Use of Ground Penetrating Radar in quality assurance of new asphalt pavements

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1. INTRODUCTION

Pavement layer thickness and density are two important factors for the quality of newly constructed asphalt pavements. They are directly related to the pavement life, and non-compliance to standards and requirements may lead to reduced quality and economic consequences.

Ground Penetrating Radar (GPR) is the most advanced technology for measuring the pavement layer thickness and air voids variations. It is a quick, reliable method, and is not-destructive. Surveys can be performed at driving speeds; they give a continuous profile of the pavement, and do not damage it.

For quality assurance projects, it is very important to achieve a high level of accuracy. As many measuring instruments, GPR needs to be calibrated. The reliability and accuracy of GPR depends greatly on how well the dielectric properties of the surveyed medium are known. The most important dielectric property is the dielectric permittivity \( \varepsilon \), and is used to convert the two-way travel time of the GPR waves into depth.

Some GPR systems are able to calculate the dielectric permittivity automatically (air-coupled horn-antennas). Other systems cannot (ground-coupled and step-frequency systems): it is therefore necessary to extract one or several cores to determine the permittivity from it/them. The value of permittivity is then used for the entire section.

The GPR technology is supposedly non-destructive, core extraction is costly and time-consuming. As the same time, quality assurance requires a very high accuracy in the measurements, which can mainly be achieved by calibration on asphalt samples. Therefore there is a trade-off to be found, between high level of accuracy and cost of core extraction.

The purpose of this study, carried out in cooperation with the Department of Transportation of Minnesota, is to help understand the benefit of core samples on the overall accuracy of pavement thickness and density measurements. Calibration cores are necessary, but for economic reasons it is important to extract them as little as possible. This project attempts to quantify: "how much is enough".
2. THE GROUND PENETRATING RADAR TECHNOLOGY

2.1 Measuring principle

Ground penetrating radar (GPR) is a geophysical survey method used to remotely and non-destructively obtain a representative image of the subsurface materials. The technique is based on the propagation of electromagnetic waves in dielectric materials, as depicted in the figure below.

- Short pulses are emitted at a certain frequency by a radar transmitter in an antenna.
- Reflected waves are received by the antenna and recorded.
- The radar signal is returned differently at distinct, abrupt dielectric non-homogeneities in the surveyed materials.
- A representation of the subsurface layers is created by graphing the differing signal travel times and amplitude.

GPR is used in a variety of applications, from geological and archaeological investigations to road and structure inspections. Typical road surveys include: layer thickness assessment, utility mapping, detection of underground cavities or structures, asphalt and concrete evaluation (pavement condition, void content, rebar spacing, frost depth), groundwater profiling.

The GPR technique is rapid, accurate and non-destructive, which makes it particularly timesaving and well-suited for many subsurface investigations. However, it has some limitations inherent in the wave propagation theory. The dielectric properties of the targeted structures or layer boundaries must have sufficient contrast with the host environment in order to be detected. Poor results are generally achieved in high-conductive media, such as clay, peat and saline soils, or in moist conditions. In addition, the selection of the operating frequency directly affects the depth of exploration. A high frequency GPR will have good resolution but a limited depth of penetration. Conversely, at low frequencies greater depths can be probed, but to the detriment of accuracy and clarity. Thus a trade-off between depth and resolution must be found during the feasibility study to achieve the best possible results.
2.2 Calculation of the pavement thickness

The calculation of the pavement thickness is based on the reflection of EM waves when a change in electrical properties occurs. The relative dielectric permittivity controls the velocity at which the EM waves travel through a material. The velocity is given by:

\[
v (\text{m/s}) = \frac{c}{\sqrt{\varepsilon_r}} \quad (Eq. 1)
\]

Where:
- \(v\) is the velocity of the propagating EM waves in the material
- \(c\) is the velocity of the propagating EM waves in free space (\(\approx 3 \times 10^8\) m/s)
- \(\varepsilon_r\) is the relative dielectric permittivity

The layer thickness \(h\) is calculated as the product of the two-way travel time (2WTT) \(\Delta t\) of reflected pulses, and the wave velocity \(v\) inside the layer:

\[
h = v \times \frac{\Delta t}{2} \quad (Eq. 2)
\]

\[
h = \frac{c \times \Delta t}{2\sqrt{\varepsilon_r}} \quad (Eq. 3)
\]

The calculation of \(h\) involves therefore the estimate of \(\varepsilon_r\). The two most common ways to assess \(\varepsilon_r\) are:

- **The estimate guess:**
  Standard values are available in the literature. They only give a rough estimate of the pavement layer thickness.

