Available online at www.sciencedirect.com
ScienceDirect
NDT&E International 40 (2007) 147–157
NDT&E international
www.elsevier.com/locate/ndteint

Accuracy of pavement thicknesses estimation using different ground penetrating radar analysis approaches

Andreas Loizos[a,*], Christina Plati[b]

[a]Laboratory of Highway Engineering, National Technical University of Athens (NTUA), 5, Iroon Polytechniou St., Zografou, Athens 15773, Greece
[b]Department of Transportation Planning and Engineering, National Technical University of Athens (NTUA), 5, Iroon Polytechniou St., Zografou, Athens 15773, Greece

Received 2 March 2006; received in revised form 28 July 2006; accepted 1 September 2006
Available online 7 November 2006

Abstract

The Ground Penetrating Radar (GPR) is a Non-destructive Testing (NDT) technique, which is able to capture continuous pavement layer thicknesses data. The radar pulse propagation is a major factor for gathering the dielectric constants of pavement materials accurately. The present research focuses on the accuracy of pavement asphalt layer thicknesses estimation using GPR data analysis by employing different estimation approaches based on material dielectric properties. A comprehensive comparative analysis of GPR and asphalt-drilled cores data incorporating a variety of pavements is performed. The major findings of the detailed comparative analysis including the effectiveness of the approaches used are reported and discussed in the present paper.

Keywords: GPR; NDT; Dielectric constants; Pavement asphalt layer thickness

1. Background and objectives

Many aspects of pavement engineering and road management require information on pavement layer thicknesses [1]. Pavement thickness measurements are necessary for quality control purposes for new, reinforced or rehabilitated road pavements. Mechanistic analysis techniques require pavement layer thickness data input in order to model pavement performance. Layer thickness information is also needed as an input to other non-destructive techniques, such as the Falling Weight Deflectometer (FWD) [2]. Furthermore, the layer thickness information is of high interest when a Pavement Management System (PMS) is applied at road network level [3].

Traditionally, pavement layer thicknesses have been determined by digging test-pits or by extracting cores from the pavement. Granular or soil layer thicknesses have also been determined by using Dynamic Cone Penetrometer (DCP) measurements, however, difficulties to distinguish interfaces between base and sub-base unbound layers and penetration refusal through stabilized layers have limited DCP to weaker pavement structures. These procedures are not only time consuming and expensive, but also result in major traffic disruptions; while on the other hand they provide information solely on the test points, so uncertainty remains regarding the conditions between these test points [4].

Ground Penetrating Radar (GPR) is a pulse Non-destructive Testing (NDT) method for locating structural objects and assessing, among others, pavement material layer thicknesses and properties. The history of GPR tests on road surveys goes back to the mid-1970s, when according to Morey [5], the USA 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 [5]. Since then, many applications concentrated on pavement thickness measurements as stated among others by Maser [6], Scullion et al. [7], Alongi et al. [8] and Scullion et al. [9].

The GPR technology has led to a powerful NDT technique capable of collecting layer thickness data at

*Corresponding author. Tel.: +30 210 7721341; fax: +30 210 8078692.
E-mail addresses: aloizos@central.ntua.gr (A. Loizos), cplati@central.ntua.gr (C. Plati).

0963-8695/$ - see front matter
doi:10.1016/j.ndteint.2006.09.001

short spatial intervals and at usual highway traffic speed. Quite significant research has been conducted to evaluate the accuracy of thickness estimation through the GPR technique. In most cases, comparison with respective in situ core data (ground truth data) provided some encouraging results. GPR proves to be a proper tool for road surveying since the calculated errors, especially in the case of new pavements, ranged within acceptable levels for practical applications [6,10–14].

However, when high accuracy is needed in particular, there are still problems and difficulties often encountered in practice. The error levels can vary from case to case. The layer interfaces can be detected more effectively when there is significant contrast between the dielectric properties of the materials involved [12]. Moreover, the results in different pavement types contradict. Saarenketo and Scullion [15] state that the GPR technique can provide better thickness data for new or defect-free flexible pavements, while Al-Qadi et al. [14] calculated a lower thickness error on plain concrete rigid pavements. However, empirical evidence has shown that there are materials used in pavement layers that might reduce the radar penetration or affect the dielectric properties estimation and give erroneous results.

The two most important factors affecting the propagation of radar pulses in any material are the electrical conductivity and the dielectric constant [16]. The present paper focuses on the later by investigating different approaches in order to attain reliable asphalt pavement layer thickness estimation. This was achieved through a comprehensive field experiment implemented by the Laboratory of Highway Engineering of the National Technical University of Athens (NTUA) on a variety of in-service pavements, which comprise a representative sample of Highway pavements. The major findings of the investigation and the related analysis are presented and discussed in the following sections.

2. Principles of GPR operation

The RADAR (**RA**dio **D**etecting **A**nd **Ra**nging) is a well-established NDT technique that uses radio waves to detect objects and determine their distance from echoes they reflect. The GPR is specialized radar for the detection and location of targets in the 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—to be discussed later.

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 to be easily positioned over the area under investigation. The transmit/receive unit consists of a transmitter for signal generation, a receiver for signal detection and timing electronics for synchronizing the transmitter and the 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.

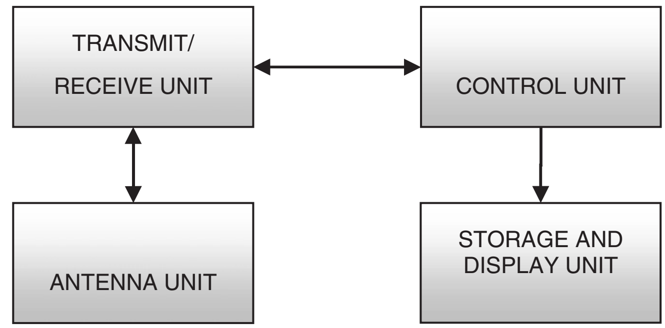

Fig. 1. Primary components of a GPR system.

