
SHRP 2 Renewal Project R06C

Pre-Implementation of Infrared and Ground-Penetrating Radar Technologies for Improving Asphalt Mixture Quality

Pre-Implementation of Infrared and Ground-Penetrating Radar Technologies for Improving Asphalt Mixture Quality

DETAILS

0 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-43363-1 | DOI 10.17226/22408

AUTHORS

Sebesta, Stephen; and Scullion, Tom

SHRP 2 Renewal Project R06C

Pre-Implementation of Infrared and Ground-Penetrating Radar Technologies for Improving Asphalt Mixture Quality

SHRP 2
STRATEGIC HIGHWAY RESEARCH PROGRAM
Accelerating solutions for highway safety, renewal, reliability, and capacity

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

SHRP 2 Renewal Project R06C

Pre-Implementation of Infrared and Ground-Penetrating Radar Technologies for Improving Asphalt Mixture Quality

Stephen Sebesta and Tom Scullion

Texas A&M Transportation Institute

The Texas A&M University System

College Station, Texas

TRANSPORTATION RESEARCH BOARD
Washington, D.C.
2014
www.TRB.org

ACKNOWLEDGMENT
This work was sponsored by the Federal Highway Administration in cooperation with the American Association of State Highway and Transportation Officials. It was conducted in the second Strategic Highway Research Program, which is administered by the Transportation Research Board of the National Academies.

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. C. D. (Dan) Mote, Jr., is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. C.D. (Dan) Mote, Jr., are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

CONTENTS

AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under the second Strategic Highway Research Program (SHRP 2) Project R06C by the Texas A&M Transportation Institute at Texas A&M University. The Texas A&M Transportation Institute was the contractor for the project, with the Research Foundation of Texas A&M University serving as the fiscal administrator.

The research team extends special thanks to the Virginia Department of Transportation and Pennsylvania Department of Transportation for participating in pilot construction projects. Also, this project would not have been possible without the input of SHRP 2 Senior Program Officers Dr. Monica Starnes, Dr. James Bryant, and Matthew Miller.

ABSTRACT

In this project, researchers performed pre-implementation of infrared (IR) and ground-penetrating radar (GPR) technologies for measuring uniformity and promoting quality of asphalt mixture paving. The project team coordinated with industry to streamline the processes required for using GPR in this application, developed draft procedures for both IR and GPR technologies, and conducted pilot projects with the Virginia and Pennsylvania Departments of Transportation. The pilot projects demonstrated that both IR and GPR provide a useful full-coverage view of the paving operation. Each pilot project employed a warm-mix asphalt (WMA) technology as a compaction aid. These pilot project results suggested that the significance and acceptance criteria of thermal segregation may need more reevaluation with WMA. The utility of GPR was realized on all pilot projects, where the radar results provided quantitative assessment of density and uniformity. A new radar system developed specifically for uniformity assessment of asphalt mixtures achieved significant advances in the state of the practice with radar. This report presents the pilot project results, draft standard specifications for both IR and GPR, and conclusions on how these technologies could be used in construction specifications.

EXECUTIVE SUMMARY

INTRODUCTION

Placement of an asphalt mixture overlay remains a common practice for highway renewal activities. A new overlay can be used to extend a pavement's acceptable service with minimal disruption to the public due to the rapid nature of construction. Advances in asphalt mixture design have enabled better performing mixtures to be produced and placed, and the maturation of warm-mix asphalt (WMA) technology has expanded paving seasons and potentially made proper field compaction more readily attainable. However, quality assurance remains a critical element of ensuring that the long-lived aspect of renewal activities gets realized. In the case of asphalt mixture construction, achieving proper density, free of segregation, remains a key component to long overlay life.

Common quality assurance practices for density and segregation rely on spot tests with density gauges to help set rolling patterns, estimate field density, or estimate localized density variations. Such spot tests remain labor intensive and provide little testing coverage. It must be recalled that segregated areas can be as small as 10 to 15 square feet at cyclical intervals along the pavement. These localized areas fail first and often result in premature resurfacing projects. It is doubtful that these small, localized problem areas could ever be reliably detected with random spot measurements.

Due to these limitations, the second Strategic Highway Research Program (SHRP 2) began efforts in March 2009 to evaluate asphalt mixture construction for uniformity and segregation using near full-coverage techniques. These techniques included infrared (IR) thermal profiling and ground-penetrating radar (GPR). The thermal profile provides a measurement of the temperature uniformity and thermal segregation of the new mat during construction. While the thermal profile occurs before any compaction rolling, the

GPR measurement occurs after all finish rolling and therefore measures the final in-place product.

Based on promising initial results showing the utility of thermal profiling and GPR for evaluating asphalt mixture construction for density, uniformity, and segregation, SHRP 2 initiated a phase of work to conduct pilot projects with two departments of transportation (DOTs). After the SHRP 2 contractor identified two states to participate in the pilots, worked with an original equipment manufacturer for development of a GPR system tailored for asphalt mixture evaluation, and developed general procedures for data collection and reporting, the team worked with the Virginia DOT (VDOT) and Pennsylvania DOT (PennDOT) to pilot the thermal profile and radar technologies on three construction projects.

FINDINGS

All three projects constructed used WMA as a compaction aid; the production temperatures used for all three mixtures were more consistent with hot-mix asphalt (HMA) temperatures. The amount of thermal segregation detected varied by project. In one project, the final in-place density clearly decreased with thermal segregation, while in another project, the density did not relate to thermal segregation within the range of placement temperatures observed. The projects with the least thermal segregation used remixing material transfer devices.

This SHRP 2 project achieved significant advances in the state of the practice with GPR. All pilot projects were evaluated with both a 1 GHz and a new 2.5 GHz air-coupled radar system. While the first-generation prototype GPR system tailored for asphalt mixture evaluation encountered some stability and overheating issues, the second-generation 2.5 GHz system did not exhibit those problems. The new second-generation

2.5 GHz system tailored for asphalt mixture evaluation provided stable readings, rapid results, and easy operation as compared to the 1 GHz system. With the radar systems, the pilot projects also revealed:

- The 1 GHz system may be limited to lift thicknesses of around 1.5 inches or greater.
- The 2.5 GHz system can measure reduced lift thicknesses without interference from lower pavement layers.
- The 2.5 GHz system resolved the problem of multi-step, labor-intensive data processing requirements historically required for asphalt mixture uniformity analysis with radar. The second-generation 2.5 GHz system processes data in real-time, and, on completion of data collection, it can automatically and quickly post-process multiple data collection runs to output uniformity and density statistics.
- The 2.5 GHz system shows promise for accurately measuring compacted lift thickness.

