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Enhanced Model for Continuous Dielectric-Based Asphalt Compaction Evaluation

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Abstract

The compaction of asphalt concrete significantly affects long-term pavement performance. Although coring provides a relatively accurate way of assessing in-place density at specific locations, the coverage of the assessment is limited, especially at longitudinal joint locations. This can be particularly problematic because it is difficult to identify problematic locations that are likely to fail prematurely using current compaction assessment methods. Ground penetrating radar (GPR) provides an attractive nondestructive testing alternative for evaluation of compaction quality, especially with recent significant improvements in the GPR technology for this specific application. However, assessment of the air void content of the asphalt mix from the GPR-measured dielectric constant of the surface requires conversion of dielectric variation to air void content variation, which is the subject of this paper. An alternative to the commonly used model is proposed, leading to more justifiable predictions for low values of dielectric constants. The proposed model was used to interpret data from a 7-mi long asphalt overlay construction project. The results of the interpretation as compared with the results obtained with the conventional model show an improvement on the stability of the prediction at low air void contents, especially when core calibration data are limited and uncertainty is considered. These results are promising in the direction of reducing field cores necessary to have a stable model providing continuous compaction assessment of new asphalt pavement construction.

Past research has shown that the performance of asphalt concrete is highly dependent on the air void content of the compacted asphalt mixture. The air void content has been shown to correlate with key asphalt characteristics such as stiffness (*1*), strength (*2*) and dynamic modulus (*3*). Kassem et al. found that increased air void content correlated with the increased occurrence of various pavement distresses including excessive aging and moisture damage that negatively affected long-term performance (*4*). The impacts on long-term performance were quantified in a study performed by Linden et al., which estimated that each 1% increase in air voids over 7% leads to an approximately 10% reduction in pavement life (*5*).

Typically, asphalt compaction is assessed using coring, which is destructive, expensive, time consuming, and limited in coverage. Though these measurements are useful for postconstruction analysis and are often used as primary components of quality assurance measurements, they cannot provide a real-time feedback during the paving operation. The issues associated with traditional measures of compaction create a need for nondestructive methods that can collect data continuously, cheaply, and quickly.

Ground penetrating radar (GPR) provides a nondestructive testing alternative that allows for walk-behind or vehicle-mounted measurements (*6*, *7*). GPR uses electromagnetic waves to explore subsurface characteristics. In transportation infrastructure survey, GPR has been commonly applied to detect free water (*8*), to estimate the dielectric property of pavement materials (*9*), to estimate the layer thicknesses (*10*), and to study the asphalt concrete (AC) layer density (*11–14*). ASTM standard ASTM D6432-11 provides a procedure of applying GPR for subsurface investigation.

Determination of dielectric properties of the asphalt layer with GPR has been traditionally done through measurement of either round trip travel time to reflection at the depth of the AC layer or surface reflection. The travel time approach covers a greater depth, but relies on a known thickness. The asphalt thickness is often

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unknown and spatially variable. Moreover, if the asphalt layer is placed in several lifts or as an overlay over an existing asphalt pavement, it may be difficult to separate the travel time in the individual lifts from the overall travel time of the electromagnetic signal in the asphalt layer.

The AC surface reflection method uses the ratio of the amplitude of the GPR signal reflection from air to the asphalt surface, A_0, to the incident amplitude (represented by the reflection from the metal plate), A_i, to determine the bulk dielectric constant of the asphalt, e_r. The dielectric constant of the surface is determined according to Saarenketo and Scullion (*15*) using:

$$e_r = \left(\frac{1 + \left(\frac{A_0}{A_i}\right)}{1 - \left(\frac{A_0}{A_i}\right)} \right)^2 \quad (1)$$

The advantage of this approach is that if the upper lift is sufficiently thick (thicker than 30 mm) then the measured AC surface reflection depends only on the properties of the upper layer.

For newly placed asphalt lift, the dielectric constant values determined from Equation 1 can be empirically related to the relative ratio of pore volume to the total volume of each specific asphalt mix because air has a lower dielectric constant than the surrounding asphalt material and the aggregate type and volumetric proportion are typically uniform (*16*, *17*). Because dielectric properties of the asphalt mix depend on the dielectric properties of other components of the mix which vary from project to project a universal dielectric constant to air void content conversion is not feasible. To account for these changes, cores need to be taken for each new mix at locations where conversion from dielectric constant to air void content is conducted. The correlation between the air voids and dielectric constants plays a key role in the accuracy of the air voids predictions made using the model.

There have been several field trials of GPR for nondestructive testing (NDT) determination of air voids. The first large scale trial was performed in Finland in 1996–1997 (*18*). Recently, several state departments of transportation in the USA have held trials of the technology (*19–22*). The most notable recent application of GPR for compaction surveying was conducted by Sebesta, Scullion and Saarenketo (*16*) as part of the SHRP2 RO6C activities. Though several implementations have consistently demonstrated the ability of GPR technology to provide real-time information on relative compaction, use of GPR to estimate actual air void content has limitations and is still a challenging problem in spite of the significant improvements in the GPR technology for this specific application under the SHRP2 project (*16*).

Various impulse radar versions of GPR have shown that the dielectric properties determined from the asphalt surface reflection amplitude correspond with core-measured air void content (*18*, *22*, *23*). Additionally, a step frequency array-based method improves the coverage and productivity of the measurements, making it an attractive alternative to current state-of-the-practice procedures (*21*). Whereas these studies showed the potential of new technology for improved quality assurance in selected locations, the focus of this study is on how a stable compaction assessment can be achieved in full-scale implementation. In the case of the step frequency array system (*24*), these technologies can require intensive data processing from the frequency domain or can be cost prohibitive, whereas the single impulse array systems do not provide necessary coverage for widespread implementation.

The GPR equipment used in this study, the rolling density meter (RDM), is based on a system that evolved from recent research conducted under a National Academies of Science sponsored Strategic Highway Research Program (SHRP2) (*16*). It uses similar antennae, but also applied in a three-channel array to obtain some of the benefits in coverage explained in (*21*), in which multiple antenna pairs are used in each pass.

