MEASURING ELECTROMAGNETIC PROPERTIES OF ASPHALT FOR PAVEMENT QUALITY CONTROL AND DEFECT MAPPING

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1. INTRODUCTION

This paper presents a status report on the development of electromagnetic test methods for testing asphalt pavements. The most popular methods in the field have been ground penetrating radar (GPR) and capacitance based dielectric probes.

In Scandinavia, the first tests with GPR were conducted in Denmark, in the early 1980s, (Berg 1984) and in Sweden (Johansson 1987) but did not gain general acceptance at that time. In Finland, the first tests were conducted, by the author, in 1986 (Saarenketo 1992) and the method became a routine tool in road surveys in the late 1980s. The first tests on asphalt were done in the late 1980s when high frequency antennas were tested in pavement thickness measurements and for detecting transverse crack growth in pavements (Saarenketo and Scullion 1994).

Capacitance probes were first tested in the early 1990s in Finland and since then it has been used especially in the Tube Suction test, developed by the author in the mid-1990s (Scullion and Saarenketo 1997). Worldwide, the most popular use of this technique is currently in asphalt density control in paving projects.

The author's idea for using GPR technique in measuring asphalt air voids content was tested in Rovaniemi, for the first time, in the summer of 1993, in a project financed by the Finnish Technology Development Centre, TEKES. This involved testing the Canadian multi-channel ground penetrating radar system, manufactured by Road Radar Inc., on experimentally surfaced pedestrian paths along HW 4 between Rovaniemi and Saarenkylä, which contained void spaces of different types depending on the number of times the pavements had been rolled. The results were not encouraging, however, mainly due to technical problems with hardware and software. Research was continued in 1994-95 in Texas Transportation Institute, when series of laboratory tests were conducted.

In summer 1996, the research continued in the form of a joint project initiated by the Finnish National Road Administration, the University of Oulu and Neste Oy. The project involved testing the measurement methods in laboratories and at actual pavement laying sites in Southern and Northern Finland. In 1997, the final laboratory and field tests were completed and, as a result of these surveys, the surface reflection technique was accepted by PANK as the standard quality control method for asphalt pavements in Finland.

In the late 1990s and early 2000s, r&d work has been done to develop techniques for detecting different types of pavement defects, such as stripping, segregation and moisture barriers.

2. ELECTRICAL PROPERTIES OF ASPHALT

2.1. Magnetic susceptibility, electric conductivity and dielectric permittivity

There is general agreement that electrical properties of materials comprise 1) magnetic permeability, i.e. magnetism of the material, 2) dielectricity and 3) electrical conductivity.

As magnetic permeability is of the same order as the vacuum in bitumen and in most crushed aggregates, the electromagnetic properties of asphalt pavements can be described by means of electrical conductivity and dielectric properties.

Electrical conductivity of materials is attributable to the free or restricted restricted transfer of electrons and ions, which may be attributable to a number of phenomena. Most of the minerals occurring in the crushed rock used for pavement, such as quartz, mica and feld-spar, are, when dry, solid electrolytes that can almost be regarded as insulators. Thus electricity is transmitted only through impurities and disorders in their crystal lattice. Since bitumen can also be regarded as an electrical insulation material, hot-rolled pavements can be regarded, for calculation purposes, as electrical insulation materials. However, the situation changes when chlorides, for de-icing purposes, are spread on the pavement, especially if the pavement is porous.

The term dielectric value or “relative dielectric permittivity" refers to the capacity of a material to store and then allow the passage of electromagnetic energy when an electrical field is imposed upon it. It can also be described as a measure of the ability of a material within an electromagnetic field to become polarized, and therefore respond to, propagated electromagnetic waves. The dielectric value of a material is a function of the volumetric proportions of its material components and the dielectric properties of these components. Dielectric permittivity is, generally speaking, a complex number (it has real and imaginary parts) and is a function of frequency. The imaginary part is often called as lossy part and it is a measure of the proportion of the charge transferred in conduction and stored in polarization.