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 highway speeds (up to 80 km/h approximately). The drawback is that the penetration depth is limited. In the ground-coupled systems, the antennas must have a close contact to ground of a few cm, with no need to have a direct contact. They can be moved similar (but with less velocity) to air coupled antennas. Also, in case of quantitative analysis of amplitudes, the distance between ground couples antenna and surface must be constant. However, the general rule is that the higher the GPR operating frequency, the higher the resolution and the smaller the depth of investigation [5].

In light of the above, the air-coupled systems are becoming increasingly popular for the evaluation of the upper part of the pavement structure, while the ground-coupled systems are used in order to get information from the entire pavement structure up to 3 m approximately. An air-coupled GPR system, which is consistent with the impulse technique, was also used for the purpose of the present investigation. The 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 constants of the pavement materials the reflected pulses from the internal pavement interfaces are recorded. Furthermore, the estimation of the dielectric constant of pavement layers is based on the amplitudes of the reflected pulses collected by an air-coupled GPR system, at highway speeds [17]. The dielectric constant is the ratio of the capacitance, with an insulating material between the plates of a capacitor, to the capacitance with air insulation. As a reference, air has a dielectric constant of 1, while other materials have higher values.

Fig. 2 shows an example for the case of a flexible pavement where the reflections from the top of the asphalt layer, the asphalt/granular layers interface and the granular/subgrade layers interface are recorded. These reflections depend on the velocity (v_i) of the waves propagation (see Fig. 3), which is governed by the dielectric properties of the materials as a function of the dielectric constant of the material mixture. It is worthwhile to be mentioned that the dielectric properties of asphalt layers depend slightly on the compaction during construction and thus on the pore/void content of the final layer material, as well on the water content.

The intensity of the recorded reflections is proportional to the strength of the contrast in dielectric properties between pavement layers. The amplitudes of these reflections, called A_1, A_2 and A_3 in Fig. 4, are used for the computation of the layer properties. However, the intensity of the reflection between two pavement layers does not only depend on the difference of its dielectric properties, but also on the interface itself. For instance in Fig. 4 the amplitude A_1 is related to the reflection at the interface air/asphalt. It is worthwhile to be mentioned that in case of a high pore content or delimitation at the interface, the reflectivity varies.

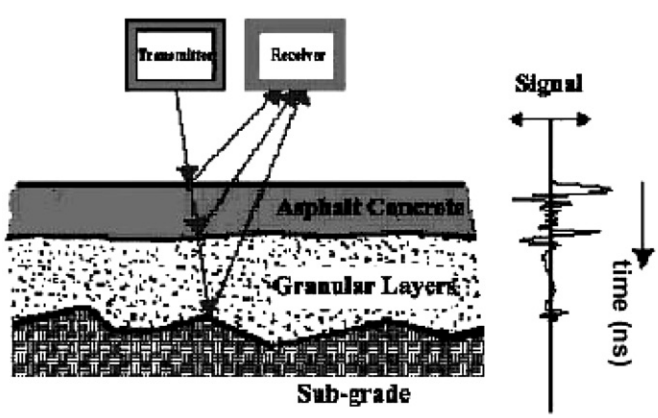

Fig. 2. The GPR principle in pavements.

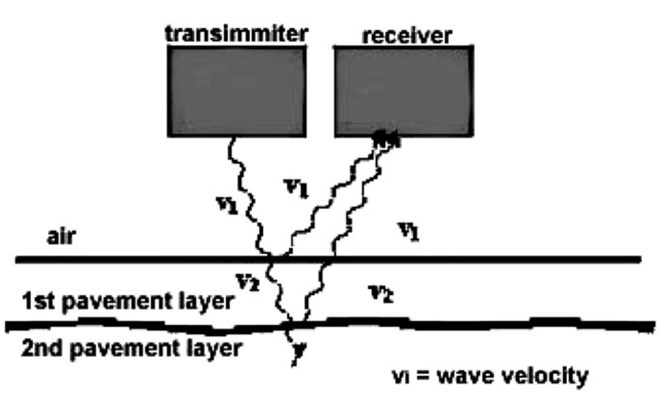

Fig. 3. Determination of pavement layer thickness.

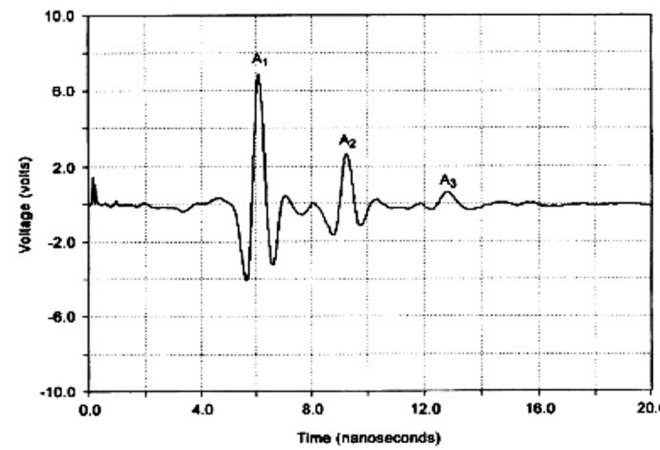

Fig. 4. GPR trace measured with a 1 GHz Horn Antenna [15].

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

$$\varepsilon_1 = \left[\frac{1 + (A_1/A_\mathrm{m})}{1 - (A_1/A_\mathrm{m})}\right]^2, \tag{1}$$

where ε_1 is the dielectric value of the asphalt surfacing layer, A_1 is the amplitude of the reflection from the surface in volts and A_m is the amplitude of the reflection from a large metal plate in volts. In particular, A_m is the amplitude of the incidental GPR signal, which is determined by collecting GPR data over a large and 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 constant ε_2 of the base layer can be computed as follows:

$$\sqrt{\varepsilon_2} = \sqrt{\varepsilon_1} \times \left[\frac{1 - \left((A_1/A_\mathrm{m})\right)^2 + \left((A_2/A_\mathrm{m})\right)}{1 - \left((A_1/A_\mathrm{m})\right) + \left((A_2/A_\mathrm{m})\right)}\right], \tag{2}$$

where ε_2 is the dielectric of the second layer (e.g. base layer) and A_2 is the reflection amplitude from the top of the base layer in volts, which is affected by the back reflection at the first interface air/asphalt, i.e. the first pavement layer of Fig. 3.

