A Practice for Including Intelligent Construction Equipment in Quality Assurance Programs

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FOREWORD

Title 23, Code of Federal Regulations (CFR), part 637, subpart B provides Federal Highway Administration (FHWA) requirements for agencies to develop a quality assurance (QA) program to ensure the quality of materials and workmanship of Federal-aid highway construction projects on the National Highway System. The purpose of this report is to provide information and suggestions for using intelligent construction equipment in QA programs conforming to 23 CFR part 637, subpart B. The report focuses on asphalt mat density and temperature for application in QA programs but can be applied to other quality characteristics.

This report is intended for use by pavement researchers, as well as practicing engineers, construction personnel, and laboratory technicians, to evaluate the quality and uniformity of in-place asphalt mixtures.

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15. Supplementary Notes

FHWA Agreement Officer's Representative: Timothy B. Aschenbrener, PE. The FHWA has an ongoing Accelerated Implementation and Deployment of Pavement Technologies (AID-PT) Program. This report was prepared under the AID-PT Program's *Development and Deployment of Innovative Asphalt Pavement Technologies* Cooperative Agreement with the University of Nevada, Reno.

16. Abstract

Many State departments of transportation (DOTs) include density of the asphalt mat as a quality characteristic in their quality assurance (QA) programs. Density values are determined from point-specific laboratory tests. State DOTs desire real-time tests to evaluate asphalt mixture consistency and mat density across the entire width and length of a paving lot. Two innovative devices that have emerged for use in evaluating the uniformity and density of asphalt mixtures are the paver-mounted thermal profiler (PMTP) and the dielectric profiling system (DPS).

Both technologies generate a significant amount of real-time data using hardware and software with spatial referencing sources. The DPS is used to test the asphalt mat after final rolling and is considered to be in the field demonstration stage or just entering the field pilot stage of research deployment. The PMTP is attached to the paver for monitoring the surface temperatures of the asphalt mat and is currently at the field pilot and specification development stage. A few State DOTs have deployed the PMTP in their QA program.

A third innovative technology referred to as intelligent compaction (IC) is used to map roller coverage of the mat during construction and monitor relative mat stiffness during breakdown rolling. The IC technology is discussed in this report, but it is still considered to be in the initial field demonstration stage.

This report provides information and suggestions for using intelligent construction equipment in a QA program conforming to 23 CFR part 637, subpart B. The document focuses on asphalt mat density and temperature for application in QA programs, but the information provided can be applied to other quality characteristics.

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ABSTRACT

Many State departments of transportation (DOTs) include density or percent density of the asphalt mat as a quality characteristic in their quality assurance (QA) programs. Density values are commonly determined from point-specific samples and laboratory tests. State DOTs desire real-time tests to evaluate asphalt mixture consistency and mat density across the entire width and length of a paving lot. Three devices have emerged for use in evaluating the uniformity and density of asphalt mixtures. These devices or technologies are the paver-mounted thermal profiler (PMTP), dielectric profiling system (DPS), and intelligent compaction (IC).

All three technologies generate a significant amount of real-time data using hardware and software with spatial referencing sources. The DPS, using ground-penetrating radar (GPR), is in the field demonstration stage or just entering the field pilot stage of research deployment. The PMTP is in the field pilot and specification development stage. A few State DOTs have deployed the PMTP in their QA program and include it as part of their acceptance criteria. IC stalled in its demonstration stage for evaluating the density of asphalt mats because the correlation between IC-indicated stiffness and mat density is considered poor. Multiple parameters or site factors impact the IC response variables being measured, not just asphalt mat density. Thus, this report focuses on the DPS and PMTP, but also provides an overview of the challenges of using IC for QA purposes.

Federal regulations at 23 CFR part 637, subpart B provide Federal Highway Administration (FHWA) requirements for agencies to develop a QA program to ensure the quality of materials and workmanship of Federal-aid highway construction projects on the National Highway System.

Multiple challenges have delayed the PMTP and DPS from being included in agencies' QA programs. A challenge with these technologies has been agency verification sampling and testing when quality control (QC) data is used as part of the agency acceptance decision.

This report provides information and suggestions for using intelligent construction equipment in a QA program conforming to 23 CFR part 637, subpart B. It focuses on asphalt mat density and temperature for application in QA programs, but the information contained herein can be applied to other quality characteristics as well.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
CFR	Code of Federal Regulations
DOT	department of transportation
DPS	dielectric profiling system
FHWA	Federal Highway Administration
GPR	ground-penetrating radar
GPS	Global Positioning System
IA	independent assurance
IC	intelligent compaction
IR	infrared
IRI	International Roughness Index
MATC	Mobile Asphalt Technology Center
MTV	material transfer vehicle
PMTP	paver-mounted thermal profiler
PWL	percent within limits
QA	quality assurance
QC	quality control
RDM	rolling density meter
SHRP2	second Strategic Highway Research Program
STD	State transportation department
TRB	Transportation Research Board
TTI	Texas Transportation Institute
USDOT	U.S. Department of Transportation
VMA	voids in mineral aggregate

A Practice for Including Intelligent Construction Equipment in Quality Assurance Programs

INTRODUCTION

Background

Good quality pavement construction improves long-term pavement performance. State departments of transportation (DOTs) use laboratory and field tests throughout various stages of a construction contract to measure properties related to asphalt mixture and mat performance.

By assessing the quality of asphalt mixtures and placement practices before and during paving operations, the State DOT can make informed decisions regarding conformance to specifications. Quality assurance (QA) programs enable the State DOT to assess the quality and anticipated long-term performance of the asphalt pavement.

Most asphalt tests used for acceptance are based on random samples, with the exception of smoothness if International Roughness Index (IRI) is specified. A random sample is a sample in which each increment in a lot has an equal probability of being chosen (TRB, 2018). Random samples are selected using a method that is not influenced by opinion or judgment, so bias is eliminated. The samples are taken at random based on time (production plant) or location (paving site). Random sampling is commonly used for asphalt mixture and mat tests such as density, asphalt content, gradation, and volumetric properties.

Mat density is one of the more important volumetric properties that has a direct impact on long-term performance and is correlated to performance properties of the asphalt mat (tensile strength, stiffness, fatigue strength, etc.) (Tran et al., 2016). Many State DOTs include asphalt mat density as a quality characteristic in their QA program and use it as a payment factor for contractors.

Asphalt mat density is typically determined from cores or a nuclear density gauge. Many State DOTs require the use of cores. Core holes have to be filled after the specimen is extracted, which can lead to extended lane closure durations. The coring process and testing of the cores takes up to a day, so the results are not available in real time. More importantly, the location- and time-specific measurements provided represent only a small fraction of the population of the asphalt mat and can easily miss localized inconsistency in areas with segregation and low or high density.

Nuclear or nonnuclear density gauges are used on a daily basis to set and check rolling patterns as a process control activity because the test results are obtained in real time. The American Association of State Highway and Transportation Officials (AASHTO) has a test method for use of nuclear density gauges: AASHTO T 355, Standard Method of Test for In-Place Density of

Asphalt Mixtures by Nuclear Methods (AASHTO, 2018).[1] Many State DOTs, however, do not allow the use of nuclear density gauges alone for acceptance testing. The nuclear density gauge is not considered intelligent construction equipment.

State DOTs typically desire real-time asphalt mixture production and/or paving controls that include the capability for full length and width evaluation of the mat and timely reporting on the quality of the asphalt mixture and mat. Three innovative technologies for evaluating the uniformity and compaction of asphalt mixtures are in various stages of deployment. The technologies are intelligent compaction (IC), paver-mounted thermal profiler (PMTP), and dielectric profiling system (DPS). All three technologies generate a significant amount of real-time data with a combination of hardware and software coupled with spatial referencing sources (satellite, Global Positioning System [GPS], rovers, etc.). Some State DOTs are evaluating the use of these technologies but only testing a portion of the mat to ensure the results are available on a timely basis for acceptance (for example, Minnesota DOT).

The Minnesota DOT is the lead State agency of a pooled fund study for the development and deployment of post processing software of data from manufacturer's equipment to generate common outputs. The number for this pooled fund study is TPF-5(334): Enhancement to the Intelligent Construction Data Management System (Veta) and Implementation. Participating federal and state agencies: FHWA, Alaska, Alabama, California, Connecticut, Georgia, Illinois, Maine, Missouri, Mississippi, North Dakota, New York, Ohio, Oregon, Pennsylvania, and Tennessee. Veta[2] and ProVAL[3] software tools are two examples. A factor to consider in implementing these innovative technologies for use in QA programs is the requirement in 23 CFR 637.207(a)(1)(ii)(B) that QC data be validated using verification testing if it is included in a State DOT's acceptance plan.