2.2. Dielectric properties of new hot mix asphalt pavements

The real part of the dielectric permittivity can vary in natural materials between 1 (air) and 81 (free polar water at 20 ^{o}C). 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 frequency-dependent, i.e. dispersive when absolutely dry. 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 (figure 1). The TTI tests also indicated that ageing of the bitumen samples in the sun for 6 months had no appreciable effect on dielectricity.

Since the electrical properties of the components of the asphalt were known, mixture models 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 imaginary part of the asphalt components in the case of new and dry asphalt showed to be very close to the value of 0 at the frequencies GPR uses, which means that dielectric losses do not have to be taken into consideration when analyzing the results of the new hot mix asphalt surfaces.

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.

2.3 Dielectric values of older bituminous pavements

During the last ten years, after measuring thousands of kilometers of new and old asphalt pavements, a better understanding of the dielectric history of asphalt pavements, as presented in figure 2, could be gained. After the paving year dielectric value rises up one unit but then the value of asphalt remains on the same level until, after 5-10 years, it starts to rise slowly. The rapidity of the rise depends on traffic volume and the use of chlorides. A few years before the pavement starts to crack, the water molecules start to penetrate between bitumen and aggregates thus breaking the bonds. This can be seen as rapidly increasing dielectric values. At that time, the imaginary part of the asphalt is also increasing from a level of 0, which can be seen in the form of electrical losses.

Dielectric values start to decrease rapidly when the pavement starts to crack. This is due to fact that cracks increase the volumetric proportion of air in the pavement. The decrease in dielectric values even out normally to a level of 4,0 – 4,5.

3. MEASURING ASPHALT USING GPR AND OTHER ELECTROMAGNETIC TECHNIQUES

3.1. Ground Penetrating Radar

Ground Penetrating Radar systems use discrete pulses of radar energy. These systems typically have the following components 1) a pulse generator, which generates a single pulse of given frequency and power, 2) an antenna or antennas which transmit the pulse into the medium being measured, and 3) a sampler/recorder which captures and stores the reflected signals from the medium. Once the return waveform is captured another input pulse is generated and transmitted into the medium. The time between the reflections from electrical interfaces in road will be measured from the stored signal as well as the amplitude of the reflection. The radar antennas in common use fall into two broad groups: air-coupled antennas (usually horn) and ground-coupled dipole antennas (Saarenketo and Scullion 1994).

The ground-coupled antennas operate in a wide range of central frequencies from 80 MHz to 1500 MHz. The clear advantage of ground-coupled antennas is their depth of signal penetration and better vertical resolution. However, these surface coupled systems have not yet been optimized for road surveys, the surface coupling antenna ringing presents the main problem. Typically, it is difficult to obtain any quantitative information from the near surface with these antennas. Another limitation of these antennas has been that they have to remain in near contact with the medium and data collection the speed is limited to typically less than 25 km/h. In asphalt quality surveys, ground coupled antennas can be used for mapping different types of defects, such as cracking and stripping in asphalt, but not for measuring asphalt air voids content due to the fact that the signal velocity measuring accuracy in these systems is not high enough.

The air-launched systems operate around 1 GHz central frequency and their depth of penetration in typical pavement structures is limited to approximately 0.5 m. During data acquisition these antennas are suspended 0.3 - 0.5 m above the pavement surface (Figure 3). Air-launched systems typically have the capability to transmit and capture up to 1000 scans per second, which means that they can collect useful pavement layer information at highway speeds (100 km/h). Pavement surface dielectric value is measured with a GPR horn antenna by using a surface reflection technique (Maser and Scullion 1991). The layer specific dielectric values are calculated from the reflection amplitudes of the interfaces and these amplitudes are compared with the reflections from a metal plate (perfect reflector).

