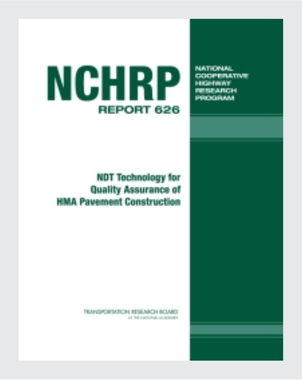

NDT Technology for Quality Assurance of HMA Pavement Construction

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 626

NDT Technology for Quality Assurance of HMA Pavement Construction

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Edward T. Harrigan
Staff Officer
Transportation Research Board

This report contains the findings of research performed to investigate the application of nondestructive testing (NDT) technologies in the quality assurance of hot mix asphalt (HMA) pavement construction. The report contains the results and analyses of the research performed and presents several key products, notably a recommended manual of practice with guidelines for implementing selected NDT technologies in an agency's routine quality assurance (QA) program for HMA pavement construction and detailed test methods for the recommended NDT technologies. Thus, the report will be of immediate interest to construction and materials engineers in state highway agencies and the private sector.

Test methods used for in-place quality assurance of individual HMA and unbound pavement layers have changed little in past decades. Such quality assurance programs typically rely on nuclear density measurements or the results of testing conducted on pavement cores. Roughness measurements are often used to confirm that the newly constructed pavement has an adequate initial smoothness.

More recently, NDT methods, including lasers, ground-penetrating radar, falling weight deflectometers, penetrometers, and infrared and seismic technologies, have been significantly improved and have shown potential for use in the quality assurance of HMA pavement construction. Furthermore, the new *Mechanistic-Empirical Pavement Design Guide* (MEPDG) uses pavement layer stiffness modulus as a key material property for design of new and rehabilitated HMA pavements. The availability of this tool to predict pavement performance will lead to increased measurement of layer moduli by owner agencies, an activity that has not been a typical component in the past for HMA project acceptance.

This research had two objectives. The first was to conduct a comprehensive field experiment to determine the effectiveness and practicality of promising, existing NDT technologies for the evaluation of the quality of unbound and bound pavement layers during or immediately after placement or for acceptance of the entire HMA pavement at its completion. The second objective was to prepare a recommended manual of practice and test methods for those NDT technologies judged ready for implementation by AASHTO.

The research identified several NDT technologies with the potential for immediate implementation in a quality assurance program of HMA pavement construction, including that of individual HMA, base, and subgrade layers. This was assessed based on (1) the ability to accurately identify construction anomalies and (2) the ability to predict material properties indicative of pavement performance. The GeoGauge is the device recommended for estimating the modulus of unbound layers, while the portable seismic pavement analyzer (PSPA) is recommended for estimating the modulus of HMA layers. The PaveTracker is also recommended for use in establishing and confirming the rolling pattern for HMA layers.

These recommendations do not mean that other NDT devices included in the evaluation—e.g., the dynamic cone penetrometer (DCP), ground penetrating radar (GPR), the electrical density gauge (EDG), and the pavement quality indicator (PQI)—do not provide useful data for pavement and materials testing purposes. Several of these devices demonstrated distinct benefits and advantages that are documented in this report for routine pavement evaluation, but were judged to require additional development or evaluation before they are fully implemented in routine practice for QA of HMA pavements.

The research was performed by Applied Research Associates, Inc. The report fully documents the research leading to the recommended manual of practice and NDT methods. The recommendations are under consideration for possible adoption by the AASHTO Highway Subcommittee on Construction and Subcommittee on Materials.

CONTENTS

AUTHOR ACKNOWLEDGMENTS

The research described herein was performed under NCHRP Project 10-65 by the Transportation Sector of Applied Research Associates (ARA), Inc. Mr. Harold L. Von Quintus served as the Principal Investigator on the project.

Mr. Von Quintus was assisted by Dr. Chetana Rao of ARA as the Project Manager and Engineer on the team. The team also included Richard Stubstad of ARA; Dr. Kenneth Maser with Infrasense; Dr. Soheil Nazarian, with the University of Texas at El Paso (UTEP); Mr. Brian Prowell with the National Center for Asphalt Technology (NCAT); and Dr. Edward Minchin with the University of Florida, Gainesville.

In addition, the project team was supported by several individuals who conducted field testing, including Mr. Ajay S. Singh, Mr. Brandon Artis, and Mr. David Goodin from ARA; Mr. Manuel Celaya from UTEP; and Mr. Dennis Andersen from EDG, LLC. Dr. Brian Prowell from NCAT and Dr. Allen Cooley from BCD, Inc., provided oversight for laboratory testing of asphalt and unbound materials, respectively. Dr. Buzz Powell assisted with coordinating field tests at the NCAT test track during the construction of the test tracks. Mr. Brandon Von Quintus, Mr. Ajay Singh, and Mr. Mark Stanley of ARA assisted with development of databases for field test results and in preparation of field notes from test sites. Ms. Robin Jones, Ms. Jaime DeCaro, and Ms. Alicia Pitlik provided editorial review, final report formatting, and tabulation of appendices, respectively.

The project team also appreciates and acknowledges the support and technical assistance of various agency and contractor personnel, as well as representatives from nondestructive testing equipment manufacturers who were involved in the construction and testing of pavement structures and mixtures included in various phases of the project. Those individuals directly involved in the coordination and construction of the projects included in the field testing plan are listed as follows:

Minnesota: Mr. John Siekmier (Minnesota DOT), Mr. Art Bolland (Minnesota DOT), Mr. Chris Dunnick (Dunnick Brothers)

Alabama: Ms. Sharon Fuller (Alabama DOT), Mr. Andy Carol (Scott Bridge Company), East Alabama Paving

Texas: Mr. Tom Scullion (Texas Transportation Institute), Mr. Gregory Cleveland (Texas DOT), Mr. James Klotz (Texas DOT), Mr. Tim Wade (Texas Turnpike Authority), Dr. Weng-On Tam (Avlis Engineering), Texas Lone Star Infrastructure

Missouri: Mr. John Donahue (Missouri DOT), Mr. Tim Hellebusch (Missouri DOT)

North Dakota: Mr. Bryon Fuchs (North Dakota DOT), Mr. Joel Wilt (North Dakota DOT), Mr. Greg Semenko (North Dakota DOT)

Ohio: Mr. Roger Green (Ohio DOT), Mr. Brian French (Ohio DOT)

NDT Devices and IC Rollers: Mr. Chris Connelly (BOMAG), Mr. Jeff Fox (Ammann), Mr. Christopher Dumas (FHWA), Mr. Bob Horan (Salut), Mr. Scott Fielder (Humbolt Scientific, Inc. [Part A testing]), Mr. Melvin Main (Humboldt Scientific, Inc. [Part B testing]), Mr. William Beck, (Dynatest), Caterpillar, Fugro/CarlBro, Transtech Systems Inc., Troxler Electronic Laboratories, Inc.

SUMMARY

NDT Technology for Quality Assurance of HMA Pavement Construction

Introduction

Quality assurance (QA) programs provide the owner and contractor a means to ensure that the desired results are obtained to produce high-quality, long-life pavements. Desired results are those that meet or exceed the specifications and design requirements. Traditional pavement construction quality control and quality acceptance (QC/QA) procedures include a variety of laboratory and field test methods that measure volumetric and surface properties of pavement materials. The test methods to measure the volumetric properties have changed little within the past couple of decades.

More recently, nondestructive testing (NDT) methods, including lasers, ground-penetrating radar (GPR), falling weight deflectometers (FWD), penetrometers, and infrared and seismic technologies have been improved significantly and have shown potential for use in the QC/QA of flexible pavement construction. Furthermore, the new Mechanistic-Empirical Pavement Design Guide (MEPDG) uses layer modulus as a key material property. This should lead to increased measurement of layer moduli—a material property that can be estimated through NDT tests, which is not included, at present, in the acceptance plan.

This research study investigated the application of existing NDT technologies for measuring the quality of flexible pavements. Promising NDT technologies were assessed on actual field projects for their ability to evaluate the quality of pavement layers during or immediately after placement or to accept the entire pavement at its completion. The results from this project identified NDT technologies ready and appropriate for implementation in routine, practical QC/QA operations.

Objectives

The overall objective of NCHRP Project 10-65 was to identify NDT technologies that have immediate application for routine, practical QA operations to assist agency and contractor personnel in judging the quality of hot mix asphalt (HMA) overlays and flexible pavement construction. This objective was divided into two parts:

1. Conduct a field evaluation of selected NDT technologies to determine their effectiveness and practicality for QC/QA of flexible pavement construction.
2. Recommend appropriate test protocols based on the field evaluation and test results.

Effectiveness and practicality are key words in the first part of the objective. The field evaluation plan was developed to determine the effectiveness and practicality of different

NDT technologies for use in QA programs. These terms are defined as follows for NCHRP Project 10-65:

- Effectiveness of NDT Technology—Ability or capability of the technology and device to detect changes in unbound materials or HMA mixtures that affect the performance and design life of flexible pavements and HMA overlays.
- Practicality of NDT Technology—Capability of the technology and device to collect and interpret data on a real-time basis to assist project construction personnel (QC/QA) in making accurate decisions in controlling and accepting the final product.

Integration of Structural Design, Mixture Design, and Quality Assurance

The approach taken for this project was to use fundamental properties that are needed for both mixture and structural design for both control and acceptance of flexible pavements and HMA overlays. Figure 1 illustrates this integration or systems approach. The material or layer properties were grouped into three areas—volumetric, structural, and functional—and the NDT technologies were evaluated for their ability to estimate these properties accurately. Using the same mixture properties for accepting the pavement layer that were used for structural and mixture design allows the agency to more precisely estimate the impact that deficient materials and pavement layers have on performance. The material tests that are needed for structural and mixture design using the newer procedures are listed in Table 1.

Two structural properties that are needed to predict the performance of flexible pavements and HMA overlays are modulus and thickness. These are called "quality characteristics," and they are defined in *Transportation Research Circular E-C037* as "That characteristic of a unit or product that is actually measured to determine conformance with a given requirement. When the quality characteristic is measured for acceptance purposes, it is an **acceptance quality characteristic** (AQC)."

Products

The final deliverables for NCHRP Project 10-65 were divided into three volumes. Volume 1 is the procedural manual for implementing the NDT methods for QA application. It is included herein as Appendix B. It contains some of the examples for application of the modulus values for controlling and accepting flexible pavements. Volume 2 is the standard NCHRP final report. Part 3 of Volume 2 is the main body of *NCHRP Report 626.* Volume 3 includes the appendices for the other two volumes. It is not published herein. The appendices in Volume 3 also include the data generated from this project. The complete three volumes are presented in *NCHRP Web-Only Document 133.*

NDT Devices Included in the Field Evaluation

A large number of NDT technologies and devices have been used for pavement evaluation and forensic studies. Table 2 summarizes the technologies and methods that have been used to measure different properties and features of flexible pavements. As tabulated, GPR has been used for estimating many more volumetric properties and features than any other NDT technology, while the deflection and ultrasonic-based technologies have been used more for estimating structural properties and features.

To narrow the list of NDT devices that have potential for QA application, several highway agencies were contacted to collect information on their practices and experiences. Research

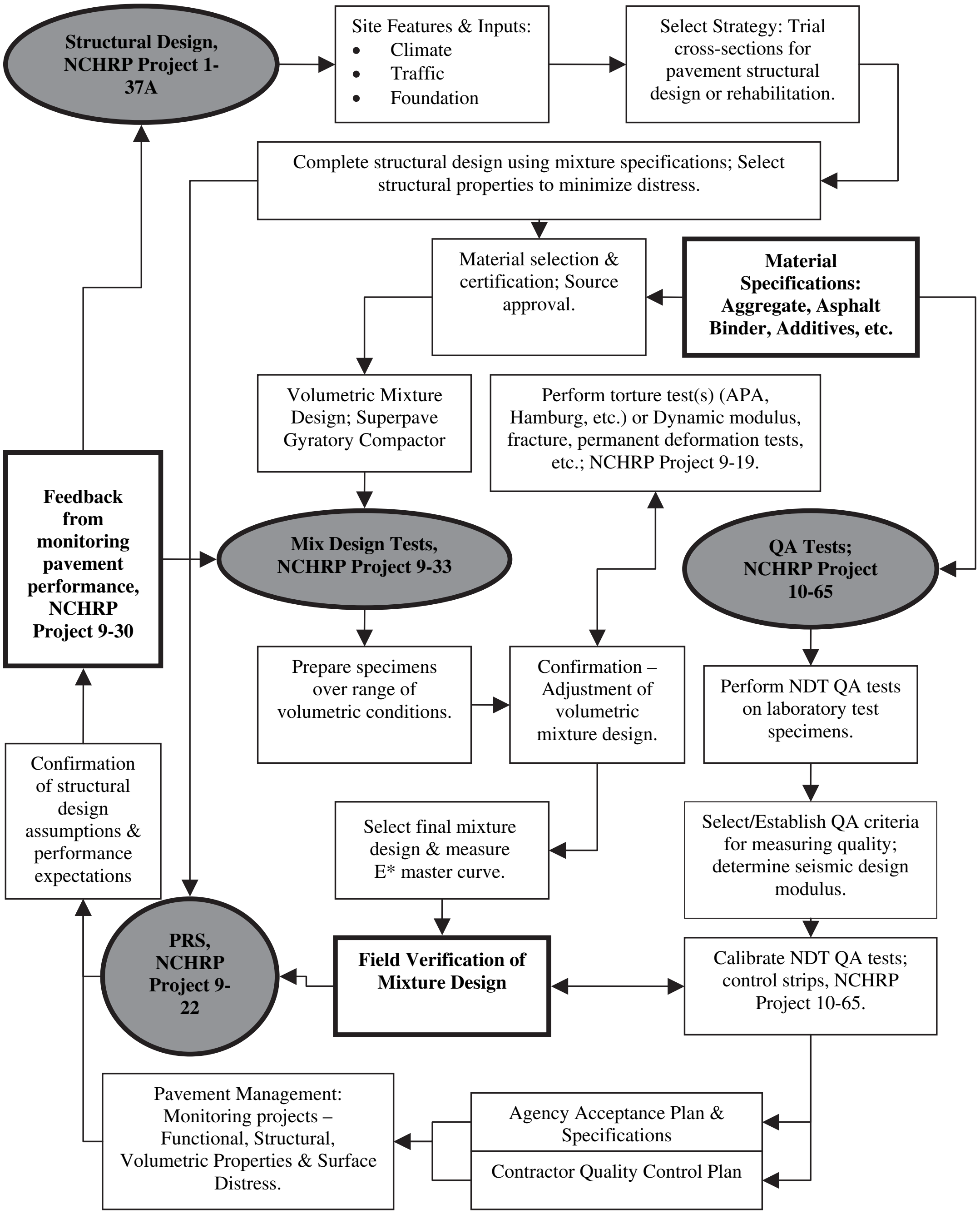


Figure 1. Example flow chart for the systems approach for specifying, designing, and placing quality HMA mixtures.

reports of several agencies were also reviewed. These agencies include Arizona, California, Connecticut, Florida, Georgia, Illinois, Maryland, New Hampshire, Minnesota, Mississippi, Missouri, Nevada, Ohio, Oklahoma, Pennsylvania, Texas, Virginia, Washington, and Wisconsin Departments of Transportation (DOTs), the Federal Aviation Administration (FAA), Federal Highway Administration (FHWA), Eastern Federal Lands Division, Central Federal Lands Division, U.S. Air Force, U.S. Army Corps of Engineers Engineer Research and Development Center, Loughborogh University, Nottingham Trent University, Transport Research Laboratory

Table 1. Summary of material and layer properties used for design and acceptance of flexible pavements and HMA overlays.

Pavement Layer	Material-Layer Property		Property Needed for:		
			Structural Design	Mixture Design	Acceptance
HMA Layers; Dense-Graded Mixtures	Density – Air Voids at Construction		Yes	Yes	√
	Voids in Mineral Aggregate		Yes	Yes	√
	Effective Asphalt Binder Content		Yes	Yes	√
	Voids Filled with Asphalt			Yes	
	Gradation		Yes	Yes	√
	Asphalt Binder Properties		Yes	Yes	
	IDT Strength and Creep Compliance		Yes	Yes	
	Dynamic Modulus		Yes	Yes	
	Flow Time or Flow Number			Yes	
	Smoothness, Initial		Yes		√
Unbound Layers; Dense Graded Granular Base, Embankment Soils	Density		Yes	Yes	√
	Water Content		Yes	Yes	
	Gradation		Yes	Yes	√
	Minus 200 Material		Yes	Yes	√
	Plasticity Index (Atterberg Limits)		Yes	Yes	
	Resilient Modulus		Yes	Yes	
	Strength	CBR or R-Value	Yes	Yes	
		DCP; Penetration Rate	Yes		

IDT – Indirect Tensile
CBR – California Bearing Ratio
DCP – Dynamic Cone Penetrometer

(formerly known as the Transport and Road Research Laboratory [TRRL]) University of Illinois, University of Mississippi, Louisiana State University, Worcester Polytechnic Institute, and Texas Transportation Institute. Some of the equipment manufacturers and suppliers were also contacted to obtain specific information and data on the different NDT devices and technologies. The manufacturers contacted include Olson Engineering; Blackhawk; Geophysical Survey Systems; Inc. (GSSI); TransTech Systems, Inc.; Dynatest; Carl Bro, and others.

The following list identifies the factors used to evaluate specific NDT devices that have reasonable success of being included in a QA program:

- Accuracy and precision of the test equipment and protocols in measuring a specific material property—one of the difficulties of this category is defining the target value of some properties for nonlinear and viscoelastic materials. The accuracy and precision of the technology is also tied to the data interpretation procedures.
- Data collection guidelines and interpretation procedures—this category examines whether there are generalized guidelines and procedures available for performing the tests and analyzing the data to estimate the material properties and/or features.
- Availability of standardized test procedures (test protocols)—this category verifies if there is a test standard available for use in collecting NDT data to estimate the required material properties and features.
- Data collection—production rate of the NDT equipment in collecting the data.
- Data interpretation—time and ancillary equipment/software required to analyze and interpret the data for estimating the specific layer property.
- Cost of the equipment—this category considers the initial cost of the test equipment, additional software and hardware requirements necessary to perform the test, and the operational and maintenance costs, including calibration.

Table 2. NDT methods used to measure properties and features of flexible pavements in place.

Type of Property or Feature		NDT Technologies and Methods	
		HMA Layers	Unbound Aggregate Base and Soil Layers
Volumetric	Density	• GPR Non-Nuclear Gauges; PQI, PaveTracker	• GPR • Non-Nuclear Gauges; EDG, Purdue TDR
	Air Voids or Percent Compaction	• GPR • Infrared Tomography • Acoustic Emissions • Roller-Mounted Density Devices	• GPR • Roller-Mounted Density Devices
	Fluids Content	• GPR	• GPR • Non-Nuclear Gauges; EDG, Purdue TDR
	Gradation; Segregation	• GPR • Infrared Tomography • ROSAN	NA
	Voids in Mineral Aggregate	• GPR (Proprietary Method)	NA
Structural	Thickness	• GPR • Ultrasonic; Impact Echo, SPA, SASW • Magnetic Tomography	• GPR • Ultrasonic; SASW, SPA
	Modulus; Dynamic or Resilient	• Ultrasonic; PSPA, SASW • Deflection-Based; FWD, LWD, • Roller-Mounted Response Systems; Asphalt Manager	• Impact/Penetration; DCP, Clegg Hammer • Ultrasonic; DSPA, SPA, SASW • Deflection-Based; FWD, LWD • Steady-State Vibratory; GeoGauge • Roller-Mounted Response Systems
	Bond/Adhesion Between Lifts	• Ultrasonic; SASW, Impulse Response • Infrared Tomography	NA
Functional	Profile; IRI	• Profilograph, Profilometer, Inertial Profilers	NA
	Noise	• Noise Trailers	NA
	Friction	• CT Meter, ROSAN	NA

SPA – Seismic Pavement Analyzer
PSPA – Portable Seismic Pavement Analyzer
SASW – Spectral Analysis of Surface Waves
LWD – Light Weight Deflectometer
ROSAN - ROad Surface ANalyzer
EDG – Electrical Density Gauge
TDR – Time Domain Reflectometry
DSPA – Dirt Seismic Pavement Analyzer
PQI – Pavement Quality Indicator
DCP – Dynamic Cone Penetrometer
CT – Circular Texture
FWD – Falling Weight Deflectometer

- Complexity of the equipment or personnel training requirements.
- Ability of the test method and procedure to quantify the material properties needed for QA, mixture design, and structural design (see Figure 1). In other words, is the NDT test result applicable to mixture and structural design?
- Relationship between the test result and other traditional and advanced tests used in mixture design and structural design.

NDT Devices Included in the Field Evaluation

The following list contains, in no particular order, the NDT technologies and devices that were selected for use in the field study:

- **Deflection Based Technologies—**The FWD and LWD were selected because of the large number of devices that are being used in the United States and the large database that has been created under the FHWA Long Term Pavement Performance (LTPP) program. The LWD was used to evaluate individual layers, especially unbound layers, while the FWD was used to evaluate the entire pavement structure at completion to ensure that the flexible pavement structure or HMA overlay met the overall strength requirements used in the structural design process. Deflection measuring devices are readily available within most agencies for immediate use in QA.
- **Dynamic Cone Penetrometer—**The DCP was selected because of its current use in QA operations in selected agencies and its ability to estimate the in-place strength of unbound layers and materials. In addition, the DCP does not require extensive support software for evaluating the test results. DCP equipment is being manufactured and marketed by various organizations, making it readily available.
- **Ground Penetrating Radar—**GPR was selected because of its current use in pavement forensic and evaluation studies for rehabilitation design and for estimating both the thickness and air voids of pavement layers. If proven successful, this will be one of the more important devices used for acceptance of the final product by agencies, assuming that the interpretation of the data can become more readily available on a commercial basis. The GPR air-coupled antenna was used successfully within the FHWA-LTPP program to measure the layer thickness within many of the 500-ft test sections.
- **Seismic Pavement Analyzer—**Both the PSPA and DSPA were selected because they provide a measure of the layer modulus and can be used to test both thin and thick layers during and shortly after placement. This technology can also be used in the laboratory to test both HMA and unbound materials compacted to various conditions (e.g., different water contents for unbound materials and soils or temperature and asphalt content for HMA to evaluate the effect of fluids and temperature).
- **GeoGauge—**The GeoGauge has had mixed results in testing unbound pavement layers in the past. It was selected for this study because it is simple to use and provides a measure of the resilient modulus of unbound pavement layers and embankment soils and can be used to test typical lift thicknesses.
- **Non-Nuclear Electric Gauges; Non-Roller-Mounted Devices—**Non-nuclear density gauges have a definite advantage over the nuclear devices simply from a safety standpoint. These gauges have been used on many projects but with varying results. They were selected for the current study because the devices have been significantly improved since their previous evaluations. Moreover, many agencies are allowing their use by contractors for QC, and some agencies are beginning to use the contractor QC results for acceptance. They also represent the baseline comparison to the results from the nuclear gauges for measuring density for use in acceptance procedures. Thus, non-nuclear density gauges that provide location-specific results were selected for evaluation under this study. The gauges selected for initial use were the PQI and PaveTracker for HMA mixtures, while the EDG was selected for unbound materials.

NDT Devices Excluded from the Field Evaluation

The following list contains NDT technologies and devices that were excluded from the field evaluation study. It also contains explanations for the exclusion.

- **Roller-Mounted-Density/Stiffness Devices**—Non-nuclear density and stiffness monitoring devices attached to the rollers (for example, the BOMAG Varicontrol and Onboard Measuring System) were excluded because these devices have not been extensively used for QC, few agencies are evaluating this technology for possible use in the future, and there are a limited number of these rollers available for contractor use. Although the roller-mounted devices were excluded from the field evaluation, the roller manufacturers were contacted to determine their availability for use on selected projects.
- **Surface Condition Systems**—None of the surface condition measuring systems or devices was suggested for further evaluation under NCHRP Project 10-65. Although the initial International Roughness Index (IRI) is an input to the MEPDG, the smoothness measuring devices used for acceptance of the wearing surface are already included in the QA programs of many agencies. In addition, none of the devices provides an estimate of the volumetric and structural properties of the wearing surface.
- **Noise and Friction Methods**—Noise and friction measuring devices were excluded from further consideration because these properties are not needed in the MEPDG or any other structural design procedure, and no agency is considering their use for acceptance.
- **Infrared Tomography**—Infrared cameras and sensors were excluded from the field evaluation because their output only provides supplemental information to current acceptance plans. In other words, the devices are used to identify "cold spots" or temperature anomalies. Other test methods are still used to determine whether the contractor has met the density specification. This statement does not imply that this technology should be abandoned or not used—the infrared cameras and sensors do provide good information and data on the consistency of the HMA being placed by the contractor. However, they do not provide information that is required for QA programs.
- **Other Ultrasonic Test Methods**—Impact echo and impulse response methods, as well as the ultrasonic scanners, were excluded because they are perceived to have a high risk of implementation into practical and effective QA operations.
- **Continuous Deflection-Based Devices**—Rolling wheel deflectometers that are under development were also excluded from the field evaluation. These devices are considered to be in the research and development stage and are not ready for immediate application into a QA program.

Projects and Materials Included in the Field Evaluation

The field evaluation was divided into two parts, referred to as Parts A and B. The primary purpose of the Part A field evaluation was to accept or reject the null hypothesis that a given NDT technology or device can accurately identify construction anomalies or physical differences along a project. A secondary purpose of this part of the field evaluation was to confirm that the NDT device can be readily and effectively implemented into routine QA programs for flexible pavement construction and HMA overlays—an impact assessment. Part B of the field evaluation was to use those NDT technologies and devices selected from Part A and refine the test protocols and data interpretation procedures for judging the quality of flexible pavement construction. Part B also included identifying limitations and boundary conditions of selected NDT test methods.

Table 3 lists the projects and materials included in the field evaluation, while Table 4 lists those defects and layer differences that should have an impact on the quality characteristics measured by the QA tests. Table 5 contains the anomalies and differences of unbound material sections placed along each project. Likewise, Table 6 lists the anomalies and differences of HMA layers. None of the NDT operators were advised of these anomalies or physical differences.

Table 3. Projects and material types included in the field evaluation.

Part	Project Identification & Location		Layer/Material Evaluated	
A	1	TH-23 Reconstruction Project; Wilmar/Spicer Minnesota	HMA	Dense-Graded Base Mixture
			Granular Base	Class 6, Crushed Aggregate
			Class 5 Embankment	Low Plasticity, Improved Soil with Gravel & Large Aggregate Particles
A	2	I-85 Overlay Project; Auburn, Alabama	HMA	12.5 mm Stone Matrix Asphalt Mix; PG76-22
A	3	US-280 Reconstruction Project; Opelika, Alabama	HMA	Coarse-Graded Base Mixture; PG67-22
			Granular Base	Crushed Limestone Base
			Embankment	Improved Soil; Aggregate-Soil Mix
A	4	I-85 Ramp Construction Project; Auburn, Alabama	Embankment	Low Plasticity, Fine-Grained Soil
A	5	SH-130 New Construction Project; Georgetown, Texas	HMA	Coarse-Graded 19 mm Base Mixture; PG64-22
			Embankment	Coarse-Grained Aggregate/Soil; Improved Soil
A	6	SH-21 Widening Project; Caldwell, Texas	Subgrade	High Plasticity Fine-Grained Soil with Gravel
B	7	US-47 Widening Project; St. Clair, Missouri	HMA	Coarse-Graded Base Mixture
			HMA	Fine-Graded Wearing Surface
B	8	I-75 Rehabilitation Project, Rubblization; Saginaw, Michigan	HMA	Dense-Graded Binder Mixture; Type 3C
B	9	US-2 New Construction; North Dakota	HMA	Coarse-Graded Base Mix; PG58-28
			Granular Base	Crushed Gravel with Surface Treatment; Class 5
			Embankment	Soil-Aggregate Mixture
B	10	US-53 New Construction; Toledo, Ohio	HMA	Coarse-Graded Binder Mixture
			Granular Base	Crushed Aggregate; Type 304
B	11	I-20 Overlay; Odessa, Texas	HMA	Coarse-Graded Mixture; CMHB
B	12	County Road 103; Pecos, Texas	Granular Base	Caliche, Aggregate Base
B	13	NCAT; Alabama Overlay, Section E-5, Opelika, Alabama	HMA	Wearing Surface with 45% RAP; PG67, no modifiers used.
		NCAT; Alabama Overlay, Section E-6, Opelika, Alabama	HMA	Wearing Surface with 45% RAP; PG76 with SBS.
		NCAT; Alabama Overlay, Section E-7, Opelika, Alabama	HMA	Wearing Surface with 45% RAP; PG76 with Sasobit.
B	14	NCAT; Florida; Structural Test Sections N-1 & N-2	HMA	PMA Mixture with SBS; PG76
			HMA	Neat Asphalt Binder Mix; PG67
			Granular Base	Limerock Base
B	15	NCAT; Missouri; Structural Test Section N-10	HMA	Polymer Modified Asphalt Mix; PG76 (SBS)
			HMA	Neat Asphalt Binder Mix; PG64
			Granular Base	Crushed Limestone
B	16	NCAT; Oklahoma; Structural Test Sections N-8 & N-9	Subgrade Soil	High Plasticity Clay with Chert Aggregate
B	17	NCAT; Alabama; Structural Test Section S-11	HMA	Coarse-Graded Base Mix; PG67; Limestone
			Granular Base	Crushed Granite Base

CMHB – Coarse Matrix, High Binder Content (mixture type term used by the Texas DOT specifications)
PG – Performance Grade
PMA – Polymer Modified Asphalt
RAP – Recycled Asphalt Pavement

Field Evaluation of NDT Devices

Identifying Anomalies and Physical Differences

A standard t-test and the Student-Newman-Keuls (SNK) mean separation procedure using a 95 percent confidence level were used to determine whether the areas with anomalies or physical differences were significantly different from the other areas tested. Table 7 lists identification of the physical differences of the unbound and HMA layers within a project. The DSPA and GeoGauge are considered acceptable in identifying localized differences in the physical condition of unbound materials, while the PSPA and PQI were considered acceptable for the HMA layers.

Table 4. Construction defects exhibited on some of the field evaluation projects.

Unbound Materials and Layers; Embankments	
All projects	No construction defect was observed in any of the Parts A and B projects. As listed in Table 5, however, there were differences in the condition of the base materials and embankments that were planned to ensure that the NDT devices would identify those differences.
HMA Mixtures	
• US-280 HMA Base	Truck-to-truck segregation observed in some areas. Cores were taken in these areas, but some of the cores disintegrated during the wet coring process. In addition, a significant difference in dynamic modulus was found between the initial and supplemental sections included in the test program. The supplemental section was found to have much higher dynamic modulus values. This difference was not planned.
• I-85 SMA Overlay	No defects noted.
• TH-23 HMA Base	No defects noted.
• SH-130 HMA Base	No defects noted during the time of testing, but there was controversy on the mixture because it had been exhibiting checking during the compaction process. Changes were made to the mixture during production. The change made and the time that the change was made were unclear relative to the time of the NDT evaluation.
• US-47 HMA Base	The mixture was tender; and shoved under the rollers.
• US-47 Wearing Surface	Portions of this mixture were rejected by the agency in other areas of the project.
• I-75 HMA Base, Type 3-C	No defects noted, but mixture placed along the shoulder was tender.
• I-75 HMA, Type E3 & E10	No defects noted, but portions of this mixture were rejected by the agency in other areas of the project.
• US-2 HMA Base	Checking and mat tears observed under the rollers.
• US-53 HMA Base	No defects noted.
• I-20 HMA CHMB Base	No defects noted.
• NCAT – Alabama HMA RAP; with & without modifiers	No defects noted on any of the test sections.
• NCAT – South Carolina HMA Base	No defects noted.
• NCAT – Missouri HMA Base	No defects noted.
• NCAT Florida – PMA Base	No defects noted.
• NCAT Florida – HMA Base, no modification	Checking and mat tears observed under the rollers.

Estimating Laboratory Measured Moduli

Laboratory measured modulus of a material is an input parameter for all layers in mechanistic-empirical (M-E) pavement structural design procedures, including the MEPDG. Resilient modulus is the input for unbound layers and soils, while the dynamic modulus is used for all HMA layers. The values determined by each NDT modulus estimating device (DCP, DSPA, PSPA, GeoGauge, and deflection-based devices) were compared to the moduli measured in the laboratory on test specimens compacted to the density of the in-place layer. Different stress states were used for determining the resilient modulus of unbound layers, while different frequencies at the in-place mat temperature were used to determine the dynamic modulus of the HMA layers.

None of the NDT devices accurately predicted the modulus values that were measured in the laboratory for the unbound materials and HMA mixtures. However, all of the modulus estimating NDT devices did show a trend of increasing moduli with increasing laboratory measured moduli.

Table 5. Physical differences in the unbound materials and soils placed along some of the projects.

Project Identification	Unbound Sections	Description of Differences Along Project
SH-21 Subgrade, High Plasticity Clay; Caldwell, Texas	Area 2, No IC Rolling	No planned difference between the points tested.
	Area 1, With IC Rolling	With intelligent compaction (IC) rolling, the average density should increase; lane C received more roller passes.
I-85 Embankment, Low Plasticity Clay; Auburn, Alabama	Lane A of Sections 1 & 2	Prior to IC rolling, Lane A (which is further from I-85) had thicker lifts & a lower density.
	All Sections	After IC rolling, the average density should increase & the variability of density measurements should decrease.
TH-23 Embankment, Silt-Sand-Gravel Mix; Spicer, Minnesota	South Section – Lane C	Construction equipment had disturbed this area. In addition, QA records indicate that this area has a lower density—prior to final acceptance.
	North Section – Lane A	Area with the higher density and lower water content—a stronger area.
SH-130, Improved Embankment, Granular; Georgetown, Texas	All Sections	No planned differences between the areas tested.
TH-23, Crushed Aggregate Base; Spicer, Minnesota	Section 2 (Middle Section) – Lane C	Curb and gutter section; lane C was wetter than the other two lanes because of trapped water along the curb from previous rains. The water extended into the underlying layers.
	Section 1 (South Section) – Lane A	Area with a higher density and lower moisture content; a stronger area.
US-280, Crushed Stone Base; Opelika, Alabama	Section 4	Records indicate that this area was placed with higher water content and is less dense. It is also in an area where water (from previous rains) accumulated.

Table 6. Different physical conditions (localized anomalies) of the HMA mixtures placed along projects within Part A.

Project Identification	HMA Sections	Description of Differences Along the Project
TH-23 HMA Base; Spicer, Minnesota	Section 2, Middle or Northeast Section	QA records indicate lower asphalt content in this area—asphalt content was still within the specifications, but consistently below target value.
I-85 SMA Overlay; Auburn, Alabama	Section 2, Middle; All lanes	QA records indicate higher asphalt content in this area, but it was still within the specifications.
	Lane C, All Sections	This part or lane was the last area rolled using the rolling pattern set by the contractor, and was adjacent to the traffic lane. Densities lower within this area.
US-280 HMA Base Mixture; Opelika, Alabama	Initial Test Sections, defined as A; Section 2, All Lanes	Segregation identified in localized areas. In addition, QA records indicate lower asphalt content in this area of the project. Densities lower within this area.
	Supplemental Test Sections near crushed stone base sections, defined as B.	Segregation observed in limited areas.
	IC Roller Compaction Effort Section, Defined as C.	Higher compaction effort was used along Lane C.
SH-130 HMA Base Mixture; Georgetown, Texas	All Sections	No differences between the different sections tested.

Table 7. Success rates of the NDT devices for identifying physical differences or anomalies.

NDT Gauges Included in Field Evaluation		Success Rates, %	
		Unbound Layers	HMA Layers
Ultrasonic	DSPA & PSPA	86	93
Steady-State Vibratory	GeoGauge	79	---
Impact/Penetration	DCP	64	---
Deflection-Based	LWD & FWD	64	56
Non-Nuclear Density	EDG & PQI	25	71
GPR	Single Air-Horn Antenna	33	54

To compensate for differences between the laboratory and field conditions, an adjustment procedure was used to estimate the laboratory resilient modulus from the different NDT technologies for making relative comparisons. The adjustment procedure assumes that the NDT response and modulus of laboratory prepared test specimens are directly related and proportional to changes in density and water content of the material. In other words, the adjustment factors are independent of the volumetric properties of the material.

Table 8 lists the adjustment ratios for the unbound layers included in the field evaluation (Parts A and B), while Table 9 contains the ratios for the HMA layers. The adjustment ratios

Table 8. Unbound layer adjustment ratios applied to the NDT moduli to represent laboratory conditions or values at low stress states.

Project Identification		Resilient Moduli, ksi		Adjustment Ratios Relating Laboratory Moduli to NDT Values			
		Laboratory Measured Value	Predicted with LTPP Equations	Geo Gauge	DSPA	DCP	LWD
Fine-Grained Clay Soils							
I-85 Low-Plastic Soil	Before IC Rolling	2.5	10.5	0.154	.0751	0.446	0.39
	After IC Rolling	4.0	13.1	0.223	0.113	0.606	0.39
NCAT; OK	High Plastic Clay	6.9	19.7	0.266	0.166	0.802	---
SH-21, TX	High Plastic Clay	26.8	19.6	1.170	0.989	3.045	2.78
Average Ratios for Fine-Grained Clay Soils				**0.454**	**0.336**	**1.225**	
Embankment Materials; Soil-Aggregate Mixtures							
TH-23, MN	South Embankment	16.0	15.7	0.696	0.367	1.053	3.13
	North Embankment	16.4	16.3	0.735	0.459	0.863	3.13
US-2, ND	Embankment	19.0	19.5	1.450	0.574	0.856	---
SH-130, TX	Improved Soil	35.3	21.9	1.337	1.029	1.657	1.43
Average Ratios for Soil-Aggregate Mixtures; Embankments				**1.055**	**0.607**	**1.107**	
Aggregate Base Materials							
Co. 103, TX	Caliche Base	---	32.3	1.214	---	1.436	---
NCAT, SC	Crushed Granite	14.3	36.1	0.947	0.156	---	---
NCAT, MO	Crushed Limestone	19.2	40.9	0.747	0.198	---	---
TH-23, MN	Crushed Stone, Middle	24.0	29.9	0.851	0.303	0.725	1.69
	Crushed Stone, South	26.0	35.6	0.788	0.235	0.560	1.69
US-53, OH	Crushed Stone	27.5	38.3	1.170	0.449	0.862	---
NCAT, FL	Limerock	28.6	28.1	0.574	0.324	0.619	---
US-2, ND	Crushed Aggregate	32.4	39.8	1.884	0.623	1.129	---
US-280, AL	Crushed Stone	48.4	49.3	1.010	0.244	0.962	1.04
Average Ratios for Aggregate Base Materials				**1.021**	**0.316**	**0.899**	
Overall Average Ratios for Processed Materials				**0.942**	**0.422**	**1.084**	

NOTES:

1. The adjustment ratio is determined by dividing the resilient modulus measured in the laboratory at a specific stress state by the NDT estimated modulus.
2. The overall average values listed above exclude those for the fine-grained clay soils.

Table 9. HMA layer adjustment ratios applied to NDT modulus values to represent laboratory conditions.

Project/Mixture	Dynamic Modulus, ksi	Ratio or Adjustment Factor	
		PSPA	FWD
I-85 AL, SMA Overlay	250	1.055	0.556
TH-23 MN, HMA Base	810	1.688	NA
US-280 AL, HMA Base; Initial Area	650	1.407	3.939
US-280 AL, HMA Base; Supplemental Area	780	1.398	2.516
I-35/SH-130 TX, HMA Base	1,750	5.117	3.253
I-75 MI, Dense-Graded Type 3-C	400	0.919	NA
I-75 MI, Dense-Graded Type E-10	590	0.756	NA
US-47 MO, Fine-Graded Surface	530	1.158	NA
US-47 MO, Coarse-Graded Base Mix	420	0.694	NA
I-20 TX, HMA Base, CMHB	340	0.799	NA
US-53 OH, Coarse-Graded Base	850	1.275	NA
US-2 ND, Coarse-Graded Base, PG58-28	510	1.482	NA
NCAT AL, PG67 Base Mix	410	0.828	NA
NCAT FL, PG67 Base Mix	390	0.872	NA
NCAT FL, PG76 Base Mix	590	1.240	NA
NCAT AL, PG76 with RAP and Sasobit	610	1.3760	NA
NCAT AL, PG76 with RAP and SBS	640	1.352	NA
NCAT AL, PG67 with RAP	450	0.881	NA
	Overall Average Ratio	**1.128**	**2.566**

NOTES:
1. The adjustment factor or ratio was determined by dividing the dynamic modulus measured in the laboratory for the in-place temperature and at a loading frequency of 5 Hz by the modulus estimated with the NDT device.
2. The laboratory dynamic modulus values listed above are for a test temperature of a loading frequency of 5 Hz at the temperature of the mixture when the NDT was performed.
3. The overall average adjustment factor excludes the SH-130 mixture because it was found to be significantly different than any other mixture tested in the laboratory; which has been shaded.

were determined for the areas without any anomalies or physical differences from the target properties.

- **Unbound Layers.** The GeoGauge and DCP provided a reasonable estimate of the laboratory measured values (average ratios near unity), with the exception of the fine-grained, clay soils. The GeoGauge deviated significantly from the laboratory values for the fine-grained soils. The results also show that both the GeoGauge and DCP over predicted or under predicted the laboratory measured values for the same material, with few exceptions.
- **HMA Layers.** The PSPA average adjustment ratios were found to be relatively close to unity, with the exception of the I-35/SH-130 HMA base mixture. Conversely, the FWD adjustment ratios were significantly different from unity. The FWD over estimated the stone matrix asphalt (SMA) modulus for the overlay project and under estimated the HMA base modulus for the reconstruction projects—suggesting that the calculated values from the deflection basins are being influenced by the supporting materials.

Accuracy and Precision of Different NDT Devices

Tables 10 through 12 summarize the statistical analyses of the NDT devices included in the field evaluation projects for unbound fine-grained soils, unbound processed materials, and HMA mixtures, respectively. This information is grouped into two areas—those NDT devices with an acceptable to excellent success rate and those with poor success rates in identifying material/layer differences.

Summary of Evaluations

The steady-state vibratory (GeoGauge) and ultrasonic (DSPA) are the two technologies suggested for use in judging the quality of unbound layers, while the ultrasonic (PSPA) and

Table 10. NDT device and technology variability analysis for the fine-grained clay soils.

Material Property		NDT Devices	Statistical Value		
			Standard Error	95% Precision Tolerance	Pooled Standard Deviation
NDT Devices with Good Success Rates Based on Modulus or Volumetric Properties					
Structural Properties	Modulus, ksi	GeoGauge	**2.5**	**4.9**	**1.1**
		DSPA	**4.5**	**8.8**	**1.2**
	Thickness, in.	None	NA	NA	NA
Volumetric Properties	Density, pcf	None	NA	NA	NA
	Air Voids, %	None	NA	NA	NA
	Fluids Content, %	None	NA	NA	NA
NDT Devices with Poor (or Undefined) Success Rates Based on Modulus or Volumetric Properties					
Structural Properties	Modulus, ksi	DCP	**3.8**	**7.4**	**1.9**
		LWD/FWD	**5.9**	**11.6**	**2.0**
	Thickness, in.	GPR, single antenna	NA	NA	NA
Volumetric Properties	Density, pcf	GPR, single antenna	---	---	4.2
		EDG	**0.8**	**1.6**	**0.7**
	Water Content, %	EDG	**0.2**	**0.4**	**0.5**

Table 11. NDT device and technology variability analysis for the processed materials and aggregate base materials.

Material Property		NDT Devices	Statistical Value		
			Standard Error	95% Precision Tolerance	Pooled Standard Deviation
NDT Devices with Good Success Rates Based on Modulus or Volumetric Properties					
Structural Properties	Modulus, ksi	GeoGauge	**2.5**	**4.9**	**1.8**
		DSPA	**4.5**	**8.8**	**1.5**
	Thickness, in.	None	NA	NA	NA
Volumetric Properties	Density, pcf	None	NA	NA	NA
	Air Voids, %	None	NA	NA	NA
	Fluids Content, %	None	NA	NA	NA
NDT Devices with Poor (or Undefined) Success Rates Based on Modulus or Volumetric Properties					
Structural Properties	Modulus, ksi	DCP	**3.8**	**7.4**	**5.3**
		LWD/FWD	**5.9**	**11.6**	**2.0**
	Thickness, in.	GPR, single antenna	**0.80**	**1.5**	**0.6**
Volumetric Properties	Density, pcf	GPR, single antenna	**3.4**	**6.7**	**3.0**
		EDG	**1.0**	**2.0**	**0.8**
	Water Content, %	EDG	**0.2**	**0.4**	**0.6**

Table 12. NDT device and technology variability analysis for the HMA mixtures.

Material Property		NDT Devices	Statistical Value		
			Standard Error	95% Precision Tolerance	Pooled Standard Deviation
NDT Devices with Good Success Rates Based on Modulus or Volumetric Properties					
Structural Properties	Modulus, ksi	PSPA	**76**	**150**	**56**
Volumetric Properties	Density, pcf	PQI & PT	**1.7**	**3.4**	**2.5**
	Air Voids, %	None	NA	NA	NA
	Fluids Content, %	None	NA	NA	NA
NDT Devices with Poor (or Undefined) Success Rates Based on Modulus or Volumetric Properties					
Structural Properties	Modulus, ksi	FWD	**87**	**170.5**	**55**
	Thickness, in.	GPR, single antenna	**0.25**	**0.49**	**0.3**
		GPR, multiple antenna	**0.27**	**0.55**	**---**
Volumetric Properties	Density, pcf	GPR, multiple antenna	**1.6**	**3.1**	**---**
	Asphalt Content, %	GPR, multiple antenna	**0.18**	**0.36**	**---**
	Air Voids, %	GPR, single antenna	**0.40**	**0.8**	**2.1**
		GPR, multiple antenna	**0.22**	**0.4**	**---**

non-nuclear density gauges (the PaveTracker was used in Part B) are the technologies suggested for use of HMA layers. The GPR is suggested for layer thickness acceptance, while the IC rollers are suggested for use on a control basis for compacting unbound and HMA layers.