Objective

This report provides information about using intelligent construction equipment in a QA program conforming to 23 CFR 637.207. The report focuses on asphalt mat density for application in QA programs, but the information could be applied to other quality characteristics.

Components of QA

The Federal Highway Administration (FHWA) requirements for an agency's QA program that will ensure the quality of materials and workmanship of a Federal-aid highway construction project

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[1] Use of American Association of State Highway and Transportation Officials (AASHTO) specifications included in this document is not a Federal requirement.

[2] Veta is a data management and analysis software tool for intelligent construction; it is a map-based tool for viewing and analyzing geospatial data: https://www.dot.state.mn.us/materials/amt/veta.html

[3] ProVAL is software tool for viewing and analyzing pavement profile data collected by inertial profilers: https://www.fhwa.dot.gov/pavement/proval/

on the National Highway System are found at 23 CFR 637.207. The regulation includes key elements for a QA program, which are listed and explained below.

1. Quality control (QC): Defined in 23 CFR 637.203 as "[a]ll contractor/vendor operational techniques and activities that are performed or conducted to fulfill the contract requirements." This includes all activities specified by the agency or owner in the QA program for a contractor to monitor, assess, and adjust its production or placement processes to ensure that the final product will meet the specified level of quality. QC includes sampling, testing, inspection, and corrective action or adjustments to maintain continuous control of a production or placement process.

2. Acceptance program: Defined in 23 CFR 637.203 as "All factors that comprise the State transportation department's (STD) determination of the quality of the product as specified in the contract requirements. These factors include verification sampling, testing, and inspection and may include results of quality control sampling and testing."

3. Qualified laboratories: Defined in 23 CFR 637.203 as "Laboratories that are capable as defined by appropriate programs established by each STD. As a minimum, the qualification program shall include provisions for checking test equipment and the laboratory shall keep records of calibration checks."

4. Qualified testing and sampling personnel: Defined in 23 CFR 637.203 as "Personnel who are capable as defined by appropriate programs established by each STD."

5. Independent assurance (IA) program: Defined in 23 CFR 637.203 as "Activities that are an unbiased and independent evaluation of all the sampling and testing procedures used in the acceptance program. Test procedures used in the acceptance program which are performed in the STD's central laboratory would not be covered by an independent assurance program." As a result, samples and test specimens used in the IA program should not be used in determining the acceptance of a lot and pay factors.

6. Dispute resolution: Described in 23 CFR 637.207(a)(1)(iii), the dispute resolution procedure is used to resolve conflicts resulting from discrepancies between the State DOT and QC results that are of sufficient magnitude to impact acceptance and payment. It may include the testing of retained split (or "referee") samples, an investigation to identify equipment or procedural deficiencies, resampling, retesting, and/or use of third-party arbitration. The Federal regulation provides details about the dispute resolution program, which is administered by the State DOT in practice.

Two additional terms used in QA programs are verification and validation which are not defined in the Federal regulation found at 23 CFR 637.207. Verification and validation are discussed below.

- Verification is the sampling and testing performed to evaluate the quality of the product. The verification sampling and testing are to be performed by qualified testing personnel employed by the State DOT or its designated agent, excluding the contractor and/or vendor.
- Validation is the mathematical comparison of two independently obtained sets of data to determine whether it can be assumed they came from the same population. In this process, statistical tests are used to compare the means and variance of the two datasets. The two datasets are typically the State DOT and QC data.

OPTIONAL STAGES FOR DEPLOYING INNOVATIVE TECHNOLOGIES

An example of five optional stages that can be used for implementing innovative technologies is displayed in table 1. The five optional stages are not included in the Federal regulation found at 23 CFR 637.207 and not considered mandatory. To date, no State DOT has fully deployed any of the three innovative construction technologies described in this report in its QA program, but as of this writing, a couple State DOTs are in the final stage of implementation. Thus, this report starts at stage 4, after the controlled field/lab demonstration stage.

Table 1. Five Optional Stages of Implementing Innovative Technologies

Stage	Activity	Outcome(s)
1	Conceptual Development Stage of NDT Approach	Establishing and setting the fundamentals for the measurement approach and data interpretation.
2	Prototype Development	Confirming the fundamental measurements, defining the limitations and boundary conditions, and listing details of the equipment and response.
3	Controlled Field/Lab Demonstration	Improving the response measurement technique, data acquisition, and data interpretation.
4	Field/Lab Pilot or First Application	Defining and determining the accuracy of the equipment and outcome, including data acquisition and interpretation software. Determining data management and storage practices and integration with other activities within the agency.
5	Specifications and Standards Development for Full Deployment	Providing the resources necessary for implementation of the technology in a construction contract.

NDT = Nondestructive testing.

MEASURING ASPHALT MAT DENSITY AND UNIFORMITY

Segregation of asphalt mixture during placement, large temperature differences of an asphalt mixture during placement, and poor mat density have adverse impacts on performance. Segregation and/or low mat density leads directly to increased cracking and deterioration and thus results in poor pavement performance. As stated by Tran et al. (2016, page 15):

> Results from the past studies clearly indicate the adverse effect of increased in-place air voids on the fatigue and rutting performance of asphalt pavements. A 1% decrease in air voids was estimated to improve the fatigue performance of asphalt pavements between 8.2 and 43.8%, to improve the rutting resistance by 7.3 to 66.3%, and to extend the service life by conservatively 10%.

In other words, a small change in in-place density can significantly affect the pavement service life. In addition, a one percent increase in in-place density between 91.0 percent and 96.0 percent of the theoretical maximum density (G_{mm}) would extend the service life of asphalt overlays by 10 percent.

IC, PMTP, and DPS do not alter the physical state of the asphalt mat. They measure a quality characteristic (asphalt mat stiffness, surface temperature, or density) continuously over a specific portion of the mat in real time. The underlying measurement principles of these technologies are different. The one common characteristic is that they do not directly measure the physical or engineering property of the material. Instead, they measure a response or reaction that is, in some form, indicative of or correlated to the quality characteristic being used for acceptance. The estimation of the quality characteristic and its accuracy is based on the following:

- An algorithm within the device to process raw data to obtain the material response.
- A previously established correlation between the measured response or reaction and the property being estimated or an analytical procedure that uses the material response or reaction to calculate the material property.

The standard deviation of the measured response or reaction (i.e., the repeatability of the test) and the error in the correlation between the measured response or reaction and the asphalt mixture or mat property being estimated are important to understand for application in QA.

Paver-Mounted Thermal Profiler

Implementation of the PMTP is between the field pilot/first application (stage 4) and specifications and standards (stage 5) for full deployment stages (see table 1). This product was initially deployed under a second Strategic Highway Research Program (SHRP2) effort. Ten field demonstration projects and nearly 20 workshops were completed as part of the SHRP2 Implementation

Assistance Program (SHRP2, 2016; Reiter and Von Quintus, 2017). The State DOTs that participated in the field demonstrations are identified in figure 1.

Thermal profiling is the use of infrared (IR) sensor technology integrated within the paving process to measure asphalt mat temperatures. An IR sensor or scanner is mounted on a paver to take continuous surface temperature readings of the mat with a GPS location reference to the accuracy stated in AASHTO PP (practice, provisional) 80-20 (SHRP2, 2017).[4] Surface temperature readings can indicate temperature differentials, usually referred to as thermal segregation. AASHTO PP 80-20, Standard Practice for Continuous Thermal Profile of Asphalt Mixture Construction[7], describes the equipment and measurement of surface temperatures to evaluate the asphalt mat uniformity based on surface temperatures of the asphalt mat in real time (AASHTO, 2020). AASHTO PP 80-20 also provides discussion of lots and sublots or segments, as included in the Veta data analysis software.[5]

Surface temperature readings are averaged over 30- by 30-cm (i.e., 1- by 1-ft) grids and the results are examined over every 45-m (150-ft) section of the mat width selected by the operator during paving. The 45-m length is defined as a sublot that was initially set so that any sublot would likely include one truck exchange. With this level of granularity in the processed data, temperature differentials can be monitored behind the paver prior to breakdown rolling in the compaction process. The information can be used to make adjustments in the paving process (such as in screed set up, screed maintenance, discontinuing folding the paver hopper wings, including a material transfer vehicle, increasing the number of delivery trucks, tarping trucks, loading and unloading trucks, etc.).

[4] Use of American Association of State Highway and Transportation Officials (AASHTO) specifications included in this document is not a Federal requirement.

[5] Veta is a data management and analysis software tool for intelligent construction; it is a map-based tool for viewing and analyzing geospatial data: https://www.dot.state.mn.us/materials/amt/veta.html.