On the whole, results from the three pilot projects showed the two different GPR systems correlated well with each other. As compared to other radar systems, the current version of the new 2.5 GHz radar system provides a much more implementable solution for uniformity analysis of asphalt mixture construction.

CONCLUSIONS

Asphalt mixture overlays will remain a renewal strategy to support rapid renewal while attaining long life. The thermal profiling and ground-penetrating radar tools used in these SHRP 2 pilot projects worked well for measuring uniformity and segregation in new asphalt mixture construction. The thermal profile measured with the system shown in

Figure ES.1 effectively quantified and documented thermal segregation. With the advent of WMA, the impact of thermal segregation on warm mixes could warrant additional research.

Figure ES.1. Pave-IR collecting thermal profile.

The development of a new ground-penetrating radar system in support of this SHRP 2 project brings the idea of operator-friendly, implementable radar profiling of asphalt mixture uniformity to reality. The new 2.5 GHz radar system overcomes hardware, data processing, and staff expertise hurdles that existed in the past. While the calibration of radar to density still appears to remain project specific, the feasibility of developing a catalog of standard calibrations for different mixtures to measure density using radar may warrant additional research. Even without such a catalog, the new GPR technology offers a solution suitable for routine operation to evaluate density and uniformity of asphalt mixture construction.

The new GPR system used in this project was a single-channel system shown in Figure ES.2. A key point of work in this project has been that of providing a rolling density measurement system to detect and help eliminate segregation. The radar system developed during this project worked well to evaluate asphalt mixture density and uniformity. Currently, plans are developing in the industry for a three-channel system that could be vehicle-mounted to obtain moving density measurements in one pass covering both wheel paths and between the wheel paths.

In addition to segregation, properly compacting longitudinal joints also can be a major problem in asphalt mixture construction. Significant advances in curing segregation and poorly compacted joints can be made if technology is available to quickly determine the existence and severity of these problems. The radar system developed during this project shows promise for providing that needed technology.

Figure ES.2. GPR System for measuring asphalt mixture uniformity.

RECOMMENDATIONS

Based on the findings and conclusions from this project, thermal profiling using the procedure outlined in Appendix A should be considered for owner-agencies desiring to promote uniform asphalt mixture construction free of thermal segregation. This specification has been provided to the American Association of State Highway and Transportation Officials (AASHTO) for review. Currently, Minnesota Department of Transportation (MnDOT) is championing thermal profiling for adoption within the AASHTO Subcommittee on Materials Technical Section 5C.

With GPR, the procedure outlined in Appendix B should be considered for evaluating the density uniformity of asphalt mixture construction.

Substantial support and interest in further developing the thermal profile and radar technologies exist within departments of transportation. Several additional DOTs volunteered projects to participate in this SHRP 2 project. To further promote adoption of these technologies, additional outreach work such as workshops, incentives, technical support or data support, or other supporting activities should occur to provide exposure to the thermal profiling and GPR tools to interested agencies and contractors.

CHAPTER 1

BACKGROUND

PROBLEM STATEMENT AND RESEARCH OBJECTIVE

In-place density is a critical factor in determining pavement durability in HMA. Localized nonuniform zones of mix, termed segregation, often become low-density areas in the mat. Segregation continues to be a major construction-related problem with a significant adverse impact on pavement service life. Real-time nondestructive testing (NDT) procedures are ideal tools for providing feedback to paving crews, and recent studies have shown that infrared imaging and ground-penetrating radar can be used to assess in-place density during construction while providing nearly 100% testing coverage of the constructed area.

The objective of this project was to demonstrate IR and GPR technologies as NDT techniques to assess asphalt mixture density and segregation and to make recommendations for how these technologies can be incorporated into existing department of transportation specifications for construction quality assurance.

SCOPE OF STUDY

Success of initial demonstrations with IR and GPR conducted in Phase 1 of this project revealed the need to conduct preliminary implementation activities. To support these activities, SHRP 2 authorized Phase 3 for the research team to develop specifications, refine software to streamline data collection and processing, and conduct pilot projects with state DOTs.

CHAPTER 2

RESEARCH APPROACH

INTRODUCTION

This project built on prior SHRP 2 R06C work by moving the project into a pre-implementation phase, in which the research team used the IR and GPR technologies to coordinate and conduct pilot projects with two state DOTs. The pilot projects served to provide interested states with experience using IR and GPR for uniformity assessment of asphalt mixture construction and allowed the RO6C contractor to further refine the state of the practice. In this Phase 3 pre-implementation work, eight tasks—summarized below—enabled the research team to identify interested states, determine expectations of each state from pilot project activities, streamline data processing of GPR, develop draft procedures in AASHTO-formatted language, and secure a medium for presenting results to a widespread audience.

PROJECT TASKS

The following list summarizes the Phase 3 project tasks:

- **Task 10:** Develop and submit to SHRP 2 a detailed work plan to meet the objectives of Phase 3. The work plan should include recommendations for pilots with at least two state DOTs.
- **Task 11:** Based on the two state DOTs selected in Task 10, develop state-specific draft specifications for both NDT technologies (IR and GPR). Development of these specifications will require close coordination with the selected DOTs.
- **Task 12:** Conduct the needed software modifications to facilitate the use of these technologies for future implementing agencies.

- **Task 13:** Develop data collection protocols, including test procedures, in AASHTO-formatted language for both NDT technologies.
- **Task 14:** Conduct pilot testing in the two DOTs that were selected.
- **Task 15:** Collect feedback from the two participating DOTs and revise specifications, test procedures, and/or data processing based on the pilot projects.
- **Task 16:** Develop and conduct a national webinar and/or a Transportation Research Board (TRB) workshop to present the current state of the practice of each technology, steps required for and lessons learned from pilot project activities, and case studies.
- **Task 17:** Prepare a draft final report documenting all work conducted, as well as findings and recommendations, and submit it to SHRP 2 for review.

