STATE OF FLORIDA

USING HIGH-SPEED GROUND PENETRATING RADAR FOR EVALUATION OF ASPHALT DENSITY MEASUREMENTS

FINAL REPORT

FDOT Contract Number: BDK05

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

METRIC CONVERSION TABLE

Symbol	When You Know	Multiple By	To Find	Symbol
		Length		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		Mass		
T	Short tons (2000 lbs)	0.907	Metric Tons	t
		Temperature		
^{o}F	Fahrenheit	(F – 32) / 1.8	Celsius	^{o}C

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16. Abstract

Ground penetrating radar (GPR) has been growing in acceptance among highway agencies and industry as a means to provide continuous pavement information nondestructively. GPR technology has been used most successfully to determine pavement layer thickness but also has been used to identify subsurface voids, assist with forensic investigations, locate utilities and reinforcement, evaluate degradation of bridge decks, and estimate volumetric properties of asphalt pavements.

The objective of this project is to evaluate the capabilities and limitations of the FDOT GPR system to estimate the in-place density of asphalt pavement for construction and rehabilitation projects. Should the equipment be found suitable for estimating the in-place densities of asphalt pavements, techniques would then be developed to take measurements, with a plan to implement the methodology.

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EXECUTIVE SUMMARY

All Florida Department of Transportation (FDOT) projects are accepted in accordance with one or more construction specifications. The purposes of these specifications are to provide guidance and establish minimum requirements that enable a quality product to be built. The final product produced must meet the expectations of the designer to protect public safety and provide the expected level of service to the roadway user. Roadway pavement surface and binder course density is currently measured in accordance with FM 1-T 166, *Florida Method of Test for Bulk Specific Gravity of Compacted Bituminous Mixtures*. Five randomly located 6-inch-diameter roadway cores from each sub-lot (initially 500 tons with subsequent sub-lots of 1,000 tons) are required to meet the sampling and testing requirements of Section 334 in the *2007 Standard Specifications for Road and Bridge Construction*. This method provides density only at the locations where the cores are taken, is a destructive procedure, is considered slow, tedious, and requires maintenance of traffic (MOT).

Several nondestructive methods have been investigated in the hopes of eliminating or reducing the amount of coring required. Preferably, new technology would allow for continuous density assessment of the full lane width during construction and prior to the placement of additional pavement layers. Therefore, the ideal method would consist of a nondestructive survey during or immediately after construction with a rapid turnaround of density or relative compaction information. This information would then be used to direct a targeted coring plan with the possibility of significantly reducing the number of required cores.

Ground penetrating radar (GPR) has been growing in acceptance among highway agencies and industry as a means to provide continuous pavement information in a nondestructive manner. GPR technology has been most successfully used to determine pavement layer thickness but has also been used to identify subsurface voids, assist with forensic investigations, locate utilities and reinforcement, evaluate degradation of bridge decks, and estimate volumetric properties of asphalt pavements.

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1.0 INTRODUCTION

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FDOT has been at the forefront of GPR research, initially investigating GPR as a tool to derive pavement information in the early 1990's. FDOT recently implemented a high-speed GPR to determine the surface layer thickness of flexible pavement rehabilitation projects. Layer thickness information, along with Falling Weight Deflectometer (FWD) data, is collected and analyzed by the State Materials Office (SMO) in Gainesville and submitted to the design engineer. FDOT also has used both high-speed and ground-coupled GPR systems to assist with forensic investigations, determine the extent of sinkhole activity, locate subsurface voids below rigid pavements, and identify buried utilities.

2.0 OBJECTIVE OF THE STUDY

The objective of this project is to evaluate the capabilities and limitations of the FDOT GPR system to estimate the in-place density of asphalt pavement for construction and rehabilitation projects. Should the equipment be found suitable for estimating the in-place densities of asphalt pavements, techniques would then be developed to take the density measurements, with a plan to implement the methodology.

3.0 BACKGROUND

GPR is a nondestructive investigation tool that is used to provide subsurface information. A GPR antenna transmits high-frequency electromagnetic waves into the ground. A portion of the energy is reflected back to the surface at the interface of adjacent (usually layered) materials with different electrical properties, which is received by the antenna. The remainder of the GPR energy continues to penetrate beneath this interface, and additional energy is continually reflected back to the receiver from other interfaces until the energy is diminished.

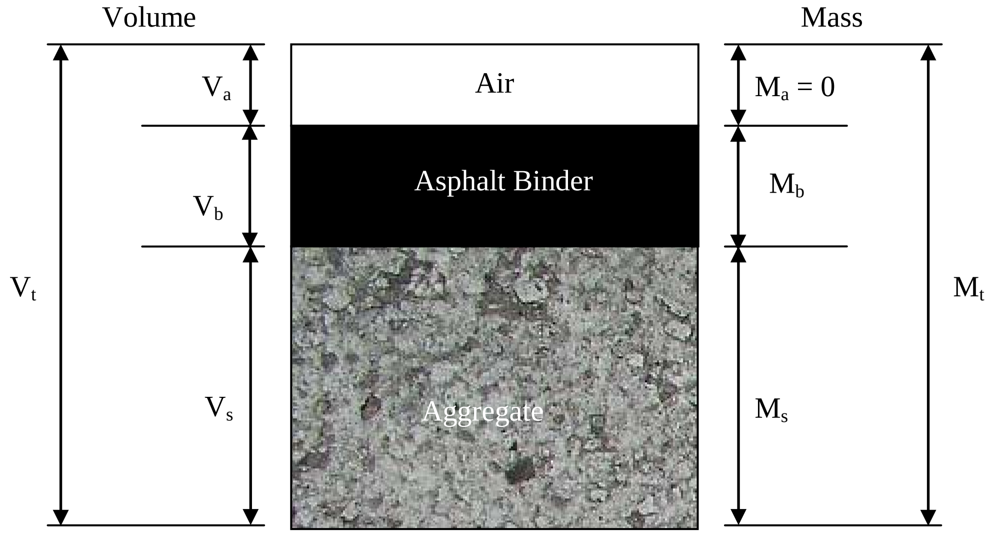
The current GPR technology used in highway and transportation applications emerged over 30 years ago through two separate efforts: (a) the development of ground-coupled antenna systems for geological and geotechnical applications and (b) the development of air-coupled horn antennas for mine detection for military purposes. The ground-coupled equipment traditionally has been used for maximum depth penetration and where information is more qualitative than quantitative. The ground-coupled technology has been widely used for a variety of subsurface applications, including mapping of groundwater, bedrock, and soil layers; detecting pipes, buried drums, and subsurface contamination; and locating concrete reinforcement. Antennas are available with center frequencies ranging from 80 MHz to 2.0 GHz, providing a wide range of penetration depths and resolutions.

Air-launched horn antennas, with center frequencies of 1 and 2 GHz, are operated 12 to 20 inches above the pavement surface from a moving vehicle and thus allow data collection at driving speed. These antenna have proven to be suitable for pavement and bridge deck applications, where quantitative results are required at high resolution but for shallow penetration.

In 2006, FDOT purchased a new 2.0 GHz GPR system manufactured by Geophysical Survey Systems, Incorporated (GSSI). The main focus of this system has been to provide high-speed layer thickness surveys for pavement rehabilitation projects. The success of this program has led to a renewed interest in furthering GPR technology in FDOT. Recent research and published reports suggest that density and volumetric properties of asphalt pavement can be determined using GPR technology. However, due to the proprietary analysis methodology used by most GPR service providers, published reports include only limited details of the techniques used. Therefore, an open and in-depth investigation is required to evaluate the capabilities and limitations of GPR technology, particularly FDOT’s GPR system, to determine the density of asphalt pavements rapidly and nondestructively.

Asphalt Density and Volumetric Measurement with Ground Penetrating Radar

A compacted hot mix asphalt (HMA) mixture is made of three phases: aggregate, asphalt binder, and air. A phase diagram, as shown in Figure 1, typically is used to demonstrate the mass and volume relationships of a compacted HMA mixture. HMA density is determined from GPR by calculation of the HMA dielectric constant from the reflection of a pulsed electromagnetic wave. The HMA dielectric constant is a function of the dielectric constant of the asphalt mixture constituents. With aggregate and binder properties relatively fixed, the dielectric constant varies directly with air content or density.



V_a	= volume of air	M_a	= mass of air
V_b	= total volume of binder	M_b	= total mass of binder
V_s	= volume of aggregate	M_s	= mass of aggregate
V_t	= total volume	M_t	= total mass

Figure 1. Compacted HMA Volumetric Composition.

The FDOT GPR system utilizes two 2.0 GHz air-launched antennas. The dielectric constant of HMA can be computed directly from the GPR horn antenna data using the following equation from Maser and Scullion.[1]

$$\varepsilon_a = [(A_{pl} + A_a)/(A_{pl} - A_a)]^2 \qquad \text{Equation (1)}$$

where,

ε_a is the asphalt dielectric constant,
A_{pl} is the radar reflection amplitude from a metal plate, and
A_a is the radar reflection amplitude from the asphalt surface.

The amplitude A_a is calculated using standard GPR analysis software such as RADAN supplied by the equipment manufacturer. The volumetric properties of the asphalt mixture can be related to the dielectric constant using one of a number of *mixture laws*. The most commonly employed mixture law is referred

[1] Maser, K. R. and Scullion, T. (1992). "Automated Pavement Subsurface Profiling Using Radar-Case Studies of Four Experimental Field Sites," *Transportation Research Record 1344*, TRB National Research Council.

to as the Complex Refractive Index Model (CRIM). The CRIM formula for the HMA dielectric constant is shown below:

$$\sqrt{\varepsilon_a} = v_{agg}\sqrt{\varepsilon_{agg}} + v_{binder}\sqrt{\varepsilon_{binder}} + v_{air}\sqrt{\varepsilon_{air}} \qquad \text{Equation (2)}$$

where,

v_{agg}, v_{binder}, and v_{air} are the volume fractions of aggregate, binder, and air respectively, and ε_{agg} , ε_{binder} (~ 2.5), and ε_{air} (= 1) are the dielectric constants of aggregate, binder, and air respectively.

The volume fractions add up to 1, but there are three unknowns on the right side of Equation 2 and only one directly measured dielectric value. Consequently, some type of calibration is required to reduce the number of unknowns and to establish a simple relationship between dielectric and air content or density.

4.0 LITERATURE REVIEW

Measurement of Asphalt Density Using Nondestructive Technologies

Recent years have witnessed a significant increase in the development and application of nondestructive testing (NDT) technologies, such as GPR, seismic concepts, and infrared thermography, in testing pavement materials. NDT methods offer a good alternative to traditional tests; they require no coring and provide instantaneous test results. However, these benefits are more than offset if the NDT devices do not produce accurate measurements. The most widely evaluated NDT device in HMA testing is the non-nuclear density gauge. Non-nuclear density gauges are being considered as a viable substitute to nuclear gauges primarily for safety concerns and to eliminate costs associated with radioactive material licensing.

Density measuring gauges adopting a non-nuclear technology have been integrated into portable devices as well as in on-board compactor-mounted systems, such as in the intelligent compaction devices. The PaveTracker and the Pavement Quality Indicator (PQI) models manufactured by Troxler and Transtech Systems, Inc., respectively, are the portable devices that have been developed and refined over the years for HMA density measurements. The PaveTracker operates on the principle of electromagnetic sensing, while the PQI estimates density by measuring the electrical impendence of the material. The most current version available today are the PaveTracker 2701B and the PQI 301, the latter being an upgrade to the previous PQI 300 version. Figure 2 shows a picture of the current models of the PQI and PaveTracker devices.

Non-nuclear gauges have been evaluated under many projects with varying results. Three previous FDOT studies have shown that both nuclear and electrical impedance devices are un reliable when measuring density on Superpave mixes.[2] The variability of the density data was too high in comparison to the actual core densities. In general, the fine grade mixes did not compare with field cores as well as coarse graded mixes. This would prevent such a device from being used for acceptance where pay factors are determined based on the in-place density of the mix.

The most extensive evaluation was performed in a Federal Highway Administration (FHWA) pooled fund study that included 144 projects in six states.[3] A consistent bias was observed between the non-nuclear density tests and conventional tests, emphasizing the need for appropriate calibration procedures for

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[2] Choubane, B., P. B. Upshaw, G. A. Sholar, G. C. Page, J. A. Musselman. *Nuclear Density Readings and Core Densities: A Comparative Study*. Research report FL/DOT/SMO/98-418, Florida Department of Transportation, Gainesville, Fl., July, 1998.

Upshaw. P. B., B. Choubane, G. A. Sholar. Non-published report comparing cores to PQI 100 and Troxler 3430 gauges. Florida Department of Transportation, Gainesville, Fl., September, 1998.

Sholar, G. A., J. A. Musselman, , G. C. Page, P. B. Upshaw,. An Evaluation of Field Density Measuring Device. Research report FL/DOT/SMO/99-437, Florida Department of Transportation, Gainesville, Fl., December 1999.

[3] Romero, P., "Evaluation of Non-Nuclear Gauges to Measure Density of Hot-Mix Asphalt Pavements," Pooled Fund Study, Final Report, University of Utah, July 18, 2002.

accurate density predictions. Other studies by Allen et al., Rogge, and Sully-Miller found a good correlation between PQI and core-measured density and recommend its use in contractor quality control (QC) testing.[4] However, some studies also have found the results to be very sensitive to moisture conditions introduced by the rolling operations.[5] This is in agreement with the manufacturer's recommendations to test on the day of paving to avoid the effects of water and debris collected in the void structure of the pavement, as both these factors can affect the dielectric constant of the materials disproportionately.[6] Manufacturers of both the devices have made significant improvements to the software and associated electronics in the equipment to balance the effect of moisture and temperature conditions on measured density.

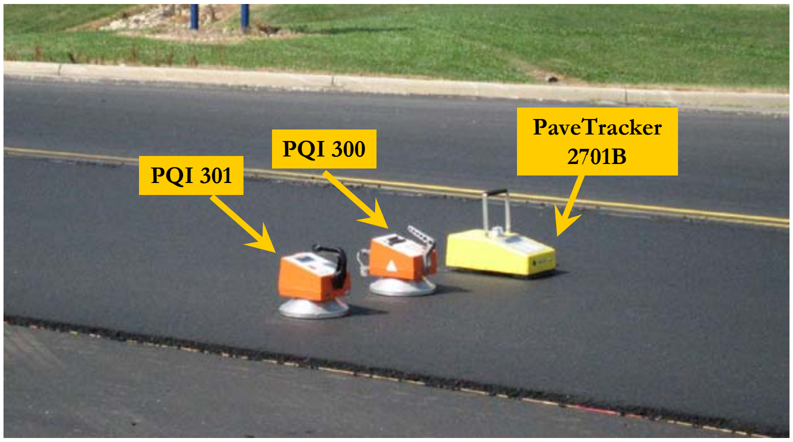

Figure 2. Non-nuclear Density Gauges PQI and PaveTracker.

Rao et al.[7] reviewed previous work on field evaluation of non-nuclear density gauges and synthesized valuable information including year of study, researcher, test devices and methods used, field experimental design, and key findings.

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[4] Allen, D.L., Schultz, D.B., Willett, D.A., *Evaluation of Non-nuclear Density Gauges*, Kentucky Transportation Center, University of Kentucky, Lexington, Kentucky, 2003.

Rogge D.F., *Compaction and Measurement of Field Density for Oregon Open-Graded (F-mix) Asphalt Pavement*, Final Report, Oregon State University, Corvallis, Oregon, 1999.

Sully-Miller Contracting Company, *A Summary of Operational Differences Between Nuclear and Non-nuclear Density Measuring Instruments*, TransTech Systems, Inc., 2000.

[5] Henault, J.W., *Field Evaluation of a Non-nuclear Density Pavement Quality Indicator*, Report No. 2227-F-01-3, Connecticut Department of Transportation, Newington, Connecticut, 2001.

[6] TransTech Systems, Inc., *Technical Note 0301*, Schnectady, NY, 2003.

[7] Rao, C., Schmitt, R., and Von Quintus, H.L., "*Non-Nuclear Density Testing Devices and Systems to Evaluate In-Place Asphalt Pavement Density*," Final Report, WHRP Project 0092-05-06, May 2006.

Table 1 summarizes previous studies.[8] The scope of these studies generally involved the comparison of cores with the PQI, and in some cases, including a nuclear density gauge and the non-nuclear PaveTracker gauge. The number of projects in each study ranged from 1 (8 studies) to 144 projects (University of Utah pooled-fund study). The number of cores on individual projects ranged from 4 to 42. The University of Utah pooled fund study stated that non-nuclear devices could be used for QC, but they were not recommended for quality assurance (QA) or acceptance testing.

Rao et al, also performed field evaluations of currently available non-nuclear density gauges for use in QC and quality acceptance of asphalt pavement construction as per the WisDOT specifications[9]. This study suggested that non-nuclear density gauges can be used to determine in-situ HMA density during flexible pavement construction. For accurate density predictions, however, appropriate calibration factors need to be established to adjust raw readings from the non-nuclear device to field density values. A correlation between true density and raw non-nuclear density readings is necessary to establish the regression coefficients that are used as the calibration constants. The study also recommended that independent calibrations be established for each day of paving.

[8] Schmitt, R., Rao, C., and Von Quintus, H.L., "*Non-Nuclear Density Testing Devices and Systems to Evaluate In-Place Asphalt Pavement Density*," Final Report, WHRP Project 0092-05-06, May 2006.

[9] See Note 11.

Table 1. Summary of Field Research Studies Evaluating Non-nuclear Devices.

Year (1)	Researcher (2)	Test Devices/Methods (3)	Experimental Design (4)	Findings (5)
2004	NCHRP 10-65	• PaveTracker • PQI model 301 • Cores • Nuclear density measurements	• 4 projects completed • 1 project scheduled • 7-8 additional projects likely depending on preliminary analysis • 3-4 sections per project • 15 test points/section 4 readings in orthogonal positions per test point	• Ongoing and pending analysis • Part A analysis will be available prior to field tests in Wisconin.
2003	Kentucky Transportation Center	• Cores, T-166 • Troxer 4640-B (nuclear) • PQI Model 300 (2 devices)	• 1 project • 33 cores • One to four nuclear readings • Five non-nuclear readings in clockwise positions	• Troxler 4640B -1.8pcf vs. core • PQI #1 +0.3pcf vs. core • PQI #2 -0.7pcf vs. core • PQI recommended for QC to obtain relative density.
2003	Texas Transport. Institute	• Cores, T-166 • Troxer 3450 (nuclear) • PQI (model unknown) • PaveTracker (model unknown)	• 3 projects • 10 cores/project • Two 1-minute nuclear readings (rotating 180 degrees between readings) • Five 5-second non-nuclear readings in 2, 4 , 8, 10, 12 o'clock positions	• Troxler 3450 ± 4.1pcf core • Pavetracker ± 5.7pcf core • PQI ± 2.6pcf core • 100-deg F drop in temp affected PaveTracker with 5pcf drop in density.
2003	Florida DOT	• Cores, T-166 • Troxler 3440 (nuclear) • PQI Model 300 • PaveTracker	• 1 project • 4 cores to develop correction factor • 12 sites (no cores) with correction factor applied	• Correction factor applied: - Troxler 3450 –1.3pcf vs core. - PQI +1.1pcf vs core. - PaveTracker +1.1pcf vs core.

Year (1)	Researcher (2)	Test Devices/Methods (3)	Experimental Design (4)	Findings (5)
2002	University of Utah, Pooled Fund Study. Participating States: Connecticut Maryland Minnesota New York Oregon Pennsy.	• Cores, T-166 • Several nuclear gauge models • PQI Model 300 • PaveTracker (model unknown)	• Lab factors Investigated: Density, NMAS, Source, Temperature, Moisture. • 2000 field study: 76 projects in 6 states • 2001 field study: 38 projects in 5 states • 5 to 15 cores/project • Two 1-minute nuclear readings or four 30-second nuclear readings • PQI: Five 5-second non-nuclear readings in 2, 5, 8, 11, 12 o'clock positions • PaveTracker: Four 5-second non-nuclear readings in 3, 6, 9, 12 o'clock positions	• 2000 lab study: Density, Source, Temperature, and Moisture had an effect on PQI readings. NMAS had a minimal effect. • 2000 field study: PQI ranged from 0.0pcf to 16.6pcf average project difference than cores, and was stat. different on 54% of projects. • 2001 field study: PQI ranged from 0.0pcf to 83.0pcf average project difference than cores, and was statistically different on 68% of projects. PaveTracker ranged from 0.0pcf to 14.0pcf average project difference than cores, and was statistically different on 82% of projects. • PQI was not adequate to measure density changes in field. • Mixture specific calibration is needed. • PQI and PaveTracker not recommended for QA. • PQI and PaveTracker suitable for QC to obtain relative density.
2002	Skanska Asphalt and Concrete Technology Region – VTO South	• Cores, T-166 • Seaman C200 (nuclear) • PQI Model 300	• 1 project • 10 cores • Twenty 30-second non-nuclear readings without moving device	• Nuclear +2.1% to +3.0% vs. core. • PQI -0.5% vs. cores. • Water content of 15% limits reliability. • Water content is 5-6% on hot mat.
2001	Connecticut DOT in cooperation with FHWA	• Cores, T-166 • CPN MC-3 (nuclear) • PQI Model 300	• 10 projects • 10 cores/project • Two 30-second nuclear readings (rotating 180 deg between readings) • Five 5-second non-nuclear readings in clockwise rotation	• PQI 300 ± 12.1pcf core, with average of +8.2 pcf across 10 projects. • CPN MC-3 ± 1.0pcf core, with average of +0.6 pcf across 10 projects. • Poor PQI performance likely the result of moisture in hot pavement mat. • Recommended not to use PQI for QA.

Year (1)	Researcher (2)	Test Devices/Methods (3)	Experimental Design (4)	Findings (5)
2001	Diamond Materials	• Cores, T-166 • PQI Model 300	• 1 project • 10 cores	• PQI +1.2pcf vs. core.
2000	Sully-Miller Contracting Co.	• Cores, T-166 • Troxler 3440 (nuclear) • PQI Model 300	• 1 project • 6 cores • Two 1-minute nuclear readings (rotating 180 deg between readings) • Five 5-second non-nuclear readings in 2, 4, 8, 10, 12 o'clock positions	• Nuclear -2pcf to -4pcf vs. core. • PQI -10pcf to -12 pcf vs. core. • Bias correction needed for PQI. • Bias correction optional for Troxler (nuclear). • PQI showed no measurable affect from pavement texture.
1999	Delaware DOT and Delaware Asphalt Pavement Association	• Cores • Troxler 3450 (nuclear) • Troxler 4640 (nuclear) • PQI Model 300	• 1 project • 5 cores (Day 1) • 12 cores (Day 2) • Two 1-minute nuclear readings • Correlated gauge to core on Day 1 and applied offset on Day 2	• Day 1: - Troxler 3450 –5.3pcf vs core. - Troxler 4640 –6.3pcf vs core. - PQI –8.3pcf vs core. • Day 2: - Troxler 3450 –1.6pcf vs. core. - Troxler 4640 –1.0pcf vs. core. - PQI –1.6pcf vs. core.
1999	NCHRP-IDEA Projects 32 and 47	• Cores, T-166 • Nuclear gauge (model unknown) • PQI Model 300 • PaveTracker	• 1 project • 8 cores	• Nuclear –2.3pcf vs. core. • PQI +0.3pcf vs. core.
No date	Nebraska Department of Roads	• Cores, T-166 • PQI Model 300	• 1 project • 42 cores	• PQI +0.2pcf vs. core

Researchers at Texas Transportation Institute (TTI) evaluated the ruggedness and repeatability of two non-nuclear density devices.[10] By testing field projects and correlating to field cores, the TTI team analyzed the accuracy of each gauge where traditional field density measurements were provided by a nuclear density gauge for comparison. Both non-nuclear devices provided satisfactory repeatability, with

[10] Sebesta, S., Scullion, T., and Liu, W., *Evaluation of Non-nuclear Density Gauges for HMAC: Year 1 Report,* Report 0-4577-1, Texas Transportation Institute, July 2005.

standard deviations of repeat readings under 0.5 lb/ft^3. The presence of moisture influenced the readings on both gauges; additional moisture resulted in an increase in the measured density. However, the impact of moisture did not become significant until the surface appeared visibly wet. At times all the gauges exhibited bias in the field, and due to the sporadic nature of observed mean errors, gauge bias could not be estimated. Based upon these observations, the PQI provides the most reliable estimate of differential density. It was recommended that the PaveTracker version evaluated should not be used for Texas DOT operations.

The Portable Seismic Pavement Analyzer (PSPA) is a nondestructive device used for the evaluation of the seismic stiffness of a pavement structure (Figure 3). The device can be used to obtain basic information on the condition of the pavement structure, including parameters such as the seismic stiffness of the combined layers, indications of layer thicknesses and indications of an-isotropy in the pavement. Nazarian et al. conducted research using the PSPA for QC during construction and developed a protocol for such QC projects.[11] The PSPA and a derivative modified for base and subgrade measurement, the Dirt Seismic Pavement Analyzer (DSPA), are being used on a trial basis by the Texas DOT for QC/QA purposes. The operating principal of the PSPA is based on generating and detecting stress waves in a medium. If used appropriately, analyses of the stress waves can be used to determine the modulus of the layered material, as well as assess the thickness of the layer. These techniques are being utilized with very promising results during construction on a few projects in Texas and are being considered for QC on pavement warranty projects in Texas and New Mexico. Other field studies are reported where the seismic moduli of pavement layers were measured and evaluated.[12] Internationally, the Institute for Transport Technology (ITT) at the University of Stellenbosch has conducted several studies using the PSPA both in the laboratory and in the field.[13]

[11] Nazarian, S., Yuan, D., Tandon, V., and Arellano, M., "*Quality Management of Flexible Pavement Layers with Seismic Methods,*" Research Project 0-1735, Texas Department of Transportation, Centre for Highway Materials Research, University of Texas at El Paso, El Paso, Texas, 2002.

[12] Chen, D-H., and Bilyeu, J., "*Assessment of Hot-in-place Recycling Process,*" Tamkang, Journal of Science and Engineering, Vol. 4, No. 4, pp. 265-276, 2001.

[13] Steyn, W.J.vdM, and Fisher, C., "*Technical Memorandum: PSPA Evaluation,*" Contract report CSIR/BE/IE/ER/2006/0001/B. CSIR BE, Pretoria, South Africa, 2007.

Figure 3. Portable Seismic Pavement Analyzer (PSPA).

Compaction of embankment, subgrade, and base materials is a significant portion of State highway construction budgets and is critical to the performance of highway pavements. Heterogeneity of earth materials, variability in equipment and operators, and difficulty in maintaining uniform lift thickness and prescribed moisture content combine to make desired earthwork compaction difficult to achieve. Current QC and QA testing devices, such as the nuclear gage, the dynamic cone penetrometer, the stiffness gauge, and the lightweight FWD, typically are used to assess less than 1 percent of the actual compacted area. In addition, each of these devices measures values unique to the device.

Intelligent compaction (IC) has the potential to improve infrastructure performance, reduce costs, reduce construction duration, and improve safety. IC involves (a) continuous assessment of mechanistic soil properties (e.g., stiffness, modulus) through compaction-roller vibration monitoring, (b) continuous modification of roller vibration amplitude and frequency, and (c) an integrated global positioning system (GPS) to provide a complete a geographic information system (GIS) based record of the earthwork site.

Research findings in Europe and in the United States have shown that soil stiffness and modulus can be obtained through vibration of the compaction roller drum and that continuous monitoring, feedback, and automatic adjustment of the compaction equipment can significantly improve the quality of the compaction process. Standard specifications for the application of IC systems in the United States are needed. Such specifications should build on existing specifications and experience gained in Germany, Switzerland, Finland, Sweden, Japan, and other countries. The objectives of this research are to determine the reliability of IC systems and to develop recommended construction specifications for the application of IC systems in soils and aggregate base materials.

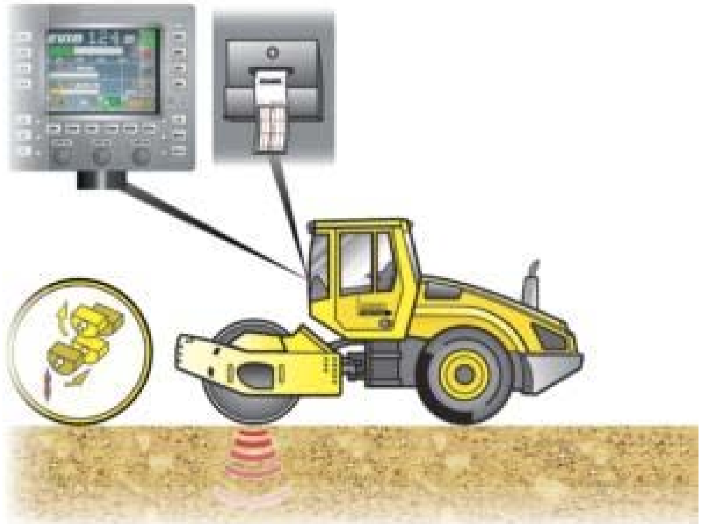

Figure 4. IC Roller from Bomag™.

The FHWA, Transportation Research Board (TRB) and State DOT's all have initiatives to promote IC technology. They are driven by the same ambition: to automate the compaction process, eliminate over- or under-compaction, and reduce risk by obtaining continuous real time assessment of job quality during construction work.

The Minnesota DOT (MnDOT) held an open house and demonstration of IC at their Mn/ROAD facility in 2006.[14] They also recently completed a 6-mile project on Highway 64. This project was one of the first in the United States to use IC on a full-scale project basis. The benefits realized were immediate. Guesswork was eliminated, avoiding over- or under-compacting subgrade materials. The constant data stream proved much more accurate than point data within the project. Time and cost savings were actualized; higher quality and uniformity were credited to the IC technology utilized.

The FHWA produced a report, "Intelligent Compaction Strategic Plan," in 2005 that establishes a 5-year plan to study IC and implement the technology. An offshoot of this is the Transportation Pooled Fund Program TPF-5(128), a FHWA study led by 12 States to accelerate development of IC QA/QC specifications and create a knowledgeable IC expertise base within participating DOT's. IC equipment will be identified and researched as QA/QC testing devices; simplifying IC use, cost-effectiveness, and improving accuracies are the objectives.

Measurement of Asphalt Density Using Infrared Thermography

Infrared thermography (IR) is a diagnostic nondestructive evaluation method that relates changes in surface temperature of a material to subsurface or internal flaws. The relationship between temperature

[14] Petersen, D. L., and Peterson, R., "Intelligent Compaction and In-situ Testing at Mn/DOT TH53," Final report, MN-RC-2006-13, St. Paul, Minn.: Minnesota Department of Transportation, Office of Research Services, 2006.

and internal flaws constitutes thermography. The use of emitted infrared radiation to measure surface temperature constitutes the infrared part of IR.

IR involves the use of non-contact surface temperature measurement to diagnose subsurface conditions. The basis of the measurement is that the surface temperature at a defect will differ from the normal or background surface temperature. In some applications, the object to be tested is artificially heated to produce the desired temperature differentials. In other applications, the heat input is either from solar radiation or from the natural temperature of the material or structure being tested. In either case, the infrared sensor detects the infrared radiation emitted from the object and converts the radiation measurement into a temperature measurement using the Stefan-Boltzmann Law:

$$Q = \sigma E(T^4 - T_0^4) \qquad \text{Equation (3)}$$

where,

Q is the radiation emitted from an object (watts/sq.meter),
σ is the Stefan-Boltzman constant ,
E is the emissivity of the object,
T is the absolute temperature of the object, and
T_0 is the absolute temperature of the surroundings.

The detection of surface temperature using infrared radiation is carried out using an infrared sensor or an infrared camera. Infrared cameras have been used for civil structures because they provide a two dimensional image of large surfaces, and they operate very much like a conventional video camera. The main difference is that the intensity levels of the infrared image are related to the infrared radiation (i.e., surface temperature) rather than the intensity of light. For example, where the infrared camera is set to a 50 degree temperature range and provides an 8-bit grey scale image, each pixel of that image provides 256 shades of gray representing the 50 degree range (or a resolution of 0.2 degree). Infrared camera operators often use a pseudo-color scale, in which the gray scale is replaced by a color scale. The use of color can highlight temperature changes that may be less obvious in the gray scale image.

An infrared sensor produces an output voltage proportional to the received infrared radiation at a point. These are much less expensive than infrared cameras, and generally used more in automated manufacturing and QC operations where the need is to monitor temperature at a fixed point or group of points.

Infrared cameras have been used in civil structure evaluation for determining heat loss in buildings, inspection of roofs for leakage, and locating subsurface leaks in steam pipes. IR has been used for the past 15 years as a method for detecting delaminations in bridge decks. The underlying principle is that, with solar radiation, the areas above delaminations will heat up more quickly than the sound areas due to the insulating effect of the delamination. These small temperature differentials (~1-2 ºF), or *hot spots*, can be observed as bright spots on a high-resolution infrared image. The results, produced by mapping these identified areas onto a plan view of the bridge deck, are used for making rehabilitation decisions, and for scoping and estimating repair projects.

The use of IR for detecting segregation in newly placed HMA was recommended in NCHRP Report 441, *Segregation in Hot Mix Asphalts.*[15] The report noted the ability of infrared to detect two types of segregation: (1) temperature segregation, where the mix has been unevenly cooled due to uneven exposure to cold surfaces during transport, and (2) gradation segregation, where coarse aggregate segregates, producing areas with high void volume and thus more rapid cooling. Both of these types of segregation appear to be associated with eventual deficiencies in asphalt properties, but the infrared measurement cannot distinguish one from the other. The report recommended that the thermal measurement be made prior to the first pass of the roller, since this is where the temperature differentials are most significant.

TTI evaluated the effectiveness of IR in identifying segregated areas, which involved taking measurements on new overlays at the time of placement, coring, then identifying relationships between changes in the IR data with changes in the measured volumetric and engineering properties of field cores.[16] Analyses of results showed that changes in IR data were significantly related to changes in HMA properties, such as air void content and gradation.

The Washington State DOT also has performed research into the use of an IR camera to view the process of placing HMA.[17] Figure 5 shows an example of their work. The figure shows temperature changes depicted with the IR camera and the correlation between temperature fluctuations and density and air void content.

Infrared Equipment and Software

The work in Texas and Washington utilized commercial infrared cameras, producing real time video images such as shown in Figure 5. These cameras allow the user to adjust to the temperature limits so that the appropriate range is being viewed. For example, the selected range for the image in Figure 5 is 20.0 to 114.2 ºC. These cameras also allow taking snapshots in addition to continuous video, and they provide a cursor that displays numeric temperature values on the image. The low viewing angle required of the video camera creates some distortion of the temperature measurement, due both to the angle and to the range of distances from the pavement surface to the camera. However, temperature differentials associated with segregation seem to be large enough to overcome this of distortion. Using the infrared

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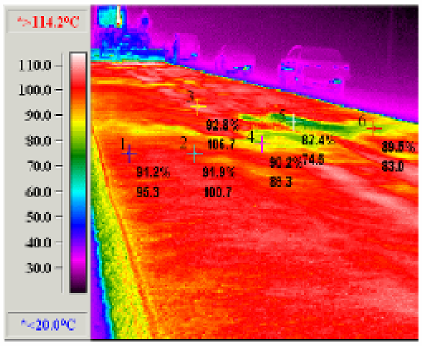
[15] Stroup-Gardiner, M., and Brown, E.R. *Segregation in Hot-Mix Asphalt Pavement*, NCHRP Report 441, Transportation Research Board, Washington, D.C., 2000.

[16] Sebesta, S., and Scullion, T. "Using Infrared Imaging and Ground Penetrating Radar to Detect Segregation in Hot Mix Overlays," TTI Report 4126-1, September 2002.

Sebesta, S. and T. Scullion "Application of Infrared Imaging and Ground-Penetrating Radar for Detecting Segregation in Hot-Mix Asphalt Overlays," Paper No. 03-3406, Transportation Research Board, 82nd Annual Meeting, Washington, D.C., 2003.

[17] Willoughby, K., Mahoney, J., Pierce, L, Uhlmeyer, J., and Anderson, K. "Construction-Related Variability in Mat Density Due to Temperature Differentials," Paper 1535, Transportation Research Board, 82nd Annual Meeting, Washington, D.C., 2003.

camera, pavement surface locations with temperature anomalies have to be manually marked on the pavement surface while the image is being viewed, since the camera has no distance scale.



Point Density/ Temperature	Temperature (°C)	Percent of Maximum Theoretical Density (%)	Change in Temperature (°C)	Change in Air Voids (%)
1	95.3	91.2	11.4	1.6
2	100.7	91.9	6.0	0.9
3	106.7	92.8	0.0	0.0
4	85.3	90.2	21.4	2.6
5	74.5	87.4	32.2	5.4
6	83.0	89.5	23.7	3.3

Figure 5. Illustration of Variable Density due to Temperature Differentials.

Subsequent work by TTI and by Auburn University[18] has favored the use of an array of infrared sensors mounted behind the screed in a line transverse to the pavement. With this setup, the collection of infrared data is automated and continuous as the screed moves. Distance is monitored continuously using a conventional distance encoder (TTI) or a GPS system (Auburn). The individual lines of temperature data are contoured to produce a continuous two dimensional strip chart thermal image of the pavement. Figure 6 shows an example of this type of equipment layout and the results. Note that this prototype equipment is separated from the screed itself so as not to interfere with the paving process. Ultimately, however, the equipment would be attached to the screed. Custom software has been designed by the TTI and Auburn research groups to automate the generation of output of the type shown in Figure 6 (b).

A third equipment option is an infrared thermometer, or *infrared gun*. This is a hand-held point sensor used to obtain spot temperature measurements. Overall thermal patterns are more difficult to obtain with this equipment, but it is simple and easy to use.

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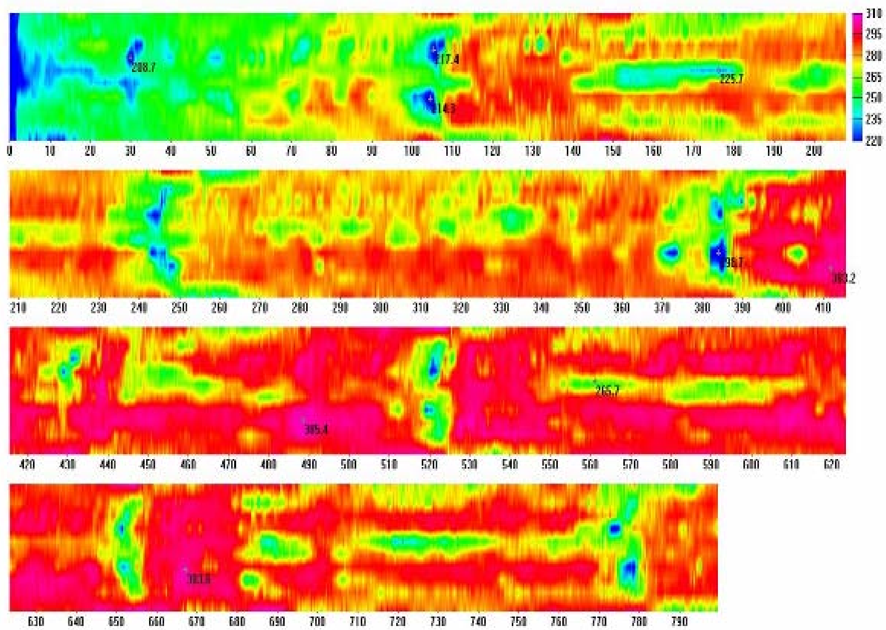
[18] Stroup-Gardiner, M. "Development of a Screed to Detect and Measure Segregation of HMA Pavements," NCHRP-IDEA Project 73 Final Report, Transportation Research Board, Washington, DC, February 2003.

(a) Infrared sensor bar behind paver screed



(b) Sample infrared strip contour plot output showing segregation at 130 foot intervals

Figure 6. TTI Continuous Infrared System (courtesy of Tom Scullion, TTI).

Highway Agency Use and Adaptation of IR for QC/QA

Washington State was an early adapter of the infrared camera as a tool for QC/QA. Their work with infrared began in 1995, and their study and use of infrared to determine variability in density has continued since then. They have concluded that significant density differentials occur when the hot mix transport vehicle dumps its load into the paver, leaving a concentrated area of lower temperature mix with every truckload. Because of this cyclic nature of density differential, traditional statistically based random sampling for QA of field density does not have the ability to characterize this problem.[19]

By investigating the relationship between temperature differentials and density, the DOT has shown that temperature differentials of >14ºC correspond to changes in air void content of >2%. Washington has implemented a density specification that locates potential areas of low density using the >14ºC (25ºF) temperature differential criterion. These areas are tested for density and must meet a specified minimum. The DOT has incorporated these temperature measurements into their nuclear density method specification, developed special data sheets, and prepared a Cyclic Density Special Provision in which the infrared based density results are incorporated as a pay item. At present, Washington has four infrared cameras—three in use by district engineers and one in use by the central office for continued studies.[20]

The University of Washington, in conjunction with the Washington State DOT, has set up an infrared image database that has incorporated documented infrared pavement images from States participating in a pooled fund study (Connecticut, Minnesota, Texas, California, and Washington State). A sample entry in this database is shown in Figure 7.

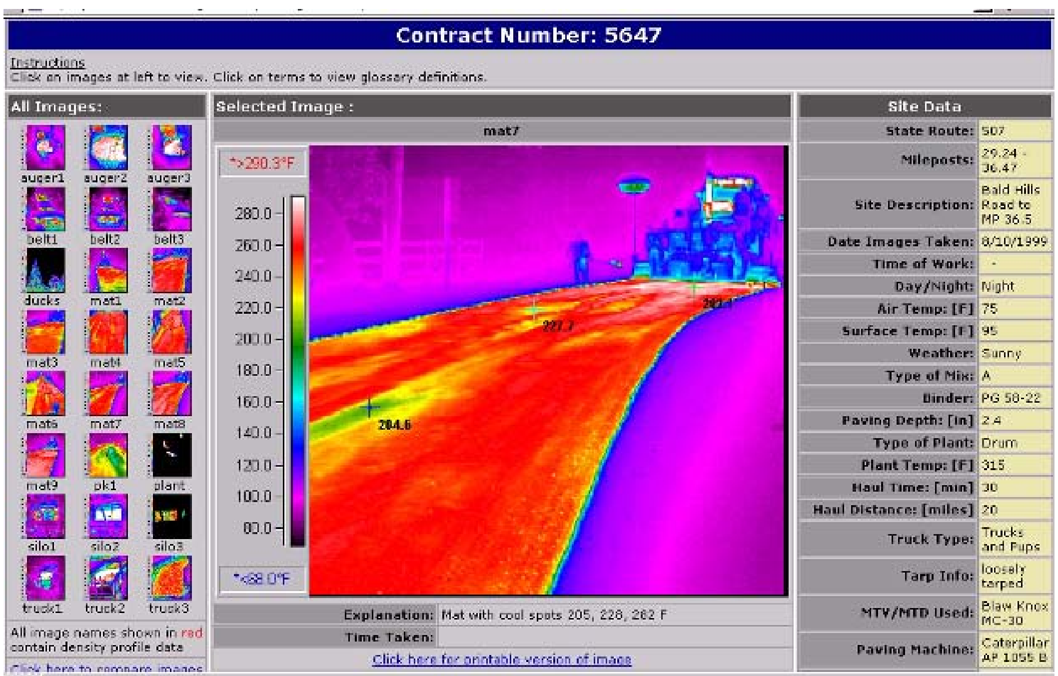


Figure 7. Sample Entry in Pooled Funded Study Database.

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[19] Willoughby, K., Mahoney, J., Pierce, L, Uhlmeyer, J., and Anderson, K. "Construction-Related Variability in Mat Density Due to Temperature Differentials," Paper 1535, Transportation Research Board, 82nd Annual Meeting, Washington, D.C., 2003.

[20] Willoughby, K., Personal Communication, 2004.

The Texas DOT has implemented specifications using the >14ºC (25ºF) temperature differential as an indication of significant problems in the HMA.[21] These differentials are measured after placement but before breakdown rolling.