However, during recent years, there have been several failures in the testing GPR of for asphalt QC. Most of them have been due to the use of poorly performing GPR systems in the test. The signals generated by air coupled antenna systems must have sufficient quality to allow the performance of automated signal processing and qualitative data analysis. To ensure the quality of a signal, the Texas Transportation Institute has proposed a series of performance specifications, which have been used in the USA and in Finland but not in other countries (Scullion, Lau and Saarenketo 1996). These tests include: 1) Noise to Signal Ratio (N/S ratio), 2) Signal Stability (amplitude and time jitters), 3) Travel Time Linearity and 4) Long-term Stability Tests (time-window shifting and amplitude stability). The GPR unit must pass these tests before it can be used reliably to compute quantitative layer properties.

3.2. Capacitance based measurements

Another electromagnetic method, which has gained more popularity recently, is the use of capacitance based probes to measure dielectric value of the asphalt surface and this value is then calculated to air voids contents using a special calibration factor. In recent years, several new units have been introduced to the asphalt quality control market. They have mainly been used in on site compaction testing.

The general experience from these units has been that they provide relatively reliable values on smooth asphalt surfaces but problems arise when the asphalt surface is rough.

4. APPLICATIONS

4.1. General

Nondestructive pavement testing methods, such has GPR, have gained increasing popularity in quality control surveys of new road structures. 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 presents the possibility of continuous data collection and thus 100 % coverage of a new road structure under inspection can be acquired. Drill core methods provide point specific information and they cannot reliably be used to find defective areas in new pavements.

4.2. Air voids content

The calculation of air void values is based on the use of mean dielectric values. The method applies the results of laboratory tests conducted to define the function between the dielectric value and air void content (Roimela 1998). The method includes taking 1-2 calibration core samples from the pavement under survey, representing sections of mean dielectric value calculated after GPR data collection. Air void content of the calibration cores are defined using laboratory methods approved by PANK. Using the air void content value obtained from the calibration samples, and their respective dielectric values, a calibration coefficient is determined for the calculation of air void contents of the pavement. The formula for calculation of air void content y is presented as formula 1:

$y = 272{,}93e^{-1{,}3012k\varepsilon_x}$, x between 1<x<n (1), where

k is the calibration coefficient
ε_x is the measured dielectric value using GPR surface reflection method

The measuring accuracy for air void content measurement using the GPR surface reflection technique is +/- 0,9 percent (Figure 4). This statistical analysis result has been achieved through comparison of core sample results and GPR measurements conducted as static shots over each individual measurement point (R=0,9223). In general the deviation of the air voids content measured using GPR is smaller because a single GPR scan covers roughly 300 * 300 mm area while the area of a standard drill core is much smaller.

The repeatability of the measurement is good as can be seen from the test results conducted in Germany in 2002. (figure 5).

4.3. Segregation

One of the major functions of bituminous pavements on highways is to provide waterproofing for the underlying structural base layers. If excessive moisture can enter the base layer then rapid load and environmental damage will occur. The surfacing layer will only function as intended if it is compacted to optimum density, and it does not contain any defects such as areas of segregation, and if the longitudinal construction joints are waterproof. Segregation manifests itself as localized periodic small areas of low-density material in the compacted surfacing layer. Upon close inspection of these small, localized areas an excess of coarse aggregates will be found.

The causes are often traced to improper handling or construction techniques. During construction, segregated areas are often impossible to detect visually and they only become apparent after one or two months in service. However these areas often have a major impact on long-term pavement performance. The segregated areas provide an opportunity for moisture to enter the lower pavement layers. The asphalt industry is well aware of the segregation problem and in the past decade several improvements have been implemented. Despite progress in this area, segregation is still a major concern in many countries and at the present time there are no ways of detecting these problems during construction. A second problem area is that of the permeability of longitudinal joints.

GPR offers tremendous potential to assist in monitoring the quality of a completed surfacing layer. The GPR parameter that can be used to detect these problem areas is the surface dielectric. GPR traces can be collected at closely spaced intervals, and, with minimal data processing, a plot of surface dielectric versus distance can be produced. 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 (Saarenketo and Scullion 2000).

