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Evaluation of a Density Profiling System for Asphalt Pavement Density Measurement

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Final Report VTRC 26-R01

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16. Abstract:

During asphalt pavement construction, obtaining adequate and uniform density throughout the pavement layer through the compaction process is critical to achieving the desired performance. Optimum pavement density reduces oxidation potential and moisture damage, decreases rutting potential, and improves fatigue life. Numerous national research projects have cited pavement density as one of the most influential parameters defining the service life of asphalt pavement.

The Virginia Department of Transportation's (VDOT) asphalt pavement program requires the contractor to perform nuclear density readings and density measurements from cores and sawn plugs for acceptance. This process is not only destructive and potentially time-consuming but assesses only the density of a small portion of the pavement mat (about 0.003%). Although VDOT and other agencies use these processes, localized substandard density may not always be identified. Furthermore, this process cannot provide real-time feedback during the paving operation. VDOT needs to use methods that can assess a larger sample more rapidly to reduce the risk of accepting substandard material. One such method is by employing density profiling system (DPS) technology. The benefits to agencies using DPS technology include the ability to conduct measurements over the entire surface area of the new asphalt pavement layer, measure the density along the longitudinal joint where many pavements experience premature failures, and implement a statistical evaluation of the achieved density. The benefits to contractors include the ability to evaluate their compaction processes and make adjustments during the course of the work when improvements can still be implemented before paving completion.

The study concluded that DPS technology can describe relative changes in the density of asphalt mixtures placed in the field based on measurements of the dielectric value and that it offers sufficient data volume for density uniformity estimates. The study also concluded that DPS is a promising technology for process control purposes but is still premature for VDOT to use for density acceptance.

The study recommends that VDOT's Materials Division not consider using DPS at this time to assess the density of paved asphalt mixtures for acceptance purposes because additional studies are needed to better understand the effects of mixture variables on the dielectric results. The study recommends that VDOT's Materials Division consider using DPS to assess relative changes in paved asphalt mixture density during construction where desired. The study recommends that VDOT's Materials Division consider using DPS density testing results to evaluate achievable density uniformity. The study also recommends that the Virginia Transportation Research Council and VDOT's Materials Division submit a research needs statement to the Pavement Research Advisory Committee to help further understand the remaining unknowns through additional testing during future construction seasons.

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FINAL REPORT

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ABSTRACT

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INTRODUCTION

During asphalt pavement construction, obtaining adequate and uniform density throughout the pavement layer through a process known as compaction is critical to achieving the desired performance. Optimum pavement density reduces oxidation potential, reduces moisture damage, decreases rutting potential, and improves fatigue life (Vivar and Haddock, 2006). Numerous national research projects have cited pavement density as one of the most influential parameters defining the service life of asphalt pavement (Brown, 2006; Hughes, 1989; Maupin, 2007; Tran et al., 2016). Furthermore, Linden et al. (1989) estimated that each 1% increase in air voids (decrease in density) above 7% leads to an approximate 10% reduction in pavement life.

The Virginia Department of Transportation's (VDOT) asphalt pavement program requires the contractor to perform nuclear density readings and measurements of density from cores or sawn plugs for acceptance. This process is not only destructive and potentially time-consuming but assesses only the density on a small portion of the pavement mat (about 0.003%). Although VDOT and other agencies use these processes, localized substandard density may not always be identified. Furthermore, this process cannot provide real-time feedback during the paving operation. VDOT needs to use methods that can assess a larger sample more rapidly to reduce the risk of accepting substandard material. One such method is by employing density profiling system (DPS) technology. The benefits to agencies using DPS technology include the ability to conduct measurements over the entire surface area of the new asphalt pavement layer, measure the density along the longitudinal joint where many pavements experience premature failures, and implement a statistical evaluation of the achieved density. The benefits to contractors include the ability to evaluate their compaction processes and make adjustments during the course of the work when improvements can still be implemented before the completion of paving.

The DPS technology used in this study operates by correlating a material property, measured by DPS, to pavement density. DPS uses ground penetrating radar (GPR) technology to measure the dielectric constant (or dielectric value) of the pavement surface. The dielectric constant of a material, or the relative permittivity, represents the ratio of the electrical permittivity of a material to the permittivity of free space (i.e., a vacuum). For use in pavement surveys, GPR operates by transmitting electromagnetic energy (in the form of pulses) into a pavement and collecting the reflected energy. A portion of the incident pulses are reflected at boundaries between two materials with differing dielectric constant values. In the case of measuring the surface layer of pavements, air and the pavement are the two materials. Hoegh et al. (2018) stated that when the surface asphalt layer is sufficiently thick (greater than approximately 30 mm), the measured dielectric values are primarily a function of the surface layer material and are not influenced by deeper layers.

The DPS technology used in this study requires a correlation to be established for each mixture between the dielectric value and pavement density. Currently, this step is performed by collecting cores from areas with a range of dielectric values. The density of these cores is assessed in the laboratory, and a correlation is established to link the measured dielectric values to the measured core density. Like the nuclear density gauge, DPS needs to be calibrated to the local material for accurate measurements but can be used without calibration to assess relative differences in density. The entire process is standardized by AASHTO (2022) in specification PP 98-19.

PURPOSE AND SCOPE

In 2020, VDOT received State Transportation Innovation Council funding to evaluate using DPS in determining asphalt pavement density. This study aimed to evaluate DPS technology—in accordance with AASHTO (2022) specification PP 98-19—for determining pavement density and density uniformity of newly placed asphalt layers. In 2021, VDOT acquired a laboratory version of the DPS equipment, referred to as DPS-L in this report, for additional testing. The purpose of including the DPS-L device was to evaluate this second device for determining pavement density and to investigate if the correlation between pavement density and dielectric value could be established before paving (using laboratory-compacted specimens fabricated from loose asphalt mixture), allowing real-time reporting of density during paving. The project's scope was limited to evaluating the equipment on nine paving projects constructed during the 2021 and 2022 construction seasons.

METHODS

The researchers conducted testing using a commercialized field- and laboratory-based DPS manufactured by Geophysical Survey Systems, Inc. The field-based system included three GPR antennas, operating at a central frequency of 2.0 GHz, mounted to a pushcart. The data recording and processing computer, as well as a global positioning system sensor, were also mounted to the pushcart, as Figure 1 shows. The laboratory-based system included a single GPR antenna with a 2.0-GHz central frequency and associated calibration equipment. Figure 2 shows the DPS-L equipment.

Figure 1. Field-Based Density Profiling System

Figure 2. Laboratory-Based Density Profiling System

The Virginia Transportation Research Council (VTRC) research team completed testing using the DPS on nine asphalt pavement projects during the 2021 and 2022 construction seasons. The projects included asphalt overlays on existing asphalt pavements, asphalt overlays placed on milled surfaces, and new construction. Table 1 provides the details of the projects.

Table 1. Project Details

Year Tested	VTRC Project ID	Location	Route	NMAS, mm	Maximum Specific Gravity	Approximate Start Location	Approximate End Location
2021	21-1090	Albemarle County	SR 22, Louisa Road	12.5	2.616	38.0214, – 78.3667	38.0232, – 78.3633
	11-1172	Powhatan County	SR 684, Bell Road	12.5	2.497	37.5662, – 77.9696	37.5869, – 77.9760
	21-1175	Amherst County	US 29	12.5	2.619	37.5849, – 79.0405	37.5807, – 79.0472
	21-1177	Fairfax County	SR 3727, Fox Den Lane	9.5	2.695	38.8905, – 77.3387	38.8937, – 77.3388
2022	22-1052	Fairfax County	SR 6813, Spradlin Court	9.5	2.643	38.7726, – 77.2762	38.7727, – 77.2750
	22-1103	Grayson County	SR 94, Scenic Road	12.5	2.490	36.7097, – 81.0107	36.7021, – 81.0137
	22-1106	City of Fredericksburg	I-95	25.0	2.683	38.3248, – 77.5021	38.3199, – 77.5038
	22-1107	City of Fredericksburg	I-95	19.0	2.737	38.3248, – 77.5022	38.3172, – 77.5039
	22-1112	Albemarle County	SR 665, Buck Mountain Road	12.5	2.714	38.1578, – 78.5556	38.1567, – 78.5622

ID = identification; NMAS = nominal maximum aggregate size; SR = state route; VTRC = Virginia Transportation Research Council.