The use of IR for pavement construction QC appears to have provided valuable feedback related to problems in the paving process. Both Washington and Texas report that the infrared data have been extremely valuable in the early stages of the construction process, where inadequate material handling and/or remixing has led to cyclic temperature segregation. Once this information is available, the problem can be isolated and corrected, and the temperature variations no longer appear.[22]

Current GPR Research for Estimating In-Place Density

Air-Horn Antenna GPR

Extensive research in Finland[23] has verified the ability to measure asphalt air void content with GPR, as shown in Figure 8. The Air Voids GPR values in Figure 8 are obtained from GPR-based dielectric measurements using a small number of cores for calibration. The graph shows a very strong correlation between the GPR-based air void measurements and the laboratory measurements. Based on these results, the GPR method is now an accepted standard for asphalt QC in Finland.

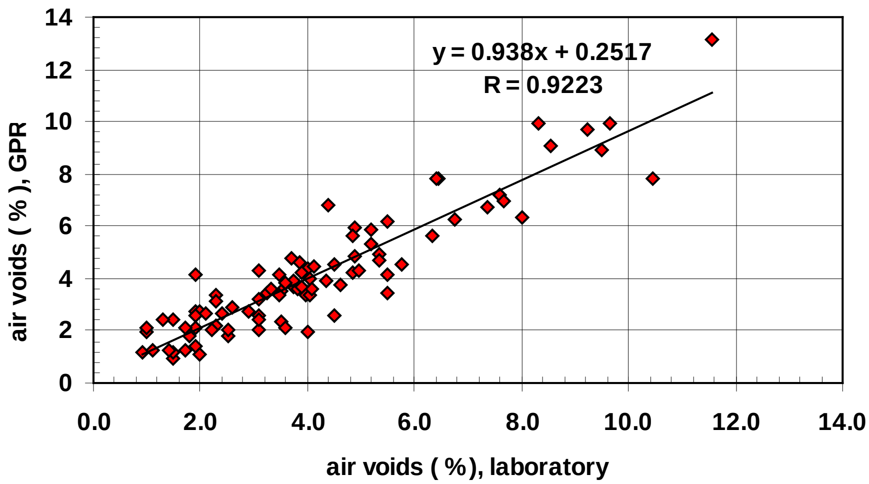

Figure 8. Results of GPR-Determined Air Void Studies in Finland.

[21] Scullion, T. (2003) Personal Communication.

[22] Scullion, T. (2004) Personal Communication

[23] Saarenketo, T. and Roimela, P. (1998). "Ground Penetrating Radar Technique in Asphalt Pavement Density Quality Control". *Proceedings of the 7th International Conference on Ground Penetrating Radar*, Lawrence, KS, pp. 461-466, May 27-30, 1998.

Recent work in the United States sponsored by the Texas DOT and the FHWA has confirmed the Finnish approach and has demonstrated the ability to map air content variations on a two dimensional plan view of the newly constructed pavement.[24]

Utilizing the methods developed in Finland for relating the surface dielectric to in-place air voids, project personnel generated probability distributions for the void content of each job site investigated by using cores to calibrate the relationship between the surface dielectric and voids, then making void predictions for each of the approximately 5,000 GPR readings on each project. The relationship used is described below.[25]

$$\text{Air Void Content} = Ae^{b\varepsilon} \qquad \text{Equation (4)}$$

where,

A and b are determined from calibration cores,
ε is the surface dielectric from GPR data, and
e is the natural log base.

The result of the correlation is shown in Figure 9. The Figure 9 data are then used to relate changes in surface dielectric to changes in air void. Using the data in this figure, the dielectric variations can be used directly to indicate excess air voids or deficiencies in density.

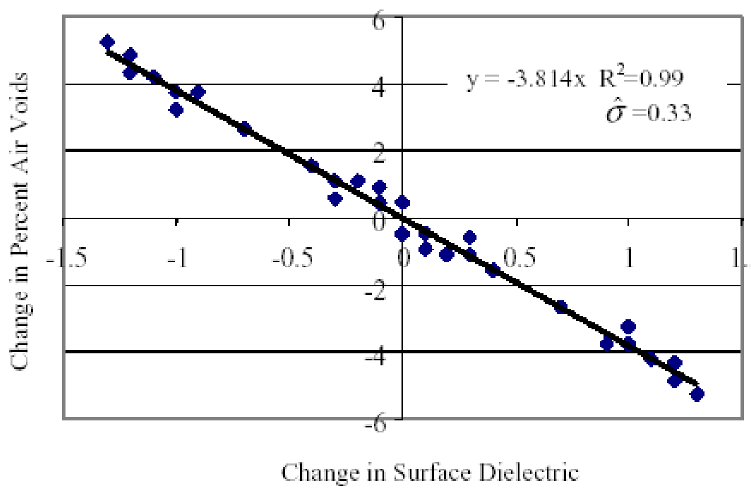

Figure 9. GPR Dielectric Data for Determining Deficiencies in Asphalt Air Void Content.

[24] Sebesta, S. and T. Scullion (2003) "Application of Infrared Imaging and Ground-Penetrating Radar for Detecting Segregation in Hot-Mix Asphalt Overlays," Paper No. 03-3406, Transportation Research Board, 82nd Annual Meeting, Washington, D.C., 2003.

[25] Saarenketo, T. and Roimela, P. "Ground Penetrating Radar Technique in Asphalt Pavement Density Quality Control," *Proceedings of the 7th International Conference on Ground Penetrating Radar,* Lawrence, KS, pp. 461-466, May 27-30, 1998.

As part of NCHRP 10-44a,[26] a GPR study on the WesTrack pavement in Nevada was carried out to correlate dielectric with asphalt air content. Each of the 26 WesTrack pavement sections represents a different asphalt mix design with a different density and air content. Figure 10[27] shows the correlation between the average dielectric constant measured with GPR in each section and the measured air content of each section. The correlation is fairly good, with an R^2 of 0.73. Note that Figure 10 is comparing the average of over 100 GPR measurements per section to the results of a small number of direct air void measurements.

As part of a Caltrans QC/QA research study,[28] an evaluation of dielectric vs. design density was conducted at the NCAT test track facility in Auburn, Alabama. This facility contains 46 pavement sections, each with a different mix design. The study revealed that the relationship between dielectric and density is sensitive to the type of aggregate used in the asphalt concrete (AC) mix. Figure 11 shows the correlation between the average GPR dielectric for the 18 sections with granitic aggregate in the AC mix. Each point in the figure is an average GPR dielectric for each of the18 sections vs. the laboratory design data for each section. The correlation is reasonably good for these sections ($R^2 = 0.80$). However, a similar study for the slag aggregate sections did not produce a good correlation.

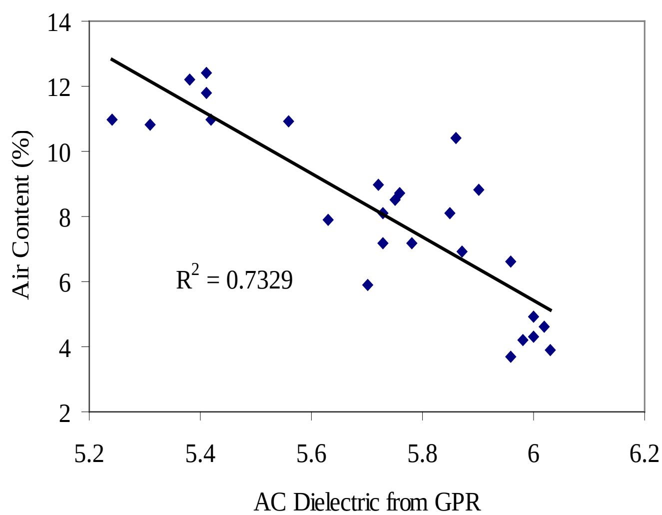

Figure 10. Air Content vs. GPR Dielectric Constant for WesTrack Sections.

[26] Von Quintus, H., Maser, K. R., and Olson, L. (1996) "Nondestructive Testing to Determine Material Properties of Pavement Layers", Interim Report, Project 10-44a, prepared for the National Cooperative Highway Research Program, National Research Council, Washington, DC.

[27] Von Quintus, H., Maser, K. R., and Olson, L. "Nondestructive Testing to Determine Material Properties of Pavement Layers," Interim Report, Project 10-44a, prepared for the National Cooperative Highway Research Program, National Research Council, Washington, D.C., 1996.

[28] Maser, K.R. (2003), "Non-Destructive Measurement of Pavement Layer Thickness" Caltrans Report FHW A/CA/OR-2003/03, April 2003.

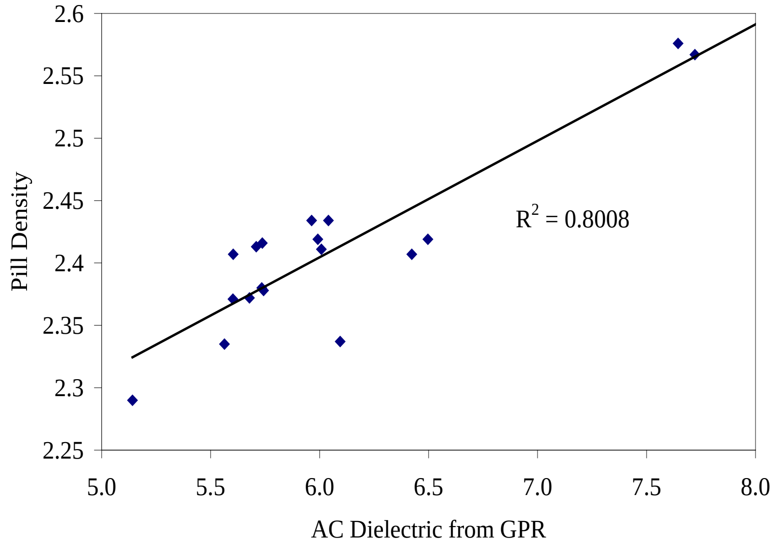

Figure 11. Correlation Between GPR Dielectric and Pill Density at NCAT.

As part of NCHRP 10-65,[29] GPR thickness/density studies were carried out on newly placed asphalt pavements for six projects located in Alabama, Minnesota, and Texas. These studies involved collecting multiple passes of GPR data on each newly paved section, calculating the dielectric constant at each measurement point, and calibrating the dielectric values using laboratory air void data at selected locations.

Each GPR survey led to the production of a dielectric map for each pavement section. Figure 12 shows a sample of one such map generated for a new pavement section on US280 in Alabama. Note that, similar to the method used in Finland, the dielectric values themselves, without calibration to density, can reveal density variations. In Figure 12, the dielectric variations appear with red areas in the color-coded plot representing lower density locations. Note that these locations are referenced to station and offset and can be accessed easily in the field.

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[29] Von Quintus, H., Rao, C., Minchen, E., Maser, K. R., Nazarian, S., and Prowell, B. "Nondestructive Testing Technology for Quality Control and Acceptance of Flexible Pavement Construction" Interim Report, Project 10-65, prepared for the National Cooperative Highway Research Program, National Research Council, Washington, D.C., 2006.

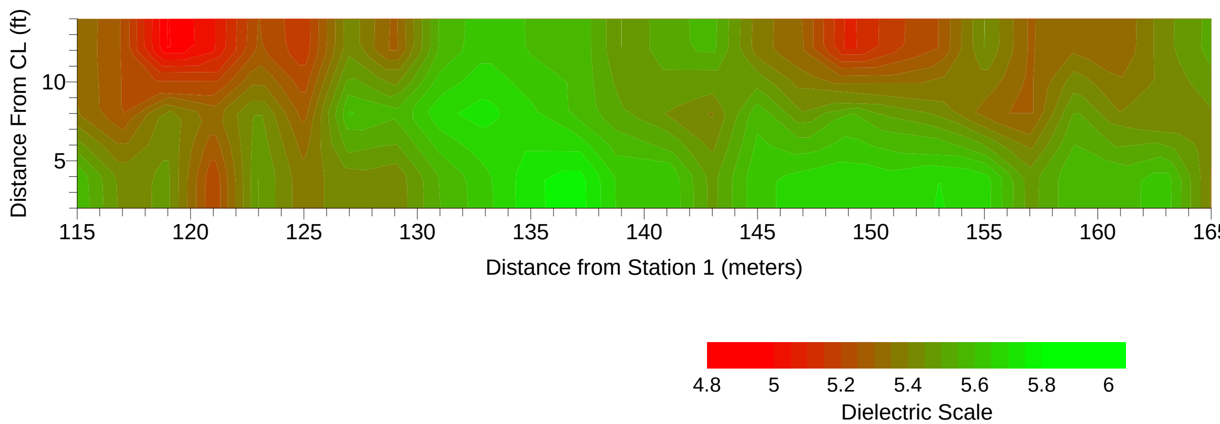

Figure 12. Contour Plot of AC Dielectric on US 280 in Alabama (red areas are low dielectrics, and indicate density deficiencies).

Ground Coupled GPR

Most of the previous work has been based on air-coupled horn antennas because of their ability to yield a direct calculation of the pavement surface dielectric and their ability to operate at any driving speed. During previous research, FDOT purchased two GSSI 1.5 GHz ground-coupled antennas to improve layer thickness determination. FDOT still owns these antennas but rarely uses them. Maser and Al Qadi et al.[30] have investigated the use of ground-coupled antennas in determining pavement dielectric. Two methods have been considered, as described below.

The Common Midpoint (CMP) method involves the use of two ground-coupled antennas moving in equal and opposite directions. The concept is shown in Figure 13. Using this configuration, the reflection from the bottom of the asphalt layer appears as a hyperbola, as shown in the right side of the figure. The hyperbola has two unknown values: thickness (d), and GPR velocity through the asphalt (V_{AC}). By fitting the bottom reflection with a hyperbola, these two unknowns are calculated. The asphalt dielectric constant can be calculated directly from the GPR velocity through the asphalt mixture.

[30] See note 28 above.

Al-Qadi, I., Lahouar, S., Loulizi, A., "Successful Application of GPR for Quality Assurance/Quality Control of New Pavements," Paper 03-3512, Transportation Research Board, 82nd Annual Meeting, Washington, D.C., 2003.

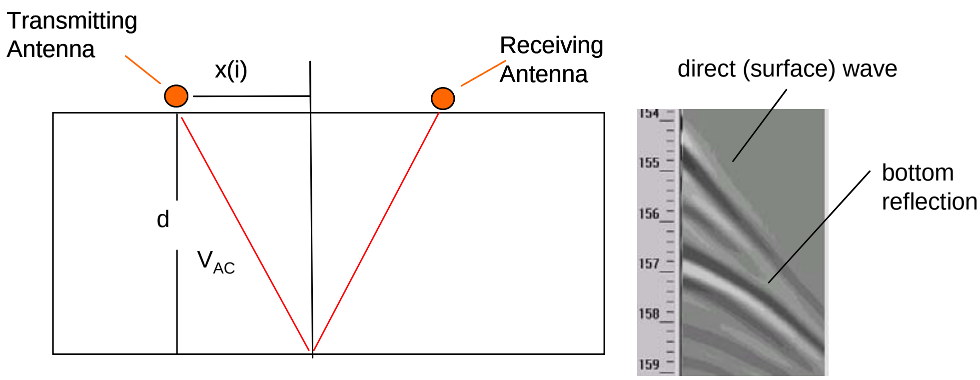

Figure 13. CMP Principle for Determining Asphalt Dielectric.

The advantage of the CMP method is that it measures the average dielectric through the thickness of the pavement layer. The disadvantage is that it is a point measurement and takes a few minutes to measure one location.

A second approach to the use of ground-coupled antennas is to correlate the antenna's direct coupling to the surface dielectric. A ground-coupled antenna actually contains two antennas, one transmitter and one receiver, as shown in Figure 14. The direct coupling is the wave transmitted directly from the transmitter to the receiver. Since this wave passes through the pavement surface, it could contain information that would correlate to the dielectric constant of the pavement.

Limited testing of this method was reported by Maser,[31] and the results show some reasonable correlation between the amplitude of the direct coupling and the surface dielectric. Further investigation would be required before this method could be recommended for application to density measurement of newly constructed pavement.

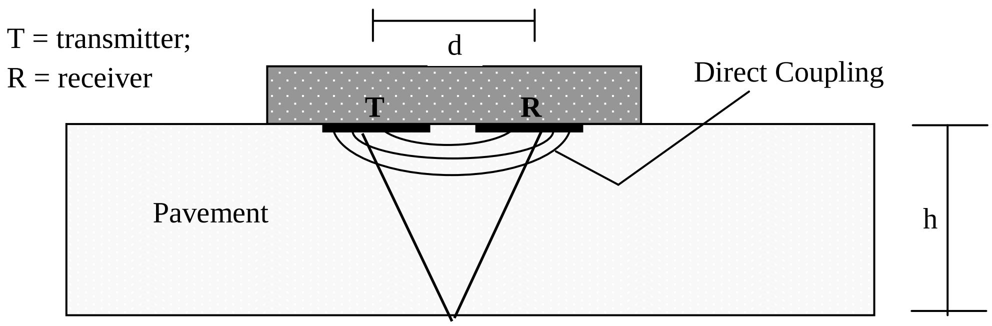

Figure 14. Direct Coupling Method for Measuring Asphalt Dielectric.

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[31] See note 28 above.

5.0 EVALUATION OF FDOT’S GPR SYSTEM

Prior to proceeding with the development of protocols for evaluating asphalt density measurements, the FDOT GPR system was evaluated to determine its capabilities and limitations, as well as to define optimal operational parameters for asphalt density determination. As part of this task, performance and operational aspects of the FDOT GPR system are being reviewed to ensure that the capabilities of the FDOT system are fully utilized and the limitations are completely understood during the course of this project. One issue of particular concern is the FDOT 2-GHz horn system's high susceptibility to ambient radio interference.

As part of this task, GPR data were collected with the FDOT system at their test track located at the SMO facility in Gainesville. GPR data also were collected on US 441, where radio interference has posed a problem in the past. The following parameters and issues were considered in this evaluation.

On-Board GPS System

As part of the evaluation of the FDOT GPR system, the accuracy of the on-board GPS was assessed to determine if geographic information reported can be depended upon to pinpoint roadway locations.

FDOT’s Trimble AgGPS (S/N 0224095765, P/N33302-03) unit consists of a receiver and antenna. The antenna is attached to the top of the GPR van and the receiver is installed inside the vehicle, as shown in Figure 15. This device is commonly quoted to have sub-meter differential accuracy. An offset can be applied to the GPS data so that the coordinates for the two radar antennas are extracted rather than that for the GPS antenna (on top of the van). However, the GPS coordinates for the radar antennas can only be as accurate as that of the GPS antenna itself. Therefore, the evaluation focused on the accuracy and the precision of the GPS coordinates of the GPS antenna itself.

Figure 15. FDOT GPS Antenna and Receiver.

The accuracy of the on-board GPS was evaluated in two manners. First, the ability to measure a horizontal distance was determined at the measured mile. Second, the two dimensional accuracy was assessed using the 2DRMS statistic. The results of the evaluation performed at the measured mile site are summarized below:

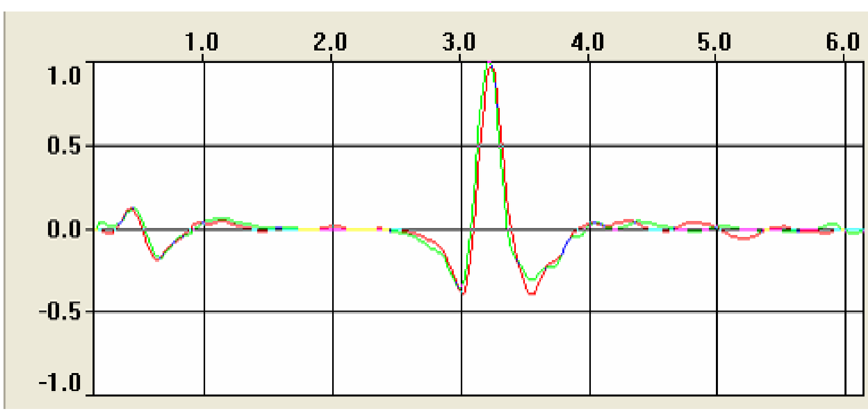
1. The average distance error determined at the measured mile was 0.5 feet. The average absolute difference was 1.5 feet.
2. At 10 mph, the 2DRMS was 2.7 feet.*
3. At 30 to 45, the 2DRMS was 6.0 feet.*
4. The 2DRMS of the combined speeds was 4.6 feet.*
5. UTM values selected from the GPR data did not always match those converted from longitude and latitude data also selected from the GPR data.

(Note: * - 2DRMS statistics were calculated using a relative positions. Greater 2DRMS values would be expected if actual GPS coordinates of test points were known.)

Based on the GPS evaluation performed at the measured mile, it is recommended that the high resolution distance encoder be used to determine the longitudinal distance for GPR projects that depend on accurately determining roadway locations. This encoder is regularly calibrated at the measured mile location, and has been found to be accurate to within 1 foot/mile. Transverse locations will be determined using the known position of the antennas during the survey.

Antenna Characteristics

Horn antennas are not mass-produced; therefore, each can have its own unique characteristics. The matching of the two FDOT antennas has been evaluated qualitatively as shown in the Figure 16 metal plate data. The red trace is from channel 1 (passenger side antenna), and the green trace is from channel 2 (driver side antenna). Note that the direct coupling for each antenna (between 0-1 ns.) is almost identical. The shape of the metal plate reflection for each antenna (between 2.5 and 4.0 ns) is very similar. The minor time shift between the two is due to slight height differences between the two antennas. The conclusion from the data shown here is that the antennas are very well matched, and that similar quality results should be expected from each antenna.



Note: Red Line – Channel 1; Green Line = Channel 2

Figure 16. Comparison of Metal Plate Data for the Two FDOT Antennas.

Time Range of the GPR Scan

Typical time range settings for the 2-GHz antenna for pavement thickness applications are 10 to 12 nanoseconds (ns). Since the surface reflection occurs at 3 ns (due to the 18-inch antenna height above the pavement), 9 ns remain for the subsurface data. Using a typical 2-way AC velocity of 2.5 in/ns, this provides a maximum depth range of 22 inches. For density estimation of new construction projects, such an extensive depth range is not necessary. Using a shorter time range provides a higher density of data samples, and thus improves the precision of the data. For this evaluation, a time interval of 6 ns was evaluated. With a 6 ns interval, 3 ns (7.5-inches) are left for pavement evaluation. Considering that the application is for quality assurance, asphalt lift thicknesses are not expected to exceed about 4 inches, which would be in the detectable range for this setting. Figure 17 shows a gray scale image of data with a 6 ns interval collected on the FDOT test track. The thickness of the AC in this section is 3 to 4 inches.

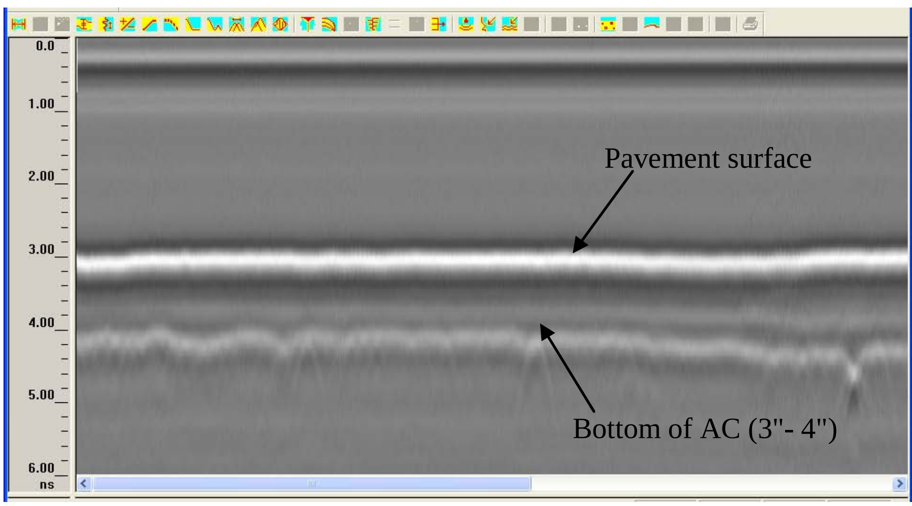


Figure 17. Sample Data from FDOT Test Track using a 6 ns Interval.

Data Rate (Scans per Foot)

Typical project-level GPR pavement thickness evaluations for rehabilitation design utilize data collection rates not exceeding one scan per foot. More densely collected data is usually not necessary. On the other hand, for the QA purposes of this project, there is an interest in obtaining precisely located data for calibration and verification purposes. Also, with potential interference due to ambient radio noise, it would be desirable to reduce the noise by stacking (averaging) multiple scans. For these two reasons, it would be desirable to run at a higher data rate than for the typical thickness survey. The drawback to a higher data rate is a lower travel speed.

The maximum data collection speed for the FDOT two-antenna system depends on the number of scans per foot collected and the number of samples per scan, as shown in Figure 18. The figure shows that the maximum speed drops rapidly when increasing to data rates higher than 1 scan per foot, and that the use of 256 samples per scan increases the maximum speed by 74 percent over that for 512 samples per scan.

For example, if a maximum speed of 10 mph is specified, then 5 scans per foot at 512 samples per scan, and 9 scans per foot at 256 samples per scan can be collected.

Since the application of GPR for density QA generally will be on pavements under construction and closed to traffic, a lower data collection speed can be tolerated. The objective of this project would be to collect the maximum possible data without diminishing the operational aspects of the system.

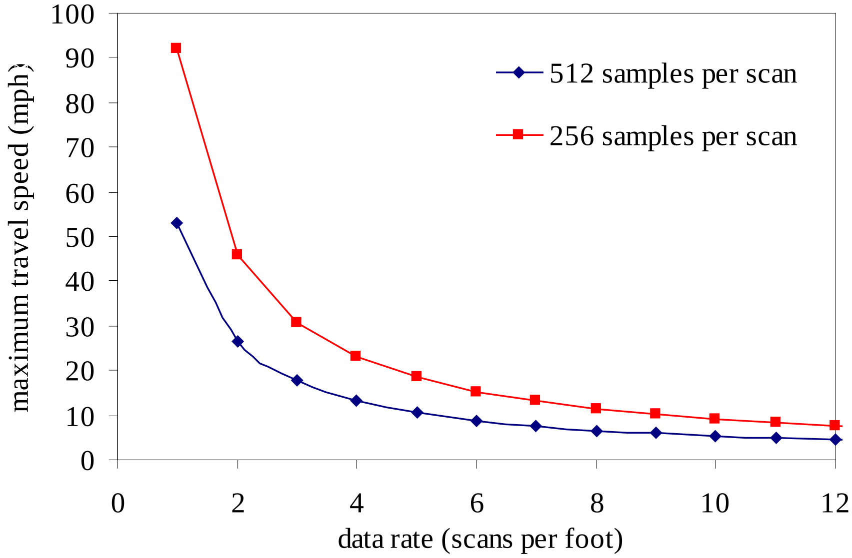
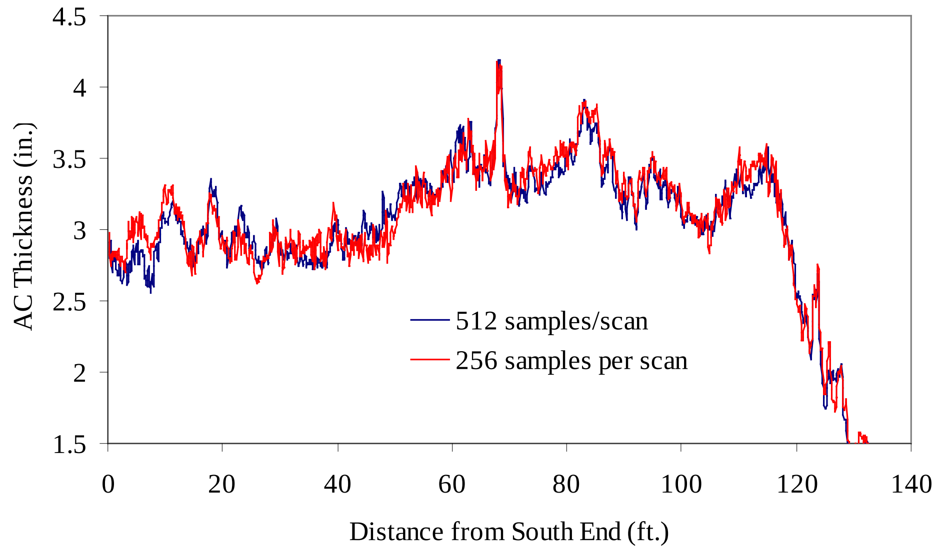


Figure 18. Survey Speed versus GPR Scan Rate.

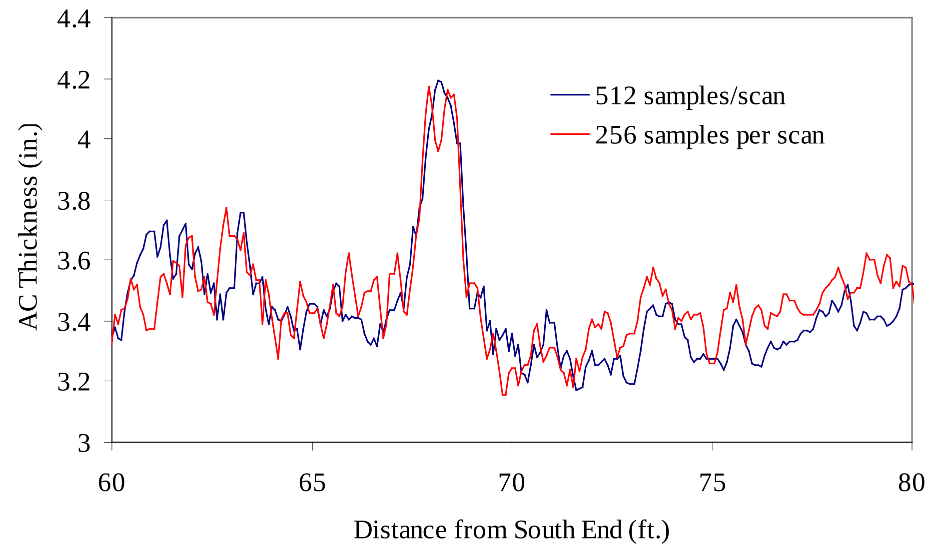
Sample Rate (Samples per Scan)

The use of a shorter, 6 ns time interval allows for two possibilities: a higher density of sample points per ns of data using the standard FDOT 512 sample rate, or a higher travel speed and/or data rate using 256 samples per scan. Using the 256 sample rate at 6 ns time range provides equivalent data density to using 512 samples at a 12 ns time range.

To test the system sensitivity to sample rate, data was collected along the test track in the northbound direction using both sample rates. Figure 19a compares the calculated thickness results obtained from channel 1 for each sample rate. The data rate for both cases was 12 scans per foot. The calculated thicknesses in the figure are quite close. The standard deviation of the difference between the two is 0.003 inches, or less than 0.1 percent. Careful examination of the data, however, reveals that the 256 sample data exhibits more local fluctuation. A magnification of the region from 60 to 80 feet (Figure 19b) shows this behavior more clearly.



a. Complete scan of the test track.



b. Magnification of data from 60 to 80 feet.

Figure 19. Calculated AC Thickness from the Test Track.

The data in Figure 19 suggest that the 256 samples per scan setting introduce some fluctuations into the data. To quantify this variability, a static test was carried out with both the 512 and 256 sample settings. In the static test, the vehicle and antenna were positioned in one spot and data was collected for an interval of time. Ideally the results are constant, but in fact there is some variation due to the reduced resolution. Figure 20 shows a typical result for calculated density from this test. The test was conducted at 78 scans per second, and the result shown is for approximately 8.5 seconds of data collection. Note that there is some scatter due to ambient interference and the inherent *jitter* of the GPR system.

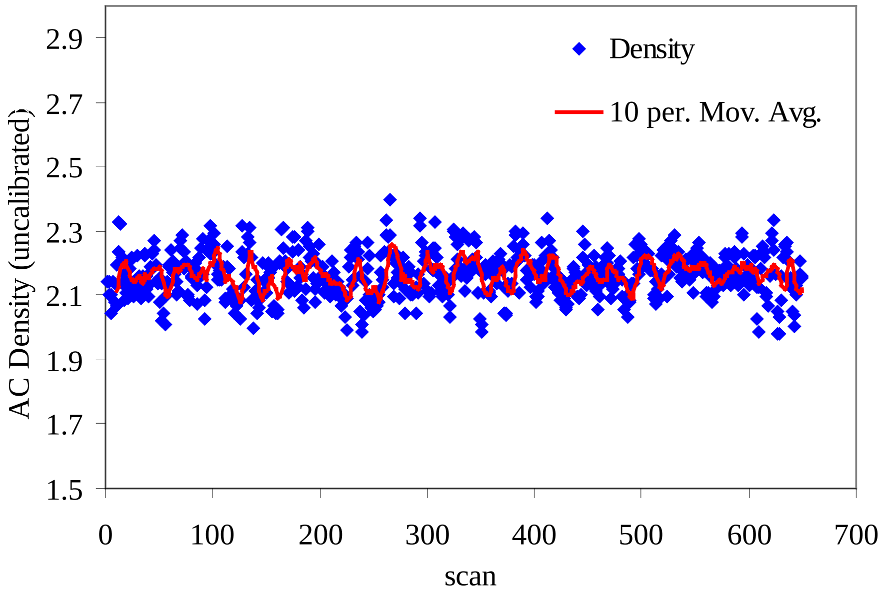


Figure 20. Stationary Density Measurements at the FDOT Test Track.

This stationary test was carried out for both sample rates, and the results for each antenna were examined. Table 2 shows the statistics for the variability of the thickness measurement for the stationary test. The table shows the standard deviation of the calculated AC density for the different settings and different antennas. Also shown is the standard deviation as a percent of the total thickness. From these results, it appears that channel 2 is more noise sensitive than the antenna in channel 1, and that the reduction to 256 samples /scan amplifies this increased noise sensitivity.

Table 2. Variability Statistics for the Stationary Density Tests at the SMO Test Track.

	256 Samples/Scan		**512 Samples/Scan**	
	Channel 1	**Channel 2**	**Channel 1**	**Channel 2**
Parameter	Raw Data			
Density Std Dev	0.06	0.14	0.07	0.08
Thickness Std Dev, %	3.1	6.0	3.2	3.9
	Running Average Data (10 Scans)			
Density Std Dev	0.05	0.07	0.04	0.05
Thickness Std Dev, %	1.8	3.2	1.9	2.4

Sensitivity to Ambient Noise

The discussion above provides one illustration of the noise sensitivity of the system based on measurements made at the FDOT SMO Test Track. In this type of environment, thickness (and density) deviations on the order of 3 to 4 percent can be expected as a result of ambient noise, and these variations can be reduced to about 2 to 2.5 percent by averaging closely spaced data points. This type of deviation appears to be acceptable in the context of the application to determining overall variations in density.

According to FDOT personnel, occasionally more severe ambient noise conditions are encountered, potentially rendering the data unusable. To test out this condition, stationary measurements were made on US 441 in the vicinity of a radio tower. Previous experience indicated that this was an area of high ambient noise. The data in Figure 21 represent a stationary test carried out at 55th Place at the intersection with US 441. The plot shows the raw data points in blue and a 10-point running average in red.

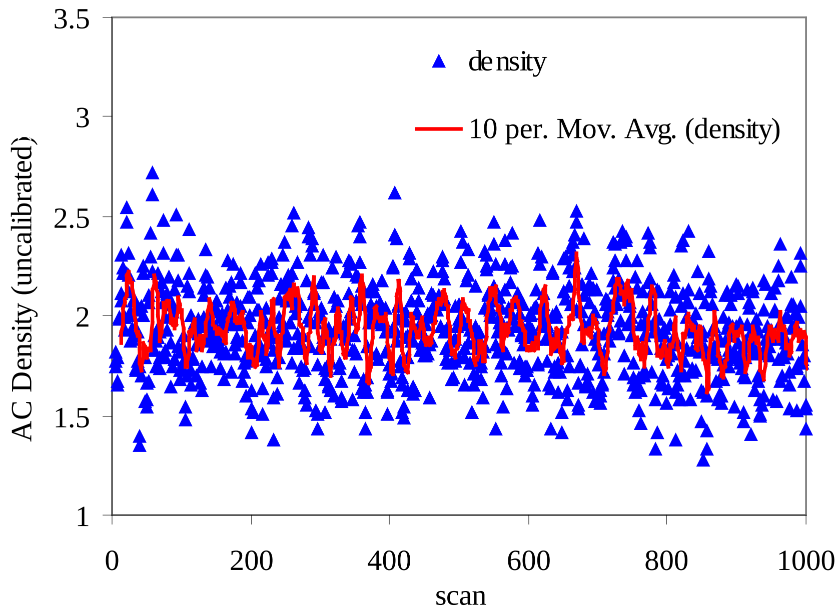


Figure 21. Stationary Density Measurements at US 441 at 55th Place.

The standard deviation of the raw density points is 0.23, or 12.1 percent, while the standard deviation for the averaged data is 0.11, or 5.9 percent. While the averaging significantly reduces the noise-related error, the resulting error level might be too high for effectively using the system for evaluating density variations at locations where significant noise is encountered.

Since the type of noise levels shown in Figure 21 occur occasionally, it is recommended that, for the density QA application, FDOT conduct a noise sensitivity test at each site prior to proceeding with the GPR data collection. The test would involve a stationary measurement as carried out in this evaluation. The result of the stationary test would be evaluated on-site and the standard deviation computed from the data. If the standard deviation exceeds a prescribed threshold, then the noise levels would be determined to be excessive and data collection would be aborted. The recommended evaluation procedure, and threshold value, will be described as part of the recommended methodology.

Analysis of the Test Strip Data

The RADAN software application was used to analyze the GPR data collected during the GPR survey of the test strip. The strip is approximately 12 feet wide by 170 feet long and was surveyed with two passes of the GPR system with resulting offsets of 2, 5, 8, and 11 feet. During construction of this test strip section, rolling patterns (compaction) on the asphalt mat was altered to produce areas of high and low densities. This altered compaction effort produced a range in densities for the test strip that is most likely greater than the typical range found during a new construction project.

The GPR data were analyzed using RADAN to determine surface dielectric constant and layer thickness. Subsequent to the data collection, cores were taken and analyzed for layer thickness, air void content, and density. Table 3 summarizes the results for each core location. As noted in the table, the GPR was successful in determining the cores with the lowest and greatest density.

Table 3. Core and GPR Density Summary.

Core Number	Core Air Void (%)	Core Gmb	GPR Dielelectric	GPR Gmb	Notes
1	6.4	2.344	4.866	2.297	
2	5.8	2.348	5.087	2.349	
3	5.8	2.358	5.245	2.386	
4	6.7	2.336	5.011	2.331	
5	6.0	2.353	5.011	2.331	
6	6.0	2.354	4.866	2.297	
7	13.1	2.175	4.400	2.188	Min core and GPR density
8	12.9	2.179	4.462	2.203	
9	11.9	2.205	4.725	2.264	
10	12.2	2.199	4.866	2.297	
11	9.2	2.272	4.658	2.249	
12	9.2	2.274	4.725	2.264	
13	6.7	2.334	4.794	2.281	
14	9.5	2.265	4.937	2.314	
15	7.1	2.325	5.087	2.349	
16	4.8	2.382	5.245	2.386	Max core and GPR density
17	5.3	2.370	4.866	2.297	
18	5.4	2.367	5.087	2.349	

Based on a linear regression of the test strip data shown in Figure 22, the dielectric results for the test strip have been converted to density results. Contour plots of dielectric and density results were generated using Surfer, a commercially available software package, and are provided in Figure 23.

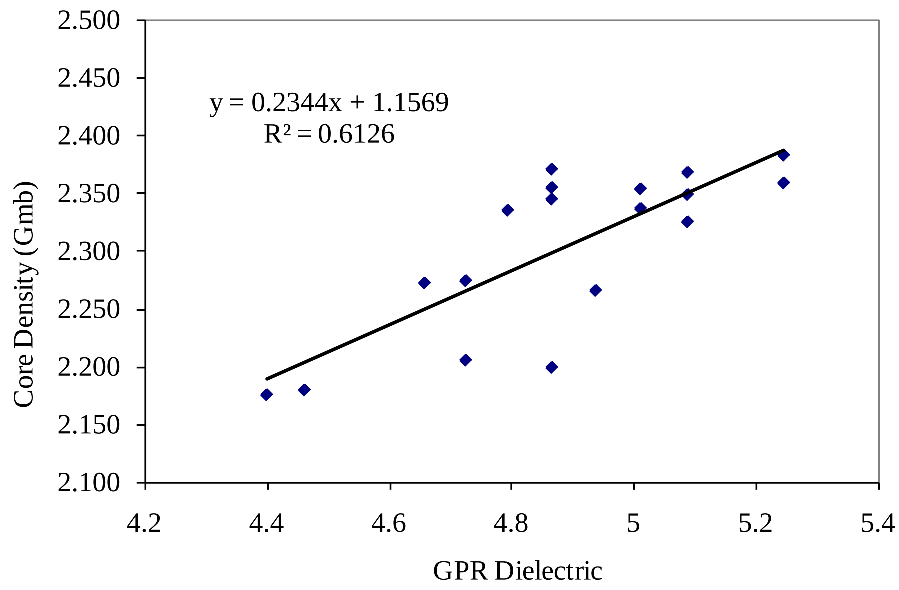


Figure 22. Core Density and GPR Dielectric Correlation.

The process of generating the contour plot using RADAN required about 3 hours to complete. This amount of time was considered inconsistent with the project objective to generate the contour plot information in the field directly after testing. As a result, a customized software application was developed that provided significant advantages over RADAN. The GPRQA program implemented under this project required about 20 minutes to analyze the same collected data and generate the required contour plots.

The GPRQA program is used to provide automated analysis of GPR data for the QA of in-place asphalt densities. Data collected from GPR passes over newly placed asphalt are analyzed to provide a summary of surface dielectric values. These values can then be mapped using a graphical software application that is capable of contour plotting. The surface dielectric map is used to locate high, low, and mid-range areas for density calibration core selection.

Surface dielectric results also can be presented graphically in histograms of the entire section. Tabular reports give both raw data values, or sorted by location, to show the section statistics. A complete user's manual for analyzing GPR density data using GPRQA is provided in Appendix A, with sample data collection sheets in Appendix B.

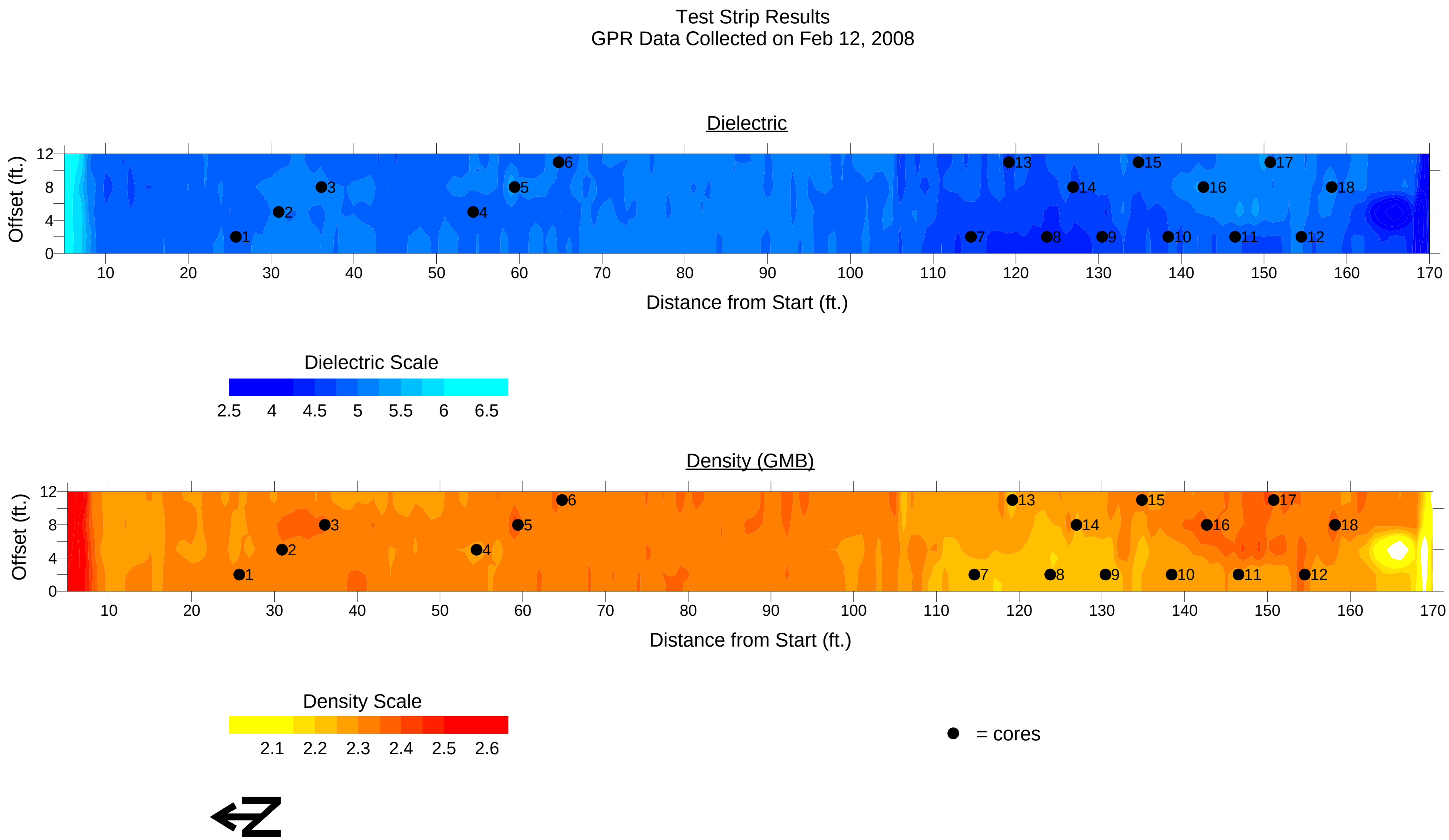


Figure 23. Dielectric and Density Contour Plots of the SMO Test Strip.