CHAPTER 3

FINDINGS AND APPLICATIONS

SUMMARY

The pre-implementation work conducted in this SHRP 2 project showed both the thermal profile and ground-penetrating radar technologies with great potential to evaluate the uniformity of asphalt mixture paving. In this pre-implementation effort, the SHRP 2 contractor worked with the Virginia Department of Transportation (VDOT) and the Pennsylvania Department of Transportation (PennDOT) to perform three pilot projects. Pilot projects with VDOT on US-29 and Route 3 used a Pave-IR system for thermal profiling, as well as a 1 GHz and a prototype 2.5 GHz air-coupled radar system for GPR analysis. On SR-220 with PennDOT, the research team again used the Pave-IR system for thermal profiling, while radar analysis relied mostly on a second-generation 2.5 GHz system, with data also collected using a 1 GHz system for comparison. The pilot projects showed

- The thermal profile system readily installs to field equipment and is straightforward to operate by contractor and DOT staff.
- In addition to thermal segregation, the thermal profile highlights locations of paver stops, which in many cases become localized low-density regions.
- The sensitivity of WMA technologies to thermal segregation appears unclear, with WMA mixtures sometimes clearly influenced by thermal segregation and sometimes seemingly uninfluenced by thermal segregation.
- The 2.5 GHz radar system significantly advanced the state of the practice for evaluating asphalt mixture construction. This new system from Geophysical Survey Systems, Inc.

(GSSI) provides an easily understood operator interface, real-time data processing, and efficient field reporting to rapidly evaluate uniformity and density.

- Since many overlays constructed now are less than 2 inches thick, the 1 GHz radar can be influenced by lower lifts. The 2.5 GHz system is well suited to evaluating overlays for uniformity and segregation without measurements being influenced by lower layers.

PILOT PROJECT ON US-29

On June 11, 2013, the Texas A&M Transportation Institute (TTI) conducted pilot implementation of thermal profiling and ground-penetrating radar nondestructive test technologies on US-29 in coordination with the Virginia Department of Transportation. This pilot implementation served to illustrate how these technologies could be used in quality assurance applications for evaluating a paving process and measuring the uniformity and density of the mat with near full-coverage testing. The TTI project team used a Moba Pave-IR system to collect the thermal profiles and performed radar analysis using TTI’s 1 GHz air-coupled GPR in parallel with a first-generation prototype 2.5 GHz air-coupled system.

Job Mix Formula

The contractor placed a 1.5-inch lift of SM-12.5D. This mix was a dense-graded Superpave™-designed wearing course that used performance grade (PG) 64-22 binder. The mix also included 25 percent reclaimed asphalt pavement (RAP) and foaming warm-mix-asphalt technology. Table 3.1 shows the job mix formula.

Table 3.1. Job Mix Formula for SM-12.5D on US-29 Test Site.

Sieve Size	Composite Formula	Acceptance Range
¾ in.	100	100

½ in.	98	95.2–100
⅜ in.	90	87.2–92.8
No. 8	43	40.2–45.8
No. 200	5.2	4.5–5.9
% AC	5.0	4.89–5.31

Paving Operation

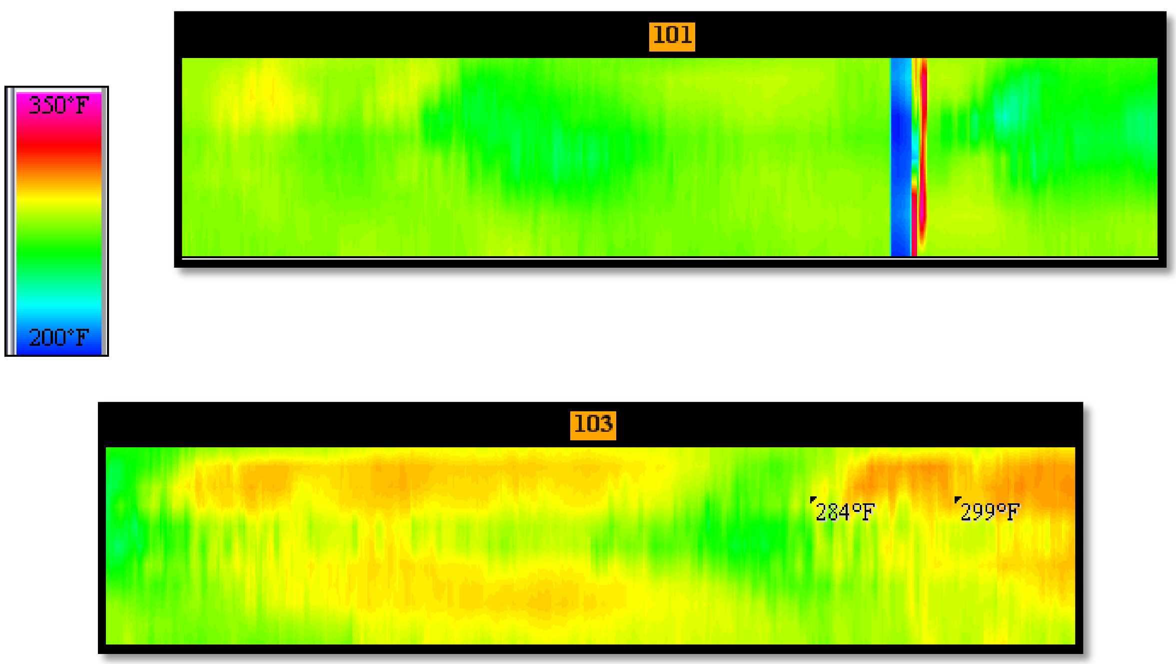
The contractor transported the mix in bobtail trucks, which offloaded into an Ingersol Rand MC 330 to transfer the mix into a Cat AP 1055D paver. Figure 3.1 shows the paving train. The contractor placed the mix overnight, beginning placement at about 7:30 p.m.

Figure 3.1. Paving operation on US-29.

Thermal Survey Result

Thermal profiles were collected from 38.10079 N, 78.46164 W to 38.08718 N, 78.47087 W. The thermal data showed cyclical patterns of truck-end thermal segregation, with temperature differentials typically between 40°F and 60°F. The average paving speed was about 22 ft/min, and, due to paver stops, the paver was idle approximately 50% of the time during the duration of the pull. The average placement temperature was 292°F, with a standard deviation of 13.9°F.

Figure 3.2 shows the thermal profile from 38.0966 N, 78.4650 W to 38.0923 N, 78.4679 W, which was the section focused on for follow-up GPR and coring analysis, resulting in a test section approximately 1,800 ft long. As shown in Figure 3.2, an arbitrary station of 100.00 was assigned at the start point of the test section, and paver stops existed at stations 101.46, 104.52, 107.34, 109.84, 109.96, 111.34, and 115.30. The temperatures measured with Pave-IR at subsequent core locations are also annotated in Figure 3.2 and presented in Table 3.2. Core locations were numbered sequentially from lowest to highest station.