Before surveying each project, the researchers calibrated the DPS equipment using the airwave and metal plate calibration procedures outlined in the user manual. Testing at each project began by scanning an approximately 500-foot-long section from which nine cores were collected. The researchers selected core locations from areas with high, intermediate, and low dielectric values that were later correlated to the density as measured in the laboratory. After selecting the core locations, the researchers used DPS to measure the dielectric value at each individual core location and then collected the cores. Next, the VTRC research team collected dielectric data on approximately 0.2 to 0.5 miles of pavement at each site. Readings were reported approximately every 6 inches. DPS collects data every 1.2 inches but reports the average every 6 inches. The data were collected in approximately 500- to 1,000-foot-long segments as the paving train advanced. Within each lane, the team collected data in two passes, with three antenna passes covering the left and right sides of each lane for six antenna passes per lane (Figure 3). The DPS onboard computer calculated and displayed the dielectric results in real-time. All DPS testing was completed immediately after paving, except for the state route (SR) 684 Bell Road site, where DPS testing was completed approximately 1 month after paving.

Figure 3. Density Profiling System Field Testing Showing Six Antenna Passes per Lane

The project team analyzed the data collected during the 2021 field trials to identify dielectric trends with respect to lane position and longitudinal distance, permeability, and cracking performance using indirect tensile asphalt cracking test (IDEAL-CT) testing. The team determined air void contents in accordance with AASHTO T 269, *Percent Air Voids in Compacted Dense and Open Asphalt Mixtures* (AASHTO, 2022). Permeability testing was performed on cores taken from each site according to VTM 120, *Method of Test for Measurement of Permeability of Bituminous Paving Mixtures Using a Flexible Wall Permeameter* (VDOT, 2014). Texas Transportation Institute researchers proposed IDEAL-CT for cracking resistance (Zhou et al., 2017). According to Zhou et al. (2017), this test shows promise in relating a laboratory-measured index to field performance. After permeability measurements, the cores were tested using IDEAL-CT, which is typically performed at 25 °C with 150-mm-diameter specimens and a loading rate of 50 mm/min. The load-displacement curve was used to determine the cracking test (CT) index, a crack susceptibility indicator.

During the 2022 field trials, the researchers again used the DPS device to identify dielectric trends with respect to lane position and longitudinal distance along the project. In addition, loose samples of the asphalt mixture were collected from each project and then later fabricated into cylindrical test specimens in the laboratory using a gyratory compactor. These test specimens were compacted to different bulk specific gravities (G_{mb}) measured in accordance with AASHTO (2022) T 166, *Bulk Specific Gravity (G_{mb}) of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens*. For those specimen sets where a specimen was found to have a water absorption greater than 2.0%, G_{mb} of the entire specimen set was measured in accordance with AASHTO (2022) T 331, *Bulk Specific Gravity (G_{mb}) and Density of Compacted Asphalt*

Mixtures Using Automatic Vacuum Sealing Method. The air void content of each specimen was calculated using the G_{mb} values and the maximum theoretical specific gravity (G_{mm}) obtained from the asphalt mixture producer for that particular day and mixture as follows:

$$\mathrm{AV} = 100\left(1 - \frac{Gmb}{Gmm}\right) \quad \text{(Equation 1)}$$

Where:
AV = air void content (%).
G_{mb} = bulk specific gravity.
G_{mm} = maximum theoretical specific gravity.

The percent maximum density was calculated as follows:

$$\text{Percent maximum density} = 100 - \mathrm{AV} \quad \text{(Equation 2)}$$

Where:
AV = air void content (%).

Next, the researchers used the DPS-L device to measure the dielectric values of the cylindrical specimens. The testing was performed in accordance with recommendations published by Sias and Dave (2023). Following these guidelines, each cylindrical specimen was measured three times with the test specimen being rotated around its long axis approximately 120° between measurements. The dielectric values were recorded, and the average of three measurements was taken as the dielectric value for that specimen so long as the difference between any three individual measurements differed by less than 0.02 dielectric units. If the difference in values exceeded 0.02 dielectric units, the measurement with the greatest difference from the average was repeated. The researchers used DPS-L to replicate the actions a contractor would take to establish a relationship between dielectric value and density before paving a mixture in the field. The advantage to this process is that DPS could then be used to directly report actual density in the field rather than relative changes in density.

RESULTS AND DISCUSSION

The researchers analyzed the results for the 2021 and 2022 projects in terms of the correlation between the percent maximum density from field cores and the dielectric value at each core location, the cumulative distribution of regressed percent maximum density (RPMD), and the percentage of RPMD less than certain thresholds. In addition, dielectric values from the 2021 projects were analyzed with respect to permeability and CT-value test results. Comparisons were also made between the dielectric values measured from field cores versus dielectric values from laboratory-prepared specimens from the same mixtures for several projects constructed in 2022.

Density Correlation from Field Cores

From each field project, the researchers collected cores to establish a correlation between percent maximum density and dielectric value. The dielectric properties of an asphalt mixture depend on the dielectric properties of the mixture components. The proportions of these components and their specific dielectric values can vary from project to project. Figure 4 shows an example of the correlation between percent maximum density and dielectric value from one project and the linear trend line. Table 2 shows the slope, intercept, and coefficient of determination (R^2) of the linear trend line describing the correlation between percent maximum density and dielectric value for each project. Table 2 shows that the correlation (R^2) between percent maximum density and dielectric value correlation ranges from 0.52 to 0.98. The project with the lowest correlation was a 25-mm nominal maximum aggregate size (NMAS) mixture. The larger particle sizes could negatively influence the correlation because of the rougher surface texture of the mixture.

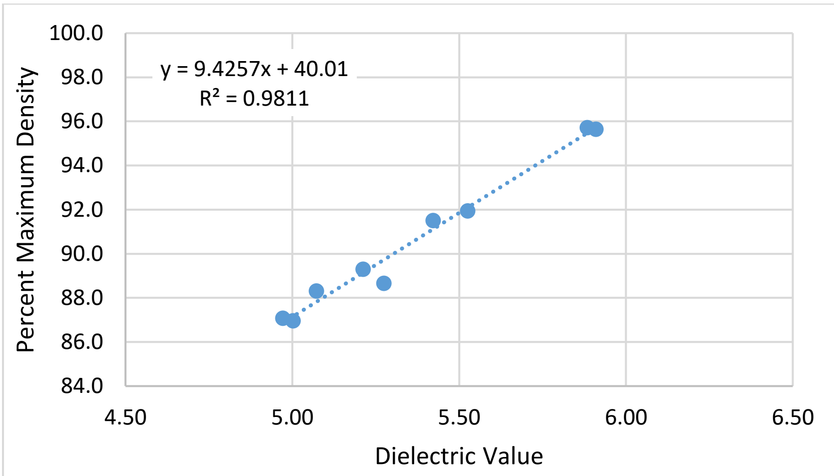

Figure 4. Example of Correlation between Percent Maximum Density and Dielectric Value (State Route 3727, Fox Den Lane)

Table 2. Linear Trend Slope, Intercept, and Coefficient of Determination Relating Percent Maximum Density from Field Cores and Dielectric Value

Year Tested	VTRC Project ID	Location	Route	NMAS, mm	Maximum Specific Gravity	Correlation Results		
						Slope	Intercept	R^2
2021	21-1090	Albemarle County	SR 22, Louisa Road	12.5	2.616	6.4729	58.5514	0.6110
	21-1172	Powhatan County	SR 684, Bell Road	12.5	2.497	13.0494	33.7098	0.8276
	21-1175	Amherst County	US 29	12.5	2.619	9.8978	41.7299	0.9612
	21-1177	Fairfax County	SR 3727, Fox Den Lane	9.5	2.695	9.4257	40.0099	0.9811
2022	22-1052	Fairfax County	SR 6813, Spradlin Court	9.5	2.643	11.9496	24.2793	0.9339
	22-1103	Grayson County	SR 94, Scenic Road	12.5	2.490	8.8197	53.8655	0.8636
	22-1106	City of Fredericksburg	I-95	25.0	2.683	3.4672	75.3110	0.5262
	22-1107	City of Fredericksburg	I-95	19.0	2.737	4.6106	72.3129	0.8400
	22-1112	Albemarle County	SR 665, Buck Mountain Road	12.5	2.714	3.0017	75.5320	0.7010

ID = identification; NMAS = nominal maximum aggregate size; R^2 = coefficient of determination; SR = state route; VTRC = Virginia Transportation Research Council.

Density Distribution

Using the regression model for each project, the researchers converted dielectric values collected during paving to density. RPMD is used herein to indicate that density was calculated from the regression model. Figures 5–7 show the test results using DPS for one project. The data in these figures come from more than 23,000 data points collected over a longitudinal distance of approximately 1,900 feet. In each figure, RPMD from each antenna pass can be seen. For this particular project, testing was conducted in the left lane of a four-lane divided route. The right lane had been recently paved, and the left lane was paved on the day of testing. Figure 5 shows RPMD with respect to distance for four of the six antenna passes for one project. Antenna passes 1 and 6 represent the outside edges of the paved lane, whereas passes 3 and 4 represent the antenna passes near the center of the paved lane. Figures 6 and 7 show the continuous and cumulative distribution of RPMD for this same project, respectively.