6.0 IDENTIFYING PROMISING TECHNOLOGIES

Although the evaluation of the FDOT GPR system found the equipment to be suitable for measuring asphalt densities, a number of additional technologies were identified as being readily available and able to work with the existing system to improve the output results. The identified technologies are discussed below.

GPR Laser Trigger

An area of improvement identified during the evaluation of the GPR system was the accuracy in positioning of the limits during a site survey. As locating the various density locations is important for the extraction of pavement cores, a laser trigger system was recommended that that will automatically place a mark within the GPR data that corresponds to reflective markers placed at the survey limits.

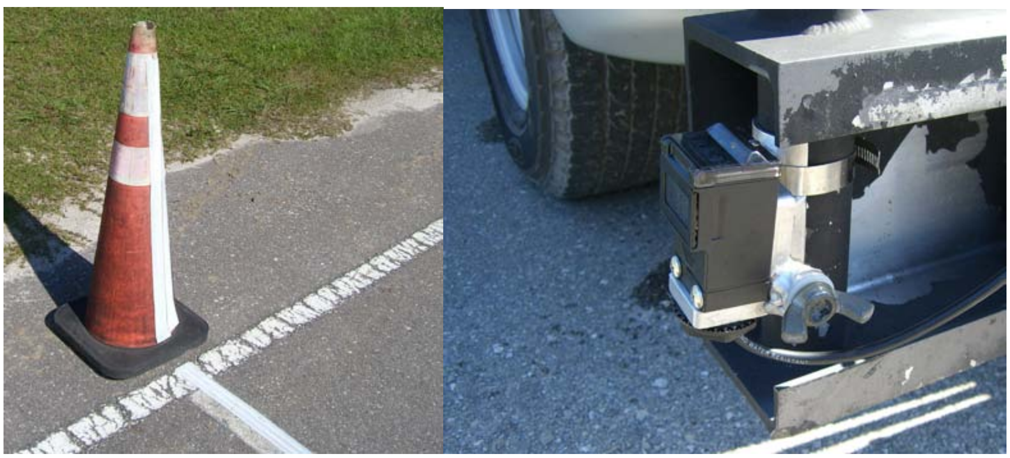


Figure 24. Laser Trigger System and Reflective Markings.

The automatic system uses a photo-reflective optical switch to mark the data automatically when polarized reflective cones are passed. These cones, positioned at an established reference station, provide reflection from the optical switch, marking the GPR data at the precise location of the station. With this method, the operator can drive continuously past start and end station locations, and these locations will be recorded automatically for station referencing of the GPR data. The laser system purchased by the project team was delivered, installed, and verified prior to the start of the field validation trials.

Graphical Software

To provide a visual presentation of the collected dielectric data, a graphical software application was required. Two possible programs were identified that would be applicable for reporting the GPR survey results.

DPlot

The first application is DPlot, which can be purchased as an add-in for Microsoft Excel. After installation, Excel will have a new menu option called DPlot. To generate a contour plot, select the three columns to use as data points for the graph, with the X-axis column appearing left of the Y-axis column and the Y-axis column appearing to the left of the Z-axis column. Contour plots of the test strip generated with DPlot are shown below.

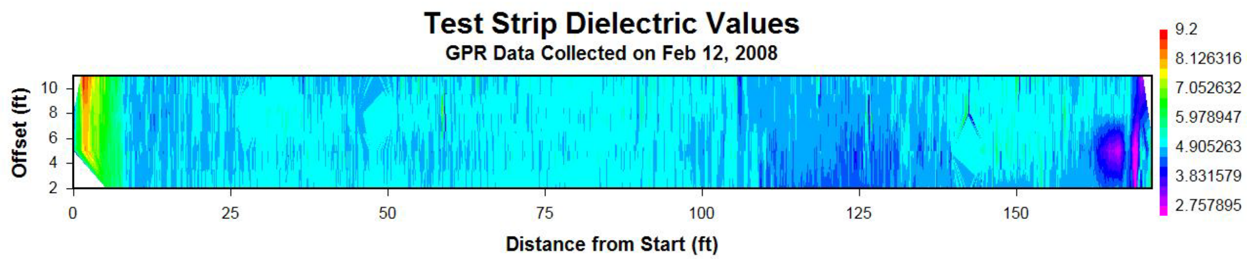


Figure 25. Contour Plots Generated with DPlot.

Although this application would plot the necessary dielectric constant values, it does not have the processing ability to produce the detailed plots required.

Surfer

Alternatively, Surfer is a more powerful contour plotting program. Although Surfer is a more expensive application, it provides significantly more appropriate results. Contour plots of the same test strip data were generated using Surfer and are provided in Figure 26.

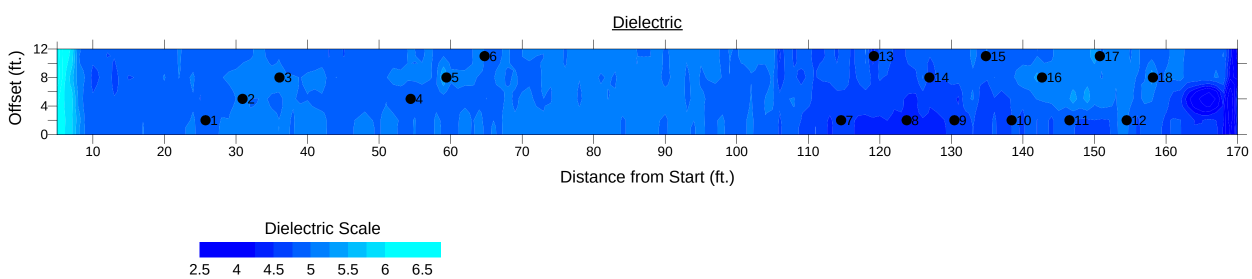


Figure 26. Contour Plots Generated with Surfer.

The use of the Surfer program is recommended in presenting the GPR survey results.

GPS Locating Device

As part of the process of identifying new technologies, the research team also evaluated the SMO handheld GPS device. The use of this device was considered to locate selected pavement coring areas after the GPR survey had been completed and analyzed.

The GeoExplorer 2005 series manufactured by Trimble includes the GoeXH, GeoXT, and GeoXM handheld models. The SMO owns the GeoXM device. This unit has built-in GPS receivers, a rechargeable battery, and a Microsoft Windows Mobile operating system. The reported accuracy of the unit is 1 to 3 meters. Notes and Word documents can be uploaded onto the unit or downloaded from the unit from any Windows PC. The unit comes with a complimentary copy of Microsoft Streets & Trips 2006, along with Pocket Streets.

The static accuracy of the GeoXM was tested at four different locations. Three of the locations were in an area that might represent a typical urban environment with tree-lined streets. The fourth location was in an open field. The GPS position of each location was measured three times at different times of the day to allow satellites to move.

In general, the results show that the device is within its reported accuracy of 2 meters. However, one location showed an average distance of 11.0 feet (3.4 meters) between measurements, which is greater than the stated accuracy of 3 meters. Large oak trees were present near this location and may have interfered with satellite reception and visibility. Although the use of this device typically falls within the manufactures reported accuracy, this accuracy does not meet the SMO requirement to have sub-meter accuracy in locating pavement core locations. It was recommended that pavement core locations continue be located using a portable walking measuring wheel.

7.0 FIELD VALIDATION TESTING

Validation and companion testing of the FDOT GPR system was completed on three different construction projects. All three projects—two new construction projects (SR 20 and SR 23), and one pavement resurfacing project (SR 222)—were located in District 2.

Field Validation Testing Protocol

Based on information collected on the test strip, during the GPR system evaluation, the research team developed a number of survey protocols that were tested as part of the field validation trials. Prior to starting each of the trial surveys, the GPR system was calibrated in accordance with GSSI specification. The data collection for all three field validation trials were conducted in ideal weather conditions (dry, sunny, with relatively low humidity).

State Road 20

An initial field validation study was completed on a construction project located on SR 20, near Interlachen. The construction project consists of four laning the existing roadway for a total of 6 miles. This site was ideal for the initial field trials because it was a closed to the travelling public and offered a variety of survey opportunities in a safe work environment. A total of five test sections were selected as part of these trials.

At the time of the field trials, the contractor was placing the second structural asphalt lift (SP 12.5), which contained 35 percent recycled asphalt pavement (RAP) material. The job mix formula (JMF) for this paving material indicated that the aggregates in the asphalt mix comprised of Georgia Granite, with an optimum asphalt binder content of 5.1 percent. The JMF for this material has been provided in Appendix C, and summarized below.

Table 4. Gradation Blending of Aggregates for SR 20 Asphalt Material.

Material Type	Product Code	Producer	Pit No.	Blend (%)
Milled Material	334-MM	213003.3.52.01 MP 8.922 – 20.396	SR 8	35
#78 Stone	C54	Conrad Yelvington	GA-383	15
#89 Stone	C51	Conrad Yelvington	GA-383	10
W-10 Screenings	F21	Conrad Yelvington	GA-383	40
Recycling Agent (RA 700)	916-RA			3.0

The testing protocol for each site is described below.

Section #1 (Station 590+00 to 596+00)

This section extended for a length of 600 ft and was paved 3 days before the GPR survey. Four GPR runs were completed, with each run offset by 2 ft, for a total of 8 channel readings. The location of each run was painted on the roadway surface at 100-ft intervals to minimize vehicle wander during data collection.

Upon completion of the GPR survey, the information was analyzed in the field to select the pavement core locations. A sketch of the data collection protocol is provided in Figure 27.

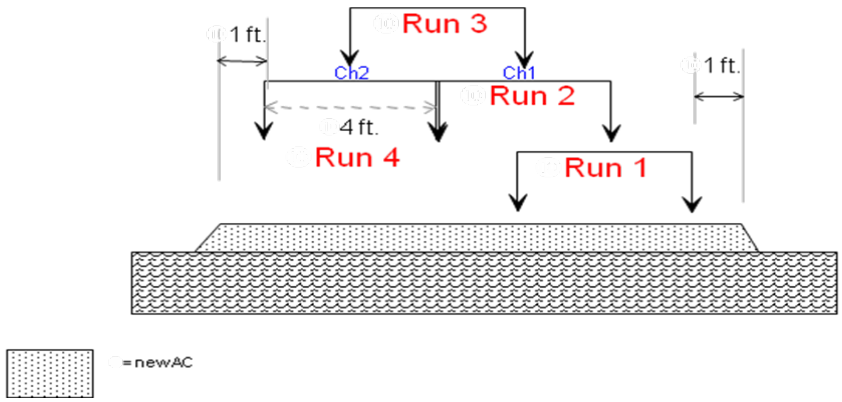


Figure 27. Data Collection Protocol on SR 20.

Six cores were extracted from this section, with two cores taken from areas where lower density was suspected, two were taken in higher density areas, and two were taken in an average density area. Bulk specific gravities (G_{mb}) were determined in the laboratory for all core samples, and the theoretical maximum specific gravity (G_{mm}) was determined on the two core samples in the average mat density area. The pavement coring and laboratory testing was completed by SMO staff.

Laboratory results were compared to the testing completed by the contractor during the paving operation. As the G_{mm} of the core samples were found to be more variable then those determined during construction, the results of the plant samples were used in calculating the percent G_{mm}. because the G_{mm} used for the density evaluation are based on the quality control test results from the corresponding sub-lots.

Section #2 (Station 670+00 to 677+00)

The second test section was selected to include an end-of-day paving joint. The entire section extended from Station 670+00 to 677+00, with the transverse paving joint at Station 673+20 (320 ft). The total length of the test section was 700 ft. The location of each run was painted on the roadway surface at 100-ft intervals to minimize vehicle wander during data collection. Following the same data collection protocol as in the previous section, a GPR survey was completed, with analysis of the collected data in the field. Similar to the first section, six pavement cores were extracted from this area, with the same laboratory testing completed on the core samples as was done for Section 1.

Section #3 (Station 736+00 to 744+00)

In this section, an initial GPR survey was completed shortly after paving. At the time of the survey, the newly placed asphalt material was still warm (hot survey), with temperatures ranging from 105 to 130 ^{o}F. The location of each run was painted on the roadway surface at 100-ft intervals to minimize vehicle wander during data collection.

For comparison purposes, this section was re-surveyed the following day when the asphalt surface had time to cool (cold survey). The surface pavement temperature at the time of the secondary survey was 84 ^{o}F.

Pavement core locations were selected based on the results of the GPR survey completed on the hot asphalt. Six pavement cores were extracted from this section: two in suspected lower density areas, two in higher density areas, and two at one average density location.

Section #4 (Station 696+00 to 704+00)

The fourth section extended for a length of 800 ft and was paved the day before the GPR survey. The data collection protocol in this section was the same as in the previous sections; however, pavement offset markers were not painted on the roadway surface at regular intervals. Instead, a guide was attempted to allow the vehicle operator to follow the longitudinal construction joint when collecting the GPR survey at the various offsets. The intent of this guide was to eliminate the delay needed to paint out the markers, while minimizing wander during data collection. A photograph of the setup is shown in Figure 28.

Figure 28. Vehicle Guide for GPR Collection.

Pavement core locations were selected based on the results of the collected GPR information. Six cores were taken from within this section, two from lower density areas, three from higher density areas, and one from an average density area. Only bulk specific gravities were determined on these core samples.

Section #5 (Station 696+00 to 766+00)

Section 5 was selected such that it extended a total of 7,000 ft and shared the same starting location as the Section 4 site, as well as continuing through Section 3. This longer section was completed on an asphalt mat placed within the same day. The GPR survey for this longer section was completed following the same protocol as the previous sections, using the same vehicle guide setup as used in Section 4.

State Road 23

The field validation program continued on April 13, 2009, using GPR to measure the HMA density on an active construction project. The construction project was located in FDOT's Duval County SR 23, near Jacksonville. The site is part of a larger construction project designed to provide traffic from Blanding Boulevard (SR 21) to Interstate 10. The site of the field validation trials was located on a newly constructed two-lane platform between 103rd Street (SR 134) and Normandy Boulevard (SR 228).

The GPR field validation survey was completed on a 4,000 ft section between SR 134 and SR 228. Survey stationing started at Station 716+00 (southern end by SR 134) and continued northerly to Station 756+00 (near SR 228). This site was another ideal location for the field validation trials, as it was a closed to the travelling public.

Prior to the GPR survey, the contractor had placed the second structural asphalt lift (SP 12.5), which contained 20 percent RAP material. Although the exact date of this paving is unknown, it is understood that the paving operation had been completed a couple of months prior to the GPR survey. However, in this time between paving the survey, only minor construction traffic were operated within the survey area.

The JMF for this paving material indicated that the aggregates in the asphalt mix were a blend between Georgia and Nova Scotia Granite, with an optimum asphalt binder content of 5.5 percent. The JMF for this material has been provided in Appendix C, and summarized below.

Table 5. Gradation Blending of Aggregates for SR 23 Asphalt Material.

Material Type	Product Code	Producer	Pit No.	Blend (%)
Crushed RAP	1-07	Atlantic Coast Asphalt Co.	A0750	20
#78 Stone	54	Martin Marietta Aggregates	GA-383	20
#89 Stone	51	Martin Marietta Aggregates	NS-315	18
W-10 Screenings	23	Martin Marietta Aggregates	NS-315	35
Sand		Atlantic Coast Asphalt Co.	Soutel Pit	7
PG 64-22	916-PG			4.5

GPR Survey #1 - Complete Survey (Station 716+00 to 756+00)

Initially, this site was surveyed for the entire 4,000 ft length. The GPR survey was completed for both lanes in accordance to a slightly modified six run format, provided in Figure 29. Field trial preparations are shown in Figure 30.

Six GPR survey runs were completed to cover the two-lane roadway platform. Twelve channel readings were all offset by 2 ft, which covered the 24-ft platform. The start and end locations were painted on the roadway surface, with no other markings in between. Upon completion of the GPR survey, the information was analyzed to select the pavement core locations.

Six cores were extracted from this section, with two cores taken in each area with suspected lower, medium, and high densities. Bulk specific gravities (G_{mb}) were determined in the laboratory for all core samples. The theoretical maximum specific gravity (G_{mm}) was obtained from construction records obtained from the paving operation. The pavement coring and laboratory testing was completed by SMO staff.

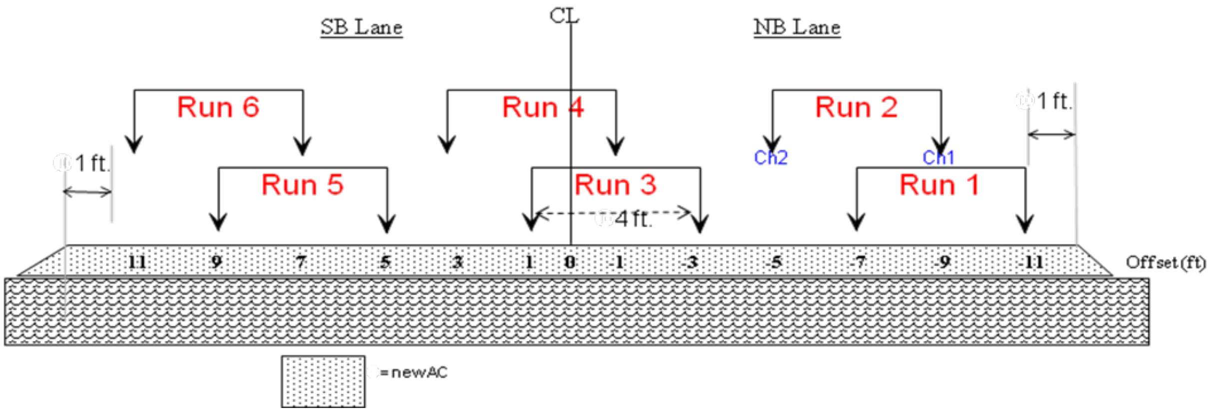


Figure 29. Initial GPR Data Collection Protocol on SR 23.

Figure 30. Field Layout of Data Collection Protocol on SR 23.

GPR Survey #2 - Uni-Directional Segment Survey (Station 723+00 to 733+00)

A 1,000-ft test section was randomly selected from within the initial 4,000-ft survey section. This segment survey extended from Station 723+00 to 733+00 and followed the same uni-directional survey protocol as provided in Figure 29.

The primary purpose of this survey was to have comparable data to check repeatability of the collected dielectric constant values, and also to serve as a direct benchmark for the multi-directional GPR survey to follow.

GPR Survey #3 - Multi-Directional Segment Survey (Station 736+00 to 744+00)

A subsequent GPR survey was completed in the same area as GPR Survey 2 (Station 723+00 to 733+00). However, instead of surveying the entire pavement platform with increasing stationing (uni-directional), the southbound lanes were surveyed in the direction of travel (multi-directional). A sketch of the GPR data collection for this survey segment is provided in Figure 31.

The intent of completing the multi-directional GPR survey was two-fold. Firstly, the project team wanted to demonstrate the ability of the equipment and software program (GPRQA) to collect and analyze the GPR data with decreasing stationing. A secondary intent of the multi-directional survey was to compare the repeatability of the equipment when surveying in the reverse direction.

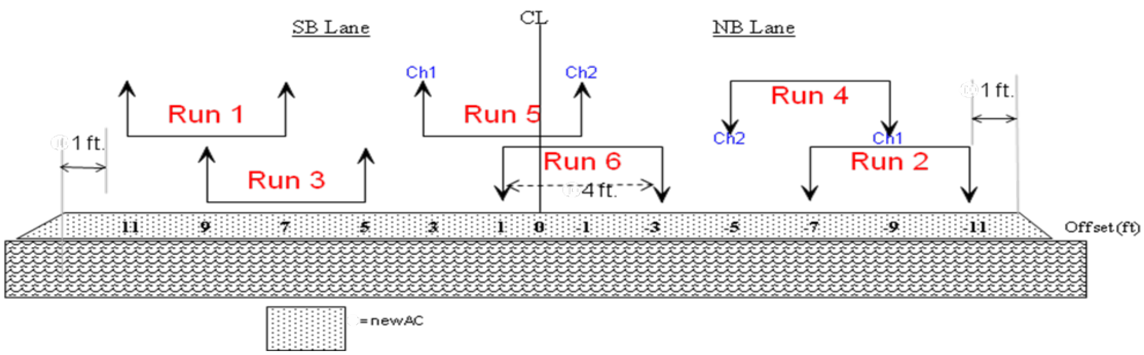


Figure 31. Multi-directional Data Collection Protocol on SR 23.

Non-Nuclear Density Gauge Readings

Measurements from a non-nuclear density gauge were completed as part of the field trials to provide a comparison as to the accuracy of the different systems. The PQI readings for the non-nuclear density gauge were taken using a Transtech device, Model #301. At each of the pavement core locations, three PQI readings were taken. These readings were averaged and compared with the determined bulk densities of the pavement cores to calculate a calibration factor which was applied to the average PQI readings measured at each core location.

State Road 222

A final field validation trial was completed on May 5, 2009, using GPR to measure the HMA density on roadway surface recently resurfaced. The construction project was located in FDOT's Alachua County SR 222, in Gainesville. The westbound driving lane was surveyed, west of SR 24.

The GPR field validation survey was completed on a 4,800-ft section between NE 15th Street and SR 24. Survey stationing started at the western end (by NE 15th St.), Station 505+00, and continued easterly to Station 553+00 (near SR 24). To complete the GPR survey, a temporary lane closure was set up (by

SMO staff) in the westbound driving lane on SR 222. All GPR surveys were completed in the direction of travel, which was in the direction of decrease stationing. As the first two field validation trial sites were on new construction, this site provided an opportunity to evaluate compaction levels achievable on a resurfacing project.

Prior to the GPR survey, the contractor had paved a surface structural asphalt lift (Fine SP 12.5), which included a 15 percent blend of RAP material. The new asphalt surface had been placed 15 days prior to completing the GPR survey.

The JMF for this paving material indicated that the aggregates in the asphalt mix were comprised of Georgia Granite, with an optimum asphalt binder content of 5.3 percent. The JMF for this material has been provided in Appendix C, and summarized below.

Table 6. Gradation Blending of Aggregates for SR 222 Asphalt Material.

Material Type	Product Code	Producer	Pit No.	Blend (%)
Crushed RAP	334-MM	213554-2-52-01	SR 93	15
#78 Stone	C54	Martin Marietta Aggregates	GA-383	17
#89 Stone	C51	Martin Marietta Aggregates	GA-383	5
W-10 Screenings	F21	Martin Marietta Aggregates	GA-383	58
Sand	334-LS	Florida Rock Industries	Putnam	5
PG 76-22	916-PG			4.4

The research team was not present during the data collection at this survey site, but the team did establish the protocol to be followed by the SMO staff carrying out the survey. Continuing from previous field trials, the protocol for this trial included the effects of GPR antenna spacing and of vehicle wander on the quality of the survey results.

In addition to completing the GPR survey, density measurements at core locations also were completed, using a non-nuclear density gauge. A summary of the methodology is provided below, along with the survey results.

GPR Survey #1 - Complete Survey (Station 505+00 to 553+00)

The site initially was surveyed along the entire 4,800-ft length. The GPR survey was completed, in the westbound outside driving lane, in accordance with the four-run format shown in Figure 32. The GPR antennas were spaced a distance 4 ft apart, which provided the six channel readings (with two overlaps) to cover the 12-ft platform.

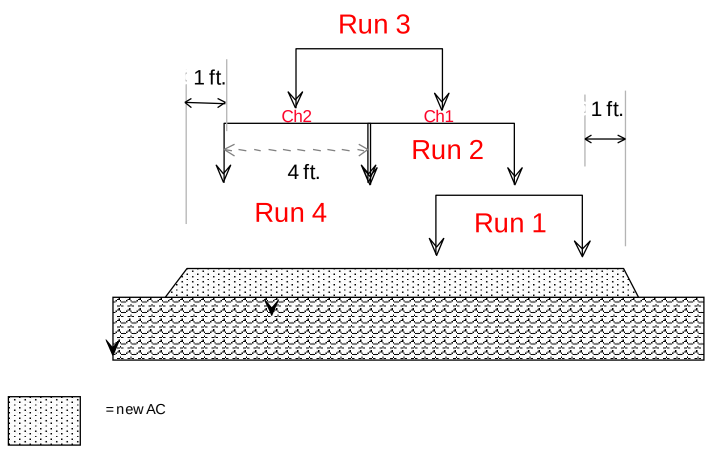


Figure 32. Initial GPR Data Collection Protocol on SR 222.

The start and end locations for the initial GPR survey were painted on the roadway surface. Prior to starting the initial GPR survey, a 500-ft sub-section was randomly selected between Station 531+50 and 536+50 that was used for the alternate surveys. Within this section, offset marking were painted on the roadway at 100-ft intervals. As part of the initial survey, extra care was taken to minimize wandering within this area, so that the collected data could be used as control data for the subsequent wandering trial surveys.

From the results of the GPR survey, the collected information was analyzed to select the pavement core locations. Twelve pavement cores were extracted from the entire section, with four cores taken from each of the suspected lower, medium, and high density areas. Bulk specific gravities (G_{mb}) were determined in the laboratory for all core samples. The theoretical maximum specific gravity (G_{mm}) was determined on samples obtained at the time of paving. The pavement coring and laboratory testing was completed by FDOT SMO staff.

GPR Survey #2 – 2.5 ft Antenna Spacing Segment Survey

Upon completing the initial survey, a 5000ft segment section was randomly selected to complete a series of GPR surveys with modified survey protocols. This segment section extended from Station 536+50 to 531+50, in the outside driving lane of the westbound lanes. Within this segment section, 1-ft survey offsets were painted on the pavement surface, every 100 ft, to improve vehicle positioning along survey lines.

The first of these segment surveys included the reduction of spacing between GPR antennas to 2.5 ft. This modification to the survey methodology allowed for a reduction in the number of survey passes from 4 to 3 runs. The run format for this segment survey is provided in Figure 33.

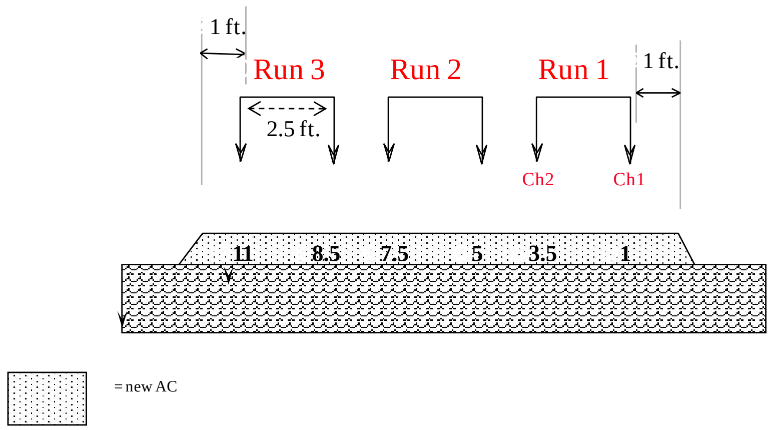


Figure 33. Modified Survey Protocol for GPR Survey 2 on SR 222.

GPR Survey #3 – 2 ft Antenna Spacing Segment Survey

Within the same segment survey area (Station 531+50 to 536+50), the GPR survey was repeated with a further reduction in antenna spacing to 2 ft. A sketch of this GPR segment survey data collection is provided in Figure 34.

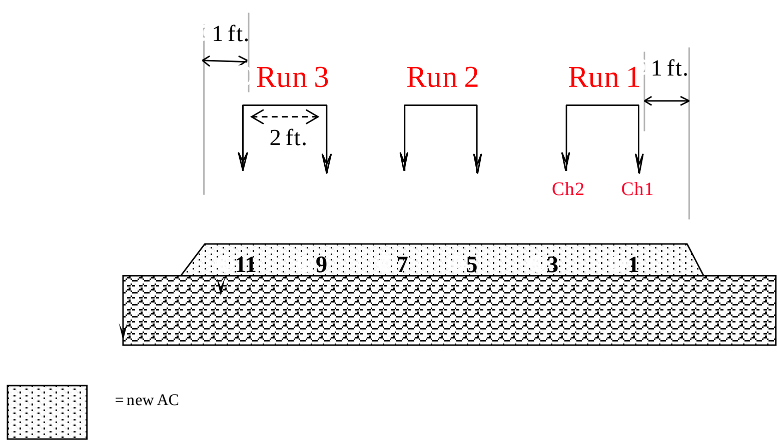


Figure 34. The 2-ft Data Collection Protocol on SR 222.

Contour plots were developed from the survey results and visually compared to the results of the previous surveys.

GPR Survey #4 – Vehicle Wander #1

Using the same segment survey area, a validation methodology was completed to investigate the effects of vehicle wander on survey results. Using the results of the initial GPR Survey 1 as the control, additional surveys were completed that intentionally introduced wandering of the survey vehicle during data collection.

Using the same survey setup as illustrated in Figure 32 (4 ft antenna spacing), an initial wander vehicle survey was completed. Using the painted markings on the pavement surface (every 100 ft) as a guide, the GPR data was collected with a 1-ft magnitude of wander, as illustrated in Figure 35.

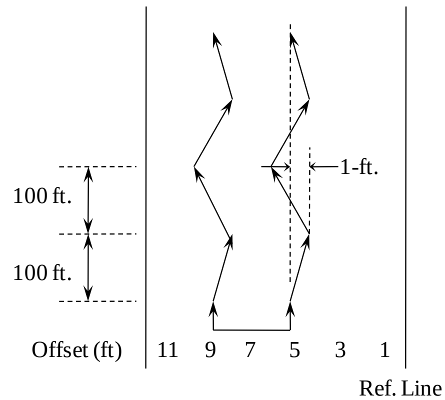


Figure 35. Survey Protocol for Vehicle Wander 1 on SR 222.

GPR Survey #5 – Vehicle Wander #2

For comparison purposes, a secondary wander survey was completed with an increased wander interval of 2 ft for every 100 ft. A sketch of this wander pattern is provided in Figure 36.

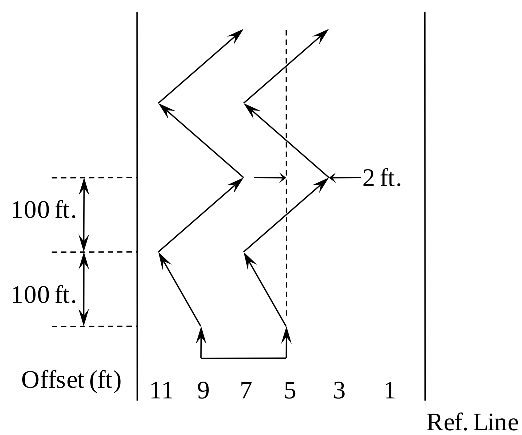


Figure 36. Survey Protocol for Vehicle Wander 2 on SR 22.

The survey results of the wander surveys were compared to the control data.

Non-Nuclear Density Gauge Readings

Asphalt density measurements were collected using FDOT's non-nuclear density gauge. Density readings were collected at all pavement core locations prior to paving. At each of the pavement core locations, three measurements were recorded at the coring location, while another four readings were taken around the core, as indicated below.

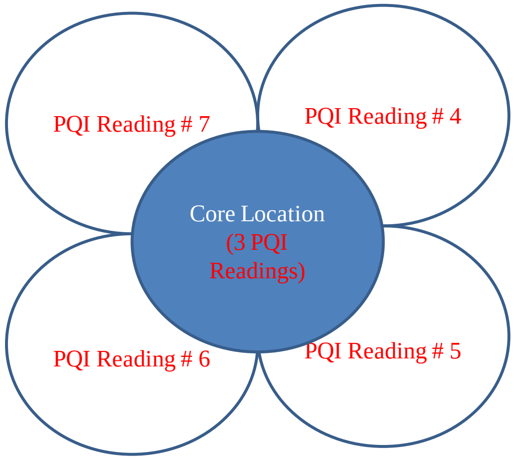


Figure 37. Non-Nuclear Density Gauge Testing Protocol.

The results of the non-nuclear density gauge readings were averaged and compared with the GPR survey results and laboratory testing of the pavement cores.

Data Collection and Analysis

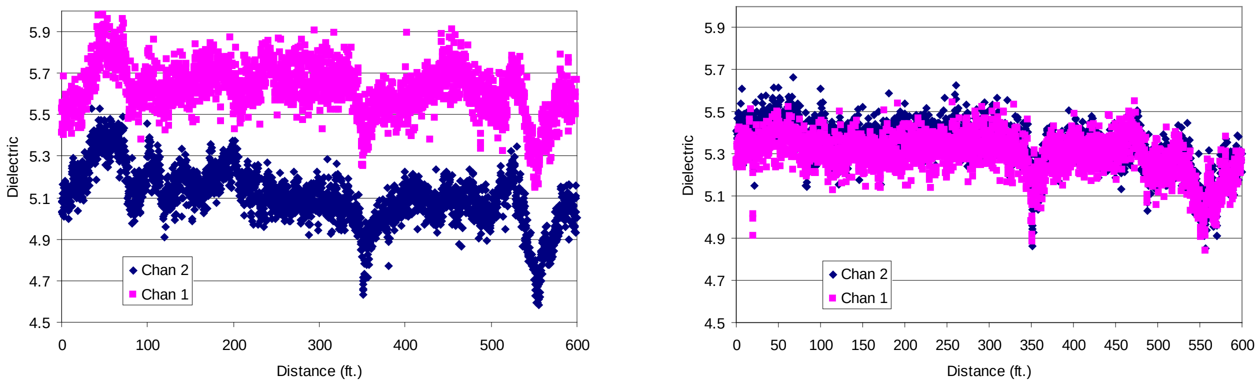
Each of the trial sections was surveyed following the outlined protocols. All data were collected using the SMO equipment, operated by their staff. Upon completion of the GPR survey, the GPR data were analyzed using the GPRQA software program. The software was operated in the field, immediately after the data collection had been completed. The collected information for each section was analyzed and a contour plot of the dielectric constants for each section was prepared. From the contour plots, core locations were selected in areas of lower/medium/higher densities. Dielectric constants were correlated to laboratory testing of core samples (G_{mb}) and plant determined samples taken by the contractor (G_{mm}).

The analyses of the collected GPR data led to several modifications to the software program, including how the program determined the dielectric constant values. The software was modified in three ways:

- The software program calculates survey dielectrics from peak-to-trough values rather than just peak values alone. Apparently, there was some amplitude drift in the data that created errors in using peak values alone, whereas using peak-to-trough values eliminates these errors. Apparently, this drift differs from one channel to another and therefore manifests itself as discrepancies between the two channels at the same offset. The difference that presently appears in the modified program is insignificant, and it is felt that no further processing will be required.

- The software program presently normalizes the data based on the current end reflection peak-to-trough value instead of using an average end reflection value. Observation of the SR 20 data, particularly the data on the long run (Section 5), shows that the end reflection amplitude (and, by reference, the entire scan amplitude) not only drifts but experiences local abrupt changes. By normalizing each scan by its end reflection amplitude, the program is able to adjust for this amplitude drift.

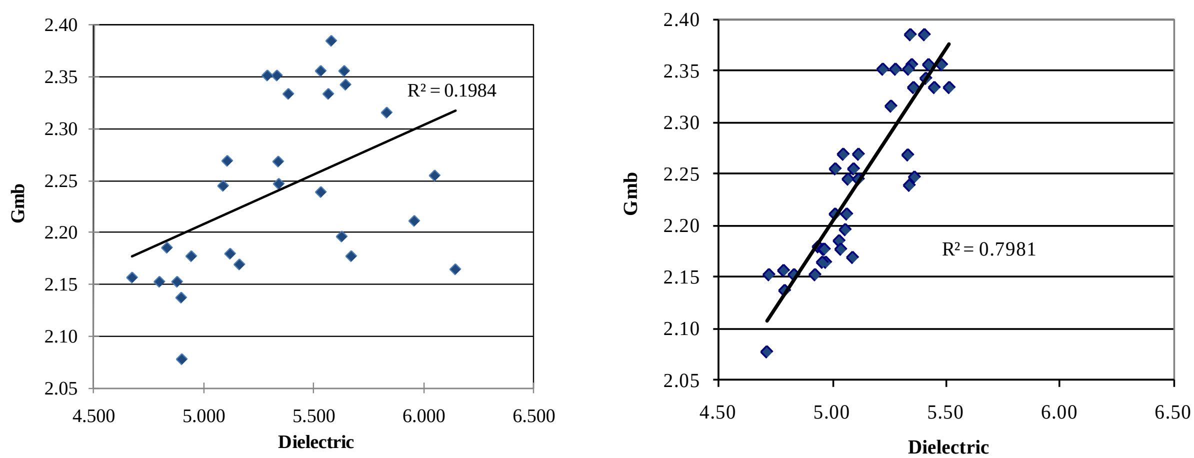
- Finally, the software program uses the raw data scan rather than an expanded data scan. In the test strip analysis, the raw data scans were expanded to 2,024 points to obtain higher precision on the plate subtraction and thickness data. The expansion process takes time, and does not appear to be necessary for the objectives of this project. By eliminating the expansion, the processing time has been reduced by a factor of 4.



(a) Using Software from December 9-10 (b) After Software Modifications

Figure 38. Comparison Plots of Channel Drift Differences.

These software improvements resulted in adjustments to the dielectric constants, as seen in Figure 38. In comparing the combined correlations (using the collected SR 20 data), the adjusted software program showed significant improvement when compared to the initial correlations completed before the software modifications. Both combined correlation plots have been provided in Figure 39 below. Although these plots show some variability in the data, they do follow a similar trend. This trend tends to indicate that selected pavement coring locations can be determined from plotted contour plots using the dielectric constants determined by the GPR survey. The adjusted values are believed to more accurately represent the in-situ asphalt conditions.



(a) Using Software from December 9-10 (b) After Software Modifications

Figure 39. Correlation Plots using Dielectric Constants at all Pavement Core Locations.

State Road 20

Section #1 (Station 590+00 to 596+00)

Based on the results of the GPR survey, contour plots were developed for this section (see Figure 40). Based on these plots, a total of six pavement cores were extracted at five different locations. Two cores were taken in low dielectric constant areas, two were taken in high dielectric constant areas, and two were taken at one location in a medium dielectric constant area (where two cores were extracted). The results of the dielectric constants, and laboratory testing, at each core location are summarized in Table 7.

Table 7. Survey and Test Results for Section 1 on SR 20.

Core Number	Expected Density Level	Dielectric Constant	Core G_{mb}	Plant G_{mm}	% G_{mm}
20-1-1	Low	5.03	2.185	2.523	86.6
20-1-2	High	5.41	2.342	2.523	92.8
20-1-3	Low	4.79	2.137	2.523	84.7
20-1-4	High	5.33	2.239	2.523	88.7
20-1-5A	Medium	5.33	2.268	2.523	89.9
20-1-5B	Medium	5.36	2.247	2.523	89.0

The results of the bulk specific gravities (G_{mb}) completed on the pavement core samples were plotted (Figure 41) against the dielectric constant values to determine the degree of correlation between the parameters. The results indicated good correlation between the dielectric constants and the determined G_{mb} (R^2 value of 0.81).

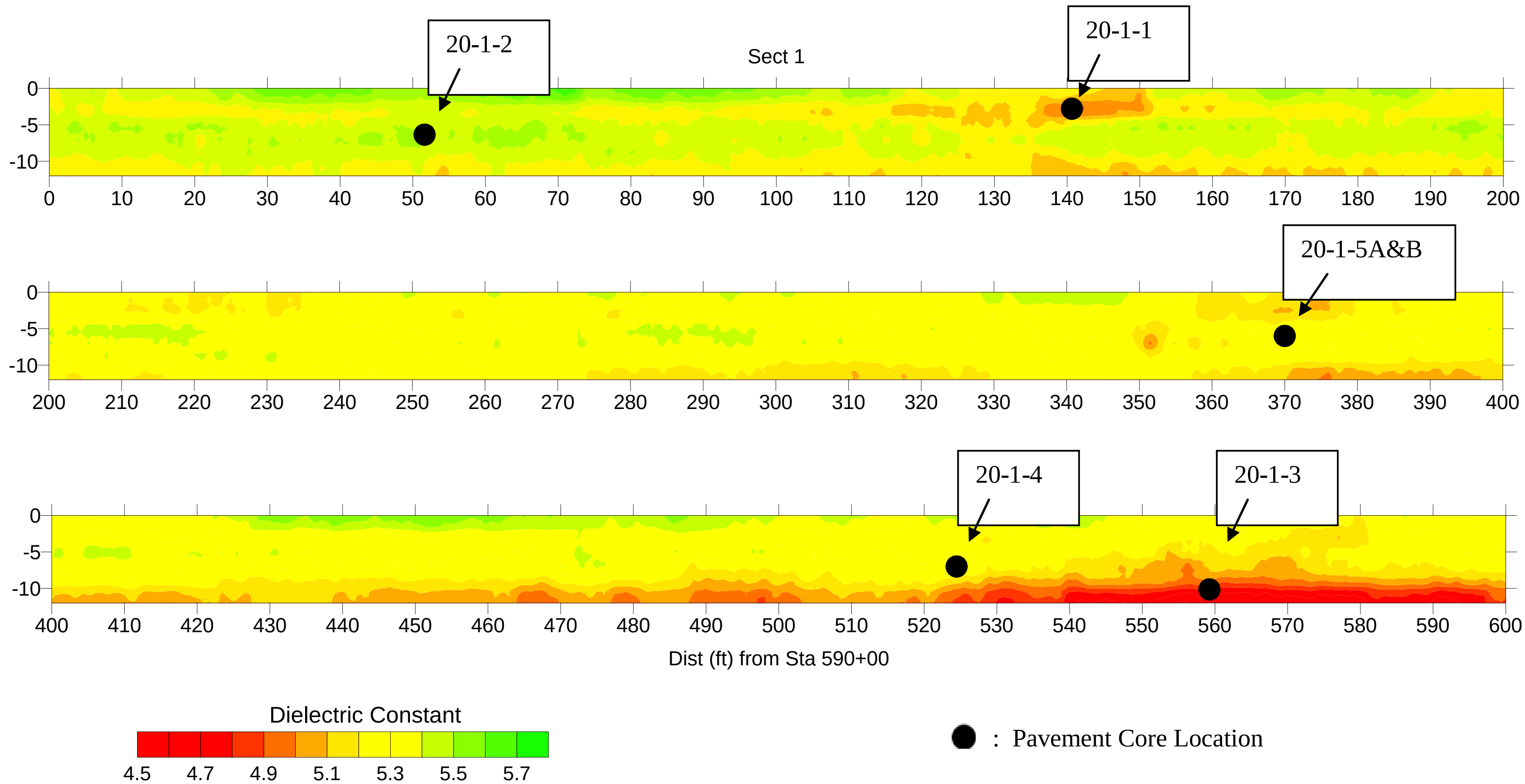


Figure 40. Dielectric Constant Contour Plot for Section 1 on SR 20.