The first use of GPR technology to monitor segregation of pavements was reported by Saarenketo (1997). Large changes in the surface dielectric were attributed to the use of an experimental paver (figure 4.3_1). Since then successful tests of using GPR to detect segregation has been reported in the USA and Sweden.

4.4. Stripping

Even though the greater part of defects observed in asphalt pavements are related to the material problems of the layers beneath the pavement there are also some pavement damages caused by problems of deterioration inside the pavement. The most common asphalt pavement damage is stripping, which is a moisture related mechanism where the bond between asphalt and aggregate is broken leaving an unstable low density layer in the asphalt. Stripped layers should always be detected and removed before placing a new overlay.

Stripping can be seen in most cases as an additional positive or negative (reversed reflection polarity) reflection in the pavement. However similar reflections can be obtained from an internal asphalt layer with different electrical properties. That is why reliability of the analysis was improved when FWD data together with confirming reference data, such as drill cores was started to be used in the analysis.. Figure 7 presents a case from Willmar, Minnesota, where 1.5 GHz ground coupled and FWD data were used to evaluate stripping (Saarenketo, van Deusen and Maijala 2000).

A good indicator for stripping is also the surface dielectric values of asphalt pavements. The data should be collected using a high sampling density, and when this is done the results should reliably indicate areas with potential stripping problems as figure 4.4_2 shows.

4.5. Moisture barriers

Another major cause of surface distress is when moisture becomes trapped within the surface layers. This happens when impermeable fabrics or chip seals are placed between asphalt layers or when the existing surface is milled and replaced with a less dense layer. The GPR signals are highly sensitive to variations in both moisture and density.

The GPR reflections from existing highways can be complex especially if the old HMA layer contains numerous thin layers constructed with different aggregates compacted to different densities. Moisture barriers within the layer and collecting data shortly after a significant rainfall can also complicate the analysis.

4.6. Other applications

Other asphalt defects that GPR technique can be used include: cracking (Saarenketo and Scullion 1994), thermal cracking and debonding, which takes place when the bonding between separate asphalt layers becomes loose.

5. CONCLUSIONS AND FUTURE ASPECTS

The research conducted during the last 15 years in order to better understand the dielectric properties of road materials has been successful and many applications have been developed for measuring pavement quality and detecting different types of defects. The advantage of these survey methods, especially the GPR technique, is that they are fast and non-destructive. The major problems with these high tech hardware systems can be related to their relatively high price and that they also require experienced staff to operate them. False conclusions have been made with the GPR technique, especially in some tests done in Scandinavia, because the tests were conducted using a poor quality or a broken GPR antenna system. The major problem in many countries is the overselling of these methods by consultants having no expertise in the technology.

In the future, the use of the electromagnetic methods in asphalt testing will be focused more on their integrated use with other test methods such as FWD testing, videos and infrared camera data etc. A real time asphalt quality assurance method will also be a future challenge. The rapid development of computers processors also allows the use of multiple channels in GPR systems and as such coverage of wider pavement areas and allowing 3D modeling and rehabilitation design of asphalt pavements.

The best hope for the future involves three critical steps recommended by Saarenketo and Scullion in 2000: a) developing user friendly packages in order to convert GPR data along with other road survey data into information which is meaningful to pavement engineers, b) gaining and understanding of the electromagnetic properties of road materials and their relation to the moisture, strength and deformation properties, and c) provide training to the road administrations and contractors who use the GPR data as well as the staff responsible for the GPR surveys.