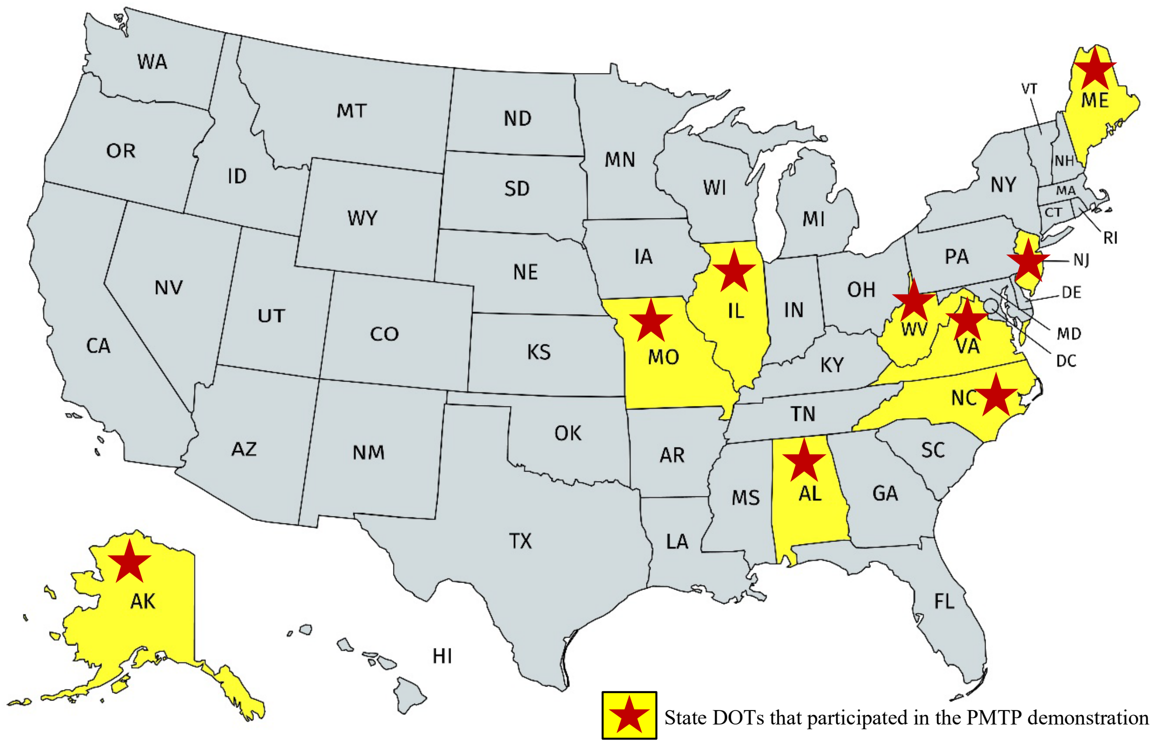


Figure 1. State DOTs that participated in the PMTP demonstration (Reiter and Von Quintus, 2017).

The PMTP (or an earlier generation) has been used on many projects to measure surface temperature differentials (Reiter et al., 2017). The Minnesota DOT uses the Thermal Segregation Index with the Veta software (Transtec Group, 2019).[8] The Missouri DOT is one of the State DOTs actively undertaking construction projects implementing PMTP and IC, having done so since 2016 (Chang et al., 2020). Review of construction quality data in Missouri showed that asphalt mat surface temperature differential continually improved from 2017 to 2019, according to AASHTO PP 80[7] specification for thermal segregation. Similar observations were made by other State DOTs that participated in the SHRP2 field demonstration projects (for example, Maine, Virginia, and West Virginia) (Reiter and Von Quintus, 2017 and 2018). Acceptable surface temperature differentials, however, do not necessarily imply adequate density is achieved because density is dependent on the compaction process and other variables (asphalt binder content, asphalt binder viscosity, gradation, moisture content, underlying support, etc.).

Data from the SHRP2 demonstration projects quantified a benefit of the use of a material transfer vehicle (MTV) for producing more uniform asphalt mats through a lower percentage of severe surface temperature differentials (Reiter and Von Quintus, 2017 and 2018). Table 2 summarizes the demonstration projects with and without an MTV and their corresponding percentage of severe surface temperature differentials. The demonstrations provided information and data to develop advice for using the PMTP for the following:

- Quantifying and monitoring temperature uniformity in real time (i.e., inspection), as well as storing and managing data for future use in explaining anomalies or resolving disputes. The information is used in real time to explain the occurrence of cold spots and/or thermal streaks. Examples of anomalies include increases in roughness, localized areas with low density, variable paver speeds, frequent paver stops in some sublots, etc.
- Prompting other actions to be taken during paving that can be quantified, such as spot testing when segregation is identified.
- Identifying areas to be further investigated with cores or other techniques in specific locations with potential or a higher probability of low density.
- Measuring compliance within placement temperature tolerances.

IR was used as a standalone technology to measure surface temperature to identify areas of the asphalt mat with low densities due to lower mat temperatures. In addition, IR technology can be integrated with IC technology to provide additional information to enhance the compaction control process in real time. This use is discussed in the next section of this report.

Recent advancements in e-Ticketing have streamlined processes to transmit and share PMTP data that can be combined with other material and construction data.[6] Another potential use of mat surface temperature readings and their variability is to strategically determine the test point locations that are used for information only within the acceptance plan, as directed by the Engineer of Record, in addition to the random test point locations.

The PMTP has benefits for documenting surface temperatures of the asphalt mat for process control (Reiter and Von Quintus, 2018; Von Quintus et al., 2020). Use of the PMTP for acceptance is not suggested because there is a need for State DOT verification sampling and testing (independent of the contractor), an IA program, and the use of qualified laboratories and personnel when QC data is used as part of the acceptance decision to remain compliant with 23 CFR 637.207(a)(2). Procedures for this have not been fully developed to date. In addition, asphalt mat temperature variability is an interim measure in the compaction process, whereas the final pavement density is directly correlated to long-term pavement performance.

A challenge for State DOTs is how to encourage the purchase and use of the device, because monitoring the PMTP outcome and taking any corrective actions can result in a more uniform product. One potential nonregulatory method to encourage contractors to use the PMTP is to tighten up the density specification or acceptance limits (reducing the variability) of the asphalt mat density, which would require more uniform asphalt mats. Another nonregulatory option is to increase the number of cores for acceptance because increasing the number of cores increases the chance of capturing the results of asphalt mat temperature differentials through the density measurements.

[6] There are a large number of e-Ticketing vendors with different capabilities. However, AASHTO has yet to prepare a ballot for a standard practice for data fields to be provided by e-Ticketing solutions.

Uniformity as measured by the PMTP is determined by surface temperatures and not mat density. The variability of mat density can be and is influenced by the variability of mat surface temperatures; higher variability in mat surface temperatures can result in higher variability of the mat density. During the SHRP2 demonstration projects, construction personnel started paying attention to the PMTP monitor on the back of the paver and would try to identify the reason for "cold spots" being displayed on the monitor and then take corrective actions.

Intelligent Compaction

IC is an equipment-based technology to monitor and improve mat density that is in the field demonstration stage (stage 3, see table 1) for research deployment. IC refers to or can be described as an improved compaction process using rollers equipped with an integrated measurement system that consists of a highly accurate GPS, accelerometers, onboard computer reporting system, and infrared thermometers for feedback control in densifying an asphalt mat (FHWA, 2013).

AASHTO PP 81-18, Standard Practice for Intelligent Compaction Technology for Embankment and Asphalt Pavement Applications (AASHTO, 2020), is a provisional nonbinding standard that describes the equipment, procedures, and recording of the compaction parameters (spatial location of roller, mat stiffness, mat surface temperature, pass count, and vibration amplitude and frequency) during the asphalt mat compaction process in real time.[7]

For this document, IC is grouped into a three-level description based on how it has been used or referred to in other studies (Von Quintus, 2010):

1. Location-specific roller – Rollers include GPS equipment and other sensors to collect ancillary or supplemental data, including asphalt mat surface temperature, speed, etc. Level 1 rollers do not meet the IC definition and are not considered intelligent rollers.
2. Stiffness-testing roller – Rollers include level 1 features with an accelerometer attached to the drum for estimating stiffness. Level 2 rollers do not meet the specific definition of IC and are not considered intelligent rollers.
3. Variable/adjustable energy roller – Rollers include level 1 and level 2 features and a response feedback feature for varying the energy from the roller being transmitted to the material based on the measured response from the accelerometer. Level 3 rollers meet the IC definition and are considered intelligent rollers.

[7] Use of American Association of State Highway and Transportation Officials (AASHTO) specifications included in this document are not Federal requirements.