NDT Devices for Unbound Layers and Materials

- The DSPA and GeoGauge devices had the highest success rates for identifying an area with anomalies, with rates of 86 and 79 percent, respectively. The DCP and LWD identified about two-thirds of the anomalies, while the GPR and EDG had unacceptable rates below 50 percent.
- Three to five repeat measurements were made at each test point with the NDT devices, with the exception of the DCP.
  - The LWD exhibited low standard deviations that were less dependent on material stiffness with a pooled standard deviation less than 0.5 ksi. One reason for the low values is that the moduli were less than for the other devices. The coefficient of variation (COV), an estimate of the normalized dispersion, however, was higher. It is expected that the supporting layers had an effect on the results.
  - The GeoGauge had a standard deviation for repeatability measurements varying from 0.3 to 3.5 ksi. This value was found to be material dependent.
  - The DSPA had the lowest repeatability, with a standard deviation varying from 1.5 to 21.5 ksi. The reason for this higher variation in repeat readings is that the DSPA sensor bar was rotated relative to the direction of the roller, while the other devices were kept stationary or did not have the capability to detect anisotropic conditions. No significant difference was found relative to the direction of testing for fine-grained soils, but there was a slight bias for the stiffer coarse-grained materials.
  - The EDG was highly repeatable with a standard deviation in density measurements less than 1 pcf, while the GPR had poor repeatability based on point measurements. Triplicate runs of the GPR were made over the same area or sublot. For comparison to the other NDT devices, the values measured at a specific point, as close as possible, were used. Use of point specific values from successive runs could be a reason for the lower repeatability, which are probably driver specific. One driver was used for all testing with the GPR.
- The COV was used to compare the normalized dispersion measured with different NDT devices. The EDG consistently had the lowest COV with values less than 1 percent. The GeoGauge had a value of 15 percent, followed by the DSPA, LWD, DCP, and GPR. The GPR and EDG are dependent on the accuracy of other tests in estimating volumetric properties (density and moisture contents). Any error in the calibration of these devices for the specific material is directly reflected in the resulting values, which probably explains why the GPR and EDG devices did not consistently identify the areas with anomalies or physical differences.
- Repeated load resilient modulus tests were performed in the laboratory for characterizing and determining the target resilient modulus for each material. Adjustment ratios were determined based on uniform conditions. The overall average ratio for the GeoGauge for the stiffer coarse-grained materials was near unity (1.05). For the fine-grained, less stiff soils, the ratio was about 0.5. After adjusting for laboratory conditions, all NDT devices that estimate resilient modulus resulted in low residuals (laboratory resilient modulus minus the NDT elastic modulus). However, the GeoGauge and DCP resulted in the lowest standard error. The LWD had the highest residuals and standard error.
- The DSPA and DCP measured responses represent the specific material being tested. The DCP, however, can be affected significantly by the varying amounts of aggregate particles in fine-grained soils and the size of the aggregate in coarse-grained soils. The GeoGauge measured responses are minimally affected by the supporting materials, while the LWD can be significantly affected by the supporting materials and thickness of the layer being tested. Thickness

deviations and variable supporting layers are reasons for LWD's low success rate in identifying areas with anomalies or physical differences.

- No good or reasonable correlation was found between the NDT devices that estimate modulus and those devices that estimate volumetric properties.
- Instrumented rollers were used on too few projects for a detailed comparison to the other NDT devices. The rollers were used to monitor the increase in density and stiffness with increasing number of roller passes. One potential disadvantage with these rollers is that they may bridge localized soft areas. However, based on the results obtained, their ability of provide uniform compaction was verified and these rollers are believed to be worth future investment in monitoring the compaction of unbound materials.
- The GPR resulted in reasonably accurate estimates to the thickness of aggregate base layers. None of the other NDT devices had the capability or same accuracy to determine the thickness of the unbound layer.

NDT Devices for HMA Layers and Mixtures

- The PSPA had the highest success rate for identifying an area with anomalies with a rate of 93 percent. The PQI identified about three-fourths of the anomalies, while the FWD and GPR identified about one-half of those areas. The seismic and non-nuclear gauges were the only technologies that consistently identified differences between the areas with and without segregation. These two technologies also consistently found differences between the longitudinal joint and interior of the mat.
- The non-nuclear density gauge (PaveTracker) was able to identify and measure the detrimental effect of rolling the HMA mat within the temperature sensitive zone. This technology was beneficial on some of the Part B projects to optimize the rolling pattern initially used by the contractor.
- Three to four repeat measurements were made at each test point with the NDT devices.
  - The PSPA had a repeatability value, a median or pooled standard deviation, of about 30 ksi for most mixtures, with the exception of the US-280 supplemental mixture that was much higher.
  - The FWD resulted in a comparable value for the SMA mixture (55 ksi), but a higher value for the US-280 mixture (275 ksi).
  - The non-nuclear density gauges had repeatability values similar to nuclear density gauges with a value less than 1.5 pcf.
  - The repeatability for the GPR device was found to be good and repeatable, with a value of 0.5 percent for air voids and 0.05 inches for thickness.
- The PSPA moduli were comparable to the dynamic moduli measured in the laboratory on test specimens compacted to the in-place density at a loading frequency of 5 Hz and the in-place mixture temperature, with the exception of one mixture—the US-280 supplemental mixture. In fact, the overall average ratio or adjustment factor for the PSPA was close to unity (1.1). This was not the case for the FWD. Without making any corrections for volumetric differences to the laboratory dynamic modulus values, the standard error for the PSPA was 76 ksi (laboratory values assumed to be the target values). The PSPA was used on HMA surfaces after compaction and the day following placement. The PSPA modulus values measured immediately following compaction were found to be similar to the values one or two days after placement—when making proper temperature corrections in accordance with the master curves measured in the laboratory.
- A measure of the mixture density or air voids is required in judging the acceptability of the modulus value from a durability standpoint. The non-nuclear gauges were found to be acceptable, assuming that the gauges have been properly calibrated to the specific mixture—as for the PSPA.

- Use of the GPR single antenna method, even with mixture calibration, requires assumptions that specific volumetric properties do vary along a project. As the mixture properties change, the dielectric values may or may not be affected. Use of the proprietary GPR analysis method on other projects was found to be acceptable for the air void or relative compaction method. This proprietary and multiple antenna system, however, was not used within Part A of the field evaluation to determine its success rate in identifying localized anomalies and physical differences between different areas. Both GPR systems were found to be very good for measuring layer thickness along the roadway.
- Water can have a definite effect on the HMA density measured with the non-nuclear density gauges (PQI). The manufacturer's recommendation is to measure the density immediately after compaction, prior to allowing any traffic on the HMA surface. Within this project, the effect of water was observed on the PQI readings, as compared to dry surfaces. The measured density of wet surfaces did increase compared to dry surfaces. From the limited testing completed with wet and dry surfaces, the PaveTracker was less affected by surface condition. However, wet versus dry surfaces was not included in the field evaluation plan for different devices. Based on the data collected within the field evaluation, wet surfaces did result in a bias of the density measurements with this technology.
- Another important condition is the effect of time and varying water content on the properties of the HMA mixture during construction. There have been various studies completed using the PSPA to detect stripping and moisture damage in HMA mixtures. For example, Hammons et al. (2005) recently used the PSPA (in combination with GPR) to successfully locate areas with stripping along selected interstate highways in Georgia. The testing completed within this study also supports the use of ultrasonic-based technology to identify such anomalies.
- The instrumented rollers used to establish the increase in stiffness with number of passes was correlated to the increases in density, as measured by different devices. These rollers were used on limited projects to develop or confirm any correlation between the NDT response and the instrumented roller's response. One issue that will need to be addressed is the effect of decreasing temperature on the stiffness of the mixture and how the IC roller perceives that increase in stiffness related to increases in density of the mat and a decrease in mat temperature as it cools. A potential disadvantage with these rollers is that they will bridge segregated areas and may not accurately identify cold spots in the HMA mat. However, based on the results obtained, the ability to provide uniform compaction was verified and the rollers are believed to be worth future investments in monitoring the compaction of HMA mixtures.

Limitations and Boundary Conditions

- All NDT devices suggested for QA application, with the exception of the GPR and IC rollers, are point specific tests. Point specific tests are considered a limitation because of the number of samples that would be required to identify localized anomalies that deviate from the population.
  - Ultrasonic scanners are currently under development so that relatively continuous measurements can be made with this technology. These scanners are still considered in the research and development stage and are not ready for immediate and practical use in a QA program.
  - GPR technology to estimate the volumetric properties of HMA mixtures is available for use on a commercial basis, but the proprietary system has only had limited verification of its potential use in QA applications and validation of all volumetric properties determined with the system.
  - Similarly, the IC rollers take continuous measurements of density or stiffness of the material being compacted. During the field evaluation, some of these rollers had both hardware and

software problems. Thus, these devices were not considered immediately ready for use in a day-to-day QA program. The equipment, however, has been improved and its reliability has increased. The technology is suggested for use on a control basis but not for acceptance.

- Ultrasonic technology (PSPA) for HMA layers and materials; suggested for use in control and acceptance plans.
  - Test temperature is the main boundary condition for the use of the PSPA. Elevated temperatures during mix placement can result in erratic response measurements. Thus, the gauge may not provide reliable responses to monitor the compaction of HMA layers or define when the rollers are operating within the temperature sensitive zone for the specific mixture.
  - These gauges need to be calibrated to the specific mixture being tested. However, this technology can be used in the laboratory to measure the seismic modulus on test specimens during mixture design or verification prior to measuring the dynamic modulus in the laboratory.
  - A limitation of this technology is that the results (material moduli) do not provide an indication on the durability of the HMA mixture. Density or air void measurements are needed to define durability estimates.
  - The DSPA for testing unbound layers is influenced by the condition of the surface. High modulus values near the surface of the layer will increase the modulus estimated with the DSPA. Thus, the DSPA also needs to be calibrated to the specific material being evaluated.
- Steady-state vibratory technology (GeoGauge) for unbound layers and materials; suggested for use in control and acceptance plans.
  - This technology or device should be used with caution when testing fine-grained soils at high water contents. In addition, it should not be used to test well-graded, non-cohesive sands that are dry (i.e., well below the optimum water content).
  - The condition of the surface of the layer is important and should be free of loose particles. A layer of moist sand should also be placed underneath the gauge to fill the surface voids and ensure that the gauge's ring is in contact with about 75 percent of the material's surface. Placement of this thin, moist layer of sand takes time and does increase the time needed for testing.
  - These gauges need to be calibrated to the specific material being evaluated and are influenced by the underlying layer when testing layers that are less than 8 in. thick.
  - These gauges are not applicable for use in the laboratory during the development of moisture-density (M-D) relationships that are used for monitoring compaction. The DSPA technology is applicable for laboratory use to test the samples used to determine the M-D relationship.
  - A relative calibration process is available for use on a day-to-day basis. However, if the gauge does go out of calibration, then it must be returned to the manufacturer for internal adjustments and calibration.
  - These gauges do not determine the density and water content of the material. Alternate devices are necessary to measure the water content and density of the unbound layer.
- Non-nuclear density gauges (electric technology) for HMA layers and materials; suggested for use in control and acceptance plans.
  - Results from these gauges can depend on the condition of the layer's surface—wet versus dry. It is recommended that the gauges be used on relatively dry surfaces until additional data become available pertaining to this limitation. Free water should be removed from the surface to minimize any effect on the density readings. However, water penetrating the surface voids in segregated areas will probably affect the readings (i.e., incorrect or high density compared to actual density from a core). The PSPA was able to identify areas with segregation.
  - These gauges need to be calibrated to the specific material under evaluation.

- GPR technology for thickness determination of HMA and unbound layers; suggested for use in acceptance plans.
  - The data analysis or interpretation is a limitation of this technology. The GPR data require some processing time to estimate the material property. The time for layer thickness estimates is much less than for other layer properties.
  - This technology requires the use of cores for calibration purposes. Cores need to be taken periodically to confirm the calibration factors used to estimate the properties.
  - Use of this technology, even to estimate layer thickness, should be used with caution when measuring the thickness of the first lift placed above permeable asphalt treated base (PATB) layers.
  - GPR can be used to estimate the volumetric properties of HMA mats, but that technology has yet to be verified on a global basis.
  - Measurements using this technology cannot be calibrated using laboratory data.
- IC rollers; suggested for use in a control plan, but not within an acceptance plan.
  - The instrumented rollers may not identify localized anomalies in the layer being evaluated. These rollers can bridge some defects (may have insufficient sensitivity to identify defects that are confined to local areas).
  - Temperature is considered an issue with the use of IC rollers for compacting HMA layers. Although most IC rollers measure the surface temperature of the mat, the effect of temperature on the mat stiffness is an issue—as temperature decreases the mat stiffness will increase, not necessarily because of an increase in density of the mat. Delaying the compaction would increase the stiffness of the mat measured under the rollers because of the decrease in temperature.
  - The instrumented rollers also did not properly indicate when checking and tearing of the mat occurred during rolling. The non-nuclear density gauges (PaveTracker) successfully identified this detrimental condition.
  - Measurements using this technology and associated devices cannot be calibrated using laboratory data.

Conclusions

Unbound Layers and Materials

- The GeoGauge is a self-contained NDT device that can be readily incorporated into a QA program for both control and acceptance testing. This conclusion is based on the following reasons:
  - It provides an immediate measure of the resilient modulus of the in-place unbound material.
  - It identified those areas with anomalies at an acceptable success rate (second only to the DSPA).
  - It adequately ranked the relative order of increasing strength or stiffness of the unbound materials.
  - It provided resilient modulus values that were correlated to the dry density over a diverse range of material types.
  - The normalized dispersion is less than for the other NDT devices that provide an estimate of stiffness.
  - The training and technical requirements for this technology are no different than what is required when using a nuclear density gauge.

  Two disadvantages of using this device in a QA program are (1) the need for measuring the water content and density using other methods, which is also the case for the DSPA and other modulus estimating devices and (2) the need to calibrate the test results to the material and site conditions under evaluation. The latter is the more important issue and is discussed in more detail.

The GeoGauge should be calibrated to the project materials and conditions to improve on its accuracy, especially when testing fine-grained soils. This calibration issue requires that laboratory repeated load resilient modulus tests be performed on each unbound layer for judging the quality of construction. Most agencies do not routinely perform resilient modulus tests for design. Eliminating the laboratory resilient modulus tests from the calibration procedure will reduce its accuracy for confirming the design values, but not for identifying construction defects. For those agencies that do not have access to or the capability to perform resilient modulus tests, use of the FHWA-LTPP regression equations is an option that can be used to calculate the target resilient modulus at the beginning of construction. The target resilient modulus should be the value used in structural design. For the MEPDG, this is the average value measured in the laboratory.

- The DSPA is also a self-contained unit that was successful in many of the areas noted for the GeoGauge. It was the device that had the highest success rate in identifying areas with different physical conditions or anomalies. An additional advantage of the DSPA is that the results can be calibrated to the specific unbound material being tested prior to construction, when the M-D relationship is measured in the laboratory. This calibration procedure allows the DSPA to be used to detect volumetric, as well as physical, changes in the materials during construction. In other words, the DSPA modulus is measured on the M-D samples prepared at different water contents and dry densities. In short, the DSPA can be used in day-to-day operations to assist contractor and agency personnel in judging construction and materials quality by itself or in tandem with other geophysical and/or ground truth sampling programs.

  Two disadvantages of the DSPA are that it consistently resulted in a higher normalized dispersion measured over a diverse range of conditions and materials, and that it requires more sophisticated training of technicians to correctly interpret the load pulse and responses to ensure that satisfactory data have been collected by the device.
- The DCP was also successful in many of the areas noted for the GeoGauge. However, testing takes much more time, especially for stiff materials and layers with large aggregate. In addition, the test results were found to be more dependent on aggregate size than the other NDT devices. The normalized dispersion was also found to be much higher than for the DSPA and GeoGauge.

  Conversely, the DCP does have the capability to readily estimate the strength of thicker unbound layers and can measure the modulus gradient with depth. In fact, it can be used in conjunction with the GeoGauge and DSPA in adjusting the modulus values from those devices to laboratory conditions for fine-grained soils for agencies that do not have resilient modulus testing capability in the laboratory. Use of the DCP can be considered an option in adjusting the test results for the GeoGauge for those agencies that have no plans to incorporate a resilient modulus testing capability within their design or materials departments.
- The GPR (single antenna method) was found to have a poor success rate in identifying anomalies. It did not provide a measure of modulus or strength of material. In addition, using the single antenna method requires that either the density or water content be assumed and the other parameter calculated. Both vary along the project, resulting in higher variations of the property being calculated. Using an inaccurate value can lead to an incorrect finding. For example, the GPR found some of the areas tested to have the highest density, while most other NDT devices found that area to be the softest and least dense. It was successful, however, in measuring the layer thickness of the unbound materials.

  Two other disadvantages of this system are in the training requirements for using this technology and the need to calibrate the dielectric values to physical properties of the in-place

material. Samples need to be recovered and tested to determine the water contents and densities of those areas prior to using the results for QC or acceptance. This requires that control strips be used prior to construction, and these calibration factors should be checked periodically during construction. Many agencies are not requiring control strips, or the first day of construction is the control strip. Training is another issue; this system requires more sophisticated training for the operator to interpret the measurements taken with the GPR. Thus, with its current limitations, it is not suggested for future use in testing unbound materials to determine the quality characteristics of the in-place material. However, it is suggested that research with the GPR continue because of its continuous coverage and speed of data collection.
- Similar to the GPR, the EDG was found to have a poor success rate in identifying areas with anomalies. However, this device is believed to have potential to provide volumetric data on the unbound materials for use in a QA program with continued use. The density estimated from this device is definitely related to resilient modulus across a wide range of unbound materials. However, further improvements in the measurements will require a program to obtain additional data. The variability of the water contents measured with this device was found to be very low. Other agencies are beginning to use this device in their research programs. For example, Texas and Nevada have ongoing programs that could provide improvements to the equipment and procedures in the near future. As a result, further detailed evaluation of this device and technology to improve its accuracy are warranted.
- The deflection-based methods (LWD and FWD) were found to have limited potential for QC purposes. The LWD devices have greater mobility than the FWD, which is an advantage for their use over the FWD. These devices have more potential for use in acceptance programs of the final structure and certainly in forensic areas for evaluating the interaction between the pavement layers and foundation. The following summarizes the conclusions reached on these devices:
  - Technology was unable to consistently identify those areas with anomalies.
  - The modulus values can be influenced by the underlying layers, resulting in lower or higher and more variable modulus values.
  - The normalized dispersion was found to be high, relative to the other NDT devices.
  - The relationship between modulus from this technology and dry density was poor.
  - Any error in thickness of the layer being tested can result in large errors and more variability that could lead to wrong decisions being made by the contractor and agency about the construction operation.

HMA Mixtures

- The PSPA is a self-contained NDT device that can be readily incorporated into a QA program for both control and acceptance testing of HMA mixtures. As noted for unbound materials, an advantage of this technology is that the device can be calibrated to the specific materials being tested during the mixture design stage for HMA mixtures. This calibration procedure allows the PSPA to be used to detect volumetric, as well as physical, changes in the materials during construction. In short, the PSPA can be used in day-to-day operations to assist contractor and agency personnel in judging construction and materials quality by itself or in tandem with other geophysical and/or ground truth sampling programs. This conclusion is based on the following reasons.
  - The PSPA is the NDT device found best suited for QA applications because it adequately identified all but one area with anomalies. The PSPA provides a measure of the dynamic modulus that is needed for pavement structural designs, even before adjusting the PSPA modulus for laboratory conditions. The PSPA modulus was found to be correlated to the dynamic modulus at elevated temperatures using the master curve developed from laboratory dynamic modulus tests.

  - Similar PSPA modulus values were measured at higher temperatures and corrected for temperature using a master curve in comparison to those measured in the laboratory.
  - An important condition that the NDT device needs to consider is the effect of time and varying moisture content on the properties of the HMA mixture near construction and how those properties will change in service. There have been various studies completed on using the PSPA to detect stripping in HMA mixtures. For example, the PSPA was used in combination with GPR to successfully locate areas with stripping along selected interstate highways in Georgia (Hammons et al. 2005). The test results from the NCHRP 10-65 study support a similar conclusion.

  However, the PSPA does have some limitations regarding full-scale use in QA programs. Use of the PSPA should be delayed after rolling to allow the mix to cool. Dr. Nazarian's recommendation is to delay all testing for one day after HMA placement and compaction. If required, this time restriction is considered a disadvantage for use in QA programs.

  A measure of the mixture density or air voids is also required in judging the acceptability of the modulus value or durability of the HMA mixture. The two devices that deserve further evaluation include the GPR and non-nuclear density gauges. The GPR provides full coverage in a short period of time.

- The non-nuclear density gauges are also well suited for QA because they can be readily incorporated into control programs. Some contractors are already using the non-nuclear density gauges in controlling the compaction operation. This technology was also used to identify anomalies at a reasonable rate and can be used to identify tender mixtures and the effects of rolling in the temperature sensitive zone.

  Variations in water have a definite effect on the HMA density measured with the PQI. The manufacturer's recommendation is to measure the density immediately after compaction, prior to allowing any traffic on the HMA surface. This type of time restriction is considered a disadvantage to the use of the PQI in a day-to-day practical QA program. This time effect, however, was not found within the Part A test program, but the moisture effect was observed in Part A of the field evaluation. Use of other non-nuclear density gauges (PaveTracker) did not exhibit this moisture sensitivity. However, the effect of water on these gauges was not included in the field evaluation as a primary variable. Measurements were taken after heavy rains in areas where the readings were previously taken prior to the thunderstorms. The same density values were measured after removing and drying all free water at the surface. This potential bias of free water on the surface is not considered a limitation but must be considered in taking measurements for control purposes.
- Use of the GPR technology using the single antenna method, even with mixture calibration, requires assumptions on specific volumetric properties that do vary along a project. Using the multi-antenna method is expected to improve on the measurement of the volumetric properties and identification of areas with deficiencies or anomalies. Thus, the GPR is suggested for continued research studies, especially with the multiple antenna system, which is a proprietary analysis system. The proprietary system needs additional validation prior to full-scale implementation into a QA program.
- The FWD is not suggested for use in QA programs, because this technology was unable to identify some of the anomalies. In addition, the FWD has high variation in elastic modulus values, and those values are influenced by the strength of the underlying materials and layers.

Recommendations

The research team's recommendations are based on the evaluation of NDT devices for immediate and practical use in QA programs. Thus the GeoGauge can be used for estimating the modulus of unbound layers, while the PSPA is the device suitable for use with HMA layers.

The PaveTracker can be used in establishing and confirming the rolling pattern for HMA mixtures. Other NDT devices may provide useful data for pavement and materials testing purposes. Each has its own benefits and advantages for evaluating and designing pavements.

The IC or instrumented rollers can be valuable to a contractor in terms of controlling the compaction operation. These rollers that operated without problems were used on too few projects to suggest their immediate inclusion in QA programs. Nonetheless, they can assist the contractor in optimizing the compaction of the material. Their disadvantage for HMA layers is the temperature of the mat issue. Decreases in temperature will cause the stiffness of the mat to increase. Thus, other devices still need to be used with the IC rollers for control. The use of IC rollers for acceptance is not suggested at this time.

Research with the multi-antenna GPR device and proprietary data interpretation system should not be abandoned and should be validated in future studies. This system definitely shows promise in providing the volumetric properties for HMA mixtures. The data can be collected at highway speeds, and the proprietary data interpretation system can provide results on a real-time basis. The disadvantage of this system is that it also needs field cores for calibrating the method to project specific conditions. These cores should be taken periodically to confirm the calibration factors being used in estimating the volumetric properties.

Data Interpretation and Application

The research team submitted the following chapters as Part III—Data Interpretation and Application. This part is published herein as Chapters 1, 2, and 3 of *NCHRP Report 626.* The chapters describe the physical characteristics and process for using each NDT technology and devices on construction projects to define construction quality. Each system was evaluated in two parts: (1) the system's potential to be integrated into the flexible pavement construction process (level of process impact) and (2) the reliability and accuracy of the system (system accuracy and reliability). Chapter 1 focuses on the level of process impact on construction. In other words, what impact will the device have on the contractor's progress, and will agencies need substantially more staff to use the technology? Chapters 2 and 3 focus on the system accuracy and reliability of the different technologies and devices included in the field evaluation study.

CHAPTER 1

Applicability of NDT Technologies on Construction Projects

Some NDT devices initially were operated by a representative of the manufacturer and then used by field technicians or engineers. Those devices that were found to have a reasonable success rate in identifying anomalies were used by the contractor and agency staff in their daily QA operations, in accordance with manufacturers' guidelines. Clustered tests were performed using each NDT device to determine the repeatability and accuracy of each system in evaluating its effectiveness in defining construction quality. The time and personnel requirements to perform each test were recorded. This information was considered in rating the level of impact that each device may have on construction. Since the technology was of primary interest (not a particular system or manufacturer), reports on each system are presented under the heading of the technology used by the system.

1.1 Ultrasonic—PSPA and DSPA

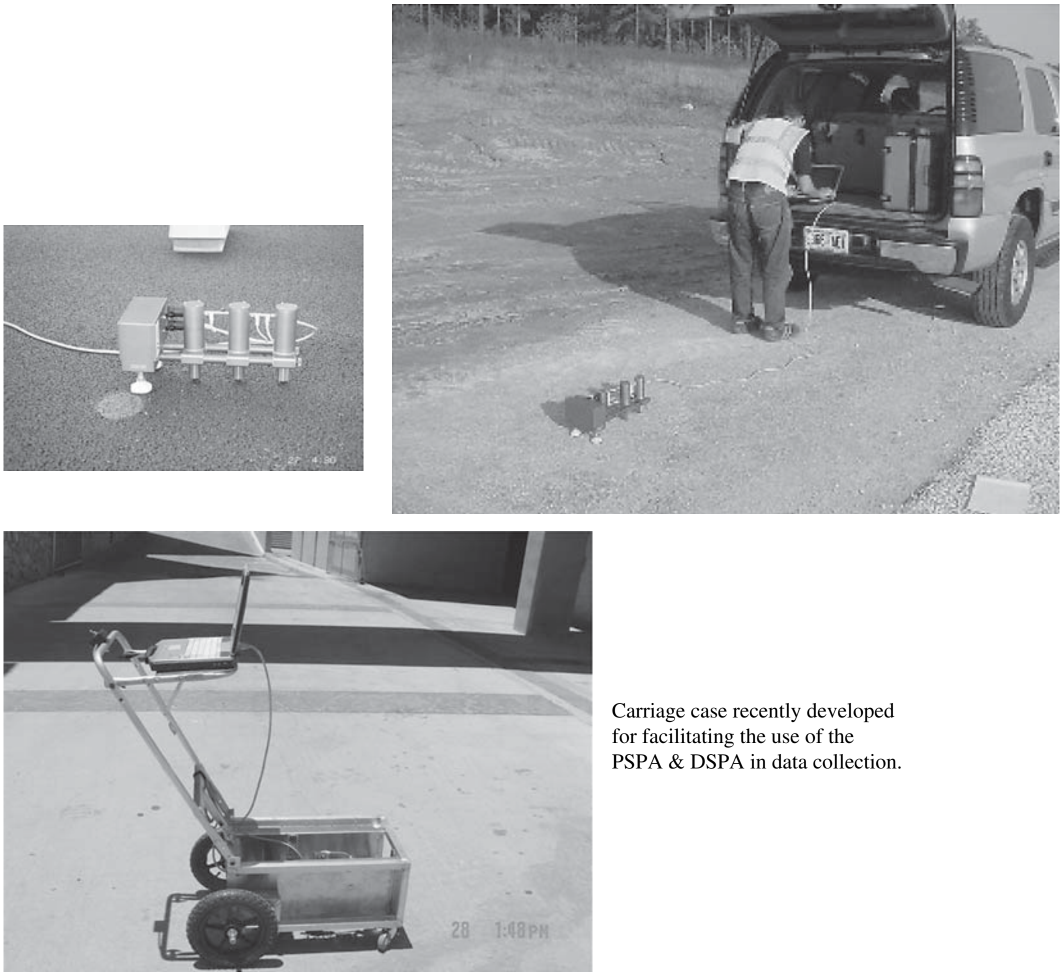
This system is applicable to HMA, unbound aggregate base, and embankment soils. The PSPA is used to test HMA, while the DSPA is used for unbound materials and soils. Both devices consist of a stand linearly connected by a stiff arm to a source and two receivers and by wire to a computer, as shown in Figure 2. The source contains a hammer which is dropped several times at regular intervals. The receivers, containing quartz-crystal accelerometers, measure the acceleration of the Rayleigh waves induced by the dropping of the hammer and report the resulting electrical charge to the data acquisition system. An FFT transforms the electrical charge or data into the frequency domain. There is also a temperature sensor in the system. Sturdiness of the laptop is an important feature.

The PSPA test can be and was performed on cold material one or multiple days after placement, as well as on surfaces at elevated temperatures immediately after compaction. The system's temperature gauge is used to incorporate the temperature into the calculation of the material's modulus. The rubber pads beneath the receivers deteriorate more rapidly when used on surfaces at elevated temperatures. In fact, they have been known to melt when used on HMA surfaces shortly after placement. The operator needs to check these periodically to ensure adequate coupling between the receivers and the surface. These pads are easily replaced.

Both devices work properly as long as all points are in firm contact (coupled) with the surface being tested. Adequate coupling is the system's primary limitation. The speed of data collection makes this technology a good candidate for QC applications, assuming that the temperature of the material is properly considered by the modulus calculation process. None of the PSPA and DSPA devices (including the laptops) used exhibited any problems. The main operational issue was inspecting and replacing the rubber pads of the receivers to ensure good contact with the surface being tested.

The data interpretation program that comes with the PSPA and DSPA devices uses this information to provide the output in the form of the mean Young's modulus to a particular depth. The spacing of the receivers determines the depth of measurement. The operator needs to be trained to visually inspect the load pulse and response data on the output screen for judging the suitability of an individual test (see Figure 3). This training is considered more sophisticated than what is required for a nuclear density gauge. The operator also needs to ensure that the spring-loaded receivers are in contact with the surface between each test. If one of the receivers gets stuck, the result will be a data anomaly or "false" reading. With proper training, the operator can easily identify false readings by viewing the shape of the load pulse and receiver response. The shapes of the load pulse and receiver response are visually displayed on the laptop screen for each reading.

The PSPA is used to test HMA mixtures, while the DSPA is used to test crushed aggregate base layers, embankments, and prepared subgrades. The DSPA was used on the shoulders of the US-280 reconstruction project instead of on the main roadway because the roadway base layer had been chip-sealed. This type of surface reduces the repeatability of the ultrasonic



Carriage case recently developed for facilitating the use of the PSPA & DSPA in data collection.

Figure 2. PSPA in operation for testing HMA layers. The DSPA is used for testing unbound layers.

device, as well as other NDT devices, because the points of the receivers and source are not always in good contact with the surface tested. Ensuring good contact with the surface being evaluated is important for both the PSPA and DSPA.

The system initially converts the readings of the load pulse and response to a seismic modulus of the material. The seismic modulus is internally adjusted to a modulus at a specific condition (temperature and load frequency for HMA). Each test location requires three to five tests for this system. Each test took 10 to 20 seconds to complete. Therefore, the entire process (3 to 5 readings at a point) takes only slightly longer than the system currently used for QC, the nuclear density gauge, which is generally set for one 60-second reading.

This system can also be used to estimate the elastic properties parallel and perpendicular to the direction of the rollers (refer to Chapters 2 and 3). Measuring the seismic properties in different directions actually increases the perceived variability of the device. The variability can be reduced slightly by always taking the readings in one direction. All other NDT devices result in an average or equivalent value at a test point. The spacing of the receivers can also be changed easily for testing thin and thick layers. Layer thickness variation that occurs along a construction project can have less of an impact on the resulting seismic modulus values than on the resulting values from other NDT technologies.

Another advantage of this technology is that the system can be calibrated easily to the specific materials being tested during the mixture design stage for HMA materials or in developing M-D relationships for unbound materials. This calibration procedure allows the PSPA and DSPA to be used to detect volumetric, as well as physical, changes in the materials during construction.

The DSPA can be used to develop modulus growth with compaction relationships during the first day of construction for the unbound layers and periodically during the project. Use of the PSPA to develop HMA modulus growth relationships can be problematic because of the elevated temperature. It is more applicable to warm-mix projects.

The equipment (including the laptop) was found to be durable, and it did not require more personnel than those now

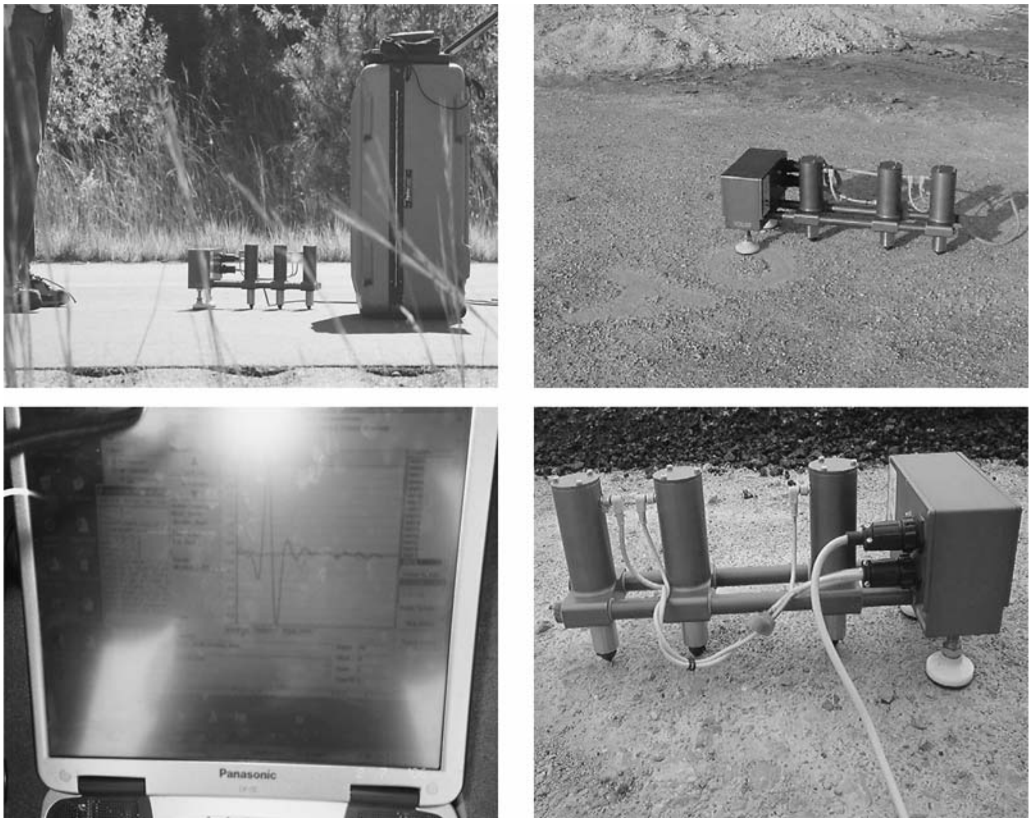


Figure 3. DSPA and PSPA being used to test different materials.

being used for control or acceptance of flexible pavement construction. In fact, the same technician using the nuclear density gauges or taking cores from the HMA layer could also operate the PSPA and DSPA at the same time. Its main disadvantage is training the operators to determine a "false" reading.

In summary, the ultrasonic technology can be used in day-to-day QA operations to assist contractor and agency personnel in judging construction and materials quality by itself or in tandem with other geophysical and/or ground truth sampling programs.

1.2 Steady-State Vibratory—GeoGauge

This system is applicable to HMA and unbound materials and soils, and is similar to the roller-mounted devices that are described in Section 1.7. The GeoGauge, however, is only used for testing unbound materials and soils. The GeoGauge provides elastic modulus values that are displayed on the gauge or stored in the device and downloaded to a computer at a later date. The resulting values were found to be similar to the resilient modulus values measured in the laboratory or calculated from the resilient modulus regression equations developed through the FHWA-LTPP program (Yau and Von Quintus 2002). The elastic modulus values from the GeoGauge were found to be a function of the material's moisture content and density. Stiffness readings were also reported by the test equipment and were a function of the structure.

The process followed by the GeoGauge operator is almost identical to that followed by an operator of the current state-of-the-art nuclear density gauge, except that the GeoGauge operator spreads a thin layer of sand on the pavement surface to set the instrument on before taking the reading (see Figure 4). The operator clears the surface to be tested with a small broom or other device to remove loose surface particles (see Figure 4). A thin layer of moist sand is used on rough surfaces to fill in surface voids to ensure that the ring under the gauge is in contact with at least 75 percent of the test surface. Moist sand should be used because the gauge vibrations will cause dry sand particles to shift under the gauge and disturb the reading. The layer of moist sand should only be thick enough to fill the surface voids of the material being tested. A light pressure and rotation of the GeoGauge was also used to ensure good contact with the test surface.

Each test takes 75 seconds, as compared to the nuclear density gauge's 60 seconds. Thus, this test takes about twice as long as the nuclear density gauge, including the time for spreading the sand. The test procedure is still quick enough not to be a hindrance to the contractor's progress and does

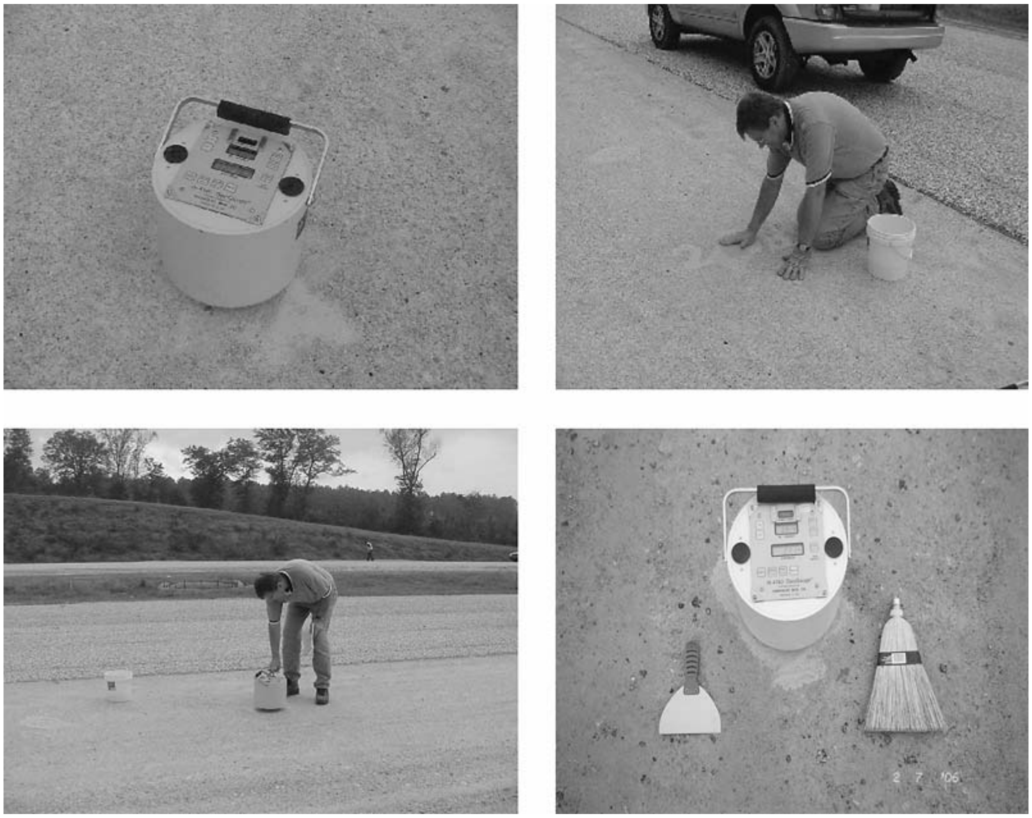


Figure 4. Humboldt GeoGauge.

not require more personnel than those now being used for control and acceptance. As for the DSPA, the same technician using the nuclear density gauge or running sand-cone tests could also operate the GeoGauge at the same time. The training and technical capability of the operator is no more than what would be required for operating a nuclear density gauge.

Similar to the DSPA, the GeoGauge can easily be used to develop relationships between modulus growth and compaction effort in unbound layers. Such relationships can be initially developed at the start of the project to optimize the compaction process and then be periodically verified throughout the project. This feature becomes advantageous when the water content significantly varies from the optimum value measured in the laboratory.

The GeoGauge should be calibrated to the project materials and conditions to improve on its accuracy, because of the potential influence of the supporting materials. This calibration issue requires that laboratory repeated load resilient modulus tests be performed on each unbound layer for judging the quality of construction. Most agencies do not routinely perform resilient modulus tests for design or for forensic evaluations, even though the 1993 AASHTO Design Guide suggests that they be performed (AASHTO 1993). Eliminating the laboratory resilient modulus tests from the calibration procedure will reduce its accuracy for confirming the design values, but not for identifying construction defects. As a replacement to the repeated load resilient modulus test, the regression equations developed from repeated load resilient modulus tests included in the LTPP program (Yau and Von Quintus 2002) or the use of the DCP is permissible.

The disadvantage of the GeoGauge is that it will result in high variability when testing non-cohesive, well-graded sands or similar soils. In addition, the elastic modulus readings from the gauge represent an equivalent modulus for the upper 10 to 12 in. of the layer. Thus, the gauge in its current form should not be used to test thin (less than 4 in.) or thick (greater than 12 in.) layers without proper material calibration adjustments or changing the diameter of the ring under the gauge.

In summary, the GeoGauge has potential use in day-to-day QA programs by both the contractor and the agency personnel.

1.3 Deflection-Based Methods

1.3.1 Falling Weight Deflectometer

The FWD is a large, expensive apparatus that is mounted on a trailer and pulled behind a tow vehicle. The operator works a computer and locates the apparatus for testing (see Figure 5). This system is capable of applying dynamic loads to the pavement surface, similar in magnitude and duration to

Figure 5. Trailer mounted FWD.

that of a single heavy moving wheel load. It is being used within the LTPP program, and most state agencies have access to at least one FWD. Thus, it is already being used in most agencies' day-to-day practice.

The response of the pavement system is measured in terms of vertical deformation, or deflection, over a given area using seismometers or geophones. An FWD enables the user to determine a deflection basin caused by a controlled load. These results make it possible to determine the stiffness of existing pavement structures for use in M-E based rehabilitation design methods.

The falling weight strikes a set of rubber buffers mounted to a 300-mm circular foot plate, which transmits the force to the pavement (see Figure 5). A thin-ribbed rubber pad is always mounted under the footplate. By varying the mass or the drop height or both, the impulse load can be varied. This load may be varied between 10 kN and 140 kN. Sensors measure the surface deflections caused by the impulse load.

Most agencies use seven sensors at the spacing recommended by LTPP. However, fewer or more sensors can be used, and those can be spaced uniformly or at some other spacing selected by the user. Peak deflections are recorded, stored, and displayed. In some cases, one of the geophones or sensors can be incorrectly placed on the test surface by the sensor bar, especially on rough surfaces. The data acquisition software will identify this anomaly, notifying the operator that the test should be rejected and redone.

The test takes about 2 minutes to complete, including the use of seating drops. Seating drops are important and should be used at each test point. This does not include time to configure the trailer and set up the data acquisition system, which should only have to be done once per day for each project. It takes about 30 minutes to configure the trailer and 2 to 3 minutes to set up the data acquisition program. Similar to the PSPA, the operator needs more technical and sophisticated training in setting up the equipment and visually interpreting the deflection basin data.

A separate data interpretation system or software is required for producing elastic modulus values from the measured deflection basins—Young's modulus for each layer. The calculated elastic modulus values are structure dependent. Most data interpretation or analysis programs used backcalculation techniques for calculating layered elastic modulus values. Backcalculation programs do not determine unique modulus values for each layer and are sensitive to layer thickness variations. Forward-calculation procedures have been developed that result in unique layer modulus values for a particular deflection basin, but these values are thickness dependent. Any errors in the layer thickness will increase the error and variability of the processed data.

Its use for acceptance of individual layers by the agency should be limited to the use of the forward-calculation procedure. Because the backcalculation procedures do not result in unique layer modulus values, it would be difficult to defend in contractor disputes where material has been rejected or payment penalties issued to the contractor. The device can be used to check or confirm the final flexible pavement for new construction or HMA overlays of existing pavements, but would probably create many disputes with the contractor when the entire pavement structure is rejected at the end of the project.

In addition, the resulting values for the upper layer are dependent on the stiffness and variability of the supporting layers. Calculating the elastic modulus of layers is generally restricted to those that are thicker than 3 in. The FWD may also require one additional field technician and tow vehicle.

The expense, size of the system, time needed to perform each test, and data interpretation software make this system less practical for QC and acceptance. Thus, the FWD is believed to be less practical and effective for the QA uses that are the focus of this study.

1.3.2 Light Weight Deflectometer

The LWDs use the same theory as the FWD, but offer an advantage of being much more portable. In addition, the training and technical requirements for the LWD operators are no different than for nuclear density gauges, with one exception—the operator needs to understand and be aware of the factors and physical features that affect layer modulus calculated from the measured deflections. Results from the LWDs were significantly influenced by the supporting materials on some of the projects.

All three LWD devices used on selected projects have similar features. Only the Dynatest and Carl Bro devices are discussed in the following paragraphs.