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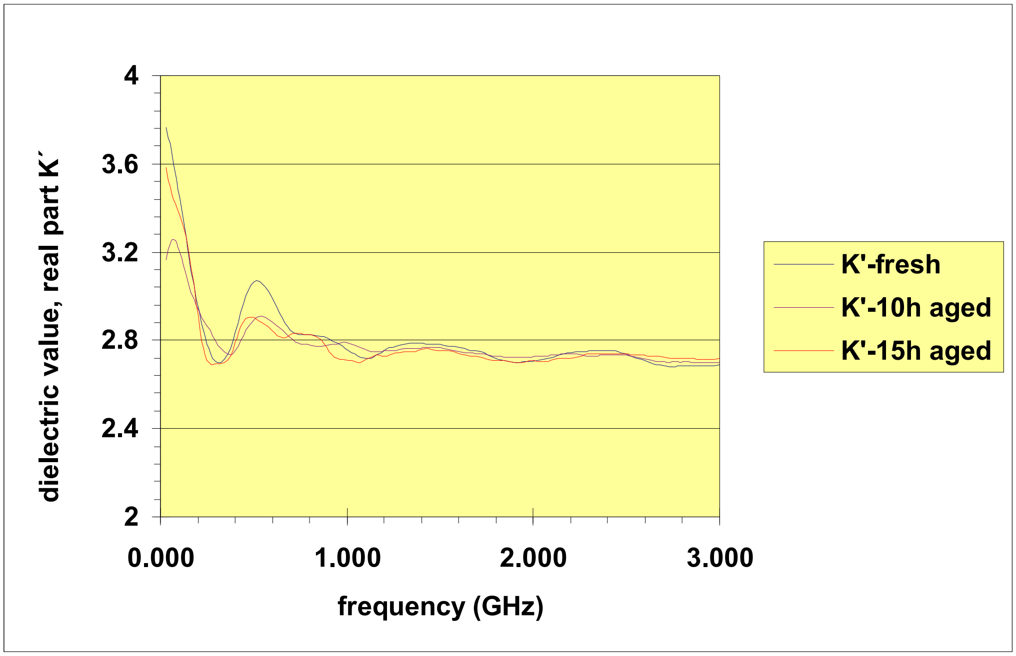

Figure 1. Real part K´ of the dielectric value of Laguna bitumen when fresh and when aged using thin film owen test device.

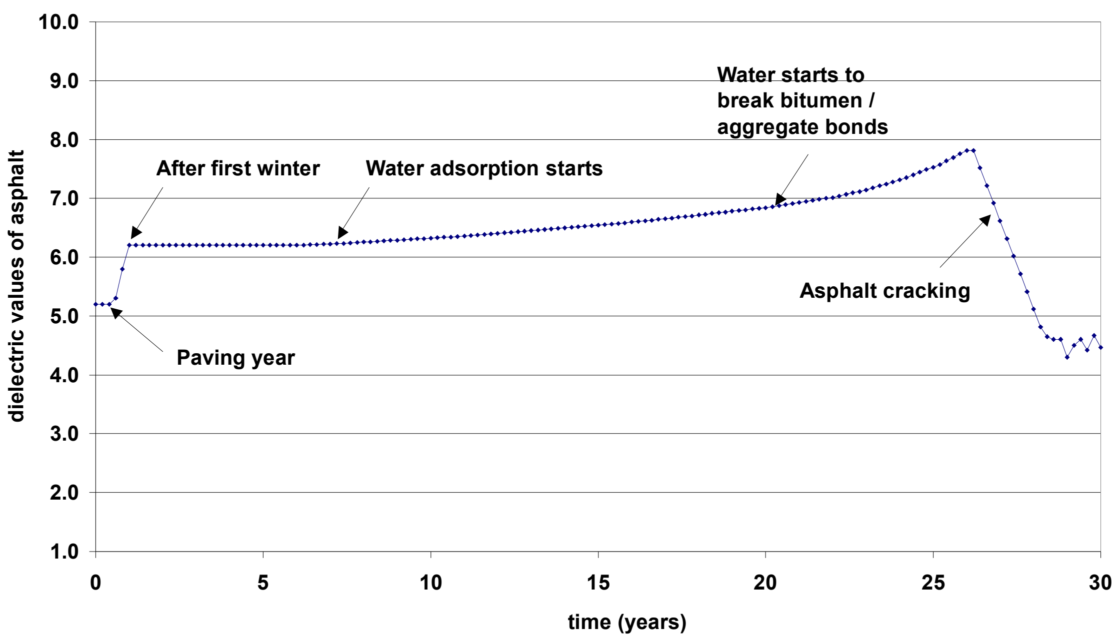

Figure 2. A schematic model of the dielectric history of an asphalt pavement.