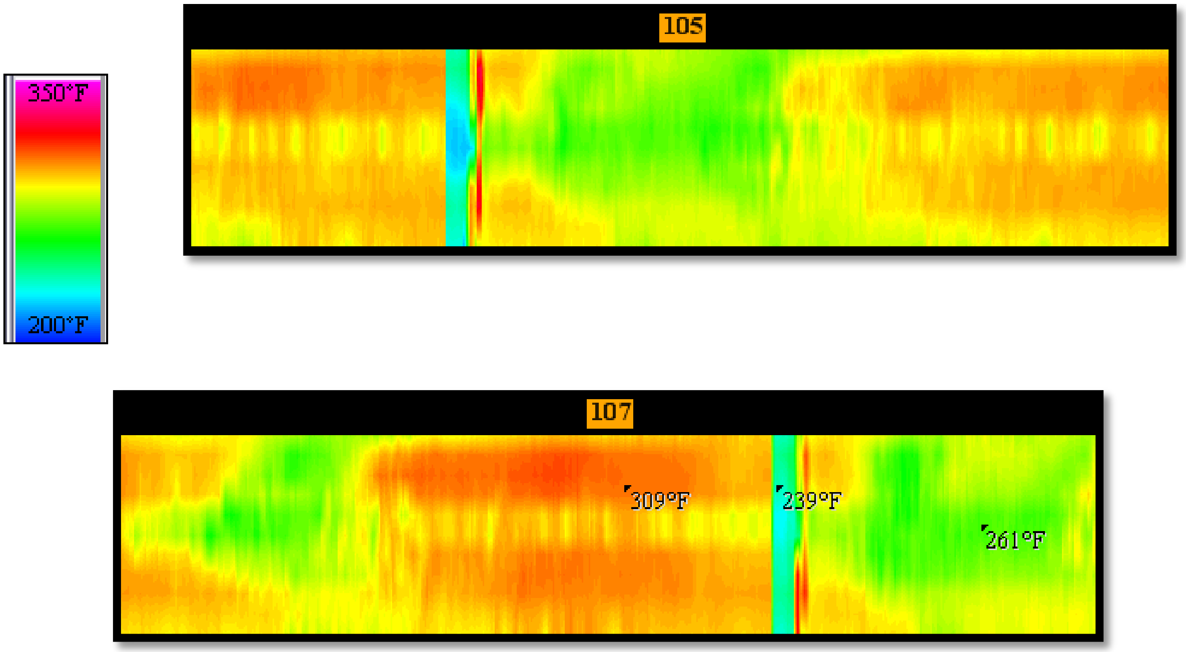
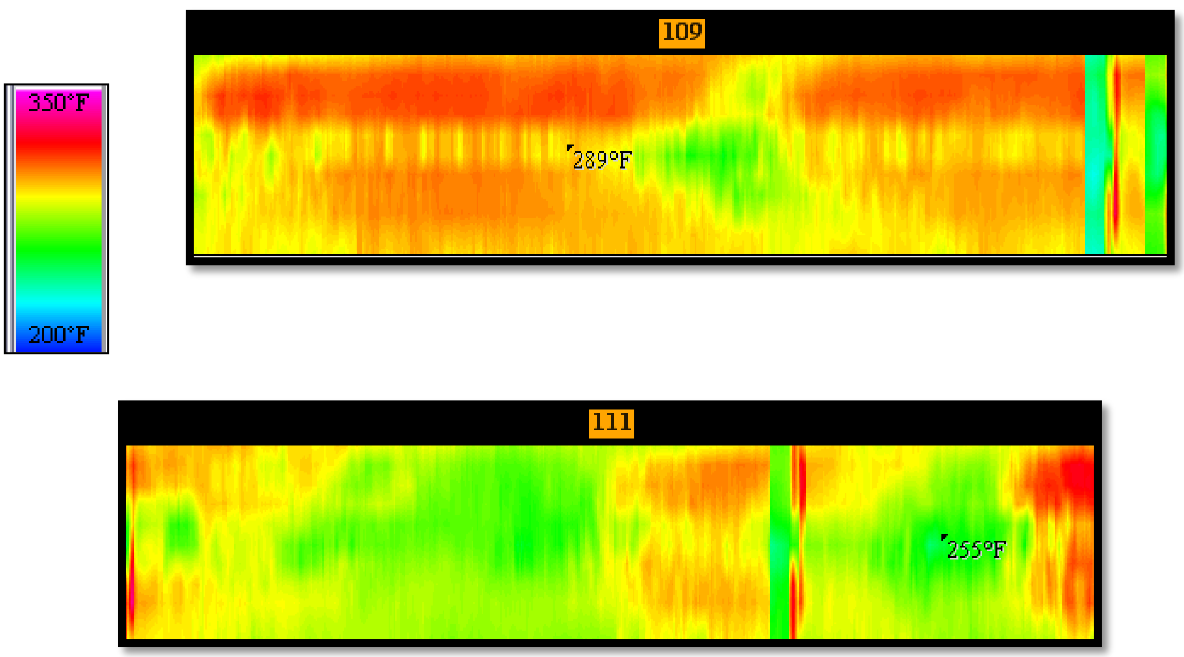


Figure 3.2. Thermal profile from US-29.