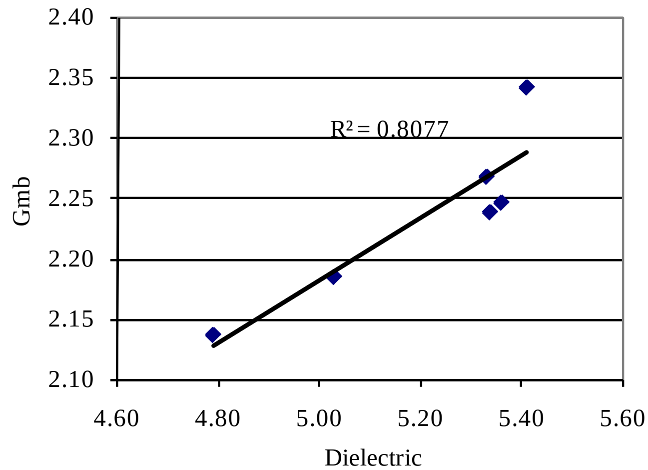


Figure 41. Dielectric Constant vs. G_{mb} for Section 1 on SR 20.

Using the provided theoretical maximum specific gravity (G_{mm}) from the plant samples, the areas selected for coring had compaction levels ranging from as low as 84.7 percent to a high of 92.8 percent.

Section #2 (Station 670+00 to 677+00)

Similar to Section 1, the results of the GPR survey of Section 2 were used to develop contour plots of the dielectric constants. The contour plots were prepared on-site, with the pavement core locations determined following the same format as in the first section. A total of six pavement cores were taken.

Table 8. Survey and Test Results for Section 2 on SR 20.

Core Number	Expected Density Level	Dielectric Constant	G_{mb}	Plant G_{mm}	% G_{mm}
20-2-1	Low	4.71	2.077	2.523	82.3
20-2-2	High	5.05	2.196	2.523	87.0
20-2-3	Low	4.78	2.156	2.523	85.5
20-2-4	High	5.25	2.315	2.523	91.8
20-2-5A	Medium	5.09	2.169	2.523	86.0
20-2-5B	Medium	4.94	2.179	2.523	86.4

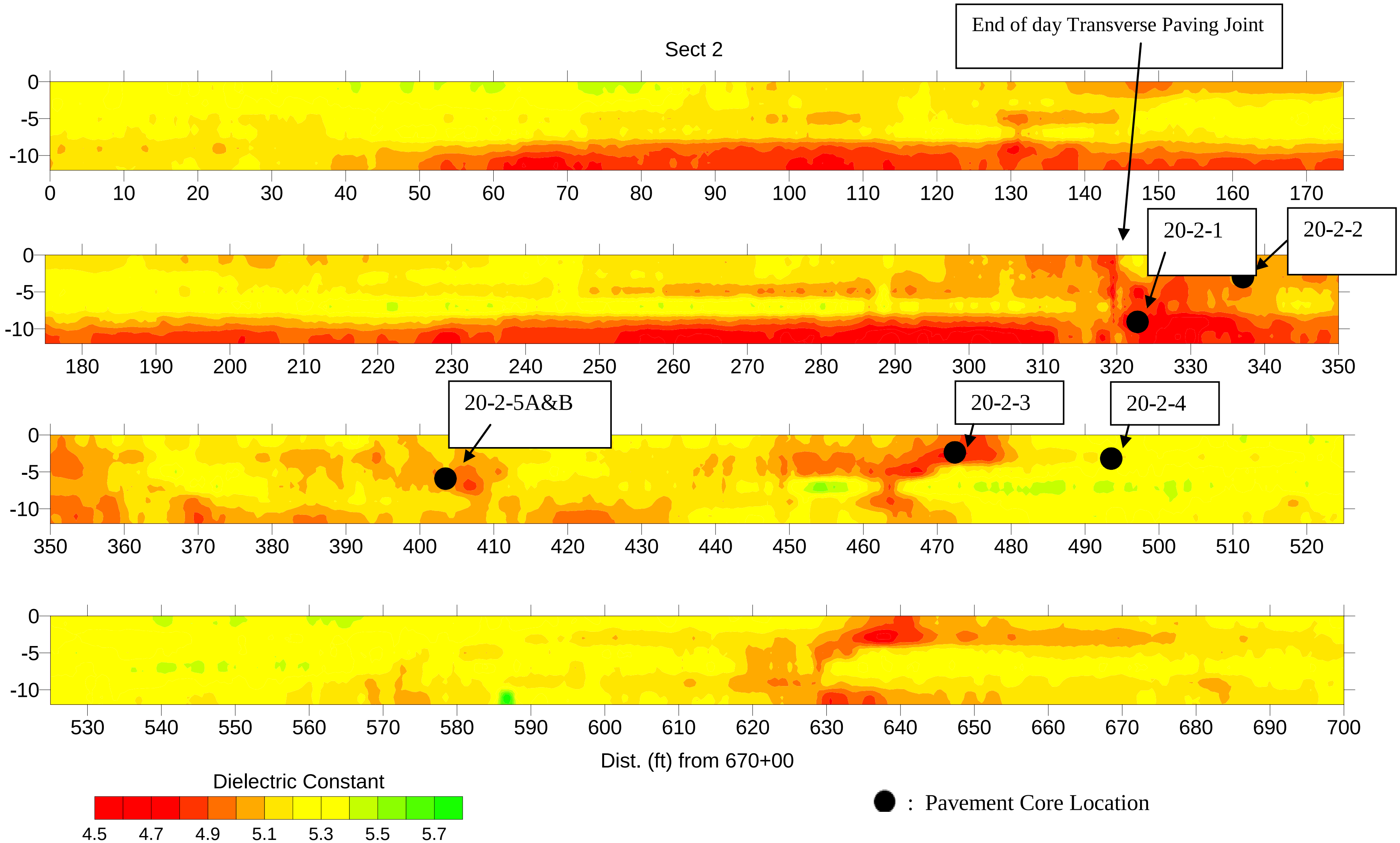


Figure 42. Dielectric Constant Contour Plot for Section 2 on SR 20.

Correlation plots for Section 2 are provided in Figure 43 and show a fairly good correlation between the dielectric constant values and the corresponding G_{mb} (R^2=0.79). At the pavement coring locations, the AC compaction varied from as low as 82.3 percent to a high of 91.8 percent.

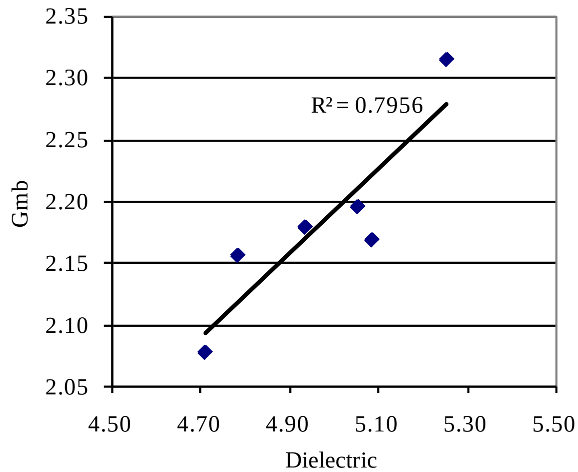


Figure 43. Dielectric Constant vs. G_{mb} Plot for Section 2 on SR 20.

Section #3 (Station 736+00 to 744+00)

The contour plots of the dielectric constant for both the hot and cold surveys are provided in Figure 44 through Figure 47. Also included in these figures is the *extracted* contour plot of the dielectric constant values extracted from the Section 5 survey. These results are discussed in subsequent sections. The dielectric constant values and laboratory results at the core locations are summarized in Table 9. Only five pavement cores were extracted from this section, as the coring crew ran out of water and could not core the last location.

Table 9. Survey and Test Results for Section 3 on SR 20.

Core Number	Expected Density Level	Dielectric Constant (Hot Mat)	Dielectric Constant (Cold Mat)	Core G_{mb}	Plant G_{mm}	% G_{mm}
20-3-1	Low	4.72	4.83	2.152	2.518	85.5
20-3-2	High	5.44	5.35	2.333	2.518	92.7
20-3-3	Low	5.42	5.35	2.356	2.518	93.5
20-3-4	High	4.96	4.96	2.177	2.518	86.4
20-3-5A	Medium	5.22	5.33	2.351	2.518	93.4
20-3-5B	Core was not extracted					

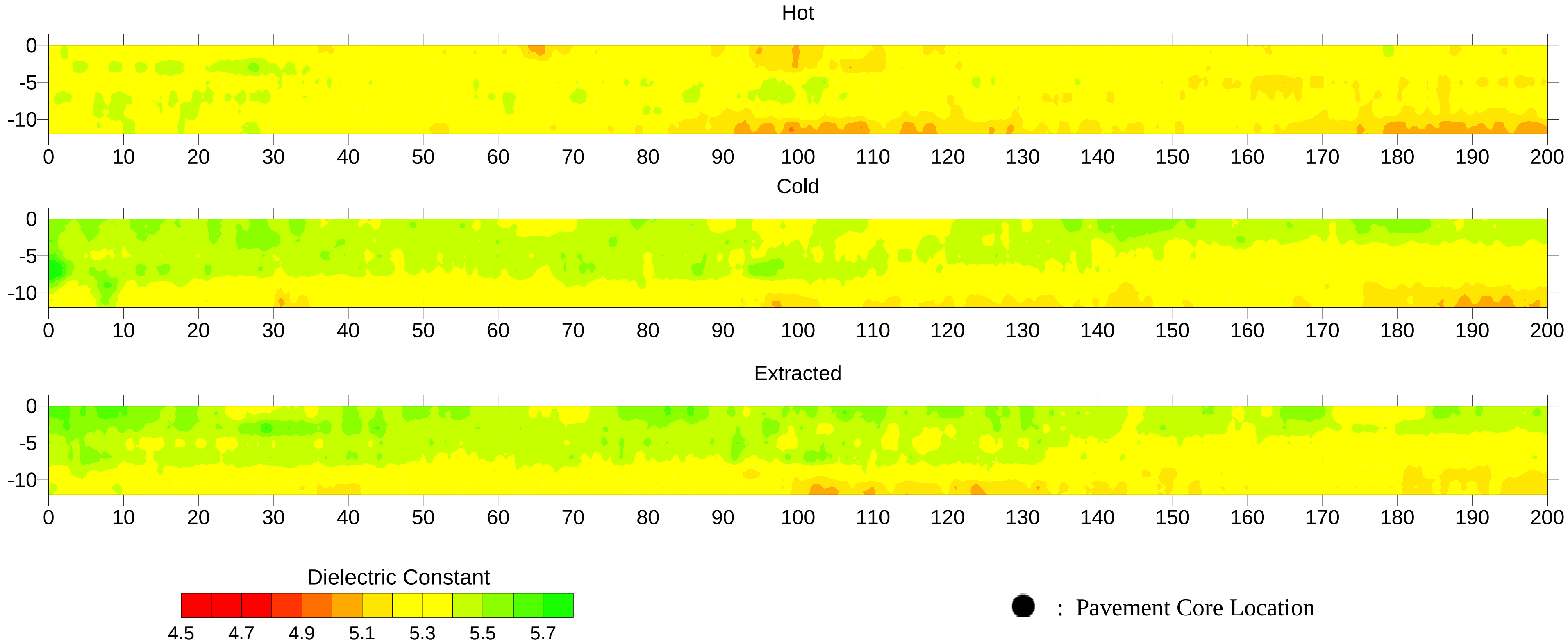


Figure 44. Dielectric Constant Contour Plot for Section 3 (0 to 200 ft) on SR 20.

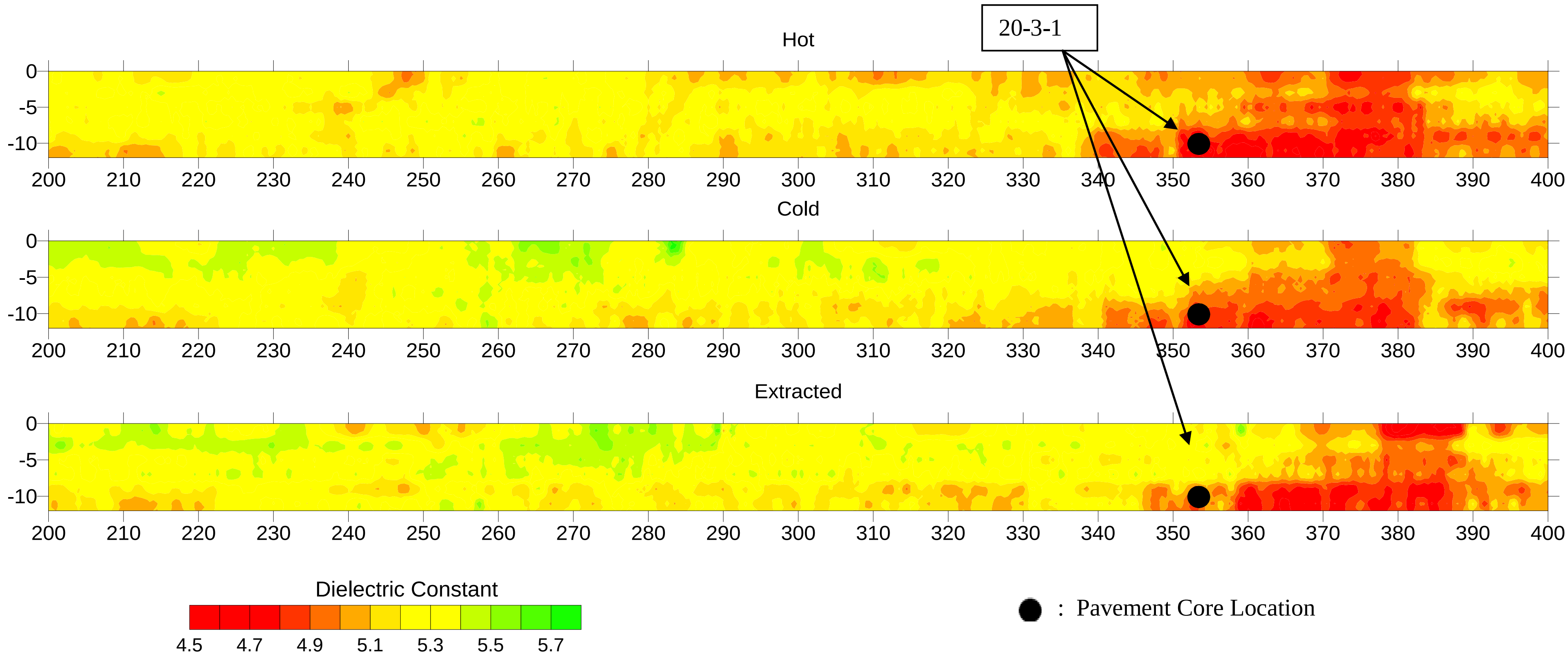


Figure 45. Dielectric Constant Contour Plot for Section 3 (200 to 400 ft) on SR 20.

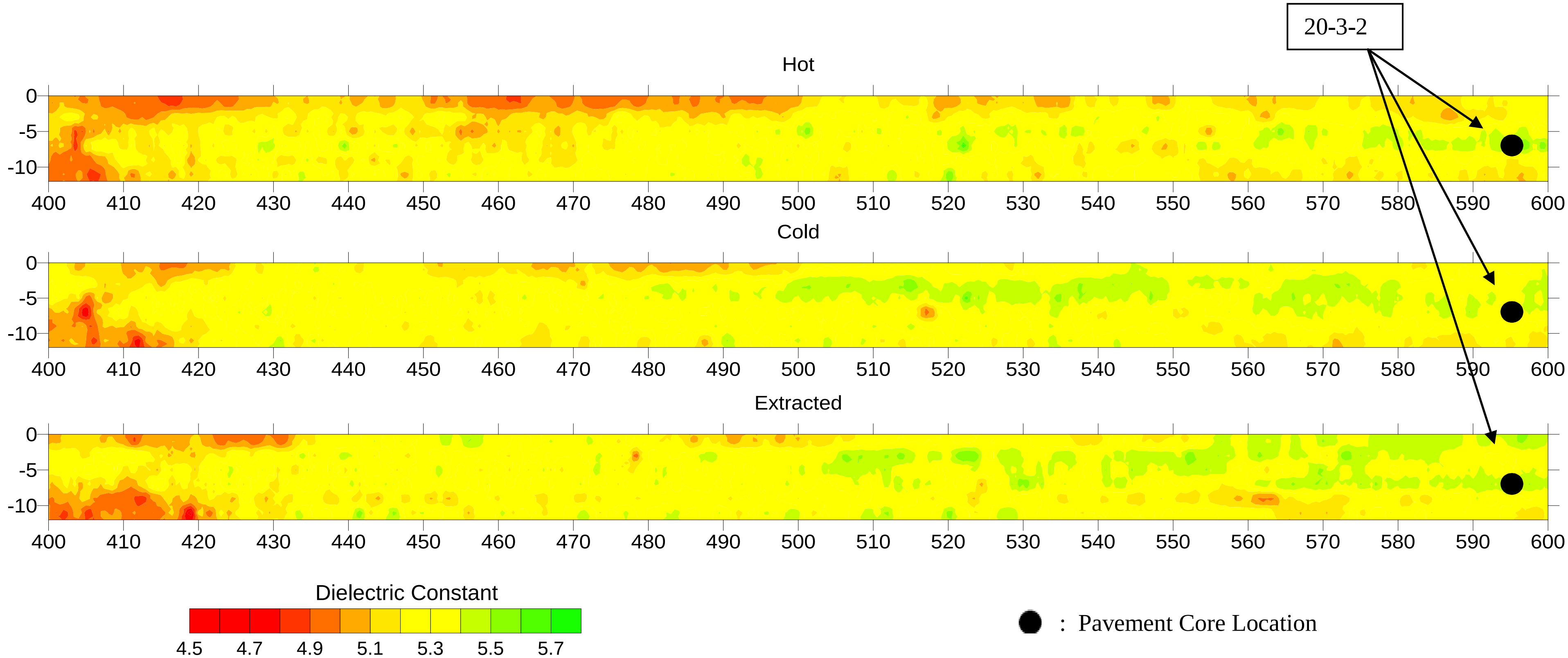


Figure 46. Dielectric Constant Contour Plot for Section 3 (400 to 600 ft) on SR 20.

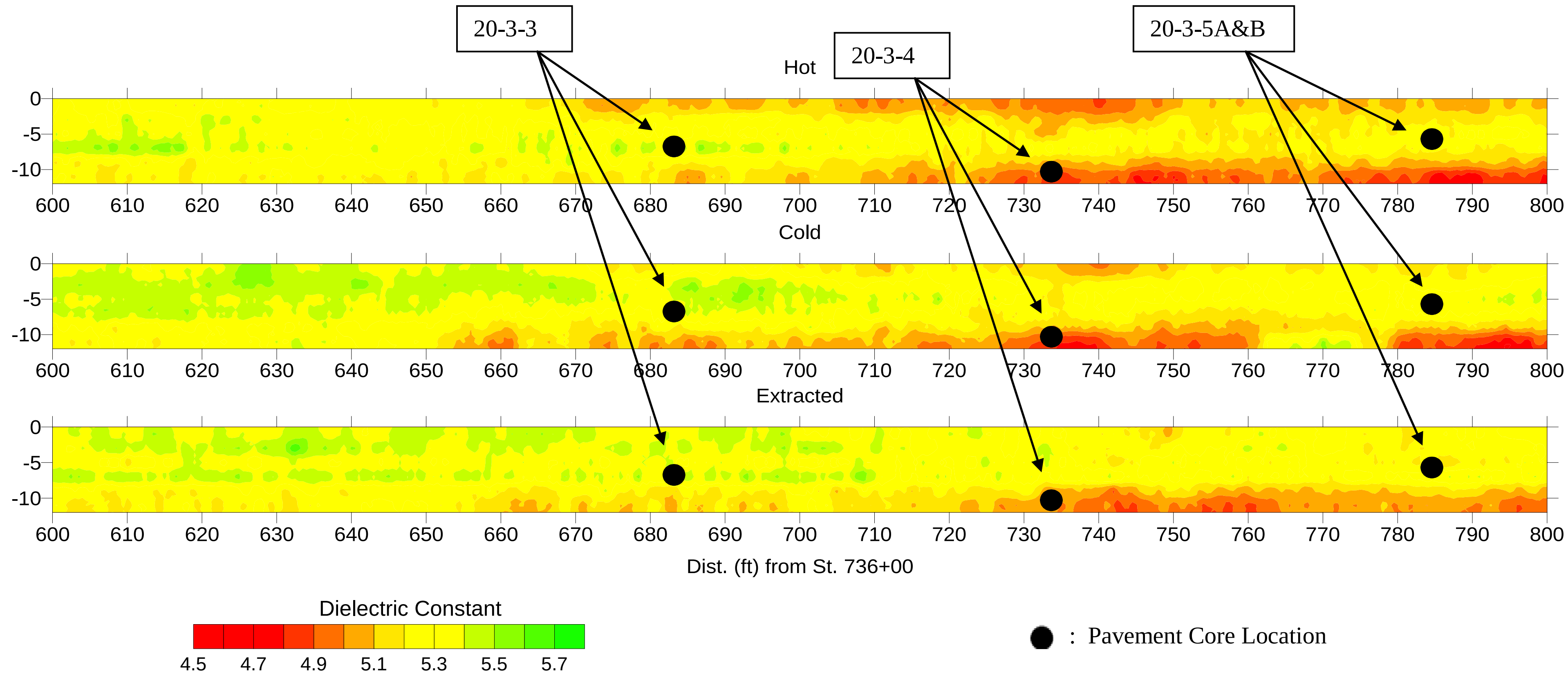
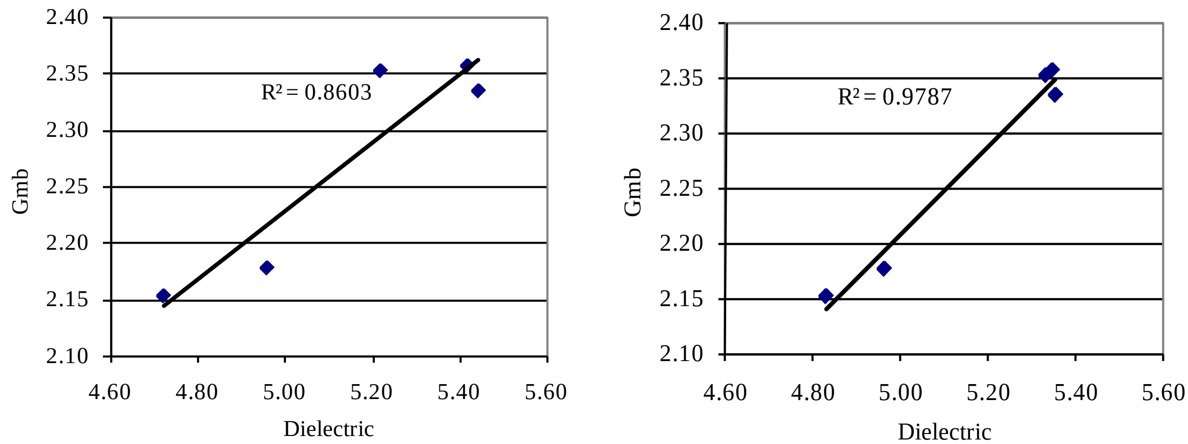


Figure 47. Dielectric Constant Contour Plot for Section 3 (600 to 800 ft) on SR 20.

In general, the contour plots show an increase in the dielectric constants from the hot survey to the cold survey. Areas with lower dielectric constant values (red areas) increased into the yellow range, while several yellow range locations increasing into the green range. In addition to the change in the dielectric constant, there was an improvement in the correlation between the dielectric constant and the laboratory determined G_{mb}. This correlation between the two plots improved from an R^2 of 0.8603, for the hot survey, to an R^2 of 0.98, for the cold survey. At the pavement coring locations, the AC compaction varied from as low as 85.5 percent to a high of 93.5 percent.



a) Hot Asphalt Surface Survey

b) Cold Asphalt Surface Survey

Figure 48. Dielectric Constant vs. G_{mb} Plot for Section 3 on SR 20.

Section #4 (Station 696+00 to 704+00)

In the preliminary presentation of the results for this section, it was thought that the concrete curb may have had an effect on the GPR survey results for this section. Changes to the software program have minimized these concerns. The revised dielectric constants do not show an influence of the concrete curb; in fact, they identify a reduction in densities along the curb line. Therefore, it is possible that the compaction equipment drum was running along the concrete curb resulting in lower compaction of the asphalt adjacent to the curb. Furthermore, the software adjustments have also provided a significant improvement in the correlation factors with the laboratory determined G_{mb}.

The revised contour plots of dielectric constant values are provided in Figure 49 and Figure 50. Also included in these figures are comparison plots extracted from the Section 5 survey. These comparison plots will be discussed later. The dielectric constant values and laboratory results at the core locations for Section 4 are summarized in Table 10.

The correlation plot for Section 4 continues to show good correlation (R^2 of 0.83) between the dielectric constant, reported by the GPR survey, and the G_{mb} determined from the extracted pavement cores. At the pavement coring locations, the compaction effort typically varied from 85.9 to 90.1 percent, with one location at 94.7 percent.

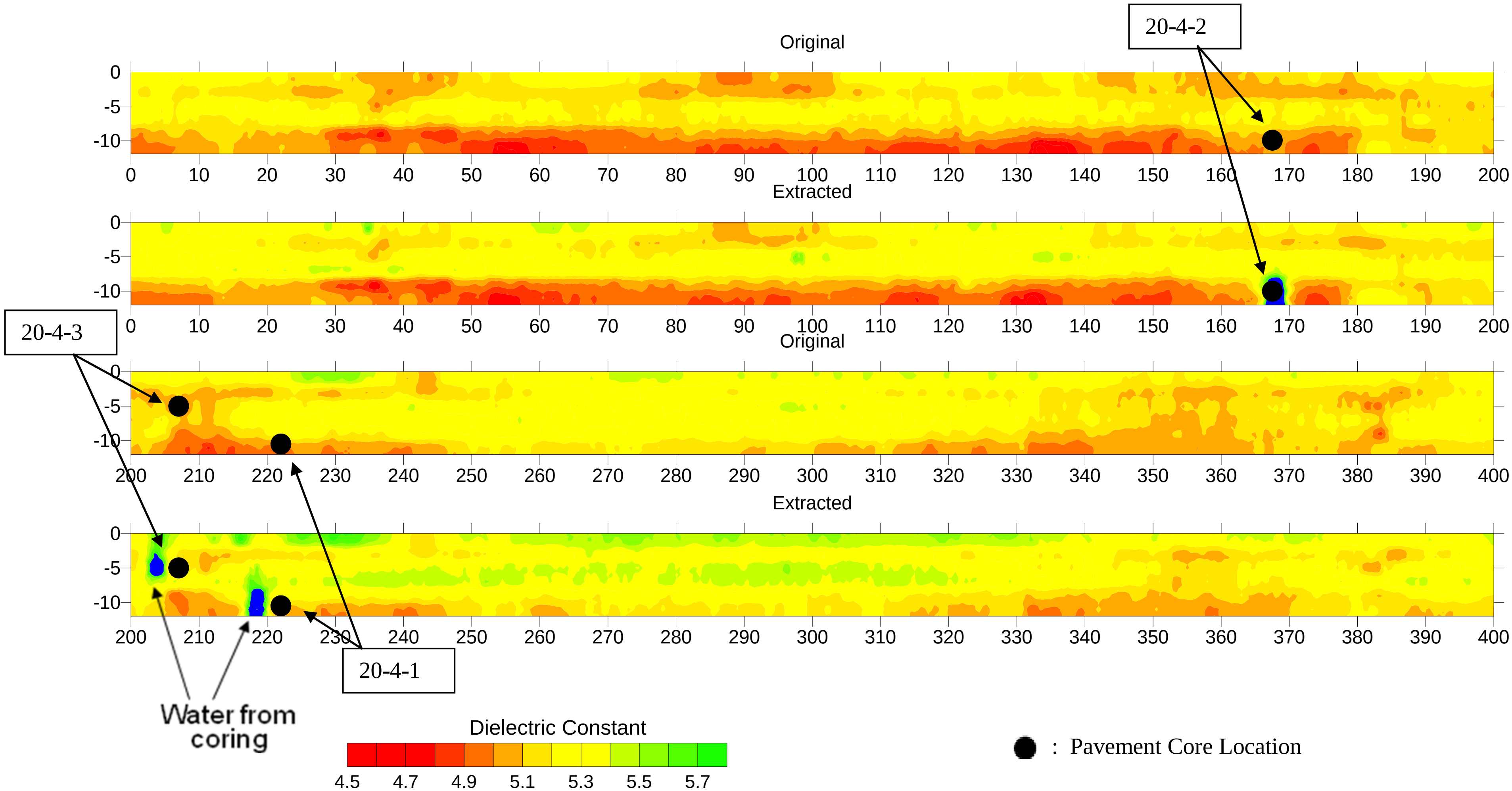


Figure 49. Dielectric Constant Contour Plot for Section 4 (0 to 400 ft) on SR 20.

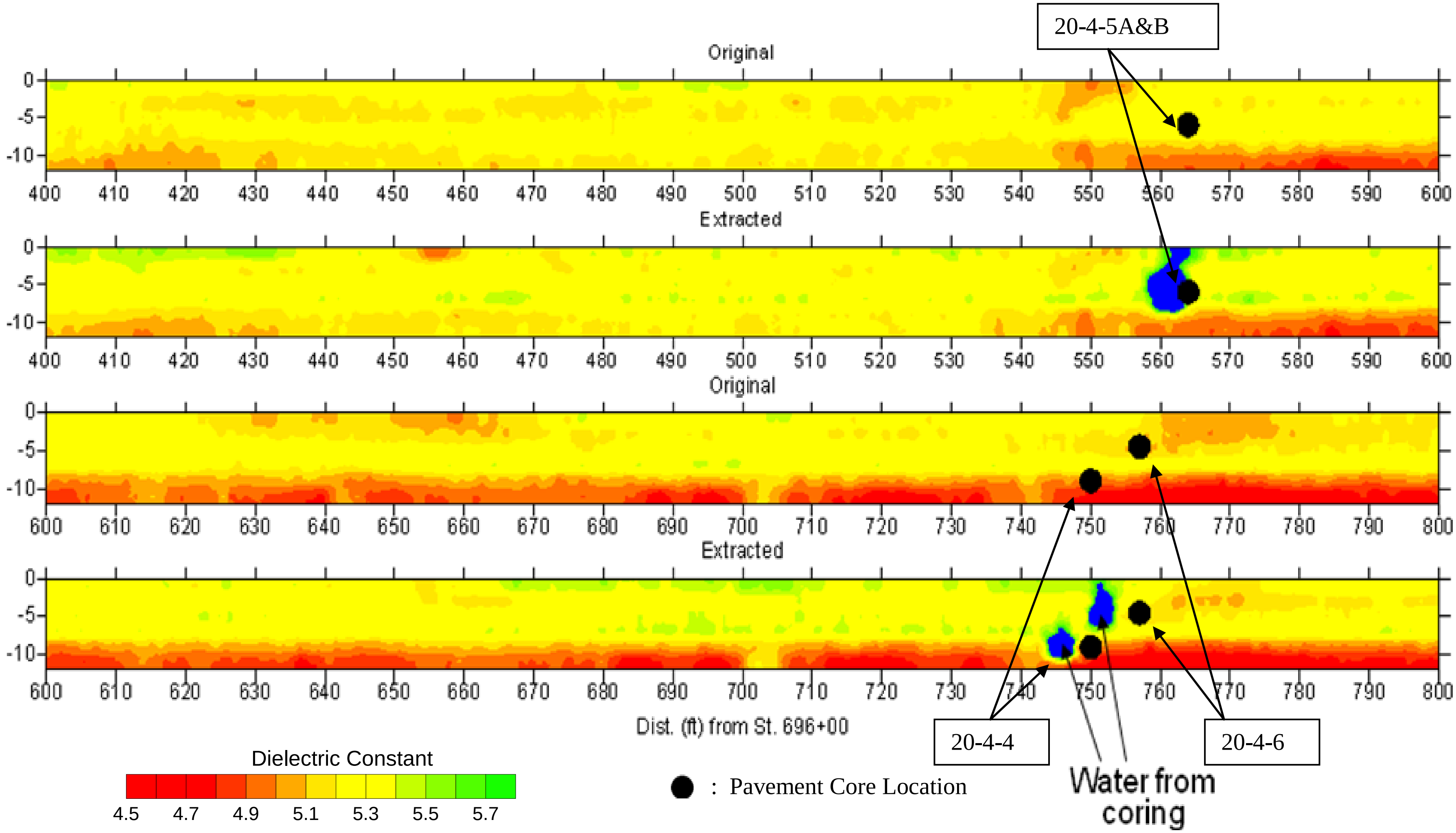


Figure 50. Dielectric Constant Contour Plot for Section 4 (400 to 800 ft) on SR 20.

Table 10. Survey and Test Results for Section 4 on SR 20.

Core Number	Expected Density Level	Dielectric Constant	Core G_{mb}	Plant G_{mm}	% G_{mm}
20-4-1	High	5.01	2.255	2.518	89.5
20-4-2	High	5.06	2.211	2.518	87.8
20-4-3	Low	5.07	2.245	2.518	89.1
20-4-4	High	4.97	2.164	2.518	85.9
20-4-5A	Medium	5.34	2.385	2.518	94.7
20-4-5B	Medium	Equipment Problems (Did not core)			
20-4-6	Low	5.05	2.269	2.518	90.1

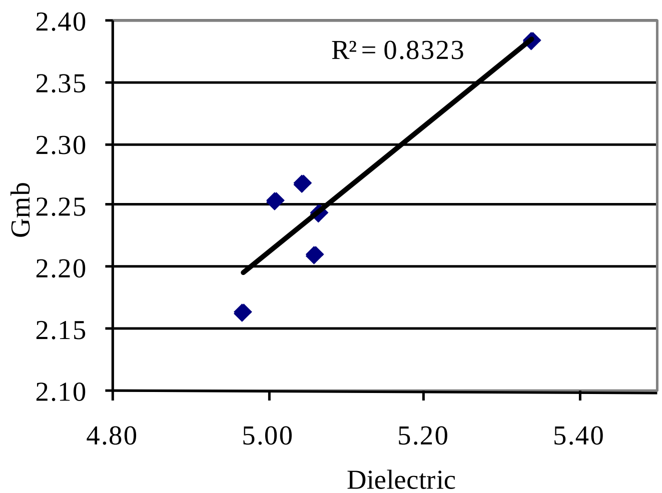


Figure 51. Dielectric Constant vs. G_{mb} Plot for Section 4 on SR 20.

Section #5 (Station 696+00 to 766+00)

The data collection efforts for the smaller sections generally were complete within a half hour, whereas this longer section took about 1.5 hours to complete. Other issues in surveying this section included:

- Ensuring the lane remains clear for the entire duration of the data collection. (This is somewhat difficult on active construction projects.)
- Ensuring the lane is relatively clean from debris.
- For longer sections, it is more difficult to keep the survey lines on track and limit vehicle wander.

Also, on account of the large file sizes, difficulties were encountered when trying to analyze the GPR files. These software problems were addressed and the larger files were analyzed. As Section 5 encompassed the two previously surveyed sections, no additional cores were taken.

With the total survey length of 7,000 ft for Section 5, dielectric plots have not been provided for the entire section in this report. Instead, the collected dielectric constants were calibrated to the G_{mb} of the pavement cores extracted from Sections 3 and 4. These calibrated results were compared to the G_{mm} values obtained from the plant samples during construction and used to determine the compaction effort for the entire section (% G_{mm}).

As a summary of the GPR survey completed throughout the entire area of Section 5, a distribution plot was prepared of the density effort (% G_{mm}) for the entire survey area. This distribution plot was generated from the total area within each compaction effort range and is given in Figure 52. The results of the survey found over 80 percent of the surveyed area varied in AC compaction from 90 to 95 percent, with a peak at 92.3 percent.

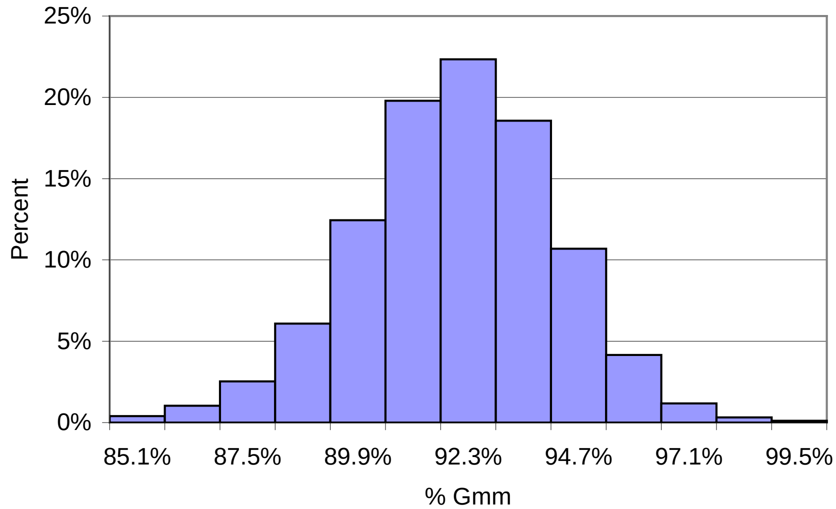


Figure 52. Distribution of Percent G_{mm} for Section 5 on SR 20.

In addition to determining the distribution of the compaction effort for the entire section, the survey of Section 5 also permitted for a consistency comparison of the data collection process to be completed in the areas that overlap with the previously surveyed Sections 3 and 4. These survey comparisons were included in Figure 44 through 47, 49 and 50. In general, the pattern of the contour plots for Section 5 closely resembled those of the surveying on the cold survey for both Sections 3 and 4. The color patterns were similar, although there did appear a slight increase in dielectric constant values in the Section 5 survey, as compared to the previous surveys.

To remove some of the noise within the raw data set, a moving average was calculated using the average dielectric constant value of 51 points (a longitudinal distance of about 13 ft). The most common measure of correlation between two variables x and y is the *Pearson Product Moment Correlation* represented by the letter "R" for a sample of the parameters x and y. R ranges between -1 to +1 and the range extreme values represent a perfect linear relationship between the two variables. A correlation of 0 means no relationship between the two variables.

The square of the Pearson correlation coefficient is called *Coefficient of Determination* (R^2) and it represents the proportion of the variance of one variable that is explained from the other variable; in other words, it is the ratio of the explained variation to the total variation. This statistical comparison of the runs, in both sections, was completed on the moving average data sets and is provided in Table 11. For Section 3, only the cold survey data was used for the statistical comparison.

Table 11. Statistical Comparison of Original Survey Data to Extracted GPR Data.

GPR Survey Comparison between the Original Section 3 Cold Data and the Extracted Data from the Section 5 Survey

	-1 ft Offset		-3 ft Offset		-5 ft Offset		-7 ft Offset		-9 ft Offset		-11 ft Offset	
	Original	*Extracted*	*Original*	*Extracted*	*Original*	*Extracted*	*Original*	*Extracted*	*Original*	*Extracted*	*Original*	*Extracted*
Mean	5.302	5.322	5.387	5.388	5.328	5.233	5.278	5.397	5.219	5.182	5.166	5.185
Variance	0.018	0.022	0.008	0.008	0.015	0.007	0.013	0.010	0.013	0.013	0.018	0.017
Observations	3146	3146	3149	3149	3146	3146	3148	3148	3146	3146	3148	3148
Pearson Correlation (R)	0.713		0.881		0.691		0.806		0.900		0.832	
Coeffecient of Determination (R^2)	0.508		0.776		0.478		0.649		0.809		0.692	

GPR Survey Comparison between the Original Section 4 Data and the Extracted Data from the Section 5 Survey

	-1 ft Offset		-3 ft Offset		-5 ft Offset		-7 ft Offset		-9 ft Offset		-11 ft Offset	
	Original	*Extracted*	*Original*	*Extracted*	*Original*	*Extracted*	*Original*	*Extracted*	*Original*	*Extracted*	*Original*	*Extracted*
Mean	5.256	5.362	5.148	5.212	5.276	5.213	5.271	5.417	5.101	5.094	4.981	4.995
Variance	0.010	0.010	0.004	0.005	0.004	0.005	0.005	0.004	0.012	0.010	0.020	0.024
Observations	3145	3145	3145	3145	3145	3145	3147	3147	3146	3146	3146	3146
Pearson Correlation (R)	0.755		0.925		0.763		0.728		0.939		0.963	
Coeffecient of Determination (R^2)	0.570		0.856		0.582		0.531		0.882		0.926	

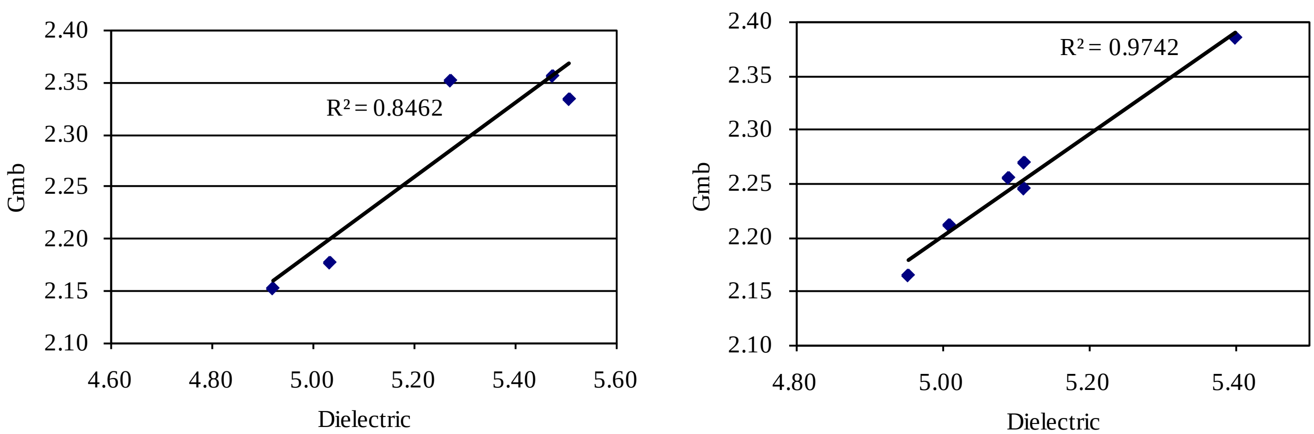
The Pearson correlations for the multiple runs varied from 0.691 to 0.963, which indicates a fairly good correlation between the two sets of data. The variability that are observed between the data sets, are likely the results of vehilce wander during data collection.

As specific dielectric constants were determined at pavement core locations, a direct comparison was prepared of the dielectric constant values between the multiple surveys. A summary of this comparison is provided in Table 12. Similar to the contour plots, the dielectric constants at pavement core locations were found to be slightly higher in the Section 5 results, when compared to the previous surveys.

Correlation plots were developed using the dielectric constant information from the Section 5 GPR survey and percent of G_{mb} as determined by the laboratory testing on extracted core samples from the areas of Sections 3 and 4. The correlation plots are provided in Figure 53.

Table 12. Comparison of Dielectric Constants on SR 20.

Core Number	Expected Density Level	Initial Survey Results		Subsequent Survey Results (Cold Testing for Section 5)
		Hot Surface	Cold Surface	
Section 3				
20-3-1	Low	4.72	4.83	4.92
20-3-2	High	5.44	5.35	5.51
20-3-3	High	5.42	5.35	5.48
20-3-4	Low	4.96	4.96	5.03
20-3-5A	Medium	5.22	5.33	5.27
Section 4				
20-4-1	High		5.01	5.09
20-4-2	High		5.06	5.01
20-4-3	Low		5.07	5.11
20-4-4	High		4.97	4.95
20-4-5A	Medium		5.34	5.40
20-4-6	Low		5.05	5.11



a) Data Extracted in Section 5 Survey in Section 3 Area b) Data Extracted in Section 5 Survey in Section 4 Area

Figure 53. Section 5 Dielectric Constants Compared Percent G_{mb} on SR 20.

For the Section 3 comparison, the correlation of the dielectric constants to the pavement core G_{mb} found a reduction in a correlation factor as compared to the correlations for the hot and cold GPR surveys. This reduction could be the result of the debris on the pavement surface prior to the Section 5 survey. When comparing the correlations at the pavement core locations in Section 4, the subsequent survey (completed as part of the Section 5 survey) found a significant improvement in this correlation as compared to the initial results.