Figure 3. A GPR horn antenna system.

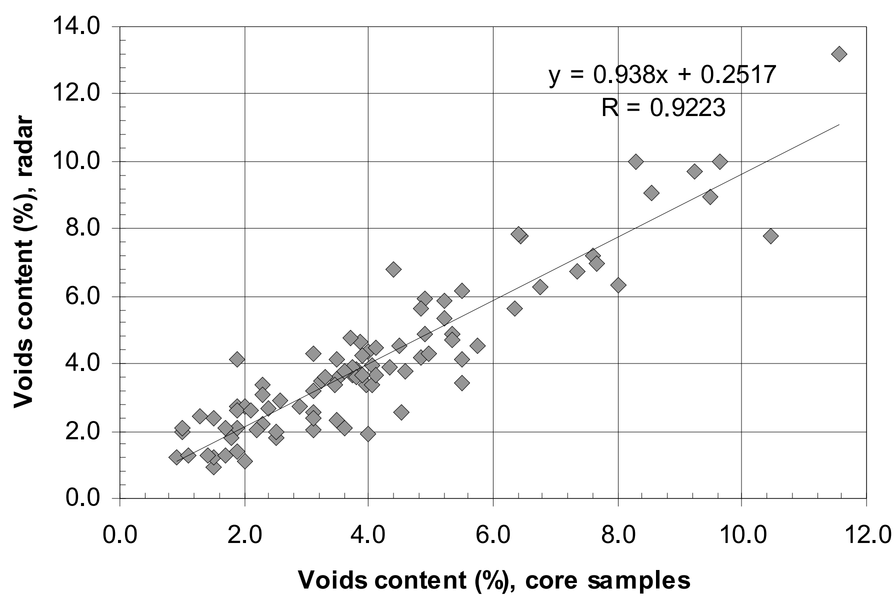

Figure 4. Correlation between voids content measured using the GPR technique and voids content from drill cores.

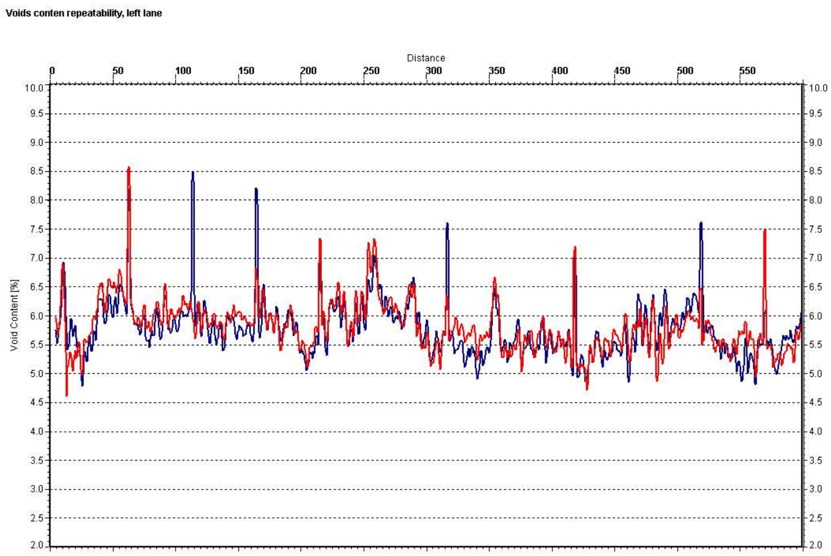

Figure 5. Repeatability of voids content. Two separate runs measured from the left lane. Voids content calculation reference point is from 257 m, where the voids content from the drill core was 7.3 %. The peaks are due to metallic sensors on pavement.