1.3.2.1 Dynatest Prima 100 LWD Device

The Prima 100 is manufactured by Dynatest and consists of the weight (hammer) on a pole and the sensors (geophones) in a plate on the ground, all encompassed in one, connected, portable structure (see Figure 6). The sensors were connected to a handheld computer by wireless remote technology.

Figure 6. Dynatest Prima 100 LWD.

The unit tested was somewhat flexible and the frame came apart on multiple occasions. Besides slowing down the process, this resulted in questionable data because the wireless remote would sense the jolt from the frame coming apart as a separate test, resulting in a deflection and modulus value for that anomaly.

The wireless remote was troublesome and kept losing contact with the apparatus. This happened anytime the technician carrying the apparatus came within a few feet of the technician holding the computer. This slowed down the operation because the computer had to be re-started each time it occurred.

When using the system on particularly stiff base material, the hammer can bounce high enough, such that it can strike the apparatus again—resulting in an appreciable rebound load. The rebound load can cause the remote to mistake that rebound as a second or separate test. The software, as written, causes the actual test results to be deleted and replaced by a reading of the rebound.

The system, however, is fast. One test takes about 10 seconds, so the five tests conducted (and averaged) at each location take approximately the same amount of time that a nuclear density reading takes at one location. However, the apparatus is bulky to handle, so the time that most non-nuclear systems gain by not having to deal with the steps of transporting the nuclear device are lost.

1.3.2.2 Carl Bro LWD Device

The Carl Bro system looks exactly like the Dynatest system, except that it has additional sensors that are not attached to the frame. These extended geophones do not change the theory and applications. Although, the algorithms are slightly different to include input from the additional sensors, the theory and application appear to be the same.

The geophones are arranged linearly at set distances from the plate. Since the sensors are connected to each other by a bar, but separate from the loading plate, connecting and placing them at a specific distance from the plate for each test becomes problematical. It is expected, however, that these perceived disadvantages can be resolved in future modifications to the equipment.

The process, from the beginning through the last of the five drops, takes an average of about 5.5 minutes. The procedure followed for using the system is listed.

1. Locate test point (surface must be even (flat) and must be cleared of anything that could cause part of the plate to lose contact with the surface).
2. Set the loading plate on the surface to be tested (plate must be flat on the surface).
3. Measure for geophone location.
4. Set the geophone arm and line up the sensors.
5. Set data acquisition key for collecting the deflection data.
6. Drop hammer (first drop "seats" the plate and is not read).
7. Repeat last two steps for five drops at each location (including the one to seat the plate).

This system had a wired connection to a laptop computer and was more cumbersome to set up because of the additional geophones. In addition, the seating drop of the plate sometimes moved the plate. This increased the variability in the data gathered from the geophones and increased the number of anomalies. The system is comparable in cost to the Prima 100.

1.3.2.3 Summary

This technology was tested on crushed aggregate base material, embankments, and prepared subgrades. However, there should be no difference between the procedures and the device's reaction to a hard base material and those of HMA mixtures. A key advantage of this technology is that it gives the operator a reading of the elastic modulus in about the same time required to obtain a nuclear density gauge reading. The disadvantages are that the devices have limited reliability because of the range and reliability of the wireless remote and its software logic. In addition, the resulting values for the upper layer are dependent on the stiffness and variability of the supporting layer.

It is expected that these disadvantages of the equipment can be easily resolved with future modifications. These devices will likely make the technology and device more expensive. It does, however, provide the agency with elastic modulus values that can be used to confirm design assumptions with proper calibration. In summary, the LWDs are believed to be less practical and effective for the uses that are the focus of this study.

1.4 Dynamic Cone Penetrometer

The DCP is used to estimate the strength and modulus of unbound materials and soils. The DCP is much like the LWD in appearance (see Figure 7); however, it uses a 15-lb (6.8-kg) steel mass falling 20 in. (50.8 cm) that strikes the anvil to cause penetration of a 1.5-in. (3.8-cm) diameter cone (45° vertex angle) that has been seated at the surface or in the bottom of a hand augered hole (see Figure 8). The blows required to drive the embedded cone a depth of 1¾ in. have been correlated by others to N values derived from the Standard Penetration Test (SPT). Experience has shown that the DCP can be used effectively in augered holes to depths of 15 to 20 ft (4.6 to 6.1 m). The system has been used in the past for the testing of soils more than anything else.

The technical skills and training requirements for the DCP operator are no different than for a nuclear density gauge. Advantages of the DCP include its simplicity, low maintenance (using disposable tips, making sure that the allen screws are kept tight, etc.), mobility, and low cost. It can also be used to test thick embankment layers, unlike some of the other NDT technologies and devices.

Conversely, the manual apparatus is slow (tests took 5 to 10 minutes at each location), its use is physically demanding, and the test is actually destructive to bases and pavements, that is, the test creates a hole in the material. Use of the device can also be dangerous, if the operator's hand gets caught

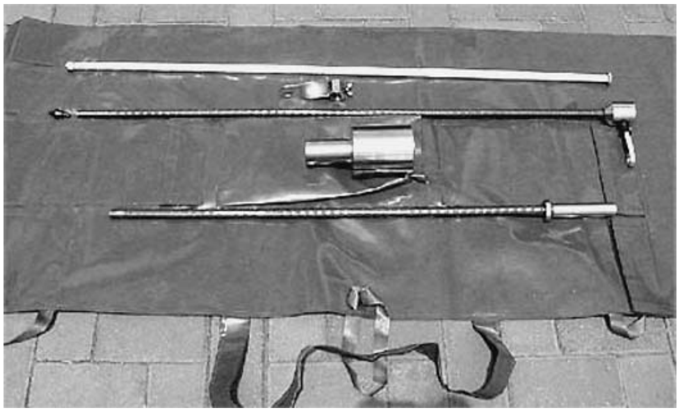


Figure 7. DCP before assembly for use in measuring the in-place strength of unbound materials and layers.

Figure 8. Manual DCP in operation (courtesy of Minnesota Road Research Section, Office of Materials, Minnesota DOT).

between the hammer and base for the hammer. Furthermore, soils or materials with boulders or large aggregate particles (refer to Figure 9) can cause refusal of the device. When this occurs, the test point should be moved and the test redone. An automated trailer mounted DCP is available, but is more expensive (see Figure 10). Only the manual DCP was used in the field evaluation of NCHRP Project 10-65.

The manual DCP is considered to have potential for QC use on a day-to-day basis, but an additional contractor and agency staff person would probably need to be assigned to use the DCP under normal practices; however, the training and maintenance of this device is considered minimal.

1.5 Ground Penetrating Radar

GPR is a pulse echo method for measuring pavement layer thicknesses and properties. GPR uses radio waves to penetrate the pavement by transmitting the wave energy into the pavement from a moving antenna. These waves travel through the pavement structure and echoes are created at boundaries of dissimilar materials. An air-coupled horn antenna attached to the back of a small SUV (see Figure 11) was used in the field evaluation of NCHRP Project 1065 to evaluate HMA, unbound aggregate base, and embankment soils.

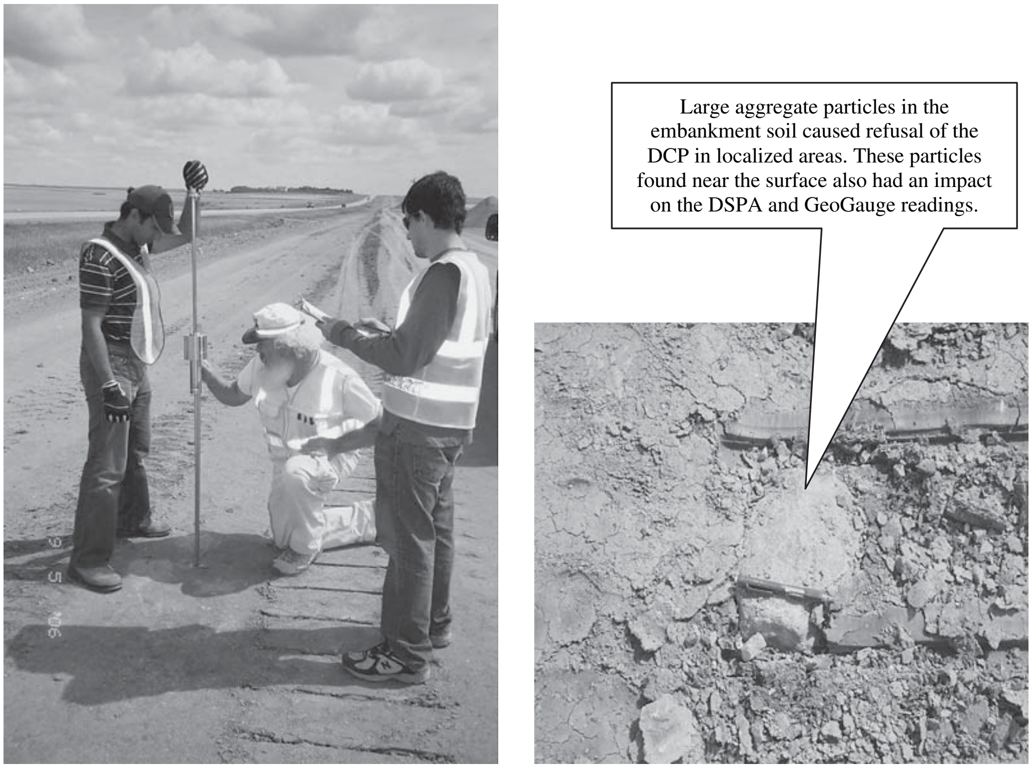
The speed of data collection is one of the biggest advantages of GPR technology. There should be no impact to the contractor's operation, because this system collects the same information regardless of material temperature and is capable of taking measurements at speeds of up to 40 miles per hour. Higher speeds have been used on more recent projects through enhancements made to the equipment and data acquisition systems. The disadvantages of the technology are the interpretation of the dielectric values that are measured and personnel requirements for calibrating and maintaining the equipment and data interpretation software.

The system is simple to operate and provides results immediately, at least in terms of dielectric values. The results are in the form of a "picture" of the pavement system, much like an X-ray. Although the transducer is located above the surface, aimed downward, the picture can be viewed from "plan" or "elevation" ("profile") perspective. Another huge advantage of this technology is that a continuous profile of the dielectric values is available. In fact, layer thickness profiles or complete contours of the layer can be developed in a short time period.

Currently, the technology requires operators with special technical skills to interpret the data that have physical meaning to the quality of construction. Software programs are available that provide color-coded charts and contours of the material. This system has been used to determine layer thickness at a reasonable accuracy—when layers with different dielectric values are tested. The accuracy of the analysis programs requires cores to accurately measure the in-place thickness and other volumetric properties.

Most of the data reduction-presentation programs, however, still require some volumetric properties to be assumed in estimating density, air voids, and other volumetric properties. These assumptions result in error of the properties that are calculated from the dielectric values. The assumptions are believed to be a reason why the GPR's analysis and interpretation from the Part A projects did not coincide with some of the other NDT devices. There are programs available that do not require many assumptions, but all of the known programs are proprietary. These proprietary programs were not used in the Part A field evaluations, but were included in the Part B summary at a few facilities. Data from some of these proprietary programs is presented and discussed in Chapter 2.

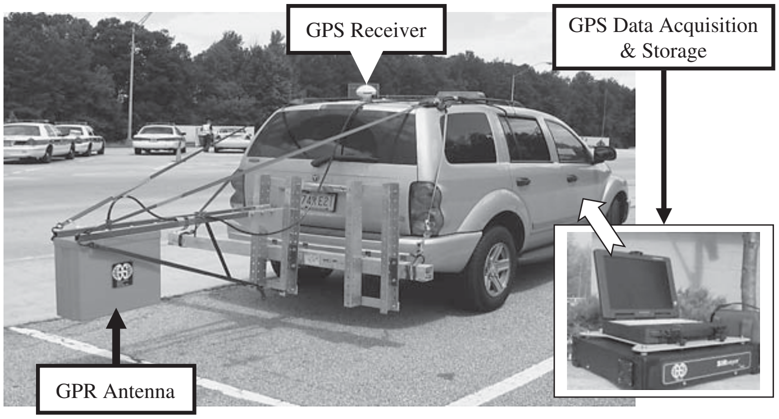
Calibration is another issue that is important to the success of GPR antennas in estimating volumetric properties of materials. Cores have to be recovered and the physical



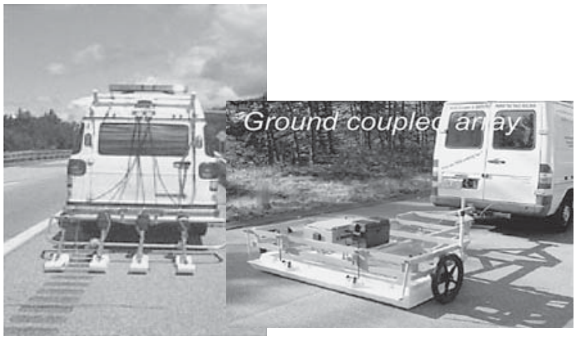
Large aggregate particles in the embankment soil caused refusal of the DCP in localized areas. These particles found near the surface also had an impact on the DSPA and GeoGauge readings.

Figure 9. DCP test and large aggregate particles encountered at some of the projects, resulting in refusal of the test.

Figure 10. Automated DCP attached to a trailer (courtesy of Minnesota Road Research Section, Office of Materials, Minnesota DOT).



a. Air-Coupled GPR Antenna Attached to Survey Vehicle



b. Ground-Coupled Antenna Arrays Attached to Survey Vehicle

Figure 11. GPR antennas attached to a standard survey vehicle.

properties of those cores determined and correlated to the dielectric values measured by the GPR prior to and during construction. This requires that control strips be used at the beginning of a project and the correlations periodically confirmed during construction. Many agencies are eliminating or not requiring the contractor to use control strips, especially for small projects. Thus, this technology has limited use in QC applications, but has greater potential for use in acceptable programs—especially those for which thickness is included in the price adjustments or pay factors.

1.6 Electric Current/Electronic Methods

This family of systems includes those that rely on technology such as electrical sensing fields, impedance, electric current, and radio waves to determine the quality of HMA pavement, base, or embankment (see Figures 12 and 13). The training and technical skills required to operate this technology are no different than those required for nuclear density gauges. In addition, the calibration requirements to improve on the accuracy of testing specific materials with the non-nuclear gauges are similar in detail and extent for nuclear density gauges.

1.6.1 Electrical Density Gauge

An electrical density gauge was used in the Part A field evaluation projects, because of the equipment's perceived ease of use and application to a diverse set of unbound materials and soils. The specific gauge used was the one manufactured

Figure 12. Electrical density gauge.

Figure 13. Purdue TDR method (courtesy of Durham Geo website).

by EDG, which is confined to use on aggregate base layers, embankments and subgrades, or any unbound layer (see Figure 14). The system uses 6-in. darts that are driven into the soil within a 1.8 square foot area. This allows the system to measure a 1.0 cubic foot volume of material.

The system uses a 3-MHz radio signal, producing a current of a certain voltage and phase, which allows measurements of the capacitance, resistance, and impedance. The connected data acquisition program uses algorithms and ratios of the measured parameters to determine the density and water content of an unbound layer (refer to Figure 14).

This test takes several minutes to perform, but it appears to have huge potential for use in replacing the nuclear density gauges and other traditional QA tests, such as the sand-cone tests. This technology does not require more personnel than are now being used for QC/QA of unbound layers. The system and devices should be easier to maintain and the operators of the equipment can be easily trained in its use—similar to a nuclear density gauge.

Figure 14. Electrical density gauge in the field.

The most time-consuming but critical part of the system is developing a proper soil model for density and moisture content measurements. To date, other more traditional tests (such as sand cones) are performed in specific locations that cover the range in density and water contents. A regression model is then developed based on correlations between the EDG values and the density and water contents measured from other tests. It is expected that this test will be improved with time, but at present, its use as a practical device for controlling construction of unbound layers is limited.

1.6.2 Pavement Quality Indicator

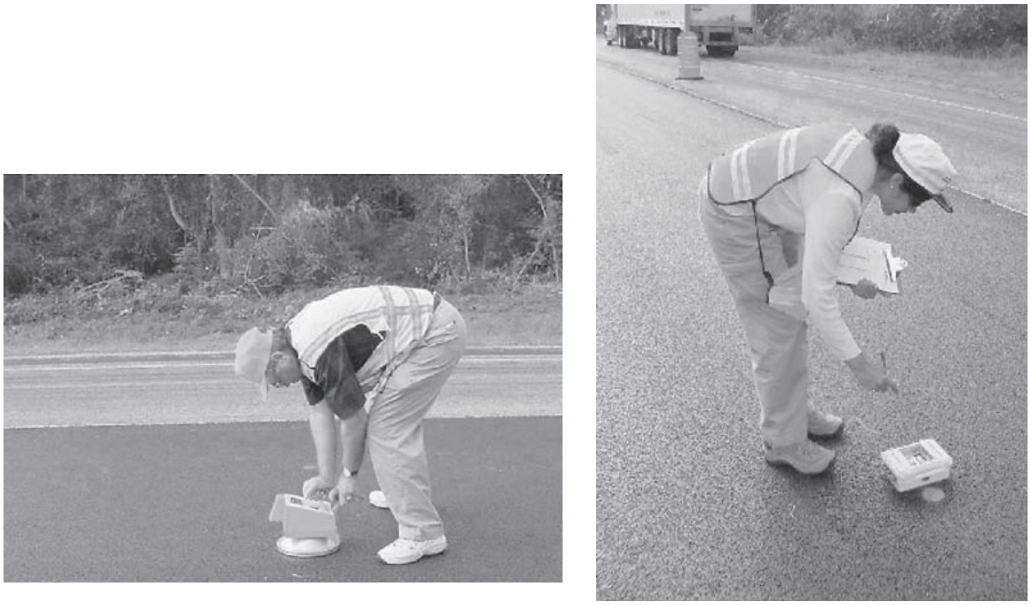
The PQI (see Figure 15[a]) uses a constant voltage, radio frequency, electrical impedance approach, in which a toroidal electrical sensing field is established in the material being tested. This allows the PQI to make quick, in-situ measurements of pavement density. The sensor consists of a set of flat plates that are interconnected to form the electrodes of a planar capacitor. Variations in density are determined through changes in the dielectric constant of the medium between the capacitor plates.

Using this technology, the PQI can be used like the nuclear density gauge, with the exception that it has the capability to adjust for moisture variations and mix type. The device also has an onboard, real-time system that takes the readings and keeps a record of them, allowing it to be integrated seamlessly into the paving process.

1.6.3 PaveTracker

The PaveTracker (see Figure 15[b]) is a light weight non-nuclear device for measuring the uniformity of HMA mixtures. The measurements are practically instantaneous when the device is placed on an HMA surface. Areas of segregation, lower density levels along longitudinal joints or other non-uniformity areas can be detected by the PaveTracker Plus, which allows the operator to correct the problem before construction is complete.

The advanced software, built-in reference plate, and enlarged display screen are some of the features offered by the PaveTracker. The large display screen is an advantage, because the device is compact and close to the ground. Like the PQI, the PaveTracker can be used exactly like the nuclear density gauge, without the use of any nuclear device. The PaveTracker also has an onboard, real-time system that takes the density readings and keeps a record of them for future use, allowing the device to be easily integrated into the paving process.



(a) PQI Non-Nuclear Density Gauge

(b) PaveTracker Non-Nuclear Density Gauge

Figure 15. Non-nuclear, non-roller-mounted devices used to measure the density of HMA layers.

1.7 Intelligent Compactors/Rollers with Mounted Response Measuring Devices

These systems offer real-time pavement quality measurement with no negative impact to the contractor's progress. They use accelerometers to measure parameters of the compactor's vibratory signature. Other sensors are also used to gain information about the pavement. Information from the sensors is then used to make decisions about pavement quality. Although these roller-mounted systems have been shown to be beneficial to a contractor from a control standpoint, they have not been used for acceptance and confirmation of the design-modulus values. Two of these systems were used in the demonstrations sponsored by FHWA at the NCAT and MnROAD facilities and included in the NCHRP Project 10-65 field evaluations. They are described in the following paragraphs.

1.7.1 Asphalt Manager and Varicontrol System

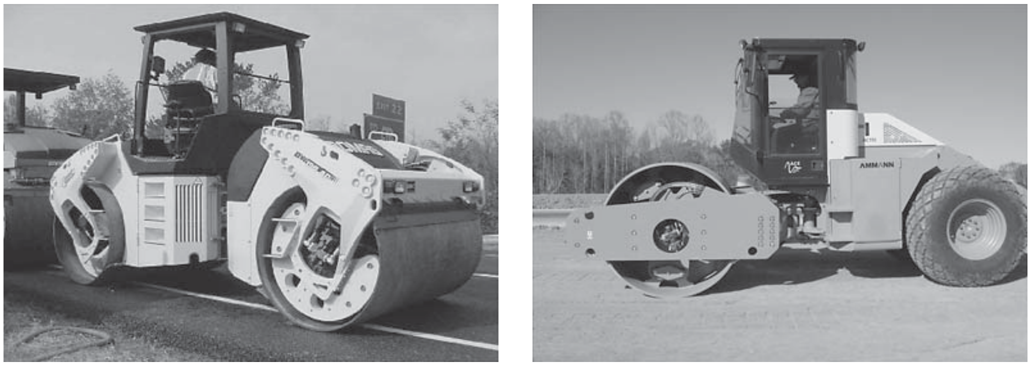
This system, developed by Bomag, contains an onboard pavement analysis system based on the electrical charge generated by strategically mounted quartz-crystal accelerometers that measure the acceleration of the vibratory drums of the compactor. An onboard computer transforms the data from the sensors using an FFT into the frequency domain. This transformation allows the computer to calculate the material's modulus. There is also a temperature sensor in the system, which feeds data into the computer for use in modulus calculations. In addition, the system takes this reading and alters the compaction effort of the roller to avoid the damaging effects of over-compaction. Stiffness readings are taken continuously and presented as a modulus value developed by Bomag and called E_{vib}, in the form of MN/m^2.

The E_{vib} value should be related to the dynamic modulus of the material being compacted. However, this computed value is expected to be affected by the underlying support conditions. To date, the E_{vib} value has not been evaluated or checked against dynamic modulus values measured in the laboratory or estimated through other NDT devices.

The system is fully integrated into a vibratory roller that is part of an operational paving train (see Figure 16). The true test of this "intelligent compaction" system is whether it actually saves time (fewer passes), improves uniformity of the mat, and renders accurate, consistent readings. As for this part of the analysis (impact on the contractor's progress), assuming that the system does what it claims, it can only help the contractor's progress.

1.7.2 Ammann Compaction Expert

Ammann-America, the U.S. branch of the Swiss manufacturer Ammann Compaction, Ltd., has introduced the Ammann Compaction Expert (ACE) to the U.S. market. The goal of the ACE is the same as for the Asphalt Manager. The major difference is that the ACE seems to take the paving environment



a. BOMAG Asphalt Manager IC Roller

b. AMMANN IC Roller

c. Caterpillar IC Roller

d. Vibratory Roller Instrumented by TTI for Use on Research Projects

Figure 16. Fully equipped rollers measuring the stiffness of the material being compacted.

into account more than the Asphalt Manager does in an automated fashion. The computer in the ACE system is capable of receiving information such as lift thickness, number of passes, mix or soil type, which is used in the calculation of the material's stiffness or modulus. Just as with the Asphalt Manager, the system is fully integrated into a vibratory roller that is part of an operational paving train.

1.7.3 Summary

The true test of this "intelligent compaction" system is whether it actually saves time (fewer passes), improves uniformity of the mat, and results in accurate, consistent readings. For impact on the contractor's progress, assuming that the roller-mounted devices do what is claimed, they can help the contractor's progress and provide information so that the contractor can make better decisions in real-time regarding compaction of pavement layers.

1.8 Summary of Process Impact

Table 13 provides a summary of process impact on flexible pavement construction for different NDT technologies and devices regarding their use in QA programs.

Table 13. Process impact of different NDT technologies and devices on QA programs.

Impact Topics or Issues	**NDT Technologies**								
	Ultrasonic Gauges	**Steady-State Vibratory**	**Deflection-Based**		**DCP**		**GPR**	**Non-Nuclear Devices**	
			Trailer	**Portable**	**Manual**	**Automated**		**Non-Roller-Mounted**	**Roller-Mounted**
Easily used to develop density or modulus growth curves?	HMA- No Unbound- Yes	Yes	No	Yes	No	No	No	Yes	Yes
Resulting Value	Seismic Modulus	Elastic Modulus	Deflection	Deflection & Elastic Modulus	Penetration Rate or Index	Penetration Rate or Index	Dielectric Values	Density & Water Content	Stiffness or Density
Conversion required to adjust readings?	Yes	No	No	No	No	No	Yes	No	No
Requires calibration to specific materials or soils?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Can readily test thin layers (<3 in.)	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes
Can readily test thick layers (>12 in.)	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No
Readily applicable to control?	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes
Readily applicable to acceptance?	Yes	Yes	No, only final structure	Yes	Yes	Yes	Yes	Yes	No
Additional auxiliary equipment needed?	No	No	Yes, tow vehicle	No	No	Yes	Yes, vehicle	No	No
Additional staff needed?	No	No	Yes, operator	No	No	Yes	Yes	No	No
Equipment readily available on commercial basis?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Software readily available on commercial basis?	Yes	NA	Yes	Yes	NA	NA	No; for Proprietary	NA	NA

CHAPTER 2

Materials Testing for Construction Quality Determination

This chapter focuses on the effectiveness of the NDT technology and device for measuring or judging the quality of construction of unbound materials and HMA mixtures. "Effectiveness" is defined as the ability or capability of the NDT technology or device to detect changes in unbound materials or HMA mixtures. The research problem statement noted that, with the development of the MEPDG, layer modulus will become a more important property and should be considered a quality characteristic. Thus, the emphasis of the interpretation of data presented in Chapter 5 (available in *NCHRP Web-Only Document 133*) was on identifying those NDT devices that can consistently and accurately determine when changes occur within the construction process, as well as confirm the assumptions used in pavement structural design.

2.1 Identification of Material Anomalies and Differences

The testing under the Part A field evaluation was to confirm that the NDT technologies can identify differences in construction quality of unbound pavement layers and HMA mixtures. The specific hypothesis used for this part of the field evaluation was that the NDT technology and device can detect changes in the physical condition of pavement materials and soils that affect flexible pavement performance. Tables 14 and 15 present the anomalies and different conditions placed along each project.

A standard t-test and the SNK mean separation procedure using a 95 percent confidence level were used to determine whether the areas with anomalies were significantly different from the other areas tested. The following subsections summarize the results from the statistical analyses of the data collected within Part A of the field evaluation.

2.1.1 Unbound Layers

Table 16 tabulates the results for checking the hypothesis for the unbound material layers. The shaded cells in Table 16 designate those where the hypothesis was incorrectly rejected or accepted. The DSPA accurately identified most of the areas with anomalies or material differences. The GeoGauge did a reasonable identification of the areas, followed by the DCP and LWD. The EDG and GPR devices did a poor job in identifying the different areas. Table 17 demonstrates the success rate by each device in identifying the physical differences of the unbound material within a project.

The DSPA and GeoGauge have acceptable success rates, while the EDG and GPR have unacceptable rates. Significantly, the modulus measuring devices (DSPA, GeoGauge, DCP, and LWD) found all the hypotheses to be true for the crushed aggregate materials (TH-23 and US-280 projects), while the volumetric devices (GPR and EDG) rejected all the hypotheses. This observation suggests systematic differences between the technologies. Some of the important differences observed between the technologies and devices and the reason for the higher success rates for the DSPA and GeoGauge are listed as follows:

- The DSPA and GeoGauge induce small dynamic stress waves into the material being tested. These small responses emphasize the effect of changes in the density and moisture content of the material being tested. Significantly, both devices measure the responses in a relatively limited area and depth. In fact, the sensors for the DSPA (refer to Figures 2 and 3) were spaced so the measured responses would be confined to the layer being tested. The GeoGauge measurements have a deeper influence, so its results can be influenced by the supporting layer. The depth of influence depends on the thickness and stiffness of the material being tested.
- The DCP is a point-based test and estimates the modulus of the material from the average penetration rate through the material. The penetration rate is dependent on the dry density of the material. However, there are other physical properties that have a greater effect on the penetration rate. The amount and size of the aggregate particles can have a larger effect on the estimated modulus than for the DSPA or GeoGauge, especially for fine-grained soils with some aggregates. For example, the DCP found all the hypotheses

Table 14. Local anomalies in the unbound materials and soils placed along each project included in Part A.

Project Identification	Unbound Sections	Description of Differences Along Project
SH-21 Subgrade, High Plasticity Clay; Caldwell, Texas	Area 2, No IC Rolling	No planned difference between the points tested.
	Area 1, With IC Rolling	With IC rolling, the average density should increase; lane C received more roller passes.
I-85 Embankment, Low Plasticity Clay; Auburn, Alabama	Lane A of Sections 1 & 2	Prior to IC rolling, Lane A (which is further from I-85) had thicker lifts & a lower density.
	All sections tested	After IC rolling, the average density should increase & the variability of density measurements should decrease.
TH-23 Embankment, Silt-Sand-Gravel Mix; Spicer, Minnesota	South Section – Lane C	Construction equipment had disturbed this area. In addition, QA records indicate that this area has a lower density.
	North Section – Lane A	The area with the higher density and lower moisture content—a stronger area.
SH-130, Improved Embankment, Granular; Georgetown, Texas	All sections tested	No planned differences between the areas tested.
TH-23, Crushed Aggregate Base; Spicer, Minnesota	Section 2 (middle section) – Lane C	Curb and gutter section; lane C was wetter than the other two lanes because of trapped water along the curb from previous rains. The water extended into the underlying layers.
	Section 1 (south section) – Lane A	Area with a higher density and lower moisture content—a stronger area.
US-280, Crushed Stone Base; Opelika, Alabama	Section 4	Records indicate that this area was placed with higher moisture contents and is less dense. It is also in an area where water (from previous rains) can accumulate over time.

Table 15. Different physical conditions (localized anomalies) of the HMA mixtures placed along projects within Part A.

Project Identification	HMA Sections	Description of Differences Along the Project
TH-23 HMA Base; Spicer, Minnesota	Section 2, Middle or Northeast Section	QA records indicate lower asphalt content in this area—asphalt content was still within the specifications.
I-85 SMA Overlay; Auburn, Alabama	Section 2, Middle; All Lanes	QA records indicate higher asphalt content in this area, but it was still within the specifications.
	Lane C, All Sections	This part or lane was the last area rolled using the rolling pattern set by the contractor, and was adjacent to the traffic lane. Densities lower within this area.
US-280 HMA Base Mixture; Opelika, Alabama	Initial Test Sections, defined as A; Section 2, All Lanes	Segregation identified in localized areas. In addition, QA records indicate lower asphalt content in this area of the project. Densities lower within this area.
	Supplemental Test Sections Near Crushed Stone Base Sections, Defined as B.	Segregation observed in limited areas.
	IC Roller Compaction Effort Section, Defined as C.	Higher compaction effort was used along Lane C.
SH-130 HMA Base Mixture; Georgetown, Texas	All Sections	No differences between the different sections tested.

Table 16. Effectiveness of NDT devices to identify areas of unbound layers with anomalies or different physical conditions.

Project	Hypothesis		NDT Device					
			GPR	EDG, pcf	Geo., ksi	DSPA, ksi	DCP, ksi	Defl., ksi
I-85 Low Plasticity Soil Embankment	Pre-IC Rolling	Lane A	**14.65**	107.6	12.6	25.2	**5.20**	---
		Lanes B,C,D	**15.99**	108.1	16.3	34.0	**5.62**	---
	Lane A is weaker		**No**	Yes	Yes	Yes	**No**	---
	Post-IC	Area 1	21.61	**108.3**	**17.1**	39.4	6.93	**9.99**
		Area 2	23.00	**107.7**	**19.0**	40.4	6.21	**11.78**
	No Planned Difference		Yes	**No**	**No**	Yes	Yes	**No**
	All areas	Pre-IC	15.65	**108.0**	15.4	31.8	5.51	---
		Post-IC	22.31	**108.0**	17.7	39.9	6.57	---
	Post-IC area is stronger		Yes	**No**	Yes	Yes	Yes	---
SH-21 High Plasticity Clay	Area 2	No IC	---	---	19.6	23.6	**11.9**	---
	Area 1	With IC	---	---	22.9	27.1	**9.1**	---
	Area 1 is stronger		---	---	Yes	Yes	**No**	---
	With IC Rolling	Lane C	---	---	**20.1**	30.4	**9.9**	12.9
		Lanes A,B	---	---	**24.4**	25.4	**8.7**	8.00
	Lane C is stronger		---	---	**No**	Yes	**No**	Yes
TH-23 Silt-Sand-Gravel Mix Embankment	So. Area	Lanes A,B	**18.24**	**122.7**	10.5	**43.6**	**15.16**	**5.65**
	No. Area	Lanes B,C	**29.16**	**124.1**	10.1	**35.7**	**19.01**	**4.77**
	No Planned Difference		**No**	**No**	Yes	**No**	**No**	**No**
	So. Area	Lane C	**19.33**	**122.9**	7.5	31.1	11.47	**5.58**
		Lanes A,B	**18.24**	**122.7**	10.5	43.6	15.16	**5.65**
	Lane C is weaker		**No**	**No**	Yes	Yes	Yes	**No**
	No. Area	Lane A	**20.32**	**123.9**	12.6	51.7	**18.52**	**4.69**
		Lanes B,C	**29.16**	**124.1**	10.1	35.7	**19.01**	**4.77**
	Lane A is stronger		**No**	**No**	Yes	Yes	**No**	**No**
SH-130 Granular Improved Embankment	All lanes	Lane A	10.29	123.2	25.4	33.9	21.60	**24.2**
		Lane B	9.30	123.0	25.5	34.7	20.95	**27.8**
		Lane C	9.78	123.8	24.77	33.3	20.74	**21.2**
	No Planned Difference		Yes	Yes	Yes	Yes	Yes	**No**
	All areas	Area 1,2	9.74	123.5	**26.3**	**36.5**	20.64	24.6
		Area 3	9.88	123.1	**22.3**	**28.9**	22.01	24.1
	No Planned Difference		Yes	Yes	**No**	**No**	Yes	Yes
TH-23 Crushed Aggregate Base	South & Middle Sections	Lanes A,B	**9.37**	**129.8**	14.4	100.4	42.05	16.75
		Lane C	**10.62**	**129.8**	10.8	50.7	21.33	8.31
	Lane C is weaker		**No**	**No**	Yes	Yes	Yes	Yes
	So. Area	Lanes A,B	**9.79**	**129.9**	15.0	110.7	46.45	19.38
	Middle Section	Lane C	**10.38**	**129.8**	9.8	28.0	18.55	7.95
	All other areas		**9.54**	**129.8**	12.8	75.0	33.14	12.31
	Lane C, middle section, is weaker		**No**	**No**	Yes	Yes	Yes	Yes
	Lanes A & B, south section, are stronger		**No**	**No**	Yes	Yes	Yes	Yes
US-280 Crushed Stone Base	All areas	Lane 4	**11.57**	**148.2**	35.1	117.4	34.31	18.53
		Lanes 1,2,3	**11.95**	**147.4**	47.9	198.6	50.29	46.46
	Lane 4 is weaker		**No**	**No**	Yes	Yes	Yes	Yes

NOTE: The results in the shaded or black cells represent areas where the hypothesis was rejected based on a 95 percent confidence interval, and are inconsistent with the construction records and experimental plan.

Table 17. Success rate demonstrated by each device in identifying the physical differences of the unbound material.

NDT Device	DSPA	GeoGauge	DCP	LWD	GPR	EDG
Success Rate, %	86	79	64	64	33	25

to be true for the coarse-grained materials and rejected many of the hypotheses for the fine-grained embankment materials with varying amounts of coarse aggregate.

- The LWD induces larger strains into the underlying materials. The measured deflections or responses are affected by a much larger area and depth than for the DSPA, GeoGauge, and DCP. The modulus calculated from the deflections is dependent on the thickness and stiffness of the material being tested, as well as the thickness and stiffness of the supporting layers. In fact, some resulting modulus values were lower than expected for the type of material being tested (TH-23 embankment and areas of the US-280 crushed stone). The LWD found all the hypotheses to be true where the layer thicknesses were well defined, but rejected many of the hypotheses for the materials where the layer thickness was less defined—the embankments.
- Both the GPR and EDG devices are dependent on the density and water content measurements made with other traditional test methods. Any errors within those traditional methods are included in the GPR and EDG results. Average water contents were assumed for each area in calculating the wet densities from the dielectric values measured with the GPR. Obviously, water contents are not constant within a specific area. Errors in the water content will be reflected in the wet density for a specific test. In addition, varying plasticity of the fines and in the gradation of the material is difficult to identify with the GPR and EDG by themselves.
- Variability of the measurements is another reason for the outcome. The GeoGauge had lower variability, followed by the DSPA and DCP. The deflection-based methods had the greatest variability. The lower the variability, the higher the probability to identify a difference, if a difference exists, given the same number of tests (refer to Section 2.3).

In summary, the DSPA and GeoGauge are considered acceptable in identifying localized differences in the physical condition of unbound materials.

2.1.2 HMA Layers

Table 18 contains the results of checking the hypotheses for the HMA layers. The shaded cells in Table 18 designate those

Table 18. Effectiveness of NDT devices to identify areas of HMA layers with anomalies or different physical conditions.

Project	Hypothesis		NDT Device			
			PSPA	FWD	GPR	PQI
I-85 SMA Overlay	Section 2	Lanes A,B	285.0	568.9	6.18	149.9
	Sections 1,3	Lanes A,B	262.0	405.4	10.14	146.6
	Section 2 is Stronger or Stiffer		Yes	Yes	Yes	Yes
	Lane C	Section 2,3	288.5	NA	**8.51**	141.6
	Lane C	Sections 1	215.4	NA	**8.62**	140.3
	Section 1 is Weaker/Less Dense		Yes	NA	**No**	Yes
TH-23 HMA Base	Section 2	All Lanes	454.4	NA	7.04	145.2
	Sections 1,3	All Lanes	489.8	NA	6.64	146.6
	Section 2 is Weaker		Yes	NA	Yes	Yes
	Section 4	All Lanes	499.5	NA	NA	**143.9**
	No Planned Difference; Sections 1,3,4		Yes	NA	NA	**No**
US-280 HMA Base	Initial Sections	Section 1	499.9	203.3	7.03	**148.0**
	Supplemental Sections	Sections 1,2	555.0	877.2	5.50	**140.4**
	Supplemental Area is Stronger/Denser		Yes	Yes	Yes	**No**
US-280 HMA Base, Initial Sections	Section 1	All Lanes	499.9	203.3	**7.03**	**148.0**
	Section 2	All Lanes	423.9	125.9	**6.81**	**154.5**
	Section 1 is Stronger/Denser		Yes	Yes	**No**	**No**
	Longitudinal Joints	Confined Joint	305.8	**125.5**	7.70	145.7
	Joints are Less Dense/Weaker		Yes	**No**	Yes	Yes
	Segregated Areas	All Lanes	329.9	**144.5**	**7.28**	147.1
	Segregated Areas are Less Dense/Stiff		Yes	**No**	**No**	Yes
US-280 HMA Base, Supplemental Sections	Section 1	All Lanes	559.8	**569.0**	5.55	140.4
	Section 2	All Lanes	550.2	**1185.3**	5.45	140.5
	No Planned Difference		Yes	**No**	Yes	Yes
	Longitudinal Joints	All Lanes	**596.0**	379.0	**5.78**	135.8
	Joints are Les Dense/Weaker		**No**	Yes	**No**	Yes
	Segregated Areas	All Lanes	391.3	**707.0**	**5.64**	136.6
	Segregated Areas are Less Dense/Stiff		Yes	**No**	**No**	Yes
I-35/SH-130 HMA Base	Section 1	All Lanes	384.9	NA	5.95	126.5
	Section 2	All Lanes	292.6	NA	5.61	124.0
	Section 3	All Lanes	461.7	NA	NA	125.1
	Section 2 is Weaker/Less Dense		Yes	NA	Yes	Yes
	Joints	All Lanes	297.5	NA	**5.08**	118.8
	Joints are Less Dense/Stiff		Yes	NA	**No**	Yes

Table 19. Success rates for identifying the physical differences of the HMA mixtures within a project.

NDT Device	PSPA	PQI	GPR	FWD
Success Rate, %	93	71	54	56

areas where the hypothesis was incorrectly rejected. Another difference that was found but not planned (so it was excluded from Table 18) was the difference between the initial and supplemental sections of the US-280 project (see Chapter 5 of *NCHRP Web-Only Document 133*). All NDT devices found a significant difference between these two areas—the supplemental section had the higher dynamic modulus, which was confirmed with laboratory dynamic modulus tests. Both the PSPA and FWD resulted in higher modulus values and the GPR estimated lower air voids, but the PQI resulted in much lower densities.

The PSPA did identify all but one of the areas with anomalies or differences. The non-nuclear density gauge did a reasonable job, while the GPR and FWD only identified slightly more than 50 percent of the areas with differences. The GPR, however, did measure the HMA lift thickness placed, which was confirmed through field cores. Table 19 contains the success rates for identifying the physical differences of the HMA mixtures within a project.

The PSPA had an excellent success rate, while the PQI had an acceptable rate. The GPR and FWD had lower rates that are considered unacceptable. Some of the important differences observed between the technologies and devices and the reasons for the lower success rates of the GPR and FWD are listed as follows:

- The FWD is believed to have been influenced by the supporting layers creating noise and additional variability making it more difficult to identify the localized areas. In addition, its loading plate probably bridged some of the localized anomalies making it difficult to detect differences near the surface of the layer evaluated (e.g., segregation).
- The dielectric values measured by the GPR are minimally affected by some of the properties that can change within a project, and its success is heavily dependent on the number of cores taken for calibration purposes—similar to that for unbound materials.

In summary, the PSPA and non-nuclear density gauges (PQI) are considered acceptable in identifying localized differences in the physical condition of HMA mixtures.

2.2 Estimating Target Modulus Values

Laboratory measured modulus of a material is an input parameter for all layers in the MEPDG. Resilient modulus is the input for unbound layers and soils, while the dynamic modulus is used for all HMA layers. None of the NDT devices accurately predicted the modulus values that were measured in the laboratory for the unbound materials and HMA mixtures (see Figures 17-1 and 17-2). All of the modulus estimating NDT devices, however, did show a trend of increasing moduli with increasing laboratory measured moduli. The following subsections describe the use of adjustment factors for confirming the assumptions used for structural design.

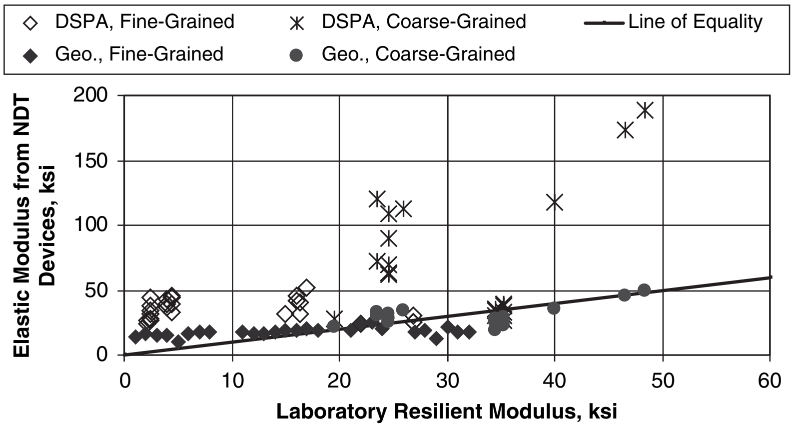
2.2.1 Unbound Layers

It has been previously reported that layer moduli calculated from deflection basins must be adjusted (multiplied) by a factor for pavement structural design procedures that are based on laboratory derived values at the same stress state (AASHTO 1993; Von Quintus and Killingsworth 1998). In the 1993 AASHTO Pavement Design Manual, the adjustment factor is referred to as the "C-factor," and the value recommended for use is 0.33. Thus, there are differences between the field and laboratory conditions that can cause significant bias when using NDT modulus values.

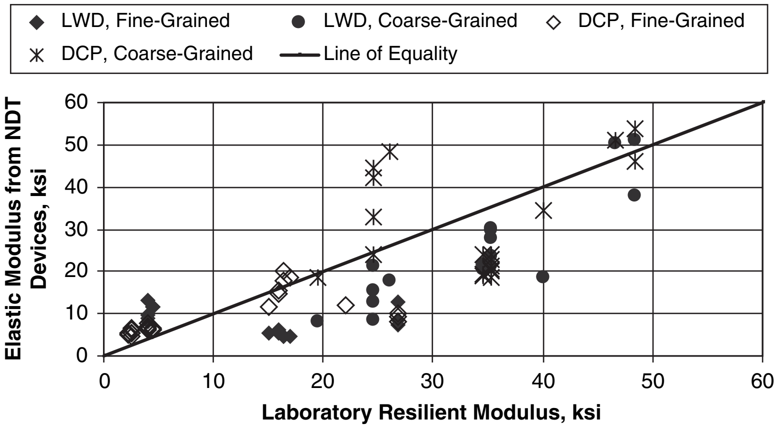
Von Quintus and Killingsworth found that this adjustment factor was structure or layer dependent but not material type dependent. Adjustment factors were determined for different types of structures. The C-factor found for embankment or subgrade soils ranged from 0.35 to 0.75 and averaged 0.62 for aggregate base materials. However, none of the deflection basins measured in this study was measured on the surface of the unbound layers themselves. Conversely, all testing under this study was directly on the surface of the layer being evaluated.

To compensate for differences between the laboratory and field conditions, an adjustment procedure was used to estimate the laboratory resilient modulus from the different NDT technologies for making relative comparisons. The adjustment procedure assumes that the NDT response and modulus of laboratory prepared test specimens are directly related and proportional to changes in density and water content of the material. Figures 18, 19, and 20 compare the seismic (PSPA) modulus measured on the samples used in preparing an M-D relationship. The PSPA modulus-water content relationship follows the M-D relationship. Thus, the assumption is believed to be valid.

