Accuracy of Ground Penetrating Radar Horn-Antenna Technique for Sensing Pavement Subsurface

Andreas Loizos and Christina Plati

Abstract—**Ground penetrating radar (GPR) is an intelligent sensor technique that has led to a powerful nondestructive testing (NDT) method for road pavement evaluation. Recent improvements in hardware and, in particular, software processing have contributed to the rapidly expanding popularity and usability of this technique in the pavement engineers community. In the present work, a GPR sensor system mounted on a driving van was used to acquire data from an asphalt pavement. Two different central frequency air-coupled horn antennas were used for data acquisition. The collected radar data was processed and analyzed in order for the accuracy of the antennas to be evaluated. For this purpose, the asphalt layer dielectric values and related thickness values were also estimated. Based on the GPR data analysis results, the performance of the two horn antennas in terms of sensing pavement subsurface is presented and discussed in the paper.**

Index Terms—**Air-coupled horn antennas, asphalt layer, asphalt pavement, dielectric values, ground penetrating radar (GPR), thickness.**

I. Introduction

THE TERM ground penetrating radar (GPR) refers to a range of electromagnetic techniques designed primarily for the location of objects or interfaces buried beneath the earth's surface or located within a visually opaque structure. GPR technology is widely application-oriented and the overall design concept, as well as the hardware, is usually dependent on the target type and the material of the target and its surroundings. As the sophistication of operating practices increases, the technology matures and GPR becomes an intelligent sensor system [1]. The intelligent sensing deals with the expanded range of GPR applications, which includes applications for archaeology, geophysical research, building and structural aspects, road quality assessment, mine detection, etc.

Focusing on road quality assessment, it has been stated that GPR is a nondestructive sensing technique and can be applied dynamically at driving speeds to achieve a continuous profile of the pavement structure. Due to recent hardware and software improvements, real-time cursory analysis can be performed in the field. Because of these and other reasons, GPR has become an increasingly attractive method for the engineering community, in particular, for shallow high-resolution applications such as pavement evaluation.

Manuscript received June 1, 2006; revised October 6, 2006; accepted October 8, 2006. The associate editor coordinating the review of this paper and approving it for publication was Dr. Subhas Mukhopadhyay.

The authors are with the Department of Transportation Planning and Engineering, National Technical University of Athens, Zografou, Athens 15773, Greece (e-mail: aloizos@central.ntua.gr; cplati@central.ntua.gr).

Digital Object Identifier 10.1109/JSEN.2007.894152

The history of GPR tests on road surveys goes back to the mid-1970s, when according to Morey [2], the U.S. Federal Highway Administration tested the feasibility of radars in tunnel applications and later on bridge decks. The first GPR mounted vehicle system for highways was developed under a FHWA contract in 1985 [2]. Since then, many applications have concentrated on pavement evaluation as stated among others in [3]–[7].

The increase in the use of GPR to evaluate pavement construction may be measured in the trebling of publications in each of the three past decades. Applications of GPR include, among others, studies of highway, runway, and bridge pavements. Specific problems being addressed include material curing and aging, moisture determination, subgrade compaction (especially on bridge approaches), void detection and mapping, subpavement hydrology, fracture and fault detection, etc.

Furthermore, in the past few years, standards have been developed for the use of GPR to determine pavement thickness [8]. Pavement thickness measurements are necessary basically for quality control purposes, for new, reinforced, or rehabilitated road pavements. In addition, mechanistic models for pavement performance and structural tests that use these models for pavement analysis require pavement layer thicknesses as input [9]. Furthermore, the layer thickness information is of high interest when a Pavement Management System (PMS) is applied at the road network level [10]. Traditionally, pavement layer thicknesses have been determined by digging test pits or by extracting cores from the pavement. However, these procedures are not only time consuming but also result in major traffic disruptions. Also, they provide information only on the test points, so uncertainty remains regarding the conditions between these test points [11].

GPR sensor technology has led to a powerful nondestructive technique capable of collecting continuous layer thickness data at driving speeds. Quite significant research has been conducted to evaluate the accuracy of thickness estimations through the GPR technique. In most cases, comparison with respective *in situ* core data (ground truth data) provided encouraging results. GPR has proved to be an appropriate tool for road surveying since the calculated thickness errors, especially in the case of new pavements, ranged within acceptable levels for practical applications [12]–[16].

GPR can be described as a remote sensing system that emits a short pulse of electromagnetic energy, which is radiated into the pavement subsurface. For pavement evaluation purposes air-coupled and ground-coupled antenna systems are used. In the air-coupled systems, the antennas are suspended above the pavement surface for operation at driving speeds (up to approximately 80 Km/h). The drawback being that penetration depth is limited. In the ground-coupled systems, the antennas rest on the pavement surface for better signal penetration into the pavement structure; however, operational speeds are limited. The general rule is that the higher the GPR operating frequency, the higher the resolution and the smaller the depth of investigation [2].

In light of the above, air-coupled systems are becoming increasingly popular for the evaluation of the upper part of the pavement structure, while ground-coupled systems are used in order to get information from the entire pavement structure up to approximately 3 m. Most GPR pavement studies have been carried out with air-coupled horn antennas, since they can be implemented at driving speeds without need for road closures. According to [16], the 1 GHz air-coupled horn antenna is often used for the estimation of pavement layer thickness. However, signals generated by horn antenna systems must have sufficient quality to allow the performance of automated signal processing and qualitative data analysis.

The implementation of the horn antenna method is dependent upon, among others, the resolution of the antenna in use. The present work investigates the application of the GPR sensor technique for the detection of subsurface pavement layers with a special focus on air-coupled antenna penetration depth and resolution. For this purpose, dielectric properties of asphalt layer materials were estimated and related thicknesses were evaluated based on data collected by an air-coupled GPR system, which operates a 1 GHz and alternatively a 2 GHz central frequency antenna. The collected data were analyzed comparatively for the two antennas. Major findings of the related analysis are presented and discussed in the following sections.

II. GPR Operation Principles

A well-established sensor technique is the radio detecting and ranging (RADAR) technique. It uses radio waves to detect objects and determine their distance from echoes they reflect. The GPR is a specialized radar for the detection and location of targets in structures; this kind of radar does not identify or evaluate the targets. The GPR operator/interpreter identifies and evaluates the targets by using the appropriate computer software. The GPR is very often referred to as the "impulse" radar, which indicates its ability to transmit radio energy over a large frequency band.

The range or depth to which GPR is effective is a function of the sensor system parameters such as transmitter pulse width (central frequency), the target parameters such as target resolution and the electromagnetic properties of the materials being probed such as the material conductivity. Briefly, sensor system performance depends on system characteristics, the medium, the target, and the distance to the target from the antenna [2].