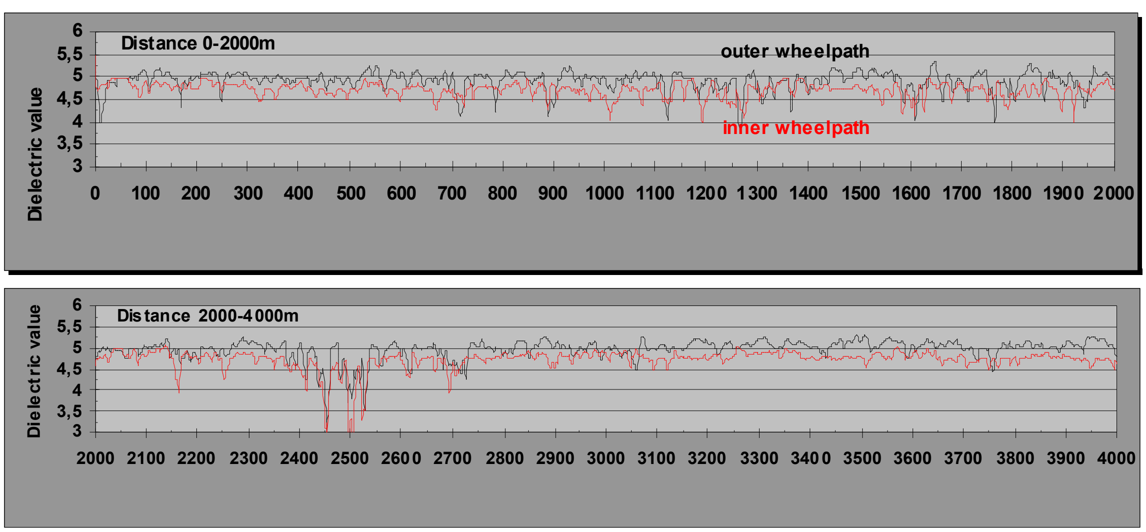

Figure 6. Dielectric value of asphalt in E4 at Ylinampa, north of Rovaniemi in Finnish Lapland. A reduction in dielectric value was observed at the end of each truckload and other places where an experimental paver had problems. The experimental paver was replaced by a conventional machine at 2700 m and after that the quality immediately improved.