In the formulation of the Eq. (2), the pavement layer is assumed to be rather homogenous. Therefore, the dielectric constant of the layer is assumed to be constant in the sense that it does not vary within the layer thickness. Also this formulation assumes that no attenuation of the GPR signal occurs in the surface layer.

The travel time of the transmit pulse within a pavement layer can be used in conjunction with the dielectric properties of the surveyed layer to determine its thickness.

The thickness of the asphalt layer can be computed according to

$$h_1 = \frac{c}{\sqrt{\varepsilon_1}} \times \frac{\Delta t_1}{2}, \tag{3}$$

where h_1 is the thickness of the asphalt layer, c is the speed of the wave in air and Δt_1 is the time delay between the waveform peaks A_1 and A_2 of Fig. 4. Because the measured time between peaks represents the round-trip travel of the radar pulse, the thickness computation is based on the time (Δt_1) divided by 2.

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. However, since in some cases the top asphalt layer is relatively thin (less than 10 cm), also the spatial lateral distance between transmitting and receiving antennas might be considered in Eq. (3), especially when the receiver and the transmitter are different antennas. This issue needs further investigation beyond the limits of the present research study.

The analysis that follows and the related software are based on the principles and equations described above, which are consistent with the ASTM standards [18].

3. Assigning dielectric values

Based on the above the estimation of the dielectric values is crucial for the calculation of the pavement layers thicknesses. Assignment of the dielectric properties can be performed in several ways. One approach is the estimation of the dielectric values of the pavement layers materials based on the amplitudes of the reflected pulses collected by an air-coupled GPR system. This approach provides practical advantages, as it is a complete NDT technique that does not require road closures and drilling cores. Using advanced software for the analysis of the collected GPR data [19] the dielectric values can be estimated directly through the related equations mentioned in Section 2. For example, Fig. 5 shows the estimated dielectric values of an asphalt pavement layer, produced directly by the GPR "*field*" measurements using a 1 GHz air-coupled antenna, which is considered as a fully NDT procedure, and Eq. (1), varying along the pavement under investigation; they are referred thereinafter as ε_f.

In the case where road closures and core drillings are possible, the "travel time–core thickness" procedure for assigning the dielectric values of asphalt pavement layers can be applied, as referred among others by Livneh and Siddiqui [11]. The asphalt core thicknesses h_i are measured, the time intervals Δt_i are generated by the GPR measurements and the dielectric values of the asphalt pavement layer materials corresponding to the specific core locations are estimated through Eq. (1). These "*calculated*" dielectric values referred thereinafter as ε_c.

Furthermore, the dielectric values of pavement materials can be measured in the laboratory using the appropriate test system. One of these test systems is the Percometer, an instrument for the simultaneous and non-destructive measurement of the dielectric constant and the specific conductivity of materials. The measurement device is composed of the Percometer Central Unit (PM) and the measurement probe (Fig. 6) [20].

The conventional probe, used in the present study, is designed for measurements from the top or the bottom of the core material. The operating frequency for dielectric constant measurements ranges between 40 and 50 MHz, while the surface probe diameter is 50 mm. To ensure accuracy of the measurement it is crucial to check that the probe fits well on the surface to be measured. An average value of the dielectric measurements, denoted as ε_L, is usually considered representative of the dielectric properties of the core material(s) measured in the "*laboratory*".

The aforementioned approaches for estimating dielectric values are summarized in Table 1. They are considered in the present work for the calibration or/and calculation of

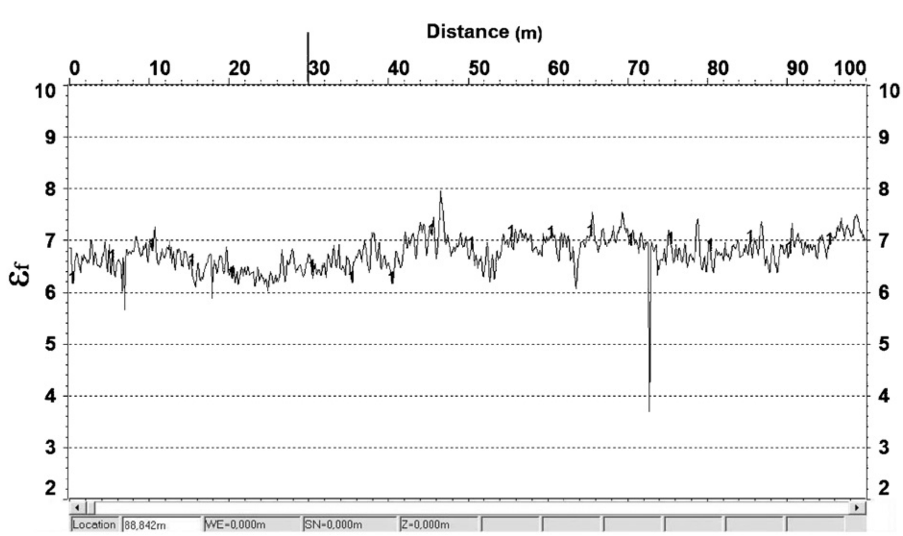

Fig. 5. Asphalt layer dielectric values.

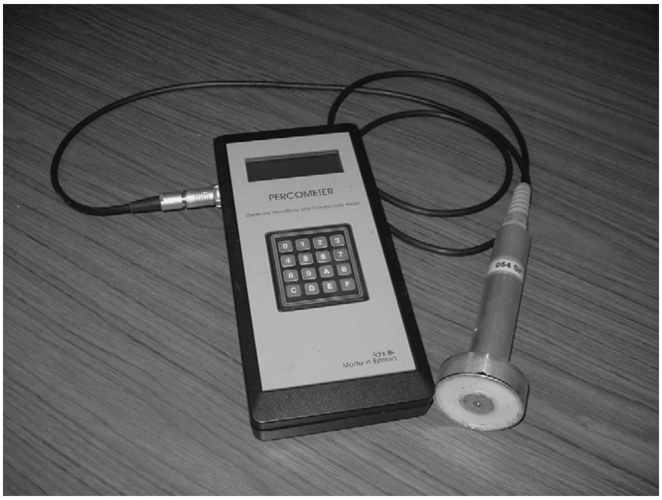

Fig. 6. The Percometer equipment.

