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Construction and Building Materials 19 (2005) 763–772
Construction and Building MATERIALS
www.elsevier.com/locate/conbuildmat

# Measuring layer thicknesses with GPR – Theory to practice

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Available online 2 August 2005

## Abstract

Ground penetrating radar (GPR) technology has been used to assess pavement performance and structure for the past 30 years in a variety of ways. Yet after all this time, the main issue remains: How well does GPR work and under what conditions? Results show that GPR works well for some situations but not as well for others. It is not currently used on a routine basis by the Departments of Transportation in the US mainly because of difficulties encountered while interpreting GPR data. These difficulties are generally attributed to the fact that the GPR reflected signals that are collected depend largely on the a priori unknown dielectric properties of the structural materials. Additional difficulties arise from the fact that physically GPR cannot detect layers unless they have sufficiently dissimilar dielectric constants. In practice, GPR has been used primarily for pavement layer thickness estimation and moisture accumulation localization within the pavement layers. To improve GPR prediction capabilities, different data processing techniques have been developed that use the GPR reflected signal to estimate the dielectric properties of surveyed structures, thus determining their thicknesses. Other signal processing techniques have also been used successfully to enhance the quality of the GPR signal in order to increase the accuracy of the data interpretation results.


*Keywords:* Non-destructive testing; Ground penetrating radar; Pavement layer thickness estimation

## 1. Introduction

Determining flexible and rigid pavement layer thicknesses is important for pavement evaluation and provides important data for pavement management systems (PMS). For example, accurate predictions of pavement layer thicknesses are needed for overlay design, quality control/quality assurance, and structural capacity estimation of existing pavements to predict their remaining service life. Currently, most Department of Transportation (DTO) agencies evaluate layer thickness and the properties of different pavement layers through the destructive process of extracting pavement cores. While this procedure provides relatively accurate thickness measurements, it is time consuming, hazardous, requires traffic control, provides limited information (as cores are usually taken every 300 m), and cannot be performed annually since it adds to the pavement distress by causing man-made defects.

Another approach to estimate pavement layer thickness is to use the deflections measured by a falling weight deflectometer (FWD). Yet this technique is slow, costly, and does not accurately predict thicknesses because its main purpose is, usually, to backcalculate the moduli of the pavement layers knowing their thicknesses. Another non-destructive alternative for pavement thickness estimation is to use GPR, which is rapid, cost effective, and allows pavement surveys to be conducted more efficiently without disturbing either the pavement structure or the highway traffic.

During the past three decades, GPR has been used in many studies for the non-destructive evaluation of pavements. In rigid pavements, GPR has proven to be

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0950-0618/$ - see front matter 
doi:10.1016/j.conbuildmat.2005.06.005

feasible in locating dowels [1] and in detecting voids or loss of support under slabs [2]. In flexible pavements, electromagnetic (EM) waves are found to serve as a tool to detect moisture in the hot-mix asphalt (HMA) layer and to locate moisture in the base layer that may lead to structural damage [3,4]. Currently, the majority of GPR applications in pavements are focused on determining layer thicknesses. For this application, different researchers have reported varying performance levels for the GPR tool, depending on the surveyed pavement structure and the data analysis technique used. For example, Maser [5] reported a thickness accuracy of ±7.5% for hot-mix asphalt (HMA) layers ranging from 51 to 500-mm thick, and ±12% for granular base layers ranging from 150 to 330-mm thick. This GPR performance evaluation was based on comparisons between the thicknesses predicted from the GPR data and the thicknesses measured from cores. In another study, Lahouar et al. [6] used GPR to assess the condition of a four-lane, 17-mile section of Interstate I-81 in Virginia, in both the northbound and southbound directions. The authors reported a 6.7% error for predicting the HMA thickness of a pavement approaching its service life. In contrast, GPR measurements of the HMA layer of a one-year old pavement (concrete and flexible pavement sections) at the Virginia Smart Road [7] were reported to have an error of only 3.5% [8]. Al-Qadi et al. [9] used GPR as a quality control/quality assurance (QC/QA) tool to check the layer thicknesses of a newly built pavement (Route 288, located near Richmond, VA). The study reported a mean thickness error of 2.9% for HMA layers ranging between 100 and 250 mm in thickness.