A variety of GPR systems were developed appropriately and tailored for the purposes of the survey. The primary components of a GPR system are illustrated in Fig. 1. The antenna unit can be a single antenna that transmits and receives radar signals or two separate antennas one for transmission and one for reception. In both cases, the antennas must be lightweight and maneuverable so that they can be easily positioned over the area under investigation. The transmition/reception unit consists of a transmitter for signal generation, a receiver for signal detection, and timing electronics for synchronizing the transmitter and receiver. The control unit is the operator interface that controls the overall operation of the GPR system and sends the received data to the data storage and display unit.

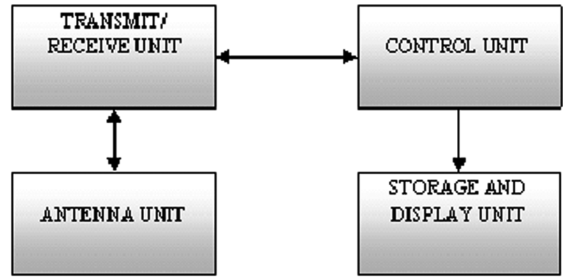

Fig. 1. Primary components of a GPR sensor system.

For the purpose of the present investigation, an air-coupled GPR system was used. The applied impulse radar technique is based on the principle that a short (0.5–1.5 ns) electromagnetic pulse is transmitted into the pavement through its surface. The pulse travels through the pavement's layers and reflects off surfaces or objects, which bear discontinuities in electrical properties, for instance, different materials or changes in either moisture content or density. In other words, where there is a contrast in the dielectric values of the pavement materials, the reflected pulses from the internal pavement interfaces are recorded. The greater the dielectric contrast between two pavement layers, the greater amount of the reflected energy; consequently, the pulses records are clearer. The amount of energy reflected is a function of the dielectric properties of the pavement layers. The reflection coefficient γ_i quantifies the reflective strength between two pavement layers according to (1)

$$\gamma_i = \frac{\sqrt{\varepsilon_i} - \sqrt{\varepsilon_{i+1}}}{\sqrt{\varepsilon_i} + \sqrt{\varepsilon_{i+1}}} \tag{1}$$

where ε_i and ε_{i+1} are the dielectric values of pavement layers i and $i+1$, respectively. Therefore, the larger the dielectrics contrast between the pavement layers, the larger the coefficient and subsequently, layer delineation and subsurface feature detection is more evident.

It is worth mentioning that not only the reflection coefficient, but also the reflection polarity can provide valuable information regarding pavement condition. Reflection polarity is also a function of the dielectrics contrast between two pavement layers. Furthermore, the interaction of an asphalt pavement with electromagnetic waves of different frequencies makes the material's dielectric properties more understandable [17].

In addition, the time it takes for the signal pulse to travel to a certain interface and back to the receiving antenna is referred to the two-way travel time (Δ_t). Variations in two-way travel times within a medium such as an asphalt concrete (AC) pavement layer suggest the presence of variable thicknesses. A shorter two-way travel time would be indicative of a thinner AC pavement layer. On the contrary, a thicker AC pavement layer would yield a longer two-way travel time.

Fig. 2 shows an example for the case of a typical asphalt pavement, where the reflections from the top of the AC layer, the AC/base layers interface, and the base/subgrade layers interface are recorded. Fig. 2 shows the geometry of the antenna

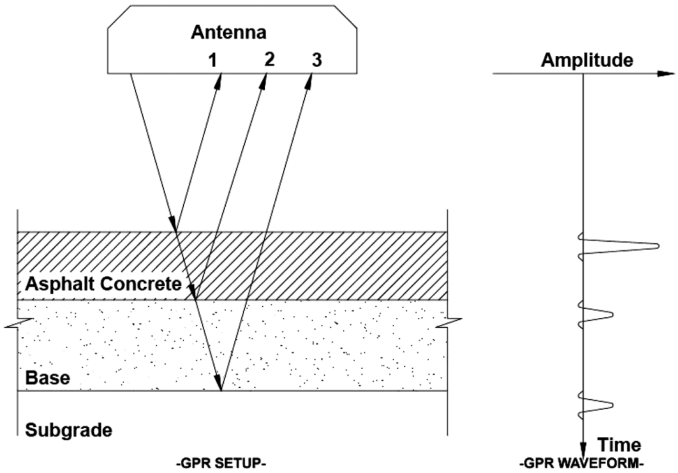

Fig. 2. The GPR principle for pavements.

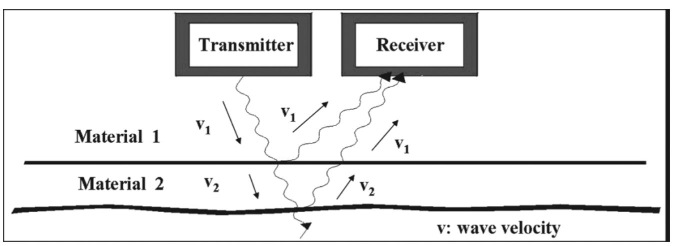

Fig. 3. Determination of pavement layer thickness.

and the GPR ray paths. The reflected pulses are received by the antenna and recorded as waveform. As the sensor equipment travels along the pavement, it generates a sequence of waveforms. The recorded reflections depend on the velocity (V_i) of the waves propagation (see Fig. 3), which is governed by the electromagnetic properties of the materials [18]. It is worthwhile to mention that following the principles of the multilayer theory for pavement analysis [19], the AC pavement material is considered as isotropic.

Fig. 4, [20] shows that the waves propagation is taken along the z axis, while the electric (E) and magnetic (H) fields are perpendicular. As considered in this figure, in free space, the magnetic susceptibility and electric permittivity are independent of frequency and the medium is not dispersive. Hence, no attenuation of the waves is encountered, which happens in real dielectric medium. The wave propagation can be represented by the one-dimensional wave equation of the following form:

$$\frac{\partial^2 \mathrm{E}}{\partial z^2} = \mu \cdot \varepsilon \frac{\partial^2 \mathrm{E}}{\partial t^2} \tag{2}$$

where μ and ε are the magnetic susceptibility and dielectric values of the medium, respectively. The dielectric value is the ratio of the material electric-field capacity to that of free space. It can be considered that the dielectric value of a purely dry asphalt core results from the combination of the volumetric ratio of asphalt, air and aggregate, and their individual dielectric values. The dielectric value of AC pavement materials is often correlated with the density, air voids, asphalt content, and moisture accumulation as stated among others by [21] and [22].