Table 1
Different approaches for the estimation of the AC pavement layer dielectric values

	"Approach"		
	GPR (NDT)	Travel time–core thickness	Laboratory
Dielectric constant	ε_f	ε_c	ε_L

the wave propagation velocity (a function of dielectric value) in asphalt layers material. The collected GPR data has been elaborated and analyzed in order to determine the asphalt layer thicknesses.

4. Data collection

4.1. Description of test sections

Nine (9) asphalt pavement sections were selected for the purpose of the present research study. The basic selection criterion was the pavement structural homogeneity along the test sections, which were located in different parts of the Greek Highway Network and included asphalt pavements, i.e. asphalt layer(s) overlaying unbound and bound granular base over the subgrade. In other words the pavement modeling consists of three layers as shown in the simplified form of Fig. 2. The asphalt mixture was a typical asphalt concrete dense bituminous mixture as specified in [21]. All the pavements were new or rather new (0–5 years) or recently rehabilitated and free of defects, while various asphalt pavement layer thicknesses were considered. The length of each section varies from 1 to 5 km.

4.2. Field data collection

The ground penetrating radar NDT technique was used in this study to determine the asphalt layer properties of the specific test sections. The control unit of the GPR system of the NTUA was connected to a 1 GHz air-coupled horn antenna (Fig. 7a), which operates as a transmitter and receiver together and has a penetration depth ranging typically between 0.5 and 0.9 m) [22]. During the data collection the antenna must be suspended approximately 0.5 m above the pavement surface.

The GPR surveys were conducted using the test van of Fig. 7b at travel speed 80 km/h, approximately. The air-coupled antenna is located at the front of the van. In addition, the van has a high-resolution distance measurement instrument (DMI) sensor connected to its 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 the test sections. It is worthwhile mentioning that the GPR system used possesses practical advantages for a large-scale survey, as road data is acquired at highway speeds that eliminates the need for lane closures and provides a safer working environment.

In general, the measuring procedure is simple. After mounting the equipment on the survey vehicle and making the necessary connections, the GPR system is switched on and let to warm up for a period of 20–25 min. Then the system is ready to create the calibration file and the measuring phase. The calibration file is essential for the calculation of A_m used in Eqs. (1) and (2). It determines the reflection amplitude of a large metal plate (Fig. 7a). Then, the system is set to scan the road section under survey.

The GPR measurements were conducted in the heavy trafficked lane of the pavement test sections at the outer wheel path. The frequency of A-scans was ranging between 250 and 3000 MHz, while for the scanning the size of the time window, i.e. the time range was 25 ns. The same GPR measurements were repeated under the same conditions in order to ensure that the antenna collected the same data [13]. The repeated tests, which are independent of the exact pavement layer properties, demonstrated that the horn-antenna collected data in the same way. Moreover, a major concern during GPR survey was the pavement surface to be dry in order to avoid possible influence of the water or moisture presence on the collected data.

After GPR testing, at least two drilling asphalt cores were extracted from each test section depending on the road closures facilities. The cores were exactly drilled at marked positions where the horn antenna had passed. One asphalt core from each test section was used for laboratory measurements and further elaboration, while the remaining cores were used as reference thickness data (h_r).

4.3. Laboratory measurements

Nine (9) dry Asphalt Concrete (AC) cores were measured in the laboratory in order to record the related dielectric values. Primarily, the dielectric measurements were implemented by placing the Percometer probe on the

Fig. 7. The 1 GHz antenna and the survey van.

Fig. 8. Measuring dielectrics on the top of the asphalt core in the laboratory.

Fig. 9. Measuring dielectrics on the sub-cores in the laboratory.

"*top*" of the asphalt cores (Fig. 8), referred thereinafter as ε_{L-t}.

However, it is questionable whether the penetration depth of the Percometer test system is adequate to incorporate the entire core. Besides this, the international literature offers no clear evidence of the Percometer's penetrability. For this reason an additional laboratory NDT testing approach was performed by sawing the asphalt cores into sub-cores of approximately 5 cm thickness (Fig. 9).

Each core was carefully sawed in homogenous material mixes, which was possible due to the mix synthesis component of the entire asphalt core. Also, special care was given to ensure that the sawed surfaces were completely flat. Then, every sub-core was measured using the Percometer (Fig. 9) and a *mean* dielectric value, referred thereinafter as ε_{L-m}, for the entire core.

Both the "on top" measured dielectric values (ε_{L-t}) and the ones considered as the "mean" dielectric values of the sub-cores (ε_{L-t}) are used below, along with the ε_f and the ε_c values mentioned in Section 3, for the analysis of the collected GPR data and the evaluation of the asphalt layer thicknesses. All the aforementioned dielectric values and the related analysis procedures are applied accordingly to the selected homogenous pavement sections.

5. Analysis of GPR thickness data

The GPR data was analyzed further in order to compute the asphalt layer thicknesses of the pavement test sections using an appropriate analysis tool [19]. 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 band pass 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, scans view 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 number of scans. A low pass of 5 scans was used in order the rapid changes of the scans to be smoothened.

Following, the interface of the asphalt layers is determined. Fig. 10 shows an example of data interpretation, along with the asphalt/base course and the base/sub-base interface. After the interpretation, the thicknesses of the AC layers were computed according to Eq. (3) (Section 2). The estimated, through different approaches, dielectric values were used further to compute the thickness. Specifically, the thickness data based on the ε_f values is denoted as h_f. Also for each homogenous test section the isolated or the average ε_c values in case where the cores number is more than one were used for the estimation of AC thickness that referred thereinafter as h_c. Similarly the estimated AC thickness based on the ε_{L-t} values is denoted as h_{L-t} and based on the ε_{L-m} values is denoted as h_{L-m} (Table 2). Moreover, the thickness measured on the asphalt cores is referred thereinafter as h_r (*reference* thickness).