- **The reflection amplitudes method:**
  When the GPR survey is carried out with a certain type of GPR and antenna (air-coupled horn antenna), one of the most accurate ways to obtain \(\varepsilon_r\) is to use the reflection amplitudes method. The dielectric permittivity \(\varepsilon\) of the asphalt layer is calculated as:

\[
\sqrt{\varepsilon} = 1 + \frac{A_0}{A_m} \quad (Eq. 4)
\]

Where:
- \(A_0\) is the amplitude of the GPR waveform from the pavement surface
- \(A_m\) is the amplitude of the GPR waveform from a metal plate (100 % of the emitted energy is reflected)
The reflection amplitudes method allows the continuous estimation of $\varepsilon$, which makes it a very effective and accurate method for layer thickness calculation. For better results it has to be calibrated on several cores, using Eq. 3.

### 2.3 Calculation of the void content

Once the dielectric permittivity $\varepsilon$ has been calculated, the void content of asphalt can be assessed using the following regression model (Saarenketo, 2012):

$$\text{Void content (\%)} = 272.93 \times e^{-1.3012k \cdot \varepsilon} \text{(Eq. 5)}$$

Where:

- $k$ is the calibration factor (obtained from cores)
- $\varepsilon$ is the dielectric permittivity

### 3. FIELD AND LABORATORY TESTS

Field measurements were performed at MnROAD, using a 2 GHz horn antenna GPR system (Figure below, left) and a 200 MHz – 3 GHz step-frequency antenna (right). MnROAD is a pavement test track using various research materials and pavements owned and operated by the Minnesota Department of Transportation, USA.

The tested section is 70 m long and consists of a dense-graded asphalt pavement and a crushed stone base. The positioning of the GPR data was done with metal tape markers. 14 asphalt cores were extracted and sent to the laboratory for density analysis.

The GPR measurements were analyzed using the softwares Examiner, RADAN, Pavement QA/QC and Surfer.

### 4. ANALYSIS

#### 4.1 ASPHALT THICKNESS

- **No calibration core:**
When no calibration core is available, a standard value of $\varepsilon$ ("educated guess") has to be used for the calculation of the pavement layer thickness. Literature usually recommends a value between 4 and 8 (Saarenketo, 2006).

As can be seen in the figure below, assigning a value of 6 instead of 5 for $\varepsilon$ ($\Delta\varepsilon = 1$) leads to an error of 8.7% in the layer thickness calculation. It is therefore important to accurately assess $\varepsilon$. The more accurate $\varepsilon$ is, the more reliable the calculated thicknesses will be.

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**One calibration core:**

When using only 1 calibration core, the accuracy of the calculated pavement thickness depends on which core is actually used for the calibration. Indeed, the dielectric permittivity varies along the road profile, and calibrating thicknesses using the $\varepsilon$ value of Core #3 or the $\varepsilon$ value of Core #12 will not give the same results.
The graph below illustrates this point: GPR thicknesses calibrated on Core #1 ($\epsilon = 6,42$) have an average error of 7,43 %, while GPR thicknesses calibrated on Core #10 ($\epsilon = 4,63$) have an average error of 11,83 % compared to actual thicknesses. On average, a calibration of GPR thicknesses on 1 core (core #1 or core #2 or core #3...) leads to a measurement error of 7,43 %.

- **Multiple calibration cores:**

  It has been investigated whether using multiple cores (2 or more) would significantly increase the overall accuracy of GPR measurements. Again, since the material properties vary along a road section, all core combinations have to be taken into account (Cores 1 & 2, or 1 & 3, or 2 & 3... etc. in the case on a 2-core calibration).

