Correlation of ground penetrating radar and nuclear density gauge data to determine the density of asphalt pavement

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Abstract. This paper demonstrates the field performance of Ground Penetrating Radar (GPR) as a non-destructive testing tool to predict in situ asphalt pavement. In previous study, GPR has been used successfully in a variety of pavements application such as determining layer thickness, detecting subsurface distresses, and others. Nuclear Density Gauge (NDG) is specifically designed to measure the moisture and density of soils, aggregates, cement, and lime treated materials, and also to measure the density of asphalt concrete. Alternative analysis approaches by correlating the GPR and NDG data had been performed for density prediction of asphalt pavement. A density model name Al-Qadi, Lahouar, and Leng (ALL model) was used to predict the density of the asphalt pavement from the GPR data correlate with NDG database. This study shows that density for asphalt pavement from GPR data provide reasonably accurate density prediction when ALL model approach was used.

1. Introduction
Asphalt mixture density greatly influences the performance of asphalt concrete (AC) pavement. Appropriate AC density increases stability and durability, and reduces maintenance and rehabilitation costs of pavement. Insufficient density leads to pavement distresses including cracking, raveling, and/or oxidation [1]. Traditional density estimation methods are through a destructive method – conducting lab-controlled tests on cores from the field. This approach is time consuming and expensive.

Non-destructive testing (NDT) techniques have been developed by determining the structural condition of an in-service pavement. NDT has two major advantages over destructive testing. First, destructive testing by definition disturbs or requires removal of the pavement materials to a laboratory for testing, whereas NDT is truly an in situ test that evaluates the pavement without any material disturbance or modification [2]. The second advantage of NDT method is providing access to material properties while remaining rapid and inexpensive, allowing more tests to be completed while causing less disruption to traffic than destructive testing [3].
Meanwhile, electromagnetic (EM) wave methods have been successfully developed and implemented for AC pavement density prediction [4]. An alternative approach is to use nuclear density gauge (NDG) [5]. Although the nuclear gauge is a non-destructive technique that provides reasonably accurate estimates of the AC layer density, this technique, too, has some drawbacks. One of the drawbacks with NDG method is the use of radioactive material and thus requires special licensing to transport, which entails increased operational costs [6].

Researchers have tried to develop techniques to overcome these disadvantages. The investigation of using ground-penetrating radar (GPR) as an alternative to the nuclear density gauge to predict in situ asphalt mixture density continuously and rapidly [7,8], GPR has the most potential because GPR surveys are nondestructive, rapid, continuous, and can provide multiple types of pavement structure information (e.g., layer thickness and substructure distresses) in addition to density [9]. GPR uses air-coupled antennas to enable high-speed (up to 96 km/h) and large-coverage (up to 2 m in transverse direction) survey. However, the GPR raw data, i.e., radargram, depends on the survey speed, sampling rate, and d properties. Therefore, the radargram is a distorted image of the subsurface condition, and specialized post-processing algorithms are needed for data interpretation [4].

To investigate the feasibility and effectiveness of using GPR to predict pavement density, several density prediction models were developed according electromagnetic mixing theory [8]. These density models enable the prediction of pavement density using GPR requires correlations between AC mixture dielectric constant and density [10]. This study uses the Al-Qadi, Lahouar, and Leng (ALL) density prediction model because its accuracy has been identified as best performance model to estimate pavement density [9,10].

The focus of this study is to develop correlation of GPR and NDG data in which to determine the density of asphalt pavement while increased capabilities of GPR as complete system for local road applications with using the ALL model equation. The GPR data used in this project was collected from the asphalt pavement test site. The accuracy of these predicted densities was validated from GPR data and compared with densities measured by the nuclear density gauge. The alternative analysis approaches that could be applied to improve the GPR accuracy when the optimum conditions are not met are also discussed.

2. Experimental Works

2.1. Experiment setup

This experiment was held on asphalt pavement in Block 60, Malaysia Nuclear Agency. The dimension of the asphalt scanning area was 2 m × 2 m with 9 points marked on the surface of the asphalt. The distance between each point were 1 m diagonally and 1 m horizontally. The GPR used was GSSI 900MHz shielded antenna and in air-coupled mode. The distance between shielded antenna and asphalt pavement was 25 cm and was held by GSSI cart system. Data was collected using SIR 4000 and then processed using RADAN 7 software. For comparison of the asphalt density value, NDG method was used to calculate the density of the asphalt using Troxler NDG system.
The experiment was divided by two parts, named Experiment 1 and Experiment 2, where the difference are thickness of metal plate and the arrangement of metal plate on measured pavement. Experiment 1 was to compare the effect of metal plate thickness while Experiment 2 is to utilise the best performance metal plate in Experiment 1 and improving other technical setups.
During experiment 1 the metal plates were put in every point to find the average of $A_{AC}$ meanwhile for experiment 2 the metal plate was put in the middle of the asphalt to find single point $A_{AC}$. Experiment 1 needed double scanning to obtain average $A_{AC}$ for the first scanning and $A_0$ for the second scanning. Meanwhile for the experiment 2, it just needed single scanning in obtaining $A_0$ and $A_{AC}$ for $G_{mb}$ calculation of the asphalt.

2.2. Calculation formula
The density of the asphalt can be calculated using ALL Model. This model used density constant from signal from GPR radargram that obtained $E_{AC}$ value from EM mixing theory. Then, $E_{AC}$ was used to back calculated the value of $E_s$ for the further calculation. Finally, the $G_{mb}$ value were calculated for each point for every experiment. The formula for $E_{AC}$ (equation 1) and $G_{mb}$ (equation 2) calculation is showed below:

Figure 3. Metal plate with (a) 2mm and (b) 5mm thickness

Figure 4. a) Schematic diagram of single point scanning. b) Schematic diagram for multi points scanning.
\[
\varepsilon_{AC} = \left( \frac{1 + \left( \frac{A_0}{A_{AC}} \right)}{1 - \left( \frac{A_0}{A_{AC}} \right)} \right)^2
\]

(1)

where \( \varepsilon_{AC} \) is dielectric constant of the top layer, \( A_0 \) is the amplitude of the surface reflection and \( A_{AC} \) is the amplitude of the incident GPR signal that produced by the plate. The \( G_{mb} \) and \( \varepsilon_s \) are obtained using ALL Model as shown below:

\[
G_{mb} = \frac{\left( \frac{\varepsilon_{AC} - \varepsilon_b}{\varepsilon_{AC} - 2.35 \varepsilon_b} \right) - \left( \frac{1 - \varepsilon_b}{Gse} \right) - \left( \frac{1 - \varepsilon_b}{1 - 2.35 \varepsilon_b + 2 \varepsilon_{AC}} \right) \left( \frac{1}{G_{mm}} \right)}{\left( \frac{\varepsilon_{AC} - \varepsilon_b}{\varepsilon_{AC} - 2.35 \varepsilon_b} \right) - \left( \frac{1 - \varepsilon_b}{Gse} \right) - \left( \frac{1 - \varepsilon_b}{1 - 2.35 \varepsilon_b + 2 \varepsilon_{AC}} \right) \left( \frac{1}{G_{mm}} \right)}
\]

(2)

where \( G_{mm} \) maximum is specific gravity, \( G_{se} \) is effective specific gravity of aggregates, \( P_b \) is binder content that can be obtained from mix design. The value is set 0.05 for Pb, 2.641 for \( G_{se} \) and 2.521 for \( G_{mm} \). \( \varepsilon_b \) is dielectric of binder that set as 3 \[11\]. \( \varepsilon_s \) is back calculated using the density that obtained from NDG result.

Root Mean Square Error (RMSE) also calculated for this experiment to compare the NDG and GPR data. RMSE is the square of all the error. It is excellent general-purpose error metric for numerical prediction according to P.Neil (2018)[12].

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (S_i - O_i)^2}
\]

(3)

where \( O_i \) is the NDG results and \( S_i \) is \( G_{mb} \) predicted values for GPR.

3. Result and analysis

The data was obtained from radargram by using SIR4000 and then was processed by Radan 7 software. Twelve radargram was obtained for experiment 1 and three radargram was obtained for experiment 2. \( A_0 \) and \( A_{AC} \) were obtained from radargram using Radan 7 software that will be used to calculate value of \( \varepsilon_s \). \( \varepsilon_s \) was calculated using ALL model for each experiment and \( G_{mb} \) was calculated using the value of \( \varepsilon_s \).
3.1. Experiment 1

The value of asphalt density using NDG was shown in the table below. The value of average $A_{AC}$ calculated for 2mm metal plate is 0.449192 and 0.471592 for 5mm metal plate. By using the value of average $A_{AC}$ and value of $A_0$ radargram, $\varepsilon_{AC}$ was calculated using density model for each metal plate. By using point 5 as reference point, $\varepsilon_s$ was calculated using ALL model. $\varepsilon_s$ for 2mm metal plate is 1.2703 meanwhile $\varepsilon_s$ for 5mm metal plate is 1.3234.

Figure 5. GPR GSSI 900 MHz radargram with scope.
Table 1. $G_{mb}$ obtained from NDG reading.

| Point | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|
| $G_{mb}$ Obtained from NDG | 1.893 | 1.822 | 1.897 | 1.908 | 1.902 | 1.835 | 1.896 | 1.894 | 1.867 |

Table 2. $\varepsilon_{AC}$ calculated by using density model.

| Point | 1 | 2 | 3 | 4 | 5 |
|-------|---|---|---|---|---|
| $\varepsilon_{AC}$ Value for 2mm metal plate | 1.583694 | 1.711280 | 1.646167 | 1.776755 | 1.776755 |

| Point | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|
| $\varepsilon_{AC}$ Value for 2mm metal plate | 1.709078 | 1.776691 | 1.776691 | 1.709079 |

| Point | 1 | 2 | 3 | 4 | 5 |
|-------|---|---|---|---|---|
| $\varepsilon_{AC}$ Value for 5mm metal plate | 1.439569 | 1.577970 | 1.549207 | 1.565185 | 1.639137 |

| Point | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|
| $\varepsilon_{AC}$ Value for 5mm metal plate | 1.481084 | 1.667686 | 1.520996 | 1.577970 |

Thus, $G_{mb}$ for each point was calculated and by using ALL model equation and percentage error for each point was calculated between GPR $G_{mb}$ and NDG $G_{mb}$.

Table 3. $G_{mb}$ estimation using ALL model equation for 2mm metal plate.

| Point | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|
| $G_{mb}$ for GPR 2mm metal plate | 1.938 | 2.025 | 2.018 | 1.902 | 1.902 | 2.027 | 1.902 | 2.017 | 2.027 |
| Error (%) | 2.32 | 10.02 | 6.00 | 0.31 | 0.00 | 10.46 | 0.32 | 6.49 | 8.69 |

Table 4. $G_{mb}$ estimation using ALL model equation for 5mm metal plate.

| Point | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|
| $G_{mb}$ for GPR 5mm metal plate | 1.474 | 1.810 | 1.752 | 1.786 | 1.902 | 1.588 | 1.925 | 1.688 | 1.810 |
| Error (%) | 22.13 | 0.66 | 7.64 | 6.39 | 0.00 | 13.46 | 1.53 | 10.88 | 2.95 |
Figure 6. Difference $G_{mb}$ value between GPR and NDG (a) 2mm metal plate (b) 5mm metal plate.
Based on experiment 1 result, it shows that 2mm metal plate gives more accurate $G_{mb}$ results compared to $G_{mb}$ value of 5mm metal plate. Besides, percentage error of 2mm metal plate was ranged from 0.32 to 10.46 percent of error with NDG result compared to 5mm metal plate which is ranging from 1.53 to 22.13 percent of error. This is also showed that GPR also capable in measuring density of the asphalt by an error of 10% compared to NDG result. Root Mean Square (RMS) error also calculated between $G_{mb}$ result between GPR and NDG for each plate. For 2mm metal plate RMS error was 0.12301 meanwhile for 5mm metal plate was 0.188245.

3.2. Experiment 2
The values of asphalt density obtained from NDG and were converted into $G_{mb}$ values are shown in the Table 5. For the Experiment 2, based on the results from the Experiment 1 which is thinner plate, 2mm, is used as it performs better in term of accuracy of density value in respect of the value from NDG. Besides, also from the Experiment 1, the data shows that the $A_0$ value is approximately same from each point. Hence, for practicality, the 2 mm metal plate is placed only on one point which is point 5. This useful when considering that this technique will used in on-field, which is on real roads, there is no need to place metal plate along the road. Therefore, $A_{AC}$ value was obtained from one point, which is at point 5, resulting no need to calculate average value of $A_{AC}$. The $A_{AC}$ value in the experiment 2 is 0.286325.

| Point | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|
| Gmb   | 1.856 | 1.747 | 1.671 | 1.889 | 1.904 | 1.885 | 1.791 | 1.818 | 1.861 |

$E_{AC}$ value is calculated by using the $E_{AC}$ formula using the obtained $A_0$ and $A_{AC}$ value from GPR radargram shown in the Radan 7 software. Table 6. shows the value of $E_{AC}$ calculated for each point.

| Point | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|
| Eac   | 5.933575 | 4.478624 | 4.183906 | 5.522527 | 5.522527 | 5.993575 | 6.382303 | 3.911595 | 5.933575 |

Then, $E_s$ value is back-calculated from the ALL model formula by using $G_{mb}$ value obtained from NDG and $E_{AC}$ value at point 5. The value of $E_s$ is 10.73686093.

Since the $E_s$ value is obtained, $G_{mb}$ value from GPR is possible to calculated using the ALL model formula. Table 7. shows the $G_{mb}$ value calculated from GPR and error percentage in respect of difference of the value from $G_{mb}$ of NDG. The difference in $G_{mb}$ value from NDG and GPR is illustrated in Figure 7.
Table 7. $G_{mb}$ estimation using ALL model equation for 2mm metal plate

| Point | $G_{mb}$ Value from GPR |
|-------|-------------------------|
|       | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
| 1     | 1.947 | 1.845 | 1.856 | 1.903 | 1.903 | 1.947 | 2.002 | 1.886 | 1.947 |
| Error (%) | 4.90 | 5.61 | 11.07 | 0.74 | 0.05 | 3.29 | 11.78 | 3.74 | 2.95 |

Figure 7. Difference $G_{mb}$ value between GPR and NDG

Based on experiment 1 result, 2mm metal plate showed promising results in terms of its low percentage error in $G_{mb}$ values compared to 5mm metal plate. That error percentage from 2mm metal plate ranging from 0.32% to 10.46% while 1.53% to 22.13% were achieved from 5mm metal plate experiment. This is due to thicker metal that causes radio waves from GPR to interfere and affect the radargram imaging resulting inaccurate $A_0$ value and further affect the calculation. These data gained from experiment 1 leads to the idea of experiment 2 which was to improve $G_{mb}$ value, which means to achieve lower error percentage. However, instead of using multiple metal plate, experiment 2 was done by using only one 2mm metal plate instead. This is due to practicality, where this method will be used on-site, it will be more difficult if every point needs a metal plate.

In experiment 2, point 3 and point 7, shows a quite large error percentage compared to others, which are 11.07% and 11.78% respectively. Noted that experiment 2 is done slightly after rainy weather resulting asphalt to contain water. This could raise a problem as water can affect the density of the asphalt. As for GPR, it may affect the radargram image, due to blurry image, and this gives difficulty during the process of obtaining the value of $A_0$ and $A_{AC}$. This problem could give error in obtaining those values and will affect further calculation. Root Mean Square (RMS) error also calculated between $G_{mb}$ result between GPR and NDG for 2mm metal plate is 0.111899.
4. Conclusion
The objective of the study was to determine the correlation of ground penetrating radar and nuclear density gauge data to determine the density of asphalt pavement can be achieved by using appropriate model such as ALL model. As part of this task, two experiment was conducted to improve the quality of the data collected. These include a comparison of two metal plate in Experiment 1 and application of the best metal plate in Experiment 2. Experiment 1 concluded that 2mm metal plate is more accurate than 5mm metal plate which result in the \(G_{mb}\) value closer to the \(G_{mb}\) value on NDG. The experiment using 2mm metal plate has error percentage ranged from 0.32\% to 10.46\% compared to 1.53\% to 22.13\% in 5mm metal plate experiment. To achieve more practicality and accuracy, experiment 2 was planned by using only one point of 2mm metal plate rather than metal plate on each point. Experiment 2 has error ranged from 0.05\% to 11.78\% from nine points. Root Mean Square (RMS) error also calculated between \(G_{mb}\) result between GPR and NDG for 2mm metal plate is 0.111899. This concluded that GPR performance in density measurement of asphalt is impressive and comparable to NDG except for some points that have larger error percentage. Fortunately, for further experiment, these errors may be lowered if the experiment is done on a hot sunny day where the absence of water on asphalts and soil beneath it to achieve lower error percentage.

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