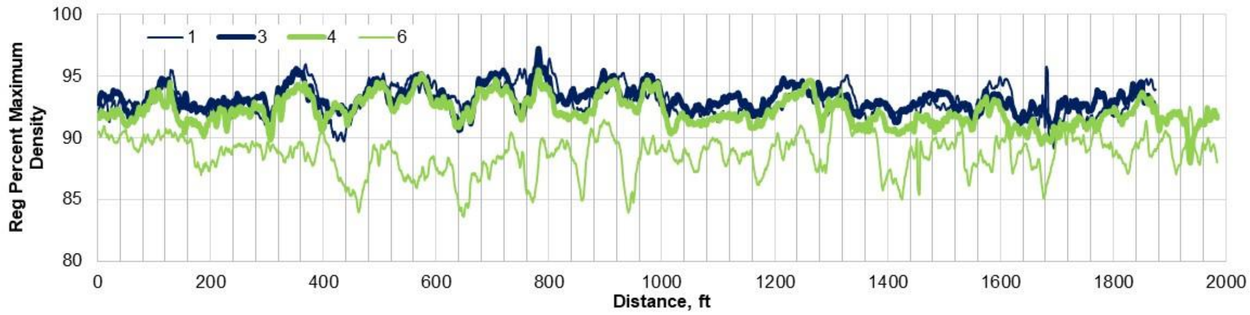

Figure 5. Regressed Percent Maximum Density with Respect to Longitudinal Distance (US 29)

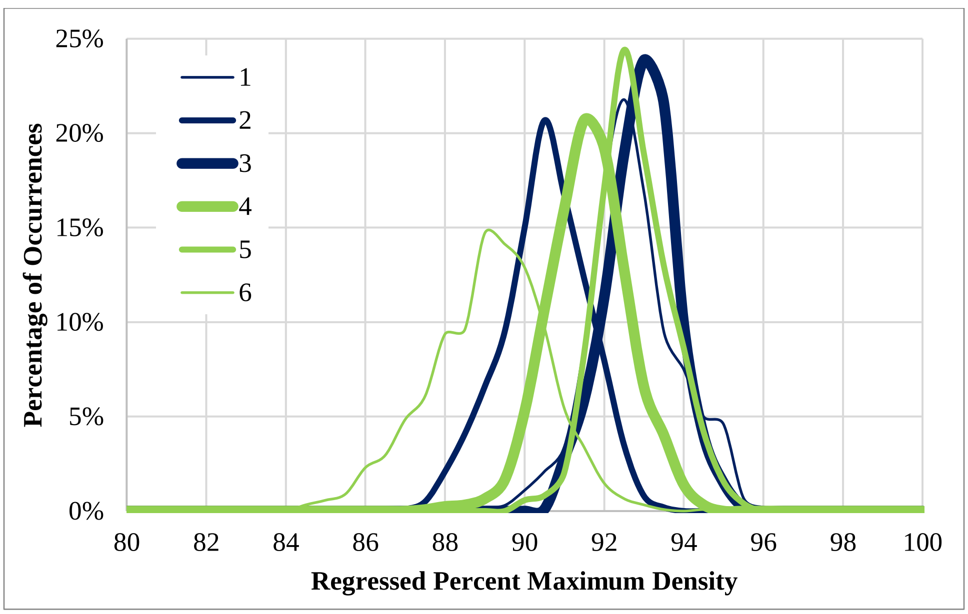

Figure 6. Continuous Distribution of Regressed Percent Maximum Density (US 29)

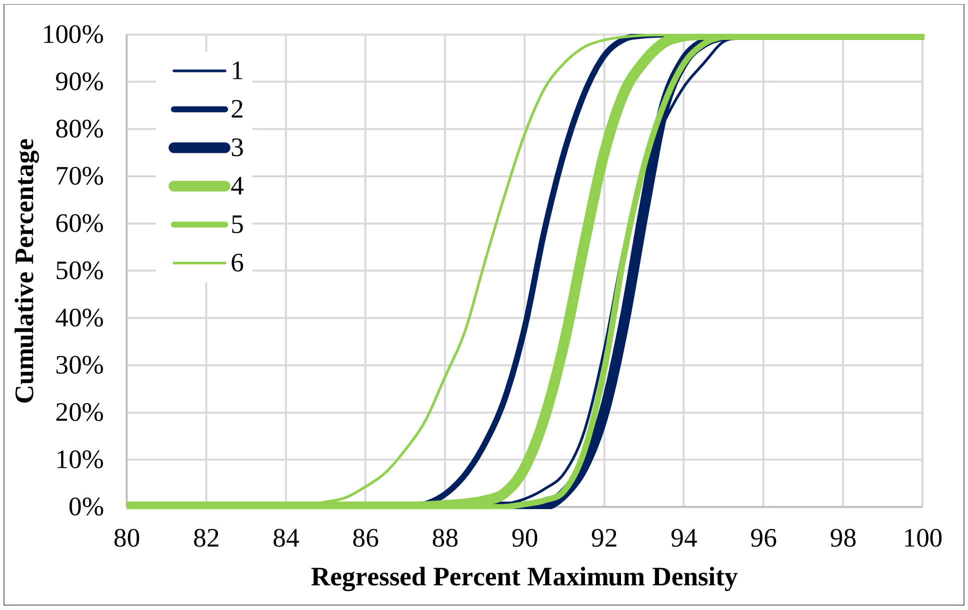

Figure 7. Cumulative Distribution of Regressed Percent Maximum Density (US 29)

Figures 5–7 show a clear reduction in density for antenna pass 6 with an average RPMD of about 89%. Antenna pass 6 represents the right-most antenna pass adjacent to the recently paved lane. Intuitively, this edge should have a relatively higher RPMD, given that the edge is a confined joint. Through discussion with the contractor staff, researchers discovered that a new operator was working on the paver and supplying an insufficient amount of mixture to the right side of the paving screed using the paver auger. Thus, the right side of the mat was consistently starved of material. Appendix A shows results similar to Figures 6 and 7 for other projectsare.

In addition to the average density values, quantifying the dispersion of the density data is useful. McGhee and Smith (2020) noted that reduced variability of asphalt pavement density could lead to an increased service life. Table 3 shows a way to view the dispersion of RPMD from the six antenna passes for the data in Figures 5–7. Table 3 shows the first and third quartile of RPMD for each antenna pass, along with their difference, or the interquartile range (IQR), for all data collected on the project. IQR shows the RPMD range spanning the middle 50% of the data. Table 3 shows that IQR from the US 29 project ranged from approximately 1.4 to 2.0%. Adding to this analysis, Figure 8 shows RPMD versus IQR calculated at 0.01-mile intervals for each antenna pass. Figure 8 could allow an agency to identify specific segments with greater than desired dispersion.

Table 3. Dispersion of Regressed Percent Maximum Density (US 29)

Statistic	**Antenna Pass**					
	1	**2**	**3**	**4**	**5**	**6**
First Quartile	92.06	90.35	92.42	91.25	92.29	87.74
Third Quartile	93.97	92.31	93.84	93.00	93.81	89.78
Interquartile Range	1.91	1.96	1.43	1.75	1.52	2.04

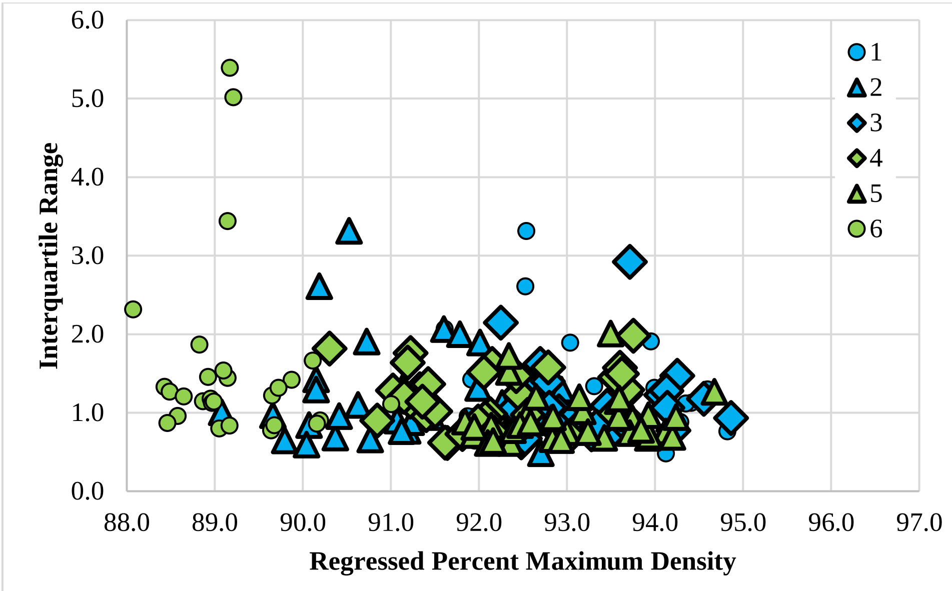

Figure 8. Dispersion of Regressed Percent Maximum Density at 0.01-Mile Intervals (US 29)