State Road 23

After the completion of the GPR surveys, the survey results were analyzed in the field to select pavement core locations. A total of nine pavement core locations were selected. Six core locations (Core # 1, 2, 6, 7, 8, and 9) were selected using the collected information from the GPR survey 1 (4,000-ft survey), while the remaining three core locations (Core # 3, 4, and 5) were selected using the results of the uni-directional 1,000-ft segment survey. Bulk specific gravities were determined on all pavement cores. The extraction of the pavement cores, and all laboratory testing, were completed by SMO staff.

GPR Survey #1 - Complete Survey (Station 716+00 to 756+00)

The contour plots for the GPR survey completed for the initial 4,000-ft section are provided below. Based on these results, a total of six pavement cores were located and extracted. Two cores were taken in each of the low, medium, high dielectric constant areas, and dielectric values were obtained at each of these six locations. The results of the dielectric constants, and laboratory testing, at each core location are summarized in Table 13.

Table 13. Survey and Test Results for the 4,000-ft Section on SR 23.

Core Number	Station (ft)	Offset (ft)	Expected Density Level	Dielectric Constant	Core G_{mb}	Plant G_{mm}	% G_{mm}
23-1	717+06	-8.1	Low	5.022	2.303	2.459	93.7
23-2	720+31	-9.6	High	5.147	2.341	2.459	95.2
23-6	733+62	-7.4	Medium	5.148	2.348	2.459	95.5
23-7	742+03	5.6	High	5.230	2.377	2.459	96.7
23-8	749+24	-3.1	Low	4.654	2.141	2.459	87.1
23-9	754+16	2.4	Medium	5.168	2.336	2.459	95.0

The results of the bulk specific gravities (G_{mb}) completed on pavement core samples are plotted (Figure 56) against the dielectric constant values to determine the degree of correlation between the parameters. The results indicated a very good correlation between the dielectric constants and the determined G_{mb}, with an R^2 value of 0.99.

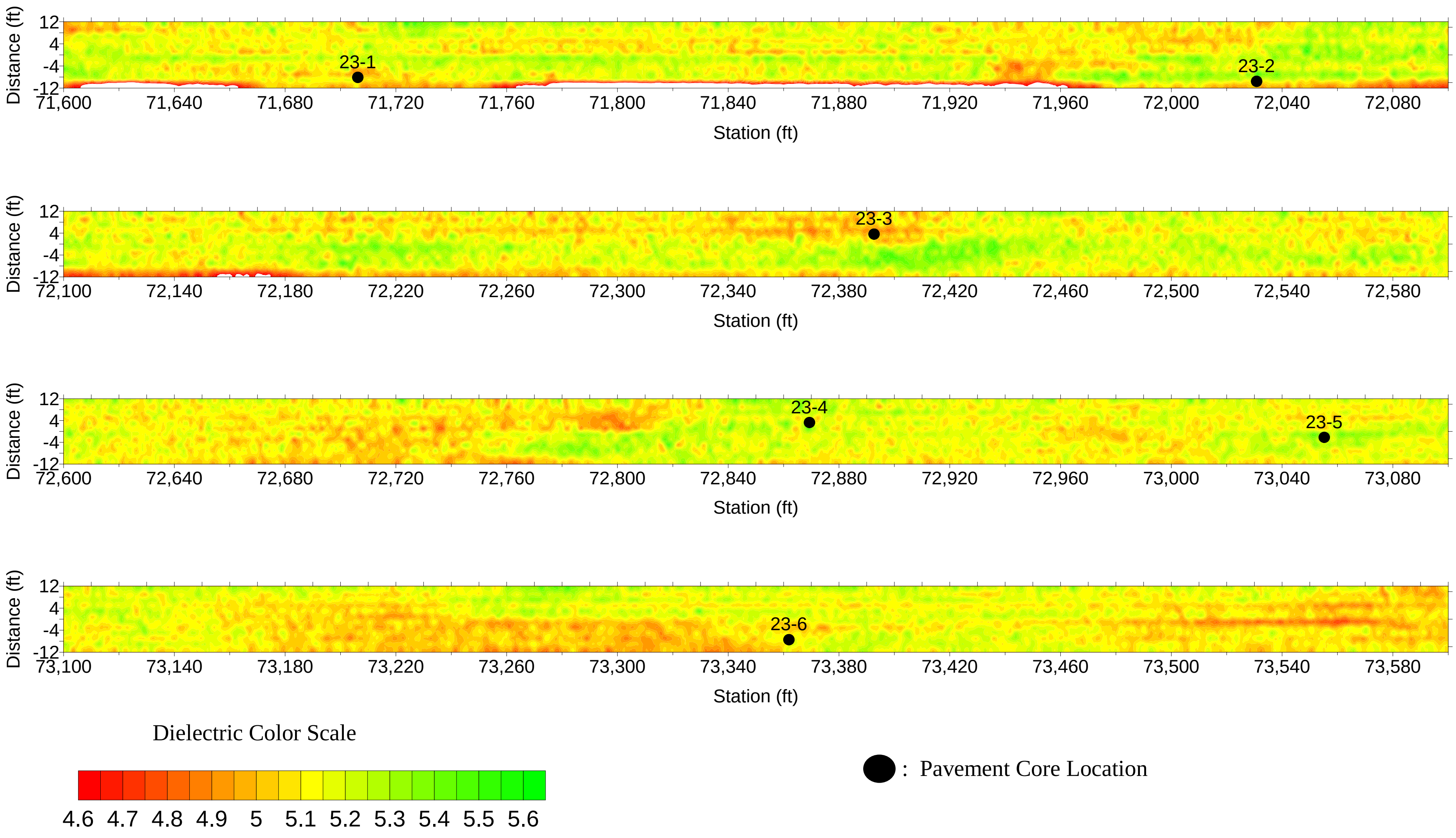


Figure 54. Dielectric Constant Contour Plot for GPR Survey 1 (Station 716+00 to 736+00) on SR 23.

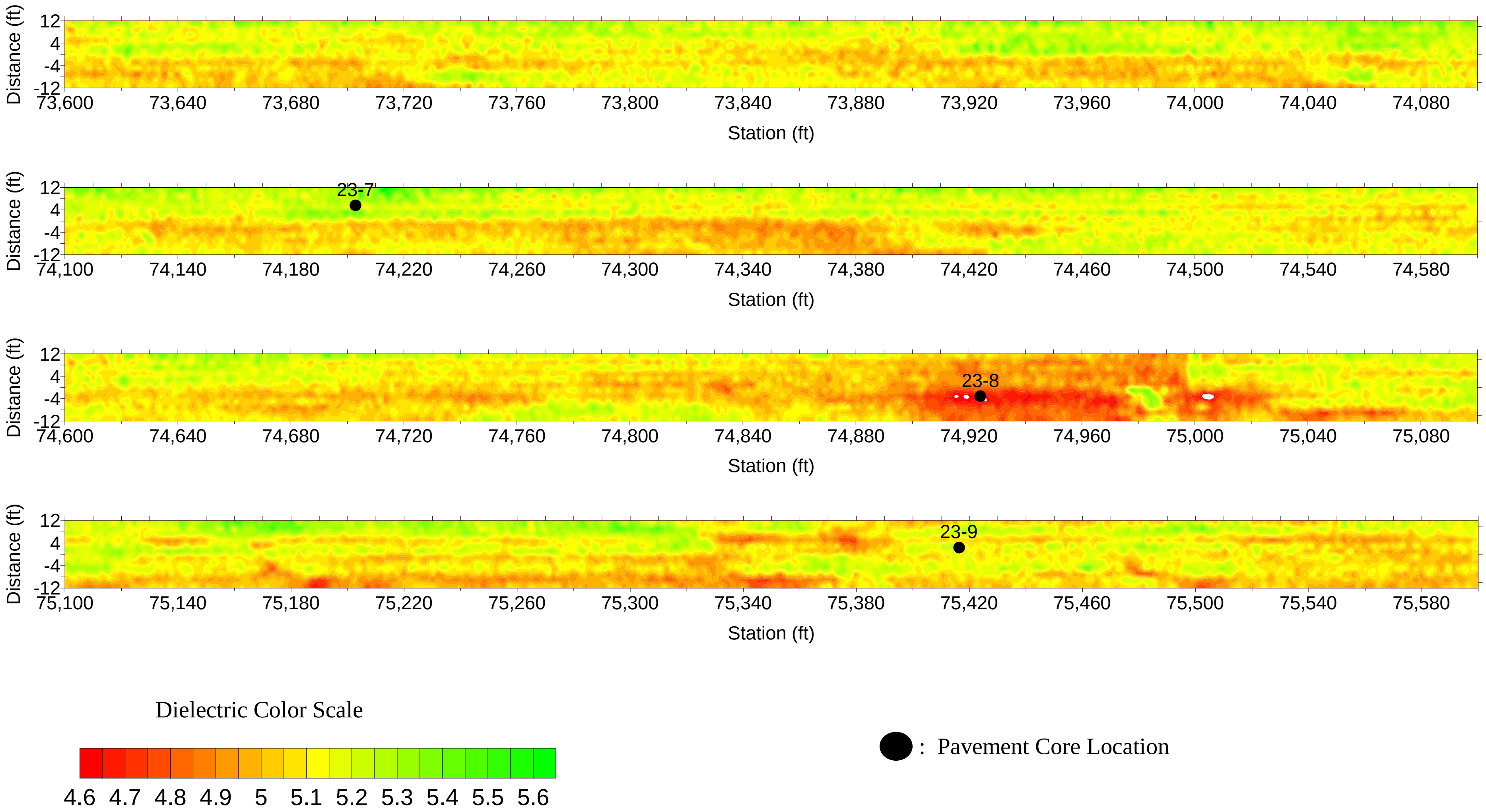


Figure 55. Dielectric Constant Contour Plot for GPR Survey 1 (Station 736+00 to 756+00) on SR 23.

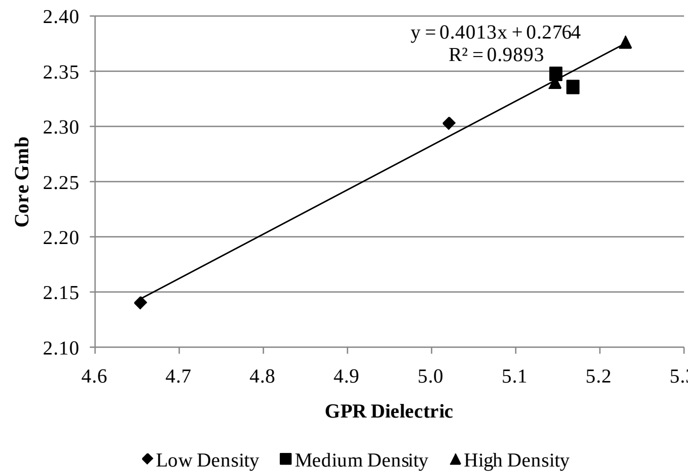


Figure 56. Correlation Plots with the 4,000-ft Survey Section Results on SR 23.

Using the provided theoretical maximum specific gravity (G_{mm}) of 2.459 (obtained from the construction records during paving), the dielectric values were calibrated to determine compaction levels throughout the survey section. The compaction effort was found to range from as low as 88 percent to a high of 99 percent. A distribution plot of the compaction effort is provided in Figure 57.

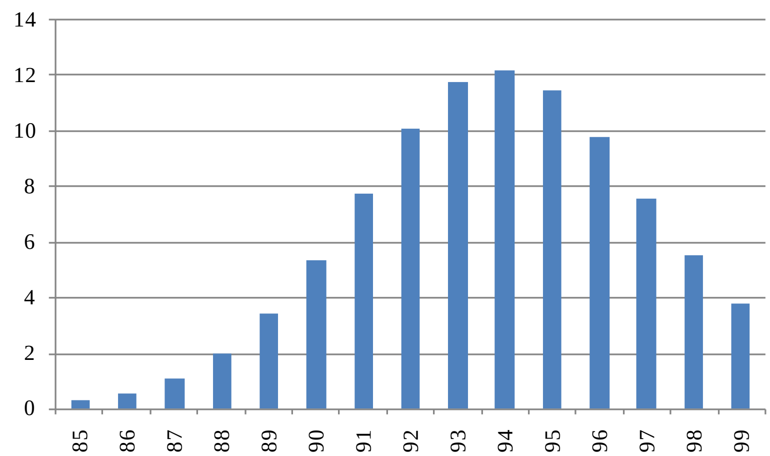


Figure 57. Distribution of Comparison Effort for Section 1 on SR 23.

GPR Survey #2 - Uni-Directional Segment Survey (Station 723+00 to 733+00)

Following the same protocol as in the GPR Survey 1, a 1,000-ft segment was selected from within the 4,000-ft survey section. Using the dielectric constant values determined from the uni-directional GPR survey, contour plots were developed. From these contour plots, three pavement core locations were selected one in each of a low, medium, and high dielectric constant value areas. Furthermore, the contour plots from this uni-directional segment survey were compared with the extracted contour plots for the same area from the 4,000-ft survey section. Both plots are provided in Figure 58.

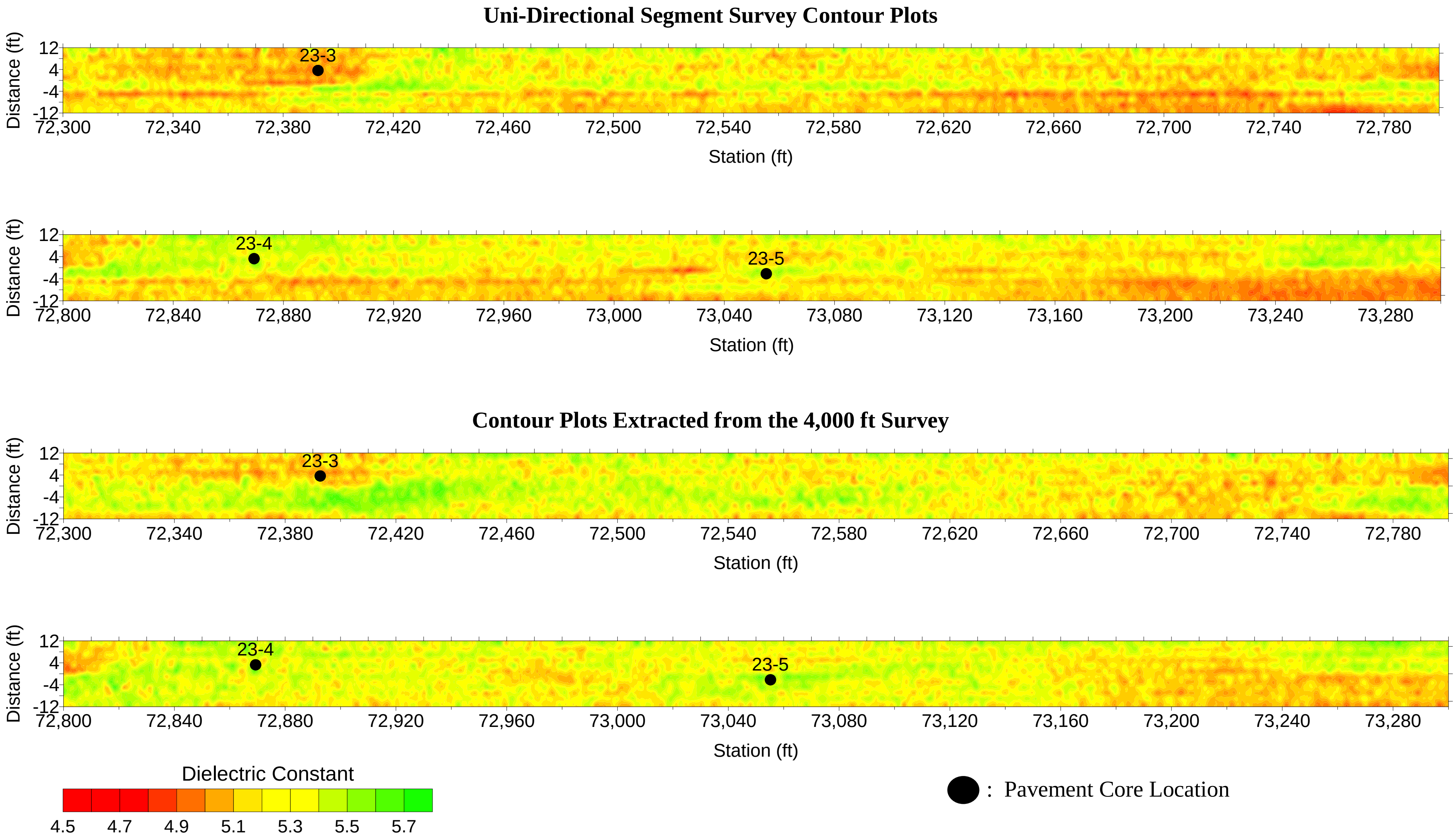


Figure 58. Comparison of Uni-Directional Dielectric Constant Contour Plot with 4,000-ft Section Survey on SR 23.

Laboratory test results from the extracted cores in this area, along with the dielectric constant values at the selected locations, are provided in Table 14. Correlation plots for the uni-directional segment survey are plotted in Figure 59. The correlation of the pavement cores with this segment survey show a fairly good correlation, with an R^2=0.74. The compaction effort of the extracted pavement core samples varied from as low as 91.7 percent to a high of 95.9 percent while the calibrated GPR results show that the level of compaction for the entire survey area was found to vary from 90 to 99 percent. A histogram of the calculated compaction effort has been provided in Figure 60.

Table 14. GPR Survey and Core Test Results for the Uni-directional Segment on SR 23.

Core Number	Station (ft)	Offset (ft)	Expected Density Level	Dielectric Constant	Core G_{mb}	Plant G_{mm}	% G_{mm}
23-3	723+93	3.6	Low	4.869	2.255	2.459	91.7
23-4	728+69	3.3	High	5.277	2.324	2.459	94.5
23-5	730+55	-2.2	Medium	5.192	2.359	2.459	95.9

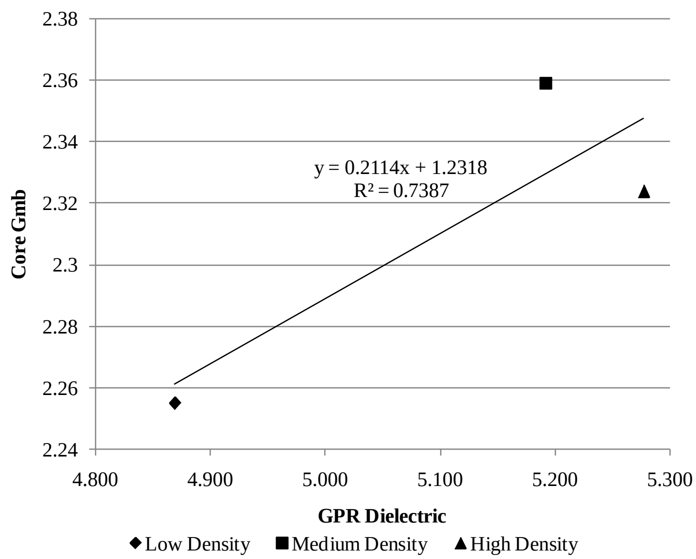


Figure 59. Dielectric Constant vs. G_{mb} Plot for Uni-directional Survey on SR 23.

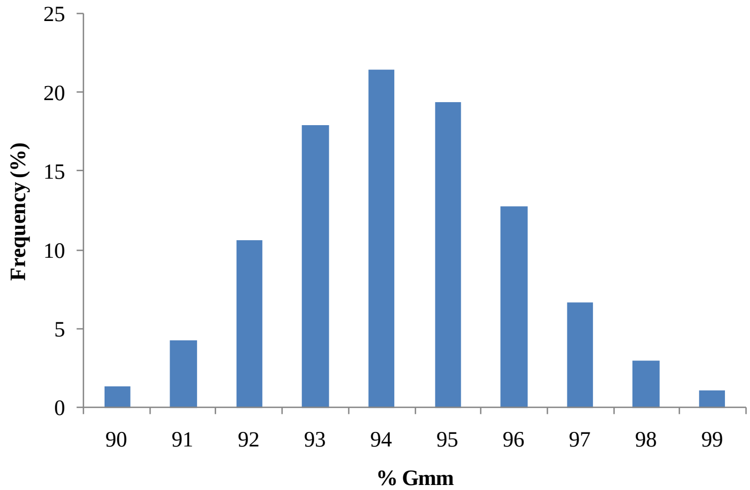


Figure 60. Distribution of Compaction Effort for the Uni-Directional Survey on SR 23.

GPR Survey #3 - Multi-Directional Segment Survey (Station 723+00 to 733+00)

Upon completing the uni-directional GPR segment survey (from Station 723+00 to 733+00), the same area was re-surveyed with a multi-directional survey pattern. The contour plots of dielectric constant values were developed and compared with the uni-directional survey results. These plots are provided in Figure 61.

The results of the multi-directional survey were calibrated with the G_{mb} results of the extracted pavement cores to determine the compaction effort for the entire survey surface. The distribution of the GPR estimated compaction level was found to vary from 86 to 99 percent (Figure 62), which shows more variability than the results of the uni-directional GPR survey.

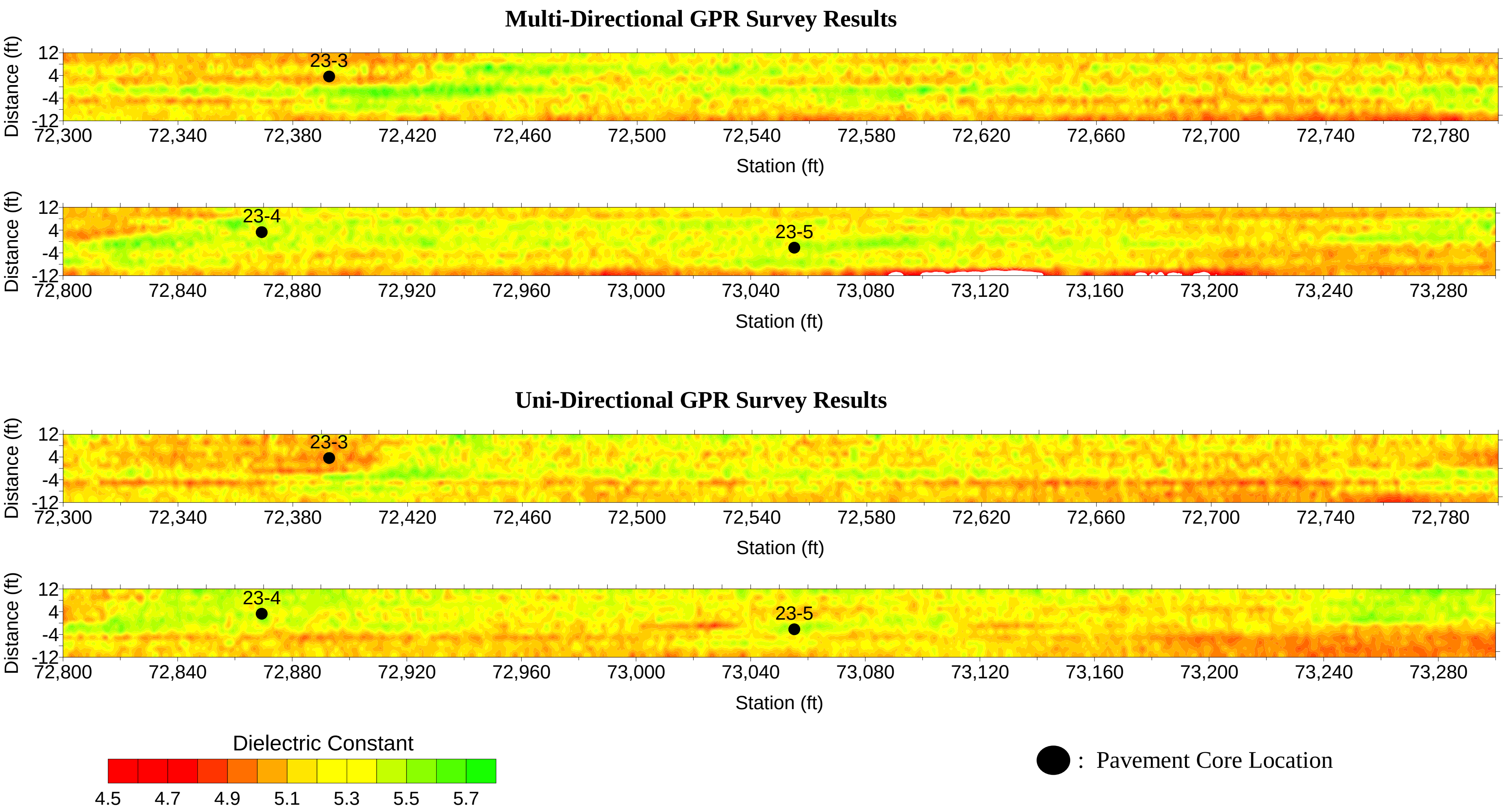


Figure 61. Dielectric Constant Contour Plot for both Directional GPR Segment Surveys (Station 723+00 to 733+00) on SR 23.

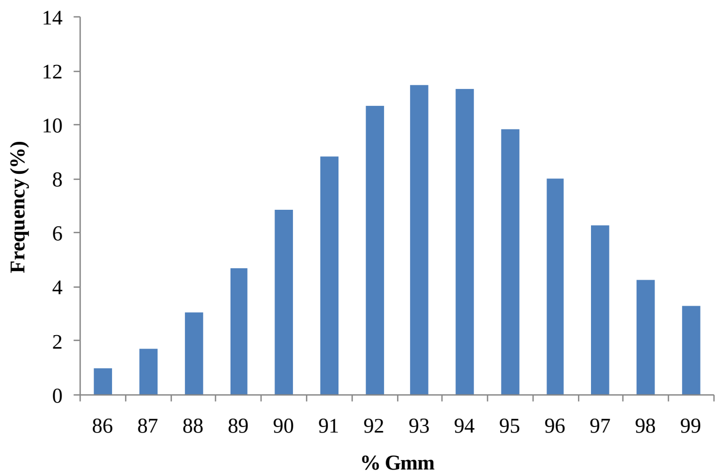


Figure 62. Distribution of Compaction Effort for the Multi-Directional Survey on SR 23.

Non-Nuclear Density Gauge

Prior to the extraction of the pavement cores, a non-nuclear density gauge was used to measure density levels at each of the pavement core locations. Three readings were taken at each location, with the measurements averaged to determine the surface density level. Five of the nine cores were used to calibrate the results of the non-nuclear density gauge. A final calibration factor of 2.8 was calculated and used in the analysis. The results of the non-nuclear density gauge are provided in Table 15.

Table 15. Measurements of the Non-Nuclear Density Gauge on SR 23.

Core ID	Station	Offset	Density Gauge Reading (Unit Wgt, pcf)				Corrected Unit Weight	Estimated Gmb (Gauge)	Core Gmb (Lab)
			#1	#2	#3	Average			
23-1*	717+06	-8.1	143.2	143.2	142.5	143.0	145.8	2.336	2.315
23-2	720+31	-9.6	143.7	144.0	144.2	144.0	146.8	2.352	2.345
23-3*	723+93	3.6	142.2	142.3	142.2	142.2	145.0	2.324	2.331
23-4	728+69	3.3	143.1	143.0	143.1	143.1	145.9	2.338	2.362
23-5*	730+55	-2.2	143.9	143.7	143.5	143.7	146.5	2.348	2.371
23-6	733+62	-7.4	143.6	144.0	143.6	143.7	146.5	2.348	2.346
23-7*	742+03	5.6	144.5	144.6	144.3	144.5	147.3	2.360	2.332
23-8*	749+24	-3.1	139.4	139.3	139.5	139.4	142.2	2.279	2.298
23-9	754+16	2.4	143.7	143.6	143.7	143.7	146.5	2.347	2.347

Note: * - Core samples used to calibrate non-nuclear density gauge results.

Pavement Core Comparisons

As three of the pavement core samples were extracted from within the segment survey area, dielectric constant values were obtained from each of the surveys completed within the area. The dielectric constant values at pavement core locations are summarized in Table 16.

Table 16. Summary of Dielectric Constant Values at Pavement Core Locations on SR 23.

Core #	Station (ft)	Offset (ft)	Expected Density Level	Core G_{mb}	Initial GPR Survey	Uni-directional GPR Survey	Multi-Directional GPR Survey
23-3	723+93	3.6	Low	2.255	5.051	4.869	5.000
23-4	728+69	3.3	High	2.324	5.227	5.277	5.209
23-5	730+55	-2.2	Medium	2.359	5.263	5.192	5.203
Correlation Factors					**0.97**	**0.74**	**0.88**

Correlation factors from each of the surveys varied from 0.74 to 0.97. It was interesting to note that the lowest correlation factor came from the survey results that were used to select the pavement core locations. The variability in correlation factors likely can be attributed to the differences in positioning of the GPR survey (vehicle wander and survey start position).

Directional Survey Results

The comparison of the contour images shows a similar trend between high and low density areas. Furthermore, in these plots there are no noticeable differences between the survey information collected in the same direction (0 to -11 ft offsets) and the data collected in the opposite direction (0 to 11 ft offset).

A subsequent analysis was completed on the dielectric values collected for the two directionally different GPR surveys. The collected data for the two surveys were plotted against each other for all 12 offsets. The information collected at offsets 1, -3, -5, -7, -9, and -11 ft were collected in the same direction, while the remaining offsets (-1, 3, 5, 7, 9, and 11 ft) were collected in opposite direction. All comparison plots are provided below. To remove some of the noise within the raw data set, a moving average was calculated using the average dielectric constant value of 51 points (a longitudinal distance of about 13 ft).

A Pearson correlation of the directional runs was calculated on the moving average data sets and is provided in Table 17.

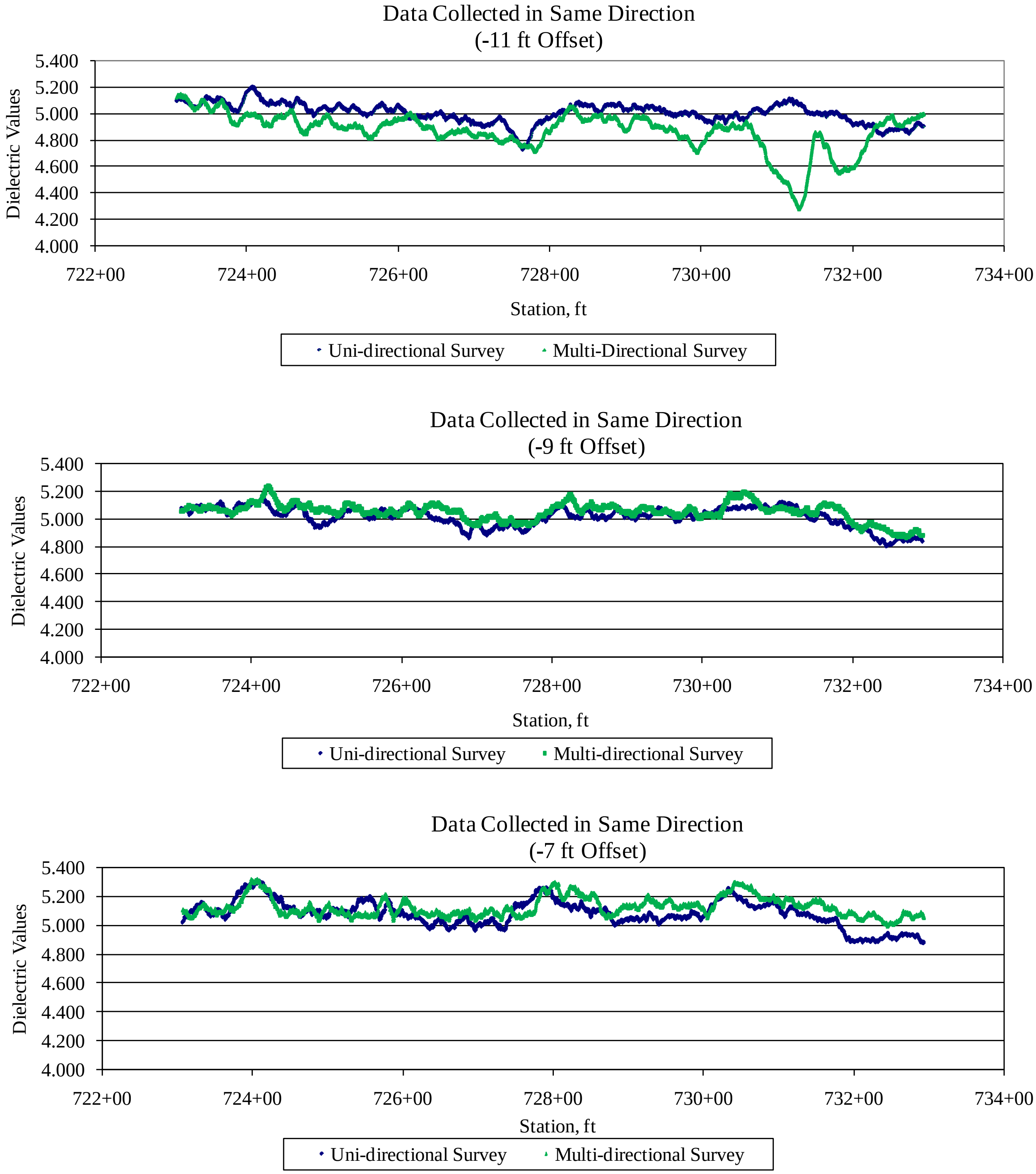


Figure 63. Comparison Plots of GPR Surveys Collected in the Same Direction on SR 23. (Offsets -11, -9, and -7)

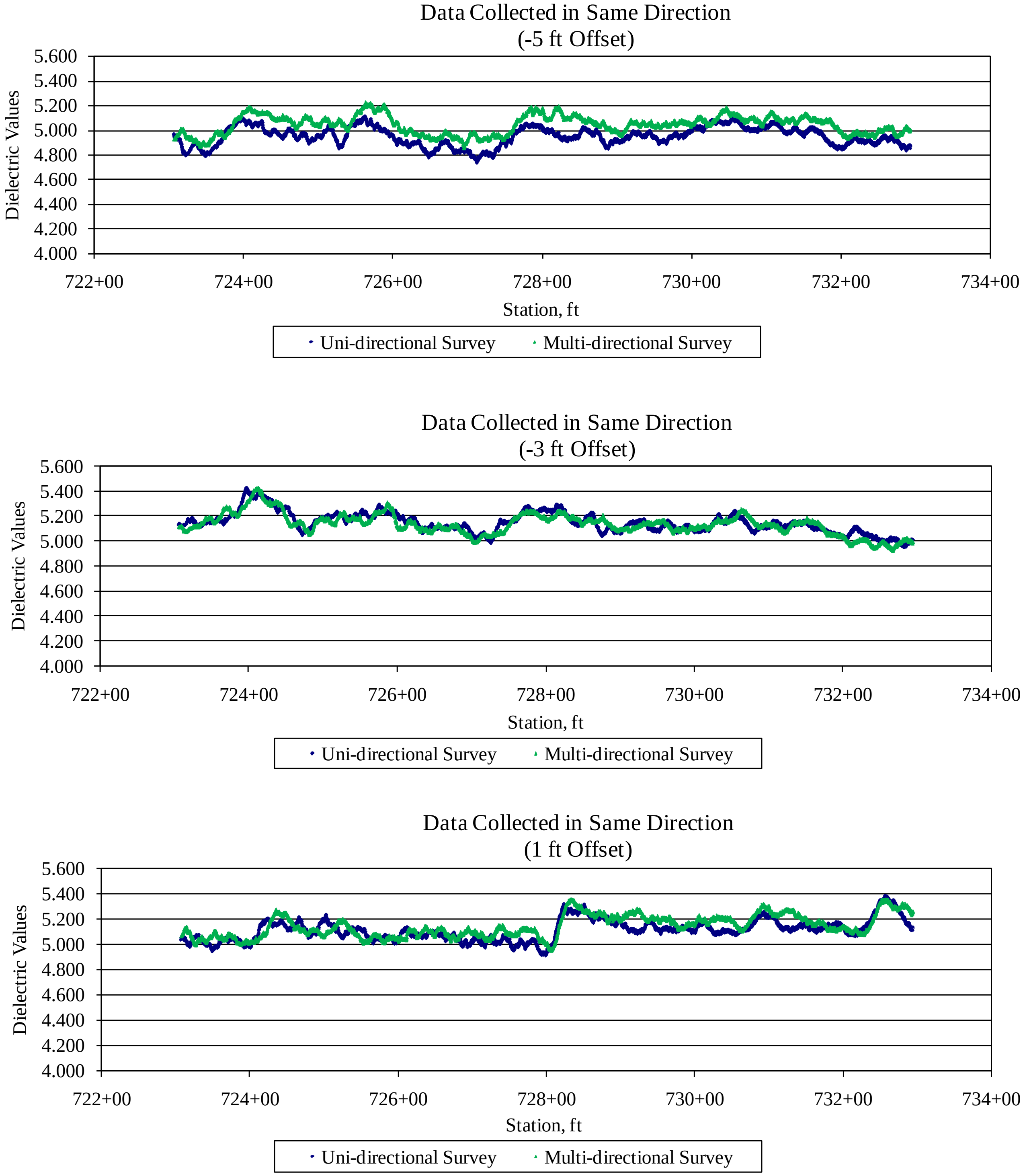


Figure 64. Comparison Plots of GPR Surveys Collected in the Same Direction on SR 23. (Offsets -5, -3, and 1)

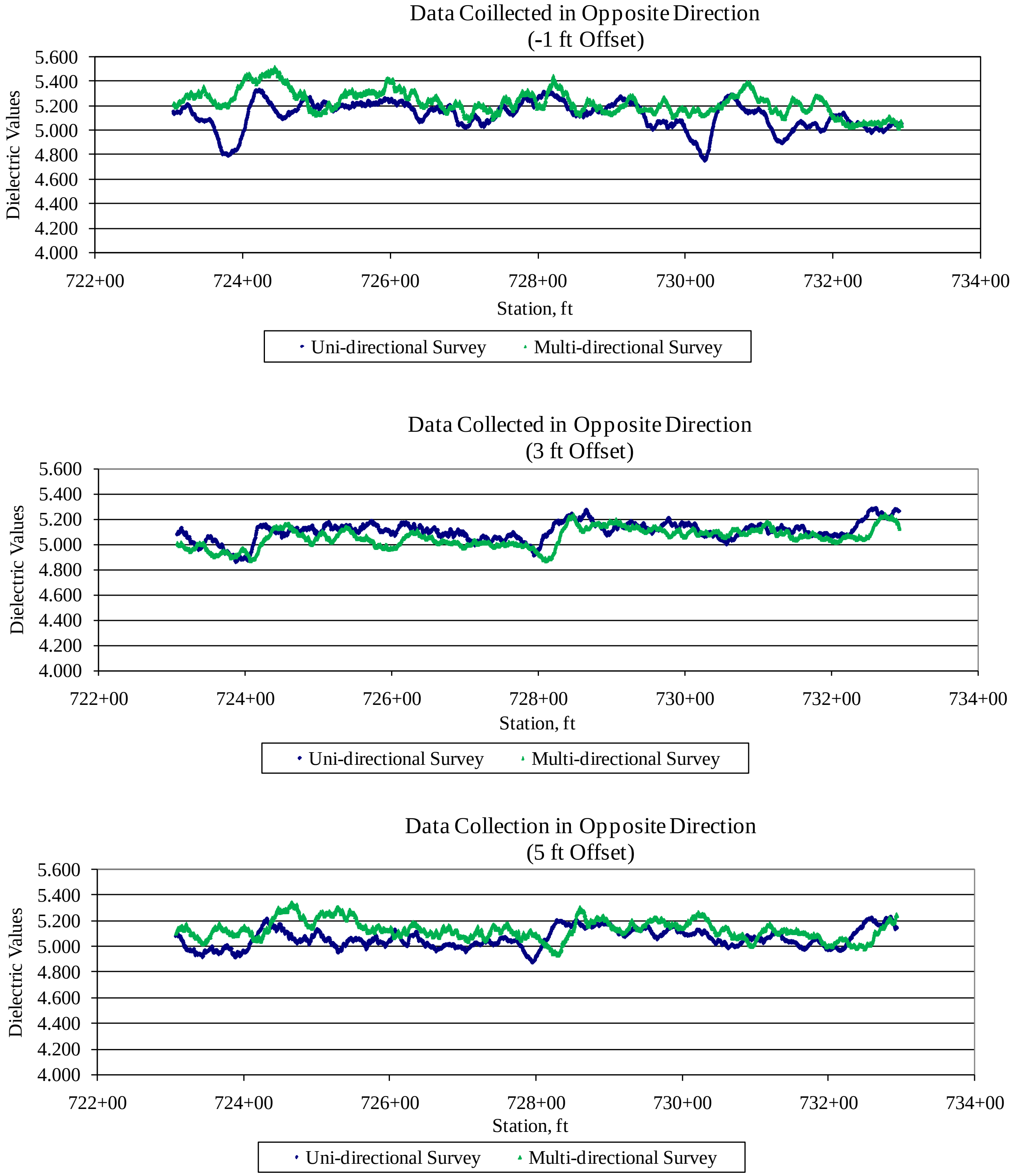
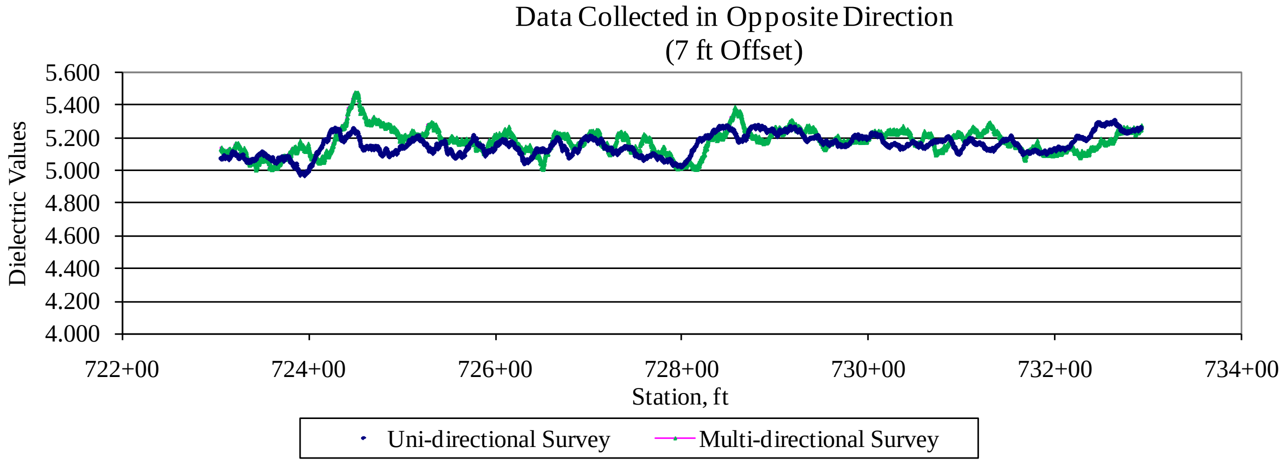
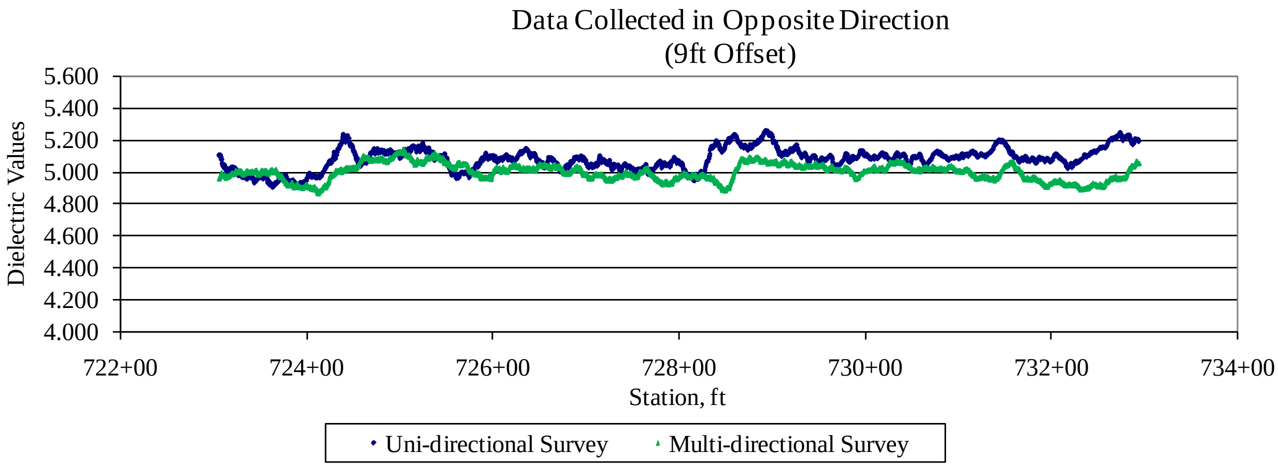


Figure 65. Comparison Plots of GPR Surveys Collected in the Opposite Direction on SR 23. (Offsets -1, 3, and 5)





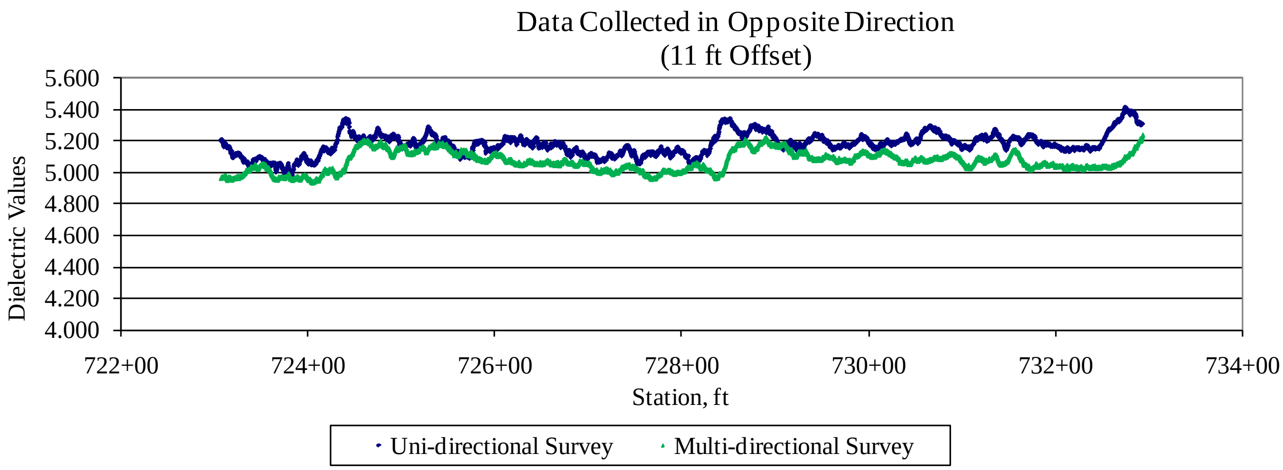


Figure 66. Comparison Plots of GPR Surveys Collected in the Opposite Direction on SR 23. (Offsets 7, 9, and 11)

Table 17. Statistical Comparison of Directional Survey Data.