Table 2. Effect of Delivery Method on Percentage of Sections within the Severe Temperature Differential Category: Summary of PMTP Data from SHRP2 Demonstration Projects (Reiter and Von Quintus, 2017)[8]

Project	Delivery Truck Type	MTV Included	Percent Severe Temp. Differentials	Thermal Streaking
Alaska	Bottom-Dump	Windrows	17	None
Missouri	End Dump & Flow Boys	Yes	25	None
Alabama	End Dump	Yes	4	None
Maine	End Dump	Yes	5	None
New Jersey	End Dump	Yes	21	None
Virginia	End Dump	Yes	5	None
North Carolina	End Dump	Yes	18	None
West Virginia	End Dump	Yes	5	None
Eastern Federal Lands	End Dump	No	83	None
Illinois	End Dump	No	40	None
West Virginia	End Dump	No	41	None

NOTE: The projects in ***bold italics*** did not include an MTV during the placement of the asphalt mat and had a significantly higher percentage of severe temperature differentials. Severe temperature differential is defined as the range of temperatures within the sublot that is greater than 27.7 °C (50.1 °F).

All three levels can be used to increase the uniformity of the asphalt mat, but only level 3 can be used to adjust the energy from the roller to increase the asphalt mat density while reducing the potential for cracking the aggregate in the asphalt mat. The level 1 IC roller can be used as a process control tool to monitor the location of the roller in real time to ensure uniform coverage of the rollers across the asphalt mat to help reduce the variability of the asphalt mat density. Level 2 and 3 IC rollers are not suggested for use in acceptance at this time because test results have not shown a consistent correlation with density and the stiffness index cannot be independently validated in accordance with 23 CFR 637.207(a)(2).

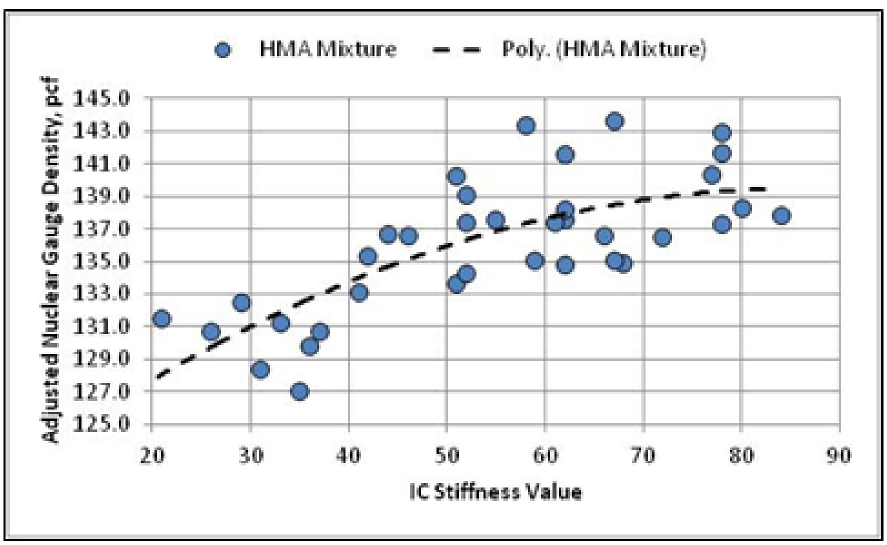
The accelerometer-based measurement system (level 3) is a core IC technology that was initiated in the early 1980s but is still evolving today (FHWA, 2017). The level 3 IC rollers provide the opportunity to monitor layer stiffness continuously during compaction, producing more uniformly compacted layers and allowing compaction modifications based on response outputs in real time. Although level 2 IC rollers include an accelerometer, there is no feedback loop, so the compaction energy is not adjusted as the mat density increases. This results in higher stiffness that is not related to a decrease in the mat's surface temperature.

[8] AASHTO PP 80 specifies Severe Temperature Differential as the difference between the 1.5 percentile level and 98 percentile level of the surface temperature readings within a sublot exceed a difference of 50 °F.

More than 20 State DOTs and Federal agencies have sponsored IC demonstration or pilot projects to date. Multiple documents provide a description of the operation, measurement systems, and outputs for different IC rollers (Von Quintus et al., 2009). Some State DOTs specify AASHTO PP 81-18[13] to measure the increase or change in material stiffness with number of roller passes.

While some of the demonstration projects have shown the value of IC, the measured responses for the asphalt mat to calculate a stiffness index can be highly variable and dependent on the mixture temperature and underlying layers, not just the asphalt mat density. Figure 2 displays the IC stiffness index versus asphalt mat density of a SHRP2 demonstration project and shows the significant variability of the IC stiffness index. Similarly, figure 3 displays a comparison of the IC stiffness index and asphalt mat density growth curves measured within one of the breakdown rolling zones of a Wisconsin DOT demonstration project (Von Quintus et al., 2010). The correlation between the IC outcome or stiffness index parameter and mat density includes a lot of variability or is highly variable.

Density specifications or acceptance plans based on IC rollers could be developed to take full advantage of IC technology; however, independent verification of the IC output would need to be developed to be used in accordance with 23 CFR 637.207(a)(1)(ii). In addition, the high variability between the IC measured response and mat density (see figure 2) presents a challenge for it to be used in a State DOTs acceptance plan. Some of the demonstration studies have suggested that IC be used as a pre-paving evaluation tool to map and identify weak-to-strong areas on which the asphalt mat is placed, which is useful information to construction personnel (Von Quintus et al., 2010).



Note: HMA – Hot-Mix Asphalt, Dense-Graded Mixture.

Figure 2. IC Stiffness Index versus Density of the Asphalt Mat from a Highways for Life Demonstration Project (Von Quintus and Mallela, 2012)

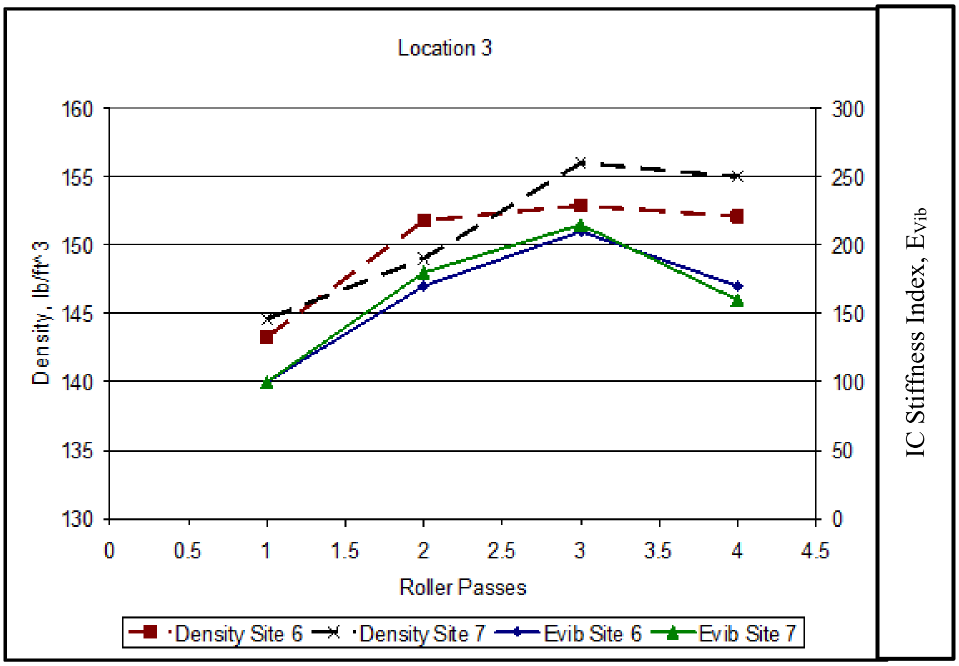


Figure 3. IC Density and IC Stiffness Index (E_{vib}) Growth Curves during Compaction of an Asphalt Mat (Von Quintus et al., 2010).

Dielectric Profiling System

DPS is in the field demonstration stage (stage 3, see table 1) and is just entering the field pilot stage (stage 4) of research deployment. DPS was developed under a SHRP2 effort, but few field demonstration projects were completed as part of the SHRP2 Implementation Assistance Program (Von Quintus et al., 2020). Minnesota DOT is leading a pooled fund research effort (TPF-5 [443]) in advancing the DPS for potential use for acceptance, with multiple State DOTs participating as well as FHWA. The Minnesota DOT, Ohio DOT, Alaska DOT&PF (Department of Transportation and Public Facilities), and New York State DOT are the lead States in deploying the DPS. AASHTO provisional specification PP 98-20 (Standard Specification for Asphalt Surface Dielectric Profiling System using Ground Penetrating Radar) is available for use, and some State DOTs are beginning to use the specification to estimate the density of the asphalt mat full-width and length (AASHTO, 2021).[9]

With the DPS, ground-penetrating radar (GPR) is used to obtain a dielectric constant (measured response) that is correlated to in-place density. The dielectric constant is the ratio of the electric permeability of the material to the electric permeability of free space. Materials with high dielectric

[9] Use of American Association of State Highway and Transportation Officials (AASHTO) specifications included in this document is not a Federal requirement.

constants can store more energy compared to those with low dielectric constants. Higher dielectric constants simply mean higher asphalt mat densities. The dielectric constant is also referred to as the relative permittivity of a material.

