptibility Evaluations of Subgrade Soils. Proceedings of the Application of Geophysics to Engineering and Environmental Problems. Comp. By R.S. Bell. Orlando, Florida, 73–85.
- Saarenketo T & Scullion T (1995) Using Electrical Properties to Classify the Strength Properties of Base Course Aggregates. Research Report 1341-2. Texas Transportation Institute, College Station, Texas. 71 p.
- Saarenketo T (1996) Electrical Properties of Water in Soils. Proceedings of the Sixth International Conference on Ground Penetrating Radar. September 30– October 3, Sendai, Japan, 129–134.
- 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, 477–482.
- Saarenketo T (1997) Using Ground Penetrating Radar and Dielectric Probe Measurements in Pavement Density Quality Control. Transportation Research Record 1997: 34–41.
- Saarenketo T (1998) Electrical Properties of Water in Clay and Silty Soils. Journal of Applied Geophysics 40 (1–3): 73–88.
- Saarenketo T, Scullion T & Kolisoja P (1998) Moisture Susceptibility and Electrical Properties of Base Course Aggregates. Proceedings of BCRA '98, July 6–8, Trondheim, Norway, Volume 3: 1401–1410.
- Saarenketo T & Roimela P (1998) Ground Penetrating Radar Technique in Asphalt Pavement Density Quality Control. Proceedings of the Seventh International Conference on Ground Penetrating Radar, May 27–30, 1998, Lawrence Kansas. Volume 2: 461–466.
- Saarenketo T (1999) Road Analysis, an Advanced Integrated Survey Method for Road Condition Evaluation. Proceedings of the COST Workshop on "Modelling and Advanced testing for Unbound and Granular materials". Lisbon, Portugal, January 21–22. Ed – A Gomez-Correia. A.A.Balkema, Lisbon, Portugal, 125–133.

- Saarenketo T (2000) Tube Suction Test – Results of Round Robin tests on Unbound Aggregates. Finnra Reports 19/2000. Finnish National Road Administration, Lapland Road Region, Rovaniemi 2000. 33 p.
- Saarenketo T, van Deusen D & Maijala P (2000a) Minnesota GPR Project 1998 – Testing Ground Penetrating Radar Technology on Minnesota Roads and Highways. In: Eighth Intl. Conference on Ground Penetrating Radar, David A. Noon, Glen F. Stickley, Dennis Longstaff, Editors, SPIEE Vol. 4084, 396–401.
- Saarenketo T, Kolisoja P, Vuorimies N, Yliheikkilä T & Ylitapio S (2000) Suction and Deformation Properties of Base Course Aggregates: Parts I and II. Tampere University of Technology, Geotechnical Laboratory, Publication Number 51, Tampere, Finland. (In Finnish).
- Saarenketo T & Vesa H (2000) The Use of GPR Technique in Surveying Gravel Road Wearing Course. In: David A Noon, Glen F Stickley & Dennis Longstaff (eds) Eighth Intl. Conference on Ground Penetrating Radar, SPIEE Vol. 4084: 182–187.
- Saarenketo T & Scullion T (2000) Road Evaluation with Ground Penetrating Radar. *Journal of Applied Geophysics* 43: 119–138.
- Saarenketo T (2001) GPR Based Road Analysis – a Cost Effective Tool for Road Rehabilitation – Case History from Highway 21, Finland. In: Proceeding of 20<sup>th</sup> ARRB Conference, Melbourne, Australia 19–21 March, 19 p.
- Saarenketo T, Kolisoja P, Vuorimies N & Ylitapio S (2001) Suction and Deformation Properties of Base Course Aggregates. Finnra Reports 10/2001. Finnish Road Administration 2001. 20 p.
- Saarenketo T, Kolisoja P, Luuro K, Maijala P & Vuorimies N (2002a) Percostation for Real-Time Monitoring of Moisture Variations, Frost Depth and Spring Thaw Weakening. Transportation Research Board Meeting Proceedings 2002 (CD-rom).
- Saarenketo T, Bell S, Berntsen G, Sundberg S & Vuontisjärvi E (2002b) Roadex – Benchmarking Low Traffic Volume Road Condition Management in EU Northern Periphery Area. Proceedings of BCRA 2002, Lisbon, Portugal. ed. Gomez-Correia and Branco. A.A. Balkema. pp 69–77.