Figures 9 and 10 show another example of the continuous and cumulative distribution of RPMD for the SR 665 project with less density dispersion. The data in these figures come from more than 24,000 data points collected over a longitudinal distance of approximately 2,050 feet. This project consisted of a straight overlay of an existing pavement on a rural, two-lane, undivided route. Testing was conducted in the opposite direction of traffic such that antenna pass 1 was on the unconfined edge, whereas antenna pass 6 was along the confined edge. Figures 8 and 9 show little difference in RPMD between the antenna passes. Table 4 shows the dispersion of RPMD. Table 4 shows that IQR for the SR 665 project ranged from approximately 0.6 to 0.8%. Figure 11 shows RPMD versus IQR calculated at 0.01-mile intervals. This figure also shows the reduced dispersion of RPMD from this project.

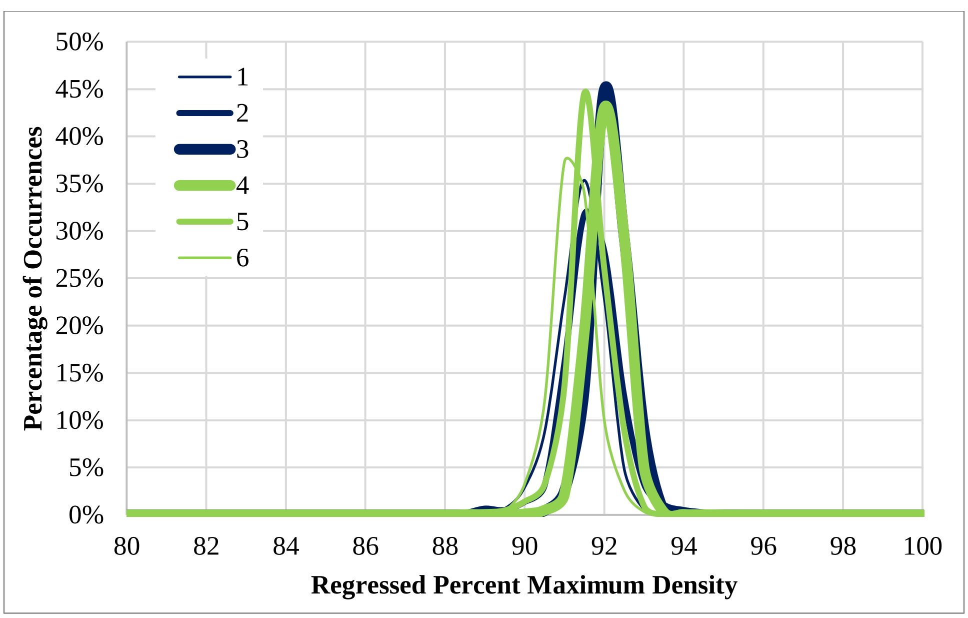

Figure 9. Continuous Distribution of Regressed Percent Maximum Density (State Route 665, Buck Mountain Road)

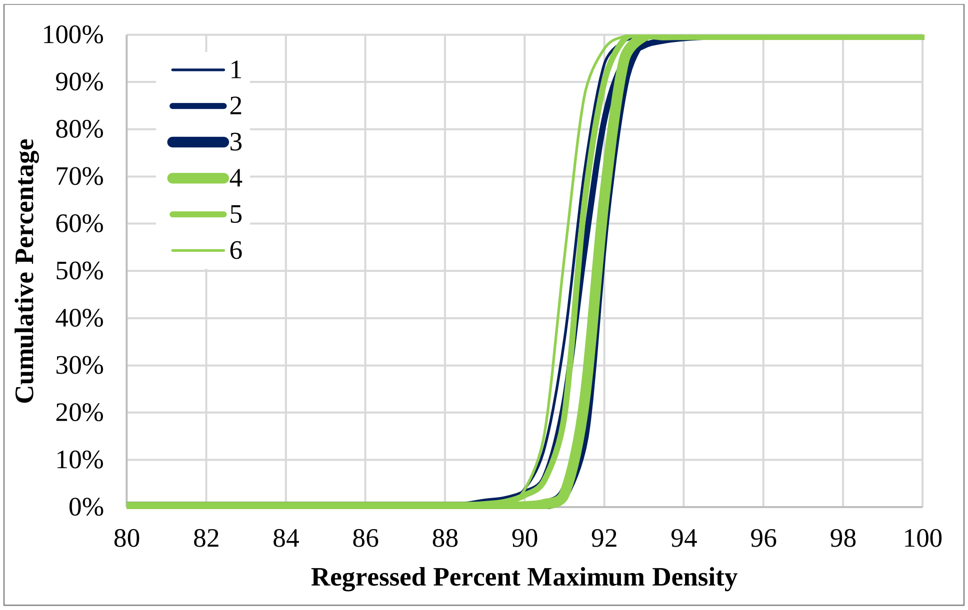

Figure 10. Cumulative Distribution of Regressed Percent Maximum Density (State Route 665, Buck Mountain Road)

Table 4. Dispersion of Regressed Percent Maximum Density (State Route 665, Buck Mountain Road)

Statistic	Antenna Pass					
	1	2	3	4	5	6
First Quartile	90.82	91.05	91.61	91.54	91.08	90.66
Third Quartile	91.56	91.85	92.19	92.11	91.65	91.26
Interquartile Range	0.74	0.79	0.58	0.57	0.57	0.60

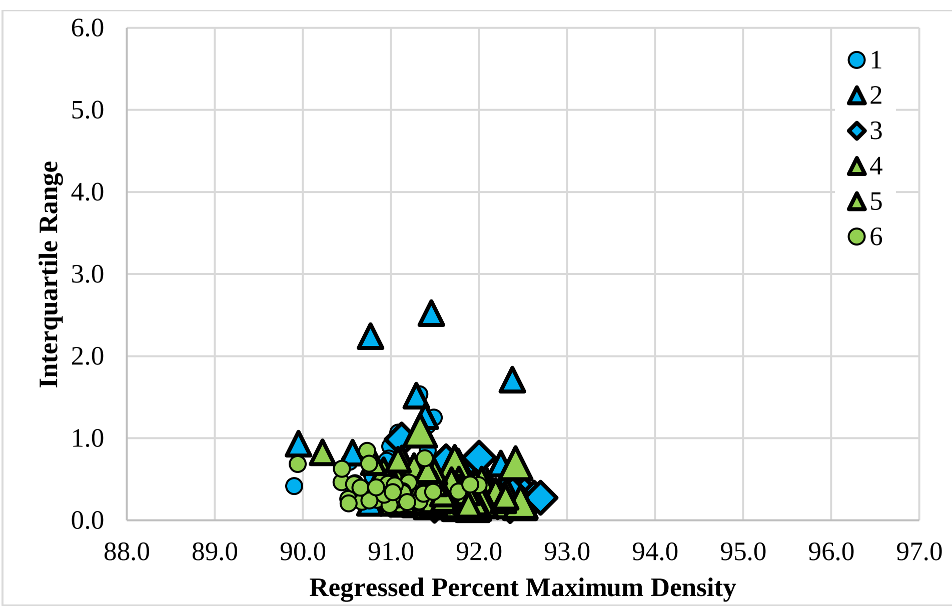

Figure 11. Dispersion of Regressed Percent Maximum Density at 0.01-Mile Intervals (State Route 665, Buck Mountain Road)

Threshold Values

Tables 5 and 6 offer another method for reviewing RPMD for the two example projects shown previously. These tables show RPMD of less than four selected threshold values (McGhee and Smith, 2020). Table 5 shows that approximately 7.3 to 49.7% of RPMD is less than 92.5% G_{mm}, depending on the antenna pass for the US 29 project. Table 6 shows that approximately 90.5 to 99.7% of RPMD is less than 92.5% G_{mm}, depending on the antenna pass for the SR 665 project. Tables 3 and 4 show that the SR 665 project has better density uniformity, but Tables 5 and 6 show that the US 29 project has higher overall density. Appendix B shows results similar to Tables 5 and 6 for other projects.