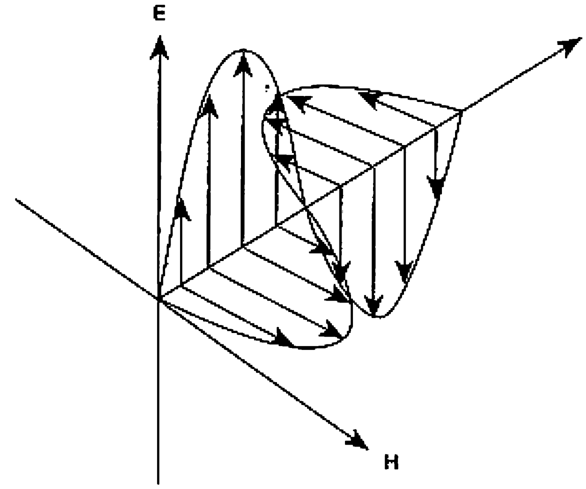

Fig. 4. Propagation of electromagnetic waves in free space [18].

The velocity of the waves' propagation in pavement materials is a function of the dielectric value of the material mixture and is primarily governed by water content. Equation (3) represents the propagation velocity (V) of electromagnetic energy through a nonmetallic medium

$$V = \frac{c}{\sqrt{\varepsilon}} \tag{3}$$

where c is the propagation velocity in free space (0.3 m/ns). It is mentioned that the velocity in air is very similar to that in free space and is normally taken as the same. In subsurface radar work, for instance pavement sensing, the elapsed time between transmitted and received pulses is measured in nanoseconds because of the short travel paths involved.

However, given the two-way travel time (Δt) and the depth (d) of the medium at specific location the propagation velocity can be based on the following equation:

$$V = \frac{2 \times d}{\Delta t}. \tag{4}$$

Equations (3) and (4) can be used to approximate the relative dielectric value ε for a medium such as an AC pavement layer. Different pavement materials have different dielectric values. As a reference, air has a dielectric value of 1, while other materials have higher values.

Furthermore, the intensity of the recorded reflections depends on the interface under investigation and is proportional to the strength of the contrast in dielectric properties between pavement layers. Fig. 5, [23] shows, after background removal, the GPR trace from a new AC pavement measured with a 1.0 GHz horn antenna. The peaks A_1, A_2, and A_3 are the reflections from the road surface, base and subgrade. The amplitudes of these reflections are used for the computation of the layer properties.

The dielectric value of an AC pavement layer can be calculated in the following manner:

$$\varepsilon_1 = \left[\frac{1 + \frac{A_1}{A_m}}{1 - \frac{A_1}{A_m}}\right]^2 \tag{5}$$

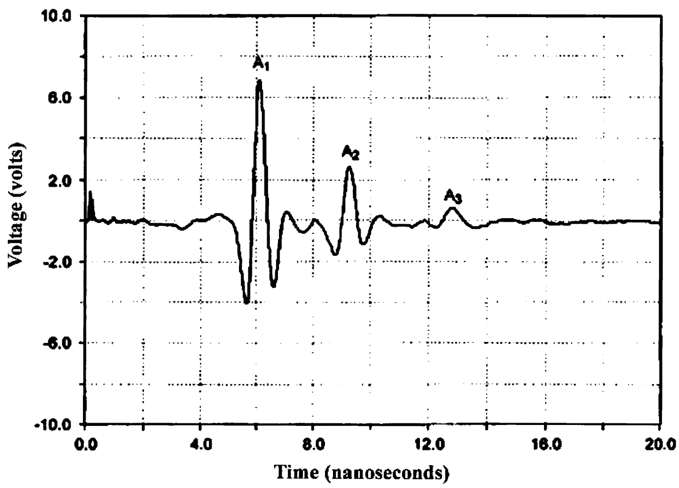

Fig. 5. GPR trace measured with a 1 GHz horn antenna [23].

where ε_1 is the dielectric value of the AC surface layer, A_1 is the amplitude of the reflection at the air/pavement interface, and A_m is the amplitude of the reflection from a large metal plate. In particular, A_m is the amplitude of the incidental GPR signal, which is determined by collecting GPR data over a large flat metal plate placed on the pavement surface. Since metal is a good conductor, it can be considered as a perfect EM reflector. Thus, the metal plate's reflected signal can be assumed to be equal to the reverse of the incidental GPR signal. The calibration measurement of the metal plate is usually conducted either at the beginning or at the end of the GPR survey.

Furthermore, the dielectric value ε_2 of the base layer can be computed as follows:

$$\varepsilon_2 = \varepsilon_1 \left[\frac{1 - \left(\frac{A_1}{A_m}\right)^2 + \left(\frac{A_2}{A_m}\right)}{1 - \left(\frac{A_1}{A_m}\right)^2 + \left(\frac{A_2}{A_m}\right)} \right]^2 \tag{6}$$

where ε_2 is the dielectric value of the base layer (second layer) and A_2 is the reflection amplitude from the top of the base layer in volts. The back reflection at the first air/pavement interface (A_1) and the amplitude of the incidental GPR signal (A_m) are also considered.

In general, the dielectric value ε_n of the nth layer for $n > 2$ is computed as follows [24]:

$$\varepsilon n = \varepsilon n - 1 \left[\frac{1 - \left(\frac{A_1}{A_m}\right)^2 + \sum_{i=1}^{n-2} \gamma i \frac{Ai+1}{Am} + \frac{An}{Am}}{1 - \left(\frac{A_1}{A_m}\right)^2 + \sum_{i=1}^{n-2} \gamma i \frac{Ai+1}{Am} - \frac{An}{Am}} \right]^2 \tag{7}$$

where n is the number of pavement layers, A_n is the reflection amplitude of the nth layer interface, ε_n is the dielectric value of the nth layer, and γ_i is the reflection coefficient at the ith layers interface. It should be noted that in the above formulation, pavement layers are assumed to be homogenous and to be composed of lossless material [24].

However, the equations that are used for the computation of the dielectric values do not consider the attenuation of the GPR signal with increased propagation distance. This has no particular impact towards the accuracy of the dielectric value referred to the initial air-surface reflection, as the attenuation of the GPR signal in air is rather low. However, signal attenuation in the pavement subsurface layers is not negligible and may reduce the accuracy of the dielectric value dictated from amplitude data recorded for deeper pavement layers [23].