A summary of the technology is included in AASHTO R 37 (Standard Practice for Application of Ground Penetrating Radar [GPR] to Highways) and AASHTO PP 98 (Standard Practice for Asphalt Surface Dielectric Profiling System using Ground Penetrating Radar).[9] Use of GPR technology for highway construction quality assessment has been researched for over 20 years but has been slow to be adopted on a wide scale by many State DOTs (Saarenko and Scullion, 2000). An initial prototype for continuously measuring asphalt layer density for use in QA of asphalt pavement layers was based on a system that evolved from recent research conducted under round 2 of the SHRP2 R06C project (Sebasta et al., 2013; Saarenko and Scullion, 2000; Khazanovich et al., 2017). The technology or equipment used to measure the density of the asphalt mat is now being referred to as the DPS based on GPR. (Note: For this document, the term DPS is used to represent the DPS-GPR technology deployment.) The DPS was designed to ensure the asphalt mat conditions (density) could be reported on a real-time basis shortly after final rolling operations so that deficiencies could be rapidly identified and corrected.

Mat thickness and moisture on the surface of the mat are two variables that impact the interpretation of mat density from the dielectric constants measured with the DPS. Other operational concerns with using the DPS include work zone safety and reducing delays through temporary traffic control. The current DPS equipment operates by manually pushing the cart with the antennas at walking speed.

The Minnesota DOT is the lead agency in pooled fund research effort TPF-5 [443] to advance the DPS toward its use in acceptance testing of asphalt mats. However, the DPS will be in stages 3 and 4 for the next 5 years before it moves to full deployment.

The DPS procedure does require developing a correlation between measured in-place density and the measured dielectric coefficient for the asphalt mixture. Figure 4 is an example of a correlation relationship between in-place density and dielectric constant or value. The term "calibration curve" is used in many documents and publications. However, the DPS device itself is not being calibrated to specific outcomes, similar to adjustments made to the readings with a nuclear or nonnuclear density gauge. There is no adjustment to the dielectric constant being measured; rather, the actual dielectric constant is correlated to the asphalt mat density or air void level.

The DPS technology and equipment were demonstrated as part of SHRP2 R06C: Technologies to Enhance Quality Control on Asphalt Pavements (Khazanovich et al., 2017).[10] Three field demonstration projects were completed to illustrate the use and effectiveness of DPS for evaluating

[10] The title of the SHRP2 R06C demonstration project included QC, but the field demonstration projects included the use of the DPS for acceptance and in identifying the change in density along the asphalt mats.

the asphalt mat and to confirm the short- and long-term benefits of the GPR technology (Khazanovich et al., 2017; Von Quintus et al., 2020).

The FHWA Mobile Asphalt Technology Center (MATC) is a traveling asphalt mixture laboratory that provides technical assistance to State DOTs with the implementation of state-of-practices. The MATC includes demonstration of the DPS, as well as the PMTP, for evaluating asphalt mixture density on a day-to-day basis for QA purposes (FHWA, 2020). The MATC, user group meetings, and pooled fund study provide State DOTs expertise in using the equipment and interpreting the test results. As noted previously, the Minnesota DOT is leading a pooled fund research effort (TPF-5 [443]) in advancing the DPS for potential use for acceptance.

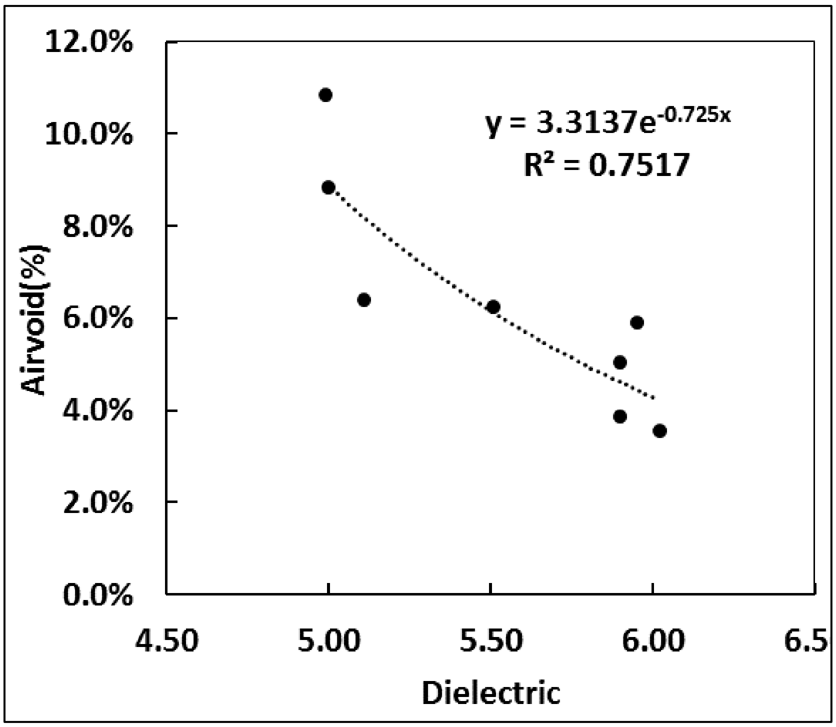


Figure 4. Correlation Curve between Asphalt Mat Core Density and the Dielectric Constant from a Nebraska DOT 2016 Pilot Project (Khazanovish et al., 2017)

Further improvement and verification of the DPS is ongoing based on suggestions from the users of the equipment and on demonstration projects sponsored by individual State DOTs following SHRP2. While the earlier development projects showed the potential use of the DPS for QA, the focus of the SHRP2 R06C demonstration project was on how a stable compaction assessment process can be achieved in full-scale implementation. In addition, it was observed that increased use of DPS and core data helped reduce the variability between the dielectric constant and air voids or percent maximum theoretical specific gravity measured from cores, as displayed in figure 4.

Figure 5 displays a relationship between the asphalt mat density in terms of percent density measured through the use of cores and the dielectric values. Figure 5 also shows the relationship between the density of laboratory-compacted pucks (gyratory-compacted specimens) and the dielectric values measured on those pucks. The current process is to develop the dielectric value and density relationship using laboratory-compacted pucks and use that relationship to estimate the density of the asphalt mat. The use of pucks that are from a laboratory- or plant-prepared mixture and compacted in the laboratory to a range of density levels significantly reduces the error because of controlled conditions in the laboratory. The variability displayed in figure 5 is much lower in comparison to figure 4.

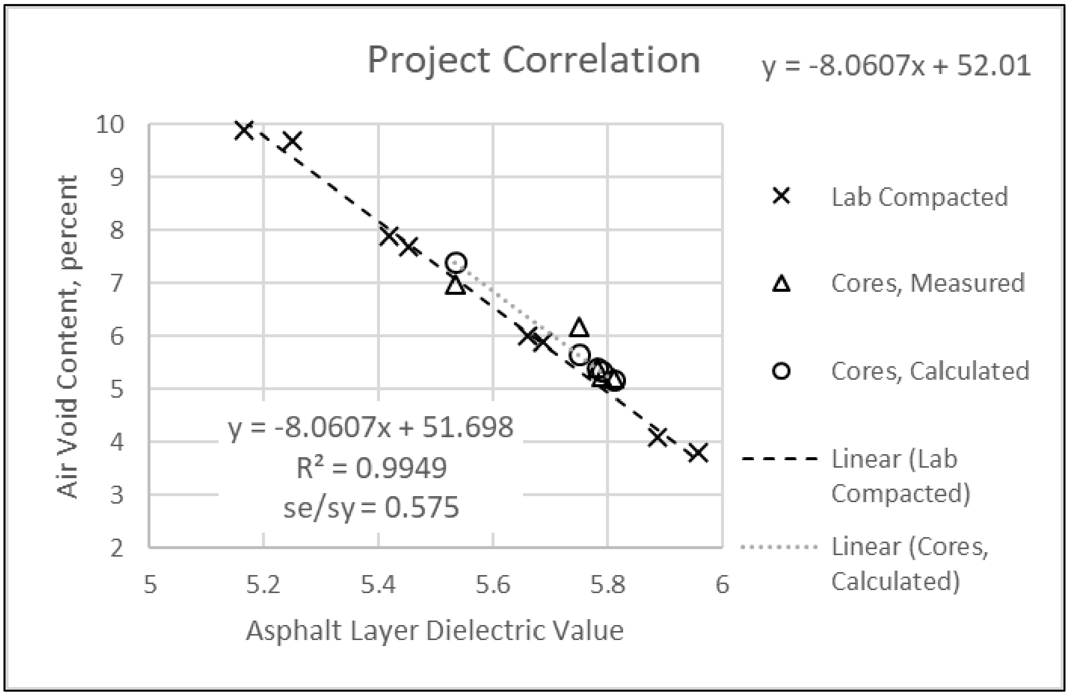


Figure 5. Correlation Curve between Asphalt Mat Core Air Voids Content and the Dielectric Constant from an Ohio DOT Project Using Cores and Laboratory-Compacted Pucks (Von Quintus and Sezen, 2022)