Table 5. Example of Regressed Percent Maximum Density Less than Selected Threshold Values (US 29)

% G_{mm}	Antenna Pass					
	1	2	3	4	5	6
87.5	0.0%	0.0%	0.0%	0.0%	0.0%	13.5%
90	0.6%	1.9%	0.1%	0.6%	0.0%	41.6%
92.5	13.7%	33.1%	10.9%	23.4%	7.3%	49.7%
95	47.2%	52.4%	47.1%	48.9%	47.2%	49.8%

G_{mm} = maximum theoretical specific gravity.

Table 6. Example of Regressed Percent Maximum Density Less than Given Threshold Values (State Route 665, Buck Mountain Road)

% G_{mm}	Antenna Pass					
	1	2	3	4	5	6
87.5	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%
90	3.8%	3.0%	0.0%	0.1%	2.5%	3.7%
92.5	98.6%	94.4%	90.5%	94.6%	99.0%	99.7%
95	99.6%	99.6%	100.0%	100.0%	100.0%	100.0%

G_{mm} = maximum theoretical specific gravity.

Permeability and IDEAL-CT Results

Table 7 shows permeability and IDEAL-CT results for the SR 22 project. VDOT's permeability requirement is less than 150×10^{-5} cm/sec (VDOT, 2014). Density values ranged from 87 to 95.8%. As Figure 12 shows, as air voids exceeded 7.8%, permeability values increased greatly and exceeded VDOT requirements. In addition, as Figure 13 shows, the permeability was lower for cores with higher dielectric values (higher density).

Table 7. Permeability and IDEAL-CT Results (State Route 22, Louisa Road)

Specimen No.	Air Void Content, %	Density, %	k_{Corr}, Permeability $\times 10^{-5}$ cm/sec	Dielectric Value	IDEAL-CT
K1	6.3	93.7	13	5.24	788
K2	13.0	87.0	1325	4.67	1,494
K3	8.3	91.7	120	5.33	596
K4	7.7	92.3	40	5.22	952
K5	7.8	92.2	0	5.06	1,174
K6	6.5	93.5	0	5.19	515
K7	11.7	88.3	577	4.69	1,026
K8	4.3	95.7	0	5.50	393
K9	4.2	95.8	0	5.82	396
K10	8.8	91.2	252	5.58	744

Specimen No.	Air Void Content, %	Density, %	k_{Corr}, Permeability $\times 10^{-5}$ cm/sec	Dielectric Value	IDEAL-CT
K12	4.8	95.2	0	5.25	350

IDEAL-CT = indirect tensile asphalt cracking test; k_{Corr} = coefficient of permeability.

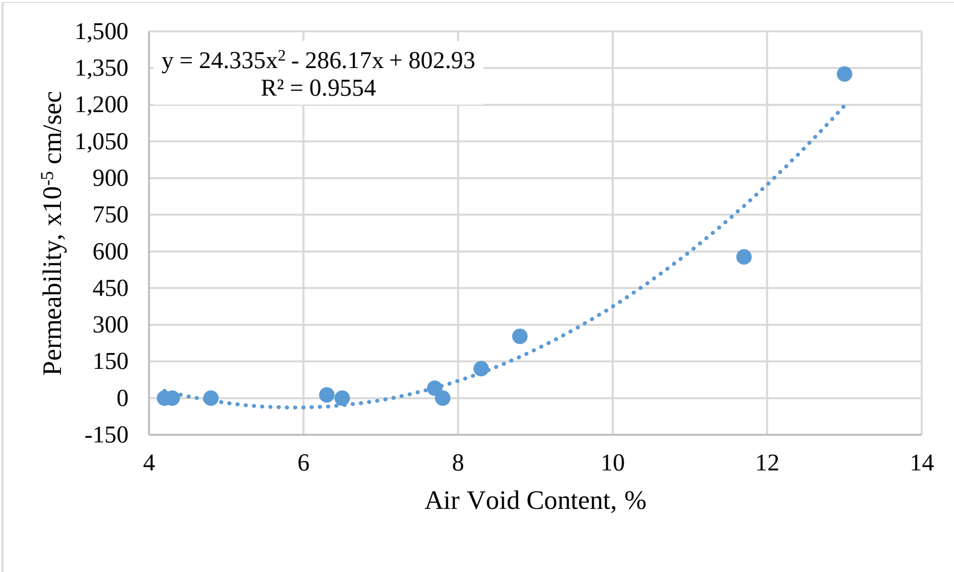

Figure 12. Relationship between Permeability and Air Voids (State Route 22, Louisa Road)

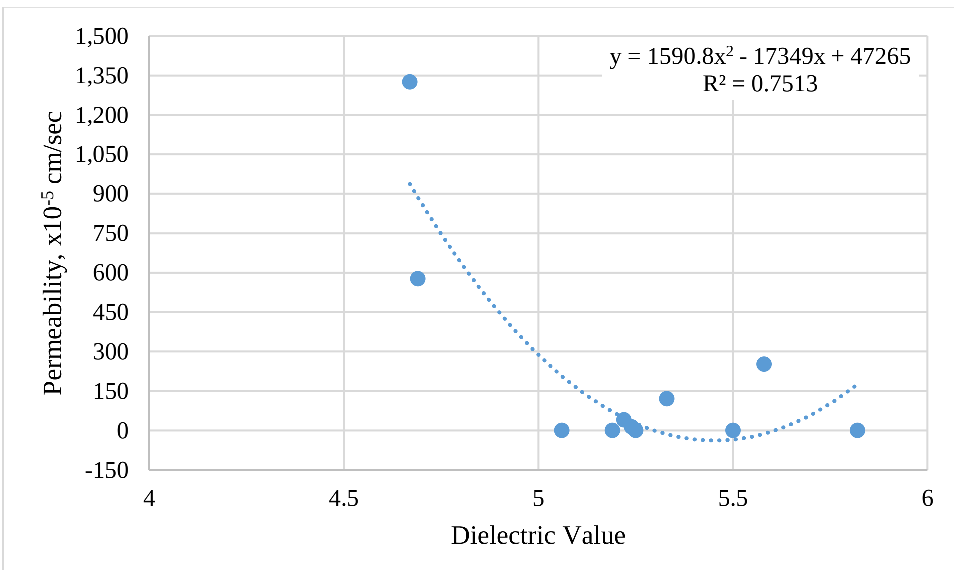

Figure 13. Relationship between Permeability and Dielectric Value (State Route 22, Louisa Road)

IDEAL-CT results were higher than suspected for all the cores tested. Higher CT index values indicate a better ability of mixtures to resist cracking. VDOT regular mixtures (SM 9.5 and 12.5, nonpolymer modified mixtures) had an average CT index value of 80 (based on gyratory-prepared samples) in a previous study (Diefenderfer and Bowers, 2019). IDEAL-CT values did not show any correlation to air voids or dielectric values. Overall results showed the importance of keeping density above 92.5% to meet VDOT permeability requirement. Appendix C shows permeability and IDEAL-CT results for other projects.

Density Correlation from Laboratory-Prepared Specimens

During the 2022 paving season, the project team used DPS-L to evaluate the relationship between dielectric value and density for cylindrical test specimens fabricated from loose asphalt mixture collected during paving. The loose asphalt mixture was sampled from each project and later fabricated into cylindrical test specimens in the laboratory using a gyratory compactor. Test specimens with different G_{mb} values, a diameter of 6 inches, and a height of approximately 4.7 inches (120 mm) were fabricated and then their air void contents were measured. The DPS-L device was then used to measure the dielectric values of the test specimens. Table 8 shows the slope, intercept, and R^2 of the linear trend line describing the correlation between percent maximum density and dielectric value for each project. Similar to Table 2, Table 8 shows that the percent maximum density from laboratory-prepared specimens and dielectric value are well correlated for nearly all projects. Only one project had a R^2 less than 0.94, and the project team believes this result is due to the 25-mm NMAS of the mixture tested.

Table 8. Linear Trend Slope, Intercept, and Coefficient of Determination Relating Percent Maximum Density from Laboratory-Fabricated Test Specimens and Dielectric Value

VTRC Project ID	Location	Route	NMAS, mm	Maximum Specific Gravity	Correlation Results		
					Slope	Intercept	R^2
22-1052	Fairfax County	SR 6813, Spradlin Court	9.5	2.643	13.6405	14.7500	0.9959
22-1103	Grayson County	SR 94, Scenic Road	12.5	2.490	9.5447	49.4839	0.9492
22-1106	City of Fredericksburg	I-95	25.0	2.683	8.8766	40.6393	0.7776
22-1107	City of Fredericksburg	I-95	19.0	2.737	12.0033	23.7718	0.9542
22-1112	Albemarle County	SR 665, Buck Mountain Road	12.5	2.714	13.4816	15.4419	0.9953

ID = identification; NMAS = nominal maximum aggregate size; R^2 = coefficient of determination; SR = state route; VTRC = Virginia Transportation Research Council.