GPR Surveys Comparison in the Same Direction

	-11 ft Offset		-9 ft Offset		-7 ft Offset		-5 ft Offset		-3 ft Offset		1 ft Offset	
	Uni-directional Survey	Multi-directional Survey	Uni-directional Survey	Multi-directional Survey	Uni-directional Survey	Multi-directional Survey	Uni-directional Survey	Multi-directional Survey	Uni-directional Survey	Multi-directional Survey	Uni-directional Survey	Multi-directional Survey
Mean	5.005	4.873	5.016	5.053	5.078	5.133	4.941	5.042	5.138	5.137	5.105	5.143
Variance	0.006	0.021	0.005	0.004	0.008	0.005	0.006	0.006	0.007	0.007	0.007	0.007
Observations	3949	3949	3949	3949	3949	3949	3949	3949	3949	3949	3949	3949
Pearson Correlation (R)	0.200		0.785		0.657		0.805		0.863		0.764	
Coefficient of Determination (R^2)	0.040		0.616		0.432		0.647		0.745		0.584	

GPR Surveys Comparison in the Opposite Direction

	1 ft Offset		3 ft Offset		5 ft Offset		7 ft Offset		9 ft Offset		11 ft Offset	
	Uni-directional Survey	Multi-directional Survey	Uni-directional Survey	Multi-directional Survey	Uni-directional Survey	Multi-directional Survey	Uni-directional Survey	Multi-directional Survey	Uni-directional Survey	Multi-directional Survey	Uni-directional Survey	Multi-directional Survey
Mean	5.124	5.231	5.101	5.059	5.063	5.135	5.150	5.179	5.079	5.002	5.177	5.068
Variance	0.013	0.010	0.006	0.006	0.005	0.006	0.004	0.006	0.005	0.003	0.005	0.004
Observations	3949	3949	3949	3949	3949	3949	3949	3949	3949	3949	3949	3949
Pearson Correlation (R)	0.436		0.669		0.215		0.491		0.295		0.548	
Coefficient of Determination (R^2)	0.190		0.447		0.046		0.241		0.087		0.300	

In general, the plotted shows little difference between the GPR survey results in the same direction and the survey results collected in the opposite direction. In the multi-directional comparison, it appears that a minor longitudinal shift in the data would result in a better match. Some variances were observed at offset locations -11, -1, and 11, but the differences at these offsets were likely the results of vehicle wandering toward the edge of pavement or centerline joints which would have an expected higher variability in compaction than in the center of the mat.

From the statistical analysis shown in Table 17, there appears to be less variance between the GPR surveys completed in the same direction as compared to the opposite directions. For the same direction data, the Pearson correlation coefficients were higher, varying between 0.657 and 0.863, except for the -11 ft offset. For the survey comparisons in the opposite direction, the Pearson correlation coefficients are much lower. However, a visual observation of the comparison plots, found some of the plots appear to have a longitudinal shift in position, which could explain the low calculated correlation values.

Non-Nuclear Density Gauge Comparison

The estimated densities using the non-nuclear density gauge were plotted against the results of the laboratory testing on the extracted core samples (Figure 67). Correlations between the gauge measurements and the laboratory test results were found to be poor, with a correlation factor of 0.46.

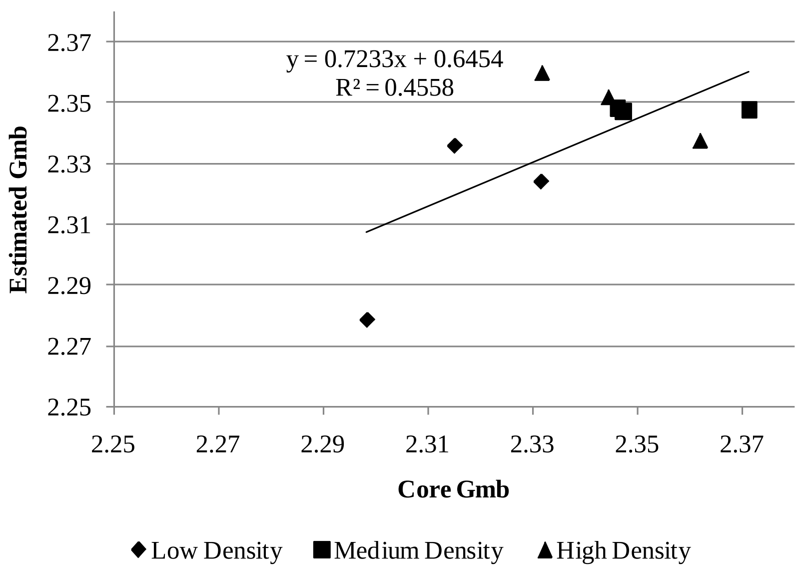


Figure 67. Non-Nuclear Density Gauge Measurements vs. Laboratory Test Results on SR 23.

The use of the non-nuclear density gauge was found to provide more variable results, compared to the extracted pavement cores.

State Road 222

The GPR data were collected by SMO staff in accordance with the prepared survey protocol. For each of the survey scenarios, contour plots were generated for a visual illustration of the data. Using the contour plots of the initial survey area (entire 4,800 ft), a total of 12 pavement coring locations were selected. The information from the survey of this section also was used as the control data for the remaining survey scenarios.

GPR Survey #1 - Complete Survey (Station 505+00 to 553+00)

As the GPR survey was completed travelling in the westbound direction, the data were collected with decreasing stationing. Contour plots, provided below, were generated using the collected information upon completion of the survey.

In the first 2,000 ft of the survey, dielectric constant values appear to be generally lower, with more extensive low value areas, than in the remaining survey section where the lower dielectric values were predominately along the outer curb line. Some unusual anomaly features (likely utility access covers) were noted at Station 550+97 and 530+09.

Four cores were taken in each of the low, medium, and high dielectric constant areas. The results of the dielectric constants, and laboratory testing, at each core location are summarized in Table 18.

Table 18. Comparison of GPR Survey and Pavement Core Lab Results for the 4,800-ft Section on SR 222.

Core #	Station (ft)	Offset (ft)	Expected Density Level	GPR Dielectric	Core G_{mb}	Sub-lot G_{mm}	% G_{mm}
2-1	551+79	9.24	High	5.103	2.346	2.526	92.9
2-2	551+02	5.26	Low	4.551	2.106	2.526	83.4*
2-3	549+48	5.26	Medium	4.862	2.312	2.526	91.5
2-4	538+75	7.08	Low	4.542	2.280	2.526	90.3
2-5	536+22	8.88	High	5.066	2.340	2.526	92.6
2-6	535+47	7.44	Medium	4.951	2.356	2.526	93.3
3-1	531+99	9.18	High	5.067	2.365	2.536	93.2
3-2	518+31	6.66	Low	4.458	2.244	2.536	88.5
3-3	515+48	1.58	Medium	4.949	2.355	2.536	92.9
3-4	512+85	9.18	High	5.230	2.362	2.536	93.1
3-5	509+74	1.94	Medium	4.926	2.320	2.536	91.5
3-6	508+50	4.48	Low	4.646	2.253	2.536	88.8

Note: * - Unusually low density results (Outlier).

The results of the laboratory testing on the pavement cores recorded G_{mb} measurements that typically varied from 2.244 to 2.365, except for pavement core 2-2 which had a G_{mb} of 2.106. The results of the core samples were generally found to match expected density groupings. Using the theoretical maximum specific gravity (G_{mm}) obtained from the construction records during paving, the percentage of compaction could be calculated. The range of compaction effort at the pavement core locations were found to range from 88.5 percent to 93.9 percent. This range did not include the percent of compaction at the core 2-2 location, which had an extremely low compaction effort of 83.4 percent.

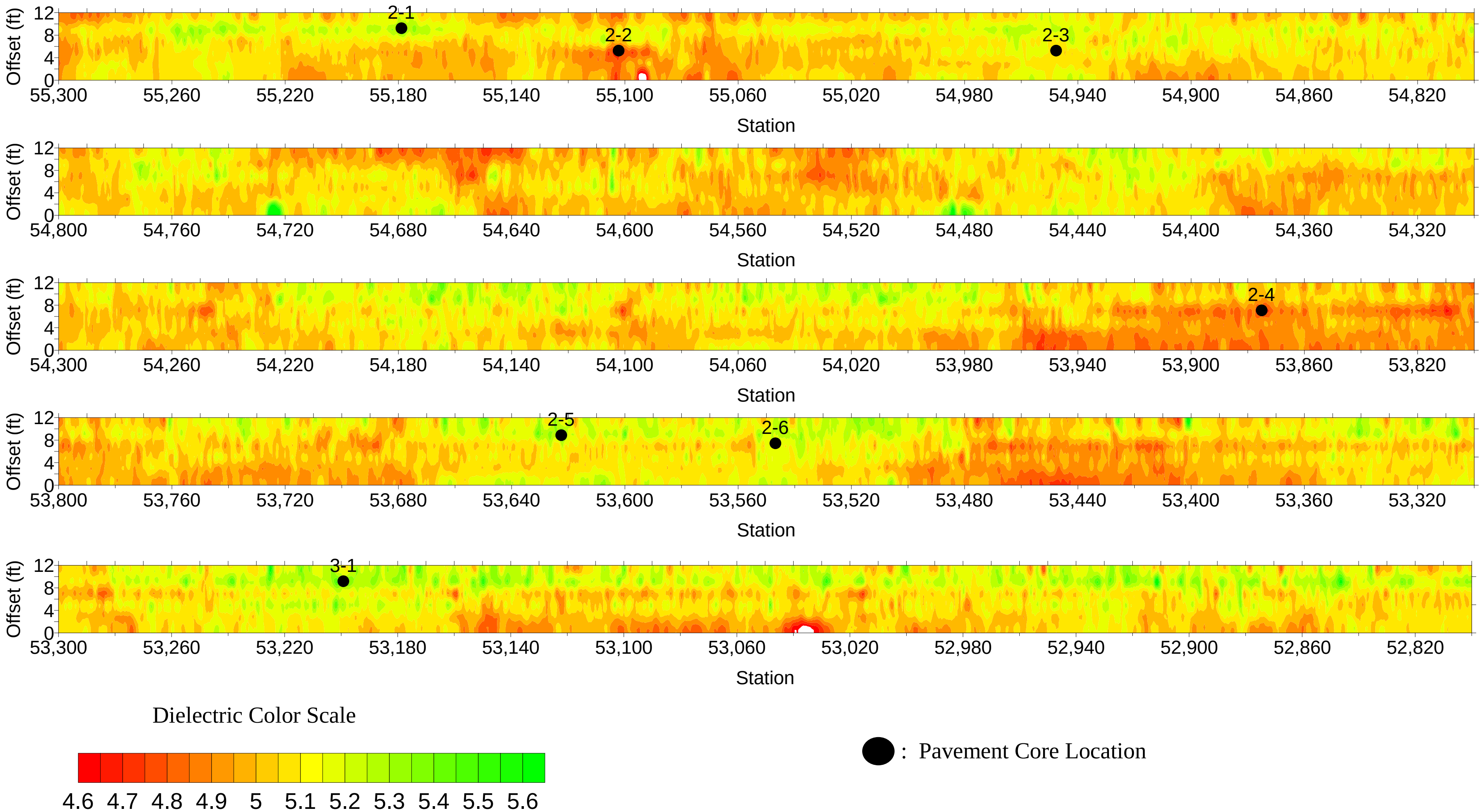


Figure 68. Dielectric Constant Contour Plot for GPR Survey 1 (Station 553+00 to 528+00) on SR 222.

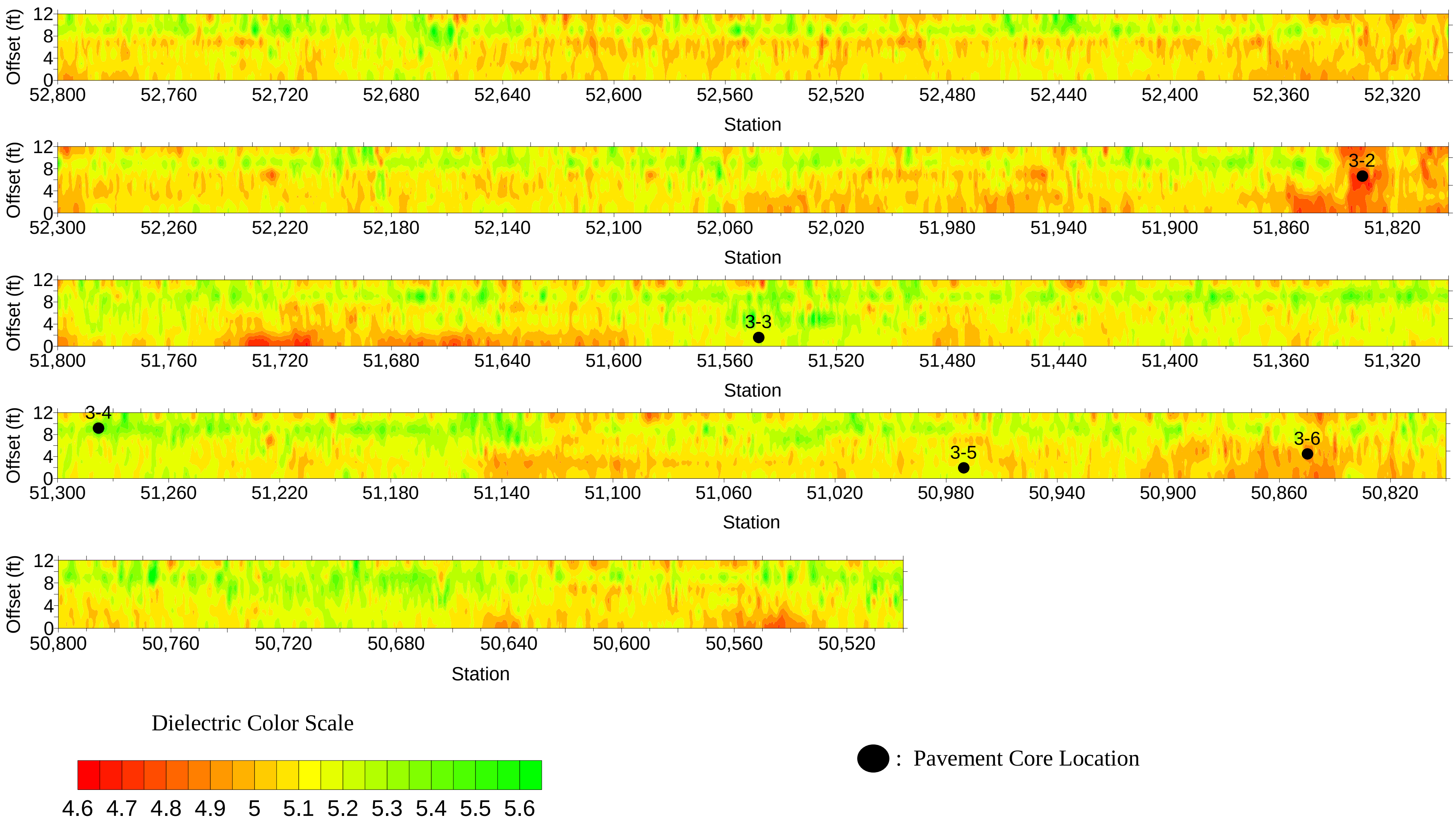


Figure 69. Dielectric Constant Contour Plot for GPR Survey 1 (Station 528+00 to 505+00) on SR 222.

A closer examination of the extracted pavement core at this location did not appear to explain the low density results. Furthermore, the offset of the pavement core location was located at 5.26 ft, which is relatively near the 5-ft offset of the GPR survey. The close proximity of the core location to the survey offset would minimize any significant error in interpolating dielectric values at the core location. As a result of this rare occurrence, the test result of pavement core 2-2 was omitted from further analysis.

GPR Survey #2 – 2.5 ft Antenna Spacing Segment Survey

After the initial survey for the entire site was completed, a random 500-ft segment was selected for additional trial surveys with modified survey protocol. The modified protocol for this first segment survey was completed with a spacing distance between the two antennas of 2.5 ft, and with only three passes. The collected information was analyzed, and contour plots were developed. A comparison of these survey results, along with the results of the initial survey, is provided in Figure 70.

A visual comparison of the two contour plots found that both plots showed the general areas of high and low dielectric constant values, with some areas varying in intensity. In the extracted data from the initial survey, the contour plot shows more intense low density concentration from Station 532+80 to 535+00, while the segment survey identified areas (Station 531+70 to 532+50 and 535+00 to 536+00) with slightly higher dielectric values.

GPR Survey #3 – 2 ft Antenna Spacing Segment Survey

The selected segment was again re-surveyed with an antenna spacing further reduced to 2 ft. The results of this segment survey are provided in Figure 70. Similar to the previous segment survey, a visual comparison of this segment plot, with the initial survey results, found that the general areas of low, medium, and high dielectric constant values were similar between both contour plots. Although some variability was noticed, the differences were relatively minor, and likely the results of the interpolation between the survey locations.

GPR Survey #4 – Vehicle Wander #1

An investigation was completed to determine the effects of vehicle wander on the GPR survey results. The GPR antennas were returned to the 4-ft spacing, and the segment section was again surveyed, however this time, a 1-ft wander (per 100 ft of segment) was introduced. A comparison of these survey results with the results of the initial survey is provided in Figure 71.

The most noticeable differences between the two contour plots are at the pavement edges. At the zero offset, the segment survey identified an area of lower density between Station 535+10 and 534+60, which was not as intense on the initial survey. Similarly, at the 12 ft offset, three separate areas of low density were also observed (Station 531+50 to 532+20, 533+30 to 534+30, and 535+50 to 536+50), which were not observed in the control plot. Furthermore, four anomalies were observed in the segment contour plot between Stations 533+50 and 534+30. These anomalies are likely the result of traffic cones too close to the survey line in this area.

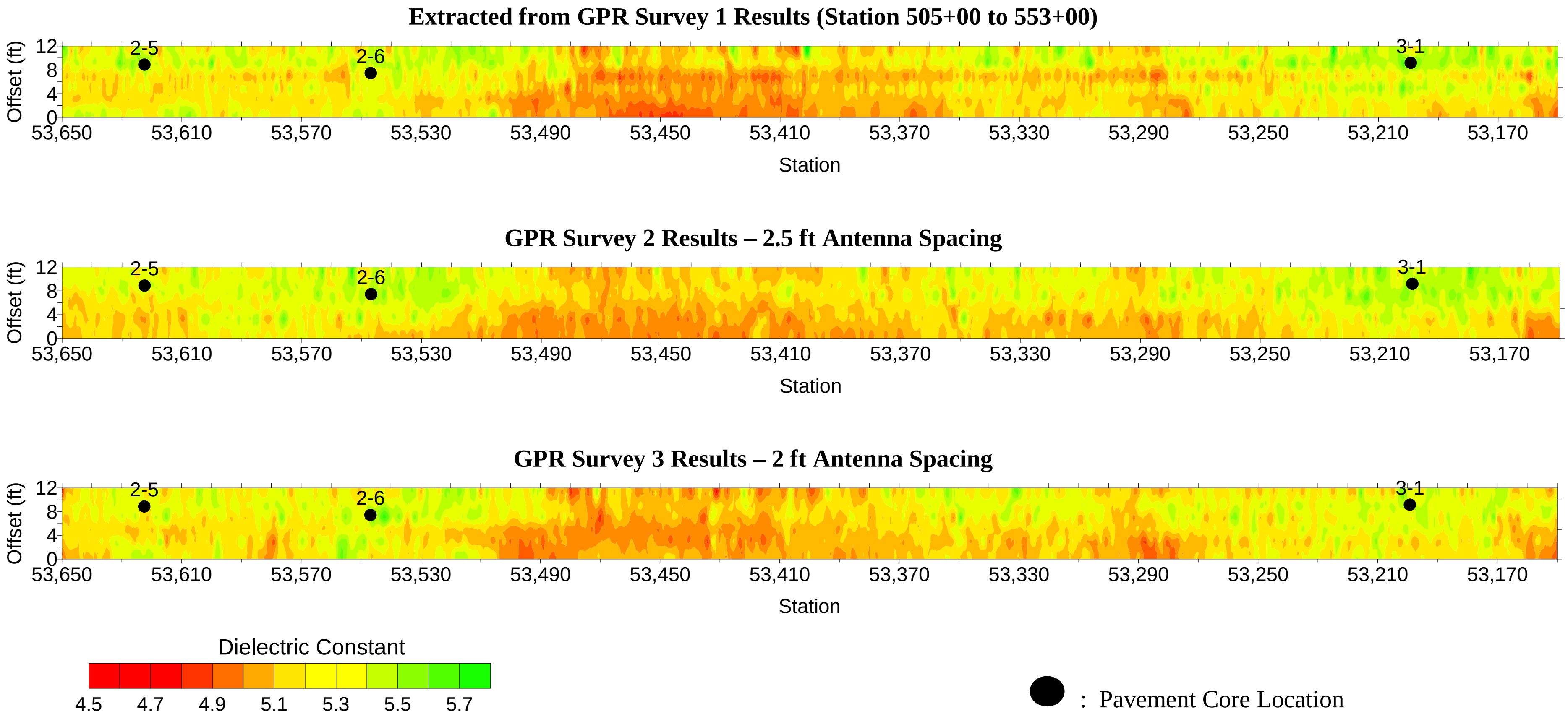


Figure 70. Comparison of Contour Plot for Multiple Antenna Spacing on SR 222.

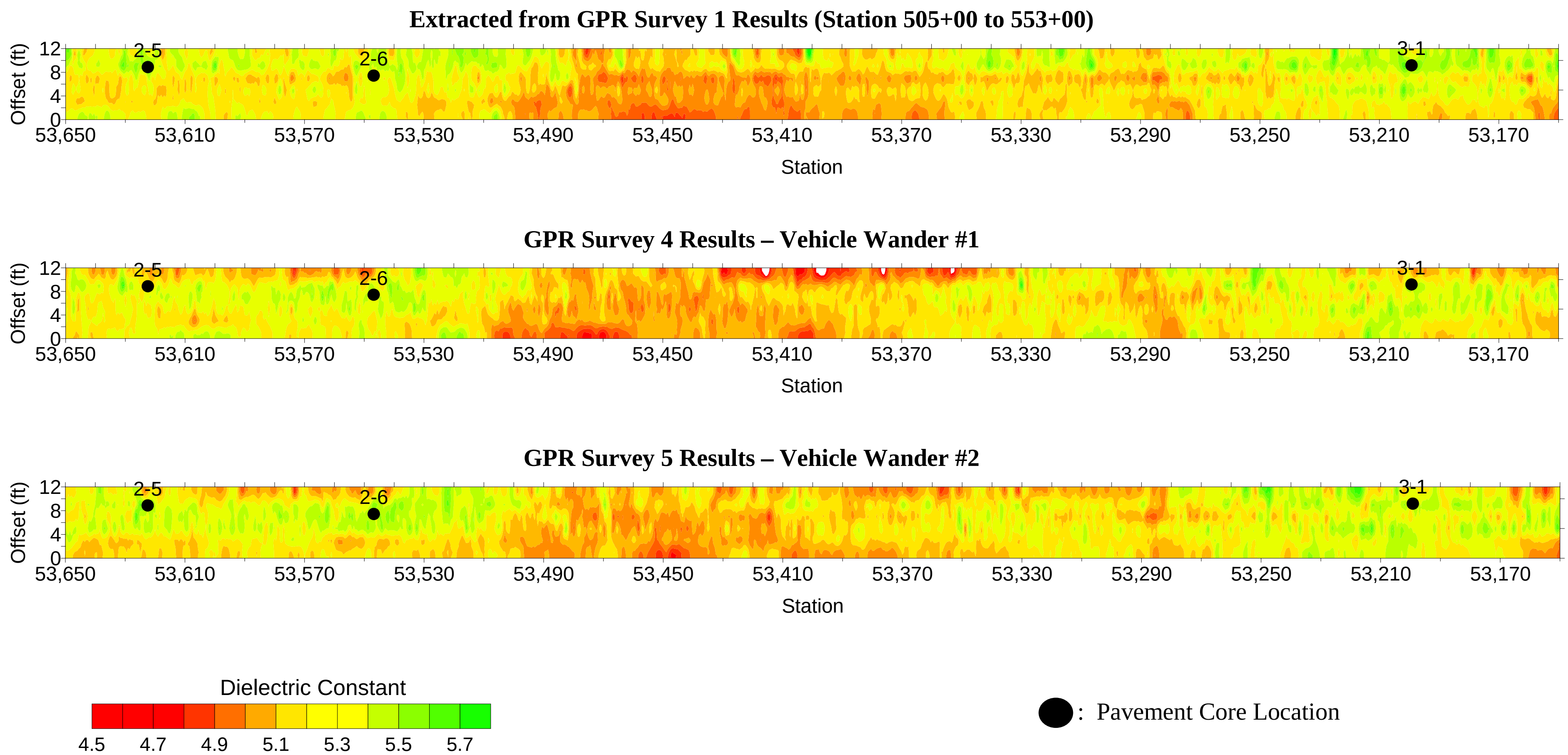


Figure 71. Comparison of Contour Plot for Wandering Surveys on SR 222.

GPR Survey #5 – Vehicle Wander #2

To further investigate the effects of vehicle wander on the survey results, the vehicle wander pattern during data collection was taken to the extreme of 2 ft (per 100 ft of segment). Contour plots illustrating the results of this secondary wander survey were also included in the comparison plots in Figure 71.

Similar to the results of the first wander survey, the most noticeable differences in the dielectric constants are at the pavement edges. Areas that were found to have low dielectric constant measurements were not as extensive and intensely low in density, while other areas of medium or high densities, measurements were also found to be less extensive and of less intensity.

Non-Nuclear Density Gauge

Prior to the extraction of the pavement cores, a non-nuclear density gauge was used to measure density levels at each of the pavement core locations. Seven readings were taken at each location, with the measurements averaged to determine the surface density. Six of the 12 cores were used to calibrate the results of the non-nuclear density gauge. An average calibration factor of 0.4 was calculated and used in the analysis. The results of the non-nuclear density gauge are provided in Table 19.

Table 19. Measurements of the Non-Nuclear Density Gauge on SR 222.

Core #	Station	Offset	Expected Density Level	Density Gauge Measurements, Unit Weight (pcf)								Cal. Factor	Corrected Unit Weight	Gauge Corrected G_{mb}	Core G_{mb}
				No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	Average				
2-1	551+79	9.2	H	143.8	143.8	143.7	144.6	144.7	143.9	141.2	143.7	2.7	145.8	2.337	2.346
2-2	551+02	5.3	L	139.3	138.9	139.1	139.4	139.4	141.6	139.5	139.6		141.8	2.272	2.106*
2-3	549+48	5.3	M	143.2	143.7	143.6	145.1	144.7	143.1	143.4	143.8	0.4	146.0	2.340	2.312
2-4	538+75	7.1	L	142.5	142.6	142.8	142.5	141.8	142.7	142.3	142.5		144.6	2.318	2.280
2-5	536+22	8.9	H	143.3	143.2	142.9	143.7	143.4	142.6	142.5	143.1		145.2	2.328	2.340
2-6	535+47	7.4	M	144.1	144.0	144.1	143.3	143.1	143.8	143.6	143.7		145.9	2.338	2.356
3-1	531+99	9.2	H	143.7	143.5	143.7	144.3	143.8	142.9	143.0	143.6	4.0	145.7	2.335	2.365
3-2	518+31	6.7	L	141.0	140.6	140.5	140.7	140.4	140.1	140.2	140.5	-0.5	142.7	2.286	2.244
3-3	515+48	1.6	M	142.9	143.2	142.6	142.7	142.6	142.9	142.8	142.8	4.2	145.0	2.323	2.355
3-4	512+85	9.2	H	142.9	142.9	143.1	143.3	143.4	142.8	142.7	143.0		145.2	2.326	2.362
3-5	509+74	1.9	M	142.6	142.4	142.6	142.3	142.9	142.3	142.2	142.5		144.6	2.318	2.320
3-6	508+50	4.5	L	141.6	141.5	141.6	140.8	140.6	141.6	141.6	141.3		143.5	2.299	2.253

Note: * - Unusually low density results (outlier).

As in previous comparisons with the pavement cores, the laboratory results for pavement core 2-2 were found to be unusually low in field density. Although the results of this sample were verified to the SMO staff, it will be removed from further analysis.

Pavement Core Comparisons

The results of the bulk specific gravities (G_{mb}) completed on pavement core samples were plotted (Figure 72) against the dielectric constant values collected from the initial GPR survey to determine whether a relationship exists between the parameters. It should be reiterated that, on account of the unusually low density obtained from the laboratory testing on core sample 2-2, this value was excluded from the comparison analysis.

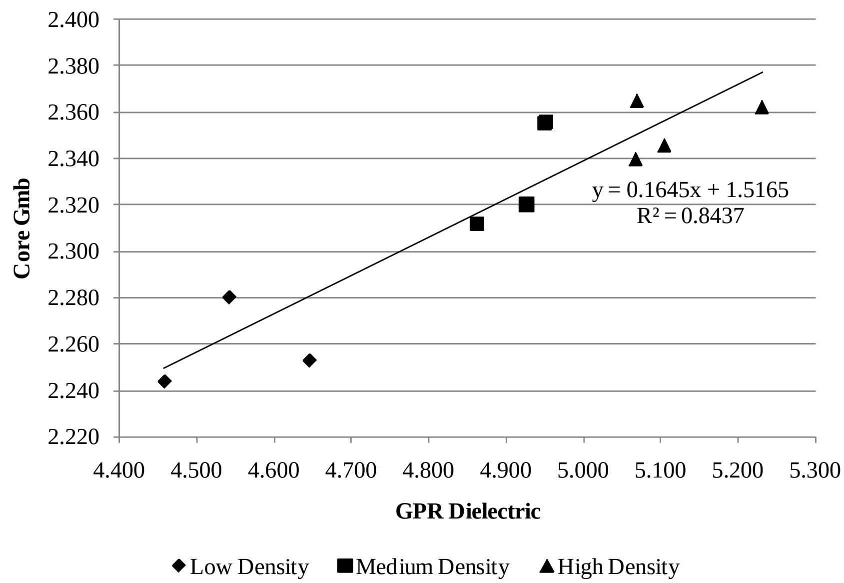


Figure 72. Comparison Plots of Core Densities and Dielectric Constant Values on SR 222.

The comparison of the dielectric constant values obtained after survey completion continues to maintain a good correlation to the determined G_{mb} of the pavement cores. For this comparison, the correlation factor was 0.84.

As three of the pavement core samples were extracted from within the segment area surveyed by each of the GPR surveys, dielectric constant values were obtained from each of the five surveys. The dielectric constant values at pavement core locations are summarized in Table 20.

Table 20. Summary of Dielectric Constant Values at Pavement Core Locations on SR 222.

Core #	Station (ft)	Offset (ft)	Expected Density Level	Core G_{mb}	Initial GPR Survey	GPR Survey #2	GPR Survey #3	GPR Survey #4	GPR Survey #5
2-5	536+22	8.9	High	2.340	5.066	4.907	4.903	4.895	5.001
2-6	535+47	7.4	Moderate	2.356	4.951	4.995	4.994	4.949	5.020
3-1	531+99	9.2	High	2.365	5.067	5.039	4.985	4.948	4.955
Correlation Factors					**0.02**	**0.99**	**0.81**	**0.87**	**0.32**

Correlation factors from the segment surveys varied from as low as 0.02 to as high as 0.99. Although it is not entirely clear why the correlation factor have such a large variance, it is speculated that better correlations are obtained the closer pavement core samples are to actual survey offsets. For instance, GPR Survey 2 was completed with survey offsets at 7.5 and 8.5 ft, with 2.5-ft antenna spacing. As all of the pavement core locations were located within 7 inches of a survey offset, interpolation to the pavement core location was minimized.

Meanwhile, for GPR Survey 5, the antenna spacing was set to 4 ft, with survey offsets set at 7 and 9 ft. Furthermore, a 2-ft wander (per 100 ft of segment) was introduced into the survey protocol. During this survey, it is likely that the interpolation of the dielectric constant values were required, increasing the margin of error. The variability in the correlation coefficients also is likely compounded by the limited amount of data (cores) and the fact that there is very little difference in the densities between the cores.

Survey Offset (Variable Antenna Spacing) Comparisons

With the varying offset intervals between the different GPR surveys, comparing the dielectric constant values becomes difficult. However, from the different contour plots a number of observations can be made:

- Increased spacing between the GPR survey lines requires more interpolation in generating the contour plots, which results in a more diluted image. These images are less accurate when selecting pavement core locations.
- Decreased spacing between the GPR runs produces contour plots with more high and low density variability. These areas are more accurate when selecting pavement core locations.
- Reduced antenna spacing may introduce cross-talk between the two GPR antennas. Therefore, completing four passes (with 4-ft antenna spacing) instead of three passes (with 2-ft antenna spacing) produces better results. The duplicate survey lines should be averaged when generating the contour plots.
- Antenna spacing should not be so close as to have the antennas interfering with each other.

Vehicle Wander Comparisons

The comparison of the contour images shows some differences between the three GPR surveys, most noticeably along the edge of the survey lane. In typical roadway construction, longitudinal tie-ins (pavement edges) are more difficult to compact, which results in lower joint densities than elsewhere on the asphalt mat. The contour plots of the first wander segment survey indicate that lower dielectric constant values are predominate along the pavement edges as compared to the interior asphalt mat surface. As this survey was completed using a 1-ft (per 100 ft) wander, the survey lines at the pavement edges would collect more pavement edge information than the other surveys.

A subsequent analysis was completed on the dielectric constant values collected for the three GPR surveys completed as part of this wander comparison. The collected data for each of the six offsets surveyed (1, 3, 5, 7, 9, and 11 ft offsets) were plotted and are provided below. To remove some of the noise of the raw data set, a moving average was calculated using the average dielectric constant value of 51 points (13 feet).

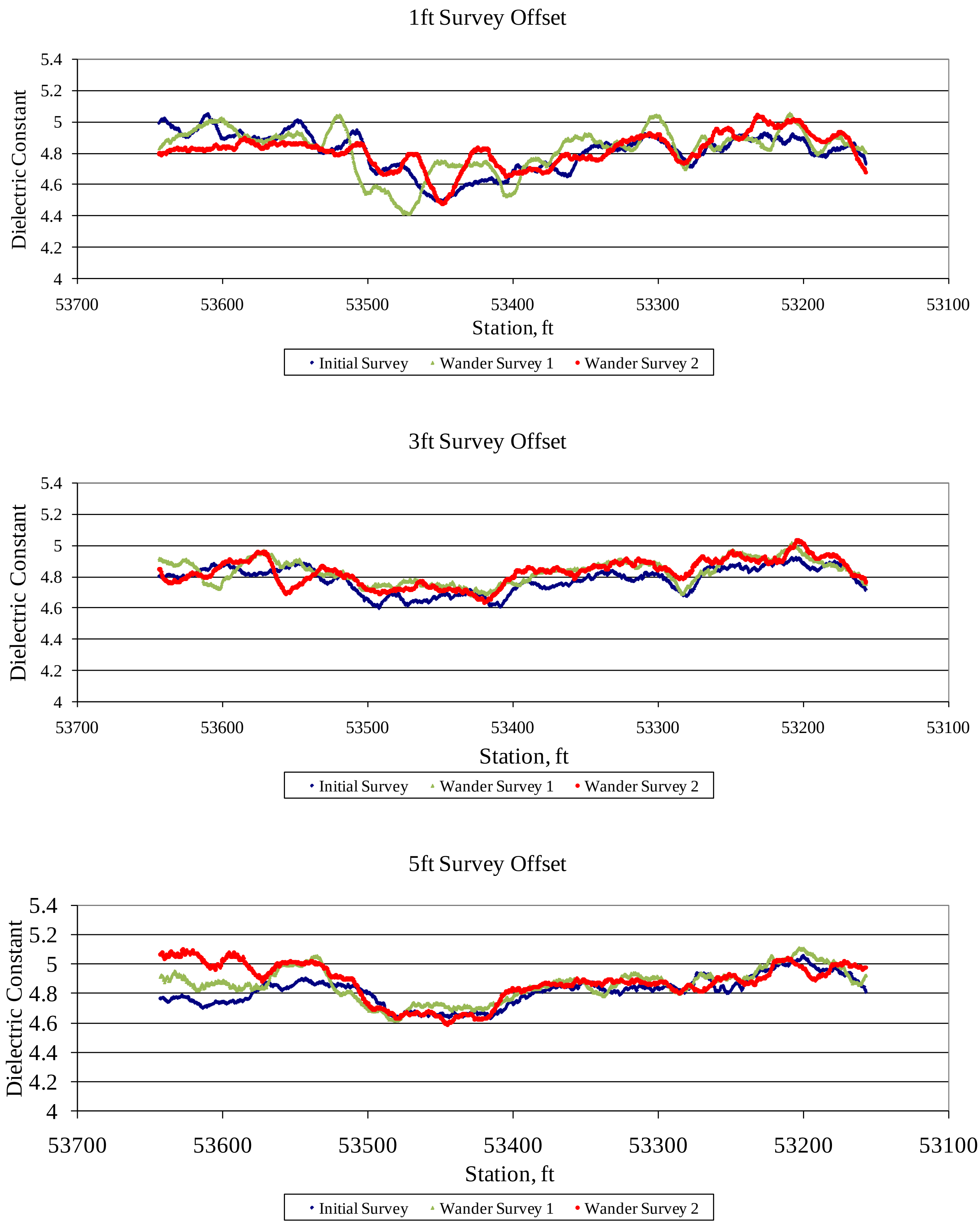


Figure 73. Comparison Plot of Collected Data at the 1, 3, and 5 ft Offsets on SR222.

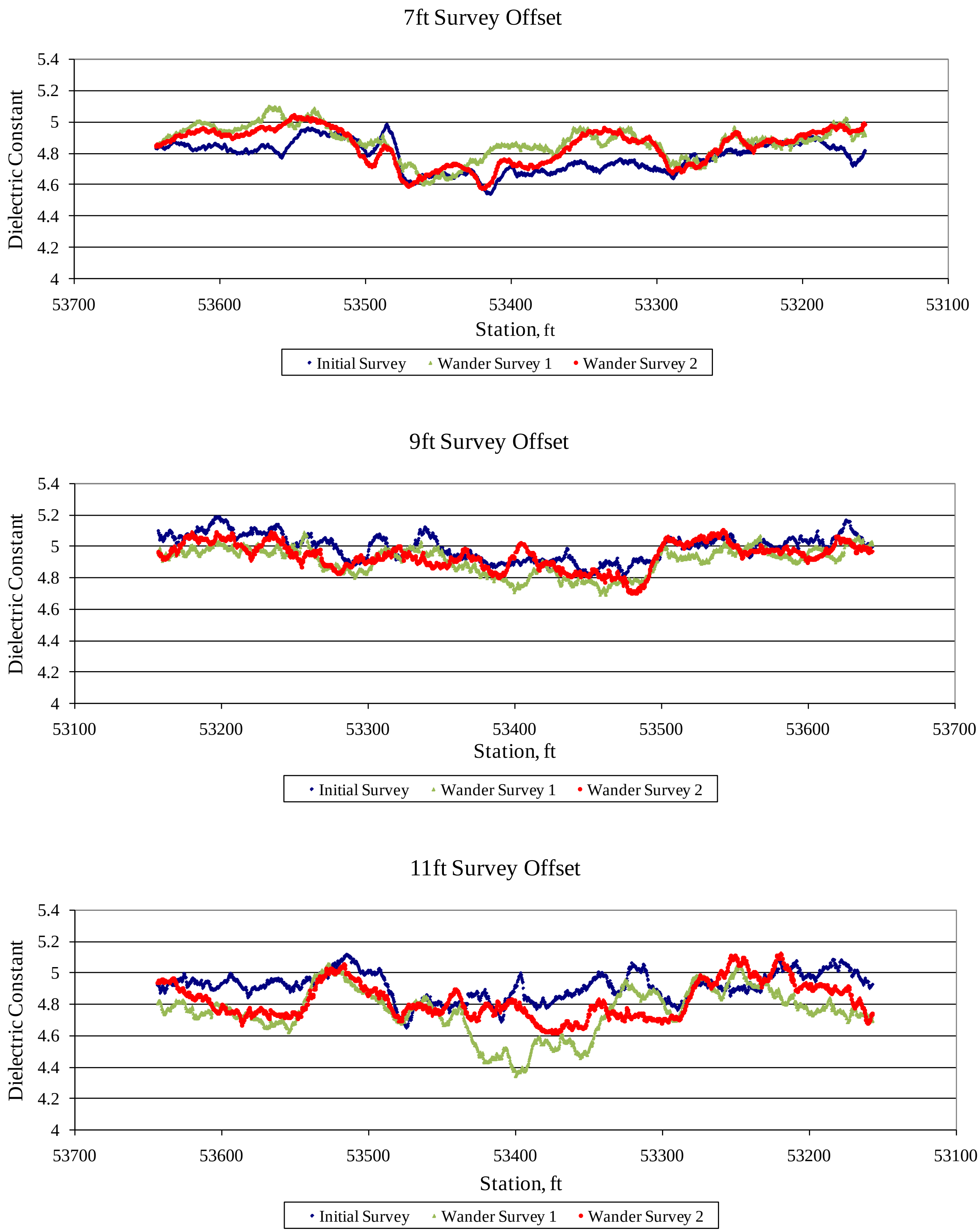


Figure 74. Comparison Plot of Collected Data at the 7, 9, and 11 ft Offsets on SR 222.

The plotted information confirms the visual observation that the largest variance in dielectric constant information occurs at the pavement edges. Furthermore, at these offset locations, the results from the 1 ft per 100 ft wander survey (segment survey 3) was found to be more variable than the results of the 2 ft per 100 ft wander survey.