In Fig. 11, the estimated GPR thickness data are compared against the h_r thicknesses with respect to sixteen (16) test locations of the investigated pavement sections (*A–I*) wherefrom the cores had been extracted. The obtained h_{L-t} values vary substantially, especially when they are compared to the h_r thicknesses. This produces evidence in support of the statement that the dielectric values measured on the top of the asphalt core in the laboratory might not be representative of the entire specimen; for this reason, the h_{L-t} values are considered as a rather inaccurate thickness estimation approach. However, for comparative purposes, the values in question will be included in the subsequent analysis approach.

A deterministic relationship between the estimated GPR thickness values and the reference thicknesses is investigated through a simple statistical linear regression model. The linear models produced are illustrated in Figs. 12–15 for each case, respectively. In light of the specific analysis a linear relationship is conclusive since r^2 is greater than 0.95 in every case.

Furthermore, in order to investigate the significance of the thickness values differences, the paired *t*-test was applied [23]. Specifically, the paired *t*-test determined whether the measured and the estimated thicknesses differ from each other in a significant way. The basic assumptions taken into account were: (a) the samples are paired, (b) the sample differences can be viewed as a random sample from a population of differences and (c) the distribution of differences is approximately normal. The mean value of the difference population is denoted as μ_d. The paired *t*-test is summarized below:

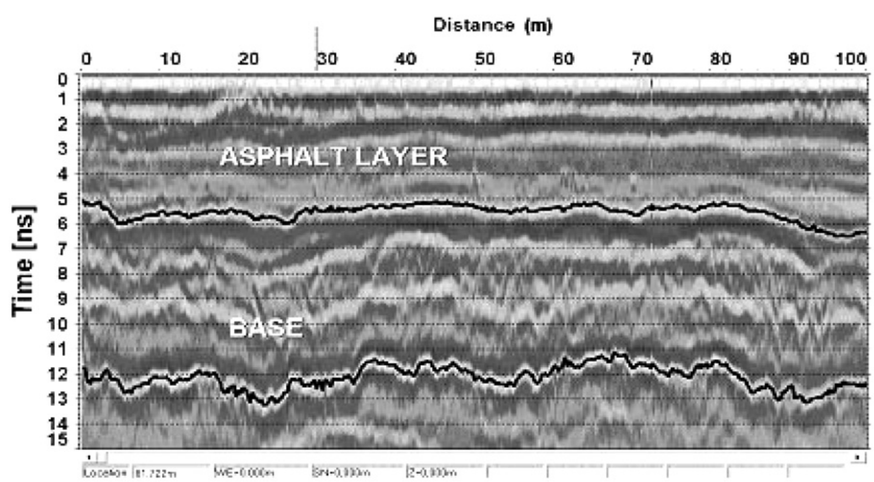

Fig. 10. Interpretation of GPR data.

Table 2
Estimated AC pavement layer thicknesses using different approaches

		AC thickness
Approach to the estimation of AC pavement layer dielectric values	Reference	h_r
	GPR	h_f
	Travel time–core thickness	h_c
	Laboratory (measurement on the top of the AC core)	h_{L-t}
	Laboratory (mean value of the sub-cores)	h_{L-m}

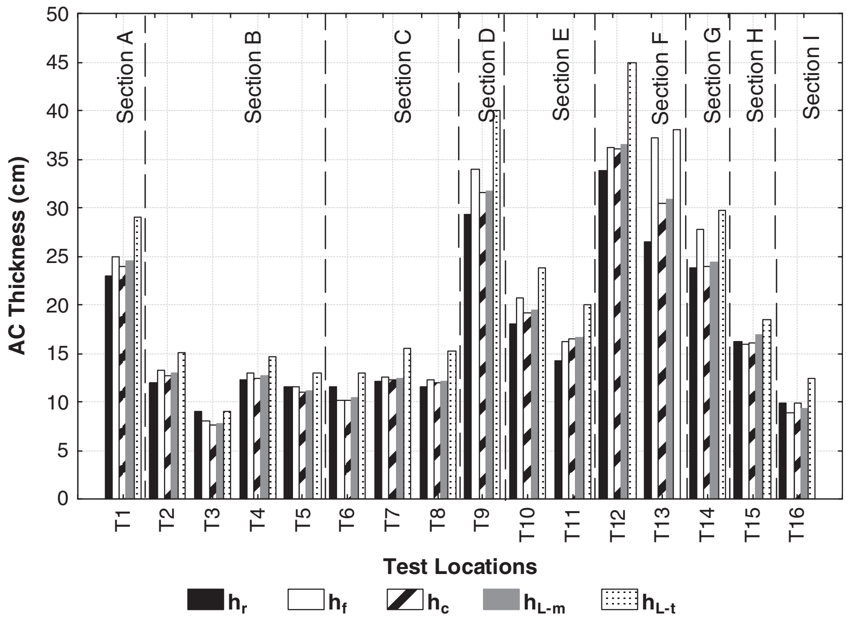

Fig. 11. Comparison of reference and estimated asphalt layer thicknesses.

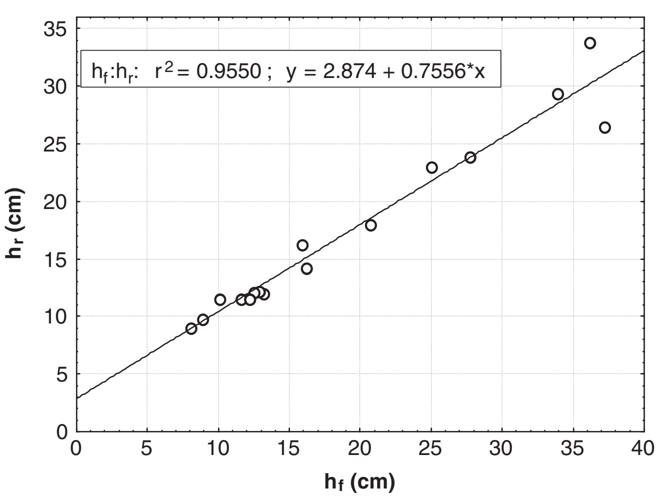

Fig. 12. Correlation between h_r and h_f values.