- Saarenketo T, Kolisoja P, Vuorimies N & Peltoniemi H (2002) Effect of Seasonal Changes on Strength and Deformation Properties of Unbound and Bound Road Aggregates. Proceedings of BCRA 2002, Lisbon, Portugal, Gomez-Correia & Branco AA (eds) Balkema, 1059–1069.
- Saarenketo T & Saari J (2002) Road Condition Management of Low Traffic Volume Roads in the Northern Periphery. Roadex Sub Project Phase I State-of-the-Art Study Report. Roadex Project 1999–2001. 70p. ([www.roadex.org](http://www.roadex.org)).
- Saarenketo T & Riihiniemi J (2002) Selvitys Kemi-Tornio Moottoritien Epätasaisuuden Syistä. Tiehallinnon selvityksiä 44/2002, Tiehallinto, Lapin tiepiiri 51 p. (in Finnish).
- Saarenketo T, Silvast M & Noukka J (2003) Using GPR on Railways to Identify Frost Susceptible Areas. In: Proceedings of 6<sup>th</sup> International Conference on Railway Engineering, April 30–May 1, London, U.K. 11 p.
- Saarenketo T (2005) Monitoring, Communication and Information Systems & Tools for Focusing Actions. Report of the Roadex II project, 61 p. ([www.roadex.org](http://www.roadex.org))
- Saarenketo T & Aho S (2005a) Managing Spring Thaw Weakening on Low Volume Roads – Problem Description, Load Restriction Policies, Monitoring and Rehabilitation. Report of the Roadex II project, 130 p. ([www.roadex.org](http://www.roadex.org))
- Saarenketo T & Aho S (2005b) Monitoring and Classifying Spring Thaw Weakening on Low Volume Roads in Northern Periphery. Proceeding of the Seventh International Conference on Bearing Capacity of Roads, Railways and Airfields, Trondheim, Norway (CR-rom) 11 p.
- Saarenketo T & Kantia P (2005) Päälysteen Laadunvalvontamittaukset Maatutkalla – Testimittaukset 2005. Roadscanners Oy:n raportti Tiehallinnolle, (in Finnish) 59 p.
- Saeed A & Hall JW Jr (2002) Comparison of Non-Destructive Testing Devices to Determine in Situ Properties of Asphalt Concrete Pavement Layers. In: IL Al-Qadi & TM Clark (eds) Proceedings of the Pavement Evaluation 2002 Conference, October 21–25, Roanoke, VA, USA, 14 p.

- Saeed A, Hall JW Jr & Barker W (2003) Performance-Related Tests of Aggregates for Use in Unbound Layers. NCHRP Report 453. Transportation Research Board, 55 p.
- Sayers MW & Karamihas SM (1997) The Little Book of Profiling. University of Michigan Transportation Research Institute, 100 p.
- Schneider J (2003) Permanent Deformation Behaviour of Low Volume Roads in Nordic Countries. Diploma Thesis. Tampere Technical University. 95 p.
- Scullion T, Lau CL & Chen Y (1992) Implementation of the Texas Ground Penetrating Radar System, Report No. FHWA/TX-92/1233-1, Texas Department of Transportation.
- Scullion T, Lau CL & Chen Y (1994) Pavement Evaluations Using Ground Penetrating Radar. Proceedings of the Fifth International Conference on Ground Penetrating Radar, June 12–16, Kitchener, Ontario, Canada, Vol 1. of 3, 449–463.
- Scullion T & Saarenketo T (1995) Ground Penetrating Radar Technique in Monitoring Defects in Roads and Highways. Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, SAGEEP. Compiled by Ronald S. Bell. April 23–26, 1995, Orlando, Florida. pp 63–72.
- Scullion T, Lau C-L & Saarenketo T (1996) Performance Specifications of Ground Penetrating Radar. In: GPR '96: 6th International Conference on Ground Penetrating Radar, September 30–October 3, 1996, Sendai, Japan. Proceedings. Sendai: Tohoku University, 341–346.
- Scullion T & Saarenketo T (1997) Using Suction and Dielectric Measurements as Performance Indicators for Aggregate Base Materials. Transportation Research Record 1577: 37–44.
- Scullion T, Servos S, Ragsdale J & Saarenketo T (1997) Applications of Ground-Coupled GPR to Pavement Evaluation. TTI Report 2947-S.
- Scullion T & Saarenketo T (1998) Applications of Ground Penetrating Radar Technology for Network and Project Level Pavement Management Survey Systems. Proceedings of the 4<sup>th</sup> International Conference on Managing Pavements, Durban, South Africa, 17<sup>th</sup>–21<sup>st</sup> May 1998.