For simplicity, the adjustment factors were derived using the same methodology within the FHWA-LTPP study, with the exception that a constant, low stress state was used to determine the adjustment factor. In other words, the average

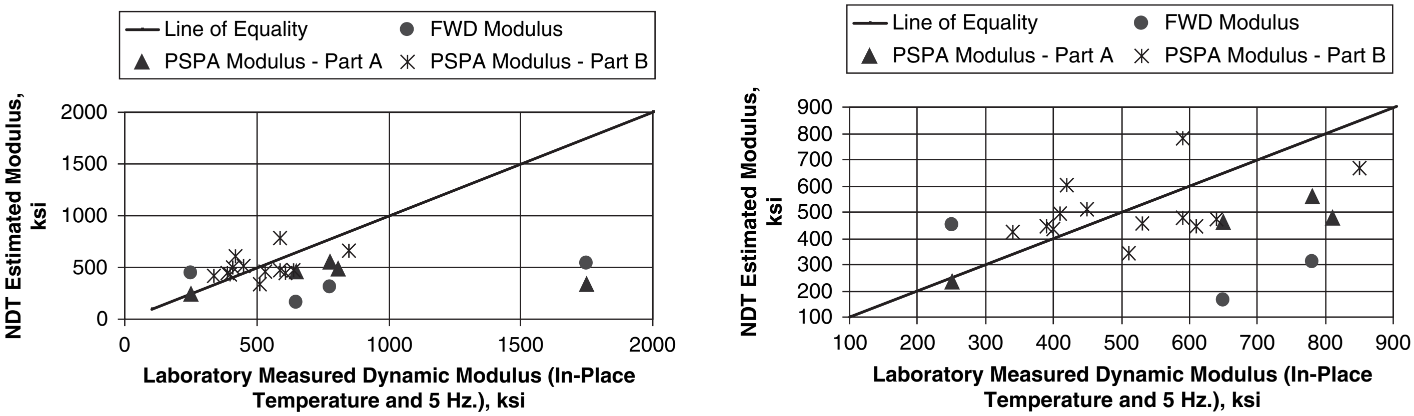


(a) DSPA and the GeoGauge.



(b) Deflection-Based and DCP methods.

Figure 17-1. Comparison of laboratory resilient modulus and the elastic modulus values estimated with different NDT technologies and devices.



(a) Entire data set.

(b) Excludes data point for very stiff HMA mixture placed along SH-130.

Figure 17-2. Comparison of laboratory dynamic modulus and the elastic modulus values estimated with different NDT technologies and devices.

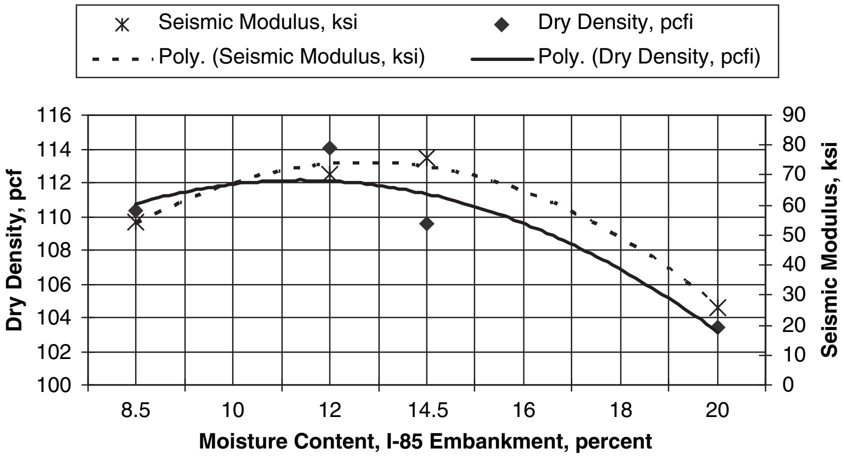


Figure 18. Comparison of the PSPA modulus to the M-D relationship for the I-85 low plasticity soil embankment.

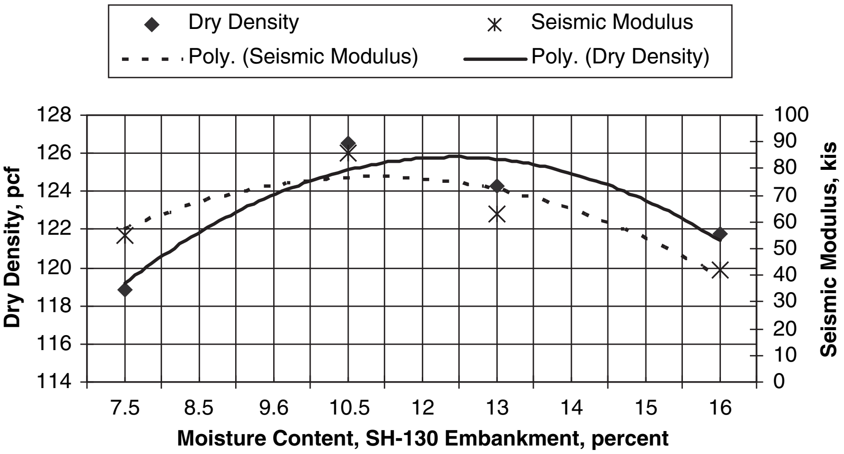


Figure 19. Comparison of the PSPA modulus to the M-D relationship for the SH-130 improved granular embankment.

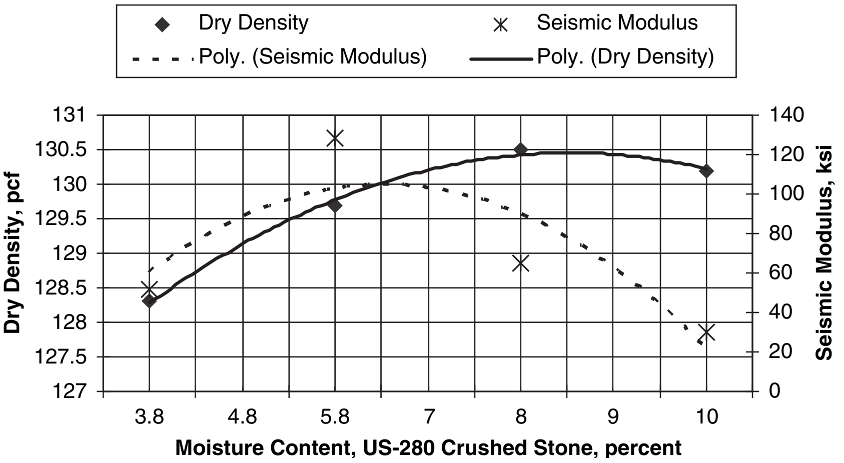


Figure 20. Comparison of the PSPA modulus to the M-D relationship for the US-280 crushed stone base.

Table 20. Adjustment factors or ratios applied to the NDT modulus values to represent laboratory conditions or values at low stress states; Part A projects.

Project	Material	Percent Compaction	Percent of Optimum Moisture	Ratio or Adjustment Factor			
				Geo.	DSPA	DCP	LWD
I-85 Embankment	Low Plasticity Clay	91	165	0.19	0.087	0.53	0.39
TH-23 Embankment	Silt-Sand-Gravel Mix	100	132	0.90	0.41	0.95	3.13
SH-21 Subgrade	High Plasticity Clay	99	84	1.16	0.99	2.94	2.78
TH-23 Base	Crushed Aggregate	104	55	0.71	0.30	0.68	1.69
SH-130 Embankment	Improved Granular Mix	105	101	1.39	1.04	1.67	1.43
US-280 Base	Crushed Stone	101	52	1.01	0.24	0.96	1.04

The adjustment ratio or factor was determined by dividing the average resilient modulus measured in the laboratory by the average modulus from the NDT device (for a specific stress state, see Table 21).

laboratory measured modulus (triplicate repeated load resilient modulus tests were performed) was divided by the average moduli estimated with each NDT device.

Table 20 contains the adjustment factors equating the NDT moduli to the resilient modulus measured in the laboratory (see Tables 21 and 22) for the Part A field evaluation projects.

The adjustment factors do not appear to be related to the percent compaction, percent of optimum water content, or material type. The adjustment factors for the deflection-based

Table 21. Average repeated load resilient modulus values measured in the laboratory at a specific stress state.

Project & Materials	Area		Dry Density, pcf	Moisture Content, %	Percent Maximum Density, %	Laboratory Resilient Modulus, ksi
I-85 Low Plasticity Clay Embankment	Before IC Rolling	Section 1, Lanes B,C,D	103.0	21.6	0.91	2.5
	After IC Rolling	Section 1, Lanes B,C,D	108.0	16.9	0.96	4.0
NCAT; Oklahoma High Plasticity Clay			96.7	21.3	0.97	6.9
NCAT; South Carolina Crushed Granite Base			130.0	4.7	0.94	14.3
TH-23 Embankment, Silt-Sand-Gravel Mix	South Section	Lanes A,B	121.0	8.2	0.98	16.0
	North Section	Lane B,C	122.4	9.1	1.00	16.4
US-2 Embankment; Soil-Aggregate Mix			123.1	12.1	0.96	19.0
NCAT; Missouri Crushed Limestone Base			124.4	9.0	0.96	19.2
SH-21 High Plasticity Clay	Area 1, with IC rolling	Lanes A,B	107.3	18.4	0.99	26.8
TH-23 Crushed Aggregate Base	Middle Area	Lane B	139.4	4.3	1.04	24.0
	South Area	All Lanes	141.1	4.2	1.03	24.6
US-53 Crushed Aggregate Base, Type 304			136.0	9.1	1.01	27.5
NCAT; Florida Limerock Base			110.5	13.4	0.95	28.6
US-2 Class 5 Crushed Aggregate Base			134.4	5.9	0.95	32.4
SH-130 Improved Granular	Sections 2, 3	Lanes A,B	128.7	9.1	1.05	35.3
US-280 Crushed Stone	Areas 1,2,3		150.6	3.2	1.01	48.4

NOTES:

- Resilient modulus values for the fine-grained soils and embankments are for a low confining pressure (2 psi) and repeated stress of 4 psi, while a confining pressure of 6 psi and repeated stress of 6 psi was used for the granular base materials. These low stress conditions are not based on any theoretical analysis. One stress state for the embankment soils and one for aggregate base layers were selected for consistency in comparing the field estimated elastic modulus values from each NDT device to values measured in the laboratory, which were considered the target values.
- Percent maximum density is based on the maximum dry unit weight or density from the moisture-density relationship (the maximum dry densities are included in Table 23 for each material tested).

Table 22. Elastic modulus values estimated from the NDT technologies and devices, without adjustments, in comparison to resilient modulus values measured in the laboratory.

Project	Material	Area	Modulus, ksi				
			Lab.*	GeoGauge	DSPA	DCP	LWD
I-85 Embankment Before IC Rolling	Low Plasticity Clay	Section 2, Lane A	2.2	10.6	24.1	5.0	---
		Section 1, All Lanes	2.5	15.4	30.0	5.9	---
		Section 2, Lanes B, C, D	2.5	17.0	36.6	5.2	---
I-85 Embankment After IC Rolling	Low Plasticity Clay	Section 1	4.0	16.8	30.4	6.9	9.99
		Section 2	4.5	19.0	40.4	6.2	11.78
TH-23 Embankment	Silt-Sand-Gravel Mix	So. Section, Lane C	15.0	13.2	31.1	11.5	5.6
		So. Sect., Lanes A,B	16.0	18.3	43.6	15.2	5.7
		No. Sect., Lanes B,C	16.4	17.8	35.7	19.0	4.7
		No. Sect., Lane A	17.0	22.0	51.7	18.5	4.7
SH-21 Subgrade	High Plasticity Clay	No IC Rolling	22.0	19.6	23.6	11.9	---
		After IC Rolling	26.8	22.9	27.1	8.8	9.6
TH-23 Base	Crushed Aggregate Base	Middle Sect., Lane C	19.5	21.6	28.0	18.6	8.0
		North Section, All Lanes; Middle Section Lanes A, B	24.6	28.2	79.3	33.1	12.3
		South Section, Lanes A, B	26.0	33.0	110.7	46.4	19.4
SH-130 Improved Embankment	Granular	Section 3	34.5	19.4	33.3	20.7	24.1
		Sections 1, 2	35.3	26.4	34.3	21.3	24.6
US-280 Base	Crushed Stone	Area 4	40.0	35.1	117.4	34.3	18.5
		Areas 1, 2, 3	48.4	47.9	198.6	50.3	46.5

NOTES:
* The repeated load resilient modulus values measured in the laboratory, but corrected to the actual dry density and moisture content measured for the specific section, in accordance with the LTPP procedure and regression equations.

devices are approximately the inverse of the values reported from the FHWA-LTPP study. Thus, the adjustment factors derived from testing on bound pavement surfaces should not be used when testing directly on the unbound layer being evaluated.

Another important observation from the Part A projects is that the adjustment factors for all NDT devices for the I-85 low plasticity clay embankment prior to IC rolling are significantly lower than for any of the other materials. This observation suggests that the resilient moduli measured in the laboratory are much lower than for any of the other soils and materials. The reason for the low values is unknown. This embankment soil had the lowest dry density and highest water content relative to its maximum dry density and optimum water content also see Table 23). However, these data were excluded from developing the adjustment factors and selection of an NDT device that can be used to confirm the structural design parameters because they were consistent across all NDT devices.

Table 24 contains the adjustment factors for all projects included in the field evaluation (Parts A and B). The LWD is not included in Table 24 because it was excluded from the Part B projects. On average, the GeoGauge and DCP provided a reasonable estimate to the laboratory measured values, with the exception of the fine-grained, clay soils. The GeoGauge deviated significantly from the laboratory values for the fine-grained soils. The results also show that both the GeoGauge and DCP over- or under-predicted the laboratory measured values for the same material, with a few exceptions.

These ratios were compared to the percent compaction, percent of optimum water content, and material type, but no relationship could be found. The GeoGauge and DSPA adjustment ratios appear to be related to the amount of fines in the material (percent passing number 200 sieve), as shown in Figure 21.

In summary, the GeoGauge can be used to estimate the resilient modulus measured in the laboratory for aggregate base materials and coarse-graded soil-aggregate embankments, while the DCP provided a closer estimate for the fine-grained soils. However, the ratios for both of these devices were variable—even within the same soil or material group. The DSPA resulted in a positive bias (over-predicted the laboratory resilient modulus) with variable ratios. It is suggested that repeated load resilient modulus tests be performed to determine the target or design value and that those results be used to calibrate the NDT devices for a specific soil or aggregate base, because of the variability of these ratios. The resilient modulus test should be performed on bulk material sampled

Table 23. Maximum dry density and optimum water content for the unbound materials and soils, as compared to the average test results from the EDG.

Project	Material	Maximum Dry Unit Weight, pcf	Optimum Water Content, %	Average Dry Density, pcf	Average Water Content, %
NCAT, Oklahoma	High Plasticity Clay	99.9	21.8	96.7	21.3
SH-21, TX	High Plasticity Clay	108.0	21.9	107.3	18.4
I-85, AL	Low Plasticity Soil; Pre-IC	112.7	13.1	107.98	16.9
	Low Plasticity Soil; Post-IC			107.98	16.9
SH-130, TX	Improved Granular Embankment	122.0	9	123.3	8.32
TH-23, MN	Silt-Sand-Gravel Mix – South Area	122.6	12	122.77	8.69
	Silt-Sand-Gravel Mix – North Area			123.80	7.87
US-2, ND	Soil-Aggregate, Embankment	128.0	9.0	123.1	12.1
NCAT, FL	Limerock Base	116.1	12.5	110.5	13.4
CR-103	Caliche Base	127.5	10.0	125.0	9.5
NCAT, MO	Crushed Limestone	130.0	10.0	124.4	9.0
TH-23, MN	Crushed Aggregate Base	135.3	7.8	129.82	4.3
US-53, OH	Crushed Aggregate Base	134.1	8.5	136.0	9.1
NCAT, SC	Crushed Granite Base	138.1	5.0	130.0	4.7
US-2, ND	Crushed Gravel Base	141.1	6.0	134.4	5.9
US-280, AL	Crushed Stone Base	148.5	6.2	147.58	3.9

NOTE: The maximum dry density and optimum water content for most of the materials and layers were determined using AASHTO T 180. The exception is the high plasticity clay from the Texas project and the North Dakota embankment material.

from the stockpiles or the roadway during construction (control strips).

Most state agencies do not have a resilient modulus testing capability, so other procedures will need to be used to establish the design or target value during construction (Darter et al. 1997). The resilient modulus was calculated at the same stress state shown in Table 21 using the regression equations that were developed from an FHWA-LTPP study (Yau and Von Quintus). The following regression equations were used:

$$M_R = k_1\left(p_a\right)\left(\frac{\theta}{p_a}\right)^{k2}\left(\frac{\tau_{oct}}{p_a}+1\right)^{k3} \tag{1}$$

Where:

θ = Bulk Stress, psi

$$\theta = \sigma_1 + \sigma_2 + \sigma_3 \tag{2}$$

τ = Octahedral shear stress, psi

$$\tau = \frac{\left((\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right)^{0.5}}{3} \tag{3}$$

p_a = Atmospheric pressure, 14.7 psi

$\sigma_{1,2,3}$ = Principal stress, psi.

$k_{1,2,3}$ = Regression constants from laboratory resilient modulus test results.

The k regression constants are material specific. The following defines the regression constants for the different materials that were tested within the field evaluation projects. These relationships for these regression constants were developed from the FHWA-LTPP study (Von Quintus and Killingsworth).

Crushed Stone Base Materials

$$k_1 = 0.7632 + 0.008\left(P_{3/8}\right) + 0.0088(LL) - 0.037\left(w_s\right) - 0.0001\left(\gamma_{dry}\right) \tag{4}$$

$$k_2 = 2.2159 - 0.0016\left(P_{3/8}\right) + 0.0008(LL) - 0.038\left(w_s\right) - 0.0006\left(\gamma_{dry}\right) + 0.00000024\left(\frac{\gamma_{dry}^2}{P_{\#40}}\right) \tag{5}$$

$$k_3 = -1.1720 - 0.0082(LL) - 0.0014\left(w_s\right) + 0.0005\gamma_{dry} \tag{6}$$

Table 24. Adjustment factors applied to the NDT modulus values to represent laboratory conditions or values at low stress states, all projects.

Project Identification		Resilient Modulus, ksi		Adjustment Factors Relating Laboratory Values to NDT Values		
		Laboratory Measured Value	Predicted with LTPP Equations	Geo Gauge	DSPA	DCP
Fine-Grained Clay Soils						
I-85 Low-Plastic Soil	Before IC Rolling	2.5	10.5	0.154	.0751	0.446
	After IC Rolling	4.0	13.1	0.223	0.113	0.606
NCAT; OK	High Plastic Clay	6.9	19.7	0.266	0.166	0.802
SH-21, TX	High Plastic Clay	26.8	19.6	1.170	0.989	3.045
Average Ratios for Fine-Grained Soil				**0.454**	**0.336**	**1.225**
Embankment Materials; Soil-Aggregate Mixture						
TH-23, MN	South Embankment	16.0	15.7	0.696	0.367	1.053
	North Embankment	16.4	16.3	0.735	0.459	0.863
US-2, ND	Embankment	19.0	19.5	1.450	0.574	0.856
SH-130, TX	Improved Soil	35.3	21.9	1.337	1.029	1.657
Average Ratios for Soil-Aggregate Mixtures; Embankments				**1.055**	**0.607**	**1.107**
Aggregate Base Materials						
Co. 103, TX	Caliche Base	---	32.3	1.214	---	1.436
NCAT, SC	Crushed Granite	14.3	36.1	0.947	0.156	---
NCAT, MO	Crushed Limestone	19.2	40.9	0.747	0.198	---
TH-23, MN	Crushed Stone, Middle	24.0	29.9	0.851	0.303	0.725
	Crushed Stone, South	26.0	35.6	0.788	0.235	0.560
US-53, OH	Crushed Stone	27.5	38.3	1.170	0.449	0.862
NCAT, FL	Limerock	28.6	28.1	0.574	0.324	0.619
US-2, ND	Crushed Aggregate	32.4	39.8	1.884	0.623	1.129
US-280, AL	Crushed Stone	48.4	49.3	1.010	0.244	0.962
Average Ratios for Aggregate Base Materials				**1.021**	**0.316**	**0.899**
Overall Average Values				**0.942**	**0.422**	**1.084**

NOTES:
1. The adjustment ratio is determined by dividing the resilient modulus measured in the laboratory at a specific stress state by the NDT estimated modulus.
2. The average ratios listed exclude the data from the I-85 low plasticity clay prior to IC rolling. The resilient modulus regression equations are provided in Equations 1 through 15.

Embankments, Soil-Aggregate Mixture, Coarse-Grained

$$k_1 = 0.5856 + 0.0130(P_{3/8}) - 0.0174(P_{\#4}) + 0.0027(P_{\#200}) + 0.0149(PI) + 0.0000016(\gamma_{max}) - 0.0426(w_s) + 1.6456\left(\frac{\gamma_{dry}}{\gamma_{Max}}\right) + 0.3932\left(\frac{w_s}{w_{Max}}\right) - 0.00000082\left(\frac{\gamma_{Max}^2}{P_{\#40}}\right) \quad (7)$$

$$k_2 = 0.7833 - 0.0060(P_{\#200}) - 0.0081(PI) + 0.0001(\gamma_{Max}) - 0.1483\left(\frac{w_s}{w_{opt}}\right) + 0.00000027\left(\frac{\gamma_{dry}^2}{P_{\#40}}\right) \quad (8)$$

$$k_3 = -0.1906 - 0.0026(P_{\#200}) + 0.00000081\left(\frac{\gamma_{opt}^2}{P_{\#40}}\right) \quad (9)$$

Embankments, Soil-Aggregate Mixture, Fine-Grained

$$k_1 = 0.7668 + 0.0051(P_{\#40}) + 0.0128(P_{\#200}) + 0.0030(LL) - 0.051(w_{opt}) + 1.179\left(\frac{\gamma_{dry}}{\gamma_{Max}}\right) \quad (10)$$

$$k_2 = 0.4951 - 0.0141(P_{\#4}) - 0.0061(P_{\#200}) + 1.3941\left(\frac{\gamma_{dry}}{\gamma_{Max}}\right) \quad (11)$$

$$k_3 = 0.9303 + 0.0293(P_{3/8}) + 0.0036(LL) - 3.8903\left(\frac{\gamma_{dry}}{\gamma_{Max}}\right) \quad (12)$$

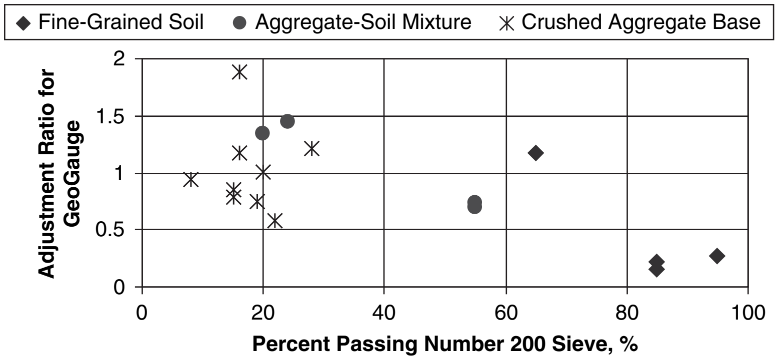
Fine-Grained Clay Soil

$$k_1 = 1.3577 + 0.0106(Clay) - 0.0437(w_s) \quad (13)$$

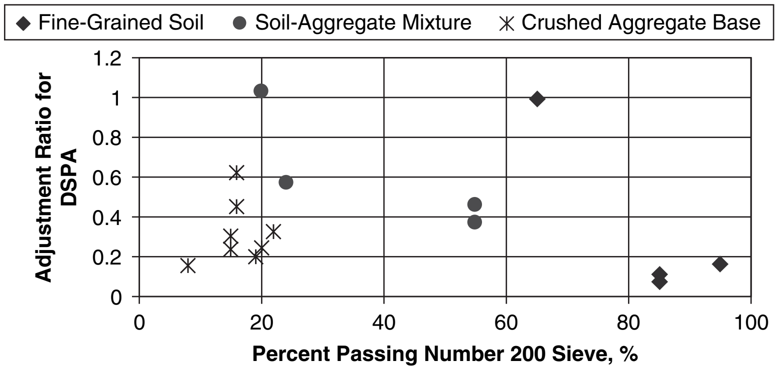
$$k_2 = 0.5193 - 0.0073(P_{\#4}) + 0.0095(P_{\#40}) - 0.0027(P_{\#200}) - 0.0030(LL) - 0.0049(w_s) \quad (14)$$

$$k_3 = 1.4258 - 0.0288(P_{\#4}) + 0.0303(P_{\#40}) - 0.0521(P_{\#200}) + 0.025(Silt) + 0.0535(LL) - 0.0672(w_{opt}) - 0.0026(\gamma_{max}) + 0.0025(\gamma_{dry}) - 0.6055\left(\frac{w_s}{w_{opt}}\right) \quad (15)$$

Figure 22 compares the laboratory measured resilient modulus values and those calculated from the regression equations (see Table 24). Use of the regression equations, on average, resulted in a reasonable prediction of the laboratory measured values. Yau and Von Quintus, however, reported that the regression equations can result in significant error and recommended that repeated load resilient modulus tests be performed.



(a) GeoGauge.



(b) DSPA.

Figure 21. Effect of the amount of fines on the adjustment ratio for the GeoGauge and DSPA devices.

2.2.2 HMA Layers

Table 25 lists the laboratory dynamic moduli measured at a loading frequency of 5.0 Hz for the in-place average mixture temperature measured during NDT. As for the unbound materials, it is expected that the modulus values determined from the deflection-based methods are affected by the supporting materials. To compensate for differences between the laboratory and field conditions, an adjustment procedure was used to estimate the modulus values from the PSPA and FWD for making relative comparisons. This field adjustment procedure is the same as that used for the unbound materials. The adjustment ratios were determined for the areas without any anomalies or physical differences from the target properties and are given in Table 26.

The PSPA adjustment ratios were found to be relatively close to unity, with the exception of the I-35/SH-130 HMA base mixture. This HMA base mixture is a very stiff mixture in the

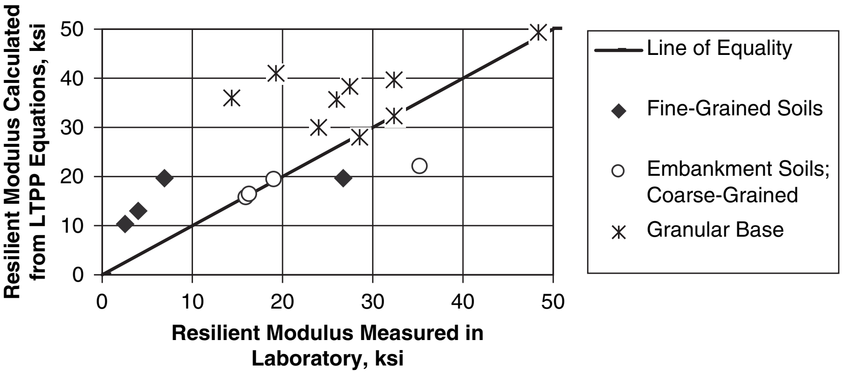


Figure 22. Comparison of the resilient modulus values measured in the laboratory to the resilient modulus values predicted with the LTPP regression equations.

Table 25. Elastic modulus values estimated from NDT devices, without any adjustments, in comparison to dynamic modulus values measured in the laboratory.

Part	Project Identification	Layer/Mixture	Laboratory Values, ksi		NDT Values, ksi	
			130 °F & 5 Hz	In Place Temp. & 5 Hz	PSPA	FWD
B	I-75, Michigan	Dense-Graded; Type 3-C	190	400	435.2	---
B	NCAT, Florida	Base, Mix; PG67	203	390	447.1	---
B	NCAT, S. Carolina	Base Mix; PG67	214	410	495.2	---
B	I-75, Michigan	Fine-Graded Surface; Type E10	255	590	676.3	---
A	I-85, Alabama	SMA Mixture	230	250	237	450
B	NCAT, Alabama	45% RAP; Sect. E-5, PG67	250	450	510.7	---
B	US-47, Missouri	Fine-Graded Surface	276	530	457.6	---
A	TH-23, Minnesota	HMA Base Mixture	319	810	480	---
A	US-280, Alabama	HMA Base; Initial Area	330	650	462	165
B	US-47, Missouri	Coarse-Graded Base	344	420	605.3	---
B	US-2, N. Dakota	Coarse-Graded Base; PG58-28	356	510	344.3	---
B	NCAT, Florida	Base Mix, SBS, PG76	366	590	475.8	---
B	NCAT, Alabama	45% RAP, Sect. E-7; PG76 (Sasobit)	421	610	444.3	---
B	NCAT, Alabama	45% RAP, Sect. E-6; PG76 (SBS)	427	640	473.4	---
B	US-53, Ohio	Coarse-graded Binder Mix	479	850	666.7	---
B	I-20, Texas	HMA Base, CMHB	520	340	435.5	---
A	US-280, Alabama	HMA Base; Supplemental Area	613	780	558	310
A	SH-130, Texas	HMA Base	965	1,750	342	725

Table 26. Dynamic modulus values measured in the laboratory and adjustment factors for the modulus estimating NDT devices.

Project/Mixture	Dynamic Modulus, ksi	Ratio or Adjustment Factor	
		PSPA	FWD
I-85 AL, SMA Overlay	250	1.055	0.556
TH-23 MN, HMA Base	810	1.688	NA
US-280 AL, HMA Base; Initial Area	650	1.407	3.939
US-280 AL, HMA Base; Supplemental Area	780	1.398	2.516
I-35/SH-130 TX, HMA Base	1,750	5.117	3.253
I-75 MI, Dense-Graded Type 3-C	400	0.919	NA
I-75 MI, Dense-Graded Type E-10	590	0.756	NA
US-47 MO, Fine-Graded Surface	530	1.158	NA
US-47 MO, Coarse-Graded Base Mix	420	0.694	NA
I-20 TX, HMA Base, CMHB	340	0.799	NA
US-53 OH, Coarse-Graded Base	850	1.275	NA
US-2 ND, Coarse-Graded Base, PG58-28	510	1.482	NA
NCAT SC, PG67 Base Mix	410	0.828	NA
NCAT FL, PG67 Base Mix	390	0.872	NA
NCAT FL, PG76 Base Mix	590	1.240	NA
NCAT AL, PG76 with RAP and Sasobit	610	1.3760	NA
NCAT AL, PG76 with RAP and SBS	640	1.352	NA
NCAT AL, PG67 with RAP	450	0.881	NA
Overall Average Ratio or Adjustment Factor		**1.128**	**2.566**

NOTES:
1. The adjustment factor or ratio was determined by dividing the dynamic modulus measured in the laboratory for the in-place temperature at a loading frequency of 5 Hz by the modulus estimated with the NDT device.
2. The laboratory dynamic modulus values listed are for a test temperature of a loading frequency of 5 Hz at the temperature of the mixture when the NDT was performed (see Table 25).
3. The overall average adjustment factor excludes the SH-130 mixture (shaded in the table) because it was found to be significantly different than any other mixture tested.

laboratory but was estimated to be similar to the US-2 HMA base with the PSPA (see Table 25). The reason for the large difference between the laboratory and field deviation from unity for this one mixture is unknown. Conversely, the FWD adjustment factors are significantly different from unity. The FWD overestimated the SMA modulus for the overlay project and underestimated the HMA base modulus for the reconstruction projects suggesting that the calculated values from the deflection basins are being influenced by the supporting materials.

On the average, the PSPA can be used to estimate the dynamic modulus measured in the laboratory HMA mixtures, while the FWD was found to be extremely variable. The PSPA ratios are variable, but that variability is less than the ratios for the unbound materials. These ratios were compared to the binder type, gradation, and other volumetric properties but no relationship was found. It is suggested that dynamic modulus tests be performed to determine the target or design value and that those results be used to calibrate the PSPA for a specific mixture. The dynamic modulus test can be performed on bulk mixture compacted to the expected in-place density during the mixture verification process or during construction of a control strip.

2.3 Accuracy and Precision

Important parameters in QA are the accuracy and precision of a test method. The higher the precision of a test method, the fewer tests need to be completed at some confidence level for estimating properties of the population or lot and making the “right” decision regarding the quality of the lot. This section evaluates and compares the variability measured within the field evaluation projects with different NDT devices. The more precise result, however, does not automatically imply that the test method can identify physical differences or information about the population related to performance.

2.3.1 NDT Devices for Unbound Layers

2.3.1.1 Variability of Response Measurements

Figures 23 through 26 compare the COV to the average modulus measured by each device. All COV point comparisons were for the same test area. Thus, the material variance should be the same between the different NDT devices.

The GeoGauge consistently had the lower COV, and that value decreases with increasing material stiffness (Figure 26). The variations of the GeoGauge measurements were found to be less dependent on type and size of aggregate, as well as less dependent on the underlying materials for the thicker layers tested. The reason for the higher COV values for the other devices is that the DCP penetration rate is dependent on the amount and size of coarse aggregate particles, while the LWD modulus values are more dependent on the underlying materials. The DSPA is dependent on the water content variations nearer the surface (water content-density gradients) and the amount of fines in coarse-gained materials.

The DSPA had higher variability when testing stiff materials that had water contents significantly below the optimum value or where the surface had been primed. Some layers tested had a significant modulus gradient near the surface, which had a much larger effect on the DSPA responses. Some sites had a positive gradient (modulus increases with depth), while other sites had a negative gradient. Those sites with positive modulus gradients generally had higher adjustment ratios, while those with negative gradients had lower ratios. These modulus gradients were confirmed with the DCP—the only device that could readily measure these gradients in real time. Figure 27 shows some examples of the change in modulus with depth, as calculated from the penetration rate (see Equation 16).

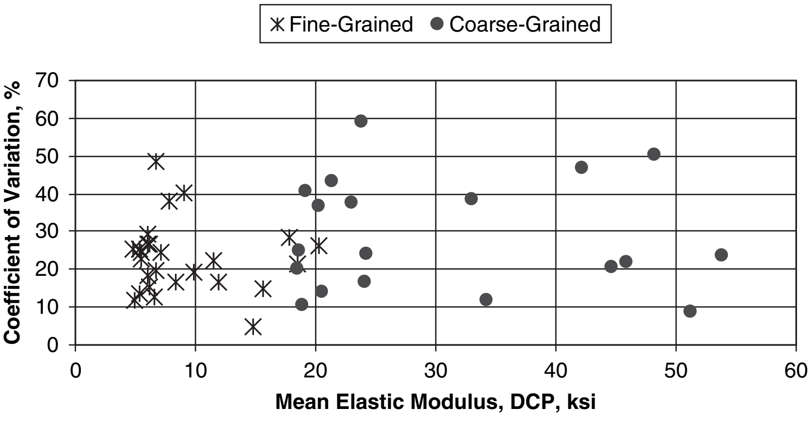


Figure 23. Coefficient of variation versus the mean modulus calculated from the DCP penetration rates.

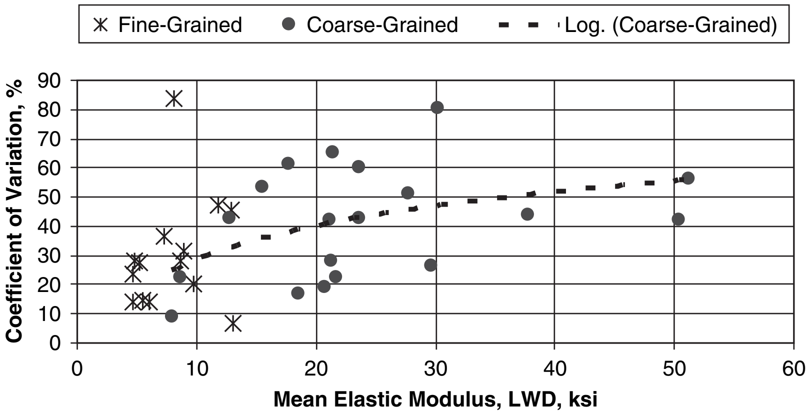


Figure 24. Coefficient of variation versus the mean modulus calculated from the LWD deflections.

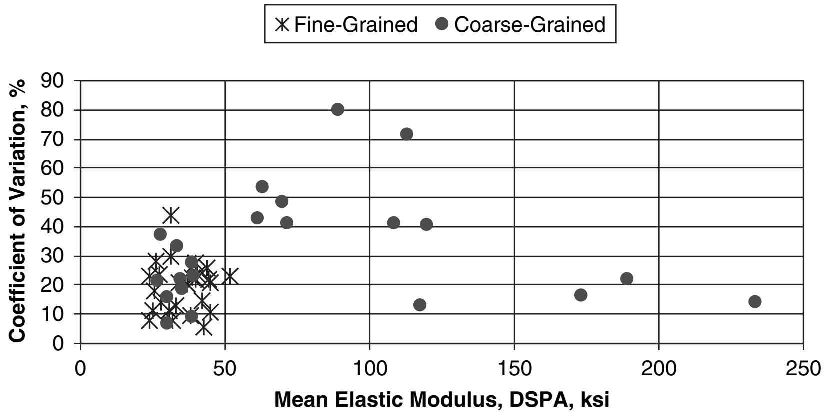


Figure 25. Coefficient of variation versus the mean modulus determined from the DSPA responses.

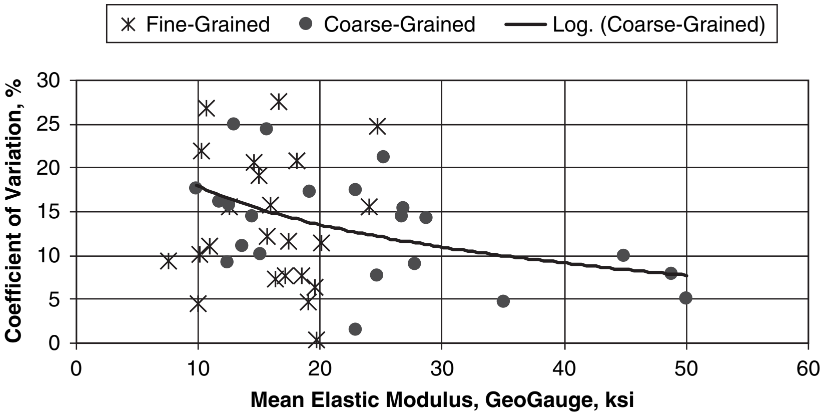
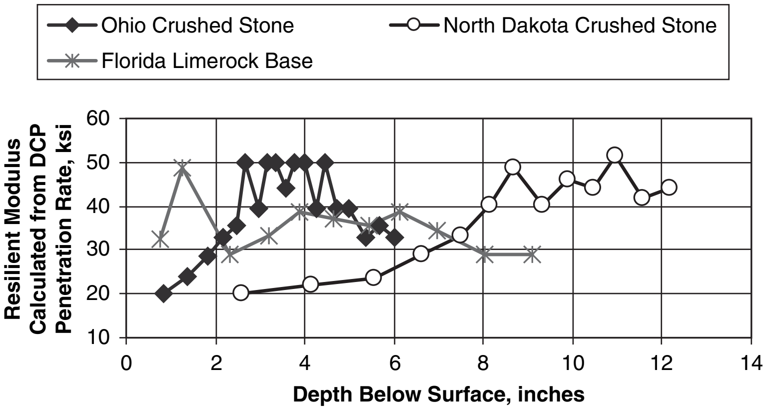
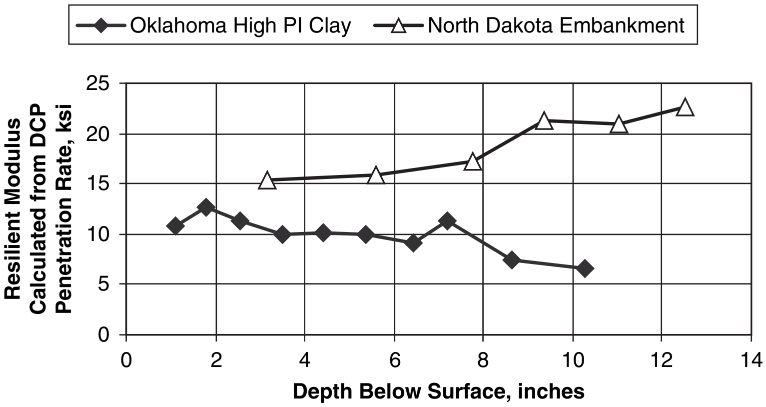


Figure 26. Coefficient of variation versus the mean modulus determined from the GeoGauge responses.



(a) Aggregate Base Materials/Layers.



(b) Subgrade and Embankment Materials/Layers.

Figure 27. Modulus gradients in unbound layers, as determined with the DCP.

$$E_R = 17.6\left(\frac{292}{(DPI)^{1.12}}\right)^{0.64} \qquad (16)$$

Where:

E_R = Resilient modulus, MPa.

DPI = Penetration rate or index, mm/blow.

The DSPA was also placed in different directions relative to the roller direction for measuring modulus; the other NDT devices do not have this capability—only an equivalent or average modulus value is reported for all directions. Figure 28 compares the difference between the modulus values parallel and perpendicular to the roller's direction to the modulus measured parallel to roller direction. For less stiff materials (especially fine-grained materials), there is no difference between the two readings. For stiffer, coarse-grained materials, however, there is a slight bias. The moduli measured parallel to roller direction were slightly higher, on the average. This difference and bias resulted in a higher COV for the clustered measurements.

The LWD had higher variability in test results and lower success rates. The higher COV value is related to the variability in the underlying layers and their influence on the measured response with the deflection measuring devices, as well as thickness variations of the layer being evaluated. A constant layer thickness and subsurface condition were used.

The variability of the GPR and EDG for measuring the volumetric properties (density and fluids content) was found to be significantly different from each other, as well as from the agencies' QA data, when available. Both of these devices had very poor success rates in identifying physical differences between different sections. The EDG resulted in very low variability in its estimates of dry density and water content within a specific area or test section. Most of the COV values for both properties were less than 2 percent (see Tables 27 and 28). Thus, the average values determined at a test point and within a test section did not deviate significantly from the project average that was determined from nuclear density gauges and/or sand-cone tests.

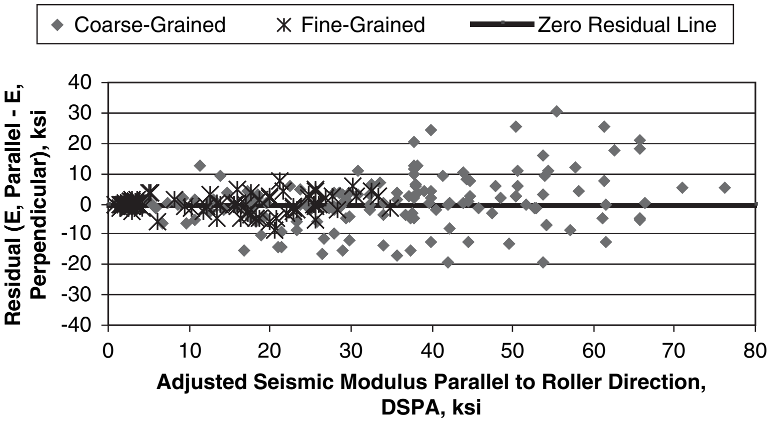


Figure 28. DSPA modulus values measured parallel to roller direction versus the difference between modulus values parallel and perpendicular to roller direction.

Conversely, the GPR resulted in high variability of the dielectric values (see Table 29), as well as for the dry densities. The dry densities determined in some areas exceeded 160 pcf (see Figure 29)—an unlikely value. The reason for the improbably high as well as low values within a project was the assumption used to convert the dielectric values to dry densities—a constant water content for all areas within a lot was assumed. As a result, the GPR data interpretation technique needs to be improved to determine the dry density and water content along the project prior to day-to-day use in QA programs.

Table 27. Dry densities measured with the EDG, pcf.

Project Identification	Area	A	B	C	D
I-85 Embankment, Silty Clay; Section 1, Before IC Rolling	Mean, pcf	**107.92**	108.9	108.6	107.7
	COV, %	**1.3**	0.5	1.1	1.7
I-85 Embankment, Silty Clay; Section 2, Before IC Rolling	Mean, pcf	**107.2**	107.5	108.9	107.2
	COV, %	**0.8**	0.8	1.1	1.9
I-85 Embankment, Silty Clay; Section 1, After IC Rolling	Mean, pcf	108.1	108.2	108.5	108.4
	COV, %	1.0	0.5	0.7	0.3
I-85 Embankment, Silty Clay; Section 2, After IC Rolling	Mean, pcf	107.4	107.7	108.0	107.6
	COV, %	0.5	0.5	0.8	1.3
TH-23 Embankment, Silt-Sand-Gravel Mix; North Section	Mean, pcf	**123.9**	123.7	124.4	---
	COV, %	**0.4**	0.1	1.0	---
TH-23 Embankment, Silt-Sand-Gravel Mix; South Section	Mean, pcf	122.5	122.9	**122.9**	---
	COV, %	1.8	1.8	**0.8**	---
SH-130 Improved Embankment; Section 1	Mean, pcf	123.7	123.7	124.9	---
	COV, %	0.3	0.1	0.6	---
SH-130 Improved Embankment; Section 2	Mean, pcf	122.6	123.1	122.7	---
	COV, %	2.0	2.0	0.8	---
SH-130 Improved Embankment; Section 3	Mean, pcf	123.3	122.3	123.7	
	COV, %	1.4	0.1	0.2	
TH-23 Crushed Aggregate; North Section	Mean, pcf	129.9	129.8	129.8	---
	COV, %	0	0	0	---
TH-23 Crushed Aggregate; Middle Section	Mean, pcf	129.8	129.8	**129.8**	---
	COV, %	0	0	**0**	---
TH-23 Crushed Aggregate; South Section	Mean, pcf	**129.8**	129.9	129.8	---
	COV, %	**0.1**	0.1	0	---
US-280 Crushed Stone; Section 1	Mean, pcf	147.4			
	COV, %	0.7			
US-280 Crushed Stone; Section 2	Mean, pcf	148.8			
	COV, %	0.3			
US-280 Crushed Stone; Section 3	Mean, pcf	145.9			
	COV, %	0.5			
US-280 Crushed Stone; Section 4	Mean, pcf	**148.2**			
	COV, %	**0.3**			
Note: The shaded cells designate those areas with anomalies (refer to Table 14); the black cells denote the weaker areas, while the gray cells denote the stronger areas tested within a specific project.					