This paper deals with a problem of conversion of dielectric variation to air void content variation. Traditionally, a simple exponential model is used for dielectric–air void content correlation. The current practice is to develop this model for each construction project to minimize the error caused by variations in mix design and properties. To minimize extrapolation outside the calibration limits, it is recommended to collect cores representing full range survey dielectric constant values (*18*, *19*, *21*). However, this is not always practical because the full range of dielectrics on a project are not known until the project is complete. Moreover, areas with a high air void content often exhibit higher local variation causing higher uncertainty in the core air void measurements. Because only a limited number of cores with a high air void content are available this increases the uncertainty in the dielectric property–air void relationship for high air void content values. At the same time, an accurate conversion of the dielectric values to the air void content is especially important for the areas with low measured dielectric values, because they often determine whether the pavement will fail prematurely.

The paper presents an approach for development of a modified model to convert dielectric variation to air void content variation. The paper considers electromagnetic mix modeling theory and is based on the conventionally accepted empirical method. The proposed model includes physics-based constraints to ensure more reliable determination of the areas with high air void content.

Table 1. Mix Model Inputs (*23*)

Model		Aggregate (ε_s)	Binder (ε_b)	Maximum bulk SG (G_{mm})	SG of binder (G_b)	Binder content (P_b)	Bulk SG of aggregate (G_{sb})
Rayleigh	Assumed	6	3	2.521	1.015	5%	2.705
	Regression	7.44	2.00	2.276	1.015	4.1%	2.610
Bottcher	Assumed	6	3	2.521	1.015	5%	2.705
	Regression	8.33	7	3.026	1.015	6.0%	2.610
Crim	Assumed	6	3	2.521	1.015	5%	2.705
	Regression	6.38	3.21	2.602	1.015	5.1%	2.610

Note: SG = specific gravity.

Overview of Electromagnetic Mix Modeling Approach

Several approaches have been developed for relating the dielectric properties of an asphalt mix to its air void content. The most commonly used approach is the use of an empirical correlation between these two mix characteristics. Many studies successfully used the exponential model (conventional model) (*15*, *16*, *21*, *22*):

$$AV = A^{*}\exp(-B^{*}\varepsilon) \quad (2)$$

where AV is the air void content, ε is the input hot mix asphalt dielectric constant, and A and B are calibration constants.

Although this purely empirical relationship is effective in converting dielectric constant to air void content when the necessary dielectric precision is achieved and sufficient core calibrations are available, a more rigorous approach should derive the air void–dielectric constant relationship for the asphalt mix from the dielectric properties and volume fractions of the asphalt mix components. Although this ideal is not fully achievable using the currently available mix models, the mix modeling approach should be considered to ensure a more stable physics-based empirical model.

Electromagnetic mix modeling has been developed for dielectric characterization of rock properties such as estimation of rock porosity (*25*), water and clay influences (*26*), and other geophysical applications (*27*). This work was further extended for application to civil engineering materials including evaluation of hot mix asphalt using GPR (*23*, *28–30*). The mix model method is based on the modeling of how an electromagnetic wave interacts with composite materials using assumptions for how the wave interacts with the different AC components. The mix models evaluated in this study differ only in form, as the coefficients used (dielectric and volumetric values) are the same in each model. A more detailed description of each model can be found elsewhere (*23*, *28–30*). Equations 3 through 5 show commonly accepted mix models for asphalt concrete.

Rayleigh Model:

$$AV = 1 - \frac{\frac{\varepsilon_{HMA}-\varepsilon_b}{\varepsilon_{HMA} + 2^{*}\varepsilon_b} - \frac{1-\varepsilon_b}{1 + 2^{*}\varepsilon_b}}{G_{mm}{}^{*}\left(\left(\frac{\varepsilon_s-\varepsilon_b}{\varepsilon_s + 2^{*}\varepsilon_b}\right)^{*}\left(\frac{1-P_b}{G_{sb}}\right) - \frac{(1-\varepsilon_s)}{1 + 2^{*}\varepsilon_b}{}^{*}\left(\frac{1}{G_{mm}}\right)\right)} \quad (3)$$

Bottcher Model:

$$AV = 1 - \frac{\frac{\varepsilon_{HMA}-\varepsilon_b}{3^{*}\varepsilon_{HMA}} - \frac{1-\varepsilon_b}{1 + 2^{*}\varepsilon_{HMA}}}{G_{mm}{}^{*}\left(\left(\frac{\varepsilon_s-\varepsilon_b}{\varepsilon_s + 2^{*}\varepsilon_{HMA}}\right)^{*}\left(\frac{1-P_b}{G_{sb}}\right) - \frac{(1-\varepsilon_b)}{1 + 2^{*}\varepsilon_{HMA}}{}^{*}\left(\frac{1}{G_{mm}}\right)\right)} \quad (4)$$

CRIM for $\alpha = 2$:

$$AV = 1 - \frac{\sqrt{\varepsilon_{HMA}} - 1}{G_{mm}{}^{*}\left(\frac{P_b}{G_b}\sqrt{\varepsilon_b} + \frac{(1-P_b)}{G_{sb}}\sqrt{\varepsilon_s} - \frac{1}{G_{mm}}\right)} \quad (5)$$

where AV is the air void content, ε_{HMA} is the input hot mix asphalt dielectric constant, and the remaining variables are given in Table 1.

The mixing models are advantageous as compared with a purely empirical approach in that they are rational. These models—combined with laboratory testing and more accurate assumptions—may eventually reduce or even eliminate the need for calibration cores. These models guarantee reasonable trends—sensitivity to the properties of the individual components, that is—so it may make them less susceptible to errors. For example, each model can be verified for the extreme conditions, such as predicting 100% air void content (0 bulk specific gravity) when a dielectric constant of 1 is used. By comparison, the conventional purely empirical model does not hold true outside of the measured dielectric ranges.

Al-Qadi et al. conducted a sensitivity study and evaluated the CRIM, Rayleigh, and Bottcher models for characterizing asphalt compaction (*23*). They employed a method of calibrating the models using laboratory mixed and compacted specimens (*23*). Table 1 gives the assumed values used in the sensitivity study as well as the values obtained from a least squares regression matching the laboratory-measured air voids.