Figures 14 and 15 show the combined regression results from Tables 2 and 8 in a single figure for two projects tested during the 2022 construction season to compare the two regression models. If the two regression models are similar, the relationship between density and dielectric value can be established before construction, and thus, density can be reported in real-time during testing. If the regression models are not similar, the actual density results will not be available until cored samples can be retrieved from a paving project, and their density will be determined in the laboratory later. This circumstance suggests that the process might be more suitable for determining relative changes in density that can be verified by other means.

Figure 14 shows the data and the regression models from the SR 6813 project. It shows that the field core and laboratory-prepared test specimen correlations line up well, based on visual inspection. Figure 15 shows the data and the regression models from the SR 665 project. It shows that the field core and laboratory-prepared test specimen correlations do not line up well, based on visual inspection, and do not appear to describe the same material, despite the good agreement when these correlations are shown independently. Appendix D shows the correlations for other projects.

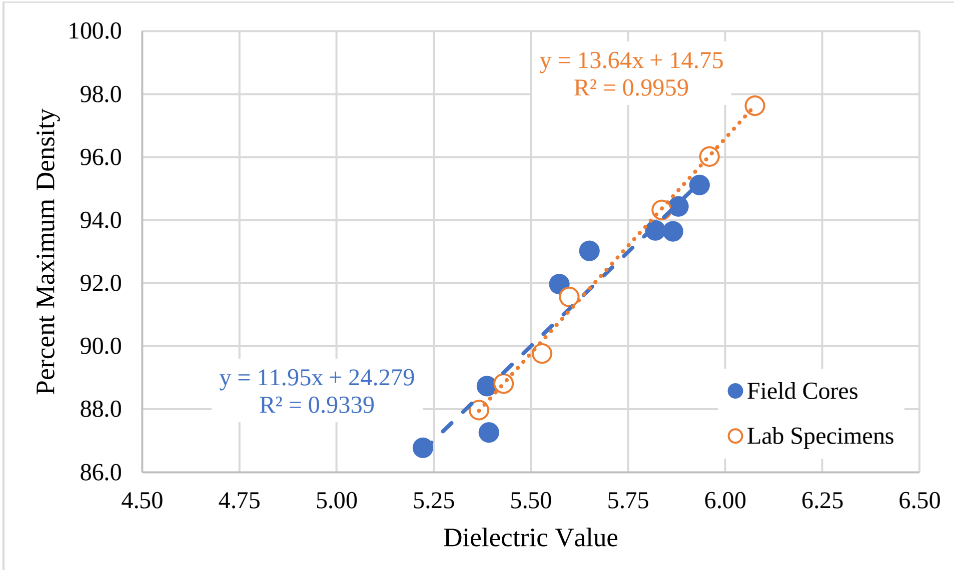

Figure 14. Correlations between Percent Maximum Density and Dielectric Value from Field Cores and Laboratory-Prepared Test Specimens (State Route 6813, Spradlin Court)

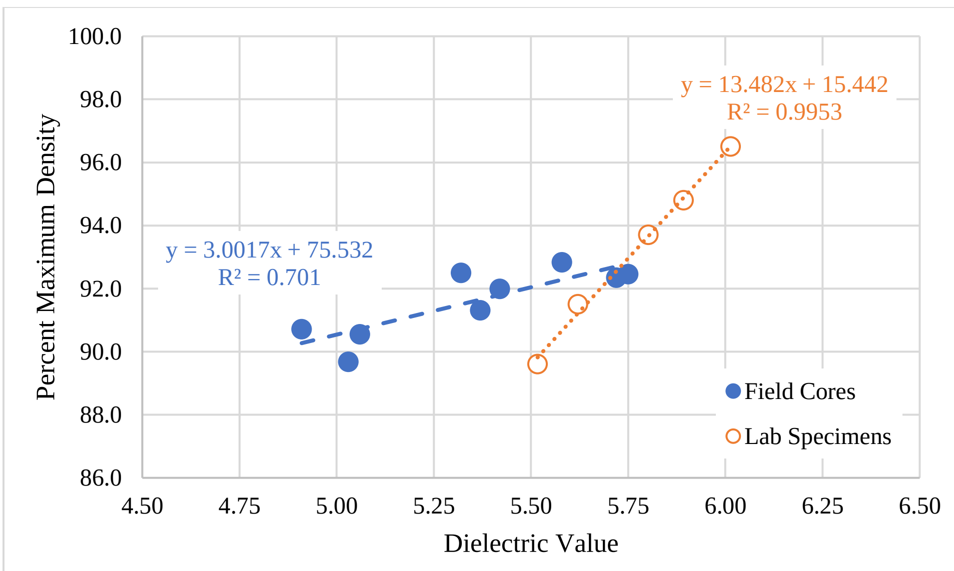

Figure 15. Correlations between Percent Maximum Density and Dielectric Value from Field Cores and Laboratory-Prepared Test Specimens (State Route 665, Buck Mountain Road)

Why the difference exists between the two correlation models for certain projects is unclear. One suggestion is that a difference in the moisture condition of the paved asphalt material occurred when the dielectric values were measured in the field (Table 2) versus the dielectric values of the laboratory-prepared test specimens (Table 8). In addition, the dielectric measurements were conducted using two devices (DPS and DPS-L) that operate using two different methods. The DPS dielectric values are calculated using a surface reflection method that compares the amplitude of the incident signal with that of a metal calibration plate. DPS-L dielectric values are calculated using a time-of-flight method. The two methods will yield different results if significant surface texture is present in the paved layer or if the constituents in the asphalt mix possess measurable magnetic properties. Additional study is needed to confirm these suggestions.

SUMMARY OF FINDINGS

- The researchers found that DPS technology offered much more data than previously possible by current VDOT density measurement procedures.
- The results showed that the correlation between dielectric values from DPS and the percentage maximum density based on measurements of field cores ranged from 0.52 to 0.98.
- DPS could identify isolated locations and larger areas with higher and lower dielectric values.
- The regressed density value results showed that lower density was obtained along certain longitudinal joints and unsupported edges. The practices used in these locations need more attention to achieve uniform compaction and to meet VDOT density requirements.
- The regressed density results also showed higher density variability in certain projects. Whether the increased variability can be mitigated with better practices or reflects the potential for more variability in pavements in certain locations is unclear.
- The results showed that the correlation between dielectric values measured by DPS-L and the percent maximum density based on measurements of laboratory-prepared test specimens ranged from 0.77 to 0.99.
- The researchers found the correlation between percent maximum density and dielectric values based on measurements of field cores versus laboratory-prepared specimens to be different for some projects. The cause of this difference is not known.

CONCLUSIONS

- DPS technology can be used to describe relative changes in the density of asphalt mixtures placed in the field based on measurements of the dielectric value.
- DPS technology offers sufficient data volume for estimates of density uniformity.
- DPS technology is promising for process control purposes but is still premature for VDOT to use for density acceptance.

RECOMMENDATIONS

1. *VDOT's Materials Division should not consider using DPS at this time to assess the density of paved asphalt mixtures for acceptance purposes. Additional studies are needed to understand better the effects of mixture variables—such as aggregate type, NMAS, texture, and so on—on the dielectric results. This type of work is already under way as part of*

Transportation Pooled Fund Study TPF-5(443) led by the Minnesota Department of Transportation (n.d.).

2. *VDOT's Materials Division should consider using DPS to assess relative changes in the density of paved asphalt mixtures during construction where desired. The relative change in density results can be used to detect relative higher and lower density areas that can then be tested by other means for verification.*

3. *VDOT's Material Division should consider using the density testing results with DPS to evaluate achievable density uniformity.*

4. *VTRC and VDOT's Materials Division should submit a research needs statement to the Pavement Research Advisory Committee to help understand further the remaining unknowns through additional testing during future construction seasons.*

IMPLEMENTATION AND BENEFITS

The researcher and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

With regard to Recommendation 1, VTRC will continue to participate in the TPF-5(443) study and report on the future progress of DPS technology (Minnesota Department of Transportation, n.d.).

With regard to Recommendations 2 and 3, VDOT's Materials Division and Fredericksburg and Richmond District Materials staff are already using DPS to assess relative density and density uniformity on asphalt pavements during construction.

With regard to Recommendation 4, VTRC and VDOT's Materials Division will develop a research needs statement and present it to the Pavements Research Advisory Committee by the fall 2026 meeting.

Benefits

This study presents significant benefits to VDOT, particularly the strong relationship between asphalt pavement density and durability. The researchers expect that by focusing on achieving the desired density, the asphalt pavement service life can be significantly improved. DPS technology has shown to be a promising tool for real-time relative density assessment where nuclear density gauge testing and coring do not provide continuous data collection or rapid results.