Table 28. Water content measured with the EDG, percent.

Project Identification	Area	A	B	C	D
I-85 Embankment, Silty Clay; Section 1, Before IC Rolling	Mean, %	**16.9**	16.8	16.9	16.9
	COV, %	**0.8**	0.3	0.3	1.0
I-85 Embankment, Silty Clay; Section 2; Before IC Rolling	Mean, %	**16.9**	16.9	16.8	17.0
	COV, %	**0.7**	0.3	0.3	1.5
I-85 Embankment, Silty Clay; Section 1, After IC Rolling	Mean, %	16.9	16.9	16.9	16.9
	COV, %	0.5	0.3	0.4	0
I-85 Embankment, Silty Clay; Section 2, After IC Rolling	Mean, %	17.0	16.9	16.9	16.9
	COV, %	0.5	0.3	0	0.7
TH-23 Embankment, Silt-Sand-Gravel Mix; North Section	Mean, %	**8.0**	8.0	7.6	
	COV, %	**5.1**	1.1	11.9	
TH-23 Embankment, Silt-Sand-Gravel Mix; South Section	Mean, %	9.8	8.7	**7.6**	
	COV, %	7.5	7.3	**15.8**	
SH-130 Improved Embankment; Section 1	Mean, %	8.1	8.05	7.23	
	COV, %	4.4	1.2	6.8	
SH-130 Improved Embankment; Section 2	Mean, %	8.85	8.43	8.7	
	COV, %	19.8	21.6	8.4	
SH-130 Improved Embankment; Section 3	Mean, %	8.35	9.1	8.05	
	COV, %	14.4	1.6	0.9	
TH-23 Crushed Aggregate; North Section	Mean, %	4.26	4.28	4.34	
	COV, %	1.3	1.0	2.1	
TH-23 Crushed Aggregate; Middle Section	Mean, %	4.24	4.28	**4.30**	
	COV, %	1.3	2.0	**1.6**	
TH-23 Crushed Aggregate; South Section	Mean, %	**4.18**	4.18	4.38	
	COV, %	**3.9**	3.9	1.0	
US-280 Crushed Stone; Section 1	Mean, %	3.92			
	COV, %	3.1			
US-280 Crushed Stone; Section 2	Mean, %	4.18			
	COV, %	2.9			
US-280 Crushed Stone; Section 3	Mean, %	3.77			
	COV, %	2.9			
US-280 Crushed Stone; Section 4	Mean, %	**4.06**			
	COV, %	**2.6**			

Note: The shaded cells designate those areas with anomalies (refer to Table 14); the black cells denote weaker areas, while the gray cells denote the stronger areas tested within a specific project.

2.3.1.2 Standard Error

Another reason for using the adjustment ratios in evaluating each NDT device is to eliminate or reduce bias by assuming that the target value is the laboratory resilient modulus measured at a specific stress state. Figure 30 compares the laboratory measured resilient modulus values to those estimated with different NDT devices but adjusted to laboratory conditions, while Figure 31 presents the residuals (laboratory resilient modulus minus the NDT modulus), assuming that the laboratory value is the target value. On the average, the adjusted elastic modulus from all devices compare reasonably well with the laboratory measured resilient modulus. Table 30 contains the tabulation of the mean of the residuals and standard error for the NDT devices that provide a direct measure of material stiffness.

In summary, the GeoGauge, DSPA, and DCP all provide good estimates with negligible bias (effect of adjustment ratios) of the laboratory measured resilient modulus values. The GeoGauge has the lower standard error. The LWD has a higher bias and over two times the standard error, in comparison to the GeoGauge.

2.3.2 NDT Devices for HMA Mixtures

2.3.2.1 Variability of Response Measurements

Figure 32 compares the COV between different technologies and devices (PSPA, FWD, PQI, and GPR). The PQI consistently had a low COV relative to the other devices, while the FWD had the largest value. It should be noted that a low COV does not necessarily mean that the device is providing an accurate measure of the HMA mixture property and variability. One reason for the lower COV values for the PQI relative to the other devices is that five tests were performed at each test point. In other words, the testing and sampling error or differences get averaged out through the testing sequence.

Two versions of the GPR air-coupled antennas were used. The first version was a single-antenna method, which was only used in Part A of the field evaluation. The second version included the use of multiple antennas and the EPIC Hyper Optics™ proprietary data interpretation system. The EPIC GPR system was supposed to be used along the NCAT, Missouri (US-47), and Texas (I-20) sections; however, weather

Table 29. Dielectric values measured with the GPR on the unbound layers.

Project Identification	Area	A	B	C	D
I-85 Embankment, Silty Clay; Section 1, Before Rolling	Mean	**15.38**	15.79	14.29	15.19
	COV, %	**17.8**	23.3	53.6	25.7
I-85 Embankment, Silty Clay; Section 2, Before IC Rolling	Mean	**13.91**	17.47	16.82	16.38
	COV, %	**29.0**	20.5	30.7	24.1
I-85 Embankment, Silty Clay; Section 1, After IC Rolling	Mean	20.37	21.23	21.61	23.23
	COV, %	15.8	10.6	15.0	12.6
I-85 Embankment, Silty Clay; Section 2; After IC Rolling	Mean	19.13	23.75	23.77	25.36
	COV	10.2	10.7	17.6	8.4
TH-23 Embankment, Silt-Sand-Gravel Mix; South Section	Mean	23.004	13.468	**19.334**	---
	COV, %	11.3	7.0	**14.4**	---
TH-23 Embankment, Silt-Sand-Gravel Mix; North Section	Mean	**20.324**	34.438	23.882	---
	COV, %	**22.2**	32.7	22.7	---
SH-130 Improved Embankment; Section 1	Mean	9.225	10.00	7.65	---
	COV	33.1	42.3	42.9	---
SH-130 Improved Embankment; Section 2	Mean	12.875	8.875	9.825	---
	COV	90.3	47.4	20.1	
SH-130 Improved Embankment; Section 3	Mean	8.775	9.025	11.85	
	COV, %	51.5	50.8	48.7	---
TH-23 Crushed Aggregate; North Section	Mean	---	8.796	10.042	---
	COV, %	---	1.6	5.4	---
TH-23 Crushed Aggregate; Middle Section	Mean	---	8.950	**10.87**	---
	COV, %	---	6.1	**10.9**	---
TH-23 Crushed Aggregate; South Section	Mean	---	9.792	10.378	---
	COV, %	---	8.2	4.3	---
US-280 Crushed Stone; Section 1	Mean	11.723			
	COV, %	8.3			
US-280 Crushed Stone; Section 2	Mean	12.222			
	COV, %	11.4			
US-280 Crushed Stone; Section 3	Mean	11.919			
	COV, %	7.3			
US-280 Crushed Stone; Section 4	Mean	**11.569**			
	COV, %	**7.0**			

Notes:

- The shaded cells designate those areas with anomalies (refer to Table 14); the black cells denote the weaker areas, while the gray cells denote the stronger areas tested within a specific project.
- Due to construction sequencing, lane A of the TH-23 crushed aggregate base sections could not be tested with the GPR after it arrived on site.

delays and equipment/plant problems resulted in changes to the testing schedule. These schedule changes resulted in conflicts with other projects, so ultimately, this system was used only on the NCAT test sections.

Data were made available for use from other projects in Florida, which were not included in the original field evaluation (Greene 2007; Greene and Hammons 2006). The EPIC system is reported to have much more accurate and repeatable estimates of HMA volumetric properties. One reason for this increased accuracy and precision is that it does not rely on the assumptions that were included in the single antenna method used along the Part A projects. The precision and bias for both devices and systems are provided in the next section.

2.3.2.2 Standard Error

As for the unbound materials, the adjustment ratios were used in evaluating the PSPA and FWD to reduce bias by assuming that the target value is the laboratory dynamic modulus measured at a specific load frequency and an average in-place mix temperature. Figure 33 compares the PSPA and FWD modulus values that have been adjusted to laboratory conditions using the factors or ratios listed in Table 26. On the average, the adjusted modulus values compare reasonably well to one another. Table 31 contains the mean of the residuals (laboratory dynamic modulus minus the NDT modulus) and standard error from the expected laboratory value—excluding all measurements taken in areas with anomalies, segregation, and along longitudinal joints.

While the difference between the two NDT devices is small, the PSPA had the lower residual and standard error.

2.3.3 Summary

Tables 32, 33, and 34 contain the statistical analyses of the NDT devices included in the field evaluation projects. This

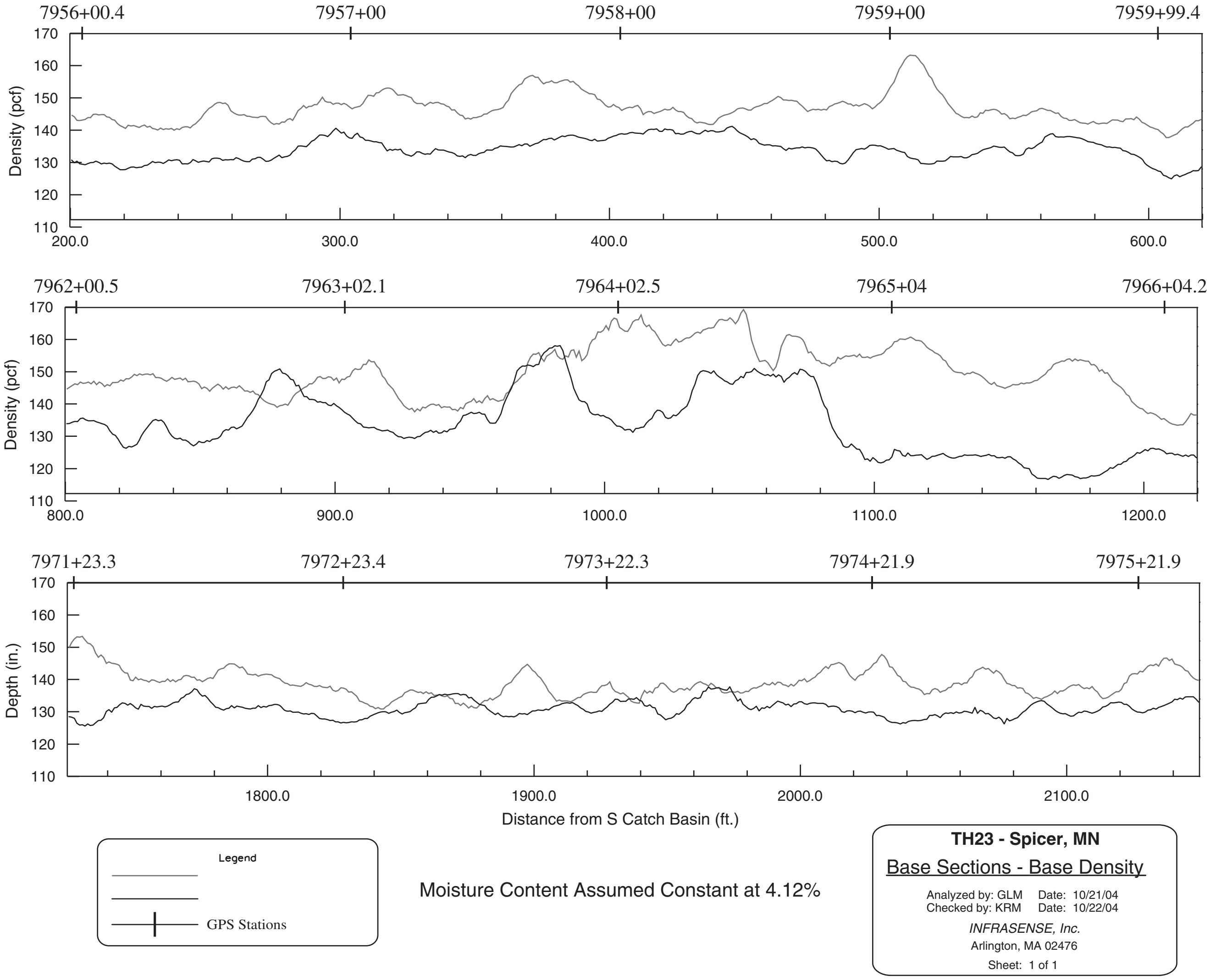


Figure 29. Density profiles generated from the GPR test results for the crushed aggregate base layer placed along the TH-23 reconstruction project.

information is grouped into two areas—those NDT devices with an acceptable to excellent success rate and those with poor success rates in identifying material/layer differences.

2.4 Comparison of Results Between NDT Technologies

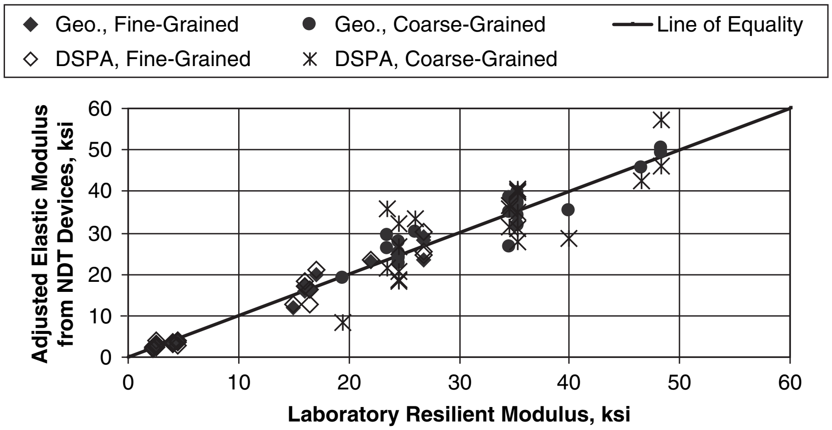
This section provides a brief evaluation and comparison of the test results between different technologies to determine the reasons for the low success rates of the DCP, LWD, GPR, and EDG.

2.4.1 NDT Modulus Comparisons

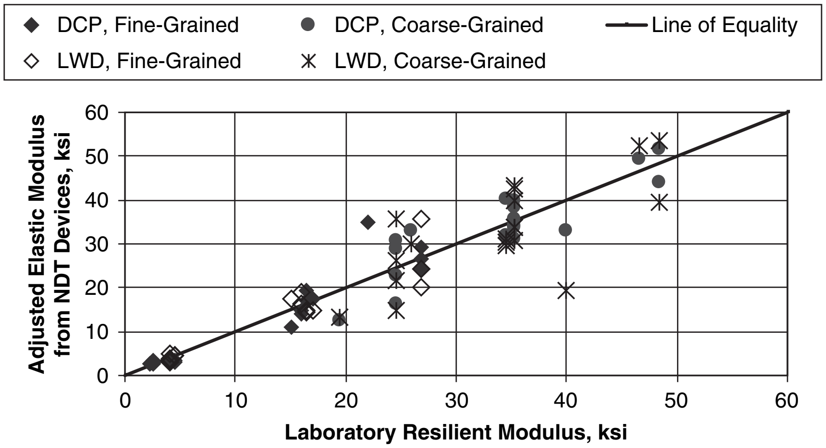
Figure 34 compares the NDT modulus values used to identify areas with physical differences in the unbound layers, except that the NDT values have been adjusted to laboratory conditions with the adjustment ratios listed in Table 24. Figure 34(a) includes a comparison of the individual test points, while Figure 34(b) compares the data on a project basis. Figure 33 compared the adjusted PSPA and FWD modulus for the HMA layers using the adjustment ratios listed in Table 25.

The adjustment procedure reduced the bias between the different devices, but not the dispersion. Thus, any of these NDT modulus estimating devices can be used to estimate the resilient modulus of the material with proper calibration at the beginning of the project, with some exceptions.

- Deflection-Based Devices: The calculated modulus values from the deflection-based devices can be affected greatly by the underlying materials and soils. For example, the crushed stone base material placed in area 4 along US-280 near Opelika, Alabama, is a stiff and dense material, even though

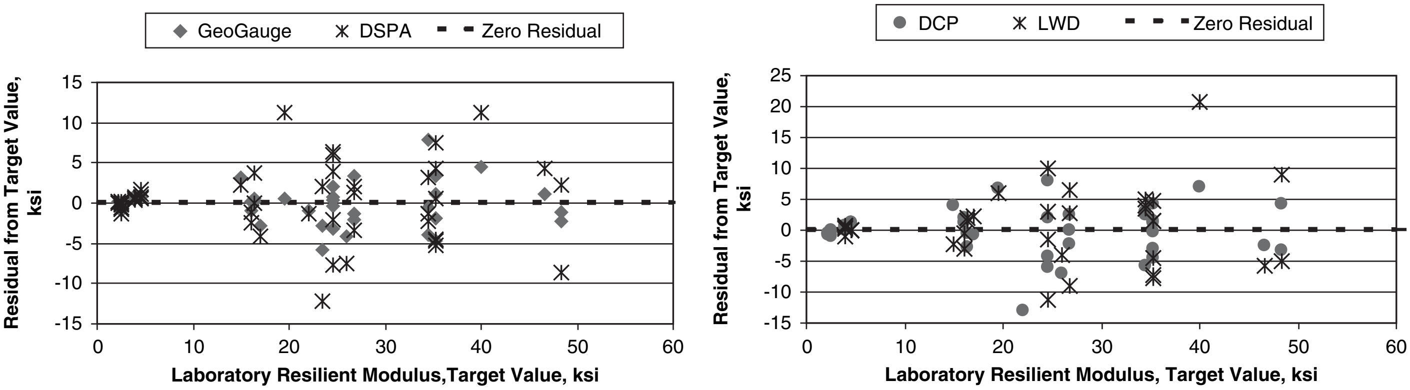


(a) DSPA and the GeoGauge.



(b) Deflection-Based and DCP methods.

Figure 30. Laboratory resilient modulus versus adjusted NDT modulus.



(a) GeoGauge and DSPA.

(b) DCP and LWD.

Figure 31. Residuals (laboratory minus NDT modulus values) versus adjusted NDT modulus.

Table 30. Tabulation of the mean of the residuals and standard error for NDT devices.

NDT Device	GeoGauge	DSPA	DCP	LWD
Mean Residual, ksi	-0.117	0.149	-0.078	0.614
Standard Error, ksi	2.419	4.486	3.768	5.884

the deflection-based devices found it to be weaker than the other areas tested with a value less than 20 ksi. All other NDT devices estimated the modulus for area 4 to be about 35 ksi or higher. An in-place modulus of 20 ksi for this material is too low. Thus, variations in the subsurface layers or materials/soils can incorrectly result in significant bias in the resilient modulus.

- DSPA: The DSPA can significantly overestimate the laboratory measured resilient modulus values. The US-280 crushed stone base was dry or significantly below the optimum water content during testing in some areas. It is believed that the surface of this dense, dry crushed stone is responding like a bound layer—resulting in a much higher modulus of the entire layer. In fact, the surface of this material actually exhibited radial cracks during the seating drop of the DCP. Figure 35 shows the estimated modulus with depth from the DCP.

Table 31. Tabulation of the mean of the residuals and standard error for NDT devices from the expected laboratory value.

NDT Device	PSPA	FWD
Mean Residual, ksi	13.5	39.0
Standard Error, ksi	76	87

2.4.2 NDT Volumetric Property Comparisons

2.4.2.1 Unbound Layers

The EDG and GPR were used to estimate the volumetric properties of the unbound materials. The following list provides a summary of the response measurements to the dry

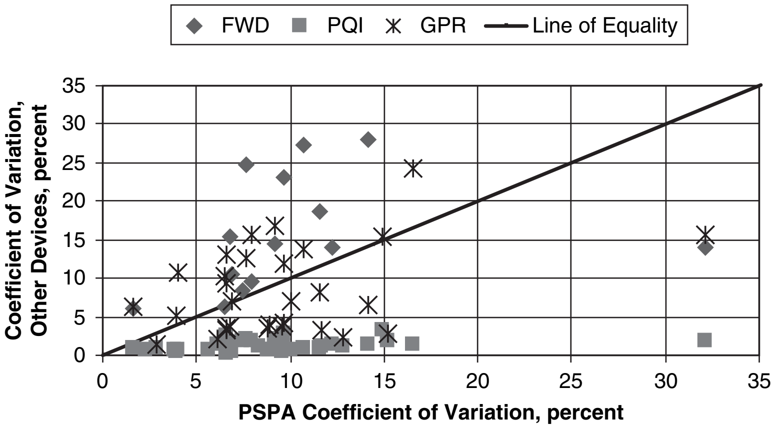


Figure 32. Comparison of coefficients of variation of different NDT devices.

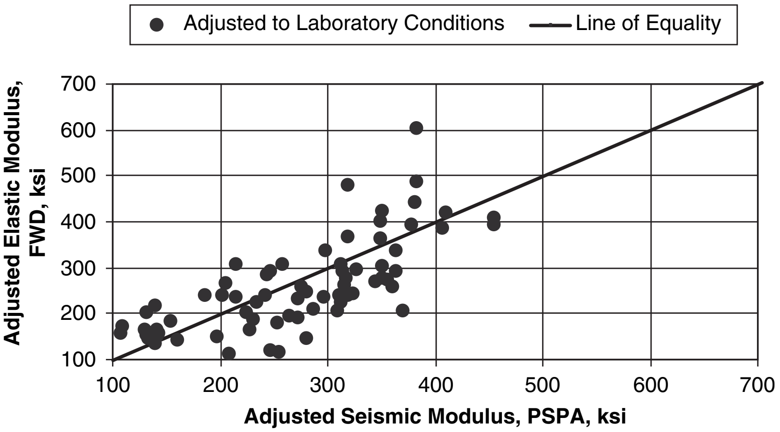


Figure 33. Comparison of the PSPA and FWD modulus values adjusted to laboratory conditions.

Table 32. NDT device and technology variability analysis; standard error.

Material	NDT Devices	Material/Layer Property				
		Structural		Volumetric		
		Thickness, in.	Modulus, ksi	Density, pcf	Air Voids, %	Fluids Content
NDT Devices with Good Success Rates Based on Modulus or Volumetric Properties; see Section 2.1.1						
Fine-Grained Soils	GeoGauge	NA	**2.5**	NA	NA	NA
	DSPA	NA	**4.5**	NA	NA	NA
Coarse-Grained Soils & Aggregate Base	GeoGauge	NA	**2.5**	NA	NA	NA
	DSPA	NA	**4.5**	NA	NA	NA
HMA Mixtures	PSPA	NA	**76**	NA	NA	NA
	PQI & PT	NA	**NA**	**1.7**	NA	NA
NDT Devices with Poor Success Rates Based on Modulus or Volumetric Properties; see Section 2.1.2						
Fine-Grained Soils	DCP	NA	**3.8**	NA	NA	NA
	LWD	NA	**5.9**	NA	NA	NA
	GPR	NA	NA	NA	NA	NA
	EDG	NA	NA	**0.8**	NA	**0.2**
Coarse-Grained Soils & Aggregate Base	DCP	NA	**3.8**	NA	NA	NA
	LWD	NA	**5.9**	NA	NA	NA
	GPR	**0.8**	NA	**3.4**	NA	NA
	EDG	NA	NA	**1.0**	NA	**0.2**
HMA	FWD	NA	**87**	NA	NA	NA
	GPR; Single	**0.25**	NA	NA	**0.40**	NA
	GPR; Multiple	**0.27**	NA	**1.6**	**0.22**	**0.18**

NOTES:
1. The standard error for the modulus estimating devices is based on the adjusted modulus values that have been adjusted to laboratory conditions.
2. The US-280 project with the PATB was removed for the GPR (single antenna) thickness data—it was the only site that resulted in a significant bias of layer thickness and the only one with a PATB layer directly beneath the layer tested.

Table 33. NDT device and technology variability analysis; 95 percent precision tolerance.

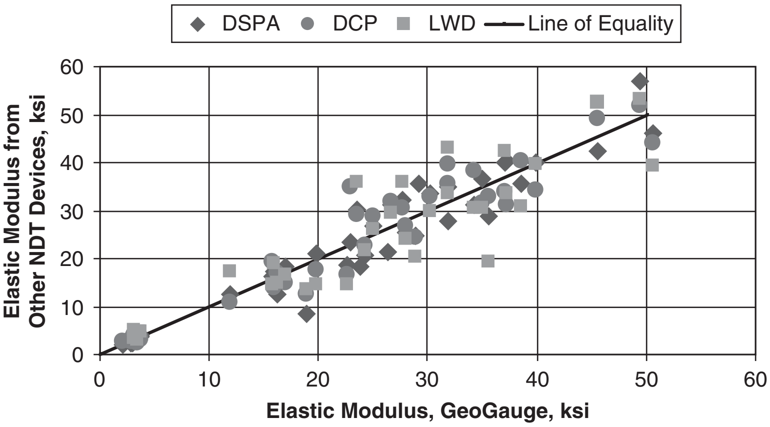
Material	NDT Devices	Material/Layer Property				
		Structural		Volumetric		
		Thickness, in.	Modulus, ksi	Density, pcf	Air Voids, %	Fluids Content
NDT Devices with Good Success Rates Based on Modulus or Volumetric Properties; see Section 2.1.1						
Fine-Grained Soils	GeoGauge	NA	**4.9**	NA	NA	NA
	DSPA	NA	**8.8**	NA	NA	NA
Coarse-Grained Soils & Aggregate Base	GeoGauge	NA	**4.9**	NA	NA	NA
	DSPA	NA	**8.8**	NA	NA	NA
HMA Mixtures	PSPA	NA	**150**	NA	NA	NA
	PQI & PT	NA	NA	**3.4**	NA	NA
NDT Devices with Poor Success Rates Based on Modulus or Volumetric Properties; see Section 2.1.2						
Fine-Grained Soils	DCP	NA	**7.4**	NA	NA	NA
	LWD	NA	**11.6**	NA	NA	NA
	GPR	NA	NA	NA	NA	NA
	EDG	NA	NA	**1.6**	NA	**0.4**
Coarse-Grained Soils & Aggregate Base	DCP	NA	**7.4**	NA	NA	NA
	LWD	NA	**11.6**	NA	NA	NA
	GPR	**1.5**	NA	**6.7**	NA	NA
	EDG	NA	NA	**2.0**	NA	**0.4**
HMA	FWD	NA	**170.5**	NA	NA	NA
	GPR; Single	**0.49**	NA	NA	**0.8**	NA
	GPR; Multiple	**0.55**	NA	**3.1**	**0.4**	**0.36**

NOTES:
1. The precision tolerance for the modulus estimating devices is based on the adjusted modulus values that have been adjusted to laboratory conditions.
2. The US-280 project with the PATB was removed for the GPR (single antenna) thickness data—it was the only site that resulted in a significant bias of layer thickness and the only one with a PATB layer directly beneath the layer tested.

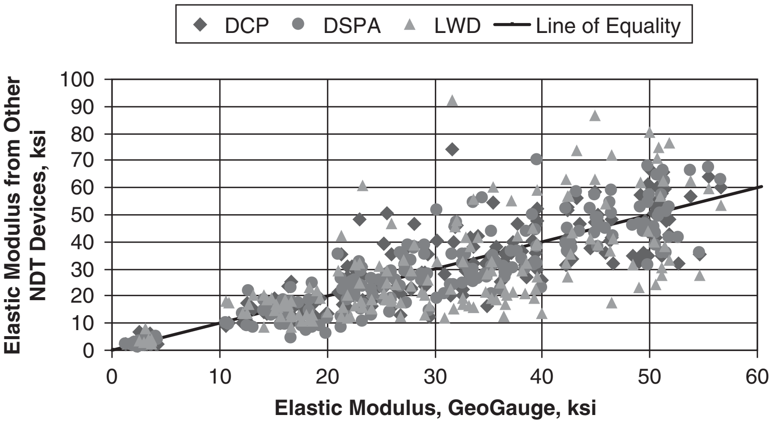
Table 34. NDT device and technology variability analysis; combined or pooled standard deviation.

Material	NDT Devices	Material/Layer Property				
		Structural		Volumetric		
		Thickness, in.	Modulus, ksi	Density, pcf	Air Voids, %	Fluids Content
NDT Devices with Good Success Rates Based on Modulus or Volumetric Properties; see Section 2.1.1						
Fine-Grained Soils	GeoGauge	NA	**1.1**	NA	NA	NA
	DSPA	NA	**1.2**	NA	NA	NA
Coarse-Grained Soils & Aggregate Base	GeoGauge	NA	**1.8**	NA	NA	NA
	DSPA	NA	**1.5**	NA	NA	NA
HMA Mixtures	PSPA	NA	**56**	NA	NA	NA
	PQI & PaveTracker	NA	NA	**2.5**	NA	NA
NDT Devices with Poor Success Rates Based on Modulus or Volumetric Properties; see Section 2.1.2						
Fine-Grained Soils	DCP	NA	**1.9**	NA	NA	NA
	LWD	NA	**2.0**	NA	NA	NA
	GPR	NA	NA	**4.2**	NA	NA
	EDG	NA	NA	**0.7**	NA	**0.5**
Coarse-Grained Soils & Aggregate Base	DCP	NA	**5.3**	NA	NA	NA
	LWD	NA	**2.0**	NA	NA	NA
	GPR	**0.6**	**NA**	**3.0**	NA	NA
	EDG	NA	**NA**	**0.8**	NA	**0.6**
HMA	FWD	NA	**55**	NA	NA	NA
	GPR; Single	**0.3**	**NA**	NA	**2.1**	NA
	GPR; Multiple	NA	NA	NA	NA	NA

NOTES:
1. The pooled standard deviations for the modulus estimating devices are based on the adjusted modulus values that have been adjusted to laboratory conditions.
2. The US-280 project with the PATB was removed for the GPR (single antenna) thickness data—it was the only site that resulted in a significant bias of layer thickness and the only one with a PATB layer directly beneath the layer tested.



(b) Comparison of adjusted modulus values on a project basis.



(a) Comparison of adjusted modulus values on a point-by-point basis.

Figure 34. Comparison of adjusted modulus values determined from different NDT devices.

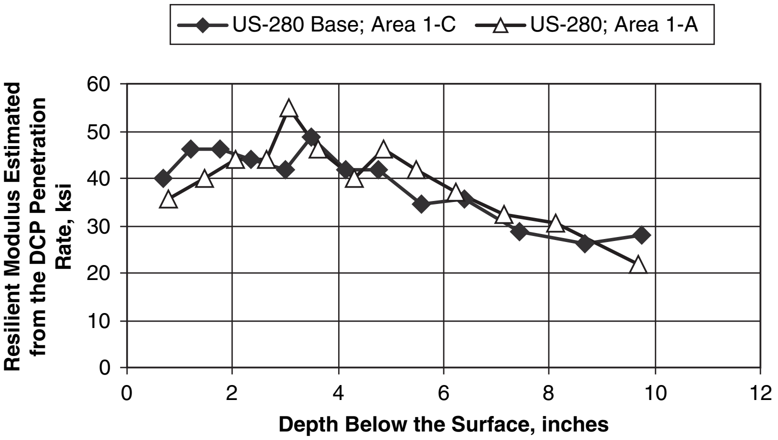


Figure 35. Modulus gradient measured with the DCP for the US-280 crushed stone base material.

densities obtained from construction records and traditional volumetric tests.

- Figure 36 compares the dielectric values to the dry densities measured with the EDG. No good correlation was found between the different materials tested. In addition, no defined relationship was found between the two response measurements for the same material. This observation suggests that there are different properties affecting the EDG and GPR results—none of which could identify the physical differences at a reasonable success rate.
- Figure 37 compares the GPR dielectric values to the dry density measured with different devices—the EDG, nuclear density gauges, and sand-cone tests. No good correlation was found; only a trend was identified between the GPR results and the densities obtained from construction records. As the dry density increased, the GPR dielectric values decreased, but across significantly different materials. Changes in material density along the same project were poorly correlated to changes in the dielectric value.
- Figure 38 compares the dry densities measured with the EDG to those measured with a traditional nuclear density gauge. There are two definite groups of data—one for fine-grained soils and the other for crushed aggregate base materials. As the dry density increased between different materials, the density from the EDG also increased. Within each group, however, no reasonable relationship was found.

2.4.2.2 HMA Layers

Figure 39 compares the air voids measured with the GPR to the results from other devices and methods. Figure 39(a) compares the densities measured directly with the nuclear density

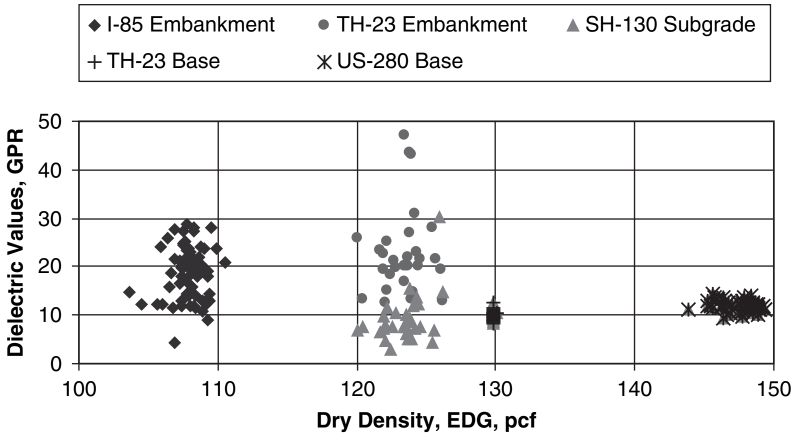


Figure 36. GPR dielectric values versus the EDG dry densities measured along different projects.

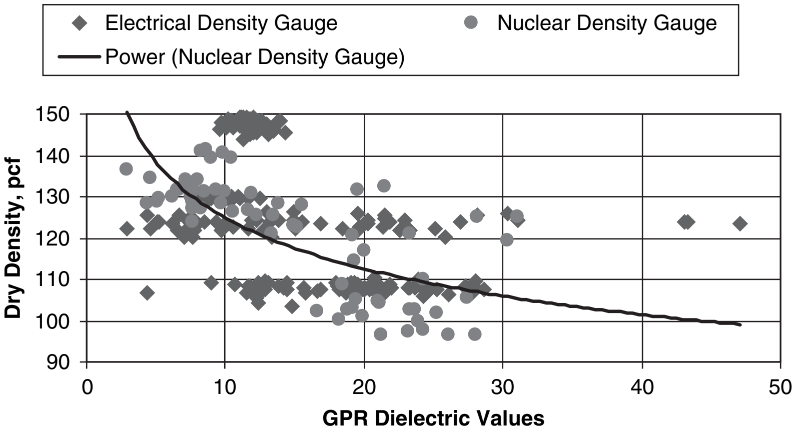


Figure 37. GPR dielectric values versus dry densities measured with nuclear and non-nuclear density gauges.

gauge and PQI. There is a general trend between the air void measurements and densities—as air voids increase, the density decreases, but any correlation is poor. There are significant differences between the volumetric properties measured with these different devices. Figure 39(b) compares the air voids calculated from the maximum theoretical density provided for each mixture to the air voids estimated from the GPR dielectric values. As shown, no correlation exists between the devices from the field evaluation projects included in this study.

Figure 40 compares the densities measured with the nuclear density gauge and the PQI along the longitudinal joints and in areas with localized segregation. These densities are compared with the values measured away from the joints and outside any noticeable segregation. There is a greater variation in density measured with the nuclear device than with the PQI. However, the wet surface may have affected the PQI readings when the measurements were recorded.

2.4.3 Volumetric—Modulus Comparisons

2.4.3.1 Unbound Layers

The in-place modulus of the unbound materials is dependent on its density. The FHWA-LTPP study reported that the laboratory resilient modulus was dependent on dry density for all unbound materials (Yau and Von Quintus). In fact, density and water content are two volumetric properties that have a significant affect on the modulus of the material. Thus, it follows that the NDT devices resulting in a material modulus should be related to the density and/or water content of the material. Dry densities and water contents were extracted from the QA reports for the different projects included in the field evaluation.

Figure 41 compares the average modulus values estimated from the different NDT devices and dry densities reported by the individual agencies during construction.

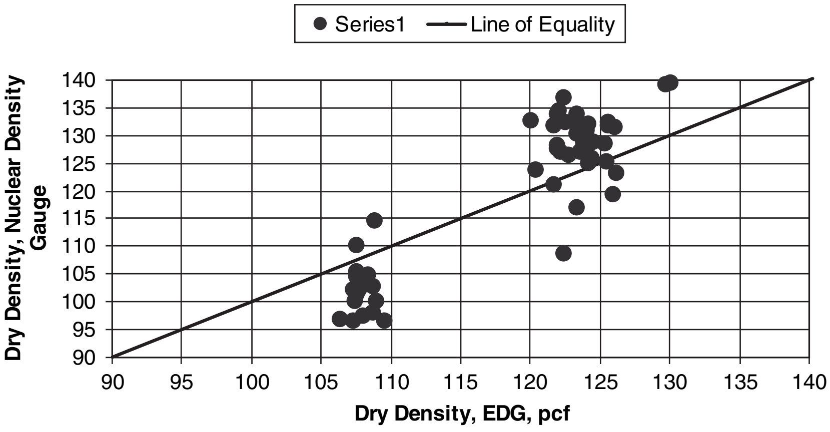
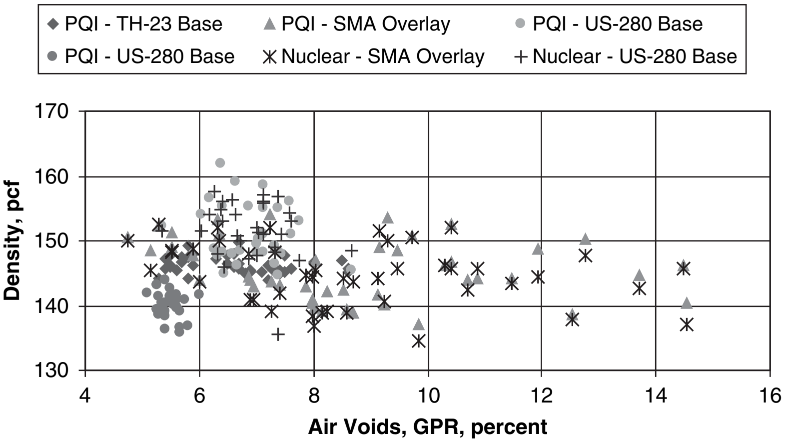
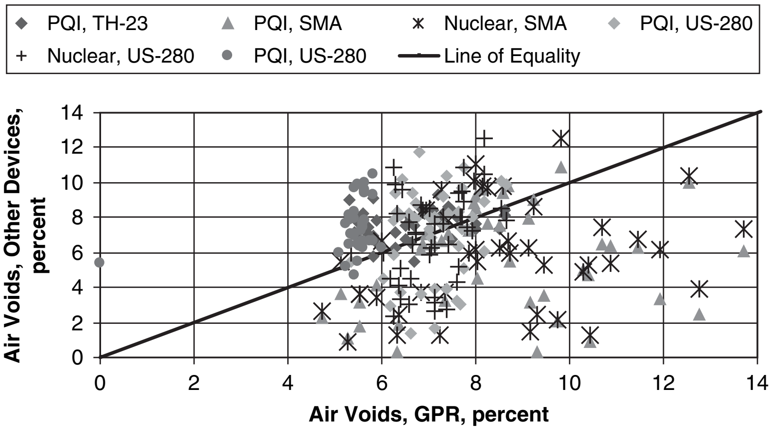


Figure 38. Dry densities measured with the EDG and nuclear density gauges.



(a) Density measured with the different devices.



(b) Air voids calculated from the maximum theoretical density for the mixture.

Figure 39. Air voids measured with the GPR versus densities measured with the PQI and nuclear density gauges for different HMA mixtures.

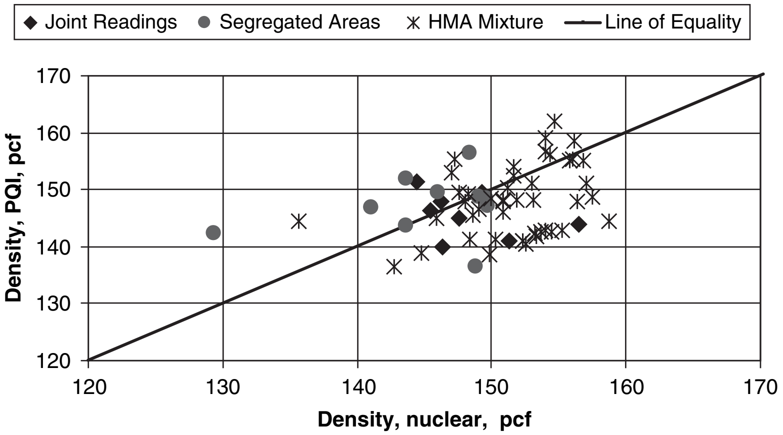
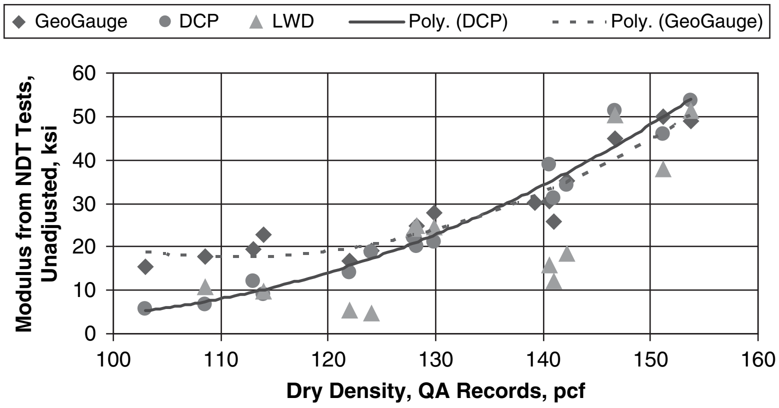
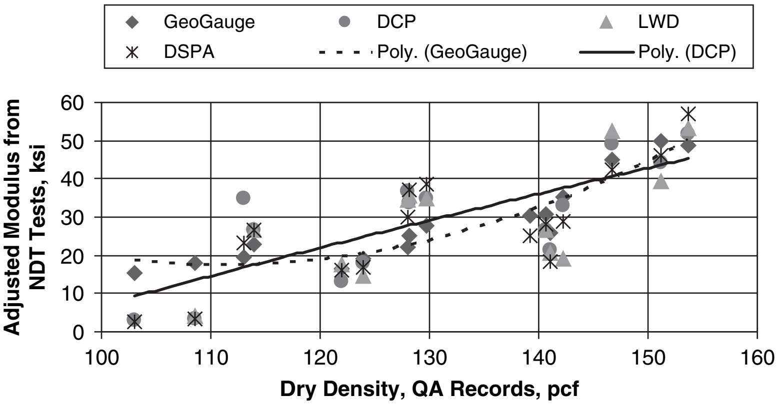


Figure 40. Nuclear density gauge measurements compared to the PQI values along longitudinal joints and in areas with segregation.



(a) Unadjusted modulus values.



(b) Modulus values adjusted to laboratory conditions.

Figure 41. Dry density versus NDT adjusted modulus values for different materials.

The important observation from this comparison is that there is a good relationship between dry density and the DCP estimated modulus, prior to adjusting the modulus values to laboratory conditions (Figure 41[a]). The resilient modulus from the GeoGauge is also related to the dry density of the material, but appears to become insensitive to dry density for less dense, fine-grained soils with high water content. The resilient modulus from the LWD is related to dry density but has the greatest variation because of the influence of the underlying materials.

Figure 41(b) graphically presents the same comparison included in Figure 40(a), but using the adjusted modulus values. The GeoGauge and DSPA have similar relationships to dry density for both conditions. The relationship for the DCP becomes less defined and it is improved for the LWD. Overall, the modulus values resulting from each NDT device are related to the dry density across a wide range material. The GeoGauge has the better correlation to dry density using the adjusted values, followed by the DSPA and DCP. Thus, the GeoGauge was the primary device used in comparing the elastic modulus to the EDG and GPR results.

The dry density and water contents from the QA records were fairly dispersed and were not taken at each NDT test location or individual area. As such, the QA data can only be used to evaluate the results for different types of materials, rather than actual density variations within a project or lot. The EDG was used to measure the density and water content at specific test locations for the other NDT devices.

Figure 42 compares the dry densities measured with the EDG and modulus values estimated from the GeoGauge and DCP. The NDT modulus increases with increasing dry density over a wide range of material types, which is consistent with previous experience. However, there are clusters of data for the EDG that correspond to similar unbound materials that were tested. Within each data cluster, the correspondence between dry density and NDT modulus is poor for both devices.