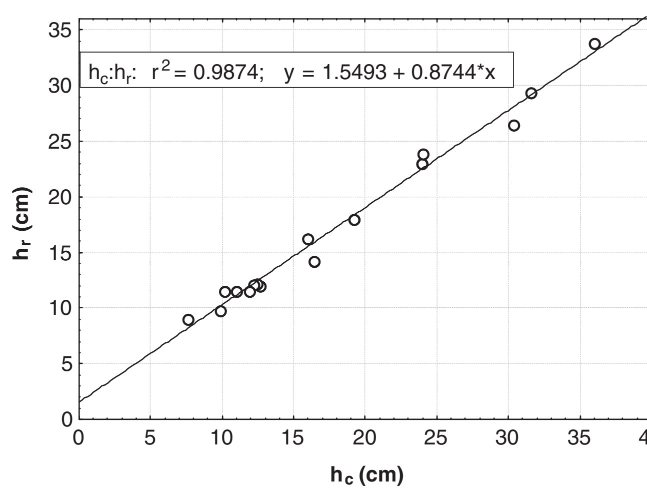

Fig. 13. Correlation between h_r and h_c values.

$$\text{Null hypothesis : Ho : } \mu_d = \text{hypnotized value} = 0. \tag{4}$$

Test statistic:

$$t = \frac{\chi_d - \mu_d}{s_d/\sqrt{n}} = \frac{\chi_d}{s_d/\sqrt{n}}, \tag{5}$$

where n is the number of sample differences (i.e. 16), χ_d and S_d are the mean and the standard deviation of the sample differences, respectively. Finally, the test is based on df $= n-1$, where df is the degrees of freedom.

A table of Student's t-distribution confidence intervals was used to determine the significance level at which the two distributions differ. The t-test critical value, with t referring to t-distribution, df = 15 and level of significance = 0.05, is 2.13. According to the absolute computed test values of Table 3, the null hypothesis is rejected for all cases except for the h_c values, where t-test value $= 1.97 < 2.13$. In other words for a confidence level of 95% the differences between the estimated h_c values and the reference h_r thicknesses are not significant.

In addition to the results of the analysis above, the quantification of the estimation errors is examined. The GPR thicknesses errors Δh_x are defined below as the deviations from the thicknesses h_r.

6. Analysis of thickness errors

The estimated GPR thicknesses relative errors in % (i.e. differences of h values to h_r in %) found for all test

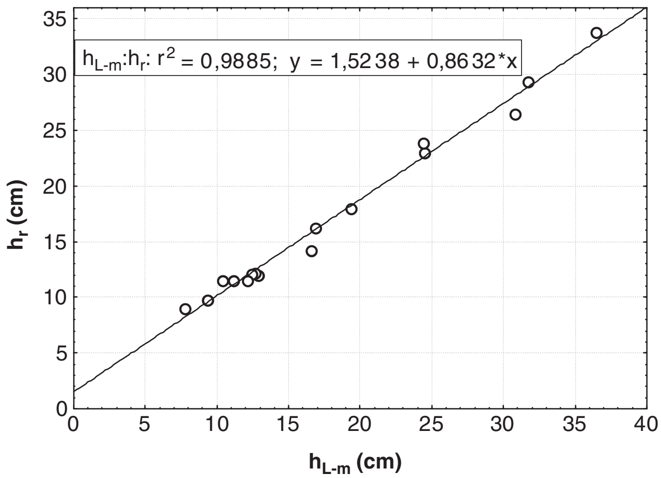

Fig. 14. Correlation between h_r and h_{L-m} values.

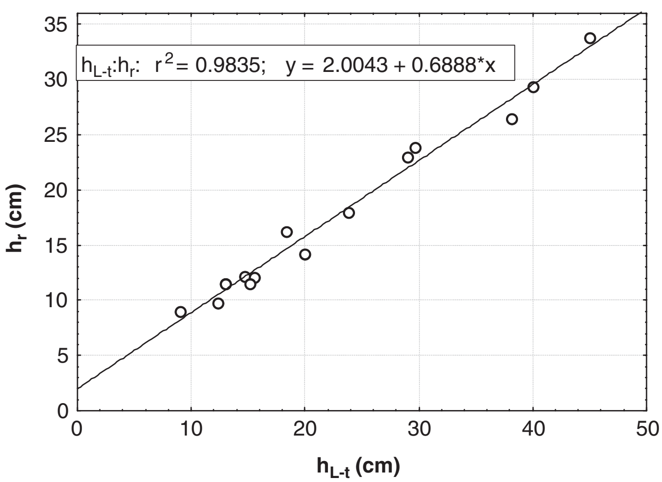

Fig. 15. Correlation between h_r and h_{L-t} values.

Table 3
Computed t-test values

t-Stat	h_f	h_c	h_{L-m}	h_{L-t}
h_r	2.37	**1.97**	2.59	5.38

locations are summarized in Fig. 16. As shown in this figure, the variations in the GPR thicknesses error are substantial. Furthermore, it is clear that the errors generated from the h_{L-t} are high. The boxplot of Fig. 17 provides additional conclusions for the thickness errors. The boxplot apart from summarizing the data provides further information on the errors with respect to the test locations.

Fig. 17 is a comparative boxplot of GPR thicknesses errors. It is compact, yet it provides information about the center and spread of the errors data. It is based on the median and interquartile range, while an observation is an outlier if it is more than 1.5 interquartile away from the closest end of the box (the closest quartile).