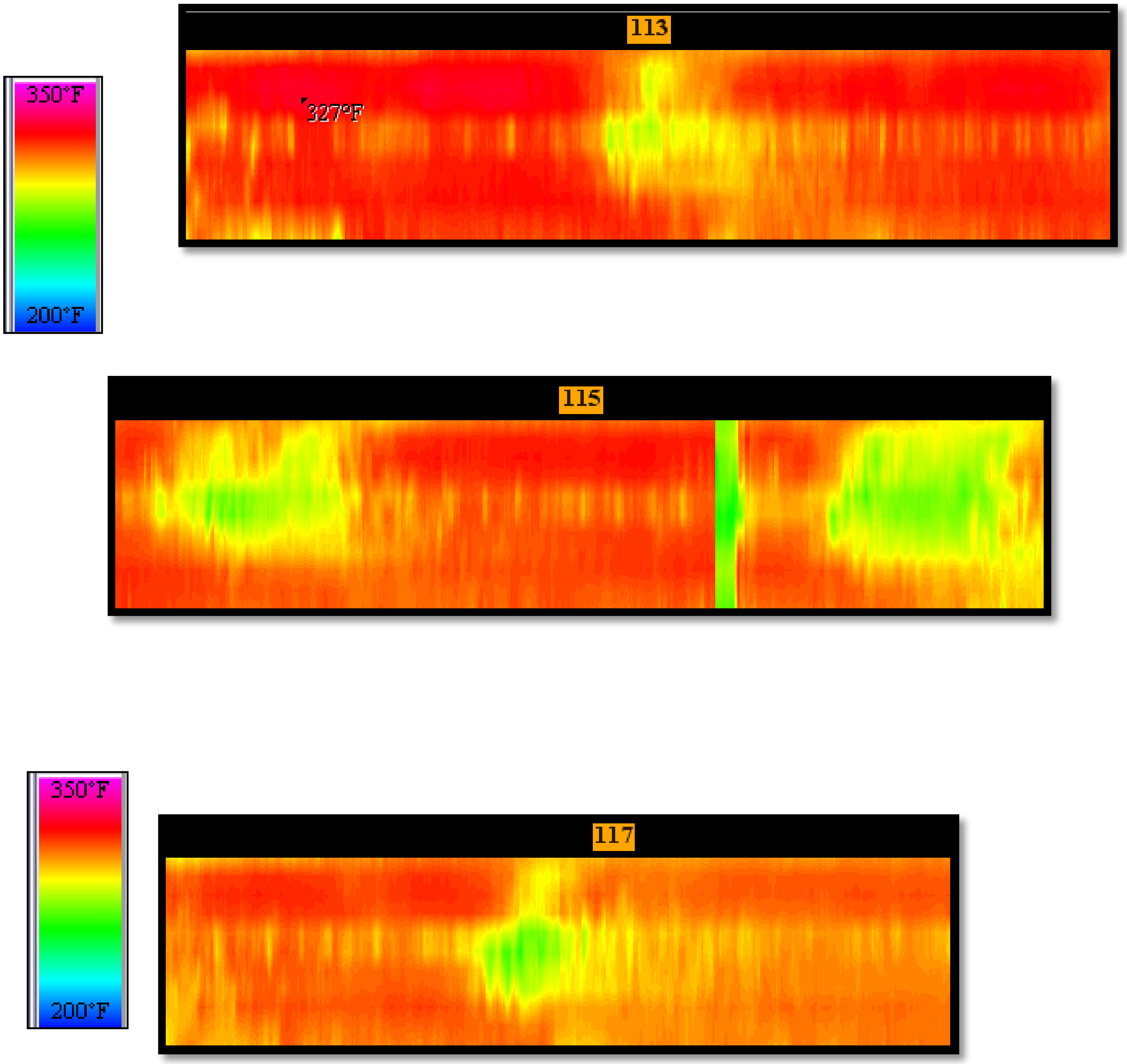


Figure 3.2. Thermal profile from US-29 (continued).

Table 3.2. SM-12.5D Measured Placement Temperatures at Core Locations

Core Number	1	2	3	4	5	6	7	8
IR Temperature (°F)	284	299	309	239	261	289	255	327

From the core results, Figure 3.3 presents the relationship observed between placement temperature and in-place density after all compaction operations. The relationship shows that a 50-degree drop in placement temperature is expected to result in about a 2.2% increase in air voids with this mix and this paving operation.

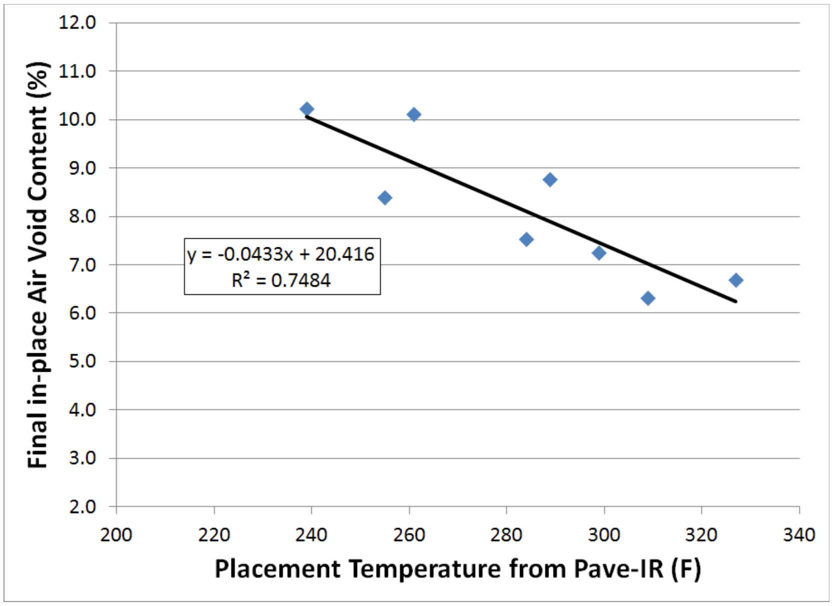


Figure 3.3. Relationship between air voids and placement temperature from US-29.

GPR Survey Result

After the contractor completed finish rolling, the researchers collected GPR data at three different transverse offsets (both wheel paths and the centerline) from 38.0966 N, 78.4650 W to 38.0923 N, 78.4679 W using both the 1 GHz and prototype 2.5 GHz air-coupled systems. After collecting these radar passes, researchers selected eight locations for focused coring based on concurrent field analysis of the thermal profile and radar data. After selecting these core locations, the radar systems were then used to collect GPR data directly over each location for calibration to in-place density. Table 3.3 shows the GPR-measured surface dielectric values (ε) and lab-determined air void content for the eight cores collected. The job mix formula (JMF)-reported Rice gravity of 2.558 g/cc was used in calculation of lab air voids.

Table 3.3. GPR-Measured Core Dielectric Values on US-29

Core Number	1	2	3	4	5	6	7	8
ε from 1 GHz	5.05	5.12	5.22	4.93	4.96	5.07	4.96	5.08
ε from 2.5 GHz	4.51	4.59	4.67	4.42	4.39	4.49	4.45	4.56
Lab Air Voids (%)	7.5	7.2	6.3	10.2	10.1	8.8	8.4	6.7

Figure 3.4 presents the observed calibration between the radar-measured dielectric values and core air voids using Table 3.3's data. Using these calibrations, the project team predicted the in-place air void content at each measurement location in the GPR runs for each radar system, resulting in about 5,400 points of air void estimation with the 1 GHz system and almost 11,000 measurements with the 2.5 GHz system. These predictions yielded the statistics in Table 3.4.