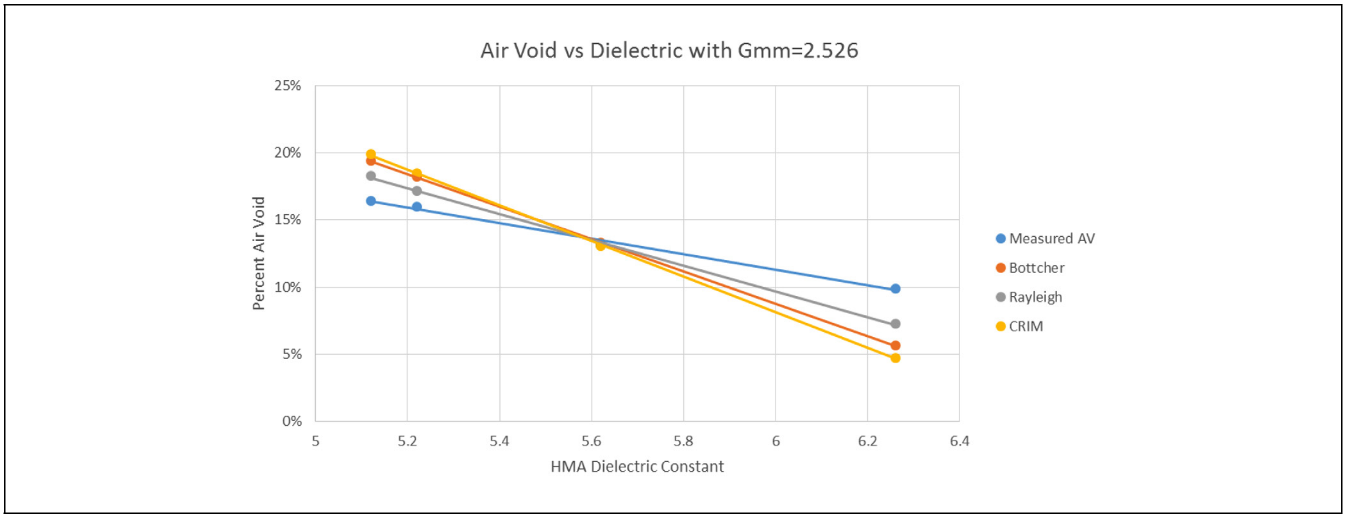

Figure 1. Measured (blue) versus predicted air void content using the CRIM, Rayleigh, and Bottcher models (*23*).

Figure 1 shows the air void content measured and predicted versus measured dielectric using the assumptions reported by Al-Qadi et al (*23*). The plot is adapted to convert the presented bulk specific gravity relationship to air void content which is compatible with the results of this study by using the assumed maximum specific gravity reported of 2.526. The results from the Al-Qadi study show a reasonable agreement between the measured and predicted values, although the measured data are less sensitive to changes in dielectric than the predicted response. Additionally, it should be noted that the air void contents were greater than typical air voids observed in the field because of limitations in their compaction process when preparing laboratory samples.

Whereas the Al-Qadi et al. study showed discrepancies and limitations with the laboratory calibration method and ability to match the sensitivity of measured air void content versus dielectric values, the Rayleigh model was determined to be the most rational mix model of the available choices (*23*). Although imperfect, this model can be used to quantify the expected effect of mix changes. For example, Figure 2 shows the Rayleigh model predicted air void content versus dielectric constant using the assumed values from Table 1 to compare the effect of aggregate dielectric and binder dielectric changes. The aggregate dielectric constant (Figure 2*a*) shows three aggregate value plots that represent a reasonable Minnesota source granite $e = 5$ (green), Al-Qadi et al. assumed limestone aggregate ($e = 6$), and reasonable Minnesota source limestone aggregate ($e = 7$). These represent a relatively conservative range as compared with the range of 4 to 9 for dielectric values of aggregates reported by multiple studies (*23*, *27*). The binder dielectric content (Figure 2*b*) of 2, 3, and 4 represents

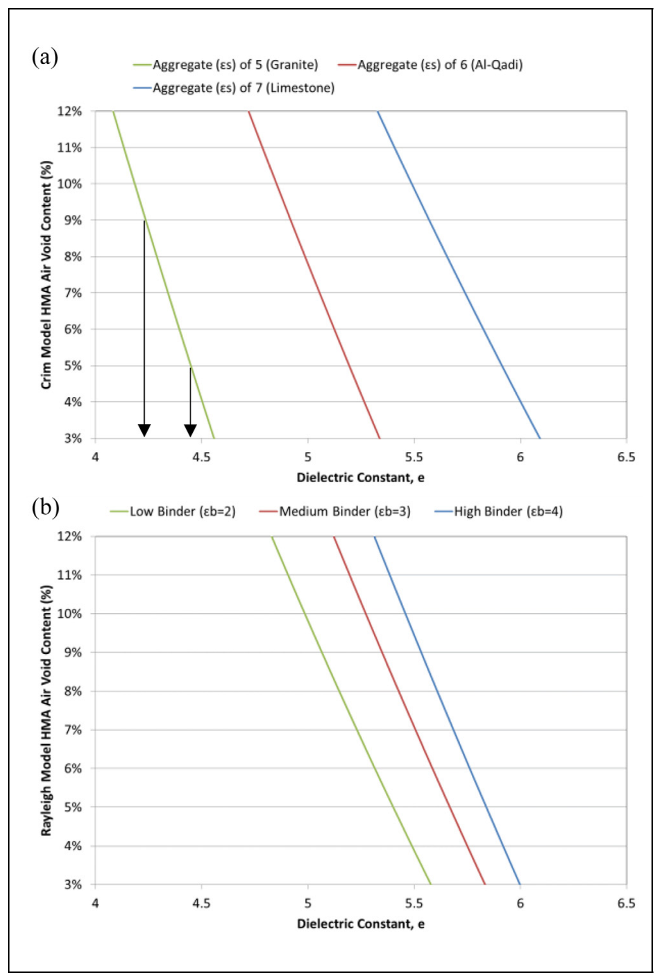

Figure 2. Predicted change in air void content using the Rayleigh model for a range in dielectric values assumed for (*a*) aggregate and (*b*) binder.

a relatively large range of dielectric values compared with the 2.5 and 3.0 values used by Araujo et al. and Al-Qadi et al., respectively (*23*, *27*). It can be observed that a significantly greater effect on air void content is caused by changes in the aggregate dielectric as compared with the binder, even for relatively small changes in possible aggregate sources. For example, Araujo reported dielectric constants from 24 samples ranged from 4 to 9, including various sedimentary, magmatic, and metamorphic rocks, which matched previous studies by Ulaby et al. (*31*) and Parkhomenko (*32*). The significance of aggregate dielectric constant is a reasonable result considering the mixing rules are based on volumetric and assumed or calculated dielectric constant values of each component, and the aggregate contributes the highest percentage of the asphalt pavement volume. These types of observations are valuable in determining when the type and magnitude of mix changes may not require unique calibration and mitigate the need for additional field cores.