- Scullion T & Saarenketo T (1999) Integrating Ground Penetrating Radar and Falling Weight Deflectometer Technologies in Pavement Evaluation. Proceedings of the Third ASTM Symposium of Nondestructive Testing of Pavements and Backcalculation of Moduli, June 30<sup>th</sup>–July 1<sup>st</sup> 1999, Seattle Washington.
- Scullion T (2001) Development and Implementation of the Texas Ground Penetrating Radar System. In: Proceeding of 20<sup>th</sup> ARRB Conference, Melbourne, Australia 19–21 March, 19 p.
- Scullion T & Saarenketo T (2002) Implementation of Ground Penetrating Radar Technology in Asphalt Pavement Testing. In: Proceedings of the Ninth International Conference on Asphalt Pavements, August 17–22, Copenhagen, Denmark, 16 p.
- Sebesta S & Scullion T (2002a) Using Infrared Imaging and Ground-Penetrating Radar to Detect Segregation in Hot-Mix Asphalt Overlays. Research Report 4126-1, Texas Department of Transportation, Texas A&M University, College Station, TX.
- Sebesta S & Scullion T (2002b) Application of Infrared Imaging and Ground Penetrating Radar for Detecting Segregation in Hot-Mix Asphalt Overlays. Transportation Research Board Paper, 15 p.
- Shin H & Grivas D (2003) How Accurate is Ground Penetrating Radar (GPR) for Bridge Condition Assessment? Transportation Research Board Paper 22 p.
- Silvast M & Johansson S (2003) Tillståndsvärdering av brodeck med georadar på E4 i Härnösand. Unpublished report, Roadscanners Sweden AB.
- Silvast M & Nurmikolu A (2005) Radan päällyks- ja alusrakenteen tutkiminen maatuokalla. Ratahallintokeskuksen julkaisuja A x/ 2005. Helsinki, Ratahallintokeskus, Kunnossapitoyksikkö. 55p. (In Finnish). (in press).
- Silvast M, Levomäki M, Nurmikolu A. & Noukka J (2006) NDT Techniques in Railway Structure Analysis. Proceedings of 7th World Congress on Railway Research June 4-8, 2006, Montréal, Canada.



- Smekal A, Berggren A & Hrubec K (2003) Track-Substructure Investigations Using Ground Penetrating Radar and Track Loading Vehicle. In: Proceedings of 6<sup>th</sup> International Conference on Railway Engineering, April 30–May 1, London, U.K. 15 p.
- Spagnolini U (1997) Permittivity Measurements of Multilayered Media with Monostatic Pulse Radar. IEEE Transactions on Geoscience and remote Sensing, Vol. 35, No. 2, 454–463.
- Staccone G & de Haan E (2003) Safe Rail Track Bed Investigation by High Speed Radar. In: Proceedings of 6<sup>th</sup> International Conference on Railway Engineering, April 30–May 1, London, U.K. 4 p.
- Sussman TR, O'Hara KR & Selig ET (2002) Development of Material Properties for Railway Application of Ground Penetrating Radar. Proceedings of the Ninth International Conference on Ground Penetrating Radar, April 29–May 2, 2002, Santa Barbara, California. Editors S. Koppenjan and H. Lee. Proc. Of SPIE, Vol. 4758: 42–47.
- Sussman TR, Selig ET & Hyslip JP (2003) Railways Track Condition Indicators from Ground Penetrating Radar. NDT and E International, Vol 36, Issue 3: 157–167.
- Sutinen R & Hänninen P (1990) Radar Profiling and Dielectric Properties of Glacial Deposits in North Finland. Proceeding of the 6<sup>th</sup> IAEG Congress, Amsterdam, 1045–1051.
- Sutinen R (1992) Glacial Deposits, Their Electrical Properties and Surveying by Image Interpretation and Ground Penetrating Radar. Geological Surveys of Finland, Bulletin 359. 123 p.
- Syed I, Scullion T & Randolph RB (2000) Tube Suction Test for Evaluating Aggregate Base Materials in Frost- and Moisture-Susceptible Environments. Transportation Research Record 1709: 78–90.
- Syed I & Scullion T (2001) Performance Evaluation of Recycled and Stabilized Bases in Texas, TRB. Transportation Research Board Paper, Washington, DC (CD-rom).
- Syed I.M & Scullion T (2002) Moisture Related Problems in Stabilized Materials. Proceedings of BCRA 2002, Lisbon, Portugal. ed. Gomez-Correia and Branco. A.A. Balkema pp. 1151–1164.