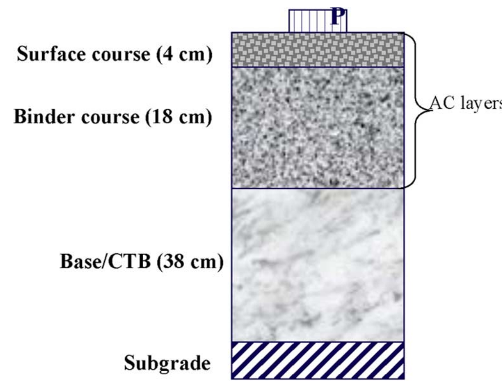

Fig. 6. Pavement design—vertical cross section.

The time difference measured between the reflections (i.e., the time delays between the reflections peaks) can be used in conjunction with the dielectric properties of the surveyed pavement layer to determine its thickness. The thickness of the AC layer can be computed according to (8)

$$h_1 = \frac{c \times \Delta t_1}{\sqrt{\varepsilon_1}} \tag{8}$$

where h_1 is the thickness of the asphalt layer and Δt_1 is the time delay between peaks A_1 and A_2 of Fig. 5.

The above equations have been proven to work efficiently for asphalt pavements. They assume that no attenuation of the GPR signal occurs in the surface layer. The analysis that follows and the related software are based on the principles and equations described above, which are consistent with ASTM standards [8].

III. Data Acquisition

For the purpose of the present research work, GPR data were acquired at two central frequencies, 1 and 2 GHz, using the air-coupled sensor system at the Laboratory of Highway Engineering at the National Technical University of Athens (NTUA). Both antennas have the same size ($21 \times 55.6 \times 49.5$ cm) and weight (7.3 Kg). GPR surveys were conducted on a heavily trafficked pavement section approximately 450 m in length, which had been recently rehabilitated and its surface was smooth. Fig. 6 shows a vertical cross section of the experimental pavement based on the considered pavement design. The pavement was described by the surface course and the binder course, which comprise the AC layers, the base, which consists of hydraulically bound materials in terms of cement treated base (CTB) [25] and the subgrade [26].

GPR surveys were implemented using the survey van shown in Fig. 7. The air-coupled antenna (1 or 2 GHz) was located at the front of the van. In addition, the van has a high-resolution distance measuring instrument (DMI) sensor connected to its

Fig. 7. GPR survey van.

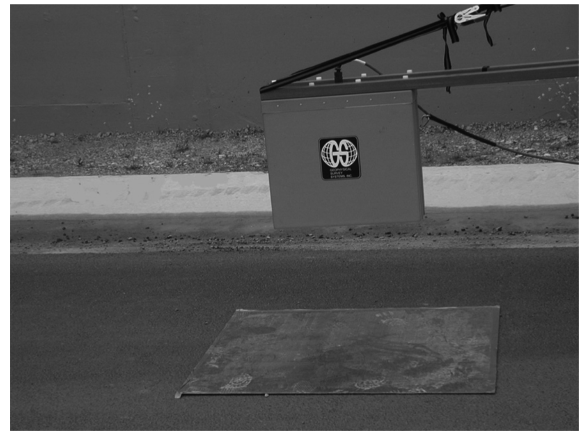

Fig. 8. Metal plate (calibration procedure).

back wheel that allows accurate triggering of the GPR scanning at user-fixed intervals. Also, a GPS system is usually connected to the GPR system in order to assign the basic position of test sections. It is worthwhile to mention that the sensor system in use possesses practical advantages for a large scale road survey, as road data is acquired at driving speeds eliminating the need for lane closures and providing a safer working environment. It can provide far more extensive measurement coverage at orders of magnitude less cost.

In general, the measuring procedure is simple. The equipment is mounted on the survey vehicle, also making the necessary connections. The distance between the antenna and the pavement surface is fixed at approximately 50 cm. The GPR system is switched on and left to warm up for a period of 20–25 min and a calibration file is created. The calibration file is essential for the calculation of Am used in (5)–(7). It determines the reflection amplitude of a large metal plate (Fig. 8). Then, the system is set to scan the road section under survey using the proper software [27].

A major concern during data acquisition was for the pavement surface to be dry in order to avoid the possible influence of water presence on collected data. GPR surveys were recorded two times under the similar conditions in order to ensure repeatability of the collected data [28]. The repeated tests, which are independent of exact pavement layer properties, demonstrated that both horn antennas (i.e., 1 and 2 GHz) collected data in the same way.

After GPR testing, one drilled asphalt core was extracted approximately every 100 m (in total four cores) at positions where the horn antennas had passed. The surface course thicknesses measured on the cores were about 4 cm, while the thicknesses of the binder course ranged between 16 and 18 cm approximately. The ground truth data (measured thicknesses) are used in the following for the investigation of the GPR thickness accuracy.

IV. Data Analysis

A. GPR Data Interpretation

Using an appropriate analysis tool [29], the GPR data was analyzed in order to identify the interfaces of the pavement layers. The raw data went through a filtering process in order to amplify the GPR signal and to remove any possible interpolations, i.e., any kind of noise that affects the signal. Specifically, vertical and horizontal filtering was applied on the collected data. The vertical filtering operation created a bandpass filter in the time-domain for local noise and interference removal. This operation can also be used to remove random high-frequency noise and signal wowing. A high-pass of 500 MHz was used for setting the bottom limit for frequencies, while a low-pass of 2000 MHz was used for setting the top limit for passed through frequencies. Furthermore, scan views are rapid and not smooth lines. So, a horizontal filter is used in order to remove the rapid changes of the scans; no relation to thickness variation is involved. The horizontal filtering is defined as the number of scans. A low-pass of five scans was used in order for the rapid changes of the scans to be smoothened.

After filtering, the color transform was changed to emphasize low amplitude sections and make pavement layers more visible. Fig. 9 shows the interpretation of the data collected using the 1 GHz antenna, as well the interpretation of the data collected using the 2 GHz antenna. Differences between the two types of data are clear. Using the 1 GHz antenna, the total AC pavement layers, as well as the pavement base are interfaced. On the contrary, the resolution of the 2 GHz antenna is higher, but the penetration depth is lower than the 1 GHz antenna. So although it can be used for the detection of the surface course and the thicker binder course, it is impractical for the interpretation of the base layer (Fig. 10).

B. Dielectric Values Estimation and Analysis

As mentioned above, the air-coupled sensor system is consistent with the impulse technique. It transmits a short electromagnetic pulse in the subsurface. The pulse travels through the pavement's layers and reflects off surfaces or objects, which represent discontinuities in dielectric properties, for instance, different materials or changes in either the moisture content or density. In other words, whenever there is a contrast in the dielectric values of the pavement materials the reflected pulses from the internal pavement interfaces are recorded.