For the Δh_f *errors*, the largest observation, i.e. 40% is an outlier, while the upper whisker extends to 17% and the lower whisker extends to 0.9%. The median marker (9.6%) is somewhat closer to the lower edge of the box suggesting a concentration of errors values in the lower part of the middle half data (5.9–9.6%).

For the Δh_c *errors*, the upper whisker extends to 15.6% and the lower whisker extends to 0.8%. The median marker (5.0%) is somewhat closer to the lower edge, suggesting a concentration of values in the lower part of the middle half (1.4–5.0%). It seems that the h_c provides lower thicknesses errors than the h_f ones.

The box for the Δh_{L-m} *errors* is narrower than the previous ones, indicating less variability in the middle half of the errors data. The largest observation, i.e. 16.9% is an outlier, while the upper whisker extends to 16.2% and the lower whisker extends to 2.5%. Also, the median marker (7.0%) is slightly closer to the higher edge, suggesting a concentration of values in the higher part of the middle half data (7.0–8.8%).

As far as the Δh_{L-t} errors are concerned, these are the higher ones. The related box is wide, which means that the h_{L-t} thicknesses vary substantially. The median marker (26.0%) is slightly closer to the higher edge, suggesting a concentration of values in the higher part of the middle half data (26.0–32.7%).

Considering the results of the above-described analysis, there is evidence that the ε_c and ε_{L-m} parameters used in the analysis of the GPR data for the estimation of the AC layer thickness contribute the optimum errors. Furthermore, the lower thickness errors Δh_c seem to accumulate between 1.4% and 5.0%, a range justified from the international experience. For example, Maser [24] defines the accuracy as the deviation between a core thickness and the GPR thickness calculated at the core location and refers, among others, that the expected accuracy is 3–5% for new asphalt. In addition Loulizi et al. [12] obtained an optimum percentage error of 3.6%, as well a maximum one of 14.7%. However, the issue concerning the error in determining the value of the amplitudes A_1 and A_m for calculating h_f as well the errors of the travel time measurement which influence all calculated h values need to be further discussed.

The error in determining the value of the amplitudes A_1 and A_m for calculating h_f is correlated to the data collection gain which depends on how reflective is the pavement surface. In the present investigation, the pavement surface was in all cases an asphaltic material and following the recommendations of the antennas manufacturer the operator set a gain of 13–14 db. The errors of the travel time measurement depend on the assessment of the wave propagation velocity, which is governed by the dielectric properties of the materials as a function of the dielectric constant of the material mixture. Taking also into account

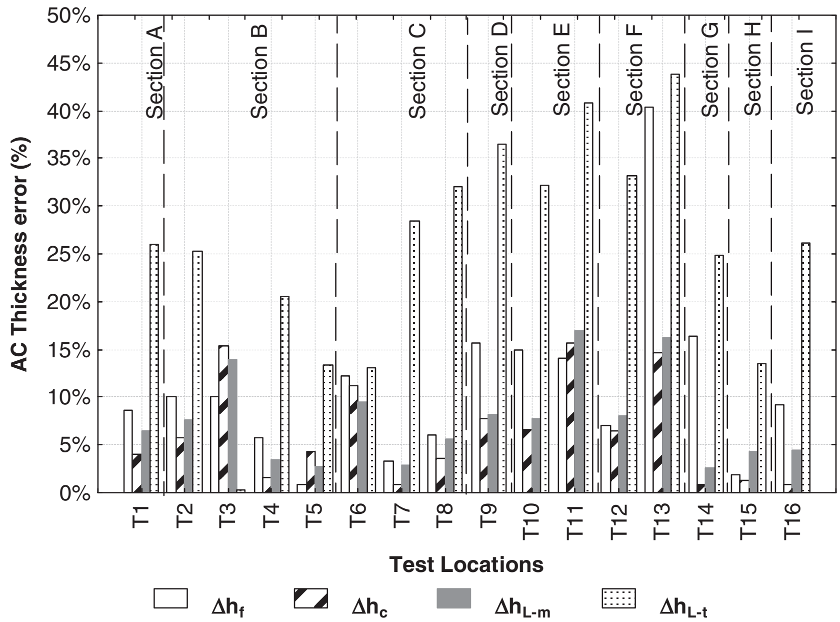

Fig. 16. GPR relative error thickness per test location.

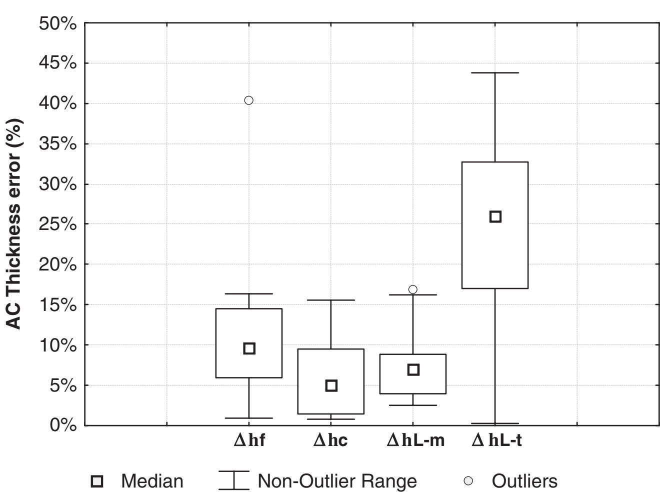

Fig. 17. Comparative boxplots of GPR thicknesses errors.

the dependency on the characteristics of the GPR system in use, the quantification of these errors seems to be a complex procedure, which needs further profound investigation beyond the scope of the present research work.

7. Conclusions

The present research focused on the accuracy of AC layer thicknesses estimation of new, rather new and recently rehabilitated pavements using GPR data collected through comprehensive field measurements on a variety of highway pavements. Three different approaches of assigning dielectric constants of AC pavement layer materials, i.e. (a) estimated directly from GPR data as a fully NDT procedure, (b) using the "travel time–core thickness" procedure and (c) based on measurements in the laboratory, were considered for the scope of the analysis.