This observation suggests that there are other factors that impact the modulus within a specific area; for example, water content and amount of coarse aggregate varying within each data cluster. The EDG did not measure large variations in water content within each area. In summary,

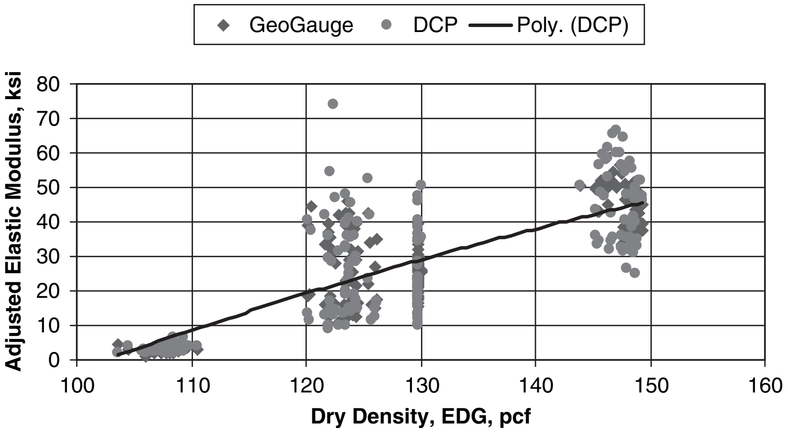


Figure 42. NDT modulus values versus dry density measured by the EDG.

the within-project area variation of the modulus values appears to be more dependent on properties other than dry density (e.g., water content, gradation)—assuming that the EDG is providing an accurate estimate of the in-place dry density. That assumption is questionable based on the data accumulated to date.

Figure 43 compares the GeoGauge modulus to the GPR dielectric values. No clear correspondence was found between the dielectric values and modulus values. Specifically, a wide range of dielectric values and moduli were measured, but no consistent relationship was found between the two properties. Thus, material/layer properties that affect modulus within an area have little effect on the dielectric values.

2.4.3.2 HMA Layers

Figure 44 compares the PSPA modulus and the GPR air voids. There is a general trend within this data set—decreasing air voids and increasing PSPA modulus, but no good correlation. All NDT devices did correctly identify the difference between the US-280 initial and supplemental sections, with the exception of the PQI. This difference was not planned but was confirmed through the use of laboratory dynamic modulus tests. The state agency's and contractor's QA data did not identify any difference between these two areas or time periods.

Figure 45 compares the PSPA modulus and the PQI density. A general trend exists for a specific mixture, but no correlation exists between these devices that can be used in day-to-day construction operations for control or acceptance. A more important observation is that the volumetric measuring devices are not being influenced by those properties that affect the modulus measuring NDT devices. As an example, changes in the asphalt content and gradation in relation to density, air voids, and stiffness changes do not affect density measurements as they do modulus measure-

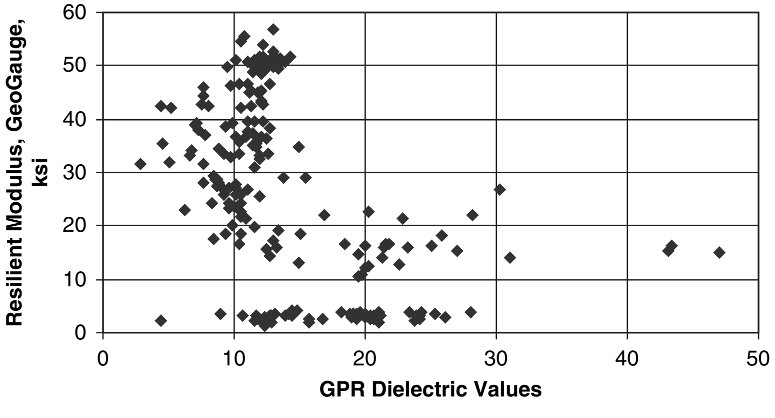


Figure 43. GPR dielectric values versus the GeoGauge modulus.

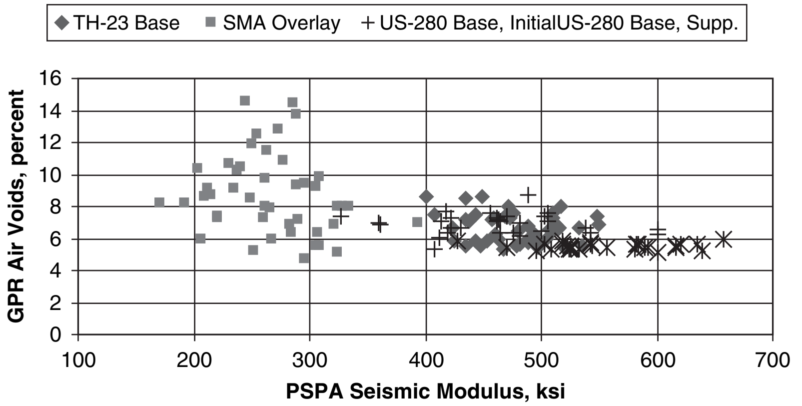


Figure 44. PSPA modulus versus GPR air voids.

ments. This finding is applicable to all the NDT devices used to test the HMA mixtures.

2.5 Supplemental Comparisons

This section provides an overview of three areas of supplementary information and data that were collected during the Part B field evaluation projects: (1) modulus and density growth relationships for monitoring the rolling operations, (2) multiple operators and NDT devices, and (3) agency and contractor use of NDT devices.

2.5.1 Modulus and Density-Growth Relationships for Monitoring the Rolling Operation

Instrumented rollers were used on projects to monitor the increase in density and stiffness of the unbound and HMA layers, where the rollers could be scheduled for use. In a couple of cases, Asphalt Manager was on the project site, but it exhibited hardware or software problems. In other cases, the unbound base layer had already been compacted by the contractor, and the instrumented roller was only used to test the surface. The contractor did not want to take the risk of potentially disturbing the aggregate base, requiring it to be recompacted and tested. Figures 46 through 48 present some of the IC roller data, as related to HMA densities measured with other devices. Overall, the densities and stiffness measured with other devices correlated well with the output from the instrumented rollers in the areas without localized anomalies. The instrumented rollers did not identify differences caused by localized anomalies (i.e., anomalies significantly less than the width of the roller).

Different NDT devices were also used to monitor the compaction operation of HMA and unbound layers to demonstrate the value of these devices in real time. The PSPA, DSPA, GeoGauge, and PaveTracker devices were used on some of the Part A and most of the Part B field evaluation projects. The following subsection contains important observations from the use of selected NDT devices for controlling the placement and compaction of both unbound and HMA layers in real time.

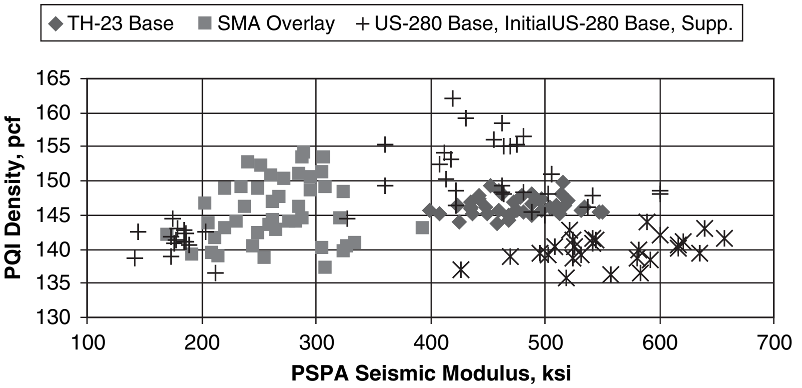


Figure 45. PSPA modulus versus PQI density of HMA mixtures.

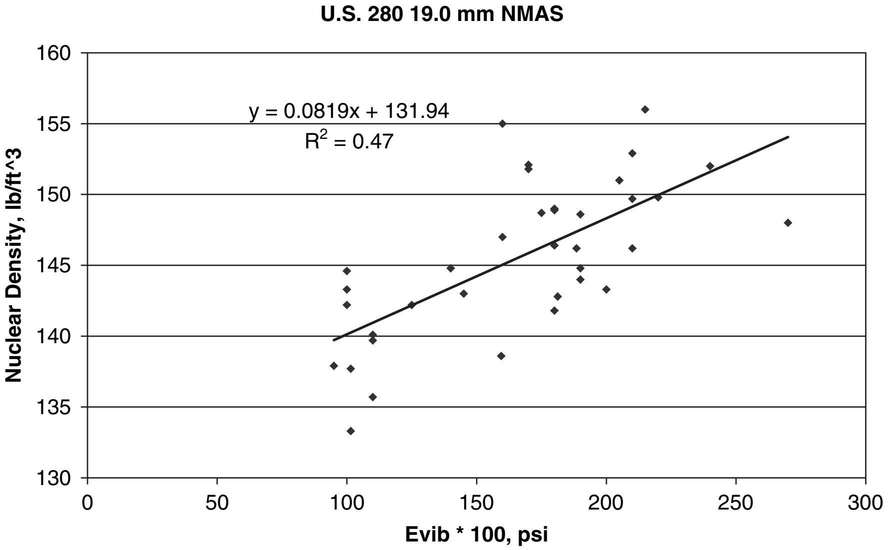


Figure 46. Comparison of the nuclear density gauge readings to the E_{vib} *values measured with the IC roller.*

2.5.1.1 Unbound Materials and Layers

Overall, the GeoGauge, DCP, and DSPA were successful in monitoring the build up of modulus with the number of roller passes for the unbound materials placed within the field evaluation, and they were beneficial in assisting the contractor in making decisions on the compaction operation used along the project. Some examples follow.

- Figure 49 presents data collected on a caliche base material placed along an entrance roadway from County Road 103 near Pecos, Texas. Both the GeoGauge and DCP were used to determine the increase in material modulus with compaction. The DCP was used along this project because it was on a private facility, and delaying the compaction of this base material was not an issue. Both devices found an increase in modulus with an increasing number of roller passes.
- Figure 50 presents data collected during the compaction of a Missouri crushed limestone base material. The first roller pass within this figure is after the material had been preliminarily compacted from other construction equipment and roller passes. The maximum modulus for this material was achieved at about eight passes of the roller over a specific area. The number of passes obviously is dependent on

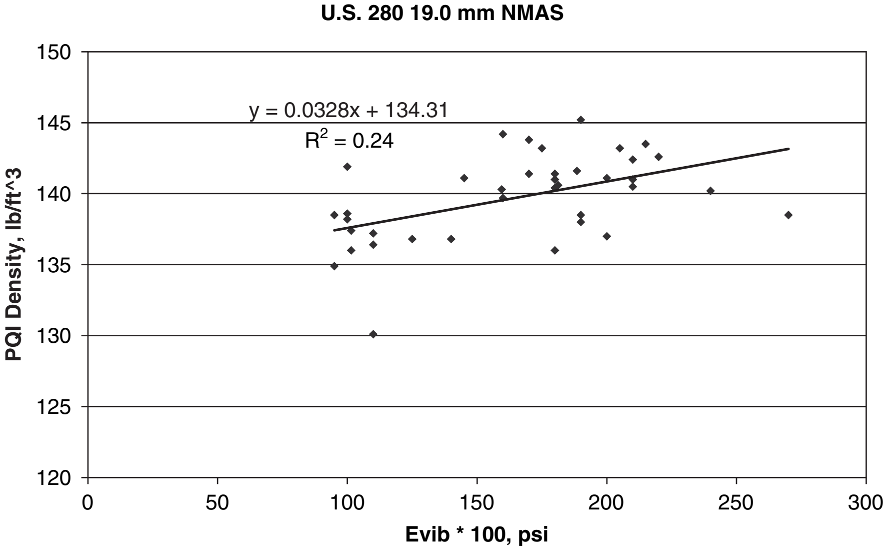


Figure 47. Comparison of the PQI density readings to the E_{vib} *values measured with the IC roller.*

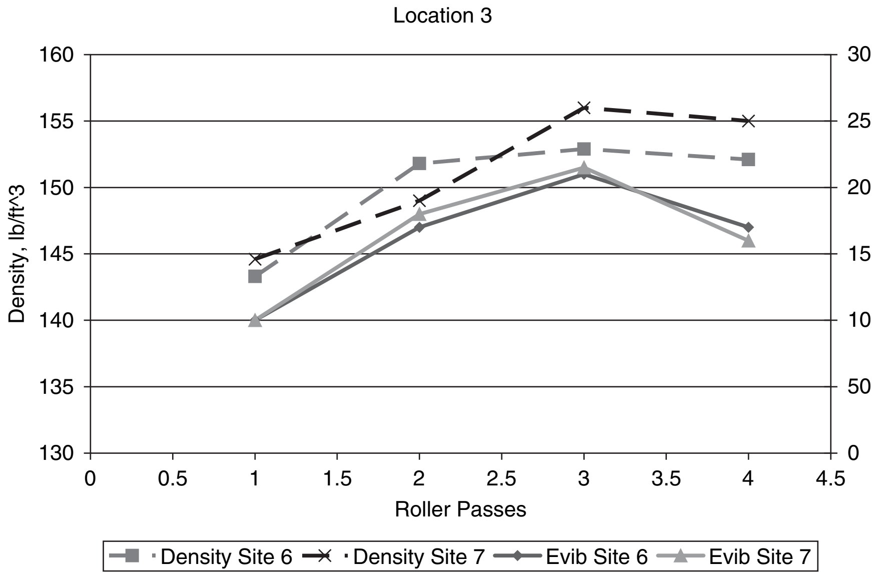


Figure 48. Example of a density growth curve prepared from the IC roller demonstration and NDT results.

the water content of the in-place material; for the Missouri crushed limestone, the in-place water content was just below the optimum value.

- Figure 51 presents data collected during the compaction of a South Carolina crushed granite base material. This crushed granite base material was difficult to compact with the roller on the project site when compaction was initiated. In addition, the water content of this base material was well below the optimum value. Both the DSPA and the GeoGauge modulus values did not increase with the number of roller passes. A nuclear density gauge was also used along the project, and it also showed no increase in density with the number of roller passes. Thus, rather than waste additional compaction effort, the contractor had to use a heavier roller and had to increase the water content of the material to obtain the specified density. This example shows the benefit and advantage of using the GeoGauge or DSPA to make decisions in real time.

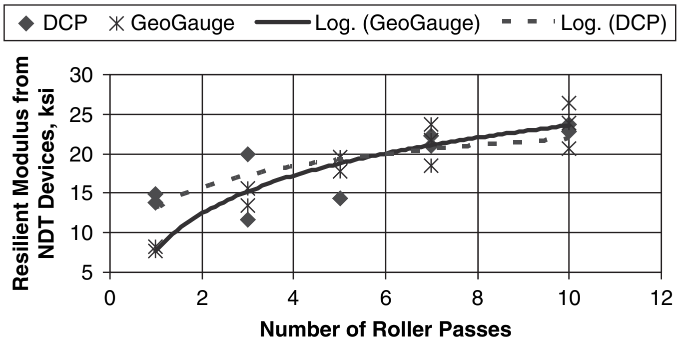


Figure 49. Modulus-growth relationships for a caliche base along an entrance roadway to a facility from County Road 103 near Pecos, Texas.

These examples show the benefit of developing modulus-growth curves using the DSPA or GeoGauge during construction for monitoring and optimizing the rolling pattern.

2.5.1.2 HMA Mixtures and Layers

Overall, the PSPA and PaveTracker were successful in monitoring the build up of modulus and density with the number of roller passes for the HMA layers placed within the field evaluation projects. Some examples follow.

- Figure 52 presents data collected along the Missouri widening project (US-47) for two different areas. Figure 52(a) compares the densities measured using the contractor's nuclear density gauge on site for QC to those values measured with the PaveTracker. The densities from the nuclear gauge were related to the non-nuclear density gauge values with mixture specific calibration values. The contractor was using one-test point readings with the nuclear gauge, while four readings at a test point were made with the PaveTracker within the same time.

  The contractor was using the cold-side pinch method for compacting the longitudinal joint adjacent to the old pavement. This HMA was tender based on visual observations of its behavior under the roller—shoving of the mat was observed in front of, as well as across, the roller's direction. Rollers marks were also present after the last pass of the finish roller. The HMA was being pushed away

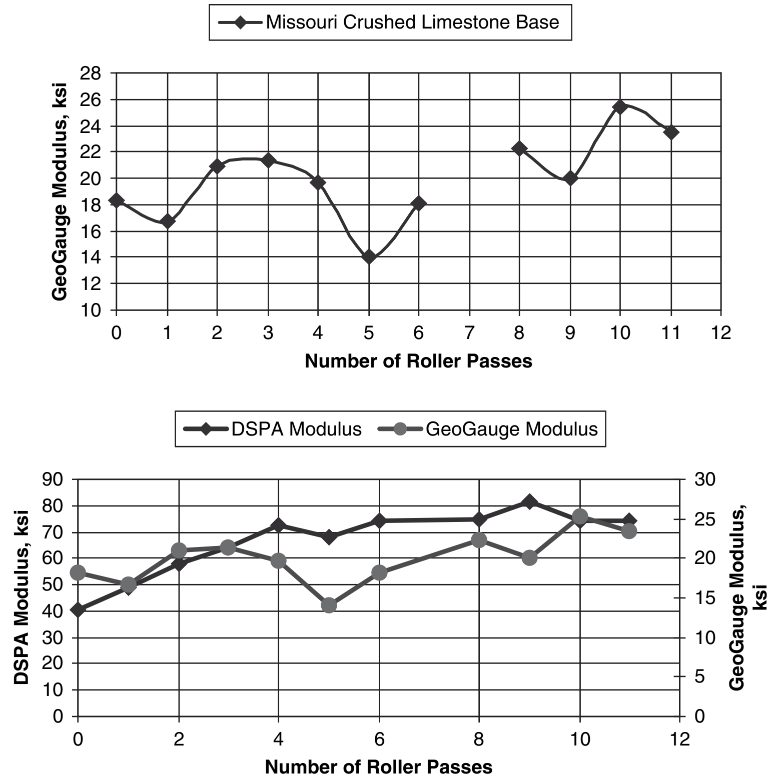


Figure 50. Modulus-growth relationships for a Missouri crushed limestone base material for two different areas.

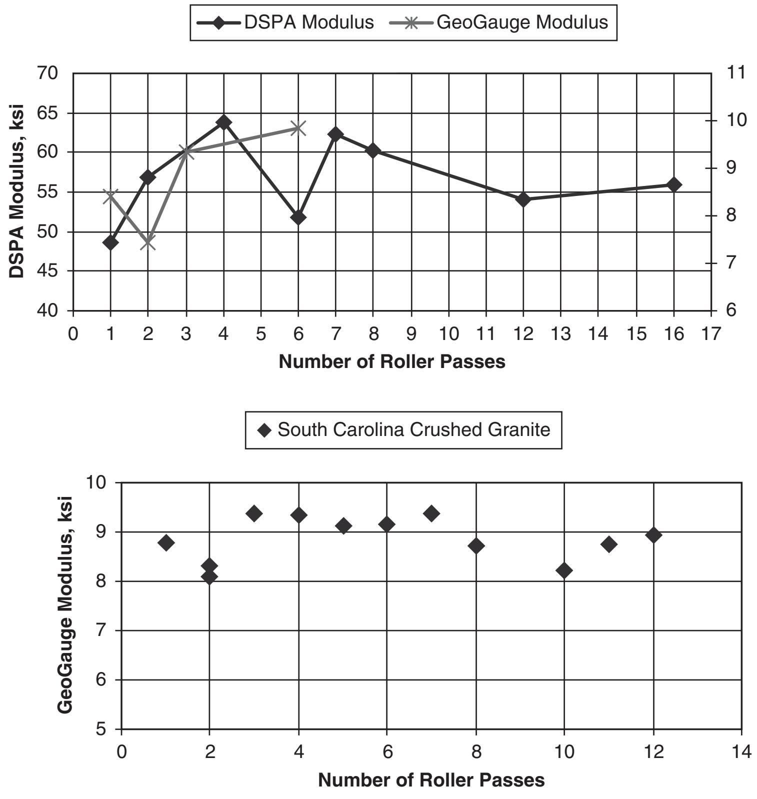


Figure 51. Modulus-growth relationships for a South Carolina crushed granite base material for two different areas.

from the confined longitudinal joint, rather than being pushed down into the joint. Joint densities were made with both the nuclear and non-nuclear density gauges along the joint, and the densities were found to be very low—about 5 to 10 pcf below the densities measured within the center of the mat. The contractor was asked to change the rolling pattern for the confined longitudinal joint using the hot-side method. With this method, the first pass of the roller is along the confined longitudinal joint, with about a 6-in. overhang off the hot mat. Densities were measured with both devices after changing the rolling pattern. Figure 52(b) shows the densities along the longitudinal joint, as compared to those in the center of the mat. The densities significantly increased after eliminating the roller pass on the cold side of the joint. Thus, the contractor was able to use the non-nuclear density gauge in real time to significantly increase the joint density by slightly revising the rolling pattern of the joint.

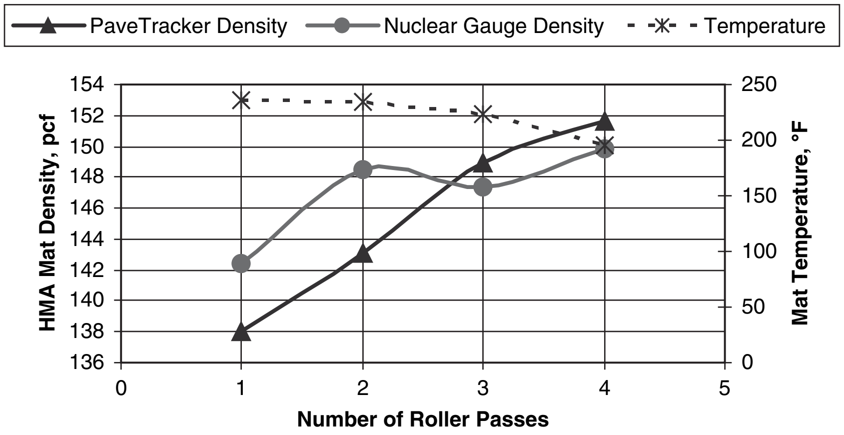
The PSPA was also used along this project, but the results were erratic during or immediately after compaction of the mat—the wave form was not consistent with HMA mixtures. The mixture was found to be too tender to obtain reliable readings, until the mix cooled below about 150°F. This HMA mixture was being used as the base for the shoulder or in a non-critical area. It was initially believed that the PSPA had been damaged in transport, but that was found to be incorrect from latter testing of the HMA after it had cooled down. At lower temperatures, the PSPA provided reasonable results. Thus, its use would have been a benefit in identifying a tender mix, if this mix had been used in a critical area under heavy traffic. Attempts were made to use the PSPA on a couple of other projects, but the temperature of those mixtures was too high to obtain reliable results. Mix temperature is a limitation on testing HMA mixtures during rolling.

- Figure 53 presents density data collected on a Missouri HMA base mixture that was not tender, but was rolled within the temperature sensitive zone. The first pass of the rubber-tired roller increased the density, but additional passes of that roller significantly decreased the density of the mat. The nuclear density gauge being used on site for QC gave the same results. The nuclear gauge, however, was not being used after each roller pass. This mixture did not exhibit the traditional mix "checking" or tearing under the rollers, but the non-nuclear density gauge did identify the detrimental effect of rolling within the temperature sensitive zone. More roller passes were required to regain the density that was lost by rolling within the temperature sensitive zone. Many of the other HMA mixtures that were included within the field evaluation projects also exhibited this temperature sensitivity under the rollers. Selecting HMA mixtures that checked and tore for the field evaluation was not planned.
- The I-75 Michigan overlay project was another project where a HMA mixture was rolled within its temperature sensitive zone. With three passes of a SAKAI vibratory roller in the primary roller position, the HMA mixture density was greater than the specified value (see Figure 54). However, an intermediate roller continued to roll the mix, and was followed by two additional rollers. The use of the PaveTracker determined that the contractor was rolling in the temperature sensitive zone—the density began to decrease. By monitoring the density of the mat during rolling, the result was that the contractor could eliminate two of the rollers and use fewer passes to obtain the required density, as long as the rollers stayed out of the temperature sensitive zone.
- Figure 55 shows an example for polymer modified asphalt (PMA) and conventional neat asphalt mixtures. These mixtures were placed during the same time period. The conventional neat asphalt mixture exhibited the traditional checking and tearing of the mat when it was rolled within the temperature sensitive zone, while the PMA mixture did not exhibit tearing or checking. After pass 3 for the neat asphalt mix and after pass 5 for the PMA mix, the densities decreased. The mix tearing and checking was observed under the roller to confirm that the mix was rolled within the temperature zone. Thus, the mat had to be rolled much more to increase density to the specified value for both mixtures.

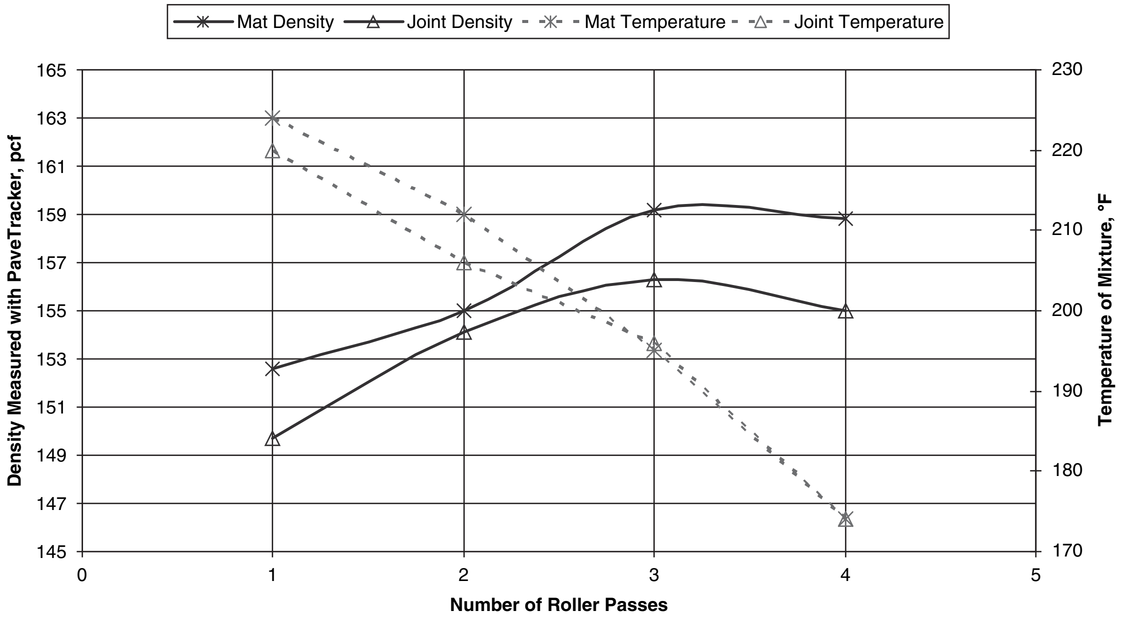
Similar to the benefit for unbound layers, the non-nuclear density gauges provide significant benefit to a contractor to optimize the rolling pattern within the center of the mat, as well as along longitudinal joints. The non-nuclear gauges can also be used to determine when the rollers are being operated within the temperature sensitive zone, so a contractor does not waste compaction effort or time and does not tear or damage the HMA mix by operating the rollers within the temperature sensitive zone.

2.5.2 Multiple Operators and NDT Gauges

For most of the Part B projects, multiple GeoGauges and PaveTrackers were used by different operators to determine the effects of multiple operators on the variability of the devices. Figure 56 compares the measured responses from the two GeoGauges that were used for testing unbound materials, while Figure 57 compares the measured densities from the two PaveTracker devices used to monitor HMA mixtures. At the end of the field evaluation testing for each project, one of each

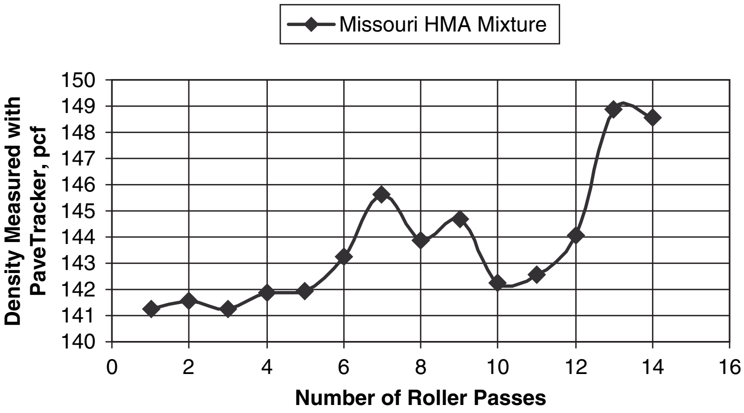


(a) PaveTracker versus nuclear gauge density measurements.



(b) PaveTracker density measurements made along a confined joint and within the center of the mat.

Figure 52. Typical density-growth curve measured with PaveTracker and nuclear density gauge for the Missouri US-47 project.



Compaction Operation:
Pass 1-2; Vibratory Roller
Pass 3-4; Static Steel Wheel
Pass 5-6; Vibratory Roller
Pass 7-11; Rubber Tired
Pass 12-14; Finish Roller

Figure 53. Density-growth relationship for an HMA base mixture from Missouri.

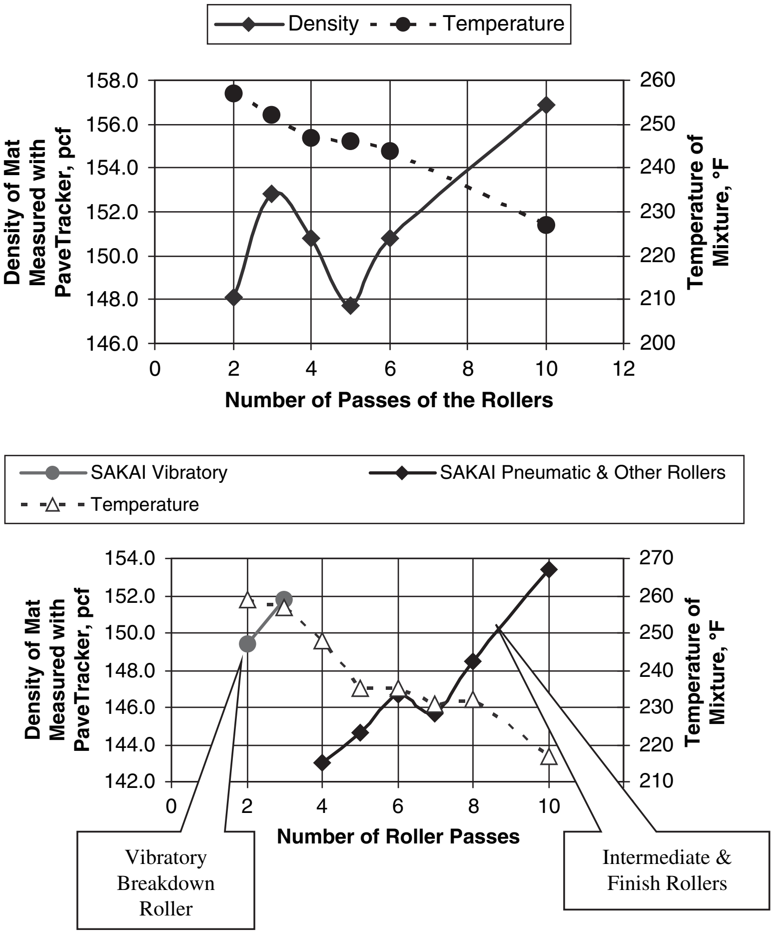


Figure 54. Density-growth curves for the Michigan mixture measured with PaveTracker and effects of rolling within the temperature sensitive zone; two different areas.

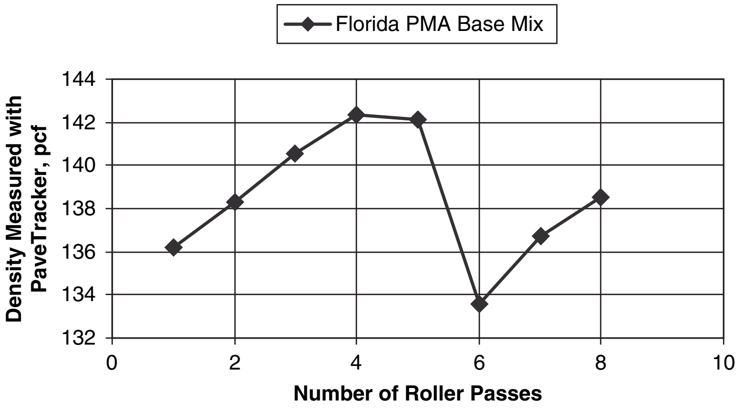
device was left with the agency and contractor personnel. The following are observations from this comparative testing.

- Use of different GeoGauges and operators resulted in some bias that was modulus dependent for some materials; more bias was exhibited for the higher modulus values or stiffer material. Material specific calibration or adjustment factors should be determined and used for each material tested (see Table 24). This material specific calibration with a sufficient number of replicate tests should minimize the bias between the different gauges. The variability between different gauges, however, will still exist.
- Use of different PaveTrackers and operators resulted in almost no bias between the two gauges, with the exception of dense or high specific gravity mixtures. Material specific adjustments should be determined for these devices for each mixture tested. The mixture specific factors should minimize bias, but the variability between different gauges will still exist.

2.5.3 Agency and Contractor Use of NDT Devices

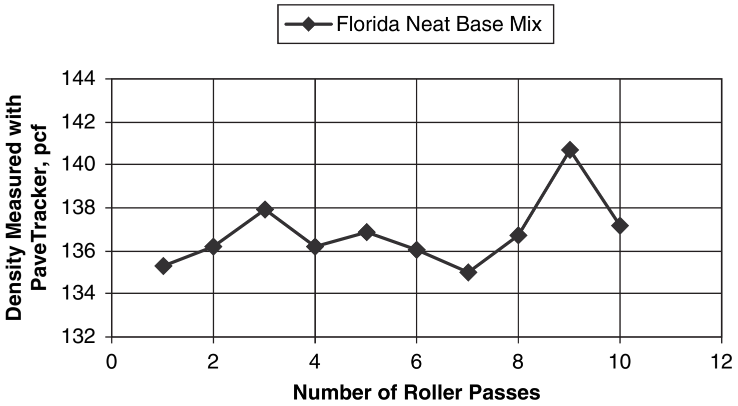
During Part B of the field evaluation, one of the multiple gauges being used on a project was left with agency and contractor construction personnel for continued use on a day-to-day QA basis. Those NDT devices left with the construction personnel included the GeoGauge, PSPA, and PaveTracker. Data from this additional use were included in the comparison of multiple operators and devices at specific project sites. This information was used in the evaluation described in Chapter 3, in determining the parameters needed to set up control and acceptance plans when using these NDT devices.

The projects where construction personnel continued to use the devices included Missouri, North Dakota, and Texas. The NDT devices were going to be left at the Michigan I-75 project, but issues with the HMA mixture resulted in the project being stopped for a short term, so the con-



Compaction Operation:
Pass 1-4; Vibratory Roller
Pass 5; Static Steel Drum
Pass 6-8; Vibratory Roller
Pass 9; Finish Roller

(b) PMA Mixture



Compaction Operation:
Pass 1-4; Static Steel Drum
Pass 5-7; Rubber Tired Roller
Pass 8-10; Finish Roller

(a) Conventional Neat HMA Mixture

Figure 55. Density-growth curves for two Florida mixtures measured with PaveTracker and effects of rolling within the temperature sensitive zone.

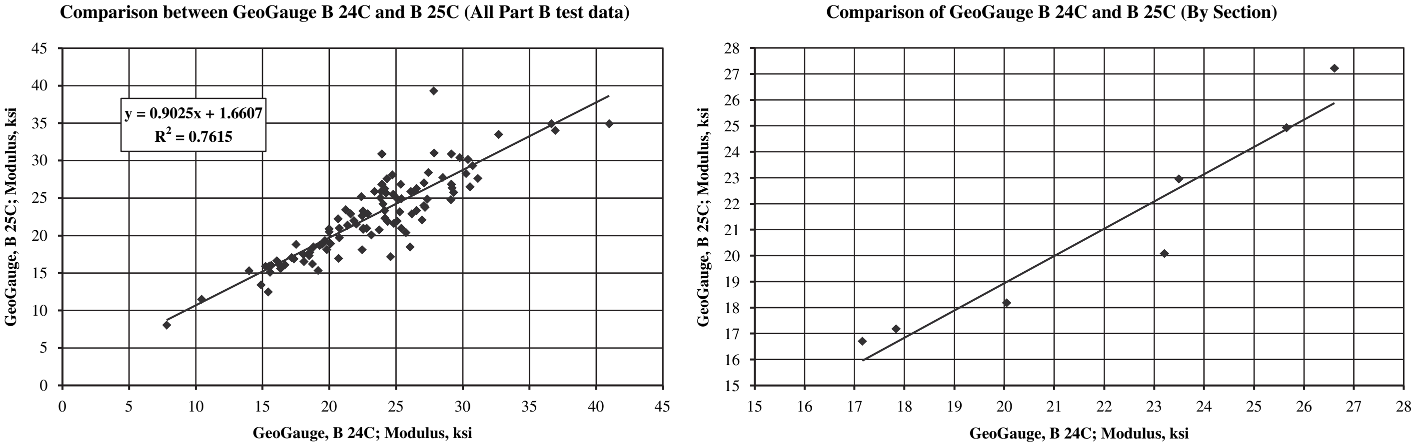
struction personnel did not actually use the devices. For the Missouri project, weather delays resulted in the contractor moving to a different project so the devices were not used on the same project, as that included in the Part B field evaluation. The devices were used for more than 2 weeks on the North Dakota and Texas projects. In actuality, the contractor had already been using the PaveTracker and PSPA on the Texas I-20 project. The PaveTracker was a part of the contractor's standard or day-to-day QC plan, while the PSPA had been used on a research basis.

2.6 Summary of Evaluations

In summary, the steady-state vibratory (GeoGauge) and seismic (DSPA) technologies are suggested for use in judging the quality of unbound layers, while the seismic (PSPA) and non-nuclear density gauges (the PaveTracker was used in Part B) are suggested for use on HMA layers. The GPR is suggested for layer thickness acceptance, while the IC rollers are suggested for use on a control basis for compacting unbound and HMA layers. The following sections provide some of the reasons for these determinations.

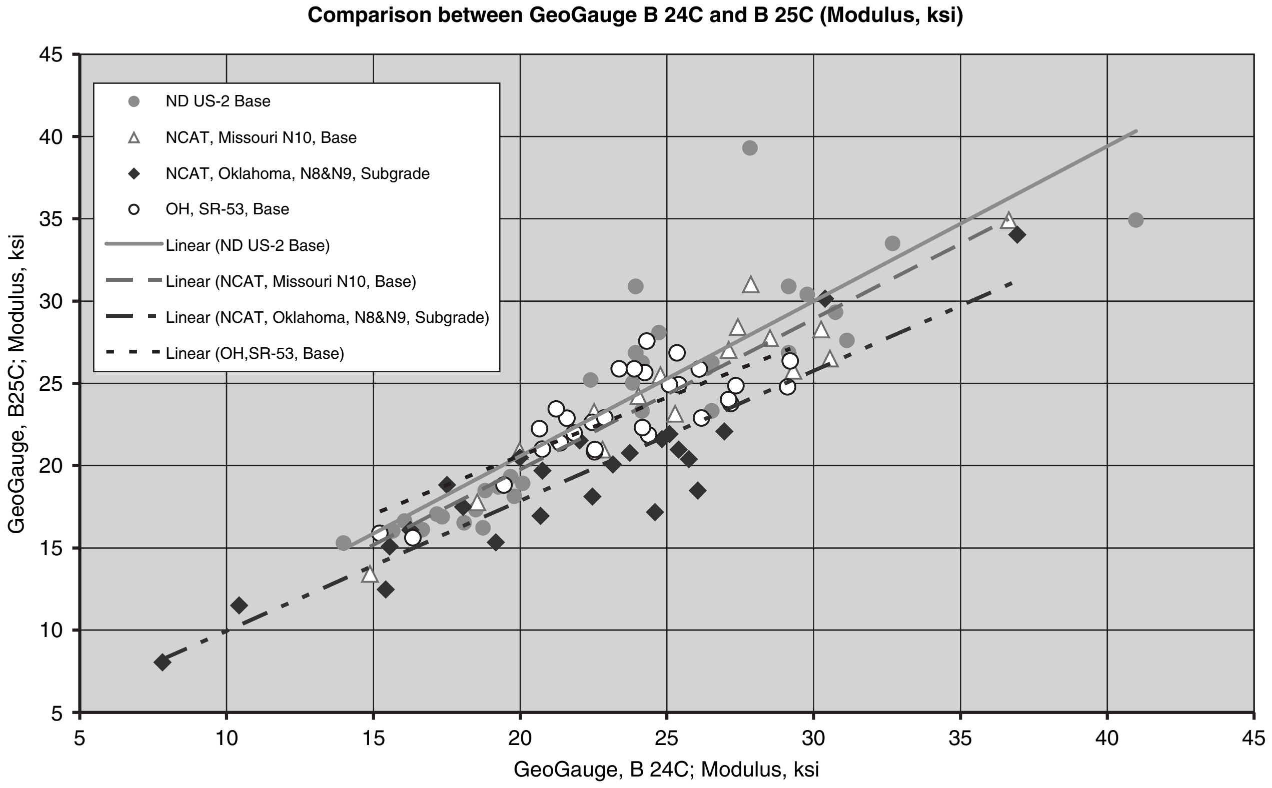
2.6.1 NDT Devices for Unbound Layers and Materials

- The DSPA and GeoGauge devices had the highest success rates for identifying an area with anomalies, rates of 86 and 79 percent, respectively. The DCP and LWD identified about two-thirds of the anomalies, while the GPR and EDG had unacceptable rates, below 50 percent.
- Three to five repeat measurements were made at each test point with the NDT devices, with the exception of the DCP.
  - — The LWD exhibited low standard deviations that were less dependent on material stiffness with a pooled standard deviation less than 0.5 ksi. One reason for the low values is that the moduli were less than for the other devices. The COV, however, was higher. It is expected that the supporting layers had an effect on the results by reducing the modulus.
  - — The GeoGauge had a standard deviation for repeatability measurements varying from 0.3 to 3.5 ksi and were material dependent.
  - — The DSPA had the lowest repeatability with a standard deviation varying from 1.5 to 21.5 ksi. The reason for this higher variation in repeat readings is that



(a) Comparison on a point-by-point basis.

(b) Comparison on a project basis.



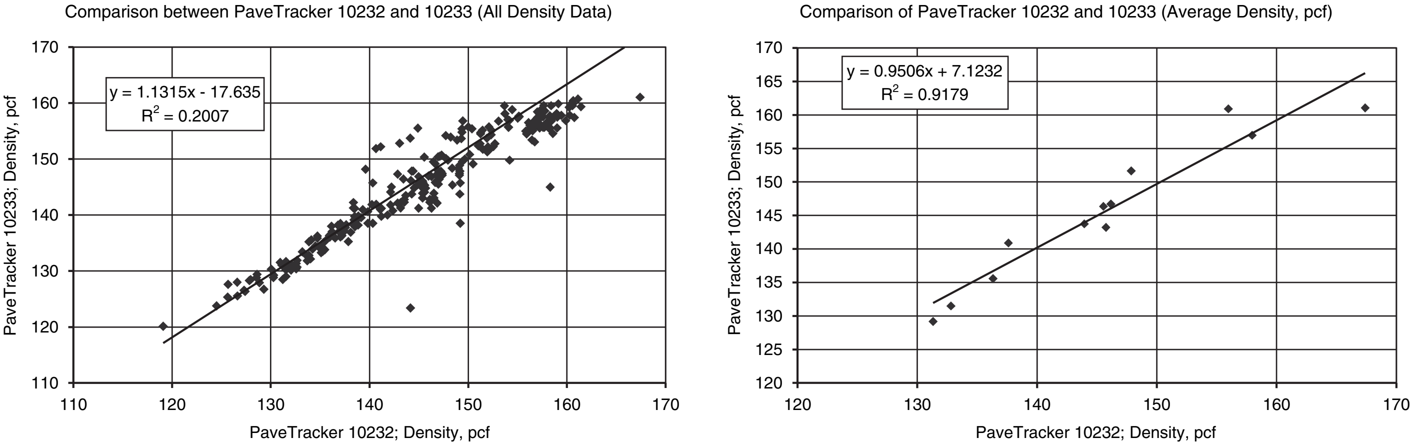
(c) Comparison on a material basis.

Figure 56. Comparison of modulus measurement with two independent GeoGauges.

the DSPA sensor bar was rotated relative to the direction of the roller, while the other devices were kept stationary or did not have the capability to detect anisotropic conditions. No significant difference was found relative to the direction of testing for fine-grained soils, but there was a slight bias for the stiffer coarse-grained materials.

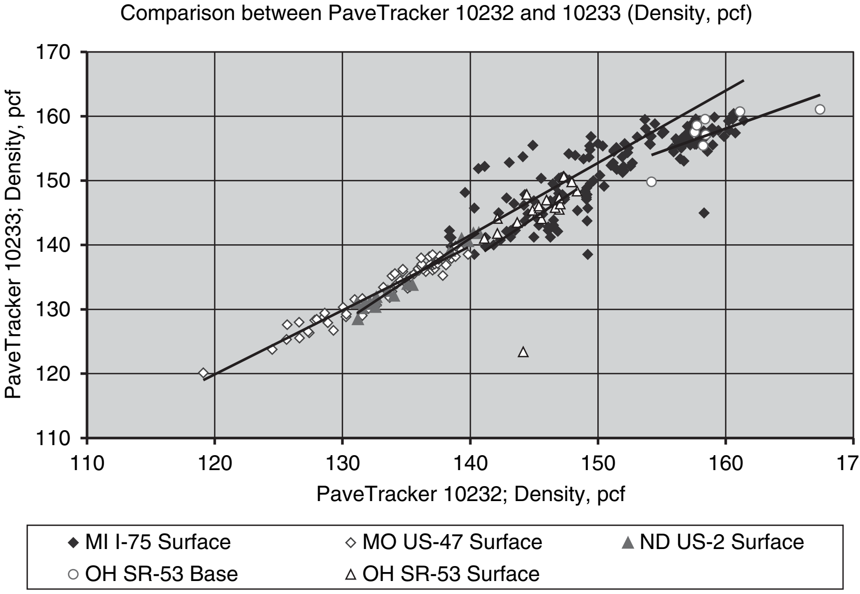
— The EDG was highly repeatable with a standard deviation in density measurements less than 1 pcf, while the GPR had poor repeatability—based on point measurements. Triplicate runs of the GPR were made over the same area or sublot. For comparison to the other NDT devices, the values measured at a specific point, as close as possible, were used. Use of point specific values from successive runs could be a reason for the lower repeatability, which were probably driver specific. One driver was used for all testing with the GPR.