Based on the GPR data interpretation and related equations, the dielectric values of the asphalt layers are estimated. Fig. 11

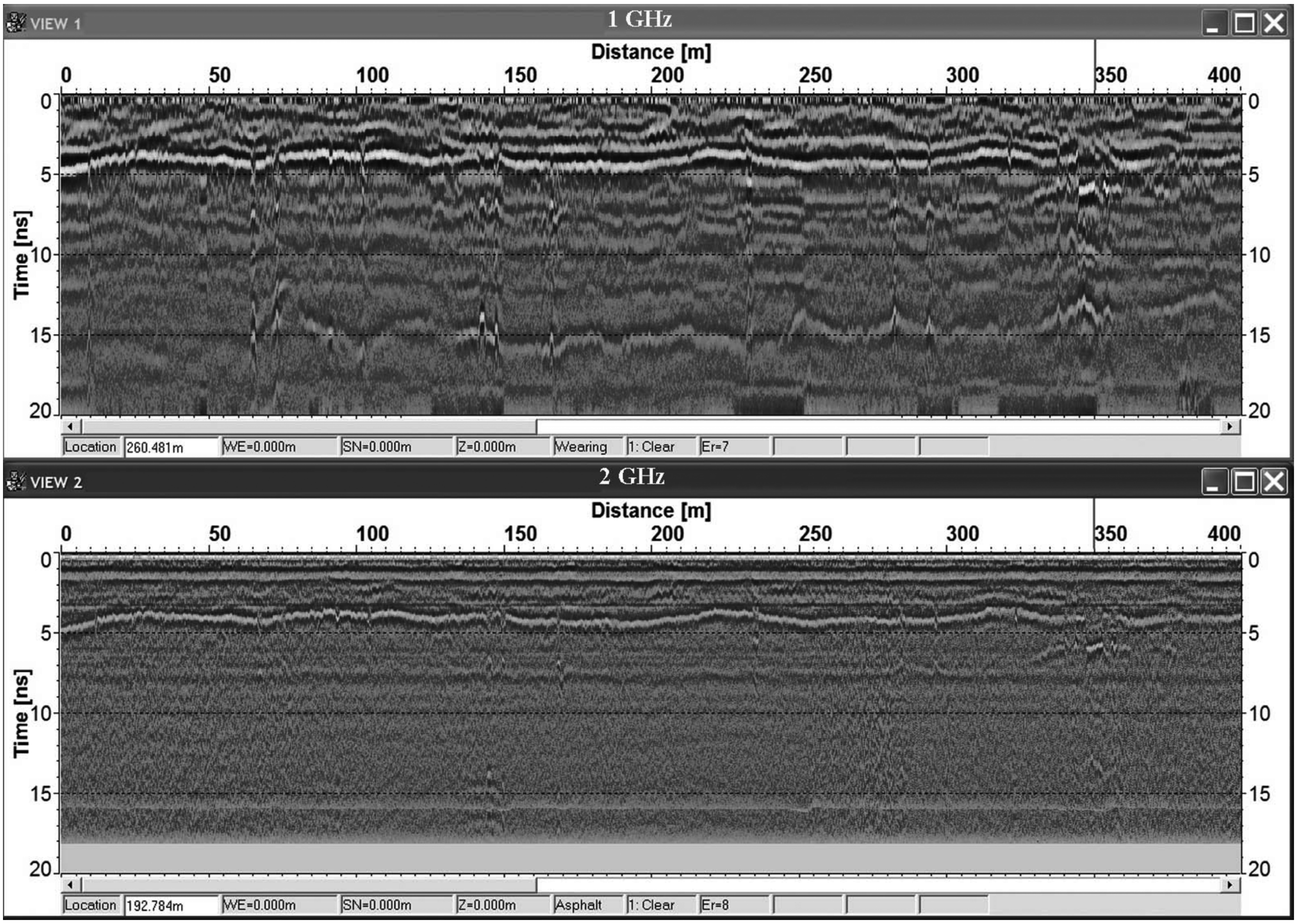

Fig. 9. Comparison of 1 and 2 GHz antennas data.

illustrates the dielectric values of the uniform AC layer estimated based on the data collected using 1 GHz. The average value of the estimated dielectric values is 7.08 with a standard deviation of 0.27. Some local variations are noted but are not considered as significant for the analysis. The low standard deviation indicates that the average dielectric value is representative of the uniform AC layer material along the experimental pavement section.

In addition, Fig. 12 illustrates the dielectric values estimated based on the 2 GHz antenna data. Specifically, the dielectrics of the surface course in comparison with the dielectrics of the AC layer underneath (binder course) are shown. The dielectric values of the surface course are lower than the ones of the binder course; the average dielectric value of the surface course is 6.27, while the one of the asphalt base is 6.93. In addition, the standard deviations are 0.21 and 0.29, respectively. The low standard deviations indicate that the average dielectric values are representative of the considered layer materials along the experimental pavement section. The higher air-void percentage of the semi-open graded surface course mixture produces evidence in support of the statement that the related dielectric values are lower than the ones of the binder course.

When compared with the 1 GHz results, the higher resolution of the 2 GHz ties in the estimation of lower dielectric values. The measurement of the dielectric value based on the initial air-surface reflection represents the semi-open graded surface material as the 2 GHz dielectric oriented measurement depth is limited. Consequently, according to the GPR reflection technique, the estimated dielectric value of the binder course is affected by the dielectric value of the surface material, while its accuracy may be reduced due to the signal attenuation.

C. Thickness Estimation and Analysis

Following the interpretation of the GPR data and estimation of the dielectric values, the asphalt pavement layer thicknesses were computed. In Fig. 13, the estimated GPR thicknesses of the uniform AC layer are compared with the measured core thicknesses (reference data) at the four test locations of the experimental pavement section. In every case, GPR thickness are higher than the core measured values. In addition, the thickness provided by the 2 GHz antenna data analysis seems always to be higher.