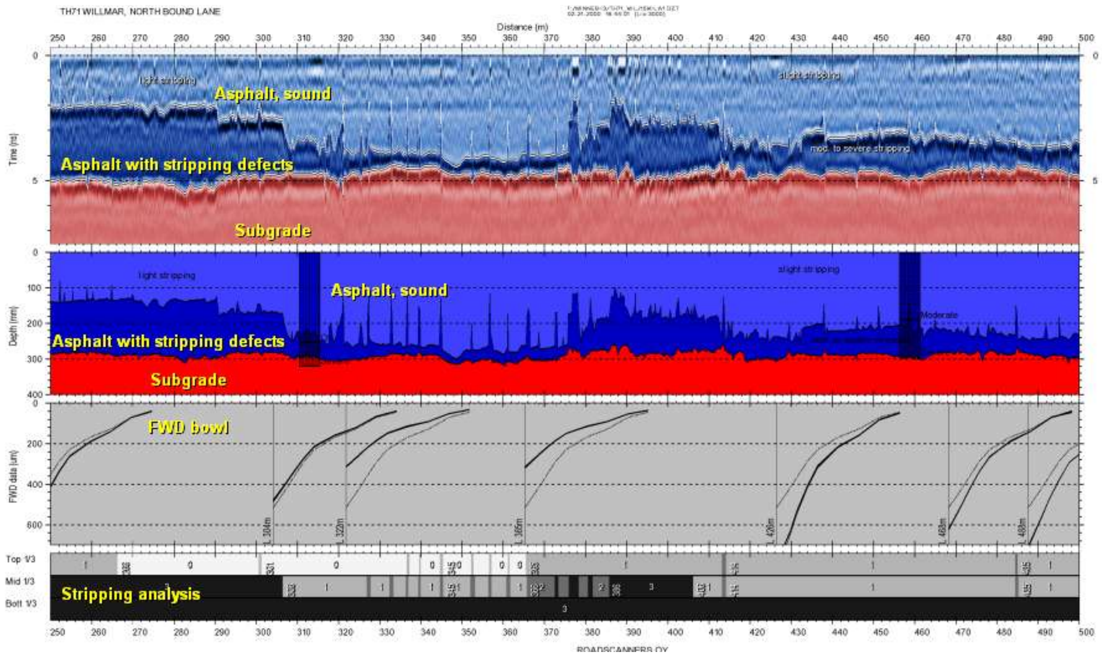

Figure 7. A 1.5 GHz ground coupled GPR profile, interpretation, falling weight deflectometer data and stripping evaluation from TH71 at Willmar, Minnesota. The slightly better section between 310 and 380 m can be seen also as better FWD deflection bowls.

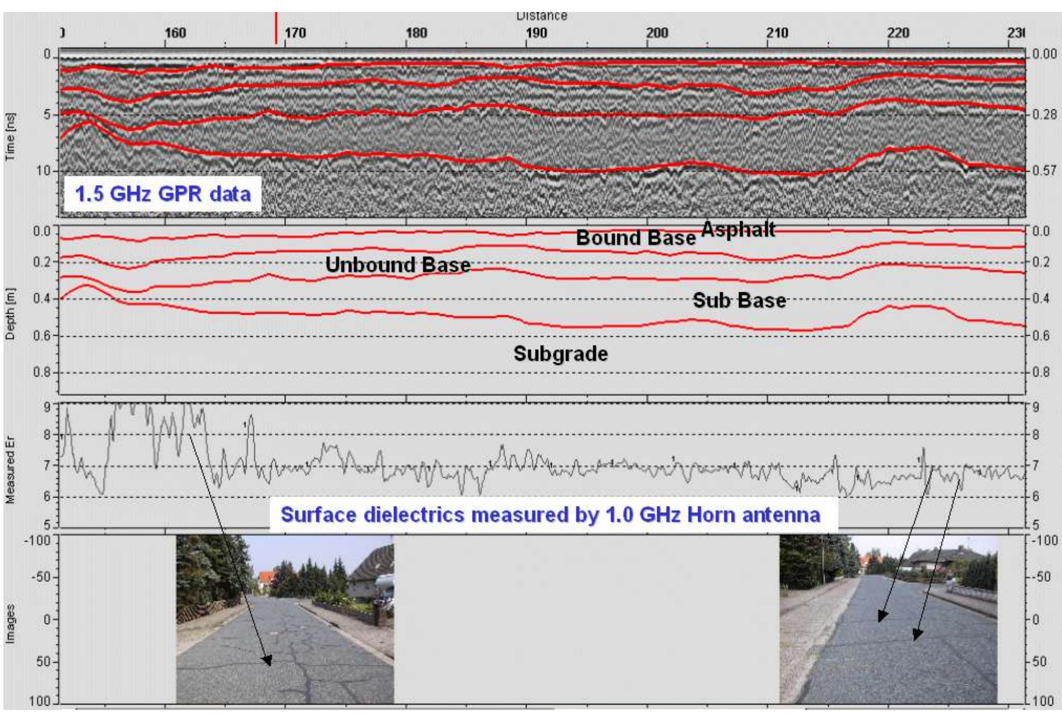

Figure 8. Detecting road sections with stripping problems in Wertlingen Germany. High surface dielectric values present the area where the stripped asphalt is saturated with water.