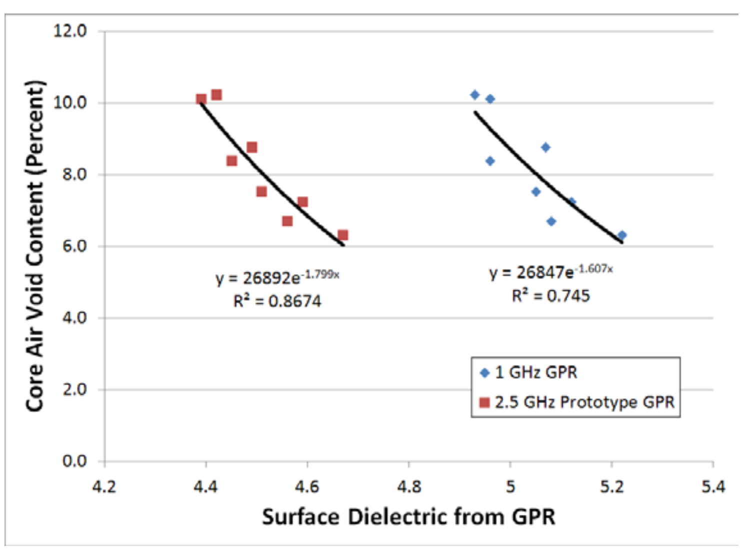


Figure 3.4. Calibration of air voids to GPR from US-29.

Table 3.4. Summary Air Void Statistics from GPR on US-29

Statistic	**1 GHz**	**Prototype 2.5 GHz**
Average	7.38	10.45
Standard Deviation	1.13	1.66
Min	4.29	3.78
Max	18.2	18.75

Using the large quantity of air void measurements, Figure 3.5 presents the expected statistical distribution of air voids in the test section from each radar system. The data listed in Table 3.4 and illustrated in Figure 3.5 show that

- The 2.5 GHz system predicted higher air void contents than the 1 GHz system.
- The statistical distributions of results between the two systems are similar, except the values from the 1 GHz system are offset toward lower air void contents.

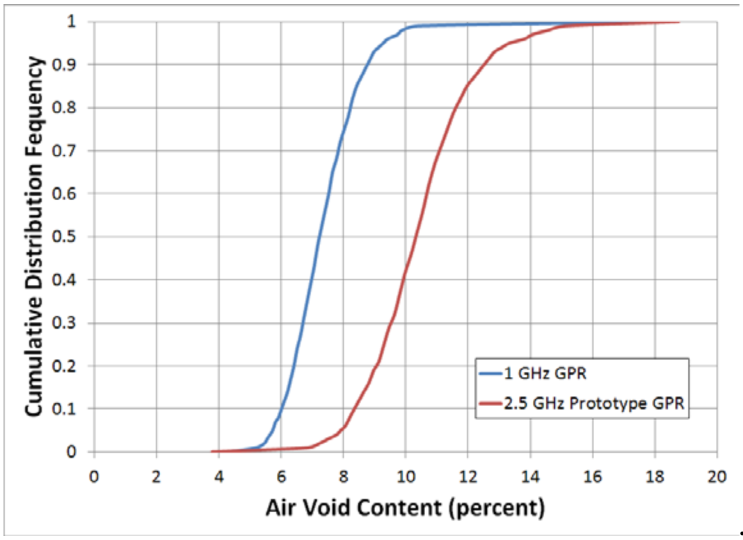


Figure 3.5. Expected distribution of air voids on US-29 from GPR. Note: VDOT desired density is ≤ 7.8% air voids.

The research team reviewed the data further to investigate the shift between the two radar systems and concluded that several system issues with the prototype 2.5 GHz system existed. During the data collection, the team collected the three GPR profiles at the centerline, inside wheel path, and outside wheel path, and then collected a repeat profile over the centerline. Figure 3.6 illustrates that, on this repeat data collection, the calculated dielectric values from the 2.5 GHz system had shifted by about 0.15. This discrepancy may have been associated with an electronics overheating condition. Figure 3.7 illustrates that if the dielectric values calculated from the 2.5 GHz data are adjusted for this shift, the results compare favorably with the results from the 1 GHz system.

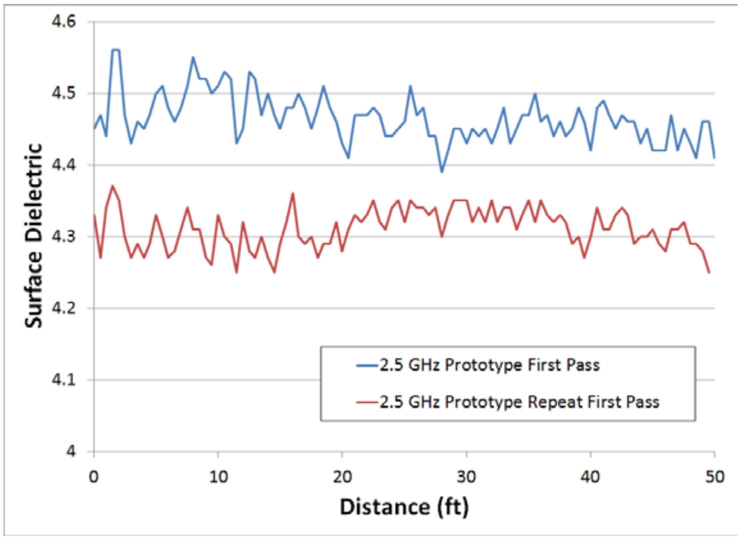


Figure 3.6. Shift in 2.5 GHz results during US-29 testing.

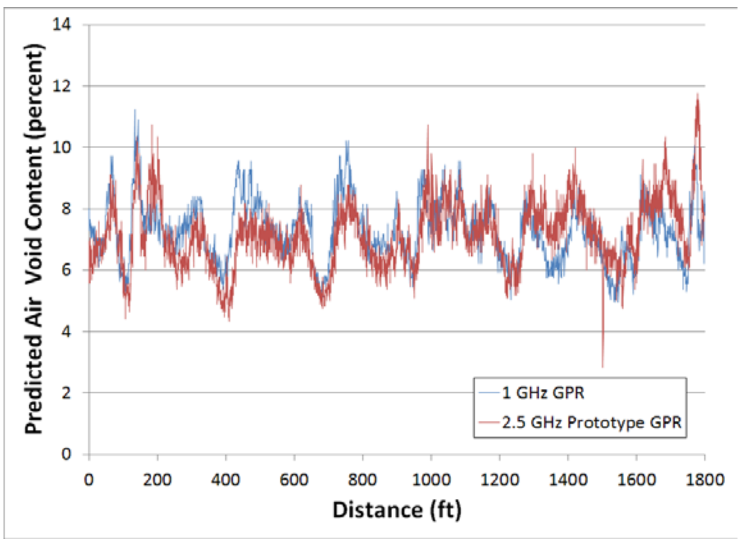


Figure 3.7. Correcting for drift with 2.5 GHz data results in favorable comparison with a 1 GHz system.