The significant effect of aggregate dielectric on measured dielectric has been recognized and a method of measuring the aggregate dielectric using a portable network analyzer and two cylindrical cavities to measure the dielectric constant of various aggregate sources has been developed (*27*, *29*, *30*). Although this approach is especially attractive in the direction of eventually eliminating the need for field cores, this method reported precision issues involving difficulties with creating a rock specimen at adequate dimensions; it also requires significant user expertise to run the test, and has to be conducted at the same frequency content as the GPR equipment used in the field. The Al-Qadi et al. and Araujo et al. studies included the Rayleigh model (least sensitive model) as the most effective model representation of asphalt pavement (*23*, *27*), and this is the one used for comparison with the method proposed in this paper.

Observed Empirical Relationships versus Mix Model Predictions

Both mix model theory and observed field relationships show that the measured dielectric is a function of the type of pavement being tested in addition to the well-established relationship between air void content and dielectric constant for a given mix. Therefore, although the RDM method for assessment of compaction is valid when the pavement material is consistent, comparison of different pavement designs within a project may not be appropriate. For example, a pavement with a higher dielectric aggregate source like limestone may have a higher overall dielectric profile than a pavement with a granite aggregate source that has a low dielectric value regardless of air void content. Figure 3 gives an example of core-measured air void content versus RDM-measured dielectric constants on a pavement test-track with six different pavement mix designs at MnROAD. These measurements were made without any assumptions

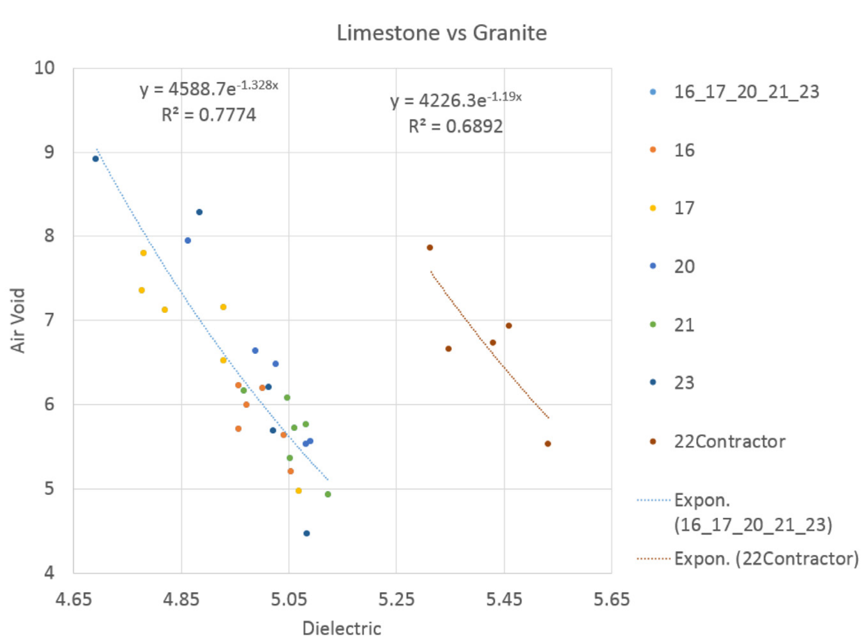

Figure 3. Example core versus dielectric data illustrating when different mixes can be combined (*left curve*) and when they need to be separated (*right curve*).

about mix components. It can be observed that a relatively good agreement between core- and RDM-measured dielectrics is obtained even when combining data from five different mix designs as long as the aggregate source is constant (granite in this case). It can also be observed that the limestone-based mix exhibited higher dielectric values than the granite-based mix regardless of the air void content. This agrees with the mix model predictions shown in Figure 2, for which changes other than aggregate dielectric constant are relatively small in comparison with the change in dielectric caused by changes in air void content.

Although the empirical data generally agree with the predicted mix model relationships, the observed sensitivity (change in air voids for a given change in dielectric) shows a similar discrepancy to that observed in the laboratory study conducted by Al-Qadi et al., even when using the Rayleigh mix model (*23*). Figure 4 shows curves developed from multiple locations (Texas, Minnesota, Maine, Nebraska), conducted by multiple agencies (University of Minnesota, Minnesota Department of Transportation, and Texas Transporatation Institute). It can be observed that each model shows a less sensitive slope between measured and mix model predicted air void content as compared with the curves shown in Figure 2. From Figure 4's superposition of an equivalent mix model curve from Figure 2 (red) along with embedded arrows in each figure placed at the granite aggregate predicted and observed curves, it can be observed that the same change from 9% air void content to 5% air void content requires over twice as much of a change in observed dielectric as the Rayleigh model predicts. This agrees with the observation from the laboratory study showing the mix models to be overly sensitive to changes in dielectric (*23*).

Proposed Model

The practicality and sensitivity issues described in the previous section preclude direct implementation of the mixing models. However, the value of incorporating a rational model in the conversion is proposed to address issues with the currently accepted conventional model. The currently accepted conventional model can be unstable in predicting air void content at the extremes (it is recommended to collect 5th and 95th percentile dielectric values to avoid extrapolation) (*18*, *19*, *21*), especially if there is a lack of dielectric versus core data to get an accurate representation. This is known from previous studies and it is recommended to select field core locations from a wide range of dielectric data to calibrate when using the currently accepted conventional method (*18*, *19*, *21*). However, selecting a wide range of core locations is not always practical. Moreover, because of a small number of replicates at the end of the measured

