Asphalt Density Estimation Using Ground Penetrating Radar

Illinois Asphalt Pavement Association (IAPA) Scholarship

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Introduction

Asphalt concrete (AC) density is the most famous quality assurance and quality control parameter (QA and QC) used during the construction of new asphalt pavements. AC density is recommended to be in the range 92-97% of its maximum theoretical specific gravity/density (G_{mm}), which corresponds to air voids percentage of 3-8%. If AC layer is under-compacted (air voids > 8%), the AC is expected to be vulnerable to moisture intrusion, raveling, cracking, and rapid asphalt binder oxidation. Contrarily, over-compacted AC (air voids < 3%) is susceptible to rutting, shoving, and bleeding [1]. An improvement of AC pavement density, which is usually used as project incentive/disincentive, by 1% may improve fatigue life and rutting resistance by up to 44% and 66%, respectively, which could extend pavement service life by about 10% [2].

Ground penetrating radar (GPR) is a nondestructive device that is usually used to detect objects like other radars used in airports or elsewhere. It used to be used in mines and is still being used in locating underground objects like pipelines and tombs. More recently, GPR has been successfully used in many pavement applications such as: detecting and determining the spacing of reinforcement bars in reinforced concrete pavements, and detecting internal concrete flaws like deterioration, spalling and moisture [3]. For asphalt pavements, it has been successfully used in estimating layer thicknesses [4], detecting stripping and other moisture related defects and most recently, estimating density of asphalt layers using prediction models [5], which was also investigated in a real-time monitoring fashion [6].

Using GPR for density prediction of asphalt has a great potential to be the future QA/QC practice. This is due to the fact that traditional density prediction methods have many disadvantages. For instance, coring, which is the most common method for asphalt density estimation, is destructive, time-consuming and labor-intensive. A nuclear gauge, which is another method for density prediction gaining popularity, uses high frequency gamma waves which represents a safety concern and thus requires licensed operators for its use. Most importantly, both mentioned methods represent spot checks only and cannot be representative of the whole constructed AC mat, which explains failure at other weak spots later on in the pavement's service life. GPR, on the other hand, is nondestructive, safe to use, provides continuous coverage of the constructed mat, has the potential to provide fast results and has the promising flexibility to be modified to be used in the most efficient way in field.

GPR's principle is very simple; a transmitter antenna sends electromagnetic waves into the ground and a receiver antenna receives back the reflected signals (transmitting and receiving antennas could also be the same antenna which is referred to as a bistatic antenna), part of the signals are reflected when materials with different dielectric properties are encountered, those reflected signals are then saved in the control unit to be later processed using signal processing techniques in order to calculate the target value. In this case, the target value is the density, but to get to density, density prediction models are used, those models could be empirical or theory-based. For the use of the density prediction models, usually two main steps are required: collection of basic mix design parameters required by the model like percent of binder, specific gravity of aggregates, maximum theoretical specific gravity, etc. which can be easily obtained from mix design sheets. Secondly, the collection of GPR scans, the scans are used to calculate the bulk dielectric constant. When these information are in hand, prediction of density is simply done by plugging numbers into the prediction model.

The dielectric constant is also referred to as the relative permittivity, this value describes the ability of the material to be polarized under an external electric field and is naturally a complex number; a real part that represents storage and an imaginary part that represents loss. But for asphalt, which can be considered a lossless material, the imaginary part can be ignored and the dielectric constant can be considered a real number. The dielectric constant is simply a material property like any other, and there are many methods to measure it or estimate it. Actually measuring the dielectric constant requires accurate laboratory-based methods like using a coaxial transmission line. For estimation of dielectric constant of asphalt using GPR, the most common method is called the reflection amplitude method. In this simple method -see equation 1 below-, only two wave amplitudes from the GPR scan are extracted: the amplitude of the reflected scan on top of a perfect reflector (in this study a copper plate is used) denoted as A_c, and the other amplitude is taken from the scan on top of the pavement, which is denoted as A_p (see figure 1 for target amplitude).

$$\epsilon_r = \left(\frac{1+\frac{A_p}{A_c}}{1-\frac{A_p}{A_c}}\right)^2 \qquad \text{Equation 1}$$

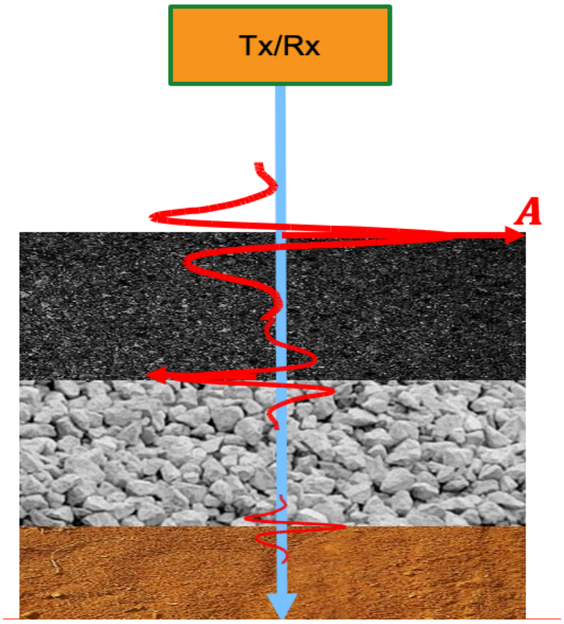

Figure 1: surface reflection amplitude (A) as seen in a GPR scan

The density prediction model to be used in this study is the modified Bottcher model or the so-called Al-Qadi Lahouar Leng (ALL) model, shown in equation 2 below. This model is special; it is not site specific, it is based on the EM mixing theory and so, it is not an empirical model. The EM mixing theory states that the bulk dielectric constant of a composite material is a function of its components' dielectric constants and volumetric proportions. Many prediction models were built based on this idea like the complex refractive index model (CRIM), Rayleigh and Böttcher models. Those models were transformed into density prediction models using mass-volume relationships of asphalt mixes. All the aforementioned models were compared for asphalt density prediction by Leng et. al [5]. In this study, the ALL model was not yet developed.