Non-Nuclear Density Gauge Comparison

The corrected G_{mb} values, as measured by the non-nuclear density gauge, were plotted (Figure 75) against the laboratory results of the extracted pavement cores. The comparison of the two sets of data was found to be variable, with a correlation factor of 0.69, which is significantly less than the correlation factor of 0.84 obtained from the GPR survey. The use of the non-nuclear density gauge continues to provide more variable results when compared to the extracted pavement cores.

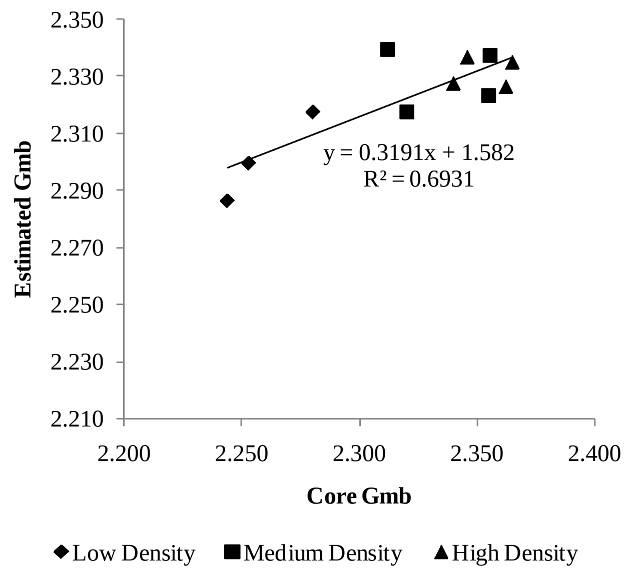


Figure 75. Comparison of Non-Nuclear Density Gauge and Pavement Core Results on SR 222.

Precision and Bias

For the development of a precision statement, GPR measurement data for each site were correlated to actual density data obtained from cores extracted and taken to the pavement laboratory. A separate regression analysis was conducted for each site to simulate a GPR calibration procedure. The comparative results for each of the three validation trials were analyzed separately, as the asphalt material at each site had a unique mix design. In this case, the models are considered unbiased because the models were specific for each site and the regression procedure provides an unbiased model.

Although multiple GPR surveys were completed for each validation trial, dielectric values used in the precision analysis were from the GPR surveys that determined the pavement core locations. A summary of the dielectric values and the pavement cores densities used in the analysis is provided in Table 21. The GPR data were correlated with laboratory density values to determine the accuracy and reliability of the relationship, and the effectiveness of the GPR equipment to measure density. Correlation plots for each of the field trials are provided in Figure 76 through Figure 78.

Table 21. Summary of Dielectric Values and Pavement Core Densities for Precision Analysis.

Core #	Station (ft)	Offset (ft)	Expected Density Level	Dielectric Constant	Core G_{mb}
State Road 20					
20-1-1	591+41	2.8	Low	5.027	2.185
20-1-2	590+52	6.4	High	5.407	2.342
20-1-3	595+59	10.1	Low	4.790	2.137
20-1-4	595+24	7.0	High	5.334	2.239
20-1-5A	593+70	6.0	Medium	5.328	2.268
20-2-1	673+23	9.0	Low	4.711	2.077
20-2-2	673+37	3.0	High	5.054	2.196
20-2-3	674+72	2.4	Low	4.785	2.156
20-2-4	674+94	3.2	High	5.254	2.315
20-2-5B	674+06	6.0	Medium	4.936	2.179
20-3-1	739+53	10.0	Low	4.721	2.152
20-3-2	741+95	7.0	High	5.443	2.333
20-3-3	742+83	6.8	High	5.418	2.356
20-3-4	743+34	10.0	Low	4.958	2.177
20-3-5A	743+85	5.7	Medium	5.218	2.351
20-4-1	698+22	10.5	High	5.011	2.255
20-4-2	697+68	10.0	High	5.061	2.211
20-4-3	698+07	5.0	Low	5.067	2.245
20-4-4	703+50	9.0	High	4.969	2.164
20-4-6	703+57	4.5	Low	5.045	2.269
20-4-5A	701+62	6.0	Medium	5.339	2.385
State Road 23					
23-1	717+06	-8.1	Low	5.022	2.303
23-2	720+31	-9.6	High	5.147	2.341
23-3	723+93	3.6	Low	4.869	2.255
23-4	728+69	3.3	High	5.277	2.324
23-5	730+55	-2.2	Medium	5.192	2.359
23-6	733+62	-7.4	Medium	5.148	2.348
23-7	742+03	5.6	High	5.230	2.377
23-8	749+24	-3.1	Low	4.654	2.141
23-9	754+16	2.4	Medium	5.168	2.336
State Road 222					
2-1	551+79	9.2	High	5.103	2.346
2-3	549+48	5.3	Medium	4.862	2.312
2-4	538+75	7.1	Low	4.542	2.280
2-5	536+22	8.9	High	5.066	2.340
2-6	535+47	7.4	Medium	4.951	2.356
3-1	531+99	9.2	High	5.067	2.365
3-2	518+31	6.7	Low	4.458	2.244
3-3	515+48	1.6	Medium	4.949	2.355
3-4	512+85	9.2	High	5.230	2.362
3-5	509+74	1.9	Medium	4.926	2.320
3-6	508+50	4.5	Low	4.646	2.253

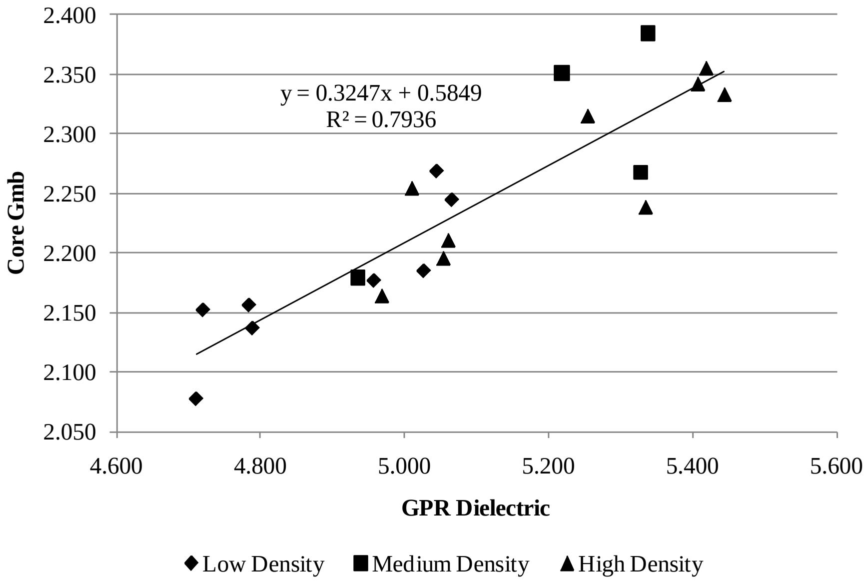


Figure 76. Correlation Plot for Field Trials on SR 20.

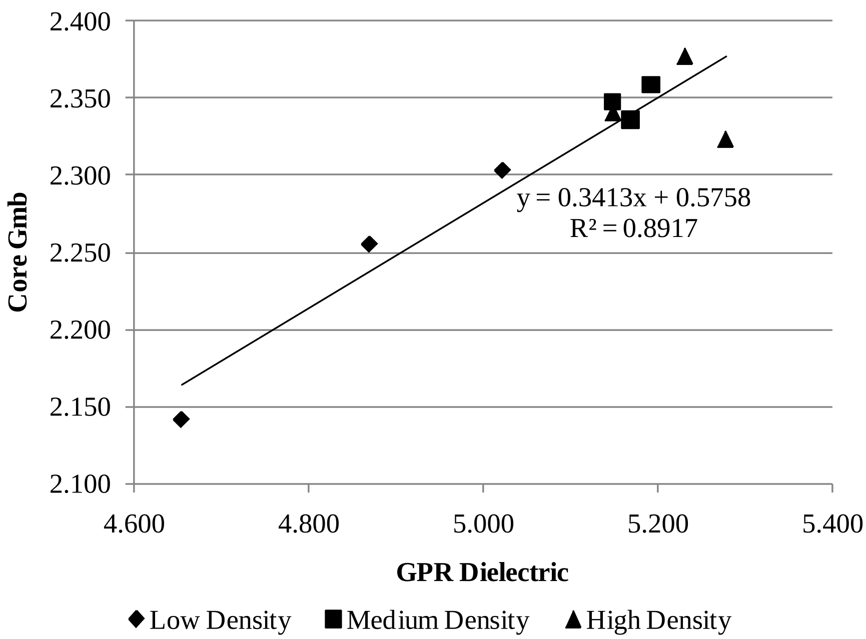


Figure 77. Correlation Plot for Field Trials on SR 23.

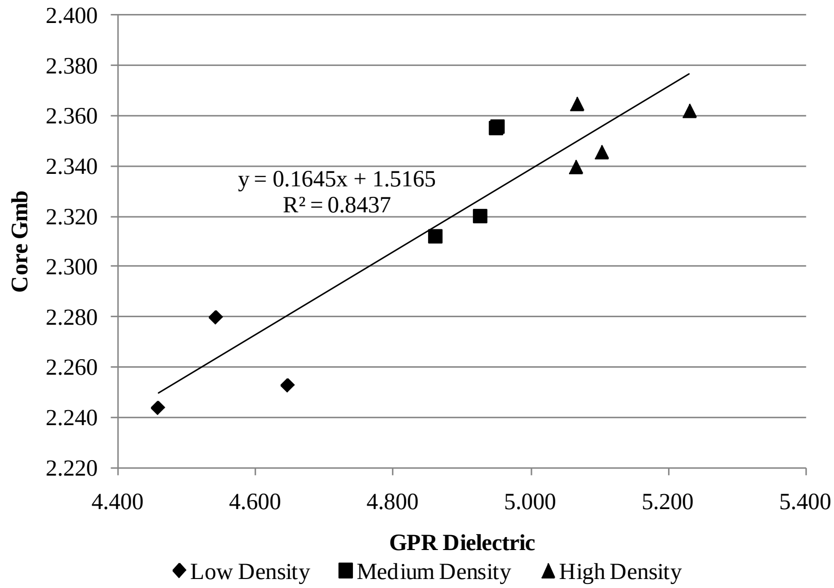


Figure 78. Correlation Plot for Field Trials on SR 222.

The regression equations generated in the plots are the ones that should be used for field testing of material densities. The procedure is analogous to that for calibrating the dielectric constants and was specific for each field trial study. The R^2 for the three sites varied from 0.79 to 0.89, which indicates that the dielectric values correlate very well to the pavement core densities.

The regression analysis also provided the standard error that can be expected in using the GPR equipment. The results of the regression analysis are summarized in the table below.

Table 22. Results of the Regression Analysis.

Regression Statistics	SR 20	SR 23	SR 222
R^2	0.79	0.89	0.84
Standard Error (%)	1.77 %	1.1 %	0.79 %
Observations	21	9	11
RAP (%)	35	20	15

The standard error for the three trials varied from 0.8 to 1.8 percent of the actual core densities. Even though the asphalt mixes in each of these sites varied, the standard error between them only varied by 1.0 percent of the pavement core density. It was also observed that the standard error was higher for the sites that contained larger amounts of RAP material in the asphalt mixtures. From the information provided in the JMF, the asphalt mix used on the SR 20 site contained 35 percent RAP material, while the 20 and 15 percent RAP material was used in the SR23 and SR 222 sites, respectively.

Nonetheless, a pooled variance for the three standard errors was calculated and resulted in an expected standard error of 1.43 percent. Therefore, based on the results of the analysis previously described, the GPR data can be expected to have an error lower than 2.86 percent of the pavement core density (2 times the standard error) with 95 percent confidence, when GPR dielectric values are calibrated to pavement cores. For example, if the calibrated GPR dielectric at a particular location was determined to have a compaction effort (percent G_{mm}) of 93 percent, the actual density of that location could vary from 90 to 96 percent.

It should be noted that this accuracy level is based on the field trials completed as part of this study. From the data and general observations, there are a number of things that can influence the degree of correlation between the GPR and field cores. These include:

- Inherent variability in the asphalt mixture (aggregates and aggregate gradations, percent binder, etc.).
- Increased delay between the GPR data collection (identification of pavement core locations) and when the pavement cores are extracted.
- Inclusion of admixtures and synthetic aggregates such as steel slab and rubber asphalt.
- Errors associated with the laboratory test results.
- Density and condition of the underlying pavement (cracking, patches, delaminations, etc.).
- Location positioning of the correlation cores compared to the survey lines
- Vehicle wander during GPR data collection.
- Weather conditions.
- Presence of ambient noise that may affect the quality of the GPR data.

Some of the bias is accounted for by calibration the GPR dielectric values with site-specific pavement cores. An increase in the number of cores likely would reduce the bias.

8.0 RECOMMENDED GPR SURVEY METHODOLOGY

From the results of the field validation trials an optimum survey protocol was developed, as described in the ensuing sections.

GPR Survey Site Suitability

In selecting a suitable survey site, a primary concern is the high susceptibility of the GPR system to ambient radio interference (noise). GPR data should not be collected when the pavement surface is wet. Radio interference has the potential of disrupting the quality of the data collected. Prior to the selection of a field validation site, an initial GPR survey should be completed at all candidate locations to determine the level of interference, if any, that would affect the survey results.

To determine if ambient noise at a potential site will affect the survey results, the following procedure should be completed.

1. Set up the GPR equipment on a section of asphalt pavement at the site to be evaluated.

2. Set up GPR data collection using the settings described in the report.

3. Collect a plate calibration file.

4. Remove the metal plates (exposing the asphalt), select the data collection option to *antenna calibration file*, and collect a second file. This second file should represent 2 full screens of data (approximately 1,200 scans). Make sure that the vehicle is stationary and that there is no personnel movement in the vicinity of the antennas during the collection of this second file.

5. Analyze this second file for pavement thickness using RADAN. Apply the standard RADAN processing procedure for layer thickness, using the plate calibration file collected in step 3 3) for this analysis, and using any reflection below the surface as the bottom of the asphalt.

6. Sort the resulting output *lay* file data to separate channel 1 and channel 2 data sections, and retain the columns representing *scan #* and *Layer 1 dielectric*.

7. Copy the channel 1 and channel 2 dielectric data in to separate worksheets in Excel.

8. Calculate the coefficient of variation (COV) of the dielectric constant data for channels 1 and 2 separately. (COV = standard deviation/mean).

9. If COV's for channel 1 and channel 2 are both less than 4 percent, then the noise level is acceptable. If not, then the noise level is unacceptably high.

Since the field validation trials, it is understood that both GPR antennas have been retrofitted with filters that are intended on reducing ambient noise interference. Although at this time it is uncertain as to the impact this new filter will have on the GPR system, it is recommended that the performance of the retrofitted antennas be thoroughly examined.

GPR Equipment Calibration Procedures

On the way to the field validation site, the distance measuring instrument (DMI) system in the vehicle should be checked by measuring the distance to the site from FDOT's *measured mile* located on SE 163rd Street. The DMI encoder should be calibrated on a regular basis to ensure accurate distance readings during the field data collection.

Upon arriving on site, the GPR system should be set up and calibrated in accordance with GSSI's "Handbook for GPR Inspection of Road Structures." These procedures should include creating a project, setting program defaults, distance calibration (as discussed above), configuring position/range, checking gain, checking filters, and collecting a *bumper jump* antenna calibration file.

Equipment Setup

After the calibration procedures have been completed, the survey equipment should be set up in accordance with the testing protocol. The proposed survey protocol consists of the following parameters:

- Transverse spacing between antennas: 4 feet
- Transverse spacing between survey lines: 2 feet
- Longitudinal spacing: four scans per foot (3 inches)
- Time range: 6 ns
- Sample rate: 512 samples per scan
- Travel speed: No greater than 10 mph
- Mark the beginning and end of test section within GPR data using the laser trigger and cones with reflective tape. Project stationing (or mileposts) also should be recorded.

The data collection methodology involves collecting data over a series of longitudinal lines on the pavement. The FDOT system, with two antennas, can collect two lines of data with one pass of the vehicle. To prevent cross-talk between the two antennas, the transverse spacing between the GPR antennas should be 4-ft. As part of the testing protocol, eight lines of data should be collected, at 2-ft lateral spacing with duplicates data at the 5 and 7-ft offsets (Figure 79). The information at these offsets should be averaged prior to plotting the results. This layout will provide a grid of GPR data points at 4 inch longitudinal and 2 foot transverse spacing that would lead to a good quality contour map of surface dielectrics and densities, and minimize inference between the two antennas should the spacing be reduced.

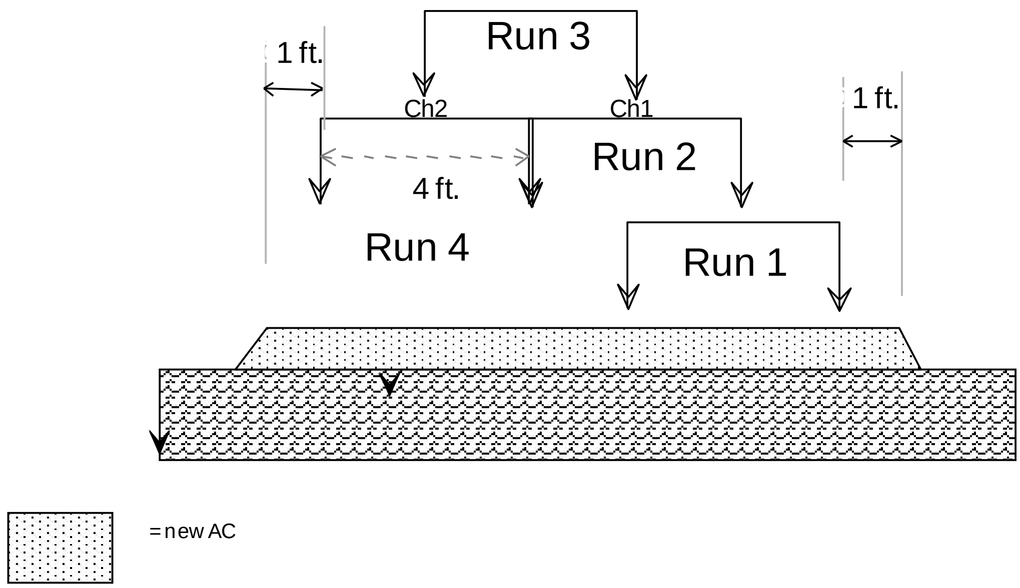


Figure 79. The Data Collection Protocol.

All project and section data collected should be recorded on the sample data collection sheets provided in Appendix B. The project file name should include Roadway ID – Section ID – Run Number (e.g., SR222-01-03). All setup information should be recorded on the Project Data Collection Sheet. This information includes the location of the survey site, equipment settings, date of survey, and general layout of the survey site (e.g., surveying Lane 1 in the westbound direction).

Once an area, or section, within the project site has been selected, all section-specific information should be recorded on the Section Data Collection Sheet. This information includes the section start and end stationing, plate file name, offset numbers, and file numbers for each run. A separate Section Data Collection Sheet should be completed for each section surveyed. Whenever possible, these sections should correspond to the paving lots and sub-lots of the construction project.

Data Collection

The GPR survey should be completed in accordance with the data collection protocol indentified in Figure 79. The file numbers (survey run sequences) should be recorded in the order completed, with each survey run saved as a separate file. Prior to starting the data collection, survey lines should be marked on the roadway surface at the start and end limits. The pavement markings at the start limit will help to line up the survey vehicle on the appropriate offsets prior to starting the survey. An example of a marked surface at the starting location is provided in Figure 80. The markings of the end limits will assist the vehicle operator to identify the end survey limits while providing offset locations to help minimize vehicle wander. Polarized reflective cones should be placed at both survey limits. Pavement marking throughout the survey section is optional, although it is recommended that some markings be placed along the survey runs at the pavement edges.

Figure 80. Example of Marked Survey Lines.

Data should be collected in the direction of paving. During the surveys, vehicle wander should be minimized, as much as practical, particularly at the pavement edges. As observed in the field trials, significant wandering near the pavement edges could be influenced by the lower densities typically found at the longitudinal construction joints.

In addition to collecting the GPR data, site-specific information should be obtained from the contractor. This information should include the type of asphalt material placed (JMF) and any laboratory testing completed on the paving material.

Data Analysis Methodology using GPRQA

Analysis of the collected GPR information will be required, and it can be completed using the customized GPRQA software application. The program provides automated analysis of GPR data for QA of mat densities during asphalt paving operations. Data collected from GPR passes over newly placed asphalt are analyzed to provide a summary of the surface dielectric values. These values can be mapped using any commercially available contour plotting program. For the purposes of this project, Surfer was identified to be the most appropriate contour plotting program.

The surface dielectric map generated by Surfer is used to locate high, low, and mid-range areas for density calibration cores. The analysis, and pavement core location selection, should be done in the field upon completing the data collection. This is to ensure accurate positioning of the core locations. Pavement core locations should be selected with a minimum of one core in each of the high, low, and mid-range areas. The locations of the core locations should be uploaded back into the GPRQA program to generate a report with the station, offset, and dielectric values at each of the selected locations.

A detailed methodology on the procedures required to use GPRQA for analyzing the GPR data is provided in Appendix A. The appendix also includes instruction on the operation of the Surfer software application.

Data Analysis Methodology using RADAN

As an alternative to the GPRQA software, the collected data could be analyzed using RADAN. A methodology for analyzing the collected information was developed for RADAN, which would calculate and provide dielectric values for the surveyed section. It should be noted that the process of generating the contour plot as described in the methodology below may require up to 3 hours to complete, whereas the same information in GPRQA would require approximately 20 minutes.

The methodology is based on the Advance Road Structure Assessment Module that is part of FDOT's RADAN analysis system. It also assumes that a series of raw data files have been collected at various offsets on a section of pavement, and that the start station of the section has been marked in each of the data files. The basic steps in the RADAN analysis are as follows:

1. Set up a *Project* in RADAN, and include all of the raw data files in the project.
2. Create an analysis *Macro* which carries out the layer picking and generates the output lay files.
3. Run the Project and generate the lay files.
4. Edit the lay files so that the x-distance has been corrected by the marked section start and the columns have x-distance, offset, and dielectric values.
5. Merge all of the "lay" files for the pavement section into a single .csv or Excel file whose columns are x-distance, offset, and dielectric.
6. Contour plot the merged section file using a commercial contour plotting program (e.g., Surfer, DPlot).
7. Calculate the dielectric values at selected core locations by interpolating the values in the merged section file.

Details of these steps are discussed below.

Set Up Project (rpj file)

This process is a standard RADAN procedure and is discussed in detail in the RADAN manual. It identifies the raw data files that are to be included in the analysis and the macro data processing file that is applied to each raw data file.

Create Analysis Macro (.cmf file)

The analysis macro file (.cmf) for this analysis includes a reflection picking analysis step and a layer interpretation step. Both of these are described in detail in the user's manual for the Advanced Road Structure Assessment Module for RADAN 6.0. For the reflection picking, only one layer needs to be selected, since one is interested primarily in the surface dielectric and perhaps the thickness of the first layer. Ringdown removal filter and calibration scan subtraction options are selected. The calibration file is the metal plate reflection test conducted as part of the section data collection.

Run the Project using the Analysis Macro

The "run" option automatically applies the analysis macro file to each raw data file in the project. The result of the analysis of each raw data file is an ASCII text file (.lay) with many columns, most of which are not of interest. The primary columns of interest are scan #, x-distance, and layer 1 dielectric. The .lay file interleaves the channel 1 and channel 2 data, so two values are provided for each scan # and x-distance, one for channel 1 and one for channel 2.

Edit the .lay Files

The x-distance in each lay file is measured from the start of the file. Each x-distance value must be adjusted so that zero is at the start of the section. The adjustment involves identifying the scan # where the laser mark was recorded (from the distance between the laser trigger and the antennas. The adjustment equation, which can be applied in Excel, is:

Adjusted x(ft) = original x(ft) – (marked scan#)/(scans per foot) +

(distance between laser marker and antennas).

For example, if the marked scan is #36, the distance between the laser marker and the antenna is 4.67 feet, and data collection is 4 scans per foot, then the equation is

Adjusted x(ft) = original x (ft) – (36/4) + 4.67 = original x(ft) – 4.33(ft)

This adjustment must be made independently for each .lay file, since the marked scan # will be different for each file.

The .lay files must also be edited to remove the unwanted columns, and to add a column representing the offset for each data channel. The offset can be entered by separating the two channels using a sort and copying in the offset values for each channel, or by using a formula to test for channel # and enter the appropriate offset.

Merge the Edited .lay Files into a Single Section File

The individual .lay files must be combined into a single ASCII, csv, or Excel file, whose columns are adjusted x-distance, offset, and dielectric value. This is accomplished by cutting and pasting in Excel or any alternative ASCII editing application.

Contour Plot the Merged Section File

A contour plot is created from the merged section file using Surfer or other commercial contour plotting program. The purpose of the contour plot is to visualize the data for selecting locations with high, low, and mid-range dielectric values for coring and laboratory density measurements. Contour plotting with Surfer is described in the GPRQA user's manual in Appendix A.

Calculate Dielectric Values at Selected Locations

This step is necessary for developing the correlation between the dielectric values and laboratory density measurements at the core locations. Typically, the cores are taken somewhere between the actual measurement lines, so some type of interpolation is required. This interpolation can be carried out directly in Excel using the merged section data file and various lookup functions. The analyst can select the specific interpolation formula to be used. For reference, GPRQA uses a weighted average within a user-selected radius around the core location, with the weighting inversely proportional to the distance from the core location.

Pavement Coring and Laboratory Testing

The coring operations should be completed as soon as practical after the GPR survey. Delays in the extraction of the core samples may affect asphalt density test results, especially if the surveyed section is opened to traffic.

Laboratory testing on extracted core samples should be performed in accordance with FM-1-T 166, "Florida Method of Test for Bulk Specific Gravity of Compacted Bituminous Mixtures." In addition to determining the bulk specific gravity of the core sample, the maximum theoretical specific gravity of the asphalt mixture also will be required. If this information is not available from the contractor (using samples collected during the paving operation), additional coring may be required. These additional cores will need to be tested using FM-1-T 209, "Florida Method of Test for Maximum Specific Gravity of Asphalt Paving Mixtures."

GPR Data Calibration

The density results of the pavement cores shall be correlated to the dielectric values obtained at the pavement coring locations. Using the correlation plots, a linear regression trendline is required to determine the linear equation of the trendline, as well as the coefficient of determination (R^2).

The results of the GPR survey should be imported into Excel, where using the linear regression equation developed above, the collected dielectric values can be calibrated/ calculated into density measurements.

Reporting Procedures

Using the obtained, or determined, maximum theoretical specific gravity for the asphalt mixture, the individual density measurements can be converted to determine the compaction effort (in percent) of the contractor. This calculated compaction effort should be plotted in a histogram to provide a distribution of the results.

Precision Statement

A precision statement for the GPR survey on newly pavement asphalt material has been developed based on the results of the field trials. The GPR data can be expected to have an error lower than 2.86 percent of the pavement core density, with 95 percent confidence, when GPR dielectric values are calibrated to pavement cores.

9.0 BENEFITS OF RESEARCH IMPLEMENTATION

Ensuring the proper placement and compaction of asphalt mixtures has long been a challenge for many State agencies. Traditional compaction surveys involve the extraction of field cores for laboratory density analysis. This destructive method provides density only at the locations where the pavement cores are taken, is a destructive procedure, is considered slow and tedious, and requires maintenance of traffic. From the results of this study, the use of GPR technology can be used in conjunction with traditional techniques to determine the in-place density of asphalt construction projects.

General Requirements for Current Density Specification

All FDOT projects presently are accepted in accordance with one or more construction specifications. The purpose of these specifications is to provide guidelines and establish minimum requirements that enable a quality product to be built. The final product must meet the expectations of the designer to protect public safety and provide the expected level of service to the roadway user.

Roadway pavement surface and binder course density is measured in accordance with FM-1-T 166, *Florida Method of Test for Bulk Specific Gravity of Compacted Bituminous Mixtures*. Five randomly located 6-inch-diameter pavement cores from each sub-lot are required to meet the sampling and testing requirements of Section 334 in the *2007 Standard Specifications for Road and Bridge Construction*.

The pavement core densities from each sub-lot are averaged with the target density being the maximum specific gravity (G_{mm}) of the sub-lot. The average densities must meet the minimum requirements identified in Table 334-4, which include 93 percent G_{mm} for coarse graded mixes and 90 percent of G_{mm} for fine graded mixes. In the event that an individual sub-lot is less than the minimum value, action must be taken to correct the situation and report the action to the engineer. Should two consecutive sub-lot averages be less than the minimum required value, then production of the mixture must be stopped until the problem is resolved.

Pavement core densities also are one of the quality characteristics required in calculating a pay factor. Based on the quality of the material, a pay adjustment is applied to the bid price of the material, as determined on a lot by lot basis. When three or more sub-lot test results are available the pay factor for the lot is calculated using the Percent Within Limits approach. Specification limits for this approach are as follows:

Table 23. Asphalt Density Specification Limits (Table 334-7).

Quality Characteristic	Specification Limits
Density – Course Mixes (percent of G_{mm})	94.50 ± 1.30
Density – Fine Mixes (percent of G_{mm})	93.00 + 2.00 – 1.20

The pay adjustments are based on the use of five cores per sub-lot.

Additional Benefits through the use of GPR

The use of GPR for asphalt concrete density will still require site cores for calibration purposes if the GPR data are going to be used to calculate pay factors. A reduction in coring frequency may be possible, but initially, it is recommended that the current coring frequency be maintained. However, the following additional benefits in using GPR would be realized:

- Using the GPR to *target* the core locations to provide a more true representation of the in-place density of the asphalt material.
- The collection of larger samples of density measurements will provide a more accurate representation of the true asphalt densities. This could potentially be used to modify construction specifications, etc.
- The density contour plots provide a visual illustration of the asphalt compaction effort, which would assist both FDOT and contractors in improving construction practices, rolling patterns, etc. to improve the consistency of the in-place AC density.
- The GPR plots provide a much better understanding of the variability of asphalt compaction effort. A lower variability in the asphalt compaction would likely lead to a reduction in localized distress and future maintenance costs.

APPENDIX A

GPRQA
USER'S MANUAL

GPRQA
(**G**round **P**enetrating **R**adar for **Q**uality **A**ssessment)
User's Manual

OVERVIEW

The GPRQA program is used to allow instantaneous feedback for supporting quality control of asphalt density during asphalt paving. Data collected from GPR passes over newly installed asphalt is analyzed to provide a summary of surface dielectric values. Core data is used to calibrate the dielectric values with core density measurements.

Surface dielectric results are presented graphically in histograms of the entire section. Tabular report results give both raw data values sorted by location and show the section statistics (mean and standard deviation) at core locations.

REQUIRED USER INPUTS
The minimal inputs required to operate the program are listed here.

General Project Information

Project Name

Section Information

Section ID	
Raw Data Directory	– directory of the GPR files
Processed Directory	– directory where processing results will be written
Results Directory	– directory where final reports will be written
Station Start	– station of section start (ft). Also, the station value at the first file mark
Station End	– station of section end (ft). Also, the station value at the last file mark
Lift Thickness (in)	– the expected mean thickness of the section
Lift Description	– if desired
Previous Lift Thickness (in)	– if available (can be a close estimate)
Previous Lift Description	– if available
Antenna Offset from Mark (ft):	– distance from marking sensor to center of antenna (see project data collection sheet for clarification)
Number of Channels:	– the number of antennas used in the data collection (must be 1 or 2)
Spacing Between Antennas (ft):	– measured from center to center of each

Data file Information (for each data file "*.dzt" collected for each section)

Datafile	– data file name
Platefile	– dzt file collected while antenna is positioned over the metal plate and the jump test is performed.
OffsetToAntenna	– Offset from antenna to mark in feet (how far from the antenna location are marks - this value defaults to the section value)
FileOffset	– Lateral offset of the file in the section (ft) – Only the data for the channel 1 antenna is entered. If 2 antennas are used, the value for channel 2 is calculated from the antenna spacing entered for the section.

Core Information (for each core collected for each section)

CoreID	– Unique name for each core in the project

Station	– Station in ft (Format 0+00.0###)
Offset	– Offset in feet (Y-offset). The lateral offset from section reference.
AirVoid	– 0.0% (if desired)
Thickness	– inches (if desired)
Density	– Gmb (if desired)
CSV File	– Allows user to load information on a number of cores by reading them in from a file instead of entering each one manually.
Corefile	– Core files are small dzt files that are taken at core locations to calibrate core data. This feature is not implemented in this version of the program.
X-coordinate	– An X-coordinate is the distance in feet from the start of section to the core location. Core locations entered this way require the designation of a Section so that correct stationing can be calculated base on X-Coordinate and Section ID. This feature is not implemented in this version of the program.

FIELD PROCEDURES

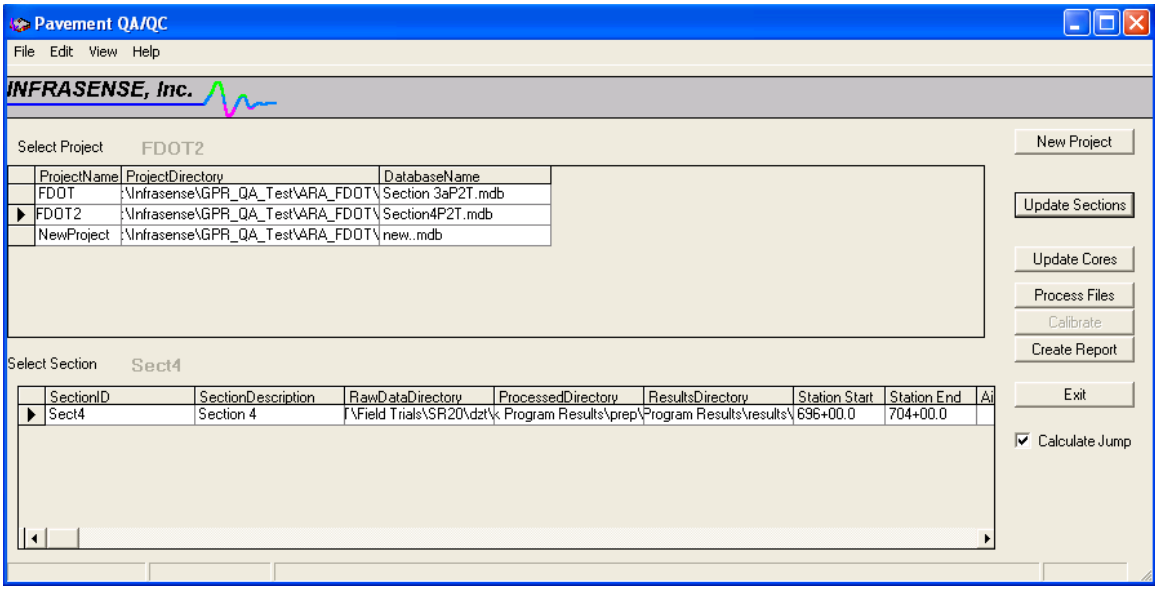
The Project and Section must be defined before Datafile and Core data may be entered. Project and Section information may be entered before going into the field. In the field, the GPR operator must obtain a plate file. A plate file is a small GPR file obtained by collecting GPR data while a metal plate is placed on the ground under each antenna. A small sample is obtained with the vehicle resting, data collection is paused, and then resumed as the antennas are made to "bounce" above the metal plates by the operator jumping on the vehicle bumper. File names must be tracked along with information regarding the type of file (plate, or data), and the offset of data files. Data sheets should be filled out as the GPR analysis proceeds. A sample project and section data collection sheet is provided in Attachment A.

All data files in a section must be collected in the same direction, passes should be parallel, and offsets defined from a common line. The first mark in the file must be entered when the antenna passes the section start location. The last mark in the data file must be entered when the antenna passes the section end location. Intermediate marks may be entered if the user needs to delineate other events, but the analysis program will ignore these marks.

PROGRAM OPERATION

Select a Project

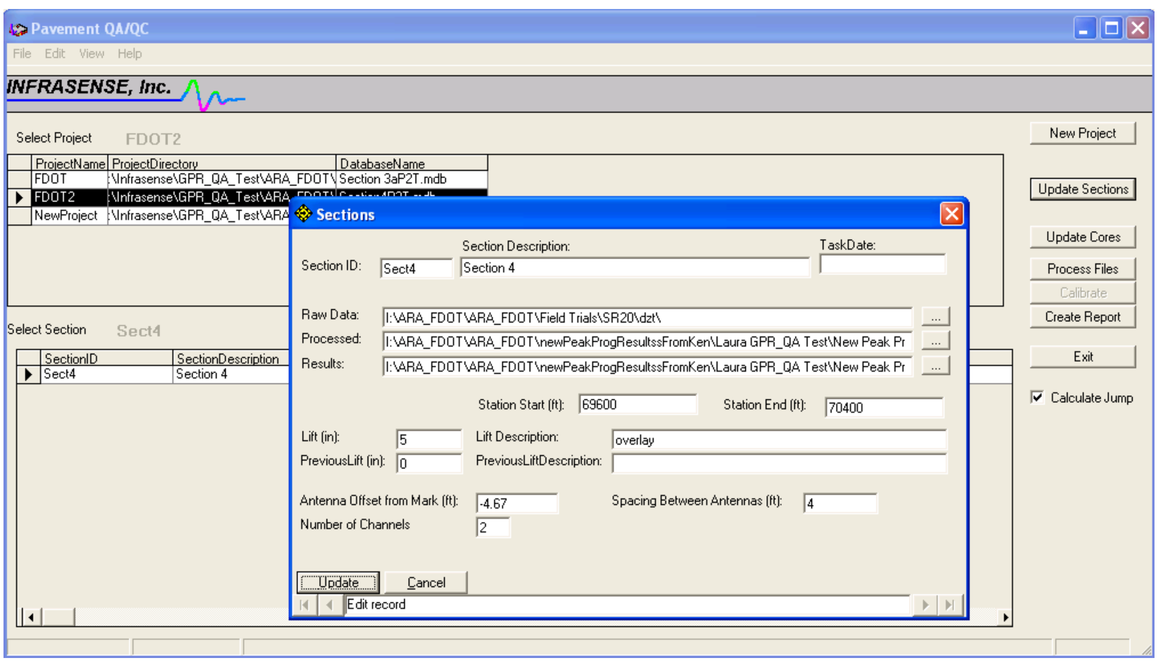
Create a new project by selecting "New Project" from the "File" menu or by selecting the "New Project" button. Enter a Project Name, Select a Project Directory for storing the Project Database, and Select a 'Database File Name'.



A database with the chosen database file name will be created in the project database directory. To select an existing project, click on the row that defines the project in the Select Project grid. A selection symbol (▸) will appear in the left margin of this row to indicate that it is selected. The Select Section grid will be filled with any sections already defined for this project.

Define Sections

Define Sections for the project by selecting the "Update Sections" button. Select "Add" to add a new section to the project. Enter section information as defined in the Required User Inputs section above. Then select "Update" to update the section information. You may continue in this way to add multiple sections to the same project, or to modify existing sections by choosing the Edit button for a selected section.



Enter Files

Enter file information for each section by selecting “Files” button in the Section window. To edit an existing file, select the file by clicking on the file row in the file grid. A selection symbol (▸) will appear in the left margin of this row to indicate that it is selected. Select “Edit” and the file becomes available for editing.

To enter a new file, select the “Add” button.

The new data file should then be selected from the DZT file Directory
for the section and the Plate file selected by choosing the [...] button next to the filename, and the Antenna Offset from Mark (ft) and File Offset (ft) defined.

The Antenna Offset from Mark will default to the value defined for the entire section. This is the distance from the antenna to the mark sensor and will be a negative value for antennas mounted in front of the vehicle, positive for antennas mounted on the rear of the vehicle.

The File Offset is the offset from the section centerline of the channel one antenna. In the section coordinate system, Station numbers increase left to right and Offset values increase bottom to top.

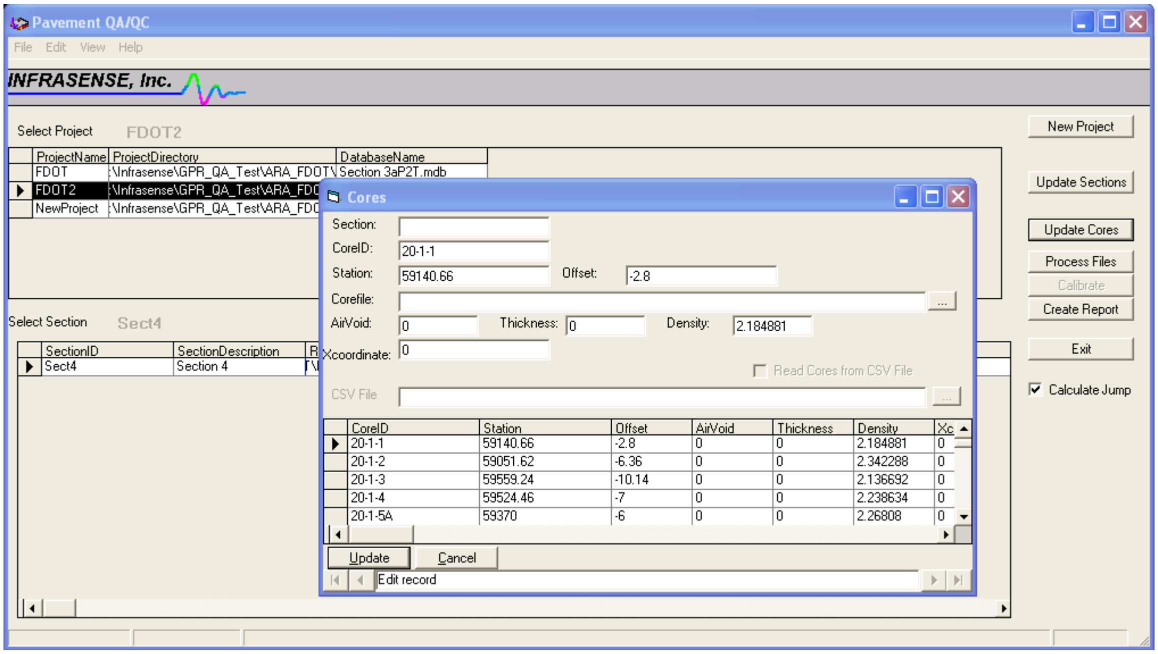
Consequently, in the case where the antenna on the passenger side is attached to channel 1 and the antenna on the driver’s side is attached to channel 2, the channel 2 antenna will be “above “ the channel 1 antenna and the Spacing between Antennas will be positive.

Note: Plate File and Antenna Offset values for the new record will automatically default to the section values selected. These values can be changed if needed.

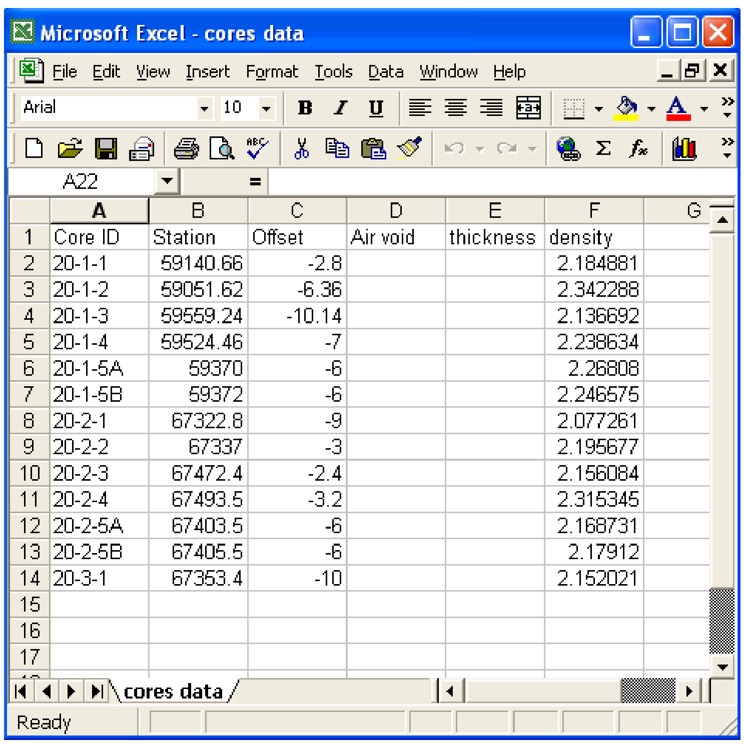
Files added to this form MUST already exist in the DZT file Directory.