- Szynkiewicz A & Grabowski P (2004) GPR Monitoring of Pavement on Airfields. Proceedings of the Tenth International Conference on Ground Penetrating Radar, Vol II, Slob, Yarovov & Rhebergen (eds) 803–805.
- Tice AN, Burrows CM & Anderson DM (1978) Phase Composition Measurements on Soils at Very High Water Contents by Pulse Nuclear Magnetic Resonance Technique. Transportation Research Board Record 675.
- Tiehallinto (2004) Rakenteen parantamissuunnittelua edeltävät maatumkatutkimukset ja tulosten esitystapa – menetelmäkuvaus 09/2004. Tiehallinto. Helsinki. 38 p. (in Finnish).
- Titus-Glover L & Fernando EG (1995) Evaluation of Pavement, Base and Subgrade Material Properties and Test Procedures, report 1335-2, Texas Transportation Institute, College Station Texas
- Topp GC, Davis JL & Annan AP (1980) Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines. Water Resources Research 16 (3): 574–582.
- Tsytovic NA (1975) The Mechanics of Frozen Ground. Swinow (Ed) McGraw-Hill Book Company, 426 p.
- Ulaby FT, More RK & Fung AK (1986) Microwave Remote Sensing, Active and Passive. Vol. III, From Theory to Applications. Appendix E. Microwave Dielectric Properties of Earth Materials, 2017–2119.
- Ullditz P (1998) Modelling Flexible Pavement Response and Performance. Polyteknisk Forslag, 205 p.
- Ulriksen CPF (1982) Application of Impulse Radar to Civil Engineering. Doctoral Thesis. Lund University of Technology. Department of Engineering Geology. 179 p.
- Uomoto T & Misra S (1993) Non Destructive Testing of RC Structures, Recent Developments in Japan. In: Proceedings of Conference on Non-Destructive Testing in Civil Engineering, 14–16 April, Liverpool, U.K., ed. J. Bungey, 65–77.

- Vuorimies N, Kolisoja P & Saarenketo T (2002) Rovaniemen Koskenkylän Percoaseman tutkimukset 2001. Tiehallinnon selvityksiä 9/2002. 48 p. Rovaniemi. (in Finnish).
- Vuorimies N, Kolisoja P, Saarenketo T & Peltoniemi H (2004a) Väylämateriaalien vuodenaikaiskäyttäytymisen tutkimukset 2001–2003. Tiehallinnon selvityksiä 4/2004. Helsinki 2004. (in Finnish).
- Vuorimies N, Kolisoja P, Saarenketo T & Peltoniemi H (2004b) Väylämateriaalien Vuodenaikaiskäyttäytymistutkimusten 2001–2003 Koetulokset. Tampereen Teknillinen Yliopisto, Pohja- ja maarakenteet, Tutkimusraportti 56, 64 p. (in Finnish)
- Vuorimies N & Kolisoja P (2005) Sitomattomien Väylärakennemateriaalien Kosteustilaherkkyyttä Vähentävät Uudet Käsittelyainetekniikat. Tutkimusrapotti. TTY/Pohja- ja maarakenteiden laboratorio. Julkaisu nro 61. 2005. 127 p. (in Finnish, English abstract).
- Vuorimies N, Kolisoja P & Raitanen T (2005) New Material Treatment Technologies in Management of the Effect of Seasonal Variations. Proceedings of BCRA'05. 6/2005 (CD-rom).
- Washer G (2003) Nondestructive Evaluation for Highway Bridges in the United States. Proceedings of International Symposium on Non-Destructive Testing in Civil Engineering (NDT-CE), September 16–19, 2003 Berlin, Germany.
- Webb DJ, Anderson NL, Newton T, Cardimona S & Ismail A (2002) Ground Penetrating Radar (GPR): A Tool for Monitoring Bridge Scour. In: Proceedings of the 2<sup>nd</sup> Annual Conference on the Application of Geophysical and NDT Methodologies and NDT Methodologies to Transportation Facilities and Infrastructure. April 15–19, California, USA, FHWA-WCR-02-001, 24 p.
- Weil GJ (1992) Non-Destructive Testing of Bridge, Highway and Airport Pavements. In: Proceedings of Fourth International Conference on Ground Penetrating Radar, June 8–13, Rovaniemi, Finland. Geological Survey of Finland, Special Paper 16: 259–266.