This paper summarizes the theoretical background that could be used to estimate pavement layer thicknesses from GPR data. This theoretical analysis is then validated by the presentation of field data that evaluates the accuracy of the GPR results and finds the conditions that maximize its performance. In addition, alternative analysis techniques that could be applied to increase the GPR accuracy when the optimum conditions are not met are also discussed.

## 2. Layer thickness estimation from GPR data

The principle of the GPR system used in this study (impulse radar) is based on sending an EM pulse through an antenna to the pavement surface and then recording the reflected pulses from the internal interfaces, where there is a contrast in the dielectric properties, as depicted in Fig. 1. The time difference measured between the reflected pulses (i.e., $t_1$ or $t_2$) can be used in conjunction with the dielectric properties of the surveyed layer to determine its thickness. The thickness of the $i$th layer could be computed according to the following equation [10]:

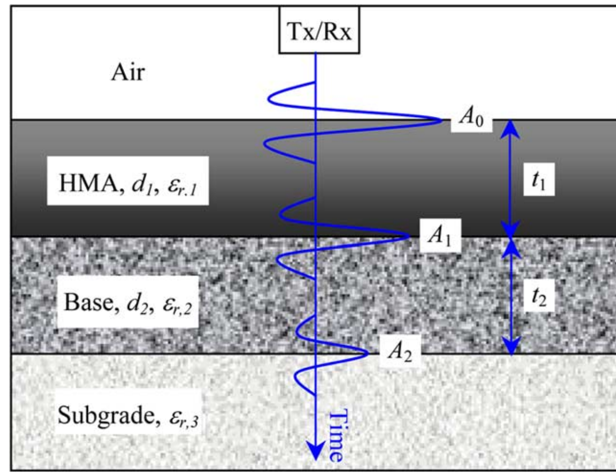


Fig. 1. Typical GPR reflections from a pavement system.

$$d_i = \frac{ct_i}{2\sqrt{\varepsilon_{r,i}}}, \quad (1)$$

where $d_i$ is the thickness of the $i$th layer, $t_i$ is the EM wave two-way travel time through the $i$th layer as shown in Fig. 1, $c$ is the speed of light in free space ($c \approx \times 10^8$ m/s), and $\varepsilon_{r,i}$ is the dielectric constant of the $i$th layer.

Electronically, impulse GPR systems function in the following manner: A trigger pulse is generated in the GPR control unit. This trigger pulse is sent to a transceiver, where it is modulated and amplified to become a bipolar transmit pulse with a much higher amplitude. The generated pulse is then sent through the transmitting antenna to the ground. After a short time (10–100 ns, depending on the antenna used), the reflected signal is collected by the receiving antenna and is transmitted to the receiver circuitry, where it is filtered and digitized. Finally, the produced data is displayed for immediate interpretation and is stored on magnetic media for later processing.

Depending on the way antennas are used, GPR systems are classified as air-coupled or ground-coupled systems. In air-coupled systems, the antennas (usually horn antennas) are typically deployed 150–500 mm above the surface. These systems give a clean radar signal and allow for highway speed surveys. However, because part of the EM energy sent by the antenna is reflected back by the pavement surface, the depth of penetration is limited. In contrast, a ground-coupled system's antenna is in full contact with the ground, which gives a higher depth of penetration (at the same frequency) but limits the speed of the survey. For pavement surveys, GPR antennae are typically rigidly mounted on a survey van, as depicted in Fig. 2. This figure shows an air-coupled system composed of a pair of separate horn antennae (bistatic: one serves as a transmitter and the other as a receiver) and a ground-coupled system comprised of a single antenna. For flexible pavements, the air-coupled system is usually preferred to the ground-coupled system