ACKNOWLEDGMENTS

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APPENDIX A: DISTRIBUTION OF DENSITY OBSERVATIONS

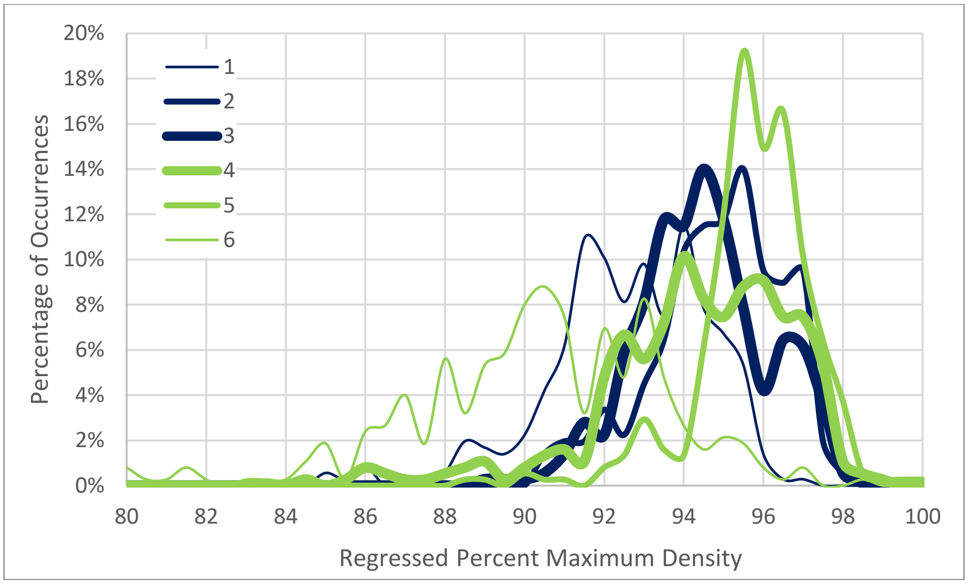

Figure A1. Continuous Distribution of Regressed Percent Maximum Density (Route 684, Bell Road)

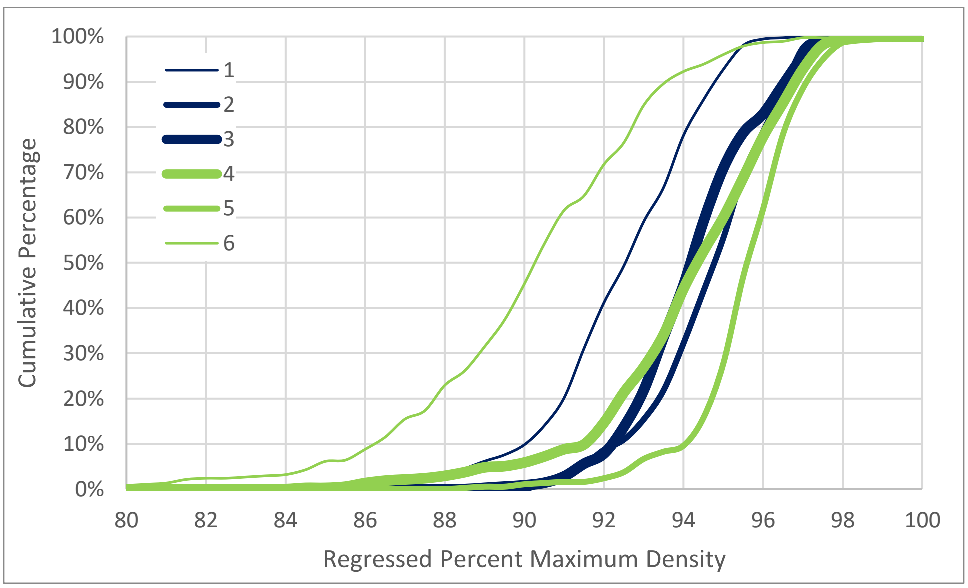

Figure A2. Cumulative Distribution of Regressed Percent Maximum Density (Route 684, Bell Road)

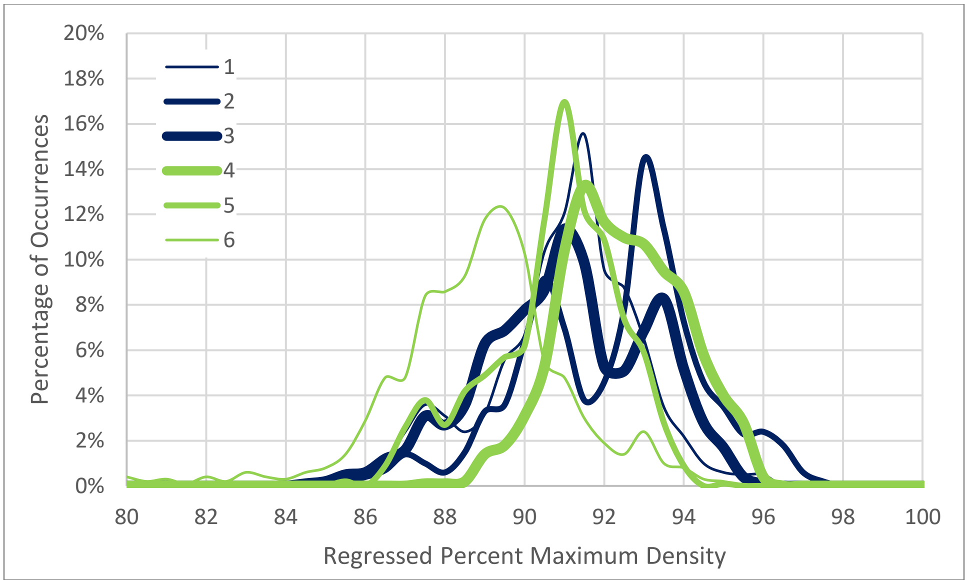

Figure A3. Continuous Distribution of Regressed Percent Maximum Density (State Route 3727, Fox Den Lane)

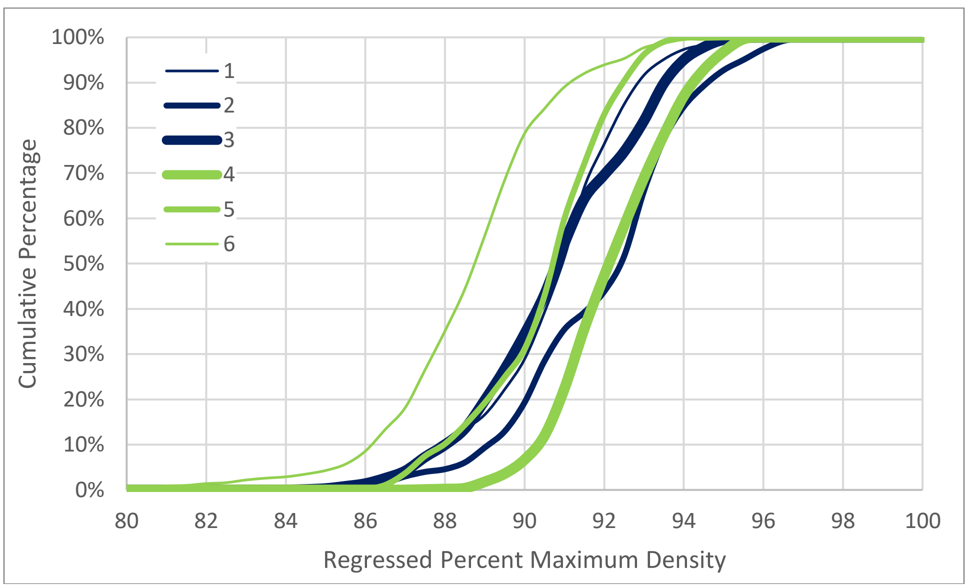

Figure A4. Cumulative distribution of Regressed Percent Maximum Density (State Route 3727, Fox Den Lane)

APPENDIX B: PERCENTAGE OF DENSITY OBSERVATIONS LESS THAN SELECTED PERCENT MAXIMUM DENSITY

Table B1. Percentage of Density Observations Less than Selected Percent Maximum Density (State Route 684, Bell Road)

% G_{mm}	Antenna Pass Number					
	1	2	3	4	5	6
87.5	0.5%	0.0%	0.0%	0.0%	0.0%	1.4%
90	7.1%	0.0%	0.0%	0.0%	0.0%	3.8%
92.5	37.5%	1.1%	1.4%	5.5%	1.9%	24.2%
95	85.8%	23.0%	44.4%	46.7%	21.7%	70.1%

G_{mm} = maximum theoretical specific gravity.