Use of the laboratory pucks does not eliminate all of the issues between the lab-prepared, lab-compacted and plant-mixed, field-compacted mixture conditions. The same differences that are well known between laboratory simulations of plant-produced mixtures for confirming the job mixture formula are also present in the correlation between air voids of the lab pucks and dielectric measured values on the asphalt mat. However, the lab-field correlation should directly consider all of these variables or differences. The correlation between the lab pucks and asphalt mat will be mat thickness-, mixture type-, and test specimen- (lab-prepared, lab-compacted and plant-produced, lab-compacted) dependent. It is suggested that plant-produced, lab-compacted pucks be used to generate the correlation at the same time the job mix formula is being verified.

Another change in the evaluation of asphalt mats using the DPS is to only test portions of the entire asphalt mat. In the earlier demonstration projects, the entire lot was evaluated, generating a massive amount of data (Khazanovich et al., 2017). Minnesota DOT, as well as a few of the other

State DOTs are testing random portions of the mat to represent the entire mat to ensure the data are processed and the results are available within the next day.

Appendix A provides a brief review of activities that occurred during and after the SHRP2 R06C field demonstration projects. Seven State DOTs have ongoing activities toward deploying the DPS for accepting asphalt pavement construction as part of the DPS pooled fund study (TPF-5-[443]). These seven State DOTs are Alaska, Maine, Minnesota, Nebraska, Ohio, Texas, and Washington State. However, not all of these State DOTs are on the same schedule for implementation and deployment. An implementation plan or roadmap for the DPS was prepared in 2021 but not formally published.[11] The implementation plan was the outcome from a workshop held in April 2021 to obtain stakeholder input in developing a roadmap for State DOTs' use of the DPS as an acceptance tool for asphalt pavements during construction.

DEPLOYING INNOVATIVE TECHNOLOGIES IN QA PROGRAMS

PMTP and DPS devices or technologies are suggested for use in QA programs. Both of the technologies have illustrated their value, through demonstration projects, in identifying localized defects to reduce the risk of producing and accepting an inferior asphalt mat (Reiter and Von Quintus, 2017 and 2018; and Khazanovich et al., 2017). IC level 1 can be used as a process control activity. IC level 1 addresses the uniformity of the rollers (breakdown to final rollers) coverage used in compacting the mat. A consistent and uniform coverage of the mat by the rollers is similar to exhibiting consistent and uniform surface temperatures. The two combined should exhibit an asphalt mat with uniform density throughout the lot.

As mentioned in an earlier section of this report, a QA program in accordance with the requirements of 23 CFR 637.207 can be said to contain several core elements. The PMTP could be used for process control, or State DOTs could require its use as a QC activity. The DPS could be used for acceptance by the State DOT or owner.

Although not identified as a requirement in 23 CFR 637.207 for a QA program, data management is an important item, especially for implementing innovative technologies that result in relatively continuous measurements within the lots. As noted in Chapter 1, the Veta software tool is a map-based tool for viewing and analyzing geospatial data.[12] Veta, or equivalent software tools, should be considered in deploying innovative technologies within QA programs.
The following provides information and some discussion on using the PMTP and DPS for judging the acceptability of the asphalt mat in day-to-day practice.

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[11] The DPS implementation plan or road map was not formally published but can be downloaded from: https://docisolation.prod.fire.glass/?guid=b0f94827-2b00-44c2-ee01-6e15481a555e

[12] Veta is a data management and analysis software tool for intelligent construction; it is a map-based tool for viewing and analyzing geospatial data: https://www.dot.state.mn.us/materials/amt/veta.html

PMTP for Use in Quality Control

The PMTP could be required by a State DOT for use as a part of QC activities or as a process control activity to monitor the surface temperatures of the asphalt mat behind the screed during placement. There is no Federal requirement that the PMTP be used. The following items could be included or referred to in using the PMTP as a QC or process control activity.

- Monitoring and Corrective Actions. The use of the PMTP could be specified in a process control or QC plan depending on whether it is required by the State DOT. A QC or process control plan can identify when the paving and/or plant personnel should take corrective actions when severe surface temperature differentials are identified and ensure that the mat surface temperatures are within the specified temperature range for the specification.
    - Use of the PMTP is important for paving personnel to continually monitor to try and prevent cold spots, severe temperature differentials, and/or thermal streaks along the asphalt mat.
    - The PMTP can also be useful in monitoring the average temperatures of the asphalt mixture being placed behind the paver to assist in the compaction process by identifying mat surface temperatures for which the rollers may start to roll the mat within the temperature-sensitive zone. Operating rollers within the temperature-sensitive zone can destroy or decrease the density of the asphalt mat.
- Laboratory and Personnel Qualifications. All equipment and personnel used in evaluating the asphalt mat should be properly trained in using and interpreting the surface temperatures with the PMTP.
    - Equipment. The equipment to be used for the thermal profiling of the asphalt mat should be in accordance with the nonregulatory AASHTO PP 80-20. The equipment (thermal sensor) should undergo an annual check for accuracy and the operator should be trained prior to testing. AASHTO R 61-12 (2020) nonregulatory Standard Practice for Establishing Requirements for Equipment Calibrations, Standardizations, and Checks could be used to define equipment calibration.[13]
    - Temperature IR Sensor. Factory certification of the calibrated IR sensor should be provided and on file by the organization operating the equipment. The temperature sensor should be calibrated prior to each project.
    - Test Procedure.
- Lot and Segment Size. The definition of a “lot” varies between State DOTs. The lot size and definition can be the same as established for the State DOT’s traditional acceptance plan if desired. The surface temperature differential is typically based on a reporting segment length of 150-ft. A segment length of 150-ft represents the typical distance for about one truckload of

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mixture. However, the distance that a truckload will go depends on the mat thickness and the size of the delivery truck or amount of asphalt mixture in the truck. The 150-ft length was derived as an overall average. The use of the segment length (continuous paving over the width of the asphalt mat, excluding the area near the mat's edge or a longitudinal joint) is to determine the average surface temperature and maximum surface temperature differential within a segment of the asphalt mat.

  - Although the length of a segment can vary, the 150-ft length has been accepted as the common value used. The segment length should be estimated so that, on the average, one truckload of mixture delivered to the paver is located within a segment.

- Tolerances and Threshold Values. AASHTO groups the surface temperature differentials into three categories in Table 3 to assess the uniformity of the asphalt mat temperature. These categories are referred to as temperature segregation and can be related to truck-to-truck segregation and cold or hot spots along the mat. The PMTP, however, can also be used to identify longitudinal segregation through thermal streaks. Reiter and Von Quintus (2018) provided suggestions to identify thermal streaks during the paving process.
  - The number of medium and severe surface temperature differentials can be reported for each segment and whether thermal streaks are present within the segment. Thermal streaks are not dependent on the type of delivery trucks, but mixtures susceptible to segregation are more prone to exhibit thermal streaks behind the paver.

Table 3. Surface Temperature Differentials for Overall Mat Uniformity

Category	Temperature Difference
Low	< 25 ^{o}F
Medium	25 to 50 ^{o}F
High	> 50 ^{o}F

- Independent Assurance. IA is used for acceptance and is typically not needed for process control tests and activities. There is no standard procedure or practice to be followed to conduct an unbiased and independent evaluation of the surface temperature readings by the PMTP. However, IR cameras are available to take an IR picture of the asphalt mat and compare the average surface temperature readings within a specific area to the PMTP recordings. The measurement accuracy parameters for the PMTP equipment (the distance measuring instrument for measuring distance and the thermal sensor for measuring surface temperatures) are included in the nonregulatory AASHTO PP 80.[13] IR cameras were used in a couple of the SHRP2 demonstration projects for identifying longitudinal thermal segregation (Reiter and Von Quintus, 2018). The IR cameras are used to establish confidence in the PMTP readings by construction personnel. Any procedure to independently check and validate the PMTP readings should be demonstrated and checked.