The related GPR thickness errors found for all test locations are summarized in Fig. 14. These errors range between 4.62% and 8.25% for the 1 GHz antenna data, while for the 2 GHz antenna they range between 10.19% and 12.96%. For the first case, the errors are rather low and consistent with international experience, which suggests differences between thicknesses measured on core and GPR estimated thicknesses [14], [15]. For the later case, the errors might be considered as rather high. These

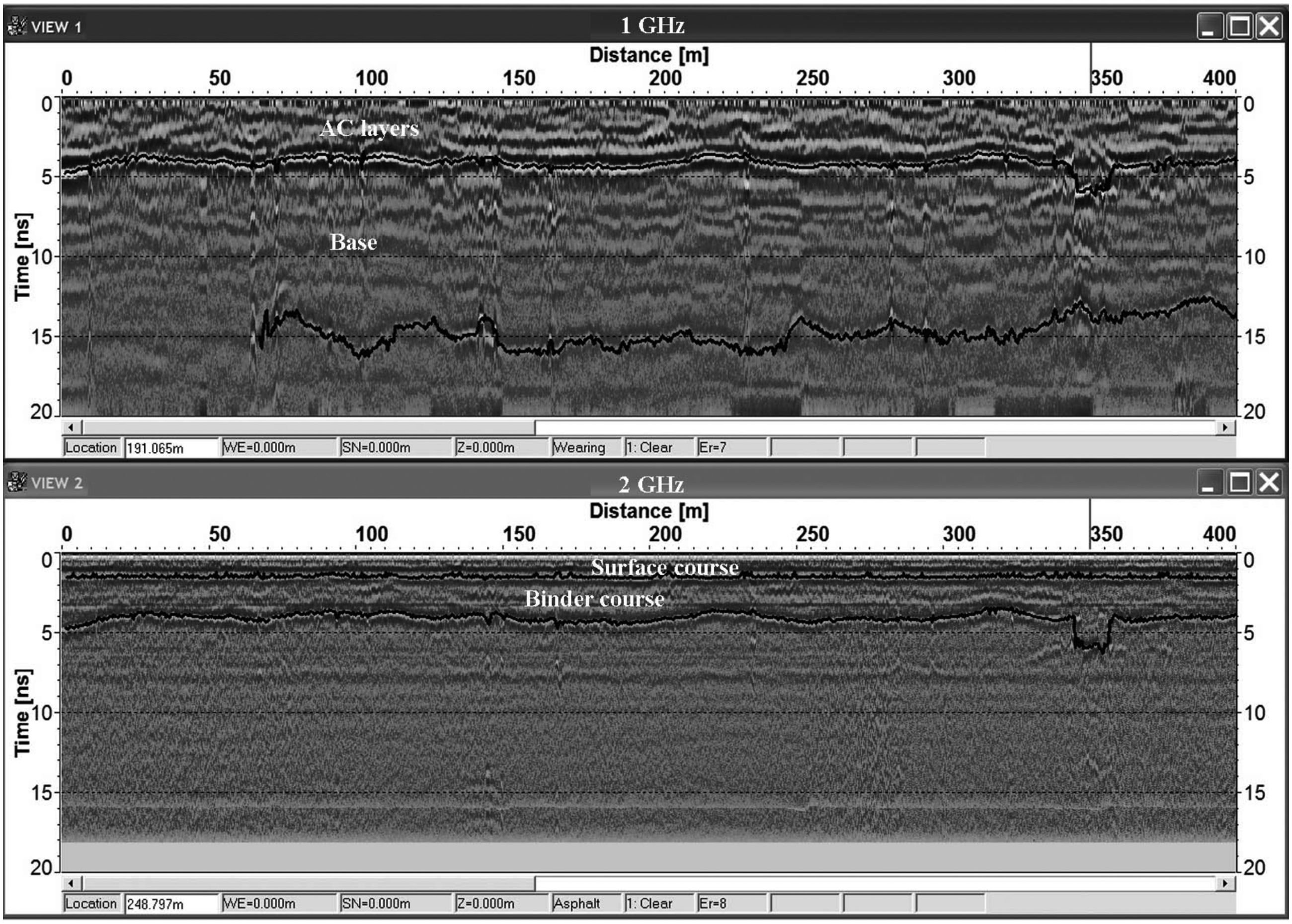

Fig. 10. Interpretation of pavement layers.

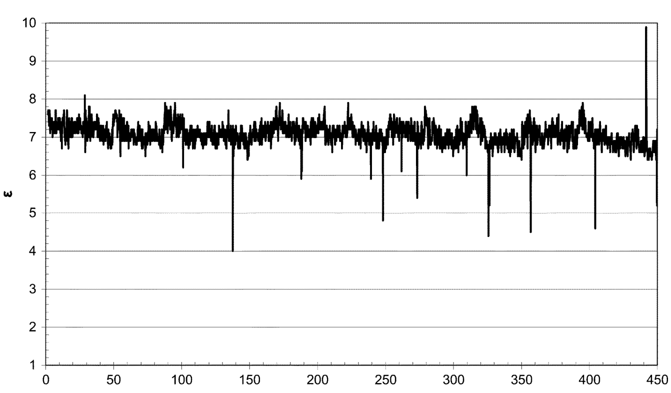

Fig. 11. Dielectric values of the total asphalt layers −1 GHz data.

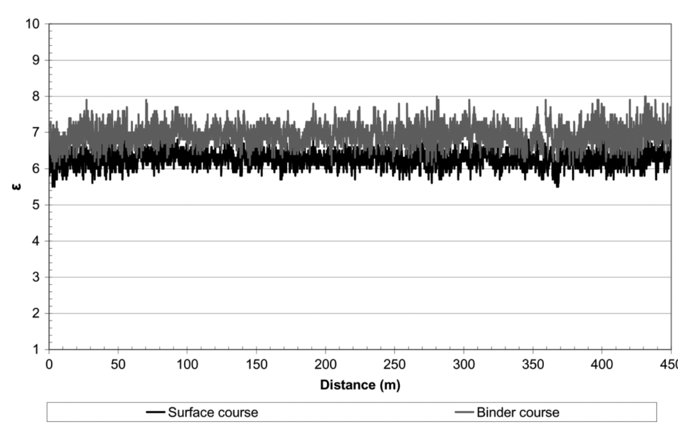

Fig. 12. Dielectric values −2 GHz data.

higher thickness errors correspond to the lower dielectric values measured with the 2 GHz antenna. These lower dielectric values result from the contribution of the lower dielectric values of the surface course in the estimation of the binder course dielectric values [see also (7)]. It is mentioned that the estimated thickness errors might be less if the dielectric values were obtained using calibration cores [16]. However, this issue is beyond the scope of the present research. Further investigation of the analysis results using a larger scale of data, which will enable statistical evidence, is needed; these data must be based on extended GPR measurements on different pavement sections and additional cores.