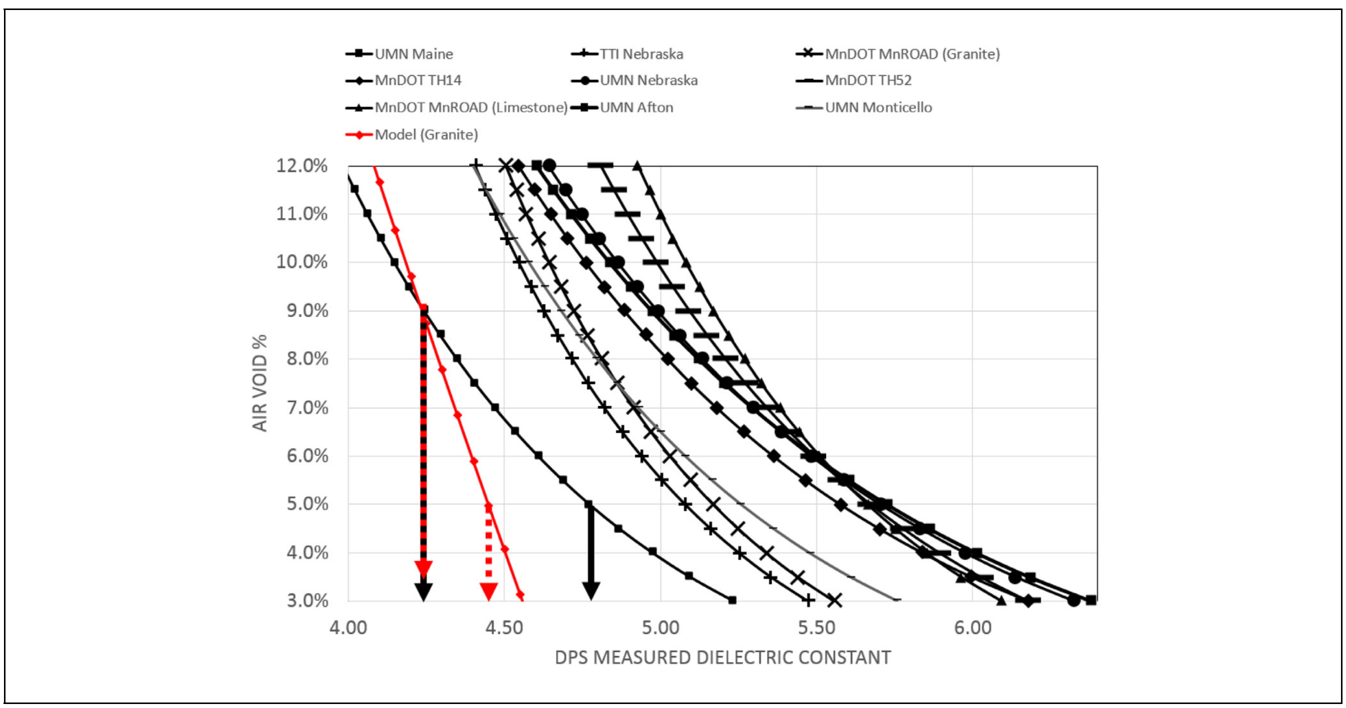

Figure 4. Relationship between dielectric and air void content for example RDM projects (*black*) in comparison with the mix model equivalent from Figure 2 (*red*).

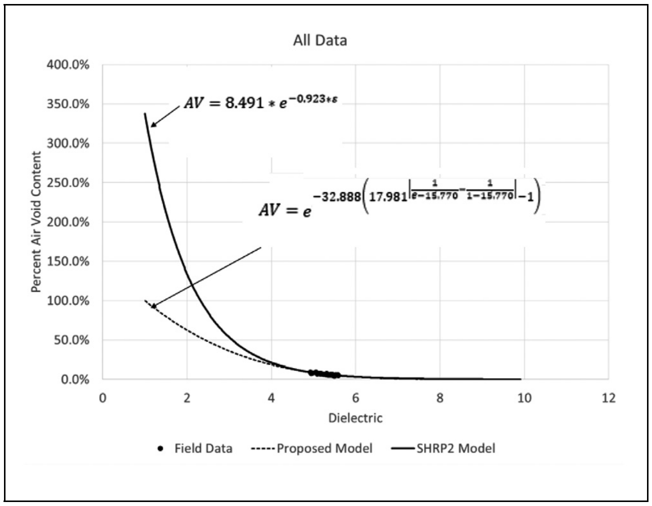

Figure 5. Field collected data along with the currently accepted and proposed models.

ranges, a small error in either the measured dielectric value at the core location or the air void value of the core may lead to a significant error in prediction, especially outside of the calibration range. This instability is magnified when extrapolating outside of the core calibrated range when using a model that is not constrained.

To evaluate the instability of the current model, consider data collected with an RDM during construction of 7 mi of 1.5-in. asphalt overlay of TH14 near Eyota, MN. Figure 5 shows 32 core-measured air void results versus RDM-measured dielectrics along with the conventional model shown in bold. It can be observed that the conventional model matches core data well. However, the conventional model predictions become unrealistic for lower dielectric values. When the dielectric constant approaches 1 a predicted air void percentage approaches 337.3%.

To address this limitation, the following model is proposed:

$$\mathrm{AV} = \exp\left(-B\left(D^{\left|\frac{1}{e-C}-\frac{1}{1-C}\right|}-1\right)\right) \tag{6}$$

where AV is the air void content, e is an input dielectric constant, and B, C, and D are constants determined by a nonlinear least-squared fit.

The proposed approach is an empirical model allowing for a slope that matches the observed field data and is constrained to physical behavior even at low dielectric/high air void content locations. If the dielectric constant input approaches 1 then the model predicts the air void content to be 100%, which is the correct value. This constraint makes the proposed model less sensitive to errors in the calibration data for cores with high air void content and more suitable for extrapolation beyond the lowest dielectric value in the calibration dataset.

The proposed model does not offer a significant improvement over the currently accepted model when many cores are available and the range of core calibrations spans the range of collected dielectric values for interpolation between known points, such as was the case in the field collected data in this study. However, the desire to limit cores, logistical challenges such as accommodating moving traffic closures, and other factors may not always be conducive to gathering a significant amount of cores covering the full measured dielectric range. These cases with extrapolation beyond the calibrated range with limited cores show the value of the proposed mechanistic model.

To demonstrate the advantage of the proposed model, both conventional and the proposed models were recalibrated using the same core data except when the measured dielectric was 5.3 or lower. Removing these highest dielectric values still provided a reasonable amount of calibration data with 12 remaining cores. To illustrate the stability of the proposed model in comparison with the currently accepted model, Figure 6 shows the predicted air void content versus a large range of dielectric values for both the conventional (solid black line) and proposed (dashed black line) models. Figure 6*a* shows the predicted air void contents with the full range of data. It can be observed from Figure 6 that within the calibration range (i.e., interpolated dielectric to air void conversions) both the conventional model and the proposed model predict similar air void contents. However the conventional model predicts a significantly higher air void content at low dielectric ranges. Comparison with Figure 5, for which the full dataset was available, shows that the calibrations with the modified dataset resulted in much greater discrepancy between the conventional and proposed model predictions than the calibrations with the original dataset. To put the discrepancy in perspective of realistically measured dielectrics for the project, Figure 6*b* shows the same comparison within a small range of dielectrics spanning the confined joint measured dielectric distribution (from 4.75 to 5.25).