Table B2. Percentage of Density Observations Less than Selected Percent Maximum Density (State Route 3727, Fox Den Lane)

% G_{mm}	Antenna Pass Number					
	1	2	3	4	5	6
87.5	8.0%	4.0%	7.3%	0.1%	7.5%	26.5
90	28.9%	19.3%	34.5%	6.7%	31.1%	78.7%
92.5	85.2%	51.6%	74.7%	58.3%	90.3%	95.3%
95	98.9%	92.7%	99.5%	96.8%	100.0%	100.0%

G_{mm} = maximum theoretical specific gravity.

APPENDIX C: PERMEABILITY AND IDEAL-CT RESULTS

Table C1. Permeability Results (State Route 684, Bell Road)

Specimen No.	Air Void Content, %	k_{Corr}, Permeability × 10^{-5} cm/sec	Dielectric Value
J-1	12.5	1,336	3.93
J-2	12.2	796	4.35
J-3	12.7	1,090	4.31
J-4	3.9	1	4.75
J-5	2.2	0	4.74
J-6	3.4	0	4.80
J-7	6.1	19	4.57
J-8	4.4	0	4.78
J-9	3.8	0	4.80

IDEAL-CT = indirect tensile asphalt cracking test; k_{Corr} = coefficient of permeability.

Table C2. Permeability and IDEAL-CT Results (US 29)

Specimen No.	Air Void Content, %	k_{Corr}, Permeability × 10^{-5} cm/sec	Dielectric Value	IDEAL-CT
1	12.2	1,481	4.61	505
2	6.5	50	5.29	395
3	4.5	1	5.42	190
4	8.9	35	5.04	469
5	13.3	2,405	4.54	715
6	5.5	1	5.24	263
7	4.1	0	5.38	162
8	6.3	8	5.27	231
9	8.3	339	5.14	308

IDEAL-CT = indirect tensile asphalt cracking test; k_{Corr} = coefficient of permeability.

Table C3. Permeability and IDEAL-CT Results (Route 3727, Fox Den Lane)

Specimen No.	Air Void Content, %	k_{Corr}, Permeability × 10^{-5} cm/sec	Dielectric Value	IDEAL-CT
1	4.4	0	5.91	256
2	4.3	0	5.88	260
3	12.9	403	4.97	726
4	11.3	572	5.27	1,318
5	10.7	969	5.21	610
6	8.5	762	5.42	444
7	8.1	137	5.52	983
8	11.7	1,470	5.07	533
9	13.0	2,283	5.00	825

IDEAL-CT = indirect tensile asphalt cracking test; k_{Corr} = coefficient of permeability.

APPENDIX D: CORRELATIONS BETWEEN PERCENT MAXIMUM DENSITY AND DIELECTRIC VALUE FROM FIELD CORES AND LABORATORY-PREPARED TEST SPECIMENS

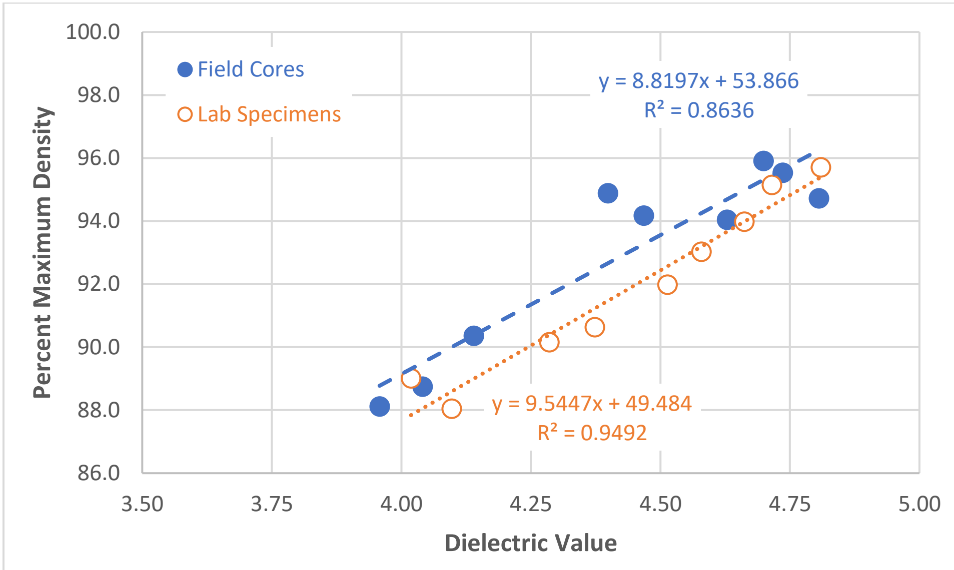

Figure D1. Correlations between Percent Maximum Density and Dielectric Value from Field Cores and Laboratory-Prepared Test Specimens (State Route 94, Scenic Road)

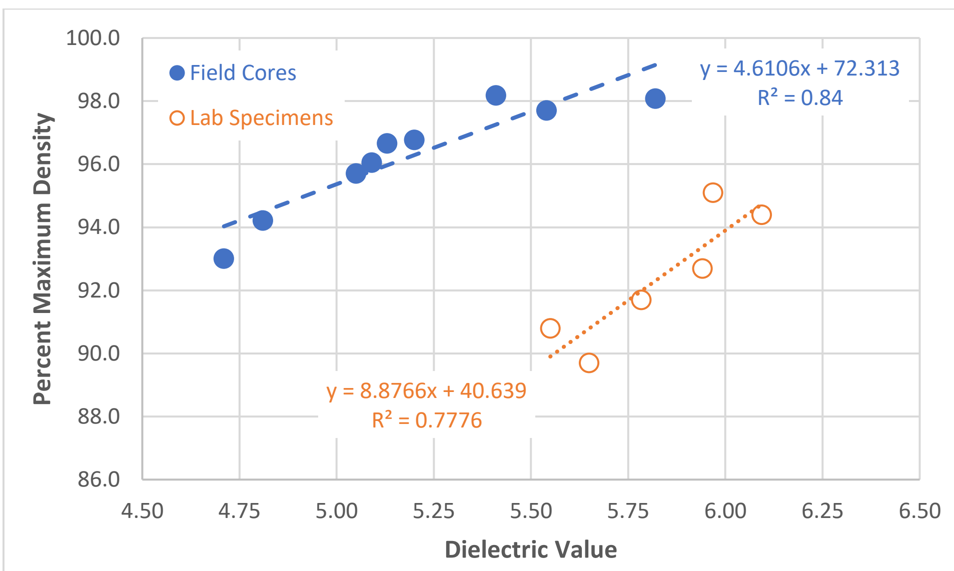

Figure D2. Correlations between Percent Maximum Density and Dielectric Value from Field Cores and Laboratory-Prepared Test Specimens (I-95, 25-mm nominal maximum aggregate size)

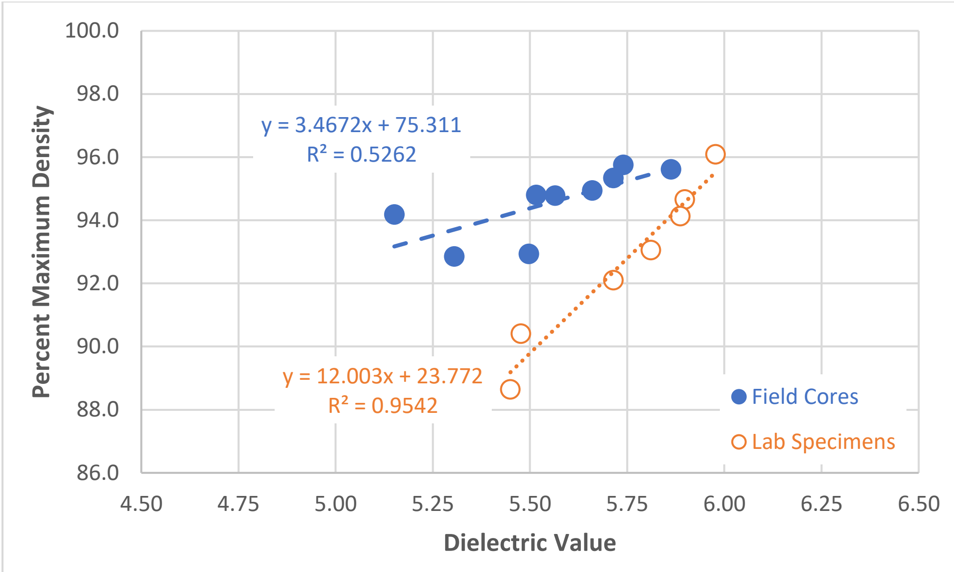

Figure D3. Correlations between Percent Maximum Density and Dielectric Value from Field Cores and Laboratory-Prepared Test Specimens (I-95, 19-mm nominal maximum aggregate size)