- The COV was used to compare the normalized dispersion measured with different NDT devices. The EDG consistently had the lowest COV with values less than 1 percent.



(a) Comparison on a point-by-point basis.

(b) Comparison on a project basis.



(c) Comparison on a material or mixture basis.

Figure 57. Comparison of the density measurements with two non-nuclear PaveTracker devices used within the Part B field evaluation.

The GeoGauge had a value of 15 percent, followed by the DSPA, LWD, DCP, and GPR. The GPR and EDG are dependent on the accuracy of other tests in estimating volumetric properties (density and moisture contents). Any error in the calibration of these devices for the specific material is directly reflected in the resulting values. This could be a probable reason why the GPR and EDG devices did not consistently identify the areas with anomalies or physical differences.

- Repeated load resilient modulus tests were performed in the laboratory for characterizing and determining the target resilient modulus for each material. Adjustment ratios were determined based on uniform conditions. The overall average ratio for the GeoGauge for the stiffer coarse-grained materials was near unity (1.05). For the fine-grained, less stiff soils, the ratio was about 0.5. After adjusting for laboratory conditions, all NDT devices that estimate resilient modulus resulted in low residuals (laboratory resilient modulus minus the NDT elastic modulus). However, the GeoGauge and DCP resulted in the lowest standard error. The LWD had the highest residuals and standard error.
- The DSPA and DCP measured responses represent the specific material being tested. The DCP, however, can be significantly affected by the varying amounts of aggregate particles in fine-grained soils and the size of the aggregate in coarse-grained soils. The GeoGauge measured responses are minimally affected by the supporting materials, while the LWD can be significantly affected by the supporting materials and thickness of the layer being tested. Thickness

deviations and variable supporting layers are reasons that the LWD had a low success rate in identifying areas with anomalies or physical differences.

- No good or reasonable correlation was found between the NDT devices that estimate modulus and those devices that estimate volumetric properties.
- The instrumented rollers were used on too few projects for a detailed comparison to the other NDT devices. The rollers were used to monitor the increase in density and stiffness with an increasing number of roller passes. One potential disadvantage with these rollers is that they may bridge localized soft areas. However, based on the results obtained, their ability of provide uniform compaction was verified and these rollers are believed to be worth future investment in monitoring the compaction of unbound materials.
- The GPR resulted in reasonably accurate estimates to the thickness of aggregate base layers. None of the other NDT devices had the capability or same accuracy to determine the thickness of the unbound layer.

2.6.2 NDT Devices for HMA Mixtures and Layers

- The PSPA had the highest success rate for identifying an area with anomalies, 93 percent. The PQI identified about three-fourths of the anomalies, while the FWD and GPR identified about one-half of those areas. The seismic and non-nuclear gauges were the only technologies that consistently identified differences between the areas with and without segregation. These two technologies also consistently found differences between the longitudinal joint and interior of the mat.
- The non-nuclear density gauges (PaveTracker) were able to identify and measure the detrimental effect of rolling the HMA mat within the temperature sensitive zone. This technology was beneficial on some of the Part B projects for optimizing the rolling pattern initially used by the contractor.
- Three to four repeat measurements were made at each test point with the NDT devices.
  - — The PSPA had a repeatability value, a median or pooled standard deviation, of about 30 ksi for most mixtures, with the exception of the US-280 supplemental mixture, which was much higher.
  - — The FWD resulted in comparable value for the SMA mixture (55 ksi), but had a higher value for the US-280 mixture (275 ksi).
  - — The non-nuclear density gauges had repeatability values similar to nuclear density gauges, a value less than 1.5 pcf.
  - — The repeatability for the GPR device was found to be good and repeatable, with values of 0.5 percent for air voids and 0.05 in. for thickness.
- The PSPA moduli were comparable to the dynamic moduli measured in the laboratory on test specimens compacted to the in-place density at a loading frequency of 5 Hz and the in-place mixture temperature, with the exception of one mixture—the US-280 supplemental mixture. In fact, the overall average ratio or adjustment factor for the PSPA was close to unity (1.1). This was not the case for the FWD. Without making any corrections for volumetric differences to the laboratory dynamic modulus values, the standard error for the PSPA was 76 ksi (laboratory values assumed to be the target values). The PSPA was used on HMA surfaces after compaction and the day following placement. The PSPA modulus values measured immediately following compaction were found to be similar to the values 1 or 2 days after placement—making proper temperature corrections in accordance with the master curves measured in the laboratory.
- A measure of the mixture density or air voids is required to judge the acceptability of the modulus value from a durability standpoint. The non-nuclear gauges were found to be acceptable, assuming that the gauges had been properly calibrated to the specific mixture—as for the PSPA.
- Use of the GPR single antenna method, even with mixture calibration, requires assumptions on specific volumetric properties that do vary along a project. As the mixture properties change, the dielectric values may or may not be affected. Use of the proprietary GPR analysis method on other projects was found to be acceptable for the air void or relative compaction method. This proprietary and multiple antenna system, however, was not used within Part A of the field evaluation to determine its success rate in identifying localized anomalies and physical differences between different areas. Both GPR systems were found to be very good for measuring layer thickness along the roadway.
- Water can have a definite affect on the HMA density measured with the non-nuclear density gauges (PQI). The manufacturer's recommendation is to measure the density immediately after compaction, before allowing any traffic on the HMA surface. Within this project, the effect of water was observed on the PQI readings, as compared to dry surfaces. The measured density of wet surfaces did increase, compared to dry surfaces. From the limited testing completed with wet and dry surfaces, the PaveTracker was less affected by surface conditions. However, wet versus dry surfaces were not included in the field evaluation plan for different devices. Based on the data collected within the field evaluation, wet surfaces did result in a bias of the density measurements with this technology.
- Another important condition is the effect of time and varying water content on the properties of the HMA mixture during construction. There have been various studies completed on using the PSPA to detect stripping and moisture

damage in HMA mixtures. For example, Hammons et al. (2005) used the PSPA (in combination with GPR) to locate areas with stripping along selected interstate highways in Georgia. The testing completed within this study also supports the use of the seismic-based technology to identify such anomalies.

- The instrumented rollers used to establish the increase in stiffness with number of passes was correlated to the increases in density, as measured by different devices. These rollers were used on too few projects to develop or confirm any correlation between the NDT response and the instrumented roller's response. One issue that will need to be addressed is the effect of decreasing temperature on the stiffness of the mixture and how the IC roller perceives that increase in stiffness related to increases in density of the mat. A potential disadvantage with these rollers is that they will bridge segregated areas and may not accurately identify cold spots in the HMA mat. However, based on the results obtained, the ability to provide uniform compaction was verified, and the rollers are believed to be worth future investments in monitoring the compaction of HMA mixtures.

2.6.3 Limitations and Boundary Conditions

The following lists the limitations and boundary conditions observed during the field evaluation for the NDT devices suggested for QA application on an immediate, effective, and practical basis.

- All NDT devices suggested for QA application, with the exception of the GPR and IC rollers, are point-specific tests. Point-specific tests are considered a limitation because of the number of samples required to identify localized anomalies that deviate from the population distribution.
  - — Ultrasonic scanners are currently under development. Relatively continuous measurements can be made with this technology. These scanners are still considered to be in the research and development stage and are not ready for immediate and practical use in a QA program.
  - — GPR technology to estimate the volumetric properties of HMA mixtures is available for use on a commercial basis, but the proprietary system has only had limited verification of its potential use in QA applications and validation of all volumetric properties determined with the system.
  - — Similarly, the IC rollers take continuous measurements of density or stiffness of the material being compacted. During the field evaluation, some of these rollers had both hardware and software problems. Thus, these devices were not considered immediately ready for use in a day-to-day QA program. The equipment, however, has been improved and its reliability has increased. The technology is suggested for use on a control basis but not for acceptance.
- Ultrasonic technology (PSPA) for HMA layers and materials is suggested for use in control and acceptance plans.
  - — Test temperature is the main boundary condition for the use of the PSPA. Elevated temperatures during mix placement can result in erratic response measurements. Thus, the gauge may not provide reliable responses for monitoring the compaction of HMA layers or for determining when the rollers are operating within the temperature sensitive zone for the specific mixture.
  - — These gauges need to be calibrated to the specific mixture being tested. However, this technology can be used in the laboratory to measure the seismic modulus on test specimens during mixture design or verification prior to measuring the dynamic modulus in the laboratory.
  - — A limitation of this technology is that the results (material moduli) do not provide an indication on the durability of the HMA mixture. Density or air void measurements are needed to define durability estimates.
  - — The DSPA for testing unbound layers is influenced by the condition of the surface. High modulus values near the surface of the layer will increase the modulus estimated with the DSPA. Thus, the DSPA also needs to be calibrated to the specific material being evaluated.
- Steady-state vibratory technology (GeoGauge) for unbound layers and materials is suggested for use in control and acceptance plans.
  - — This technology or device should be used with caution when testing fine-grained soils with high water contents. In addition, it should not be used to test well-graded, non-cohesive sands that are dry.
  - — The condition of the surface of the layer is important and should be free of loose particles. A layer of moist sand should also be placed to fill the surface voids and ensure that the gauge's ring is in contact with about 75 percent of the material's surface. Placing this thin layer of moist sand takes time and increases the time needed for testing.
  - — These gauges need to be calibrated to the specific material being evaluated. They are influenced by the underlying layer when testing layers that are less than 8 in. thick.
  - — These gauges are not applicable for use in the laboratory during the preparation of M-D relationships that will be used for monitoring compaction. The DSPA technology is applicable for laboratory use to test the samples used to determine the M-D relationship.
  - — A relative calibration process is available for use on a day-to-day basis. However, if the gauge does go out of calibration, it must be returned to the manufacturer for internal adjustments and calibration.

  - These gauges do not determine the density and water content of the material. The water content and density of the unbound layer should be measured with other devices.
- Non-nuclear density gauges (electric technology) for HMA layers and materials are suggested for use in control and acceptance plans.
  - The results from these non-nuclear density gauges can be dependent on the condition of the layer's surface—wet versus dry conditions. It is recommended that the gauges be used on relatively dry surfaces until additional data become available relative to this limitation. Free water should be removed from the surface to minimize any affect on the density readings. However, water penetrating the surface voids in segregated areas will probably affect the readings—incorrect or high density readings, compared with the actual density from a core. The PSPA was able to identify areas with segregation.
  - These gauges need to be calibrated to the specific material under evaluation.
- GPR technology for thickness determination of HMA and unbound layers is suggested for use in acceptance plans.
  - The data analysis or interpretation is a limitation of this technology. The GPR data requires some time to estimate the material property—the time for layer thickness estimates is much less than those for other layer properties.
  - This technology requires the use of cores for calibration purposes. Cores need to be taken periodically to confirm the calibration factors used to estimate the properties.
  - Use of this technology, even to estimate layer thickness, should be used with caution when measuring the thickness of the first lift placed above PATB layers.
  - GPR can be used to estimate the volumetric properties of HMA mats, but that technology has yet to be verified on a global basis.
  - Measurements using this technology and associated devices cannot be calibrated using laboratory data.
- IC rollers are suggested for use in a control plan, but not in an acceptance plan.
  - The instrumented rollers may not identify localized anomalies in the layer being evaluated. These rollers can bridge some defects, that is, they lack the level of sensitivity required to identify defects that are confined to local areas.
  - Temperature is an issue with the use of IC rollers for compacting HMA layers. Although most of these rollers have the capability to measure the surface temperature of the mat, the effect of temperature on the mat stiffness is an issue—as temperature decreases, the mat stiffness will increase, not necessarily because of an increase in the density of the mat. Delaying the compaction would increase the stiffness of the mat measured under the rollers because of the decrease in temperature.
  - The instrumented rollers also did not properly identify when checking and tearing of the mat occurred during rolling. The non-nuclear density gauges (PaveTracker) did identify this detrimental condition.
  - Measurements using this technology and associated devices cannot be calibrated using laboratory data.

CHAPTER 3

Construction Quality Determination

The approach taken for this project was to use fundamental properties needed for mixture and structural design for the control and acceptance of flexible pavements and HMA overlays. The NDT technologies included in the field evaluation were evaluated for their ability to determine these properties accurately on a practical and effective QA program. The NDT technology or QA tests are used to confirm the design assumptions for the materials placed.

Chapter 2 identified those devices that were able to identify or discriminate areas with different material properties or conditions. Chapter 3 presents the evaluation of the NDT devices with the potential to determine the quality of the unbound and HMA mixtures placed on some of the projects. These devices include the GeoGauge for unbound materials and the PSPA for HMA mixtures. Other evaluated devices, such as the DCP, were not as successful in identifying anomalies. In addition, the intent of this chapter is to show the use of NDT devices that estimate modulus for defining construction quality.

3.1 Quality Control and Acceptance Application

Of the many process control procedures that can be used in highway construction, process control charts, particularly statistical control charts, are most commonly used by contractors and material producers for verifying that their process is under control. Although there are different approaches that can be taken in implementing NDT technologies to verify that the process is in control, statistical control charts were used within this project. As a result, the NDT test methods must produce results that can be adapted to existing AASHTO procedures in pavement construction. The ASTM *Manual on Presentation of Data and Control Chart Analysis* was used for preparing practical procedures that contractors can use in deciding whether their process is in control (ASTM 1992).

Similarly, there are different acceptance procedures that are used to judge whether the pavement material meets the required specifications. Two of the more common methods that have been used and adopted by most agencies are percent within limits (PWL) and average absolute deviation (AAD). PWL is the procedure used by over 75 percent of the agencies that have adopted statistical-based acceptance specifications. AASHTO R9, *Acceptance Sampling Plans for Highway Construction,* was used for preparing practical but effective procedures that agencies can use in deciding whether the product meets their specifications (AASHTO 2003).

Statistical control charts are the primary method for determining whether the construction is in-control or out-of-control, and PWL is the primary method for judging the acceptability of construction. To demonstrate the use of the NDT technology for use in a QA program, specific projects were selected to cover the range of conditions encountered during construction. The following table contains the steps needed to set up a QA program that uses NDT devices to judge the quality of construction of unbound materials and HMA mixtures using the material modulus.

3.2 Control Limits for Statistical Control Charts

The upper and lower control or action limits are calculated from the NDT modulus tests in accordance with the following equations.

$$UCL_{\bar{X}} = \bar{\bar{X}} + (A_3)(\bar{s}) \tag{17a}$$

$$LCL_{\bar{X}} = \bar{\bar{X}} - (A_3)(\bar{s}) \tag{17b}$$

Where:

$UCL_{\bar{X}}$ = Upper control limit for the sample means.

$LCL_{\bar{X}}$ = Lower control limit for the sample means.

$\bar{\bar{X}}$ = Target value for a project.

$\bar{s}$ = Pooled standard deviation that represents the process variance.

Unbound Materials	HMA Mixtures
1. Develop M-D relationships in the laboratory prior to construction for the unbound material to determine the maximum dry unit weight. Select the target density and water content for compacting the unbound layer.	1. Conduct an HMA mixture design to determine the target gradation and asphalt content. Select the target density and job mix formula for the project mixture or lift being tested. The target job mix formula will likely be revised based on plant produced and placed material.
2. Prepare and compact test specimens at the average water content and dry density expected during construction; based on the project specifications.	2. Prepare and compact test specimens at the target asphalt content and the average density expected during construction; based on the project specifications.
3. Measure the repeated load resilient modulus in accordance with the agency's procedure (AASHTO T307 or NCHRP 1-28A, as required by the MEPDG). Determine the resilient modulus at a selected stress state. The resilient modulus should equal or exceed the value used during design. If the agency does not have a resilient modulus testing capability, the FHWA-LTPP regression equations can be used to estimate the target value, until the laboratory resilient modulus test has been completed (see Equations 1 through 15).	3. Measure the dynamic modulus in accordance with the agency's procedure or the test protocol in accordance with the MEPDG. Determine the dynamic modulus for the test temperature expected during acceptance testing. Two values should be extracted from the test results or master curve; one for the day of paving (an elevated temperature expected after compaction) and the other for one or multiple days following placement. This target value for one or more days following placement will need to be adjusted back to a standard temperature depending on the actual pavement temperature.
4. Define the adjustment factor or ratio for the unbound material to laboratory conditions. Low stress states were used in establishing the ratios for this project.	4. Define the adjustment factor for the HMA mixtures to laboratory conditions. A load frequency of 5 Hz was used in establishing the adjustment ratios for this project.
5. Determine the combined or pooled standard deviation of the modulus for setting up the control limits of the unbound layer for the contractor (see Section 3.3). Establish the action, as well as warning, limits for the statistical control charts; upper and lower control limits (see Section 3.2).	5. Determine the combined or pooled standard deviation of the seismic modulus for setting up the control limits of the HMA mixture for the contractor (see Section 3.3). Establish the action, as well as warning limits for the statistical control charts; upper and lower control limits (see Section 3.2).
6. Determine the upper and lower specification limits (see Section 3.3) for the resilient modulus of the unbound material. This includes the upper and lower specification limits for the resilient modulus of the unbound layer.	6. Determine the upper and lower specification limits (see Section 3.3) for the dynamic modulus of the HMA mixture. This includes the upper and lower specification limits for the dynamic modulus of the HMA mixture.
7. Prepare the statistical control charts.	7. Prepare the statistical control charts.
8. Determine the PWL criteria for different conditions.	8. Determine the PWL criteria for different conditions.

The target value of the control chart for each material is the average value measured in the laboratory in accordance with AASHTO T 307 or the test protocol used by the agency. Both action and warning limits are normally included on the statistical control charts. The upper and lower action limits are set at three standard deviations from the target value, while the warning limits are set at two standard deviations from the target.

3.2.1 Target Modulus or Critical Value

The target value of the control chart for each material and project is the modulus measured in the laboratory. This average laboratory value should be the same as the input to the MEPDG for structural design. Tables 35 and 36 list the target values for the unbound and HMA layers included in the field evaluation projects, respectively.

3.2.2 Combined or Pooled Standard Deviation

The pooled standard deviation was calculated in accordance with the AASHTO R9-03, *Standard Recommended Practice for Acceptance Sampling Plans for Highway Construction.* The pooled standard deviation was determined for each project and unbound material using the NDT results for the areas without anomalies or physical differences. The pooled standard deviations for each project and material are listed in Tables 35 and 36 for the unbound and HMA layers, respectively. These values were used to determine whether the projects were in-control or out-of-control, using the action limits: upper control limits (UCL) and lower control limits (LCL) provided in Tables 35 and 36.

3.3 Parameters for Determining PWL

3.3.1 Determining Quality Indices

The upper and lower quality indices are calculated in accordance with Equations 18 and 19, respectively. The upper and lower specification limits were determined using data from all projects with similar materials.

$$Q_L = \frac{\overline{X} - LSL}{s} \tag{18}$$

Table 35. Parameters used to prepare statistical control charts for the unbound layers included in the field evaluation projects.

Project Identification	Material	Target Modulus, ksi	Pooled Standard Deviation, ksi	Action Warning Limits, ksi	
				UCL	LCL
I-85, AL	Low Plasticity Clay	4.0	0.8	5.6	2.4
NCAT, OK	High Plasticity Clay	6.9	2.0	10.8	3.00
SH-21, TX	High Plasticity Clay	26.8	2.5	30.4	23.2
TH-23, MN	Soil-Aggregate Embankment	16.4	1.0	17.8	15.0
US-2, ND	Soil-Aggregate Embankment	19.0	2.6	22.7	15.3
SH-130, TX	Improved Soil Embankment	35.3	2.8	39.3	31.3
NCAT, SC	Crushed Granite Base	36.1	2.7	41.4	30.8
NCAT, MO	Crushed Limestone Base	19.2	2.7	24.5	13.9
TH-23, MN	Crushed Stone Base	24.0	2.6	27.7	20.3
US-53, OH	Crushed Stone Base	27.5	1.6	30.6	24.4
NCAT, FL	Limerock Base	28.6	3.5	35.4	25.5
US-2, ND	Crushed Aggregate Base	32.4	4.5	38.8	26.0
US-280, AL	Crushed Limestone Base	48.4	10.0	62.7	33.7

NOTE: The target modulus for the South Carolina crushed granite base was determined using the FHWA-LTPP regression equation, because the densities were significantly below the maximum dry unit weight of the material during NDT testing. The pooled standard deviation for this project was assumed to be equal to the Missouri limestone base because the same contractor placed both materials.

$$Q_L = \frac{USL - \bar{X}}{s} \qquad (19)$$

Where:

Q_L = Lower quality index.
Q_U = Upper quality index.
USL = Upper specification limit.
LSL = Lower specification limit.

s = Sample standard deviation of the lot.
$\bar{X}$ = Sample mean of a lot.

The upper and lower quality indices are used to determine the total PWL for each lot of material using Equation 20. The upper and lower PWL values are then determined from the Q-tables provided in the AASHTO QC/QA Guide Specification.

Table 36. Parameters used to prepare statistical control charts for the HMA layers included in the field evaluation projects.

Project Identification	Material	Target Modulus, ksi	Pooled Standard Deviation, ksi	Action Warning Limits, ksi	
				UCL	LCL
I-85, AL	SMA	250	14	270	230
TH-23, MN	HMA Base	810	35	860	760
US-280, AL	HMA Base	650	45	715	585
I-35, TX	HMA Base	800	57	910	690
I-75, MI	Type 3-C	400	86	520	280
I-75, MI	Type E-10	590	86	715	465
US-47, MO	Surface Mix	530	60	615	445
US-47, MO	Base Mix	420	36	470	370
I-20, TX	CMHB Base	340	40	420	260
US-53, OH	HMA Base	850	44	915	785
US-2, ND	HMA Base	510	33	555	465
NCAT, SC	HMA Base	410	58	525	295
NCAT, FL	HMA Base	390	40	470	310
NCAT, FL	PMA Base	590	45	675	505
NCAT, AL	PG76-Sasobit	610	40	690	530
NCAT, AL	PG76-SBS	640	45	725	555
NCAT, AL	HMA Base	450	50	550	350

NOTE: The Texas SH-130 target modulus was determined from Witczak's regression equation because changes were made to the mixture just before NDT testing.

Table 37. Upper and lower specification limits for the unbound layers and materials included in the field evaluation projects.

Project Identification	Material	Median Standard Deviation, ksi	Specification Tolerance, (-) ksi
I-85, AL	Low Plasticity Clay	2.0	3.3
NCAT, OK	High Plasticity Clay		
SH-21, TX	High Plasticity Clay		
TH-23, MN	Soil-Aggregate Embankment	2.1	3.5
US-2, ND	Soil-Aggregate Embankment		
SH-130, TX	Improved Soil Embankment		
NCAT, SC	Crushed Granite Base	3.0	5.0
NCAT, MO	Crushed Limestone Base		
TH-23, MN	Crushed Stone Base		
US-53, OH	Crushed Stone Base		
NCAT, FL	Limerock Base		
US-2, ND	Crushed Aggregate Base		
US-280, AL	Crushed Limestone Base		

$$PWL = PWL_L + PWL_U - 100 \qquad (20)$$

Where:

PWL = Percent within limits.

PWL_L = Percent within limits from the lower specification limit.

PWL_U = Percent within limits from the upper specification limit.

3.3.2 Determining Specification Limits

Tables 37 and 38 list the target values for the unbound and HMA layers included in the field evaluation projects, respectively. These values were used to determine the PWL for the different materials used in the field evaluation projects and were compared to the control limits determined for each project.

Table 38. Upper and lower specification limits for the HMA layers and mixtures included in the field evaluation projects.

Project Identification	Material	Median Standard Deviation, ksi	Specification Tolerance, ± ksi
I-85, AL	SMA	15	30
TH-23, MN	HMA Base	50	100
US-280, AL	HMA Base		
I-35, TX	HMA Base		
I-75, MI	Type 3-C		
I-75, MI	Type E-10	70	140
US-47, MO	Surface Mix		
US-47, MO	Base Mix	50	100
I-20, TX	CMHB Base		
US-53, OH	HMA Base		
US-2, ND	HMA Base		
NCAT, SC	HMA Base		
NCAT, FL	HMA Base		
NCAT, FL	PMA Base		
NCAT, AL	PG76-Sasobit	45	90
NCAT, AL	PG76-SBS		
NCAT, AL	HMA Base	50	100

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APPENDIX A

Glossary

Abbreviations and Nomenclature

AAD	Average Absolute Deviation
AASHTO	American Association of State Highway and Transportation Officials
ADCP	Automated Dynamic Cone Penetrometer
ASNT	American Society of Nondestructive Testing
ASTM	American Society for Testing and Materials
BCI	Base Curvature Index
CBR	California Bearing Ratio
CCC	Continuous Compaction Control
CMV	Compaction Meter Value
CT	Circular Texture
DBP	Deflection Basin Parameter
DCP	Dynamic Cone Penetrometer
DMI	Distance Measuring Instrument
DOT	Department of Transportation
EDG	Electrical Density Gauge
EPIC	Electronic Pavement Infrastructure, Inc.
EMAT	Electromagnetic-Acoustic Transducer
FAA	Federal Aviation Administration
FCC	Federal Communication Commission
FFT	Fast Fourier Transform
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
GDP	German Dynamic Plate
GPR	Ground Penetrating Radar
HMA	Hot Mix Asphalt
HWD	Heavy Weight Deflectometer
IC	Intelligent Compaction
IE	Impact Echo
IR	Infrared
IV	Impact Value
JMF	Job Mix Formula
KTC	Kentucky Transportation Center
LCL	Lower Control Limit
LSL	Lower Specification Limit
LTPP	Long Term Pavement Performance
LWD	Light Weight Deflectometer
M-D	Moisture-Density
M-E	Mechanistic-Empirical
MEPDG	Mechanistic-Empirical Pavement Design Guide
MMA	Machine Milled Accelerometer
MnROAD	Minnesota Road Research
MTV	Material Transfer Vehicle
NCAT	National Center for Asphalt Technology
NDE	Nondestructive Evaluation
NDT	Nondestructive Testing
ODMS	Onboard Density Measuring System
OGFC	Open-Graded Friction Course
OMV	Oscillo-Meter-Value
PATB	Permeable Asphalt Treated Base
PCA	Pavement Composition Analysis
PCC	Portland Cement Concrete
PFWD	Portable Falling Weight Deflectometer
PG	Performance Grade
PQI	Pavement Quality Indicator
PR	Penetration Rate
PRS	Performance Related Specification
PSPA	Portable Seismic Pavement Analyzer
PTA	Pavement Thickness Analysis
PVA	Pavement Void Analysis
PWL	Percent Within Limits
QA	Quality Assurance
QC	Quality Control
QC/QA	Quality Control/Quality Acceptance
RAP	Recycled Asphalt Pavement
RCP	Relative Compaction Profile
RDD	Rolling Dynamic Deflectometer
ROSAN	Road Surface Analyzer
RTRRM	Response Type Road Roughness Meter
RWD	Rolling Wheel Deflectometer
SASW	Spectral-Analysis-of-Surface-Waves
SHRP	Strategic Highway Research Program

SMA	Stone Matrix Asphalt
SPA	Seismic Pavement Analyzer
SPL	Standard Plate Load
SPS	Special Pavement Studies
SSG	Soil Stiffness Gauge (now referred to as the GeoGauge)
SSR	Subgrade Stress Ratio
TDR	Time Domain Reflectometry
TF	Transfer Function
TFT	TRL Foundation Tester
TTI	Texas Transportation Index
UBW	Ultrasonic Body Wave
UCL	Upper Control Limit
USL	Upper Specification Limit
USW	Ultrasonic Surface Wave
VMA	Voids in Mineral Aggregate
VTM	Voids in Total Mix

Terms and Symbols

a = Acceleration
A_{GPR} = Amplitude of the reflection from the top of the layer
a_{GPR} = Regression coefficient from calibration of GPR data using cores
Apl = Amplitude of the reflection from a metal plate
b_{GPR} = Regression coefficient from calibration of GPR data using cores
CBR = California Bearing Ratio
C = Damping coefficient
$Clay$ = Percent clay in the soil
D = Depth of the reflector
E = Young’s or elastic modulus
E = Emissivity of an object
E_{vib} = Dynamic stiffness under vibratory loading
f = frequency
f_r = Resonance frequency
G = Shear modulus
IV = Impact Value
$k_{1,2,3}$ = Regression constants from resilient modulus tests
K = Spring stiffness
L_r = Wave length
LL = Liquid limit
M = Constrained or Bulk modulus
M_R = Resilient Modulus
N = Phase spectrum
p_a = Atmospheric pressure, psi
$P_{3/8}$ = Percent passing the 3/8 in. sieve
$P_{\#4}$ = Percent passing the number 4 sieve
$P_{\#40}$ = Percent passing the number 40 sieve
$P_{\#200}$ = Percent passing the number 200 sieve
PI = Plasticity index
PR = Penetration rate (from DCP)
Q = Radiation emitted from an object
$Silt$ = Percent silt in a soil
t = Travel time of a wave between the source and receiver
t_{GPR} = Time delay between the reflections from the top and bottom of the layer from GPR readings
T_{IR} = Absolute temperature of an object
$T_{o[IR]}$ = Absolute temperature of the surroundings
TF = Transfer function
V = Velocity of object from vibrations
V_{GPR} = Velocity from GPR reflection
V_P = Compression wave velocity
V_R = Rayleigh (surface) wave velocity
V_S = Shear wave velocity
w_s = Water content of the soil
w_{opt} = Optimum water content of the soil; AASHTO T 180
X = Receiver spacing
$X(f)$ = FFT of the hammer input
$Y(f)$ = FFT of the receiver output
Δ = Displacement
$\epsilon_a[GPR]$ = Dielectric constant of the layer
$\epsilon_s[GPR]$ = Dielectric constant of surface layer
θ = Bulk stress
Φ = Phase angle or shift
ρ = Mass density
$\sigma_{1,2,3}$ = Principal stress
σ_{IR} = Stefan-Boltzman constant
τ_{oct} = Octahedral shear stress
λ = Lame’s constant
γ = Density of layer
γ_{Max} = Maximum dry density of a material, AASHTO T 180
γ_s = Dry density of a material
ν = Poisson’s ratio

APPENDIX B

Volume 1—Procedural Manual

This appendix contains the Volume 1—Procedural Manual for NCHRP Project 10-65.

Project No. 10-65

NONDESTRUCTIVE TESTING TECHNOLOGY FOR QUALITY CONTROL AND ACCEPTANCE OF FLEXIBLE PAVEMENT CONSTRUCTION

FINAL REPORT
VOLUME 1—PROCEDURAL MANUAL

Prepared for:
National Cooperative Highway Research Program
Transportation Research Board
National Research Council
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Volume I—Procedural Manual
Judging the Quality of and Accepting Flexible Pavement Construction Using NDT Methods

1.1 INTRODUCTION

Key properties that are needed to predict the performance of flexible pavements and hot mix asphalt (HMA) overlays are modulus, thickness, and density—called quality characteristics. Transportation Research Circular Number E-C037 defines a quality characteristic as (TRB 2005): "*That characteristic of a unit or product that is actually measured to determine conformance with a given requirement. When the quality characteristic is measured for acceptance purposes, it is an* ***acceptance quality characteristic*** *(AQC).*" Agencies and contractors have been using density as a quality characteristic for many years. Density is normally measured using nuclear density gauges for control, while cores are almost always used for acceptance of HMA layers. Modulus is not included in the acceptance plan of any agency but is a required input for structural design. Modulus is also becoming a material property for selecting and designing materials.

Using the same mixture properties for accepting the pavement layer as those used for structural and mixture design allows an agency to more precisely estimate the impact that deficient and superior materials or construction quality have on performance. This direct relationship to the mixture and structural design methods is especially important when developing and implementing performance-related specifications (PRS). The Guide for the Mechanistic-Empirical Design of New and Rehabilitated Pavements developed under NCHRP Project 1-37A and 1-40D (MEPDG[1]) as well as the simple performance tests developed under NCHRP Project 9-19 in support of the Superpave volumetric mixture design procedure use modulus and other fundamental engineering properties for characterizing the materials.

Nondestructive testing and evaluation offers a high production method of determining the structural and volumetric properties of pavement layers that are required for both mixture and structural design. This document provides a procedure for including the material modulus as a quality characteristic in controlling and accepting flexible pavements and HMA overlays.

2.1 SCOPE OF MANUAL

The manual provides guidelines for implementing the selected NDT technologies in routine quality control and acceptance (QC/QA) procedures of an agency's quality assurance program (QA). The manual contains 5 sections. The first section covers the introduction to using NDT for QA of flexible pavement construction, and discusses the basis for selecting NDT technologies for implementation; the second section summarizes the scope of this manual. The third section provides a description of the devices that are recommended for use in QC/QA and also refers to the procedures used in developing quality control and quality

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[1] The product from NCHRP 1-37A project is also alluded to in industry as the Mechanistic-Empirical Pavement Design Guide (MEPDG).

acceptance plans for agencies. The recommended QA procedures using NDT devices are covered in the fourth and fifth sections for HMA mixtures and unbound materials, respectively. Each of these two sections is further divided into two subsections that list the step-by-step procedures for including material modulus in quality control and acceptance (QC/QA) plans.

3.1 SUMMARY OF EQUIPMENT TO MEASURE QUALITY CHARACTERISTICS

The procedures presented herein use the dynamic modulus for HMA mixtures and resilient modulus for all unbound materials. The dynamic modulus is estimated with the Portable Seismic Pavement Analyzer (PSPA), while the resilient modulus is estimated with the GeoGauge. The PSPA uses ultrasonic methods, and the GeoGauge uses steady-state vibratory methods. Adjustment ratios have to be developed or determined for the specific material being evaluated to relate field to laboratory conditions. Both the PSPA and GeoGauge can be used for controlling and accepting HMA mixtures and unbound materials, respectively.

The PSPA is designed to determine the average modulus of an in-place HMA layer (see Figures 1 and 2). The PSPA consists of two receivers (accelerometers) and a source packaged into a hand-portable system, which can perform high frequency seismic tests. The device measures the velocity or propagation of surface waves that is used to determine the material's modulus. A software program that controls the testing comes with the device and keeps record of all measurements taken.

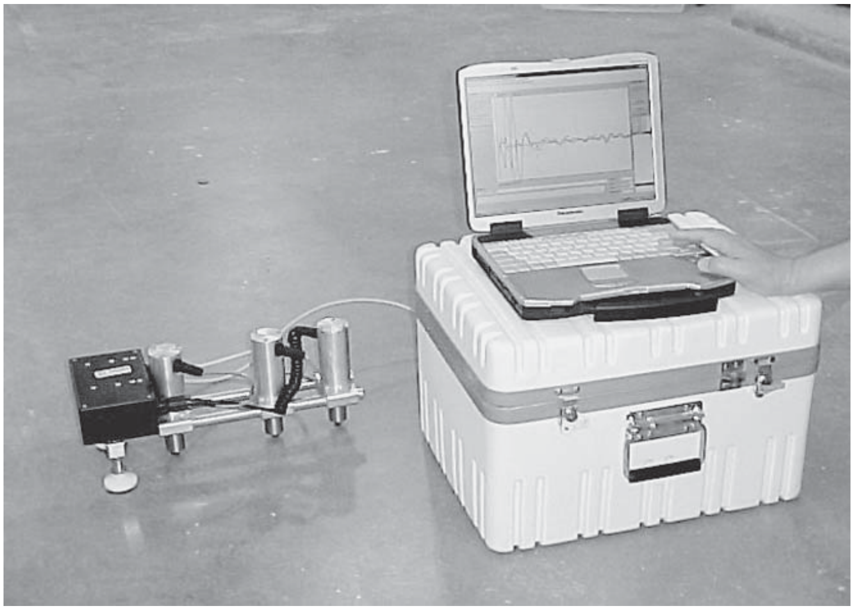
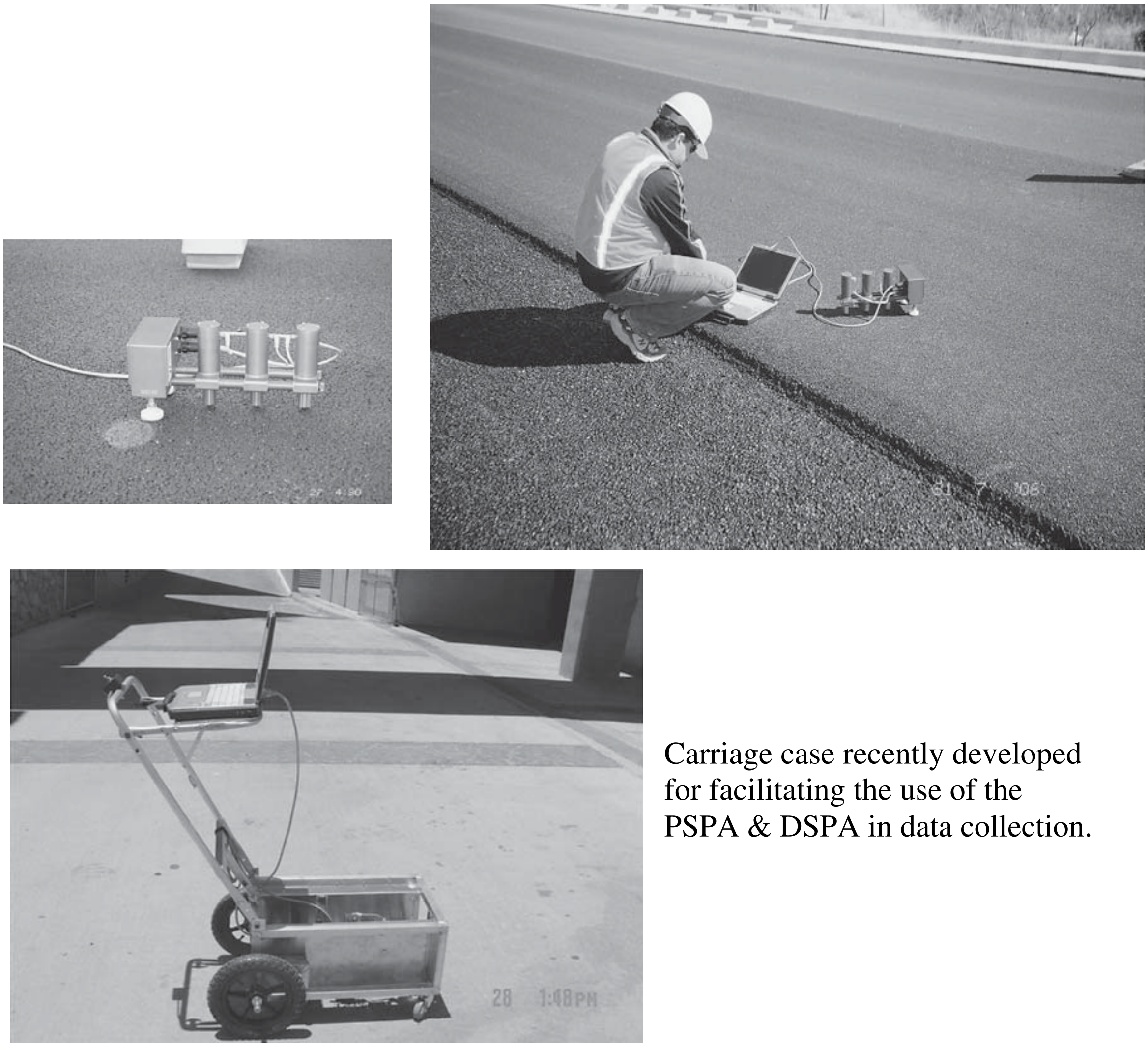


Figure 1. PSPA, Carrying Case, and Laptop



Carriage case recently developed for facilitating the use of the PSPA & DSPA in data collection.

Figure 2. PSPA for Testing HMA Layers

The GeoGauge measures the impedance at the surface of an unbound layer (see Figure 3). It imposes small displacements and stresses to the surface of a layer and uses 25 steady-state frequencies between 100 to 196 Hz. The resulting surface velocity is measured as a function of time. This device also has a built-in data acquisition system to keep a record of the test results.

The other device that is recommended for use in the control of HMA layers is the non-nuclear density gauge—specifically, PaveTracker (see Figure 4). This is an electromagnetic sensing device that contains software and a built-in reference plate that takes the density readings and keeps a record of them. The non-nuclear density gauges for unbound layers are not recommended for QC/QA at this point in time. Future updates and improvements will likely result in the use of these devices for process control.

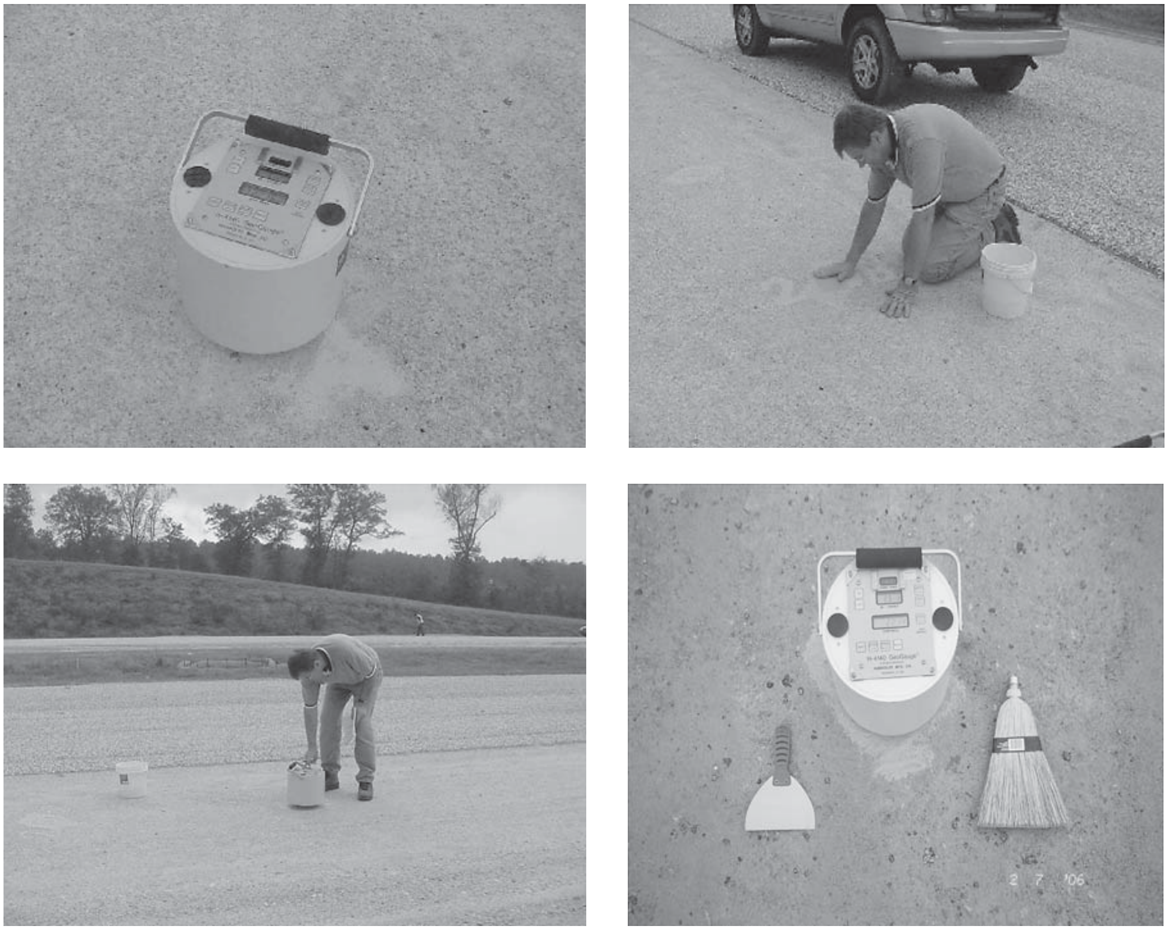


Figure 3. Humboldt GeoGauge

Figure 4. Non-Nuclear Density Gauge, PaveTracker

3.1.1 Acceptance Plan

Different acceptance procedures are used in judging whether the pavement material meets the required specifications. Two methods used by most agencies are Percent Within Limits (PWL) and Average Absolute Deviation (AAD). This document uses PWL for determining acceptance and specification compliance. AASHTO R 9-03, *Acceptance Sampling Plans for Highway Construction,* is recommended for use in preparing practical but effective procedures that agencies can use in deciding whether the product meets their specifications (AASHTO 2003). AASHTO R 9-03 should be followed in determining the number of tests per lot, lot size, and other specifics of the acceptance sampling plan.

The upper and lower quality indices are calculated in accordance with Equations 1 and 2, respectively.

$$Q_L = \frac{\overline{X} - LSL}{s} \quad \text{.......................} \quad (1)$$

$$Q_L = \frac{USL - \overline{X}}{s} \quad \text{.......................} \quad (2)$$

Where:

Q_L = Lower quality index.
Q_U = Upper quality index.
USL = Upper specification limit.
LSL = Lower specification limit.
s = Sample standard deviation of the lot.
$\overline{X}$ = Sample mean of a lot.

The upper and lower quality indices are used to determine the total PWL for each lot of material using Equation 3. The upper and lower PWL values are then determined from the Q-tables provided in the AASHTO QC/QA Guide Specification.

$$PWL = PWL_L + PWL_U - 100 \quad \text{.......................} \quad (3)$$

Where:

PWL = Percent Within Limits.
PWL_L = Percent Within Limits from the lower specification limit.
PWL_U = Percent Within Limits from the upper specification limit.

<u>Determine the Combined Variability for HMA Mixtures</u>

The combined variability includes the within-process variability and the target-miss variability or the precision of the target value. A reasonable combined variability for the initial use in setting the specification is provided for both HMA and crushed aggregate base layers in latter parts of this document. The combined variability is expected to be dependent on the target stiffness of the material.