It can be observed that significant discrepancies occur, even within realistic dielectric ranges with the predicted air void content from the conventional model at the low end of 4.75 resulting in a 17% air void content compared with less than 12% using the proposed method. Comparison with the full dataset predictions, expected realistic air void content, and measured core air void content support the proposed model prediction as compared with the conventional model. These observations lead to the conclusion that the proposed model offers a significant improvement of the predictions for the low dielectric value areas, especially when the accuracy of the measurements is low or an insufficient number of cores

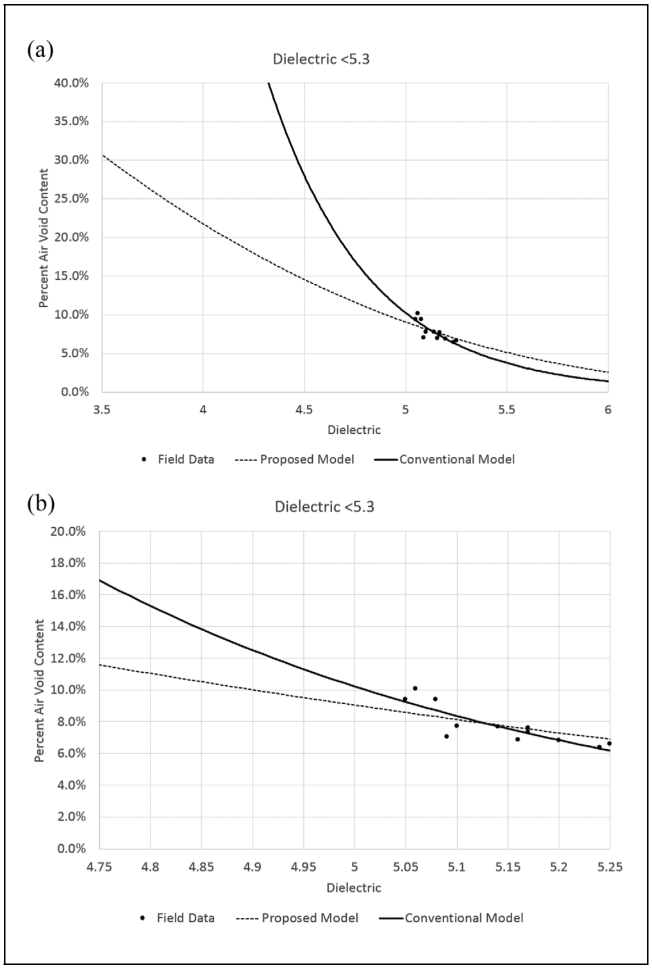

Figure 6. Comparisons of the predictions of the models calibrated with the field data and the modified dataset for (*a*) the conventional model with full range of dielectrics and (*b*) the proposed model, with realistic range of dielectrics for confined joint.

on the extremes (high or low dielectric values) is available.

Field Testing Results

As observed above, the conventional and modified models produce very similar results for a wide range of the measured dielectric values, except when the dielectric values extend to low dielectric and air void contents. Whereas the conventional model leads to unreliable and physically inadmissible air void contents for low dielectric values, the modified model offers a more rational and justifiable alternative. To evaluate the significance of this enhancement when applied to a full-scale field implementation, consider the data collected with an RDM from 7 mis of a 1.5-in. asphalt overlay of TH14 near Eyota, MN. Figure 7 shows histograms of dielectric values measured with the RDM along a stretch of pavement and separated into two groups:

- Mat—a GPR sensor path is at least 2 ft from the closest joint.
- Confined joint—a GPR sensor path is within 1 ft of the longitudinal joint compacted when the adjacent lane has been already constructed.

Using the conventional and modified calibration models, dielectric frequency distributions were converted into the distributions of the relative densities, RD, defined as:

$$RD = 1 - AV \tag{7}$$

Figure 8*a* shows the histograms obtained from these distributions with the conventional model and Figure 8*b* shows the histograms obtained with the proposed model. Table 2 presents summary statistics obtained using these

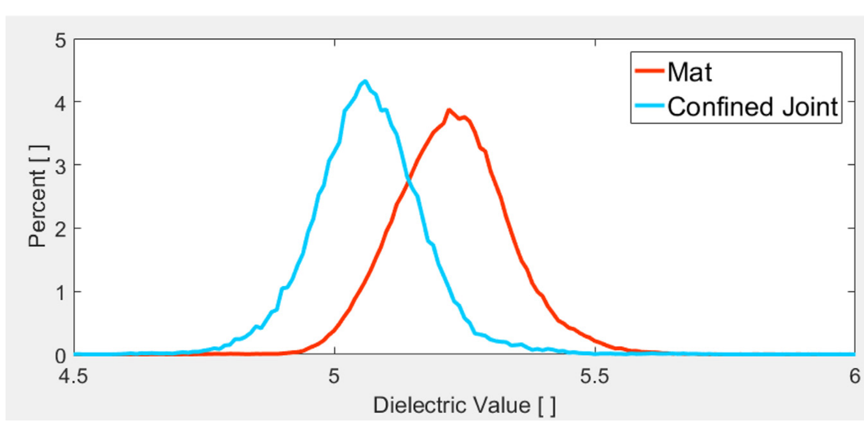

Figure 7. Distribution of dielectric value measured over a 7-mi stretch of TH14 asphalt pavement.

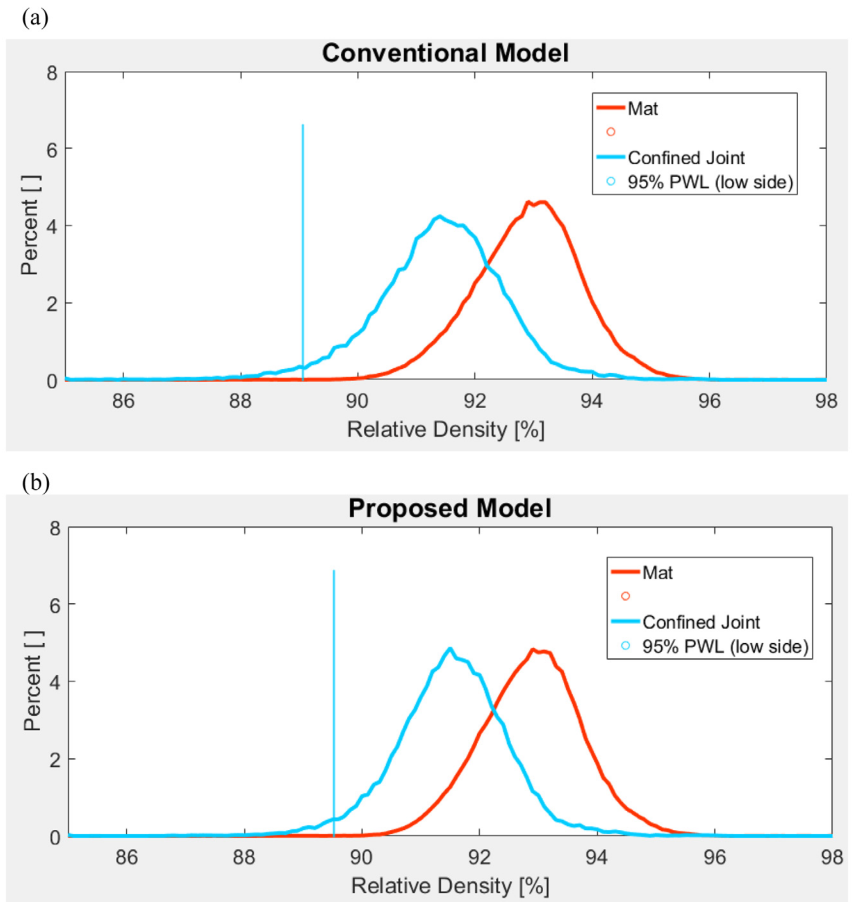

Figure 8. Histograms of the relative densities for mat and confined joint of TH14, MN, showing (*a*) the conventional model and (*b*) the proposed model.

distributions. Comparison of Figures 8*a* and 8*b* reveals that the relative density distributions for the mat are almost identical. Table 2 shows that these distributions have the same mean and median values. The relative densities corresponding to 95% within limits are also very similar: 91.0% and 91.2% from the conventional and proposed models, respectively. The confined joint exhibited a lower relative density compared with the mat compaction level, as expected. It is also not a surprise that a greater discrepancy between the relative density distributions is observed for the confined joint. Although the mean and median values are also very similar, the difference between the relative densities corresponding to 95% within limits is significantly greater: 89.0% and 89.5% from the conventional and proposed models, respectively. This suggests that the conventional model tends to overestimate the percentage of the area with low compaction. Similar analysis of the unconfined side of the joint showed an even greater difference between the models.

Conclusions

Early deterioration and long-term performance of asphalt pavements is highly affected by quality of compaction. To minimize potential delay in traffic closure on rehabilitation of heavily trafficked areas where quality of compaction is especially important, it is often desirable that the measurements can be taken over longer sections in a short timeframe immediately after final roller compaction, while still providing the necessary pavement coverage. An accurate conversion of the dielectric values to the air void content is especially important for the areas with low measured dielectric values such as longitudinal joints, because they often cause early pavement failure.

This study shows the potential of compaction assessment using a SHRP2 recommended technology referred to as the RDM, which assesses compaction using a continuous dielectric profile. A key to the success of this continuous, nondestructive technology is relating the

Table 2. Summary Statistics for Mat and Confined Joint RDM Scanned Locations

Statistical measures	Relative density			
	Conventional model		Proposed model	
	Mat	Confined joint	Mat	Confined joint
Mean	92.9%	91.5%	92.9%	91.5%
Median	92.9%	91.4%	92.9%	91.5%
Low compaction end of 95% within limits	91.0%	89.0%	91.0%	89.5%

dielectric constant to actual achieved air void content. Several approaches for development of an implementable model to convert dielectric variation to air void content variation were considered in the paper including the conventional empirical model and physics-based electromagnetic mixing models. Although the empirical model often produces reliable predictions, it requires a wide range of calibration cores to ensure stability, and produces unrealistic results for low dielectric constant values. The mixing models are advantageous in that they are derived from the dielectric properties and volume fractions of the asphalt mix components. However, it was found that the currently available mix models do not correctly predict the change in the air voids at a similar sensitivity to those observed in the field by multiple studies. A modified empirical model is introduced, matching the accuracy of prediction within the core calibration range, and improving the prediction at low air void contents. The improvement is magnified when a lack of core data and uncertainty is considered at low air void contents. The findings when using the modified empirical model as applied to a full-scale construction project are promising because of the implications in reduction of field cores necessary to convert dielectric measurements to a continuous compaction assessment of new asphalt pavement construction.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Kyle Hoegh, Lev Khazanovich, and Shongtao Dai; data collection: Kyle Hoegh, Trevor Steiner, and Shongtao Dai; analysis and interpretation of results: Kyle Hoegh, Shongtao Dai, Lev Khazanovich, Trevor Steiner; draft manuscript preparation: Kyle Hoegh, Shongtao Dai, Lev Khazanovich, Trevor Steiner. All authors reviewed the results and approved the final version of the manuscript.

References

1. Bonnaure, F., G. Gest, A. Gravois, and P. Uge. New Method of Predicting the Stiffness of Asphalt Paving Mixtures. *Association of Asphalt Paving Technologists Proc.*, Vol. 46, 1977, pp. 64–104.
2. Pellinen, T. K., J. Song, and S. Xiao. Characterization of Hot Mix Asphalt with Varying Air Voids Content using Triaxial Shear Strength Test. *Proc., 8th Conference on Asphalt Pavements for Southern Africa (CAPSA'04)*, Vol. 12, Sun City, South Africa, 2004.
3. Witczak, M., and O. Fonseca. Revised Predictive Model for Dynamic (Complex) Modulus of Asphalt Mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, 1996. 1540: 15–23.
4. Kassem, E., A. Chowdhury, T. Scullion, and E. Masad. Measurements of Asphalt Pavement Density using Ground Penetrating Radar and Its Relationship to Performance. Presented at 91st Annual Meeting of the Transportation Research Board, Washington, D.C., 2012.
5. Linden, R. N., J. P. Mahoney, and N. C. Jackson. Effect of Compaction on Asphalt Concrete Performance. *Transportation Research Record: Journal of the Transportation Research Board*, 1989. 1217: 20–28.
6. Evans, R., M. Frost, M. Stonecliffe-Jones, and N. Dixon. A Review of Pavement Assessment using Ground Penetrating Radar (GPR). *Proc., 12th international conference on Ground Penetrating Radar*, Birmingham, UK, 2008.
7. Lai, W., T. Kind, S. Kruschwitz, J. Wöstmann, and H. Wiggenhauser. Spectral Absorption of Spatial and Temporal Ground Penetrating Radar Signals by Water in Construction Materials. *Nondestructive Testing Evaluation International*, Vol. 67, 2014, pp. 55–63.
8. Al-Qadi, I. L., D. K. Ghodgaonkar, V. K. Varada, and V. V. Varadan. Effect of Moisture on Asphaltic Concrete at Microwave Frequencies. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 29, No. 5, 1991, pp. 710–717.
9. Al-Qadi, I. L., S. Lahouar, and A. Loulizi. In Situ Measurements of Hot-Mix Asphalt Dielectric Properties. *NDT & E International*, Vol. 34, No. 6, 2001, pp. 427–434.
10. Al-Qadi, I. L., and S. Lahouar. Measuring Layer Thicknesses with GPR: Theory to Practice. *Construction and Building Materials*, Vol. 19, No. 10, 2005, pp. 763–772.
11. Leng, Z. *Prediction of In-Situ Asphalt Mixture Density using Ground Penetrating Radar: The Theoretical Development and Field Verification*. PhD thesis. University of Illinois at Urbana–Champaign, Champaign, IL, 2011.
12. Leng, Z., I. L. Al-Qadi, and S. Lahouar. Development and Validation for In Situ Asphalt Mixture Density Prediction Models. *NDT & E International*, Vol. 44, No. 4, 2011, pp. 369–375.

13. Shangguan, P., and I. L. Al-Qadi. Content-Based Image Retrieval Approaches to Interpret Ground Penetrating Radar Data. *Construction and Building Materials*, Vol. 69, 2014, pp. 10–17.
14. Shangguan, P., and I. L. Al-Qadi. Calibration of FDTD Simulation of GPR Signal for Asphalt Pavement Compaction Monitoring. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 53, No. 3, 2015, pp. 1538–1548.
15. Saarenketo, T., and T. Scullion. Road Evaluation with Ground Penetrating Radar. *Journal of Applied Geophysics*, Vol. 43, No. 2, 2000, pp. 119–138.
16. Sebesta, S., T. Scullion, and T. Saarenketo. *Using Infrared and High-Speed Ground-Penetrating Radar for Uniformity Measurements on New HMA Layers*. Report S2-R06C-RR-1. Strategic Highway Research Program, National Transportation Board, Washington, D.C., 2013.
17. Leng, Z., and I. L. Al-Qadi. An Innovative Method for Measuring Pavement Dielectric Constant using the Extended CMP Method with Two Air-Coupled GPR Systems. *NDT & E International*, Vol. 66, 2014, pp. 90–98.
18. Saarenketo, T., and P. Roimela. Ground Penetrating Radar Technique in Asphalt Pavement Density Quality Control. *Proc., 7th International Conference on Ground Penetrating Radar,* Vol. 2, 1998.
19. Popik, M., K. Maser, and C. Holzschuher. Using High-Speed Ground Penetrating Radar for Evaluation of Asphalt Density Measurements. *Annual Conference & Exhibition of the Transportation Association of Canada*, Halifax, Nova Scotia, Canada, 2010.
20. Wilson, B. T., and S. Sebesta. Comparison of Density Tests for Thin Hot-Mix Asphalt Overlays. *Transportation Research Record: Journal of the Transportation Research Board*, 2015. 2504: 148–156.
21. Hoegh, K., L. Khazanovich, S. Dai, and H. T. Yu. Evaluating Asphalt Concrete Air Void Variation via GPR Antenna Array Data. *Case Studies in Nondestructive Testing and Evaluation*, Vol. 3, 2015, pp. 27–33.
22. Maser, K., and A. Carmichael. *Ground Penetrating Radar Evaluation of New Pavement Density*, Washington Department of Transportation Report No. WA-RD 839.1, Olympia, WA, 2015. Retrieved from https://www.wsdot.wa.gov/research/reports/fullreports/839.1.pdf.
23. Al-Qadi, I., Z. Leng, S. Lahouar, and J. Baek. In-Place Hot-Mix Asphalt Density Estimation Using Ground-Penetrating Radar. *Transportation Research Record: Journal of the Transportation Research Board*, 2010. 2152: 19–27.
24. Scott, M. L., N. Gagarin, M.K. Mills, and M. Oskard. Step Frequency Ground Penetrating Radar Applications to Highway Infrastructure Measurement and System Integration Feasibility with Complementary Sensors. *AIP Conference Proceedings*, Vol. 820, No. 1, 2006, pp. 1624–1631.
25. Tong, M., and H. Tao. Permeability Estimating from Complex Resistivity Measurement of Shaly Sand Reservoir. *Geophysical Journal International*, Vol. 173, No. 2, 2008, pp. 733–739.
26. Bona, N., A. Ortenzi, and S. Capaccioli. Advances in Understanding the Relationship between Rock Wettability and High-Frequency Dielectric Response. *Journal of Petroleum Science and Engineering*, Vol. 33, No. 1, 2002, pp. 87–99.
27. Araujo, S., L. Delbreilh, L. Laguerre, H. Dumont, E. Dargent, and C. Fauchard. Rock Permittivity Characterization and Application of Electromagnetic Mixing Models for Density/Compactness Assessment of HMA by Means of Step-Frequency Radar. *Near Surface Geophysics*, Vol. 14, No. 6, 2016, pp. 551–562.
28. Benedetto, A., and F. Tosti. Inferring Bearing Ratio of Unbound Materials from Dielectric Properties using GPR: The Case of Runaway Safety Areas. *Airfield and Highway Pavement 2013: Sustainable and Efficient Pavements*. 2013, pp. 1336–1347.
29. Fauchard, C., B. Beaucamp, and L. Laguerre. Non-Destructive Assessment of Hot Mix Asphalt Compaction/Density with a Step-Frequency Radar: Case Study on a Newly Paved Road. *Near Surface Geophysics*, Vol. 13, No. 3, 2015, pp. 289–297.
30. Fauchard, C., B. Li, L. Laguerre, B. Héritier, N. Benjelloun, and M. Kadi. Determination of the Compaction of Hot Mix Asphalt using High-Frequency Electromagnetic Methods. *NDT & E International*, Vol. 60, 2013, pp. 40–51.
31. Ulaby, F. T., T. H. Bengal, M. C. Dobson, J. R. East, J. B. Garvin, and D. L. Evans. Microwave Dielectric Properties of Dry Rocks. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 28, No. 3, 1990, pp. 325–336.
32. Parkhomenko, E. I. *Electrical Properties of Rocks*. Springer Science & Business Media, Berlin, Germany, 2012.

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