- Weil GJ (1998) Nondestructive Testing of Airport Concrete Structures. In: Proceeding of the Seventh International Conference on Ground Penetrating Radar. May 27–30, Lawrence, Kansas, USA, 443–448.
- Westerdahl HR, Austvik R & Kong F-N (1992) Geo-Radar in Tunneling – The Tunnel Radar. Geological Survey of Finland, Special Paper 16: 41–45.
- White TD & Coree BJ (1990) Threshold Pavement Thickness to Survive Spring Thaw. Third International Conference on Bearing Capacity of Roads and Airfields Proceedings. Volume I. The Norwegian Institute of Technology. Trondheim, 41–51.
- Wilson LW & Garman KM (2002) Identification and Delineation of Sinkhole Collapse Hazards in Florida Using Ground Penetrating Radar and Electrical Resistivity Imaging. In: Proceedings of the 2<sup>nd</sup> Annual Conference on the Application of Geophysical and NDT Methodologies and NDT Methodologies to Transportation Facilities and Infrastructure. April 15–19, California, USA, FHWA-WCR-02-001, 13 p.
- Wimsatt A, Scullion T, Ragsdale J & Servos S (1998) The use of ground penetrating radar in pavement rehabilitation strategy selection and pavement condition assessment. TRB-Paper 980129, 21 p.
- Wittman FH & Schlude F (1975) Microwave Adsorption of Hardened Cement Paste. Cement and Concrete Research 5: 63–71.
- Wobschall D (1977) A Theory of the Complex Dielectric Permittivity of Soils Containing Water: the Semidispersive Model. IEEE Transaction on Geoscience Electronics, Vol. Ge – 15, No. 1: 49–58.
- Xie X, Liu Y, Huang H & Shao J (2004) Research of GPR Non-Damaged Test of Grouting Behind Lining of Shield. Proceedings of the Tenth International Conference on Ground Penetrating Radar, Vol I, Slob, Yarovov & Rhebergen (eds), 419–422.
- Yamamoto M, Inigaki M, Ikeya K & Koyama T (2004) A Vector Diagram to Determine Anomaly Conditions in a Thin Layer. In: Slob, Yarovov & Rhebergen (eds) Proceedings of the Tenth International Conference on Ground Penetrating Radar, Vol II, 647–650.

- Yan D & Nazarian S (2003) Variation in Moduli of Base and Subgrade with Moisture. Transportation Research Record 2003, 14 p. (CD-rom).
- Yelf R (2004) Where is True Time Zero? Proceedings of the Tenth International Conference on Ground Penetrating Radar, Vol I, Slob, Yarovov & Rhebergen (eds), 279–282.
- Yliheikkilä T (1998) Kemiällisen koostumuksen vaikutus murskeiden vedenherkkyyteen. Pro Gradu tutkielma, Tielaituksen tutkimuksia, Lapin tiepiiri. 108 p + 3 app. (in Finnish).
- Ylitapio S (1997) TS-testin käyttö sitomattomien ja bitumilla sidottujen murskeiden laadun arvioinnissa. Insinööriyö, Rovaniemen Teknillinen oppilaitos, 37 p. (in Finnish)



## Original articles

- I Saarenketo T (1998) *Electrical Properties of Water in Clay and Silty Soils*. In: Sato M & Versteeg R (eds) *Ground penetrating radar (GPR '96)*. *Journal of Applied Geophysics* 40 (1–3): 73–88.
- II Saarenketo T (1999) *Road Analysis, an Advanced Integrated Survey Method for Road Condition Evaluation*. *Proceedings of an International Workshop on Modelling and Advanced Testing for Unbound and Granular Materials*, January 21–22. Ed A Gomes Correia. AA Balkema, Lisbon, Portugal, 125–133.
- III Saarenketo T & Scullion T (2000) *Road Evaluation with Ground Penetrating Radar*. *Journal of Applied Geophysics* 43: 119–138.
- IV Saarenketo T, Kolisoja P, Vuorimies N & Peltoniemi H (2002) *Effect of Seasonal Changes on Strength and Deformation Properties of Unbound and Bound Road Aggregates*. *Proceedings of BCRA 2002*, Lisbon, Portugal, 1059–1069.
- V Kolisoja P, Saarenketo T, Peltoniemi H & Vuorimies N (2002) *Laboratory Testing of Suction and Deformation Properties of Base Course Aggregates*. *Transportation Research Record* 1787. Paper No 02-3432, 83-89.

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