In general, all three approaches have a satisfactory performance. The travel time–core thickness procedure seems to provide the minimum error for the estimated AC thicknesses compared to reference thicknesses measured on the AC cores. However, the accuracy of this procedure depends in particular on the amount of cores obtained, while obviously coring, especially for heavy-duty pavements, is quite unpopular to the road authorities due to the road closures disruptions and delays.

For a rough and quick evaluation of pavements and more specifically, when considered at road network level, as for example for PMS purposes, the estimation of the AC layer thicknesses directly from collected GPR data (fully NDT approach) can be not only a sufficient but also an effective procedure. In addition, when pavement coring is tolerated and a more profound investigation of pavement layer material characterization is anticipated, the laboratory-based procedure might be of value when it yields from the calculation of a mean dielectric value, representative of the entire AC core.

References

[1] Maser KR, Scullion T, Roddis WMK, Fernando E. Radar for pavement thickness evaluation. In: Quintas HLV, Bush III AJ, Baladi GY, editors. Non-destructive testing of pavements and backcalculations of moduli: ASTM STP 1198, vol. 2. Philadelphia, USA: American Society of Testing and Materials; 1994. p. 343–60.

[2] Scullion T, Saarenketo T. Integrating ground penetrating radar and falling weight deflectometer technologies in pavement evaluation. In: Tayabji SD, Lukanen EO, editors. Nondestructive testing of pavements and backcalculation of moduli: ASTM STP 1375, vol. 3. West Conshohocken, PA: American Society for Testing and Materials; 2000. p. 23–37.

[3] Roberts J, Roper R, Loizos A. A new engine for the implementation of HDM technology for road infrastructure analysis. In: Proceedings of the sixth International Transportation Research Board conference on pavement management systems, Brisbane, 2004, p. 1–19.

[4] Hartman AM, Baston-Pitt J, Sedgwick A, Böhmer G. Pilot study assessing the feasibility of advanced ground penetrating radar in pavement assessment. In: Proceedings of the eighth conference on asphalt pavements for Southern Africa (CAPSA '04), SA, Sun City, 2004, p. 1224–9.

[5] Morey RM. Ground penetrating radar for evaluating subsurface conditions for transportation facilities. Transportation Research Board, National Research Council: NCHRP Synthesis 255. Washington, DC: National Academy Press; 1998.

[6] Maser KR. Ground penetrating radar surveys to characterize pavement layer thickness variations at GPS sites. Strategic Highway Research Program, National Research Council: Report SHRP-P-397. Washington, DC: National Academy of Science; 1994.

[7] Scullion T, Lau CL, Chen Y. Pavement evaluations using ground penetrating radar. In: Proceedings of the fifth international conference on ground penetrating radar, vol. 1. Ontario, Canada: Kitchener; 1994. p. 449–63.

[8] Alongi T, Clemena GG, Cady PD. Condition evaluation of concrete bridges relative to reinforcement corrosion. Strategic Highway Research Program, National Research Council: Report SHRP-S/FR-92-105, vol. 3. Washington, DC: National Academy of Science; 1992.

[9] Scullion T, Lau CL, Chen Y. Implementation of the Texas ground penetrating radar system. Report no. FHWA/TX-92/1233-1. Texas, USA: Department of Transportation; 1992.

[10] Roddis WMK, Maser K, Gisi AJ. Radar pavement thickness evaluations for varying base conditions. In: Transportation Research Record 1355. Washington, DC: National Academy Press; 1992. p. 90–8.

[11] Livneh M., Siddiqui MH. Assessment of radar technology for determining the thickness of pavement layers. In: Proceedings of the seventh international conference on asphalt pavements, vol. 2, Nottingham, UK, 1992, p. 228–44

[12] Loulizi A, Al-Qadi IL, Lahouar S. Optimization of ground penetrating radar to predict layer thicknesses in flexible pavements. ASCE: Journal of Transportation Engineering 2003;129(1):93–9.

[13] Hopman V, Beuving E. Repeatability, reproducibility and accuracy of GPR. In: Proceedings of bearing capacity of roads, railways and airfields conference (BCRA), Lisbon, Portugal, 2002, p. 637–45.

[14] Al-Qadi IL, Lahouar S, Jiang K, MeGhee KK, Mokarem D. Validation of ground penetration radar accuracy for estimating pavement layer thicknesses. In: Proceedings of the Transportation Research Board 84th annual meeting, Washington, DC, 2005.

[15] Saarenketo T, Scullion T. Road evaluation with ground penetrating radar. J Appl Geophys 2000;43:119–38.

[16] Saarakento T. Using ground penetrating radar and dielectric probe measurements in pavement density quality control. In: Transportation Research Record 1575. Washington, DC: National Academy Press; 1997. p. 34–41.

[17] Al-Qadi IL, Jiang K, Lahouar S. Analysis tool for determining flexible pavement layer thickness at highway speed. In: Proceedings of the Transportation Research Board 85th annual meeting, Washington, DC, 2006.

[18] ASTM D4748-98. Standard test method for determining the thickness of bound pavement layers using short-pulse radar. Annual book of ASTM standards. West Conshohocken, PA: American Society for Testing and Materials; 2005.

[19] ROADSCANNERS. RoadDoctor software: user's guide. Finland: Roadscanners Oy; 2001.

[20] Plakk T. Permittivity measurements by capacitive probe. Estonia: Adek Ltd.; 1994.

[21] ASTM 3515-01. Standard specification for hot-mixed, hot-laid bituminous paving mixtures. Annual book of ASTM Standards. West Conshohocken, PA: American Society for Testing and Materials; 2005.

[22] GSSI. Radan for Windows: user's manual. Geophysical Survey Systems Inc.; 2001.

[23] Devore J, Peck R. Statistics, the exploration and analysis of data, 4th ed. USA: Duxbury; 2001.

[24] Maser KR. Pavement characterization using ground penetrating radar: state of the art. In: Tayabji SD, Lukanen EO, editors. Nondestructive testing of pavements and backcalculations of moduli, ASTM STP 1375, vol. 3. Philadelphia, USA: American Society of Testing and Materials; 2000. p. 313–26.