The 2 GHz antenna data seems to be more valuable when the surface course is investigated. Fig. 15 shows the comparison of the estimated 2 GHz surface course thicknesses with the respective measurements of core thicknesses. This comparison analysis encourages the use of the 2 GHz sensor antenna for the estimation of the surface course thickness as the related error is less that 4% for all cases. This error could be considered as a

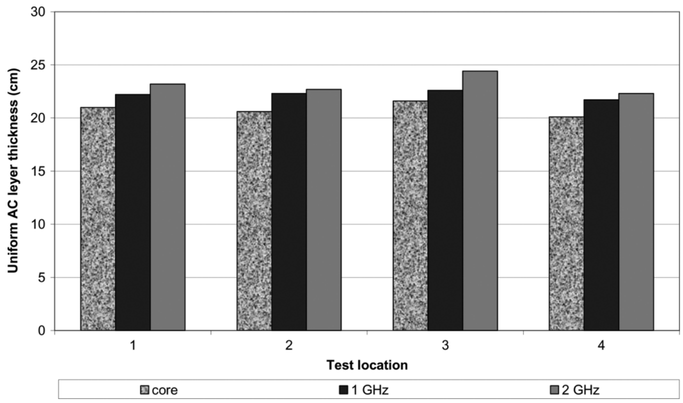

Fig. 13. Comparison of GPR thicknesses with core thicknesses.

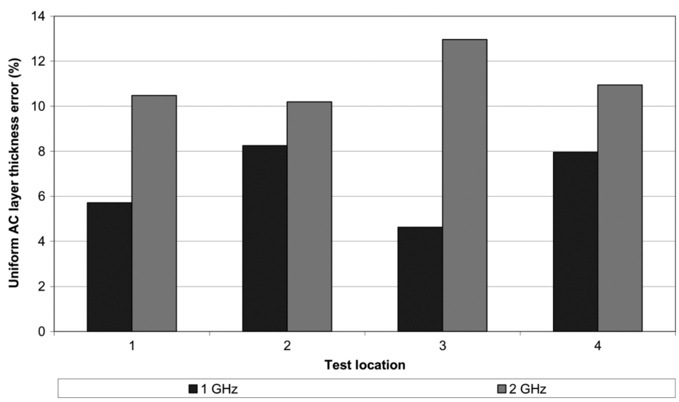

Fig. 14. Estimated GPR thickness error.

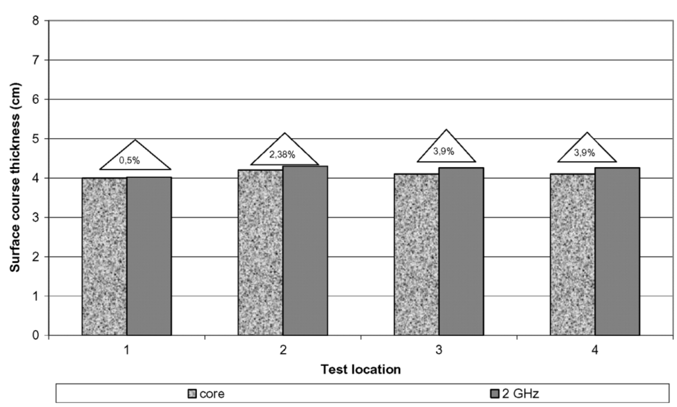

Fig. 15. Estimated against measured surface course thicknesses and related errors (%).

statement that the resolution of the 2 GHz antenna deals well with depths up to 4 cm.

V. Concluding Remarks

GPR is a nondestructive sensor technique for locating structural objects and assessing, among others, pavement layer thicknesses and related material properties. A variety of GPR systems have been developed appropriately to suite the type of pavement survey. Air-coupled antenna pavement data can be collected at driving speeds and can be used to determine the dielectric values and estimate the thickness of the upper pavement layers. Although the penetration depth of air-coupled antenna is usually limited, this is not a drawback for the evaluation of the asphalt pavement layers.

Two GPR horn antennas at different central frequencies (1 and 2 GHz) were used for sensing the subsurface of the trial heavy-duty asphalt pavement section under investigation. Both antennas operated well at driving speeds and supported the repeatability of the collected data. The use of the 1 GHz antenna seemed to provide adequate information for the total pavement structure, at least down to the level of the base/subgrade interface, while the resolution of the 2 GHz antenna limited the subsurface investigation down to the level of the AC layers/base interface.

Focusing on the detection of AC pavement layers, it is proved that the 1 GHz horn antenna provides slightly higher dielectric values than the 2 GHz. This produces evidence in support of the statement that the lower dielectric values of the surface course, which is signalized by the 2 GHz antenna, affect the dielectric values estimation of the binder course in this case. Also, based on the 1 GHz antenna data, the thickness of the total AC pavement layer can be estimated with accuracy as the related errors, with reference ground truth data, are acceptable; for this reason, the estimated thicknesses can be exploited either for further pavement mechanistic analysis or for pavement management purposes. However, when specific focus is given for the quality control of the pavement surface course, the 2 GHz antenna can be used effectively. So, although the total AC layer thicknesses estimated through the 2 GHz data differ significantly from the ground truth data values, the computed thicknesses errors of the surface course are rather low. It is believed that the 2 GHz GPR horn antenna technique for sensing pavement subsurface might be suitable and extended for sensing other pavement characteristics such as the *in situ* void content of the AC surface course mixture.

The best way for the involvement of the two in question sensor antennas is for the clarification of the purpose of the pavement monitoring and evaluation. The lower frequency antenna (i.e., 1 GHz) seems to cover the needs for pavement analysis, while the higher frequency antenna (i.e., 2 GHz) is more advantageous for a profound evaluation of the surface course, which is rather occult for usual GPR surveys at driving speeds.

References

[1] O. Duran, K. Althoefer, and L. D. Seneviratne, "State of the art in sensor technologies for sewer inspection," *IEEE Sensors J.*, vol. 2, no. 2, pp. 73–81, 2002.

[2] R. M. Morey, "Ground penetrating radar for evaluating subsurface conditions for transportation facilities," in *Transportation Research Board, National Research Council: NCHRP Synthesis 255*. Washington, D.C.: National Academy Press, 1998.

[3] K. R. Maser, "Ground penetrating radar surveys to characterize pavement layer thickness variations at GPS sites," Strategic Highway Research Program, National Research Council, Washington, D.C., Rep. SHRP-P-397, 1994.

[4] T. Scullion, C. L. Lau, and Y. Chen, "Pavement evaluations using ground penetrating radar," in *Proc. 5th Int. Conf. Ground Penetrating Radar*, Kitchener, ON, Canada, 1994, vol. 1, pp. 449–463.

[5] T. Alongi, G. G. Clemena, and P. D. Cady, "Condition evaluation of concrete bridges relative to reinforcement corrosion," Strategic Highway Research Program, National Research Council, Washington, D.C., Rep. SHRP-S/FR-92-105, 1992, vol. 3.