  All possible combinations (without repetition) have been determined using the binomial coefficient:

  \[
  \binom{n}{p} = \frac{n!}{p!(n-p)!}
  \]

  Where:
  
  - $n$ is the number of cores to choose from (14)
  - $p$ is the number of selected cores (from 2 to 11)
<table>
<thead>
<tr>
<th>How many calibration cores are available (n)?</th>
<th>14</th>
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</tr>
</thead>
<tbody>
<tr>
<td>How many calibration cores are used (p)?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Number of combinations</td>
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<td>91</td>
<td>364</td>
<td>1001</td>
<td>2002</td>
<td>3003</td>
<td>3432</td>
<td>3003</td>
<td>2002</td>
<td>1001</td>
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<td>Average Error (%)</td>
<td>7.53</td>
<td>6.01</td>
<td>5.65</td>
<td>5.47</td>
<td>5.35</td>
<td>5.27</td>
<td>5.20</td>
<td>5.15</td>
<td>5.11</td>
<td>5.07</td>
</tr>
</tbody>
</table>

The table above shows the number of combinations for each case and the calculated average error. As we can see, the accuracy of GPR measurements increases significantly when using 2 or more calibration cores. Above 3 cores, it only improves a little. The curve tends to flatten around 5% and never goes below that level.

4.2 VOID CONTENT

The void content of asphalt can be derived from the dielectric permittivity using Eq. 5. Since $\varepsilon(\text{air}) = 1$ and $\varepsilon(\text{asphalt}) = 4 - 8$ the greater the dielectric value, the greater the density.

The dielectric permittivity values calculated using the reflection amplitude method can be plotted in Surfer. As one can see, they are in the range 5.5 – 6.5. They are a bit lower on the left edge, which may indicate that the asphalt material might be slightly less compacted in this area.
In contrast with pavement layer thicknesses that can roughly be determined with no calibration core (educated guess for $\varepsilon$), the calculation of air voids in asphalt requires at least one sample for the determination of $k$.

$k$ is determined as follows:

\[
Void \ content \ (\%) = 272.93 \times e^{-1.3012 \cdot k \cdot \varepsilon} \quad (Eq. 5)
\]

\[
\ln(Void \ content \ (\%)) = \ln(272.93) - 1.3012 \cdot k \cdot \varepsilon
\]

\[
k = \frac{\ln(272.93 \cdot Void \ content)}{1.3012 \times \varepsilon} \quad (Eq. 6)
\]

The results of the analysis show that a calibration of air voids on 1 core (core #1 or core #2 or core #3...) leads to a measurement error of 17.15% on average.

It is a quite high measurement error, that can probably be reduced by using multiple calibration cores instead of one. However, the method is cumbersome and a better way to increase the overall accuracy would be to ensure a better match between the core location and the GPR measurements. Since the density of the asphalt may vary significantly along a road section, an offset of 20 – 50 cm between the core location and the GPR radar pulse may lead to measurements errors.
5. SUMMARY

An accurate measurement of the asphalt thickness and void content is essential in quality assurance of new pavements. As every instrument, GPR needs to be calibrated. The calibration for both pavement thickness determination and void content assessment are made on extracted cores.

- **Pavement thickness measurements:**
  - The study shows that the accuracy of pavement thickness measurement (same type of pavement all over the section) increases significantly from one core calibration.
  - It reaches an acceptable level for quality assurance purposes from 2 – 3 calibration cores.
  - Above 3 cores, the benefits of calibration are not significant.
  - The maximum achievable accuracy seems to be in this study about 95%.

- **Void content of asphalt**
  - It is possible with certain types of GPR systems to continuously calculate the dielectric permittivity of asphalt pavements.
  - Although the accurate relationship is not currently known, the void content derived directly from the permittivity. The higher the permittivity, the lower the percentage of air voids.
- A regression model for the calculation of the % air voids from $\epsilon$ has been tested. It gave mixed results, with an average measurement error of 17.15 %. A possibility to increase the overall accuracy could be to calibrate the results on multiple cores.

- Another likely source of error can be a mismatch between the core locations and, the GPR sampling. This issue can be solved by the use of a reliable and calibrated GPS.

REFERENCE