Since some system issues occurred with the new prototype 2.5 GHz system on this project, the 1 GHz system probably provides a more accurate assessment of the true distribution from US-29. In Figure 3.5, the data suggest about 68% of the tested mat area met VDOT's desired maximum air void content of 7.8%.

With the known offsets of each GPR run, the radar data can also be presented as a contour plot. Figure 3.8 presents this plot for US-29 from the 1 GHz radar system. This plot presents the expected in-place air voids over the mat area and shows the approximately 32% of the mat area that failed to meet VDOT's desired in-place density. The plot also illustrates that

- The zones of most severe low density tended to primarily exist around locations of known paver stops.
- Beginning at 1200 ft into the test section, the overall density improved. Referring back to Figure 3.2, the mean mixture placement temperature also increased beginning at 1200 ft.

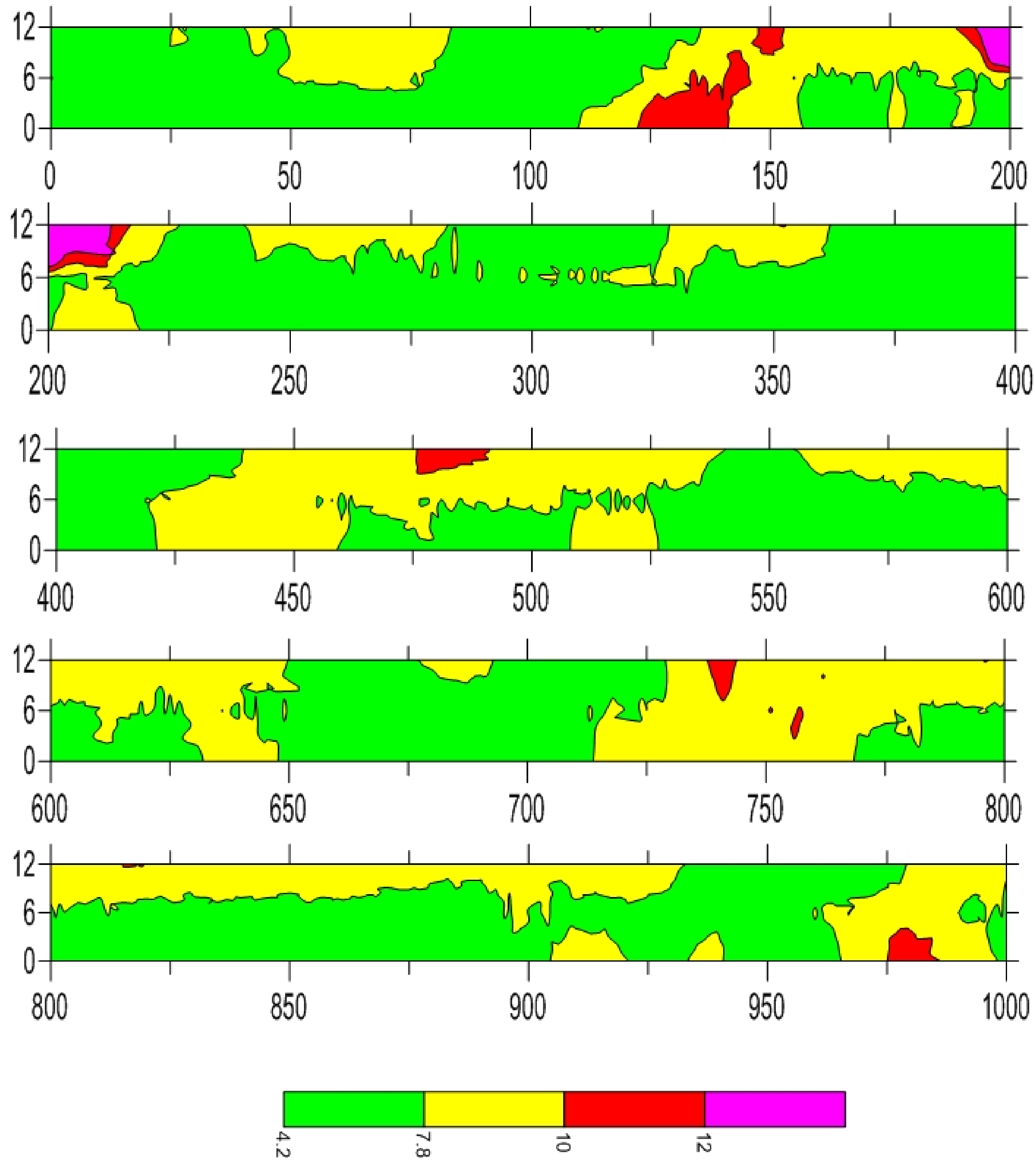


Figure 3.8. Geospatial distribution of air voids on US-29.