Enter Core Data

Enter core information for each section by selecting “Cores” from the “Edit” menu or by selecting the “Update Cores” button. To edit an existing core, select the core by clicking on the core row in the core grid. A selection symbol (▸) will appear in the left margin of this row to indicate that it is selected. Select “Edit” button and the core becomes available for editing. To enter a new core, select the “Add” button. Enter core information as defined in the Required User Inputs - Core Information section above.



Another option to entering information for each core one by one is to bring the core information in via a CSV (comma separated value text file) File. To do this, select the "Read Cores from CSV File" check box and then the "…" button to select the applicable CSV file. From here, select the "Read Core File" button to bring in core information. Below is an example of a typical CVS file that can be read into the program.



The core file must have a header line that will be discarded when read into the program followed by lines of core data, one core per line. The core file input format must be comma-separated values as shown above:

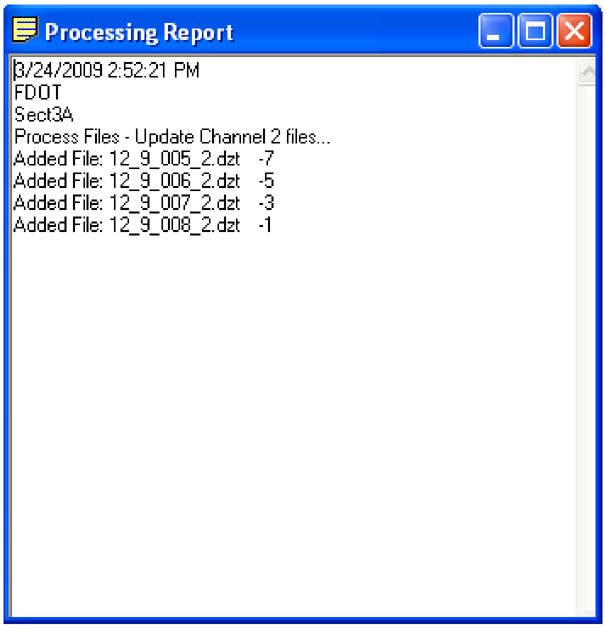
CoreID, Station (ft), Offset (ft), AirVoid (%), Thickness (in), and Density.

The Core Station and Offset values must be in the same coordinate system as the File Station and Offset values. For core calibration of the data files, core locations that fall between file offsets will be scaled in proportion to the distance between the core offset and the adjoining file offsets.

Process Files

To begin the automated analysis, select the section to process in the Section Grid. A selection symbol (▸) will appear in the left margin of this row to indicate that it is selected. Choose “Process Files” from the “File” menu or by selecting the “Process Files” button.

The Processing Report will list progress as it occurs.



Processing proceeds for each file as follows:

- The Data file surface is normalized to a set horizon, Plate reflections are removed, and a processed data file is saved to the processed directory. An average surface dielectric constant is determined for the file.
- Marks are extracted for the file - the start and ending scan are found. These locations define the starting and ending stations for the section and determine the extent of analysis in the file.
- A first pass is made to find the layer boundary in the data file at the expected thickness.
- A second pass is used to locate the surface reflection and the reflection closest to the lift thickness for the section.
- The located surface dielectric and layer information is stored in the Processed Directory as <filename>
- .fmp

After all files are processed, a combined report file, <sectionName>.rpt, is created in the Results Directory. This file is in csv format listing Station (ft), Text formatted Station (0000.00.0###), Offset (ft), Thickness (in), Dielectric.

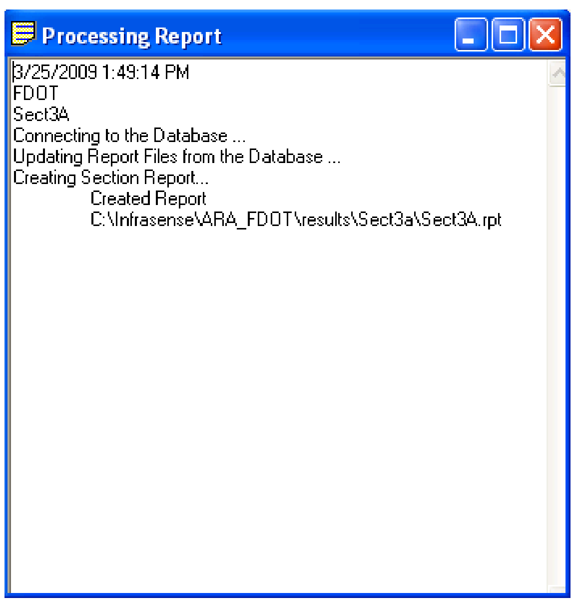
Create Reports

Select the section to process in the Section Grid. Choose “Create Report …” from the “File” menu or by selecting the “Create Report” button. Then choose the report to create…

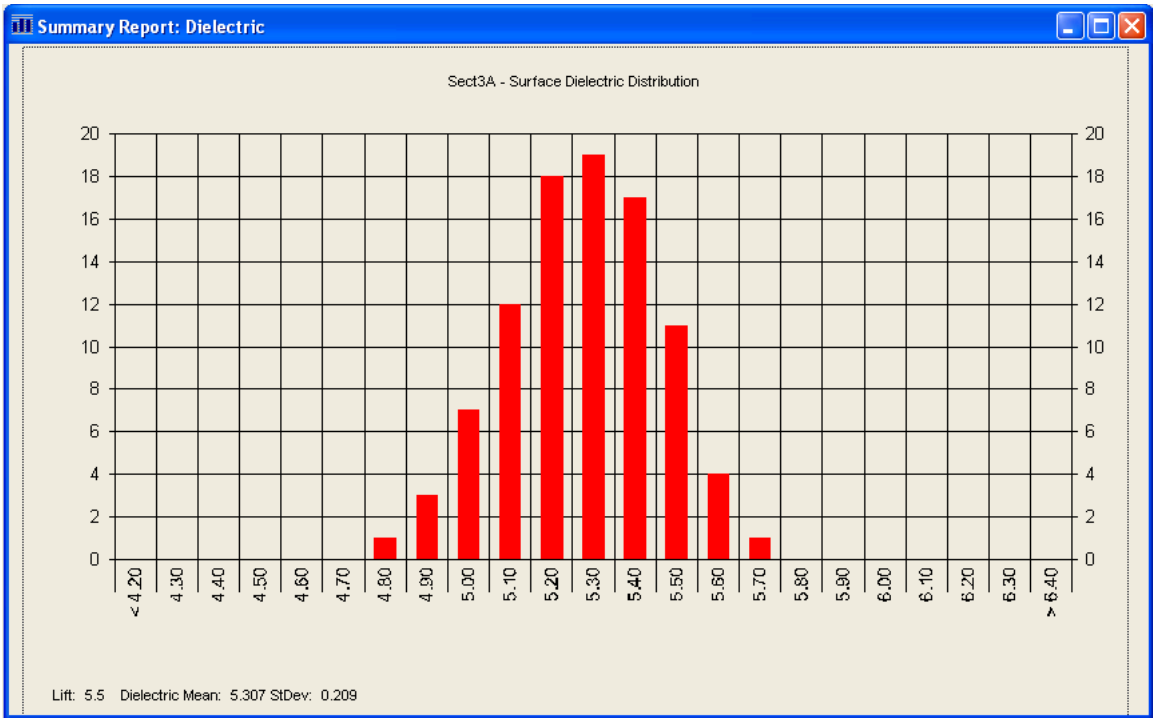
- Thickness/Surface Dielectric Report – This report is based on un-calibrated thickness results calculated from the surface dielectric and the location in ns of the lift surface found during the 2-pass surface location operation performed during file processing, and surface dielectric results The report will be named “<sectionID>.rpt” and be placed in the section results directory along with a corresponding SURFER lvl file.
- Core Calibrated Thickness Report– The calibrated thickness report can only be created if there are calibration cores available in the project. Thickness data calculated above divided by the regression calibration slope found during the core calibration procedure creates the calibrated thickness report. (Not currently enabled)
- Air Void Report – The air void report can only be created if there are calibration cores available in the project. Air void is calculated from the air void calibration constants found during the core calibration procedure defined above using the file dielectric constants. (Not currently enabled)
- Core Locations Report – Gives a report of the pavement properties at the core locations specified for a given section. Properties include; the core location (Station(ft), Offset(ft)), the core values reported (Air Void(%), Thickness(in), Density (G_{mb})), and the average values found in the file for Surface Dielectric, as well as the statistics of the sample estimate Count, Standard Deviation, Minimum, and Maximum values. A Weighted surface dielectric value is also reported. This value is the average value at the core location based upon a linear decline from the core to the requested radius,

If a Core Locations Report is selected, the user must enter a search radius (in feet). The program will use this radius to combine the dielectric values from the dzt files that are within this distance from the core. A report file named <section Name>_Core.rpt, is created in the Results Directory.

After the desired report is selected, the processing report screen will be displayed along with the report window.



If Thickness/Dielectric Report is selected, the report will generate a histogram of the surface dielectric values from the entire section. The histogram title indicates the section name and the type of distribution. Charts from the report may be copied to the clipboard by double-clicking the chart. A report file named <section Name>.rpt, is created in the Results Directory



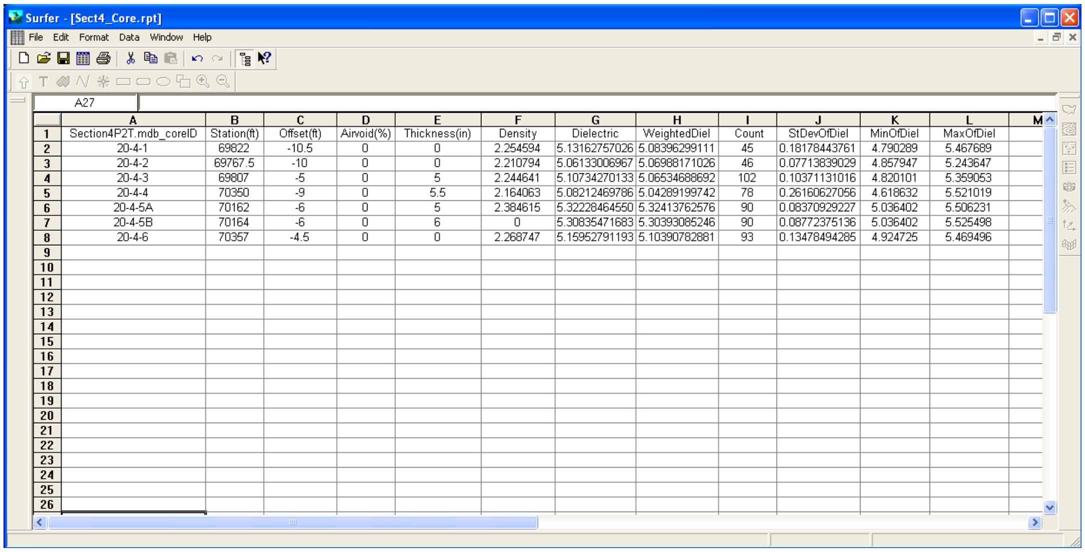
The Dielectric report shows the surface dielectric data for the entire section. Also reported are the expected lift and the mean and standard deviation of surface dielectric found in the section.

The software program also has the capability to generate a calibrated thickness report, which shows the calibrated thickness data for the entire section. Also reported are the expected lift, the allowable tolerance, and the mean and standard deviation of thickness found in the section. The outlier report shows thickness values less than the expected lift minus the tolerance. However, as this feature was not part of the scope of this work, it remains inactive.

In addition to the thickness report, an 'Air Void Report' also shows the calculated air void data for the entire section. Also reported as part of this feature are: the expected air void, the allowable tolerance, and the mean and standard deviation of air voids found in the section. The outlier report shows air void values greater than the expected air void plus the tolerance. However, as this feature was not part of the scope of this work, it remains inactive.

Core Locations Report

Cores from the section are found and an average surface dielectric is determined. If no cores are found, the core report will not proceed. Below is a look at the report output when brought into Surfer.



Section4P2T.mdb_coreID	Station(ft)	Offset(ft)	Airvoid(%)	Thickness(in)	Density	Dielectric	WeightedDiel	Count	StDevOfDiel	MinOfDiel	MaxOfDiel
20-4-1	69822	-10.5	0	0	2.254594	5.13162757026	5.08396299111	45	0.18178443761	4.790289	5.467689
20-4-2	69767.5	-10	0	0	2.210794	5.06133006967	5.06988171026	46	0.07713839029	4.857947	5.243647
20-4-3	69807	-5	0	5	2.244641	5.10734270133	5.06534688692	102	0.10371131016	4.820101	5.359053
20-4-4	70350	-9	0	5.5	2.164063	5.08212469786	5.04289199742	78	0.26160627056	4.618632	5.521019
20-4-5A	70162	-6	0	5	2.384615	5.32228464550	5.32413762576	90	0.08370929227	5.036402	5.506231
20-4-5B	70164	-6	0	6	0	5.30835471683	5.30393085246	90	0.08772375136	5.036402	5.525498
20-4-6	70357	-4.5	0	0	2.268747	5.15952791193	5.10390782881	93	0.13478494285	4.924725	5.469496

Plotting Thickness or Surface Dielectric Report Data in Surfer

1. From the top tool bar select the "Grid" drop down menu and then "Data."
2. Select *.* and choose the Thickness/Surface Dielectric report file just created <section>.rpt (select "comma" and "Double Quote" options when opening the file)
3. Scattered Data Interpolation settings (Settings not addressed, leave as program defaults). Here is a suggested starting scenario:
   a. Data Tab
      i. X: Station
      ii. Y: Offset
      iii. Z: Dielectric
      iv. Under "Duplicates",
         1. "to keep", select "average"
         2. "X tolerance", enter 0.24
         3. "Y tolerance", leave at 0

   b. General Tab
      i. X Direction Min and Max: Set to section limits
      ii. Y Direction Min and Max: Set as section max and min offsets
      iii. Spacing: 0.5 (ft) for x and y
      iv. Gridding Method: Inverse Distance to Power
      v. Select "Options" button
         1. Inverse Distance Options settings
            a. Power: 1.5
            b. Smoothing: 0.5
      vi. If desired, select a name of grid file to save by selecting the folder icon under "Output Grid File". The default name will be the same name as the input report file with the grd extension.
   c. Search Tab
      i. Search Ellipse: Radius 1 and 2= 8. (feet)

4. Once the grid file is created, choose "Map" from the drop down menu and select "Contour Map" then "New Contour Map." Choose the grid file you just created.
5. Contour Map Properties settings
   a. Select "Fill Contours" Option

b. Go to “Level” tab and Select “Load” button.
c. Locate and select .lvl file generated by the report function of the GPRQA program for the section being mapped in the section results directory.
d. Return to “Options” tab and select “Apply” button.

Checking High, Medium and Low Dielectric Points on the Map

1. Digitize Map: Right click on map and select “digitize”.
2. Using curser, select points of interest on the contour plot.
3. The X and Y coordinates of the points will be displayed in a window as they are selected.
4. In the window, select “File” then “Save as”, to save the digitized points to file
5. Open this file in surfer and in Column A give each location a unique “core ID” name and indicate if dielectric was picked as high, medium or low value. Column B will have the station number and column C will have the offset. Save this file as a .DAT file with comma separated values.
6. In the GPRQA program, select Update Cores and read in .DAT file just created.
7. Run a “Core Locations” report in the GPRQA program and enter an appropriate radius for the area around the core to use in calculating the surface dielectric value at each core location. See “Create Reports” section above for instruction.
8. This report will give the dielectric values at the core locations.

APPENDIX B

SAMPLE DATA COLLECTION SHEETS

Attachment B
Sample Data Collection Sheets

GPR-QA for Asphalt Density
Project Data Collection Sheet

GPR Operator: ______________________________ Date: ________________________

DRIVER/CREW CHIEF: ____

Project Title: ______________________________ Project No.: ________________________

Onsite Inspector: ______________________________ Contact Info: ________________________

PAVING CONTRACTOR: ____

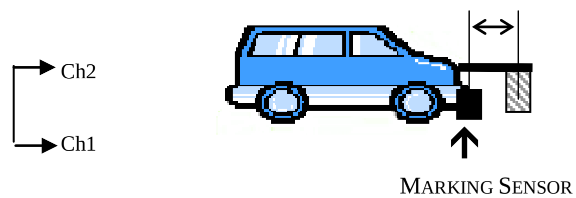
Data Collection Equipment/Settings

ANTENNA INFO: ☐ **2 GHz** ☐ ________

SPACING BETWEEN ANTENNAS: ☐ **4 FT** ☐ ________

ANTENNA OFFSET FROM MARK: ☐ **-4.674 FT** ☐ ________

ANTENNA CONFIGURATION:



GPR Settings

SAMPLES PER SCAN: ☐ **512** ☐ ______

RANGE (NS): ☐ **6** ☐ ______

SCANS PER FOOT: ☐ **4** ☐ ______

Site Layout/Coordinate System

Attachment B

Sample Data Collection Sheets

GPR-QA for Asphalt Density Measurements

Section Data Collection Sheet

SECTION ID: ______________________________ DATE: ____________________________________

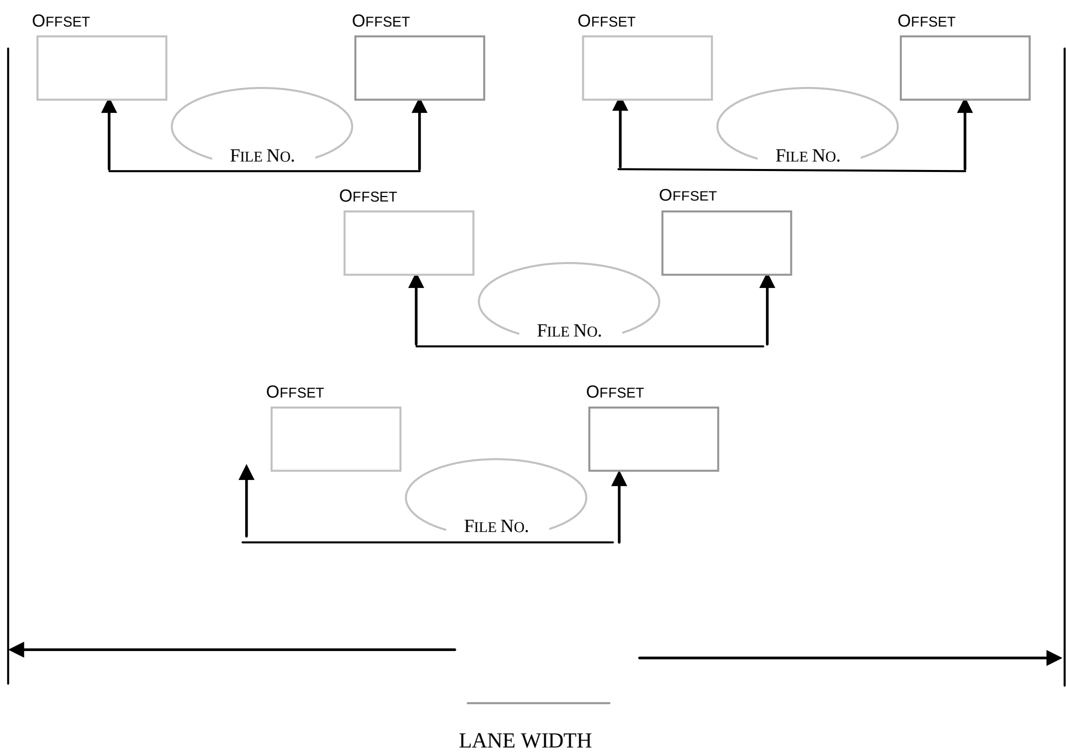
PAVEMENT LIFT TESTED: ____

LOCATION & DIRECTION: ____

START STATION: ____

END STATION: ____

FILE PREFIX: ______________________________ PLATE FILE: _______________________________



Core Locations

Core #	Station (ft.)	Offset (ft.)

APPENDIX C

Paving Material

Job Mix Design Information

State Road 20

STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION

STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR BITUMINOUS CONCRETE

SUBMIT TO THE STATE MATERIALS ENGINEER, CENTRAL BITUMINOUS LABORATORY, 5007 NORTHEAST 39TH AVENUE, GAINESVILLE, FLA. 32609

Contractor: APAC-Southeast, Inc., First Coast Division
Address: 6602 Colray Ct. Jacksonville, FL 32258

Phone No.: (904) 260-1565
Fax No.: (904) 260-8940
E-mail: david.mcnabb@apac.com

Submitted By: APAC-Southeast, Inc.
Type Mix: Fine SP-12.5 Recycle
Intended Use of Mix: Structural

Design Traffic Level: C
Gyrations @ Ndes: 75

Product Description	Product Code	Producer Name	Product Name	Plant/Pit Number	Terminal
1. Milled Material	334-MM	213003-3-52-01 MP 8.922 - 20.396	SR-8	A0621	
2. #78 Stone	C54	Conrad Yelvington	#78 Stone	GA383	
3. #89 Stone	C51	Conrad Yelvington	#89 Stone	GA383	
4. W-10 Screenings	F21	Conrad Yelvington	W-10 Screenings	GA383	
5.					
6.					
7. Recycling Agent	916-RA		RA 700		

PERCENTAGE BY WEIGHT TOTAL AGGREGATE PASSING SIEVES

	Blend	35%	15%	10%	40%			JOB MIX	CONTROL	PRIMARY
	Number	1	2	3	4	5	6	FORMULA	POINTS	CONTROL SIEVE
SIEVE SIZE	3/4" 19.0mm	100	100	100	100			100	100	
	1/2" 12.5mm	98	94	100	100			98	90 - 100	
	3/8" 9.5mm	92	55	99	100			90	- 90	
	No. 4 4.75mm	69	8	20	98			67		
	No. 8 2.36mm	54	6	7	69			48	28 - 58	39
	No. 16 1.18mm	46	2	3	39			32		
	No. 30 600µm	40	2	3	25			25		
	No. 50 300µm	29	2	2	16			17		
	No. 100 150µm	17	1	2	9			10		
	No. 200 75µm	9.3	1.0	1.5	5.0			6.3	2 - 10	
	G_{SB}	2.639	2.772	2.768	2.725			2.705		

The mix properties of the Job Mix Formula have been conditionally verified, pending successful final verification during production at the assigned plant, the mix design is approved subject to F.D.O.T. specifications.

JMF reflects aggregate changes expected during production

SP 08-6655B (TL-C)

SP 08-6655A (TL-C) revised to reflect change in the recycling agent.

Director, Office of Materials

Original document retained at the State Materials Office

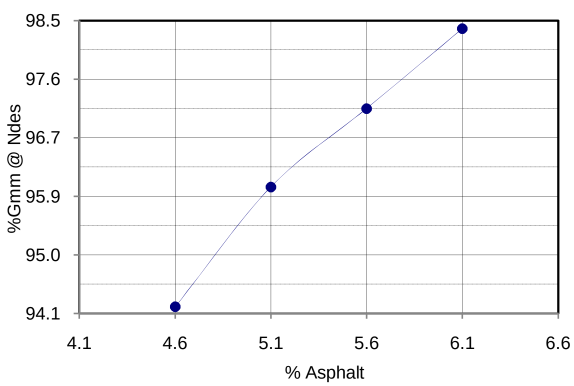
Effective Date: 11 / 28 / 2008

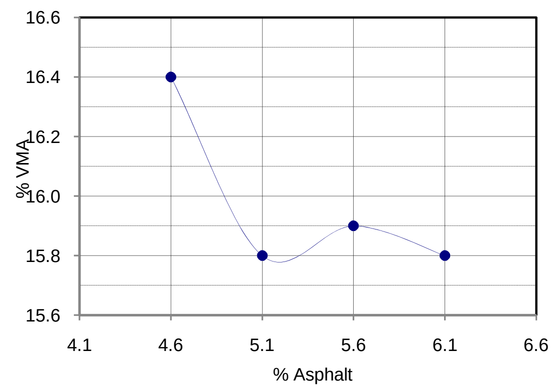
Expiration Date: 10 / 09 / 2011

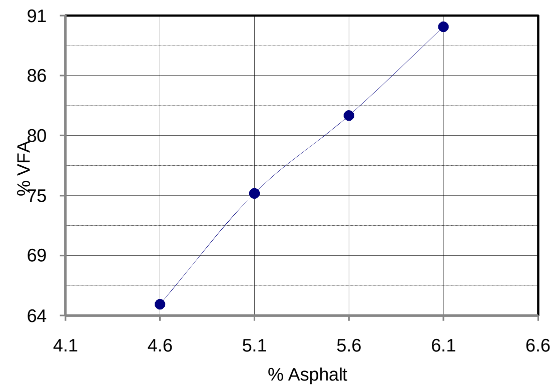
HOT MIX DESIGN DATA SHEET

SP 08-6655B (TL-C)

P_b	G_{mb} @ N_{des}	G_{mm}	V_a	VMA	VFA	P_{be}	$P_{0.075}$ / P_{be}	$\%G_{mm}$ @ N_{ini}	$\%G_{mm}$ @ N_{max}
4.6	2.370	2.516	5.8	16.4	65	4.6	1.4	89.0	
5.1	2.400	2.500	4.0	15.8	75	5.1	1.2	88.4	97.5
5.6	2.410	2.480	2.8	15.9	82	5.6	1.1	90.4	
6.1	2.425	2.465	1.6	15.8	90	6.0	1.1	92.6	







Total Binder Content 5.1 %

FAA 45.0 %

(Plant)
Mixing Temperature 315 °F 157 °C

Spread Rate @ 1" 108 lbs/vd^2

$\%G_{mm}$ @ N_{des} 96.0

(Roadway)
Compaction Temperature 300 °F 149 °C

VMA 15.8 %

NCAT Oven Calibration Factor -0.05

(+To Be Added)/(-To Be Subtracted)

Arr-Maz Ad-Here LOF 65-00 (S916-1012)
Additives Antistrip 0.5 % ______ %

Optimum Asphalt = 5.10%

Asphalt using 35% Milled Material @ 6.1% = 2.10%

RA 700 to be added = 3.00%

State Road 23

S. _ OF FLORIDA DEPARTMENT OF TRANSPC ION

STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR BITUMINOUS CONCRETE

SUBMIT TO THE STATE MATERIALS ENGINEER, CENTRAL BITUMINOUS LABORATORY, 5007 NORTHEAST 39TH AVENUE, GAINESVILLE, FLA. 32609

Contractor: Atlantic Coast Asphalt Co. Address: 5154 Edwards St., Jacksonville, FL 32254

Phone No. (904) 786-1020 Fax No. (904) 695-0433 E-mail dbrown@hubbard.com

Submitted By: Asphalt Technologies, Inc. Type Mix: Fine SP-12.5 Recycle Intended Use of Mix: Structural

Design Traffic Level: E Gyrations @ Ndes: 100

TYPE MATERIAL	F.D.O.T. CODE	PRODUCER	PIT NO.	DATE SAMPLED
1. Crushed R.A.P.	1-07	Atlantic Coast Asphalt Co.	A0750	01 / 17 / 2007
2. #78 Stone	54	Martin Marietta Aggregates	TM-337 GA-383	01 / 17 / 2007
3. #89 Stone	54	Martin Marietta Aggregates	TM-579 NS-315	01 / 17 / 2007
4. W-10 Screenings	23	Martin Marietta Aggregates	TM-579 NS-315	01 / 17 / 2007
5. Sand		Atlantic Coast Asphalt Co.	Soutel Pit	01 / 17 / 2007
6.				
7. PG 64-22	916-PG			

PERCENTAGE BY WEIGHT TOTAL AGGREGATE PASSING SIEVES

	Blend	20%	20%	18%	35%	7%		JOB MIX	CONTROL	PRIMARY
	Number	1	2	3	4	5	6	FORMULA	POINTS	CONTROL SIEVE
SIEVE SIZE	3/4" 19.0mm	100	100	100	100	100		100	100	
	1/2" 12.5mm	99	88	100	100	100		97	90 - 100	
	3/8" 9.5mm	93	60	95	100	100		90	- 90	
	No. 4 4.75mm	73	12	42	91	100		63		
	No. 8 2.36mm	54	4	11	57	100		41	28 - 58	39
	No. 16 1.18mm	41	3	4	32	100		28		
	No. 30 600μm	33	3	3	16	100		20		
	No. 50 300μm	27	2	2	10	100		17		
	No. 100 150μm	17	2	2	5	30		8		
	No. 200 75μm	7.1	1.0	1.0	3.5	2.0		3.2	2 - 10	
	G_{SB}	2.638	2.772	2.625	2.610	2.620		2.650		

The mix properties of the Job Mix Formula have been conditionally verified, pending successful final verification during production at the assigned plant, the mix design is approved subject to F.D.O.T. specifications.

SP 07-5451A (TL-E)

Director, Office of Materials: Thomas O. Malerk, P.E.

Original document retained at the State Materials Office

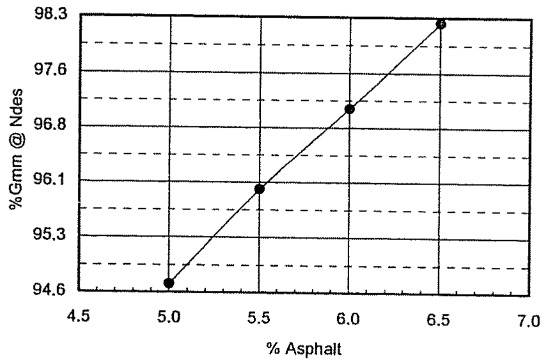
Effective Date: 07 / 10 / 2007

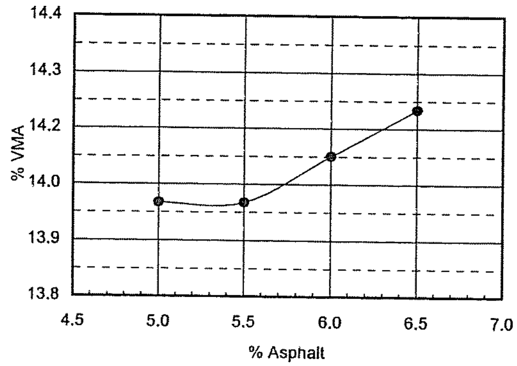
Expiration Date: 07 / 10 / 2010

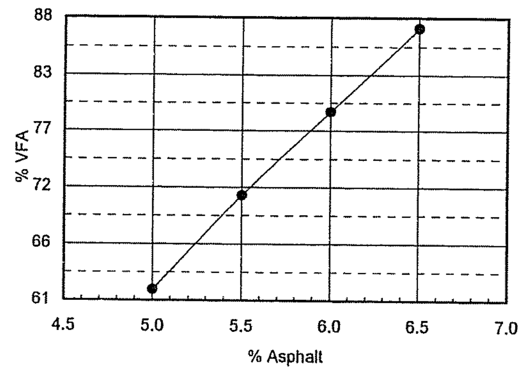
HOT MIX DESIGN DATA SHEET

SP 07-5451A (TL-E)

P_b	G_{mb} @ N_{des}	G_{mm}	V_a	VMA	VFA	P_{be}	$P_{0.075}$ / P_{be}	%G_{mm} @ N_{ini}	%G_{mm} @ N_{max}
5.0	2.399	2.533	5.3	14.0	62	3.7	0.9	87.3	96.6
5.5	2.413	2.514	4.0	14.0	71	4.2	0.8	88.4	97.4
6.0	2.422	2.495	2.9	14.1	79	4.7	0.7	89.4	98.3
6.5	2.432	2.476	1.8	14.2	87	5.3	0.6	90.5	99.1







Total Binder Content 5.5 %

Spread Rate @ 1" 109 lbs/yd^2

VMA 14.0 %

FAA 45.0 %

%G_{mm} @ N_{des} 96.0

NCAT Oven Calibration Factor -0.19
(+To Be Added)/(-To Be Subtracted)

Mixing Temperature 310 °F 154 °C

Compaction Temperature 305 °F 152 °C

Arr-Maz Ad-Here LOF 65-00 (S916-1012)

Additives Antistrip 0.5 % ______ %

Optimum Asphalt = 5.50%

Asphalt using 20% Crushed R.A.P. @ 5.0% = 1.00%

PG 64-22 to be added = 4.50%

CORRECTED COPY

CORRECTED COPY

STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION

STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR BITUMINOUS CONCRETE

SUBMIT TO THE STATE MATERIALS ENGINEER, CENTRAL BITUMINOUS LABORATORY, 5007 NORTHEAST 39TH AVENUE, GAINESVILLE, FLA. 32609

Contractor: Atlantic Coast Asphalt Co. Address: 5154 Edwards St., Jacksonville, FL 32254

Phone No.: (904) 786-1020 Fax No.: (904) 695-0433 E-mail: dbrown@hubbard.com

Submitted By: Asphalt Technologies, Inc. Type Mix: Fine SP-12.5 Recycle Intended Use of Mix: Structural

Design Traffic Level: E Gyrations @ Ndes: 100

TYPE MATERIAL	F.D.O.T. CODE	PRODUCER	PIT NO.	DATE SAMPLED
1. Crushed R.A.P.	1-07	Atlantic Coast Asphalt Co.	A0750	08 / 13 / 2007
2. # 7 Stone	44	Martin Marietta Aggregates	TM-579 NS-315	08 / 13 / 2007
3. # 89 Stone	54	Martin Marietta Aggregates	TM-579 NS-315	08 / 13 / 2007
4. W-10 Screenings	23	Martin Marietta Aggregates	TM-579 NS-315	08 / 13 / 2007
5. Sand		Atlantic Coast Asphalt Co.	Soutel Plant	08 / 13 / 2007
6.				
7. PG 76-22	916-PG			

PERCENTAGE BY WEIGHT TOTAL AGGREGATE PASSING SIEVES

	Blend	15%	25%	10%	40%	10%		JOB MIX FORMULA	CONTROL POINTS	PRIMARY CONTROL SIEVE
	Number	1	2	3	4	5	6			
SIEVE SIZE	3/4" 19.0mm	100	100	100	100	100		100	100	
	1/2" 12.5mm	99	95	100	100	100		99	90 - 100	
	3/8" 9.5mm	93	65	95	100	100		90	- 90	
	No. 4 4.75mm	73	14	42	91	100		65		
	No. 8 2.36mm	54	3	11	60	100		44	28 - 58	39
	No. 16 1.18mm	41	2	4	36	100		31		
	No. 30 600μm	33	2	3	21	100		24		
	No. 50 300μm	27	2	2	12	100		20		
	No. 100 150μm	17	2	2	7	40		10		
	No. 200 75μm	7.1	1.0	1.0	4.0	2.0		3.2	2 - 10	
	G_{SB}	2.638	2.629	2.625	2.610	2.620		2.621		

The mix properties of the Job Mix Formula have been conditionally verified, pending successful final verification during production at the assigned plant, the mix design is approved subject to F.D.O.T. specifications.

SPM 07-5665A (TL-E)

This corrected copy cancels and supersedes the original due to incorrect data for component #5.

Director, Office of Materials: Thomas O. Malerk, P.E.
Original document retained at the State Materials Office

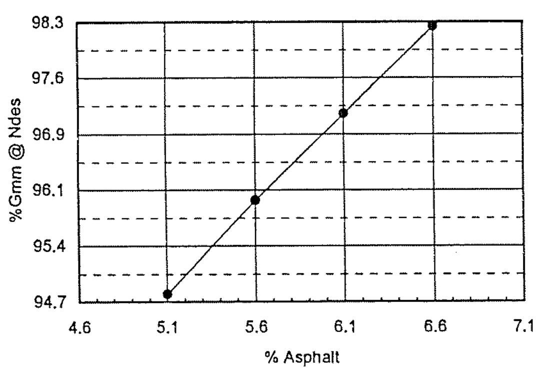
Effective Date: 10 / 22 / 2007

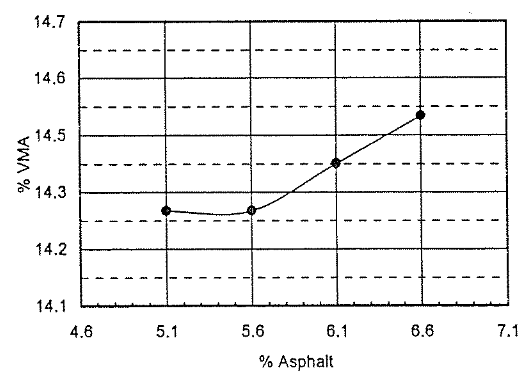
Expiration Date: 10 / 22 / 2010

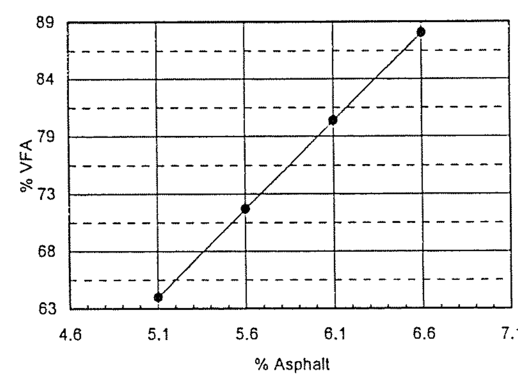
HOT MIX DESIGN DATA SHEET

SPM 07-5665A (TL-E)

P_b	G_{mb} @ N_{des}	G_{mm}	V_a	VMA	VFA	P_{be}	$P_{0.075}$ / P_{be}	%G_{mm} @ N_{ini}	%G_{mm} @ N_{max}
5.1	2.367	2.497	5.2	14.3	64	4.0	0.8	86.8	95.8
5.6	2.379	2.478	4.0	14.3	72	4.5	0.7	88.1	96.9
6.1	2.389	2.460	2.9	14.4	80	5.0	0.6	89.2	97.9
6.6	2.399	2.442	1.8	14.5	88	5.5	0.6	90.3	98.8







Total Binder Content 5.6 %

FAA 45.0 %

Mixing Temperature 330 °F 166 °C

Spread Rate @ 1" 107 lbs/yd^2

%G_{mm} @ N_{des} 96.0

Compaction Temperature 325 °F 163 °C

VMA 14.3 %

NCAT Oven Calibration Factor -0.15

(+To Be Added)/(-To Be Subtracted)

Arr-Maz Ad-Here LOF 65-00 (S916-1012)

Additives Antistrip 0.5 % ______ %

Optimum Asphalt = 5.60%

Asphalt using 15% Crushed R.A.P. @ 5.0% = 0.80%

PG 76-22 to be added = 4.80%

State Road 222

STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION

STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR BITUMINOUS CONCRETE

SUBMIT TO THE STATE MATERIALS ENGINEER, CENTRAL BITUMINOUS LABORATORY, 5007 NORTHEAST 39TH AVENUE, GAINESVILLE, FLA. 32609

Contractor: APAC-Southeast, Inc., First Coast Division   Address: 6602 Colray Ct., Jacksonville, FL 32258

Phone No.: (904) 338-6328   Fax No.: (904) 288-8940   E-mail: dmcnabb@apac.com

Submitted By: APAC-Southeast, Inc.   Type Mix: Fine SP-12.5 Recycle   Intended Use of Mix: Structural

Design Traffic Level: C   Gyrations @ Ndes: 75

Product Description	Product Code	Producer Name	Product Name	Plant/Pit Number	Terminal
1. Milled Material	334-MM	213554-2-52-01	SR-93	A0752	
2. #78 Stone	C54	Martin Marietta Materials	#78 Stone	GA383	TM614
3. #89 Stone	C51	Martin Marietta Materials	#89 Stone	GA383	TM614
4. W-10 Screenings	F21	Martin Marietta Materials	W-10 Screenings	GA383	TM614
5. Local Sand	334-LS	Florida Rock Industries	Putnam		
6.					
7. PG 76-22	916-76		PG 76-22		

PERCENTAGE BY WEIGHT TOTAL AGGREGATE PASSING SIEVES

SIEVE SIZE	Blend	15%	17%	5%	58%	5%		JOB MIX	CONTROL	PRIMARY
	Number	1	2	3	4	5	6	FORMULA	POINTS	CONTROL SIEVE
	3/4" 19.0mm	100	100	100	100	100		100	100	
	1/2" 12.5mm	98	94	100	100	100		99	90 - 100	
	3/8" 9.5mm	86	55	99	100	100		90	- 90	
	No. 4 4.75mm	47	8	20	97	100		71		
	No. 8 2.36mm	30	6	7	63	100		47	28 - 58	39
	No. 16 1.18mm	23	3	3	42	91		33		
	No. 30 600µm	18	3	3	26	89		23		
	No. 50 300µm	15	3	3	18	65		17		
	No. 100 150µm	12	3	2	9	19		9		
	No. 200 75µm	8.8	1.3	1.0	4.7	1.0		4.4	2 - 10	
	G_{SB}	2.654	2.772	2.768	2.725	2.648		2.720		

The mix properties of the Job Mix Formula have been conditionally verified, pending successful final verification during production at the assigned plant, the mix design is approved subject to F.D.O.T. specifications.

SPM 09-6956B (TL-C)

SPM 09-6956A (TL-C) revised to reflect JMF change (No.200)

Director, Office of Materials

Original document retained at the State Materials Office

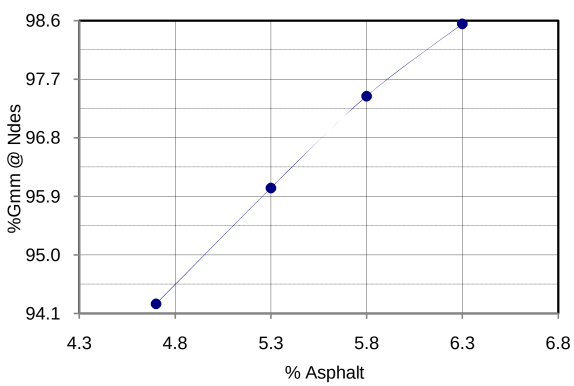
Effective Date: 04 / 10 / 2009

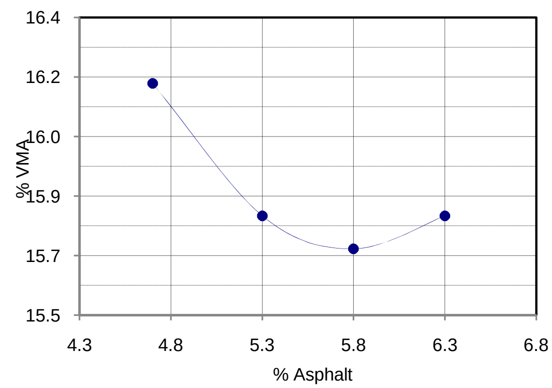
Expiration Date: 03 / 13 / 2012

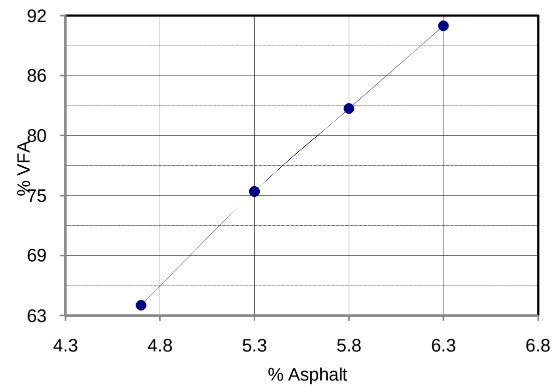
HOT MIX DESIGN DATA SHEET

SPM 09-6956B (TL-C)

P_b	G_{mb} @ N_{des}	G_{mm}	V_a	VMA	VFA	P_{be}	$P_{0.075}$ / P_{be}	$\%G_{mm}$ @ N_{ini}	$\%G_{mm}$ @ N_{max}
4.7	2.391	2.537	5.8	16.2	64	4.5	1.0	87.8	
5.3	2.417	2.517	4.0	15.8	75	5.1	0.9	88.2	97.5
5.8	2.435	2.499	2.6	15.7	83	5.5	0.8	89.8	
6.3	2.445	2.481	1.5	15.8	91	6.0	0.7	92.0	







Total Binder Content 5.3 %

Spread Rate @ 1" 109 lbs/yd[2]

VMA 15.8 %

FAA 48.0 %

$\%G_{mm}$ @ N_{des} 96.0

NCAT Oven Calibration Factor +0.05
(+To Be Added)/(-To Be Subtracted)

(Plant)
Mixing Temperature 330 °F 166 °C

(Roadway)
Compaction Temperature 325 °F 163 °C

Arr-Maz Ad-Here LOF 65-00 (S916-1012)
Additives Antistrip 0.75 % ______ %

Optimum Asphalt = 5.30%
Asphalt using 15% Milled Material @ 5.8% = 0.90%
PG 76-22 to be added = 4.40%