$$G_{mb} = \frac{\frac{\varepsilon_{AC}-\varepsilon_b}{3\varepsilon_{AC}-2.3\varepsilon_b}-\frac{1-\varepsilon_b}{1-2.3\varepsilon_b+2\varepsilon_{AC}}}{(\frac{\varepsilon_s-\varepsilon_b}{\varepsilon_s-2.3\varepsilon_b+2\varepsilon_{AC}})(\frac{1-P_b}{G_{se}})-(\frac{1-\varepsilon_b}{1-2.3\varepsilon_b+2\varepsilon_{AC}})(\frac{1}{G_{mm}})} \quad \text{Equation 2}$$

For the ALL model, the needed mix design parameters are: G_{mm}: maximum theoretical specific gravity, G_{se}: effective specific gravity of aggregates and P_b: percentage of asphalt binder by weight (in decimal). Also, ε_{AC} is the dielectric constant calculated from equation 1 using the GPR scan, ε_b is the dielectric constant of the asphalt binder, which is usually considered a constant and taken as 3, and finally, ε_s is the dielectric constant of aggregates which can be back-calculated for a specific aggregate type or a value for it can be used from an available database.

Objective and Scope of Work

The objective of the work is to validate the ALL model for asphalt density prediction using GPR and compare it to the performance of the other prediction models evaluated in [5]. A full-scale asphalt test section that consists of 5 lanes was built in the backyard of Advanced Transportation Research and Engineering Laboratory (ATREL) in 2010 to compare the three different asphalt density prediction models, namely the CRIM, Böttcher and Rayleigh models, the study concluded that the Rayleigh model was the best performing model, however, Rayleigh model is a sparse model that might not be suitable for dense mixes like asphalt. In this report, data from that same section is used to validate the ALL density prediction model and compare its performance to the three above-mentioned models' reported performances.

Work Plan and Methodology

The work plan for this objective is to use the existing dataset of mix properties for one of the built lanes (lane II-(b)) and its corresponding static GPR scans for 8 different locations along the lane to estimate the specific gravity using ALL prediction model (Figure 2 below shows the usual GPR setup on a van). The results will be checked against lab-measured bulk specific gravities of extracted field cores at the same locations where the GPR static scans were taken, considering extracted cores' specific gravity values as ground truth values, those core data were also reported in the paper by Leng el. Al [5]. Simple statistical analysis will be performed at the end to judge on the accuracy of the ALL model compared to the previously tested models and the feasibility of using GPR for in-situ density estimation of asphalt pavements will be judged accordingly.

Figure 2: Typical GPR setup on a van

Results and Discussion

Table 1 shows the mix design information for lane II-(B) and Table 2 shows the dielectric constants for locations 1-8 calculated using the reflection amplitude method explained before. To find the value of the aggregate dielectric constant discussed before, the first core is randomly used to back-calculate it; in this case, the bulk dielectric constant ε_{AC}, the dielectric constant of binder ε_b, mix properties are all used in the ALL model as input and only ε_s is unknown and calculated. This core is later eliminated when judging the accuracy of the ALL model, because it was used as an input.

Table 3 shows the predicted specific gravities using the ALL model in comparison to core specific gravities and their related squared error of estimate, again the error is zero for core 1 because it was used as an input in the back-calculation process.

Table 1: Lane II-(B) mix design information

Lane II-(B)	**G_{mm}**	**G_{se}**	**P_b (%)**	**ε_b**
	2.481	2.661	6.0	3.0

Table 2: Dielectric constant for 8 locations using reflection amplitude method

Core No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
ε_{AC}	5.77	5.78	5.77	5.66	5.49	5.35	5.28	5.37

Table 3: Comparison between core specific gravities and predicted ones using ALL model

Core No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**

Core Gmb	2.288	2.314	2.309	2.286	2.216	2.211	2.188	2.177
Predict-ed Gmb	2.288	2.290	2.288	2.265	2.229	2.201	2.188	2.205
Squared Error	0.0	0.00057	0.00044	0.00046	0.00018	0.00010	0.0	0.00080
Error (%)	0.0%	1.03%	0.91%	0.94%	0.60%	0.44%	0.01%	1.3%

The back-calculated dielectric constant of aggregates from core No.1 is around 7.36, which checks well with the usual value of 8 for limestone aggregates used in this test lane. Also, the summation of squared errors (SSE) for all other cores is 0.00254, this corresponds to a relative average error of 0.75% and a root mean squared error (RMSE) of 0.019; this means that the ALL model can predict the specific gravity ∓ 0.019, which is very accurate and far outperforms the other three models: CRIM, Rayleigh and Böttcher models, which had RMSE values of 0.0857, 0.0443 and 0.0727 respectively, in the same study.

Summary

In this short report, ALL density prediction model was validated using real full-scale testing site data, its performance was also compared to performance of other very common density models. ALL model outperformed other models with an RMSE of only 0.019. We can conclude that using GPR for density prediction of asphalt concrete is feasible and can be the future of QA/QC practices due to the many advantages of GPR over other conventional methods for this task. Next steps include employing GPR in field for compaction monitoring and building a prototype of how that would look like, some other complications can also arise in field and need further research, including convincing contractors and agencies to use GPR.

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