- The frequency for checking the PMTP surface temperature readings should be made in at least three segments randomly located during the first lot. After the first lot has been completed, the check on PMTP surface temperature readings can be reduced to one randomly located segment within each lot.
- Acceptance and Payment. Thermal profile data from the PMTP does not directly correlate with density and pavement performance. Therefore, it is not well suited as an acceptance criterion. For State DOTs considering PMTP use in their QA program, 23 CFR 637.207(a)(1)(ii) requires the use of QC data for acceptance to be validated with agency verification sampling and testing procedures.

- Dispute Resolution. The PMTP surface temperature readings and data could be used to assist in dispute resolution as related to defining the reasons for or explaining potential discrepancies or differences between the density readings or higher pavement roughness data measured along a lot. The previous SHRP2 demonstration projects showed increases in IRI and/or increases in the variability of mat density in lots and/or segments with severe temperature differentials recorded by the PMTP (Reiter and Von Quintus, 2018). It should be understood, that the PMTP is not being used to determine acceptance or establish payment.

Dielectric Profiling System for Use in Acceptance

The DPS is applicable for use by a State DOT to evaluate the density and uniformity of the asphalt mat for acceptance within its QA program. As noted in the beginning of this section, the DPS could also be used by the contractor as a QC activity to ensure or confirm the rolling pattern and equipment result in a uniform asphalt mat.

The following items can be included or referred to in the State DOT plan for accepting asphalt pavement based on density.

- Laboratory and Personnel Qualifications. All equipment used in evaluating the asphalt mat for acceptance should be certified and personnel trained and certified in properly using and interpreting the dielectric constants measured with the DPS.
  - Equipment. The type of equipment to be used for dielectric measurements to estimate asphalt mat density should be in accordance with the nonregulatory AASHTO PP 98-20.[14] The testing equipment should undergo an annual certification process and the equipment operator should be trained and certified by the agency prior to testing. The test equipment should also undergo a verification process a few days prior to the actual testing. AASHTO R 61-12 (2020)[14] could be used to define equipment calibration.

[14] Use of American Association of State Highway and Transportation Officials (AASHTO) specifications included in this document is not a Federal requirement.

  - Factory Certification. Factory certification of the calibrated GPR sensor(s) should be provided and kept on file by the agency and contractor. Adequate calibration of the GPR sensors is an important item to have on file for use in a State DOT's QA program.
  - Test Procedure. The testing should be done in accordance with AASHTO PP 98-19.[14]
    - A potential source of error or bias during the daily measurements for assessing the asphalt mat is water or moisture on the surface and/or retained in the asphalt mixture. Water from steel wheel rollers can cause a bias in the readings if the DPS takes measurements directly behind the final roller. More importantly, water from a recent rain event or wet conditions (heavy fog or a light mist) can cause a bias in the test results. The pavement surface should represent "dry" conditions.
- Stability of Sensors, Measuring Dielectric Values. It is important that the readings from the GPR sensors be evaluated or checked over time (refer to the Validation section included later in this bullet list). The checks on the stability of the sensors are different from preparing the correlation curves that can be asphalt mixture-specific (refer to the Mat Density-Dielectric Constant Relationship section later in this bullet list). The following are some suggested methods for checking the stability and accuracy of the readings over time. The key is in maintaining the test section or block specimen so that the density does not change over time or for some designated time period.
  - A designated control segment located at the State DOT's laboratory or test facility can be identified and used to check the GPR readings over time. The designated control segment needs to be a section of pavement located in an area that is not exposed to continued traffic and the climate. The DPS equipment is used to ensure the readings remain consistent over time as well as for checking the equipment on some periodic basis. For this method, the actual density is not mandatory because only the GPR response is checked, not the estimated density. For this case, the density gradient throughout the lift is not important because only the GPR response is being compared from time to time and sensor to sensor.
  - Control test blocks or slabs made with a standard material (asphalt mixture and lift thickness) can be prepared and used for testing. The test blocks need to be protected so that their density does not change over time, including storing these blocks in a controlled climate condition. These blocks could be slabs prepared in the laboratory to a designated density level or cut from a test pavement and the density of the cut block measured. The blocks or test specimens can be placed on a standard metal plate each time the GPR sensor(s) is checked for consistency in the readings.
- Lot and Sublot Size. The lot and sublot size and definition can be the same as established for the State DOT's traditional acceptance plan based on using random samples for evaluating the lot with current density-based methods.
- Mat Density-Dielectric Constant Relationship. The fundamental activity behind the DPS device is establishing a correlation curve or relationship between the density of cores or laboratory-compacted test specimens and the dielectric constant for the material for the entire

project. Calibration has been used in some cases, but correlation is used within this document because one is not calibrating or adjusting the outcome from individual DPS devices. The relationship is a correlation between the dielectric constant and air voids or mat density; no adjustments are made to the measured dielectric constant. Asphalt mixture produced in the laboratory during mixture design to establish the job mix formula should not be used to prepare the correlation relationship because of the differences that can occur between plant- and laboratory-prepared mixture. The material used to verify the job mix formula with plant-mixed, lab-compacted pucks can be used. The following are options to establish the asphalt mat density versus dielectric constant correlation curve, as the dielectric constant can be aggregate type dependent:

- Test specimens could be prepared and compacted in a laboratory-controlled environment. The compaction device used by many State DOTs is a Superpave gyratory compactor, in accordance with AASHTO T 312 (Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor).[15] The number of gyrations should vary to produce test specimens with air voids varying from 4 to 10 percent (suggested air void levels include two specimens each at 4, 6, 8, and 10 percent). The asphalt mixture used to establish the correlation should be plant mixed because the dielectric constant is dependent on the moisture content in the mixture. If laboratory-prepared test specimens are used to develop the correlation relationship, a State DOT could consider using field cores to confirm that relationship and remove any bias between the laboratory compacted and field compacted specimens during the control strip or first lot of paving.
- Cores could be used to prepare the mixture correlation relationship during the control strip, if required by the State DOT, or within the first paving lot. The variability within the correlation relationship could be relatively high because errors between the dielectric-generated mat density values and the true mat density can depend on the lift thickness, underlying layers, and other volumetric properties of the mix besides density (asphalt content, absorption, gradation). The variability of the estimated asphalt mat density from the dielectric constant could be defined and considered in the acceptance plan. The variability for the correlation relationship could be evaluated and included as part of the acceptance criterion (tolerance). The variability and bias derived from densities measured on cores will likely be greater than the variability and bias derived from laboratory-prepared, laboratory-compacted specimens. A State DOT could consider the use of cores for deriving the final variability and bias between the dielectric values and densities from cores.

- Continuous Density-Based Acceptance Plan or Specification. Many State DOTs use a percent within limits (PWL) based acceptance plan in their QA program. PWL is based on taking random samples of the asphalt mat to estimate the average density and variability of the asphalt mat within a given lot. The PWL is the percent of the lot that falls between the lower and upper

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specification limits using statistical relationships assuming a normal distribution. Using the DPS-determined asphalt mat density for acceptance represents a continuous, full-width assessment of the asphalt mat in each lot. Since the entire area of the lot is measured, a normal distribution does not need to be assumed and statistical relationships are not needed to determine the percentage of a lot between the lower and upper specification limits. Percent conforming is the preferred term to be used to differentiate from the statistical PWL approach. Percent conforming can be calculated directly for each lot from the DPS-determined density values. The width of the lot used in the assessment is typically defined as the area of the mat between 1-ft from each edge of the mat (excludes the area near each longitudinal and transverse construction joint). State DOTs are still encouraged to have a joint density specification. Thus, mat and joint density would be treated independently.

- Tolerances and Threshold Values or Lower and Upper Specification Limits. The lower and upper limits of density can be the same as included in the State DOT's current QA program or specifications, assuming a normal distribution of density measurements or estimates. Several State DOTs use a minimum limit of 92.5 or 93.0 percent (Tran, 2016), but there is no general consensus on the threshold values for determining incentives or disincentives (Tran, 2016; Aschenbrener, 2021).
- Validation. If a State DOT, or third party hired by a State DOT, develops the density-to-dielectric correlation relationship and operates the DPS for density determination, then validation is not needed. For State DOTs considering the use of DPS data collected by the contractor for acceptance, the asphalt mat density must be independently validated in accordance with 23 CFR 637.207(a)(1)(ii and iii). Split samples are not available, so the following are suggestions for properly using the DPS results in the acceptance decision.
    - If laboratory-compacted test specimens are used to develop the correlation relationship, a State DOT should develop and analyze the correlation relationship to develop State-specific comparison criteria. The evaluation will lead to a minimum number of cores to be tested by the State DOT for independent validation of the density after final rolling or compaction.
    - If a sufficient number of cores are used to develop the correlation relationship and those cores are controlled and tested by the State DOT, then additional cores for independent validation may not be needed.
    - In either case, the State DOT should consider doing the testing to develop the correlation curve or relationship (the use of cores and/or plant-produced, lab-compacted test specimens). If QC data is allowed for use in the acceptance plan, the State DOT should check and confirm the correlation curve or relationship at periodic intervals during the project.
- Measurement and Payment. All other elements typically included in a QA specification (as an example: Full Pay, Incentive Pay, Disincentive Pay, Corrective Action) could follow the State DOT's existing QA specification. However, the limits for a specific element could be affected by the standard error from the correlation curve or relationship.

- Referee Testing for Dispute Resolution. The QA program should include a dispute resolution process or paragraph and serve as the basis for resolution, consistent with the State DOT's QA specifications. Dispute resolution can include checks for biases or differences caused by the sampling and testing activities.

- One method of evaluation is to use cores. If the evaluation of the cores concludes that the standard error and average density-based value are statistically different from the corresponding DPS data, then additional analyses may be needed and the correlation relationship revised. In other words, explaining why the original correlation relationship changed. For example, the difference could be a material change, lift thickness changes, or moisture content changes in the stockpiles.

SUMMARY

Many State DOTs recognize that consistent asphalt mats, compacted to adequate density, contribute to positive pavement performance. In addition, State DOTs typically desire real-time tests to evaluate asphalt mixture consistency and mat density across the entire width and length of a paving lot. Three innovative technologies being used to evaluate the consistency and density of asphalt mixtures in real-time or near real-time are PMTP, IC rollers, and DPS. These technologies are in different phases of research and implementation though, independently and collectively, they all represent opportunities to positively impact asphalt pavement performance while giving State DOTs significantly more spatial quality information. This report introduces the technologies and their potential deployment in the context of QA programs conforming to 23 CFR 637.207(a). Current opportunities and challenges were identified, as well as ongoing work nationally to address identified challenges and leverage current opportunities that will assist with further refinement and implementation.

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APPENDIX A – Summary of DPS Implementation Efforts for Selected State DOTS

Appendix A includes brief summaries of the implementation efforts for selected State DOTs that have ongoing implementation and/or demonstration projects related to using the DPS.

- The Minnesota DOT purchased GPR-based DPS equipment in 2015 and began using it to set up data collection and calibration procedures. The agency sponsored field pilot projects starting in 2016. The vehicle-mounted system was used on the field evaluation projects in 2017 by an independent consultant – American Engineering Testing. In 2018, the agency issued a contract to the University of Minnesota for developing a robot-based DPS and started using the AASHTO specification – AASHTO PP 98. The Minnesota DOT has conducted demonstration projects on more than 10 construction projects, giving continuous assessment of the joint and mat density including special projects. Moving the technology forward in 2020, the agency issued contracts to about four contractors for data collection to improve on the procedure. The Minnesota DOT uses a limited number of asphalt cores to check the calibration relationships or curves that were previously developed from the earlier pilot projects. The following lists some observations from the Minnesota DOT pilot projects:

    - The technology does work and can be used to identify high- and low-density areas.
    - Aggregate type has a significant impact on the measured asphalt mat dielectric constant.
    - Constructing a histogram of the relative or percent density values derived from the DPS measurements and calibration curve provides a good method for assessing compaction quality for acceptance.
    - Minnesota DOT developed a method to measure laboratory-compacted (gyrated) asphalt mixture specimens, instead of using field cores, to convert the measured dielectric constant to the asphalt mixture density. The method measures the dielectric constant of laboratory, gyratory-compacted specimens using a "time-of-flight-based" calculation and relating the measured dielectric constant to the specimen density by compacting the specimens to different density levels. The new method of calibrating without using field cores has been shown to reasonably predict asphalt mat density.
    - Minnesota DOT is leading the TPF 5(443) pooled fund study (Continuous Asphalt Mixture Compaction Assessment using Density Profiling System), which initiated in 2019 and included 14 financially participating agencies: FHWA, Idaho, Maine, Maryland, Minnesota, Mississippi, Missouri, New York, North Dakota, Ohio, Pennsylvania, Utah, Wisconsin, and Washington State. The website for the pooled fund study is https://www.pooledfund.org/Details/Study/667. A number of friend agencies are actively participating in the pooled fund user group (for example Alaska, Florida, and Hawaii, to name a few).

  - Minnesota has developed a roadmap for implementing the DPS, with full deployment planned to occur within the next 2 to 4 years.

- The Alaska DOT&PF started using a rolling density meter (RDM) in 2016 and has continued to use the equipment on an increasing number of projects. The driving force for its use in Alaska was 100-percent coverage to replace the limited number of cores drilled within a lot to judge the quality of the asphalt mat. A key change or revision to the agency's acceptance plan for the pilot projects was substituting percent conformance for PWL for establishing Alaska's density pay factor. The Alaska asphalt mat density pay factors are tied to percent conformance of the asphalt mat and vary from 0.80 to 1.05. Percent conformance values less than 50-percent require removal and replacement of the asphalt mat. The Alaska DOT&PF is also using the DPS to measure the density along longitudinal construction joints and has established pay factors for joint density readings. Overall, Alaska is continuing to use the DPS for determining the quality and acceptance of asphalt mats.

- The Ohio DOT started using the RDM in field evaluation projects in 2018 and continued to assess asphalt mats in 2019. Currently, Ohio uses nine asphalt cores to establish the linear calibration curve to calculate the density from the measured dielectric values. Results from the pilot projects suggest cores recovered from the asphalt mat for acceptance may not always be representative of the quality of the mat itself. The number of cores was simply too small to be used for a PWL-type of acceptance specification. It was concluded from Ohio's pilot projects that the RDM measurements and estimated densities were more reliable for the entire lot. Additional conclusions from Ohio DOT's RDM pilot projects are listed below.

  - The RDM can provide an accurate assessment of the mat density because of the higher sampling rates. It also provides real-time information and can be used to assess the quality of construction.

  - Daily verification of the calibration curve is needed.

  - ODOT is continuing to collect data through additional pilot projects to develop standard procedures and determine the number of cores needed for calibration. Future deployment of the RDM or DPS is expected to change the method used to inspect and accept asphalt pavement construction in Ohio.

- The Nebraska DOT participated in the SHRP2 R06C demonstration project using the DPS technology and has continued to use the equipment on other projects. The agency completed five pilot projects in 2019 to establish the correlation between the dielectric constant and asphalt mat density. The results from the pilot projects were positive. The Nebraska DOT, however, expects full deployment to take place over many years.

- The Maine DOT also participated in the SHRP2 R06C demonstration project using the DPS technology. A total of nine projects were evaluated using the DPS in 2018 and 2019.

The results from the Maine pilot projects were less encouraging than some of the other demonstration projects completed under SHRP2 R06C. Specifically, the laboratory-measured dielectric constants had poor correlation to the bulk dielectric constant measured on the asphalt mat. As such, there was poor correlation between the dielectric constant and mat density derived from cores. The Maine DOT does plan to continue the field evaluation of the DPS because other agencies, such as the Alaska DOT&PF, Minnesota DOT, and Ohio DOT, found positive results relating dielectric constant to asphalt mat density.

- The Washington State DOT obtained the DPS in 2017 and started using the equipment to assess a few asphalt pavement projects. Additional field evaluation projects were completed in 2018. A total of 11 projects were assessed with the DPS in 2017 and 2018. The Washington State DOT found the dielectric constant has a reasonable correlation to the asphalt mat density, similar to that of nuclear density gauges. The DPS can be used to assess uniformity of the asphalt mat and identify areas with potentially low density that can be cored for further evaluation of the asphalt mat quality. The Washington State DOT is continuing to use the DPS by participating in the national pooled fund study being led by the Minnesota DOT and developing a draft specification for acceptance. However, the timeframe for developing the specification or acceptance plan is uncertain at the current time.

- The Texas DOT has been using GPR-based assessments of asphalt pavements for many years. Most of this effort has been done through research projects or forensic investigations completed by the Texas Transportation Institute (TTI). The Texas DOT, through research with the TTI, is continuing to use the RDM or DPS on future pilot projects for QA purposes. The Texas DOT, however, also plans to look at other GPR equipment. Full deployment for using the GPR technology to assess the quality of the asphalt mat for QA purposes is not expected in the near future.