[6] T. Scullion, C. L. Lau, and Y. Chen, "Implementation of the Texas ground penetrating radar system," Dept. Transportation, TX, Rep. No. FHWA/TX-92/1233-1, 1992.

[7] A. Benedetto, F. Benedetto, M. R. De Blassis, and G. Giunta, "Reliability of signal processing technique for pavement damages detection and classification using ground penetrating radar," *IEEE Sensors J.*, vol. 5, no. 3, pp. 471–480, 2005.

[8] "Standard test method for determining the thickness of bound pavement layers using short-pulse radar," in *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for Testing and Materials, 2005, ASTM, D4748-98.

[9] T. Scullion and T. Saarenketo, "Integrating ground penetrating radar and falling weight deflectometer technologies in pavement evaluation," in *ASTM STP 1375, Nondestructive Testing of Pavements and Backcalculation of Moduli*, S. D. Tayabji and E. O. Lukanen, Eds. West Conshohocken, PA: American Society for Testing and Materials, 2000, pp. 23–37.

[10] J. Roberts, R. Roper, and A. Loizos, "A new engine for the implementation of HDM technology for road infrastructure analysis," in *Proc. 6th Int. Transp. Res. Board Con. Pavement Management Systems*, Brisbane, 2004, pp. 1–79.

[11] M. Hartman, J. Baston-Pitt, A. Sedgwick, and G. Böhmer, "Pilot study assessing the feasibility of advanced ground penetrating radar in pavement assessment," in *Proc. 8th Conf. Asphalt Pavements for Southern Africa (CAPSA '04)*, Sun City, South Africa, 2004, pp. 1224–1229.

[12] W. M. K. Roddis, K. Maser, and A. J. Gisi, "Radar pavement thickness evaluations for varying base conditions," *Transp. Res. Record 1355*, pp. 90–98, 1992.

[13] M. Livneh and M. H. Siddiqui, "Assessment of radar technology for determining the thickness of pavement layers," in *Proc. 7th Int. Conf. Asphalt Pavements*, Nottingham, U.K., 1992, vol. 2, pp. 228–244.

[14] Loulizi, I. L. Al-Qadi, and S. Lahouar, "Optimization of ground penetrating radar to predict layer thicknesses in flexible pavements," *J. Transp. Eng. ASCE*, vol. 129, no. 1, pp. 93–99, 2003.

[15] I. L. Al-Qadi, S. Lahouar, K. Jiang, K. K. MeGhee, and D. Mokarem, "Validation of ground penetration radar accuracy for estimating pavement layer thicknesses," in *Proc. 84th Annu. Meeting of the Transp. Res. Board*, Washington, D.C., 2005, CD compendium.

[16] D. A. Willet, K. C. Mahboub, and B. Rister, "Accuracy of ground penetrating radar for pavement-layer thickness analysis," *J. Transp. Eng. ASCE*, vol. 132, no. 1, pp. 96–103, 2006.

[17] E. J. Jaselskis, J. Grigas, and A. Brilingas, "Dielectric properties of asphalt pavement," *J. Materials in Civil Eng. ASCE*, vol. 15, no. 5, pp. 427–434, Oct. 2003.

[18] K. Grote, S. Hubbard, J. Harvey, and Y. Rubin, "Evaluation of infiltration in layered pavements using surface GPR reflection techniques," *J. Appl. Geophys.*, vol. 57, pp. 129–153, 2005.

[19] Y. H. Huang, *Pavement Analysis and Design*, 2nd ed. Englewood Cliffs, NJ: Prentice-Hall, 2004.

[20] D. J. Daniels, *Ground Penetrating Radar*, 2nd ed. London, U.K.: The Institution of Electrical Engineers, 2004, IEE Radar, Sonar and Navigation Series 15.

[21] I. L. Al-Qadi, S. Lahouar, K. Jiang, and T. E. Freeman, "Effects on asphalt aging on hot-mix asphalt dielectric constants," in *Proc. 83th Annu. Meeting of the Transp. Res. Board*, Washington, D.C., Jan. 11–15, 2004, CD compendium.

[22] J. Q. Shang and J. A. Unama, "Dielectric constant and relaxation time of asphalt pavement materials," *J. Infrastructure Syst. ASCE*, vol. 5, no. 4, pp. 135–142, Dec. 1999.

[23] T. Saarenketo and T. Scullion, "Road evaluation with ground penetrating radar," *J. Appl. Geophys.*, vol. 43, pp. 119–138, 2000.

[24] I. L. Al-Qadi and S. Lahouar, "Use of GPR for thickness measurement and quality control of flexible pavements," *J. Assoc. Asphalt Paving Technologists*, vol. 73, 2004, CD Compendium.

[25] "Hydraulically bound mixtures," in *European Standards*, 2005, EN, EN 14227-1.

[26] FEHRL, "A guide to the use of long-life fully-flexible pavements," FEHRL Rep. 2004/1, Brussels, Belgium.

[27] GSSI, Radan for Windows: User's Manual Geophysical Survey Systems, Inc., 2001.

[28] V. Hopman and E. Beuving, "Repeatability, reproducibility and accuracy of GPR," in *Proc. Bearing Capacity of Roads, Railways and Airfields Conference*, Lisbon, Portugal, Jun. 24–26, 2002, vol. 2, pp. 637–645.

[29] Roadscanners, "Road Doctor: User's Guide," Roadscanners Oy, 2001.

Andreas Loizos received a Diploma degree in civil engineering from the National Technical University of Athens (NTUA), Athens, Greece, and the Dr.-Ing. degree in pavement engineering from the University of Hannover, Hanover, Germany, in 1986.

He is a Professor at the Department of Transportation Planning and Engineering and Director of the Laboratory of Highway Engineering of NTUA. He is a member of several international committees and has been involved in several research programs at national and international level. He has given internationally a number of invited presentations and has published numerous papers and technical reports; his contributions have appeared in international journals on Transportation Engineering and several International Conference Proceedings. His main interests include road and airfields pavement engineering, as well as railway track assessment, functional and structural evaluation of pavements, NDT's and monitoring systems, pavement rehabilitation, performance, and durability of pavement materials.

Christina Plati received the Civil Engineer degree from the National Technical University of Athens (NTUA), Athens, Greece. She is currently working towards the Ph.D. degree in pavement engineering at NTUA.

She is a Research Associate in the Laboratory of Highway Engineering, Department of Transportation Planning and Engineering, NTUA, since 1999. Her main research interests lie in nondestructive testing (NDT) techniques and mechanistic analysis tools for pavement evaluation.