Agencies should develop agency-specific values based on reasonable standard care and workmanship of producing, placing, and compacting HMA layers. A minimum of 10 projects should be used to determine the combined variability for a range of mixtures. The within-process and center or target-miss variability should exclude areas with anomalies or construction defects.

Determine Specification Limits for an HMA Mixture

Establishing the specification limits for a specific mixture requires that the acceptable and unacceptable (defined as rejectable material) be defined. The acceptance and rejectable quality levels are dependent on the within-process variability. These all become engineering decisions of the agency and are used to determine the PWL for the different materials.

3.2.1 Quality Control Plan

Of the many process control procedures that can be used in highway construction, process control charts, particularly statistical control charts, are commonly used by contractors and material producers for verifying that their process is under control. Although there are different approaches that can be taken in implementing NDT technologies to verify that the process is in control, statistical control charts are being used within this document. The ASTM *Manual on Presentation of Data and Control Chart Analysis* was used for preparing practical procedures that contractors can use in deciding whether their process is in control (ASTM 1992).

The upper and lower control or action limits for the sample means are calculated in accordance with Equations 4 and 5.

$$UCL_{\overline{X}} = \overline{\overline{X}} + (A_3)(\overline{s}) \tag{4}$$

$$LCL_{\overline{X}} = \overline{\overline{X}} - (A_3)(\overline{s}) \tag{5}$$

Where:

$UCL_{\overline{X}}$ = Upper control limit for the sample means.
$LCL_{\overline{X}}$ = Lower control limit for the sample means.
$\overline{\overline{X}}$ = Target value for a project.
$\overline{s}$ = Pooled standard deviation that represents the process variance.
A_3 = Factor for computing control chart limits and dependent on the number of observations in the sample.

The target value of the control chart for each material is the average modulus measured in the laboratory. Both action and warning limits are normally included on the statistical control charts. The upper and lower action limits are set at three standard deviations from the target value, while the warning limits are set at two standard deviations from the target.

The upper and lower control limits for the sample standard deviations are calculated in accordance with Equations 6 and 7, while Equations 8 and 9 are the limits when the range ($\overline{R}$) is used.

$$UCL_{\overline{s}} = (B_3)(\overline{s}) \tag{6}$$

$$LCL_{\overline{s}} = (B_4)(\overline{s}) \tag{7}$$

$$UCL_{\overline{R}} = (D_3)(\overline{R}) \tag{8}$$

$$LCL_{\overline{R}} = (D_4)(\overline{R}) \tag{9}$$

Where:

$B_{3,4}$ = Factors for computing control chart limits based on sample standard deviations and dependent on the number of observations in the sample.

$D_{3,4}$ = Factors for computing control chart limits based on the range within the sample and dependent on the number of observations in the sample.

4.1 HMA MIXTURES AND LAYERS

4.1.1 Acceptance Testing of HMA Mixtures and Layers

The dynamic moduli measured in the laboratory and the moduli measured with the PSPA were found to have a normal distribution, excluding areas with construction defects. Thus, the assumption of normality is applicable but should be checked, especially for harsh and tender HMA mixtures.

Step 1: Determine JMF and Target Mixture Properties

A master curve for each HMA mixture included in the design strategy (new construction or rehabilitation with HMA overlays) is normally assumed for structural design. This assumed master curve or specific modulus values are used within the mixture design process for determining the job mix formula (JMF) to ensure that the mixture design satisfies the structural design assumptions. The materials selection and mixture design should be completed in accordance with NCHRP Project 9-33.

Step 2: Verify the JMF with Plant Produced Mixture

The HMA mixture JMF should be verified with a plant produced mixture. If minor revisions are needed to satisfy the design criteria, those revisions should be completed and confirmed prior to determining the target modulus value for acceptance. The procedures recommended within NCHRP Project 9-33 should be followed for making any revisions to the JMF to ensure that the assumptions used for structural design have been met.

Step 3: Determine Target Dynamic Modulus for HMA Mixture

a. After the HMA mixture design has been verified from plant produced material, dynamic moduli should be determined for the mixture compacted to the target density specified for the in-place mixture (93 to 94 percent compaction or percent maximum theoretical density). The target density or percent compaction should be established by the agency. These dynamic moduli are used to determine the seismic shift factor. The purpose of the seismic shift factor is to translate the seismic modulus into a design modulus (see step 5).

   The test temperatures should include those that are expected during the acceptance testing of the mixture. The recommended temperatures include 90, 110, 130, and 150 °F (see Figure 5). Higher temperatures may need to be used if the acceptance testing is completed the same day of paving. The load frequencies used during testing should include 0.1, 0.5, 1.0, 5.0, and 10.0 Hz. If an approved master curve was already measured from the mixture plant verification process, it is not necessary to redo the test. The results from the earlier testing can be used.

   Not all agencies have the laboratory equipment in their district or field laboratories for HMA mixtures. Two options are provided: one for the case where the equipment is available for measuring the dynamic moduli and the second for the case where that equipment is unavailable.

   Option A—Measure Dynamic Modulus
   Sample plant produced mixture from the control strip or at the beginning of the project and compact three test specimens using a Superpave gyratory compactor to the density or air void level targeted or specified. Dynamic moduli are measured on the approved, plant verified JMF in accordance with AASHTO TP 62 over the range of temperatures expected during acceptance testing.

   Option B—Calculate Dynamic Modulus of HMA Mixture with Regression Equations
   Calculate the dynamic modulus over the range of frequencies and temperatures selected in accordance with NCHRP Project 9-33 or NCHRP Report 465 (see Figure 5). Use of regression equations is considered permissible because adjustments need to be made for the specific mixture.

b. The target dynamic modulus is determined for a specific or reference frequency (5 Hz is suggested) and temperature (the mid-range temperature expected during acceptance testing is suggested). See step 5 for additional discussion on the reference frequency and temperature. The target dynamic moduli should be compared to the value used for structural design. If the measured or calculated modulus is significantly different than the assumed value at the same frequency and temperature, revisions should be made to the mixture or structural designs.

c. The test specimens used to verify the JMF and prepared for dynamic modulus testing are also used in step 4 for measuring the seismic modulus of the mixture at different temperatures.

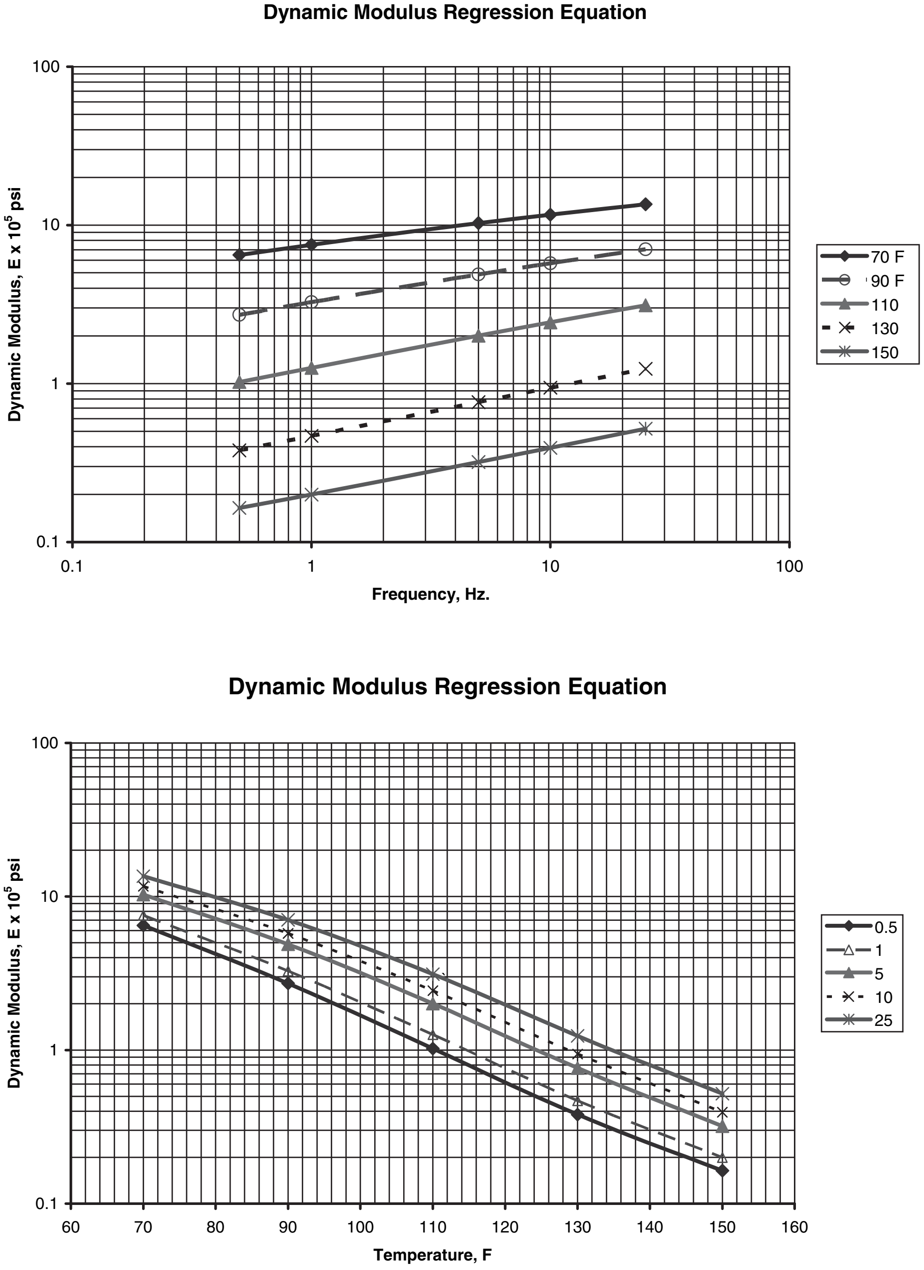


Figure 5. HMA Dynamic Moduli, Measured in the Laboratory or Calculated Using MEPDG Regression Equation

Step 4: Measure Laboratory Seismic Modulus on Plant Produced Mixture

The seismic modulus should be measured in accordance with ASTM D 5345. The seismic modulus can be measured on those test specimens that were prepared for the mixture verification process (see step 2), as long as they were compacted to the expected or specified in-place target density or air void level. The seismic modulus is measured on test specimens for each temperature selected under step 3 using a device, known as a V-meter, containing a pulse generator and a timing circuit, coupled with piezoelectric transmitting and receiving transducers (see Figure 6). The timing circuit digitally displays the time needed for a wave to travel through the test specimen. The measured travel time, the dimensions, and the mass of the test specimen are used to calculate the modulus.

The free-free resonant column (FFRC) test is a laboratory test to measure the modulus of the HMA mixture during the mixture design and field verification process. A cylindrical specimen is subjected to an impulse load at one end. Seismic energy over a large range of frequencies will propagate within the specimen. Depending on the dimensions and the stiffness of the specimen, energy associated with one or more frequencies are trapped and magnified (resonate) as they propagate within the specimen. The goal with this test is to determine these resonant frequencies. Since the dimensions of the specimen are known, if one can determine the frequencies that are resonating (i.e., the resonant frequencies), one can readily calculate the modulus of the test specimen.

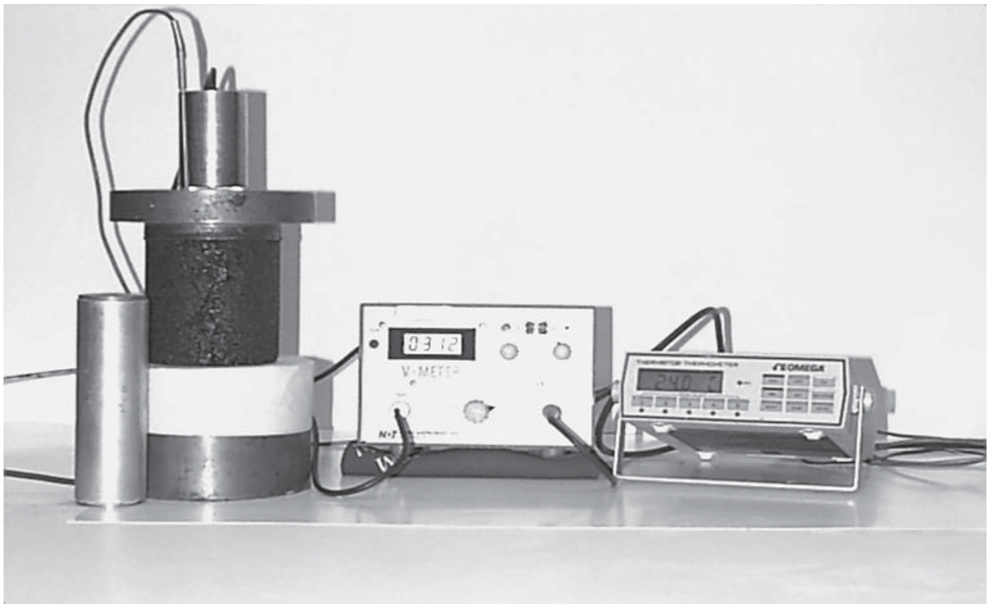


Figure 6. Equipment for Measuring the Seismic Modulus of Laboratory Compacted Test Specimens

Step 5: Determine Seismic Shift Factor to Translate the Seismic Modulus into the Design Modulus

The seismic modulus should be translated into a design modulus (see Figure 7). This step is necessary because seismic moduli are low-strain, high-strain-rate values, whereas the design moduli are based on low-strain, low-strain-rate values. The method of calculating the design modulus is to develop a master curve based on the recommendations of NCHRP Report 465, "Simple Performance Test for Superpave Mix Design," or in accordance with the NCHRP Project 9-33 mixture design procedure.

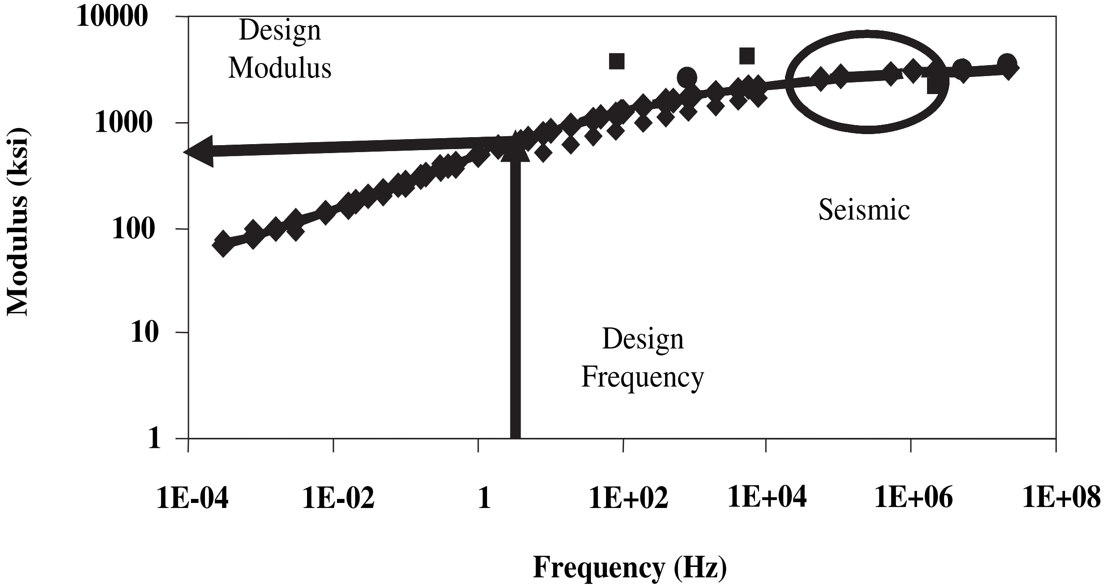


Figure 7. Graphical Illustration for Shifting the Seismic Moduli to the Dynamic Moduli for a Specific Load Frequency Using the Mixture Master Curve

Select the mat temperatures that are expected during the acceptance testing (see step 3). Typical values that can be used include 90, 110, 130, and 150 °F. The seismic shift factor is determined using Equation 10.

$$Log\left(a_T\right) = \frac{-c_1\left(T_o - T\right)}{c_2 + \left(T_o - T\right)} \tag{10}$$

Where:

c_1 = Regression coefficient determined from the dynamic modulus tests or calculations (for neat mixtures this value has been reported to be 19 and for polymer modified asphalt mixtures the value is 17.44).

c_2 = Regression coefficient determined from the dynamic modulus tests or calculations (for neat mixtures this value has been reported to be 92, while for polymer modified mixtures this value is 51.6).
T_o = Reference temperature, which should be the median value expected during acceptance testing.
T = Test temperature.

Equation 10 is used to translate the PSPA seismic moduli measured at varying surface temperatures during acceptance testing to the design modulus at the reference temperature and frequency. The reference temperature should be the approximate mid-range temperature during acceptance testing. Using the mid-range temperature should reduce or minimize potential bias that could be present if always translating to a higher or lower temperature.

The seismic shift factors are entered in the PSPA software to adjust the seismic values to the design frequency selected (see Figure 7). It is recommended that a load frequency of 5 Hz be used to determine the design modulus. However, the agency can select other frequencies to be consistent with the posted speed limit of the project—an input to the MEPDG.

Step 6: Determine the Field Adjustment Factor (Adjusting Field to Laboratory Conditions)

This step is to determine the field ratio for adjusting the design moduli to laboratory conditions. In other words, that ratio should be used to adjust the design moduli measured with the PSPA to laboratory conditions.

a. Select 8 to 10 random locations within the control strip or first day's production and measure the PSPA modulus and surface temperatures in accordance with step 7.

b. Drill and recover cores at a minimum of three locations. One core should be recovered from a location where the higher seismic modulus was measured, one at the location of the lowest seismic modulus, and the third at the median modulus value.

c. Measure the bulk specific gravity (G_{mb}) of each core from the HMA mat in accordance with AASHTO T 166.

d. Measure the maximum specific gravity (G_{mm}) of each core in accordance with AASHTO T 209.

e. Calculate the air void level (V_a) of each core in accordance with AASHTO T 269 and determine the percent compaction using Equation 11.

$$\%Compaction = 100 - V_a \tag{11}$$

f. Calculate or measure the dynamic modulus of the mixture using the average air void level measured from the three field cores.

g. Determine the specific adjustment ratio for the mixture in accordance with Equation 12.

$$R = \frac{E^*_{Lab}}{E_{Design}} \tag{12}$$

h. Determine if the field ratio deviates significantly from values near unity. The following provides a summary of the average ratios that have been measured on other HMA mixtures. It is expected that the ratio should be within three standard deviations. If the field ratio is outside three standard deviations from the mean value, it is expected that a significant change has occurred to the mixture between field verification and production. If the values are outside three standard deviations from those listed in Table 1, the mixture should be evaluated in more detail to ensure that the values are correct.

HMA Mixture Type	Field Adjustment Ratios	
	Mean	Standard Deviation
High binder content mixtures that exhibit tenderness, including SMA type mixtures	0.89	0.153
Harsh mixtures, coarse-graded mixtures including PMA	1.34	0.231

Table 1. Summary of the Average Ratios That Have Been Measured on Other HMA Mixtures

Step 7: Acceptance Testing with the PSPA for Measuring Modulus of HMA Mixtures

a. Allow the mixture to cool prior to using the PSPA. Elevated temperatures can cause the rubber pads on the tips of the receivers to melt. The test should be performed on areas with surface temperatures less than 200°F. The PSPA test should be performed in accordance with the manufacturer's recommendations.

b. Remove any loose material on the surface. The receivers or sensors should be in direct contact with the test surface.

c. Place the PSPA on the HMA surface. Align the sensor bar parallel to the direction of the paver and rollers. Slightly push the sensor bar to ensure that the receivers are in good contact with the surface. If mat tears or checking is observed in the test area, the PSPA should not be moved; the test should be conducted on that area, regardless of the surface condition.

d. After seating the PSPA, activate the software. Enter the type of surface tested and the mat thickness into the software. Inspect the graphical display of the load response and receivers on the screen of the laptop. If the load pulse has an irregular shape, repeat the test. One of the receivers may not be in good contact with the surface.

e. Record the seismic-design modulus and surface temperature reported by the PSPA.

f. Lift and rotate the PSPA 90° to the first direction of testing and repeat steps b to d.

g. Lift and rotate the PSPA by 45° between the first two readings and repeat steps b to d.

Step 8: Determine the Combined Variability for Setting the Specification Limits

The specification limits are defined by the combined variability for the HMA. Most agencies will have insufficient data to date for estimating this value in terms of setting the specification limits. Based on multiple operators and gauges, the following provides the recommended combined variability for dense-graded HMA mixtures to be used until sufficient data become available (based on the number of tests recommended above).

- Dynamic Modulus Combined Variability = 95 ksi

The target dynamic modulus for the specifications was defined under step 3.

Step 9: Determine Quality Indices and PWL for a Lot

The upper and lower quality indices are calculated in accordance with Equations 1 and 2, respectively, and used to determine the total PWL for each lot of material using Equation 3. The upper and lower PWL values are then determined from the Q-tables provided in the AASHTO QC/QA Guide Specification.

4.2.1 Quality Control Testing of HMA Mixtures and Layers

The quality control plan uses the non-nuclear density gauges. The PaveTracker gauge was specifically used to determine the control limits and other required information; that gauge is referred to specifically within this document, but other non-nuclear density gauges can be used if found to be acceptable.

Step 1: Determine the Density Correction Factor for the Non-Nuclear Density Gauge Used for Process Control

a. The density of the HMA mat should be measured with the PaveTracker device at each of the 8 to 10 locations selected for seismic testing within the control strip of the first day's production (see Acceptance Testing).

b. Determine the average density correction factor (*DCF*) between the PaveTracker density values and the densities (bulk specific gravities) measured on the field cores.

$$DCF = \frac{\gamma_{Core}}{\gamma_{Gauge}} \text{ or } \frac{G_{mb(Core)}}{G_{mb(Gauge)}} \qquad (13)$$

It is recommended that a contractor take a total of five cores at the beginning to increase the sample size for determining the average density correction factor. As the contractor becomes more familiar with the non-nuclear density gauges, that number for the control strips can be reduced to three for most mixtures. In addition, make sure that the surface is dry when establishing the DCF.

c. The densities measured with the PaveTracker or other non-nuclear density gauges are multiplied by the DCF to obtain the in-place density.

Step 2: Establish Density-Growth Curve and Temperature Sensitive Zone

a. At the beginning of the paving process, it is recommended that a density-growth curve be developed for the specific mixture and compaction train being used.

b. Measure the density after each pass of the roller over a specific point, in at least two locations or test points. Two readings should be taken at each point, and the average value recorded and used to determine the DCF. The surface temperature should also be recorded after each pass of the roller used in the compaction train—including the finish roller(s). The reason for reducing the number of density measurements in developing the density-growth curve is avoid delaying the compaction operation of the rollers. If time permits between each roller pass over a specific point, a minimum of three readings should be taken and the average value used.

c. A density-growth curve should be prepared for each test point used during the control strip or first day's production (see Figure 8). This testing is recommended for two reasons:

- To determine the number of passes of each roller for obtaining the target or specified density level.
- To determine whether the rollers will be operating within the temperature sensitive zone, and if so, to determine the temperature range through which the rollers should be restricted from rolling the mat (see Figure 9). Rolling within the temperature sensitive zone can significantly reduce the density of the HMA mat and cause the mat to check and tear. If this condition occurs, the owner agency will likely require that the mat be removed and replaced.

Step 3: Process Control Testing with Non-Nuclear Density Gauges

a. The non-nuclear density gauge should be operated according to the manufacturer's recommendations.

b. If the surface is wet (free water or water ponded on the surface), all free water should be removed and the surface allowed to dry in the area of the test prior to taking any readings.

c. Determine the number of test points per lot and sublot for controlling the HMA compaction. As a minimum, it is recommended that three test points per sublot be used for process control. The lot should be determined based on other tests being used by the contractor for process control (i.e., sampling the mixture for volumetric property determination using the gyratory compactor in the field or plant laboratory).

d. Identify or mark the area to be tested within each sublot.

e. Take four readings around the sides of each test point or test location. The gauge should be oriented in the same direction for each reading—in the direction of the paver and rollers is recommended. After the first reading, lift the gauge and move it to the next consecutive or adjacent side of the test point. Repeat until all sides of the test point have been taken. All four readings should be taken within a 1- to 2-foot square area.

f. Record all four readings and the surface temperature at each test point, and average the values for the test point.

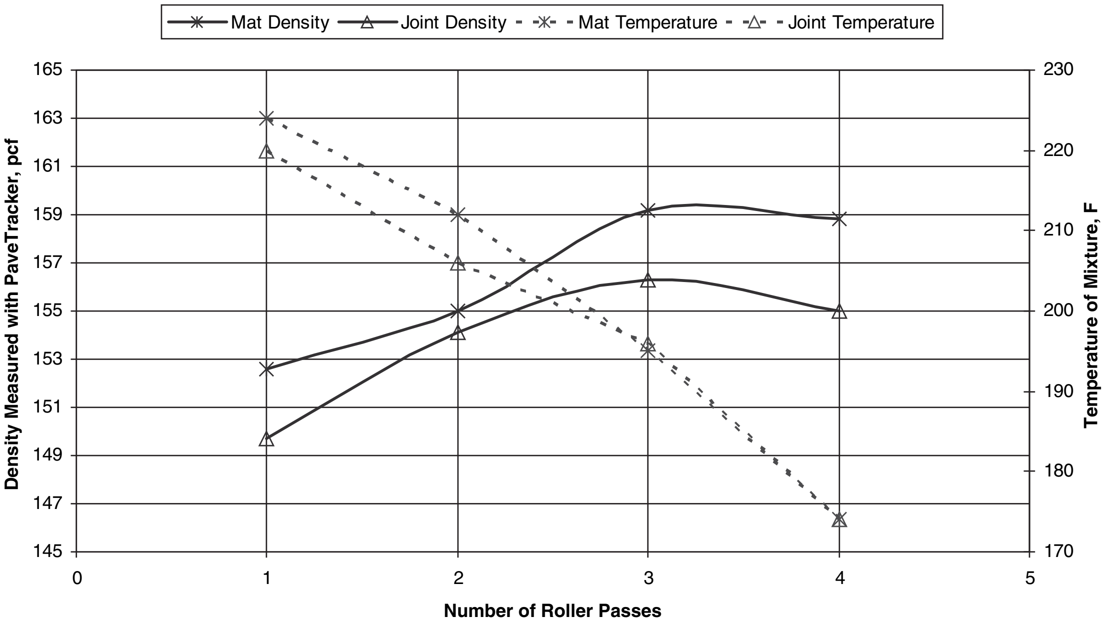


Figure 8. Density-Growth Curve Measured with the PaveTracker

Step 4: Determine the Combined Variability for Setting the Control Limits

The control limits are defined by the contractor’s within-process variability of density for HMA. Most contractors should have sufficient data for estimating this value in terms of setting the action and warning limits for the statistical control charts. Based on multiple operators and gauges, the following provides the recommended pooled standard deviation for density of the non-nuclear density gauges (PaveTracker), excluding all areas with anomalies and those areas where mat checking and tearing were exhibited.

Pooled Standard Deviation for Density = 2.5 pcf

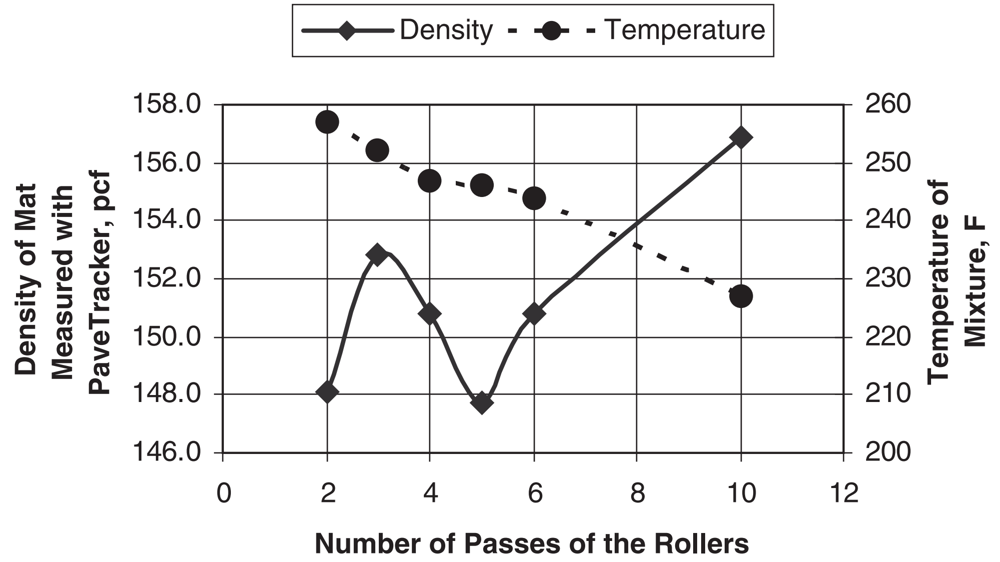


Figure 9. Density-Growth Curve Showing the Effects of Rolling within the Temperature Sensitive Zone

5.1 UNBOUND MATERIALS AND LAYERS

5.1.1 Acceptance Testing for Unbound Materials and Layers

The resilient moduli measured in the laboratory and the moduli measured with the GeoGauge were found to have a normal distribution, excluding areas with construction defects.

Step 1: Determine the Moisture-Density Relationship of the Soil and Material

Determine the moisture-density (M-D) relationship of the unbound material or soil in accordance with AASHTO T 180. The optimum water content and maximum dry density are the target values for determining the resilient modulus of the unbound layer.

Step 2: Determine Target Resilient Modulus

The target value for acceptance should be the average resilient modulus used as the input to the MEPDG. This value may have been determined from other physical properties and may or may not relate to the optimum water content and maximum dry unit weight of the material.

The resilient modulus, however, should be determined in the laboratory on test specimens prepared and compacted to the target density specified for the in-place mixture (100 percent of the maximum dry density as determined by AASHTO T 180). The target density should be established by the agency. The resilient modulus determined for the specified density and water content is the target resilient modulus for process control (see Figures 10 and 11). This target resilient modulus may or may not be the target value for acceptance.

Not all agencies have the laboratory equipment in their district or field laboratories for measuring the resilient modulus of the unbound layers. Thus, two options are provided: one for the case where the repeated load resilient modulus measuring equipment is available and the second for the case where that equipment is unavailable.

Option A—Measure Resilient Modulus

Sample the unbound materials from the stockpiles or from the control strip and compact three test specimens. Measure the resilient modulus of the unbound material over the range of stress states in accordance with AASHTO T 307. Determine the target resilient modulus at a low confining pressure and repeated vertical stress suggested below.

Layer & Material Type	Confinement, psi	Repeated Stress, psi	Total Vertical Stress, psi
Subgrade; Fine-Gained Soils with Plasticity	2	2	4
Embankment; Soil-Aggregate Mixture	4	4	8
Crushed Aggregate Base	6	6	12

Table 2. Option A—Measure Resilient Modulus

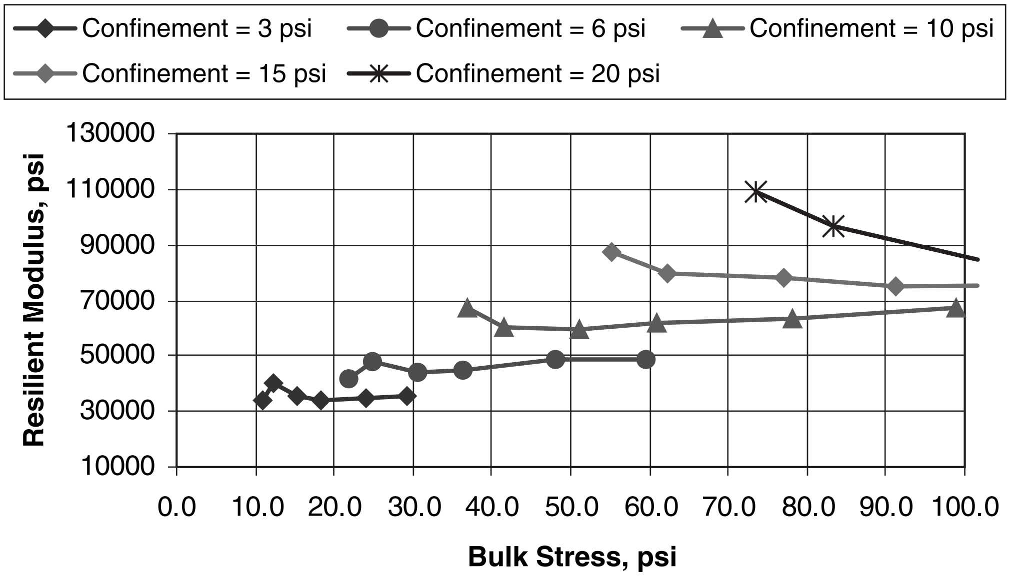


Figure 10. Resilient Modulus Measured in the Laboratory for a Crushed Stone Base Material

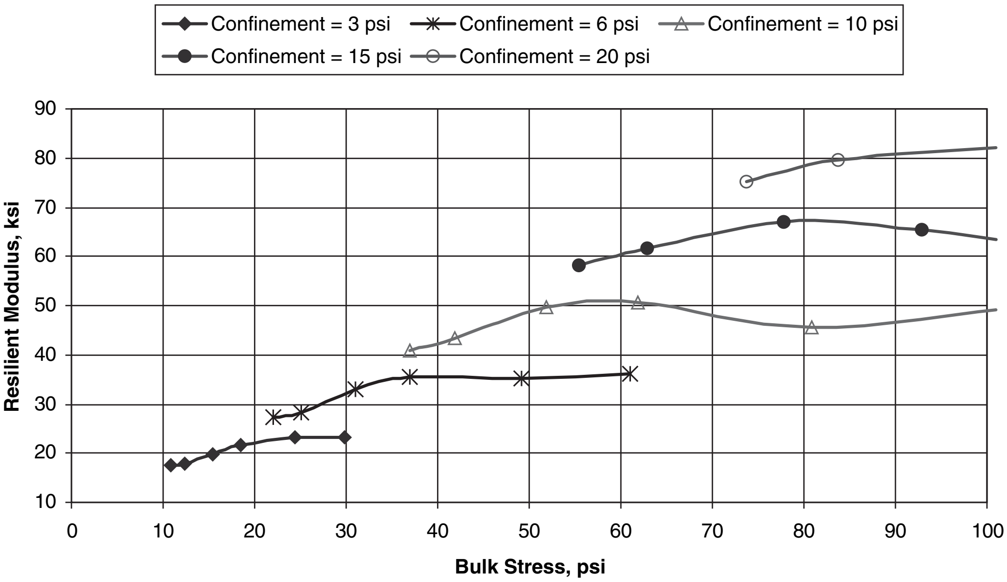


Figure 11. Resilient Modulus Measured in the Laboratory for a Crushed Stone or Aggregate Base Material

Option B—Calculate Resilient Modulus of the Unbound Material with Regression Equations

Calculate the resilient modulus for the stress states listed above in accordance with one of the regression equations from the Federal Highway Administration (FHWA) Long Term Pavement Performance (LTPP) program. These regression equations are shown below. Use of the regression equations is considered permissible because adjustments need to be made for the specific material.

$$M_R = k_1\left(p_a\right)\left(\frac{\theta}{p_a}\right)^{k_2}\left(\frac{\tau_{oct}}{p_a}+1\right)^{k_3} \tag{14}$$

Where:

θ = Bulk Stress, psi

$$\theta = \sigma_1 + \sigma_2 + \sigma_3 \tag{15}$$

τ = Octahedral shear stress, psi

$$\tau = \frac{\left(\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2\right)^{0.5}}{3} \tag{16}$$

p_a = Atmospheric pressure, 14.7 psi.

$\sigma_{1,2,3}$ = Principal stress, psi.

$k_{1,2,3}$ = Regression constants from laboratory resilient modulus test results.

The *k* regression constants are material specific. The following defines the regression constants for the different materials that were tested within the field evaluation projects. These relationships for these regression constants were developed from the FHWA-LTPP study (Von Quintus and Killingsworth 1998)

<u>Crushed Stone Base Materials:</u>

$$k_1 = 0.7632 + 0.008(P_{3/8}) + 0.0088(LL) - 0.037(w_s) - 0.0001(\gamma_{dry}) \tag{17}$$

$$\begin{aligned} k_2 &= 2.2159 - 0.0016(P_{3/8}) + 0.0008(LL) - 0.038(w_s) \\ &- 0.0006(\gamma_{dry}) + 0.00000024\left(\frac{\gamma_{dry}^2}{P_{\#40}}\right) \end{aligned} \tag{18}$$

$$k_3 = -1.1720 - 0.0082(LL) - 0.0014(w_s) + 0.0005\gamma_{dry} \tag{19}$$

<u>Embankments, Soil-Aggregate Mixture, Coarse-Grained</u>

$$\begin{aligned} k_1 &= 0.5856 + 0.0130(P_{3/8}) - 0.0174(P_{\#4}) + 0.0027(P_{\#200}) + 0.0149(PI) \\ &+ 0.0000016(\gamma_{Max}) - 0.0426(w_S) + 1.6456\left(\frac{\gamma_{dry}}{\gamma_{Max}}\right) + 0.3932\left(\frac{w_s}{w_{Max}}\right) \\ &- 0.00000082\left(\frac{\gamma_{Max}^2}{P_{\#40}}\right) \end{aligned} \tag{20}$$

$$\begin{aligned} k_2 &= 0.7833 - 0.0060(P_{\#200}) - 0.0081(PI) + 0.0001(\gamma_{Max}) - 0.1483\left(\frac{w_s}{w_{opt}}\right) \\ &+ 0.00000027\left(\frac{\gamma_{dry}^2}{P_{\#40}}\right) \end{aligned} \tag{21}$$

$$k_3 = -0.1906 - 0.0026(P_{\#200}) + 0.00000081\left(\frac{\gamma_{opt}^2}{P_{\#40}}\right) \tag{22}$$

<u>Embankments, Soil-Aggregate Mixture, Fine-Grained</u>

$$\begin{aligned} k_1 &= 0.7668 + 0.0051(P_{\#4}) + 0.0128(P_{\#200}) + 0.0030(LL) \\ &- 0.051(w_{opt}) + 1.179\left(\frac{\gamma_{dry}}{\gamma_{Max}}\right) \end{aligned} \tag{23}$$

$$k_2 = 0.4951 - 0.0141(P_{\#4}) - 0.0061(P_{\#200}) + 1.3941\left(\frac{\gamma_{dry}}{\gamma_{Max}}\right) \tag{24}$$

$$k_3 = 0.9303 + 0.0293(P_{3/8}) + 0.0036(LL) - 3.8903\left(\frac{\gamma_{dry}}{\gamma_{Max}}\right) \tag{25}$$

Fine-Grained Clay Soil

$$k_1 = 1.3577 + 0.0106(Clay) - 0.0437(w_s) \tag{26}$$

$$k_2 = 0.5193 - 0.0073(P_{\#4}) + 0.0095(P_{\#40}) - 0.0027(P_{\#200}) - 0.0030(LL) - 0.0049(w_s) \tag{27}$$

$$k_3 = 1.4258 - 0.0288(P_{\#4}) + 0.0303(P_{\#40}) - 0.0521(P_{\#200}) + 0.025(Silt) + 0.0535(LL) - 0.0672(w_{opt}) - 0.0026(\gamma_{\max}) + 0.0025(\gamma_{dry}) - 0.6055\left(\frac{w_s}{w_{opt}}\right) \tag{28}$$

Step 3: Determine the Field Adjustment Factor (Adjusting Field to Laboratory Conditions)

The GeoGauge results in a field modulus and needs be adjusted to be consistent with the structural design assumptions based on laboratory resilient modulus. This step is to determine the field ratio for adjusting the GeoGauge measurements to laboratory conditions. Once this field ratio or factor is determined, that ratio should be used to adjust the GeoGauge modulus to laboratory conditions for all readings.

a. At a minimum of two locations within the control strip or first day's production, use the GeoGauge to measure the increase in modulus of the material under the roller. In other words, develop a modulus-growth curve (see Figure 12). The number of passes of the roller should be increased until the modulus remains the same.

b. Select 8 to 10 random locations within the control strip or first day's production and measure the GeoGauge modulus in accordance with step 7.

c. Measure the density and moisture content at three of these locations using the sand-cone test to ensure that the material has been compacted to the dry density established by the agency's specifications.

d. Calculate or measure the resilient modulus of the in-place material using the average density and moisture contents measured from the sand-cone tests.

e. Determine the specific field ratio for the layer in accordance with the following equation.

$$R_{Resilient\ Modulus} = \frac{M_R\,(Lab)}{M_R\,(Design)} \tag{29}$$

f. Determine if the field ratio deviates significantly from values near unity. The following provides a summary of the average ratios that have been measured on other unbound materials. It is expected that the ratio should be within three standard deviations. If the adjustment ratio is outside three standard deviations from the mean value, it is expected that a significant change has occurred to the material between field calibration and production. If the values are outside three standard deviations from those listed below, the material should be evaluated in more detail to ensure that the values are correct.

Field Adjustment Ratios for Aggregate Base Materials and Soil-Aggregate Mixtures for Embankments:

Mean Value	=	1.031
Standard Deviation	=	0.370

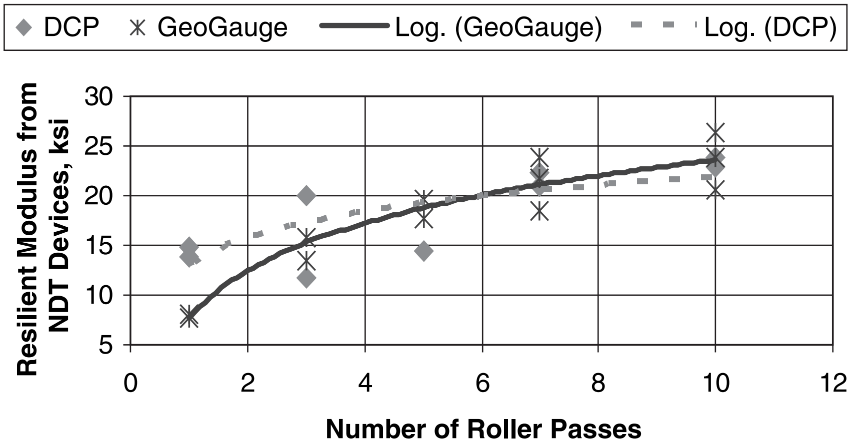


Figure 12. Modulus-Growth Curve Measured with the GeoGauge

Step 4: Use GeoGauge for Measuring Modulus of Unbound Layers for Acceptance and Conformance

a. The material modulus should be measured on the in-place material using the GeoGauge in accordance with the manufacturer's recommendations.

b. Remove any loose material on the surface, being careful not to disturb or remove an excessive amount of material. Figure 3 shows the tools that can be used to clean the test surface.

c. Place the moist sand on the test surface and pad it into place to fill any surface voids. The layer of moist sand should just cover the test surface and be sufficient in area so that three different readings of the GeoGauge can be made within this test area. This area should be about 1 to 2 square feet in size. This thin, moist sand layer is to ensure that the bottom ring of the GeoGauge is in contact with the surface for at least 75 percent of it surface area.

d. Place the GeoGauge on the surface of the sand. Lightly twist the GeoGauge, but do not push the GeoGauge into the test material. The bottom plate of the GeoGauge (not the bottom of the ring) must not be in contact with the material being tested. After the test, the surface of the layer should be inspected to ensure that it was not in contact with the GeoGauge.

e. Take a reading of the GeoGauge and record the modulus displayed. These readings can be stored in the device and downloaded at the end of the lot testing.

f. Adjust the readings externally to determine the laboratory equivalent resilient modulus values read by the GeoGauge.

g. Lift the GeoGauge and observe the surface of the thin layer of sand and test area. The thin layer of sand or test surface should not be indented by the gauge such that the bottom of the GeoGauge was in contact with the surface. If that was the case, the test result should be so noted and not used in the acceptance testing and the test repeated in a different area of the test area.

h. Move it to a different area with the sand layer and repeat steps d to g.

i. Lift the GeoGauge and move it to a third location and repeat steps d to g.

Step 5: Determine the Combined Variability for Setting the Specification Limits

The specification limits are defined by the combined variability for the unbound layers. Most agencies will have insufficient data to date for estimating this value in terms of setting the specification limits. Based on multiple operators and gauges, the following provides the recommended combined variability for dense-graded crushed stone base layers to be used until sufficient data become available (based on the number of tests recommended above).

- Resilient Modulus Combined Variability = 3.10 ksi

The target resilient modulus for the specifications was defined under step 2 and is the value assumed and used as an input to the MEPDG.

Step 6: Determine Quality Indices and PWL for a Lot

The upper and lower quality indices are calculated in accordance with equations 1 and 2, respectively, and used to determine the total PWL for each lot of material using equation 3. The upper and lower PWL values are then determined from the Q-tables provided in the AASHTO QC/QA Guide Specification.

5.2.1 Quality Control Testing of Unbound Materials and Layers

The quality control plan uses the GeoGauge to determine the control limits and other required information. The non-nuclear electrical density gauges require future improvements for use in process control. Thus, most of the steps included for acceptance testing also apply to process control, with the following exceptions.

- The target value of the control chart for the unbound layers is the average value measured in the laboratory in accordance with AASHTO T 307 and compacted to the specified density and water content specified by the agency.

- Both action and warning limits are normally included on the statistical control charts. The upper and lower action limits are set at three standard deviations from the target value, while the warning limits are set at two standard deviations from the target. The pooled standard deviation used to set the control limits will be contractor and material specific. The following provides the overall pooled standard deviation until contractors develop sufficient information and data for setting their own control limits.

    - Overall pooled standard deviation for setting the limits of statistical control charts for process control = 3.10 ksi

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation