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ABSTRACT

Ground-penetrating radar (GPR) is a nondestructive testing technology that has been used for years to determine pavement layer thicknesses. More recently, several studies have shown that GPR can also be used to evaluate the in-place density of the pavement (i.e., density profiling system) as well as the uniformity of the compaction operations. However, the potential effect of the thickness of the evaluated layer and the type of material located underneath on GPR-measured dielectric constants is still under investigation. As part of the National Pooled Fund study TPF-5(443) sponsorship, the National Center for Asphalt Technology (NCAT) evaluated the effect of thickness in the laboratory using 60 cm by 60 cm compacted slabs and evaluated the effect of the base material by placing and testing such slabs on two different asphalt pavements, one concrete pavement, and steel plates. Steel was used to have significant contrast from typical pavement materials. This evaluation also included field testing on several pavement sections built in 2021 as part of the NCAT Test Track new testing cycle. The results of this study indicated that dielectric constants of thin layers (50 mm) may be affected by the base materials with significantly different dielectric constants compared to asphalt pavement. In addition, field evaluation of thinner layers (25 mm or less) indicated that measured dielectric constants can be highly affected by the type of base material, the density of these layers, and presence of water. A potential negative effect is the increase in variability and probability of obtaining fewer results within specified limits.

Keywords

ground-penetrating radar, dielectric constant, density profile, asphalt pavement, thickness, nondestructive testing, construction

Introduction

Construction quality assurance (QA) programs play a critical role for state highway agencies (SHAs) in ensuring that the materials and workmanship used on transportation projects are satisfactory and in reasonable conformance with the SHAs' plans and specifications. One key aspect of an effective QA program is that test results (either quality control or acceptance) need to be available quickly enough to determine potential problems with the mixture being placed and allow the contractor adequate time to make adjustments to their production and paving operations to correct the problem. According to the determination process of pavement density, the time required for coring the pavement and performing bulk specific gravity measurements on the cores can potentially result in multiple days of asphalt pavement being placed by the contractor before the in-place density is known via acceptance testing. As a result, projects may be delayed while the substandard pavement sections are removed and replaced, or the pavement life may be shortened because of the acceptance of noncompliant material.

Ground-penetrating radar (GPR) is a nondestructive testing technology that has been used for years to determine layer thicknesses. More recently, several studies have shown that GPR can also be used to evaluate the in-place density of the pavement (i.e., density profiling system [DPS]) as well as the uniformity of the compaction operations.[1–7] GPR identifies the real-time in-place compaction levels of pavements by measuring the surface dielectric constant profile, which is dependent on the compaction level. Unlike coring, DPS provides continuous measurements, resulting in nearly 100 % coverage of the constructed layers. However, there are still some limitations regarding this new technology:

- Field cores are still required to calibrate the measured dielectric constant to the actual pavement density.
- Training is required not only to conduct the test but also to process and evaluate the results.

The potential effect of the thickness of the evaluated layer and the type of material located underneath on GPR-measured dielectric constants is still under investigation. Therefore, the objective of this project was to evaluate laboratory and field surface layer thickness and the underlying material effect on measured dielectric constants of asphalt pavements built at the National Center for Asphalt Technology (NCAT) Test Track in 2021. This study is part of National Pooled Fund study TPF-5(443), "Continuous Asphalt Mixture Compaction Assessment Using Density Profiling System (DPS)."

Experimental Plan

The effect of surface layer thickness on measured dielectric constants was evaluated using laboratory-compacted slab specimens. The laboratory testing included fabrication of slabs with a minimum dimension of 60 cm by 60 cm, compacted at various thicknesses. Two unmodified hot asphalt mixtures (plant-produced mixtures) were utilized in this task with nominal maximum aggregate sizes (NMASs) of 9.5 mm and 19 mm. Twelve Superpave gyratory specimens (puck samples) with different air void levels (from 3.0 to 12.0 %) were compacted per mixture to establish the calibration equation between air voids and the dielectric constant of asphalt mixtures considered. Each puck sample was tested according to AASHTO T-331, *Standard Method of Test for Bulk Specific Gravity* (G_{mb}) *and Density of Compacted Asphalt Mixtures Using Automatic Vacuum Sealing Method.*

In relation to the dielectric constant testing process of puck samples, operators were required to take three different dielectric constant measurements of each sample (centered, rotated 90°, and flipped over) and then average them. This is part of the preliminary testing protocol developed by the Minnesota Department of Transportation (MnDOT). Additional measurements using a reference high-density polyethylene (HDPE) puck were taken every time a DPS sensor was changed for consistency verification. HDPE has relatively constant dielectric constants that range from 2.3 to 2.4. Calibration equations were developed for two mixtures between lab-measured air voids and dielectric constant results.

Testing on slabs was conducted on two separate occasions. During the first round, a total of 12 slabs were compacted (6 per mix type) at 3 different thicknesses and 2 density levels. All the slabs were placed on top of three different surfaces: asphalt pavement, concrete, and steel. During the second round, four additional slabs were compacted at two different thicknesses and at the same density level. These slabs were tested on four different surfaces: two separate asphalt pavements, concrete, and steel.

Field testing included six 30 m sections built at one of the access ramps at the NCAT Test Track that contained six different base layers with a hot mix surface layer about 25 mm thick. In addition, several thicker asphalt layers (greater than 35 mm) were built at the NCAT Test Track. This layer was placed over newly constructed asphalt pavements, milled layers, and granular base. Testing on these sections was performed to capture a wider range of mixtures, thicknesses, and underlying conditions.

LABORATORY DIELECTRIC CONSTANT REGRESSION RESULTS

Figure 1 shows the average regression equation to estimate air voids from dielectric constants when having four density levels and when the low density/high air void level was removed. All the plots in **figure 1** include estimated air void ranges based on the variability of the measured dielectric constants. Particularly for the 19.0-mm mix, a

FIG. 1 (*A*) shows predicted air voids as function of dielectric constant for the 9.5-mm mixture for samples compacted at four air voids levels. (*B*) shows predicted air voids as function of dielectric constant for the 19-mm mixture for samples compacted at four air voids levels. (*C*) shows predicted air voids as function of dielectric constant for the 9.5-mm mixture for samples compacted at three air voids levels. (*D*) shows predicted air voids as function of dielectric constant for the 19-mm mixture for samples compacted at three air voids levels.

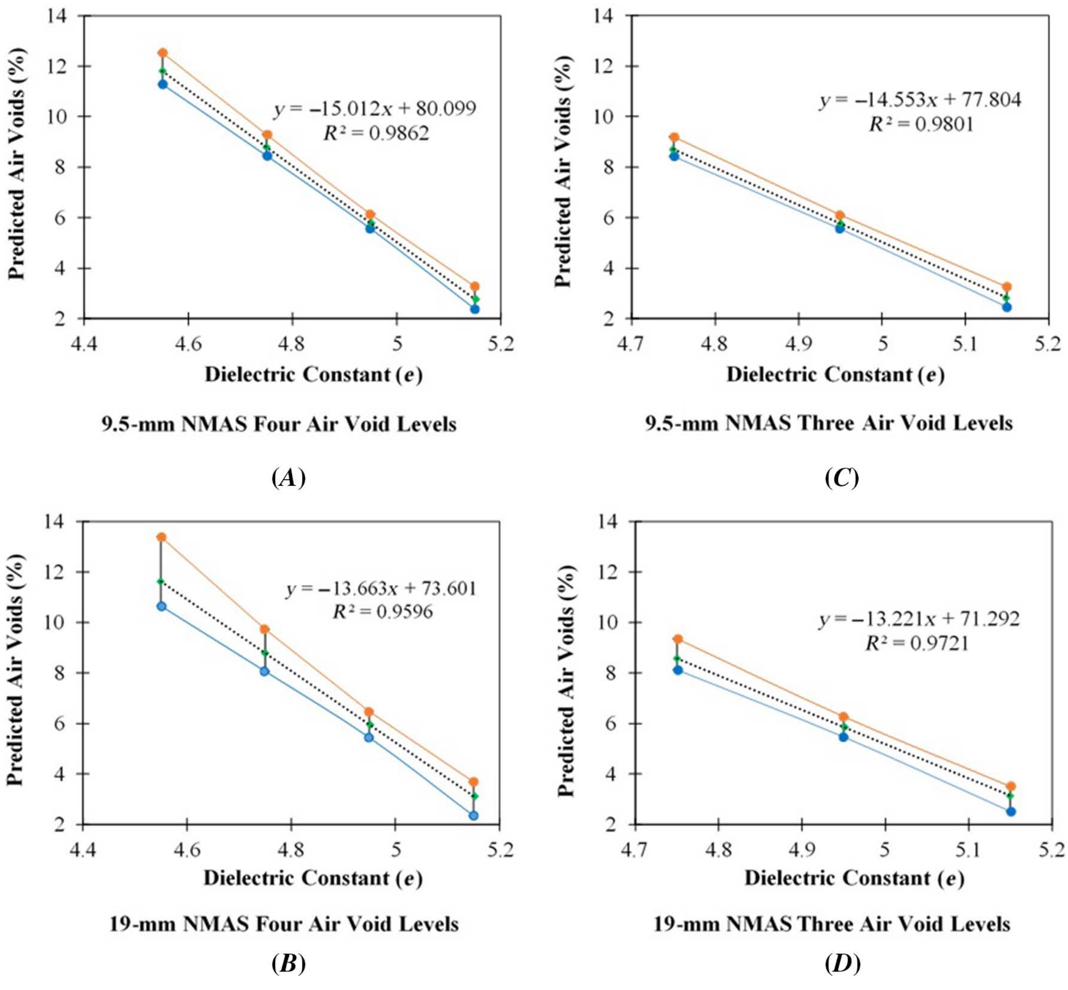

TABLE 1

Analysis of variance and Tukey test results – phase I

9.5-mm Mixture					19.0-mm Mixture				
Slab	Material	Mean	Standard Deviation	Group	Slab	Material	Mean	Standard Deviation	Group
25 mm, 3 % AV	Steel	4.555	0.131	A	2.2 in, 3 % AV	Concrete	4.697	0.212	A
	Concrete	4.507	0.229	A		AC slab	4.674	0.272	A
	AC slab	4.565	0.224	A		Steel	4.58	0.197	A
45 mm, 3 % AV	Steel	4.828	0.146	A	3.1 in, 3 % AV	Concrete	4.717	0.183	A
	Concrete	4.863	0.141	A		Steel	4.714	0.115	A
	AC slab	4.847	0.120	A		AC slab	4.652	0.183	A
77.5 mm, 3 % AV	AC slab	4.84	0.120	A	4.2 in, 3 % AV	Concrete	4.701	0.170	A
	Steel	4.814	0.146	A		AC slab	4.699	0.090	A
	Concrete	4.808	0.141	A		Steel	4.667	0.194	A
27.5 mm, 12 % AV	Steel	4.497	0.349	A	2.1 in, 12 % AV	Concrete	4.554	0.075	A
	AC slab	4.223	0.126	B		Steel	4.500	0.092	A
	Concrete	4.185	0.104	B		AC slab	4.494	0.146	A
42.5 mm, 12 % AV	Steel	4.758	0.543	A	3.0 in, 12 % AV	AC slab	4.643	0.409	A
	Concrete	4.594	0.347	A		Steel	4.446	0.437	A
	AC slab	4.528	0.435	A		Concrete	4.416	0.384	A
75 mm, 12 % AV	Steel	4.69	0.191	A	4.0 in, 12 % AV	Concrete	4.498	0.168	A
	AC slab	4.527	0.201	A, B		AC slab	4.483	0.195	A
	Concrete	4.413	0.197	B		Steel	4.278	0.775	A

Note: Shaded cells = Tukey statistical analysis.

maximum confidence interval of about 2 % in air voids was estimated at the highest air void level. Typical tolerances in specifications for acceptance limit air voids by less than 1 %. The effect of removing measured results from high air void is shown in **figure 1*C*** and **1*D***, and it provided significantly lower and consistent estimated confidence intervals throughout.

When the equations shown in **figure 1** were used to estimate air voids of laboratory-compacted slabs, a poor agreement was observed with respect to measured air voids from cores obtained from the same locations where testing was conducted. At the same time, high air void variability was obtained from the cores extracted from each slab. This was the case for both mixtures with more scattered air voids and with a wider range of air voids for the 9.5-mm mixture than the 19.0-mm mixture. Overall, the 9.5-mm mixture slabs were thinner than the 19.0-mm mixture slabs, which could be one of the factors for the obtained variability. In addition, estimation of air voids from dielectric constants was initially performed (Phase I of the study) using all four air void levels (equations from **fig. 1*A*** and **1*B***), which have higher predicted confidence levels. Later on, equations with three air void levels (Phase II) exhibited predicted air voids with lower variability. Because of the uncertainty found on measured air voids estimated from regression equations, the evaluation of the effect of thickness and underlying materials was performed using dielectric constants instead of air voids or level of compactions of the slabs.

Phase 1 Slab Thickness and Underlying Material Evaluation

Twelve slabs of Phase I were placed and tested on top of three different surfaces: asphalt pavement (dielectric constant = 4.84), concrete (dielectric constant = 6.098), and steel (dielectric constant = 100). The purpose of the testing was to evaluate the potential effect of the slab thickness and base or underlying material on the dielectric constant measurements. The dielectric constant of steel is the maximum value that the equipment can record, and it was included in the experiment to simulate a material significantly different from asphalt pavement. The dielectric constant of water is about 81; thus, using steel could also simulate the presence of water in granular base or cold recycled mixtures.

Four different locations of the slabs were selected to measure dielectric constants with three replicates per location, and testing was performed in static or time mode. A Tukey statistical analysis (**Table 1**) indicated that the dielectric constants of the 27.5 mm slab with 12 % air voids placed on steel were higher than the dielectric constants obtained on the same slab placed on concrete and asphalt surfaces (shaded cells). **Table 1** also shows that on average, dielectric constants obtained on all 9.5-mm slabs were higher when slabs were placed on steel. Further analysis of the variability of the results indicated that thin slabs (below 50 mm) that were compacted at target air voids of 12 % had slightly more variability.

Phase 2 Slab Thickness and Underlying Material Evaluation

Four additional slabs were fabricated with the same two mixtures to repeat the process followed in the first round with several changes:

- In this case, target air voids of the slabs were set to 7.0 %, which was more representative of field conditions and an easier target to achieve in the laboratory.
- Five different locations of the slabs were selected to measure dielectric constants with three replicates per location. One of the selected locations was the center of the slab, where static (time mode) and dynamic testing (distance mode) were performed to determine if the dynamic testing provides better estimated air voids.
- One additional base material (asphalt pavement with a dielectric constant of 5.497) was added to evaluate the effect of different base materials on dielectric constants.

Average dielectric constants of the thin compacted slabs of both mixtures (22.5 mm for the 9.5-mm mixture, 1.8 in for the 19.0-mm mixture) placed on steel were higher than the rest of the base materials. A Tukey statistical analysis (**Table 2**) confirmed this conclusion (highlighted cells) with the addition of dielectric constants of the 22.5 mm, 9.5-mm mixture slab placed on steel and concrete being statistically similar but different from the two asphalt pavement bases.

TABLE 2
Second round of slab analysis of variance and Tukey test results

Slab	Material	Mean	Standard Deviation	Grouping
9.5 mm, 22.5 mm	Steel	5.119	0.229	A
	Concrete	5.063	0.218	A
	AC-1	4.903	0.171	B
	AC-2	4.864	0.178	B
9.5 mm, 45 mm	Concrete	4.885	0.223	A
	AC-2	4.832	0.199	A
	AC-1	4.819	0.167	A
	Steel	4.793	0.160	A
19 mm, 45 mm	Steel	4.932	0.205	A
	Concrete	4.769	0.214	B
	AC-1	4.740	0.165	B
	AC-2	4.729	0.174	B
19 mm, 75 mm	Concrete	5.094	0.231	A
	AC-1	5.004	0.212	A, B
	Steel	4.973	0.174	A, B
	AC-2	4.901	0.171	B

Note: Shaded cells = Tukey statistical analysis.

Field Testing

Six 30 m sections were built at one of the access ramps at the NCAT Test Track that contained six different base layers with a hot mix surface layer about 25 mm thick. Base layers were 15 cm thick, and five of them were cold mixtures. Cold mixtures technologies were as follows: foam, straight emulsion, soy-based emulsion, rejuvenator, and rejuvenated emulsion. All cold mixtures had water present at the moment of construction of the surface layer and presented significantly lower densities (10 to 15 % lower) compared to hot mix asphalt. The surface layer was a densely graded 9.5-mm NMAS mixture with a PG 67-22 asphalt binder and 20 % recycled asphalt pavement (RAP). The target air voids for all the asphalt mixtures placed at the NCAT Test Track in 2021 were 6.0 % air voids or 94 % compaction level of G_{mm}.

Table 3 shows the summary of the percent within limits (PWL) analyses performed on each section on calculated level of compaction (from dielectric constant regression equations). A typical tolerance range (from 92 to 99 %) was used to conduct PWL analyses. Table 3 shows that the majority of the percent defective results were obtained with respect to the lower limit. Table 3 also shows that the control section, which was placed on top of another asphalt pavement, had the highest PWL and the soy emulsion section had the lowest PWL. This indicated that the measured dielectric constants were highly affected by the thickness of the asphalt layer (1.0 in), the lowest density of the cold mix, the presence of water in the cold mix, and potentially the use of soy in the emulsion.

Table 4 shows a summary of the compaction level and PWL analyses performed on selected sections built on the NCAT Test Track in the 2021 NCAT Test Track cycle. These sections included a variety of materials that included polymer-modified binders, recycled materials such as RAP, rubber and plastic, and different underlying conditions. The equipment used to place and compact each layer was the same used in the ramp sections. In addition, the breakdown and intermediate roller compaction patterns were kept relatively unchanged.

Of these test sections, lower average compaction levels and lower PWL results were obtained for sections with thin layers (37.5 mm). Sections with thicker asphalt surface layers not only had higher densities and PWL results but also were more uniform. The target density level was also 94 %, and the lower density levels obtained with the DPS on thinner layers (50 mm) were confirmed with extracted samples as shown in Table 4.

TABLE 3
Compaction compliance analyses of sections with cold mixtures

Material	Control	Foam	Emulsion	Soy Emulsion	Rejuvenator	Rejuvenated Emulsion
Mean % G_{mm}	93.6	92.9	93.5	92.2	92.7	93
Standard deviation	1.64	2.03	2.13	1	2.35	2.85
Percent defective lower limit	15.0 %	29.0 %	24.8 %	45.4 %	34.9 %	35.1 %
Percent defective upper limit	0.30 %	0.30 %	0.10 %	0.00 %	1.60 %	3.40 %
Percent within limits	84.7 %	70.7 %	75.1 %	54.6 %	63.5 %	61.5 %

TABLE 4
Compaction analysis test track sections

Test Track Section	S7A	S7B	S4	N8-1	N6	N8-2	N5	N7
Thickness, in	36 mm	37.5 mm	40.7 mm	56.2 mm	58.2 mm	79.5 mm	13.8 cm	14.2 cm
Mean % G_{mm}	91.2 %	91.6 %	94.8 %	94.6 %	97.2 %	94.8 %	95.3 %	96.3 %
Standard deviation	2.96 %	3.21 %	1.33 %	2.21 %	1.15 %	1.71 %	1.50 %	1.93 %
PDL	59.1 %	48.0 %	2.4 %	12.4 %	0.0 %	2.7 %	0.2 %	1.9 %
PDU	0.4 %	0.0 %	0.0 %	0.7 %	6.8 %	0.5 %	0.7 %	9.7 %
PWL	40.5 %	52.0 %	97.6 %	86.9 %	93.2 %	96.8 %	99.1 %	88.4 %
% G_{mm} (cores)	92.4 %	93.0 %	92.7 %	95.3 %	94.4 %	94.5 %		96.1 %

Conclusions

The following conclusions and recommendations have been derived from the results of this study:

- Dielectric constants of thin layers (50 mm) may be affected by the base materials with significantly higher dielectric constants compared to asphalt pavement.
- The compacted asphalt pavement slabs of this study had high variability in air voids, and that was reflected in the variability of the measured dielectric constants.
- Based on statistical analyses of the regression equations determined in the laboratory using gyratory-compacted samples, high levels of air voids (more than 10 %) can increase the variability of estimated air voids from dielectric constants. Therefore, for the development of laboratory regression equations, fabrication of gyratory samples with a maximum of 10 % air voids is recommended.
- Field evaluation of thinner layers (37.5 mm in or less) indicated that measured dielectric constants are highly affected by the type of underlying materials, density, and moisture. The main effect was the increased variability and probability to obtain fewer results within specified limits.
- On the other hand, it was confirmed that measured dielectric constants on asphalt layers placed over layers with similar materials and dielectric constants tend to have lower variability and a higher percent conforming.
- Higher than expected variability in air voids was obtained with compacted slabs. This may have contributed to the observed variability in dielectric constants. Further evaluation of the effect of thickness on dielectric constants is recommended to include larger slabs or field sections with different base materials.

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