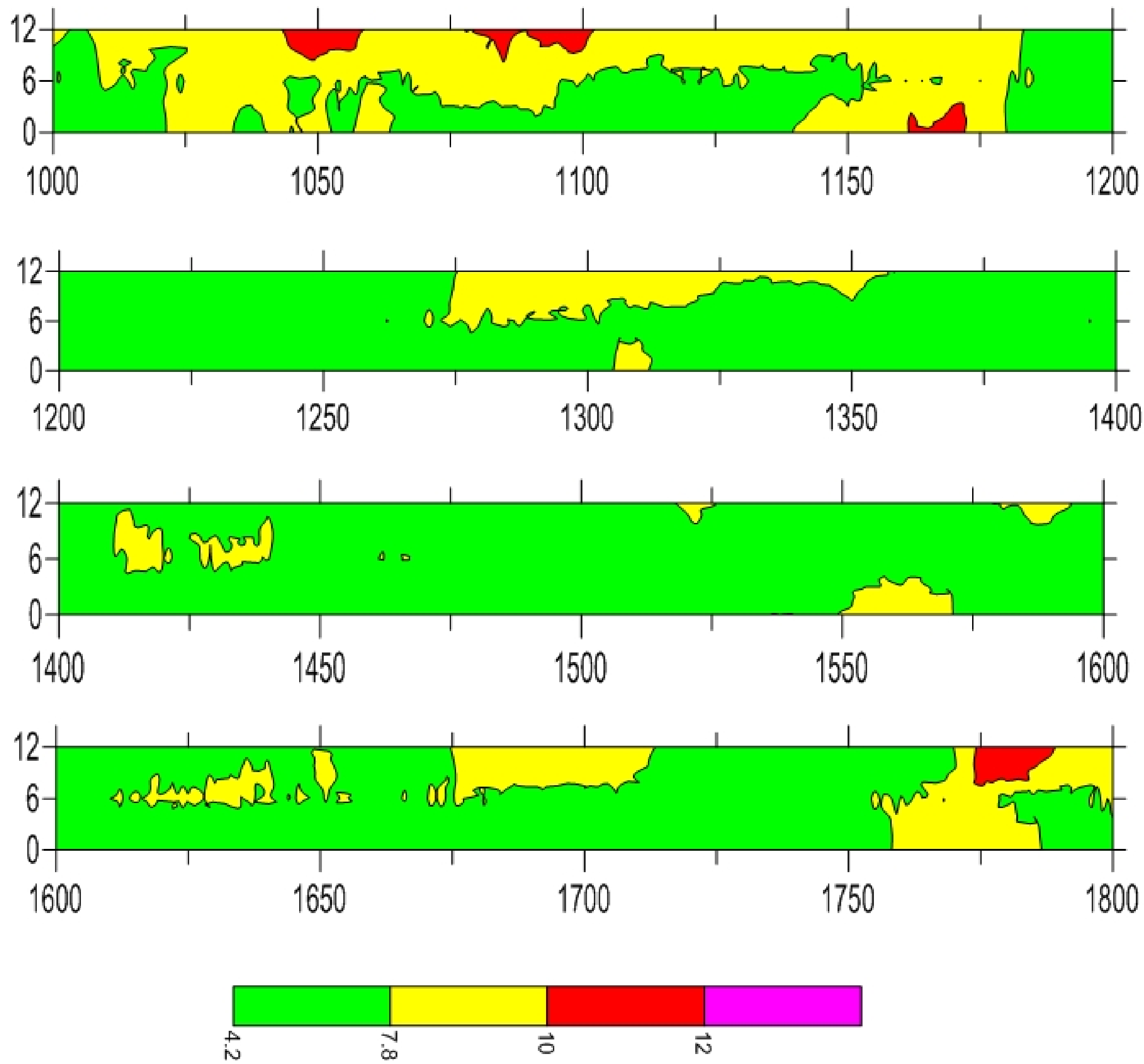


Figure 3.8. Geospatial distribution of air voids on US-29 (continued).

Conclusions from US-29 Pilot Project

The thermal profile in conjunction with the radar analysis on US-29 highlights the importance of mixture temperature and temperature uniformity in compaction with this particular mix and paving operation, the importance of minimizing paver stops, and the utility of GPR for measuring and mapping the final density of the in-place mat. Both devices worked well for evaluating uniformity and showed:

- Cyclical truck-end segregation existed, with temperature differentials typically between 40°F and 60°F.
- Due to paver stops at truck exchanges, the paver was idle approximately 50% of the time of the pull.
- A 50°F decrease in placement temperature correlated with a 2.2% increase in in-place air voids after all compaction operations.
- The average in-place air void content on the section tested was expected to be 7.4%, with a standard deviation of 1.1%.
- About 68% of the tested mat area was expected to have air voids less than 7.8%.
- The most severe cases of low density were concentrated around zones of known paver stops.

To improve this operation, the contractor should make efforts to eliminate paver stops and reduce thermal segregation. Increasing the placement temperature also could help achieve better density. Finally, additional work may be needed in setting the rolling patterns after these and any other changes are implemented in the paving process.

The two different radar systems employed indicated similar uniformity. However, the estimated mean in-place air void content significantly differed between the two radar systems. Analysis of results between the two systems indicated some system issues with the first-generation prototype 2.5 GHz radar, specifically a signal drift with that system.

PILOT PROJECT ON ROUTE 3

On June 13, 2013, the SHRP 2 R06C research team conducted pilot implementation of thermal profiling and ground-penetrating radar on Route 3 in coordination with the Virginia Department of Transportation. This pilot implementation served to illustrate how these technologies could be used in quality control applications for evaluating a paving process and measuring the uniformity and density of the mat with near full-coverage testing. The project team used a Moba Pave-IR system to collect the thermal profiles and a 1 GHz air-coupled GPR system along with a first-generation prototype 2.5 GHz system from GSSI for the radar analysis.

Job Mix Formula

The contractor placed a 2-inch lift of SM-12.5D. This mix was a dense-graded Superpave-designed wearing course that used PG 64-22 binder. The mix also included 30% RAP and foam warm-mix asphalt (WMA) technology. Table 3.5 shows the job mix formula.

Table 3.5. Job Mix Formula for SM-12.5D on Route 3 Test Site

Sieve Size	Composite Formula	Acceptance Range
¾ in.	100	100
½ in.	97	94.2–99.8
⅜ in.	89	86.2–91.8
No. 8	36	33.2–38.8
No. 200	5.1	4.4–5.8
% AC	5.10	4.89–5.31

Paving Operation

The contractor transported the mix in bobtail trucks, which offloaded into a Roadtec SB 1500D to transfer the mix into a Roadtec RP 190 paver. Figure 3.9 shows the paving train.

Figure 3.9. Paving operation on Route 3.

Thermal Survey Result

Thermal profiles were collected from 38.23899 N, 77.14980 W to 38.23197 N, 77.12434 W. While truck exchanges were visible in the thermal profile, the temperature differentials were typically between 23°F and 30°F, which indicates good thermal uniformity. The average paving speed was 16.7 ft/min, and the paver was idle about 12% of the time during the pull.

Figure 3.10 shows the thermal profile from 38.23899 N, 77.14980 W to 38.23832 N, 77.14729 W, which was the section focused on for follow-up GPR and coring analysis, resulting in a test section approximately 750 ft long. As shown in Figure 3.10, an arbitrary station of 0.00

was assigned at the start point of the test section. The temperatures measured with Pave-IR at subsequent core locations are also annotated in Figure 3.10 and presented in Table 3.6. Core locations were numbered sequentially from lowest to highest station.

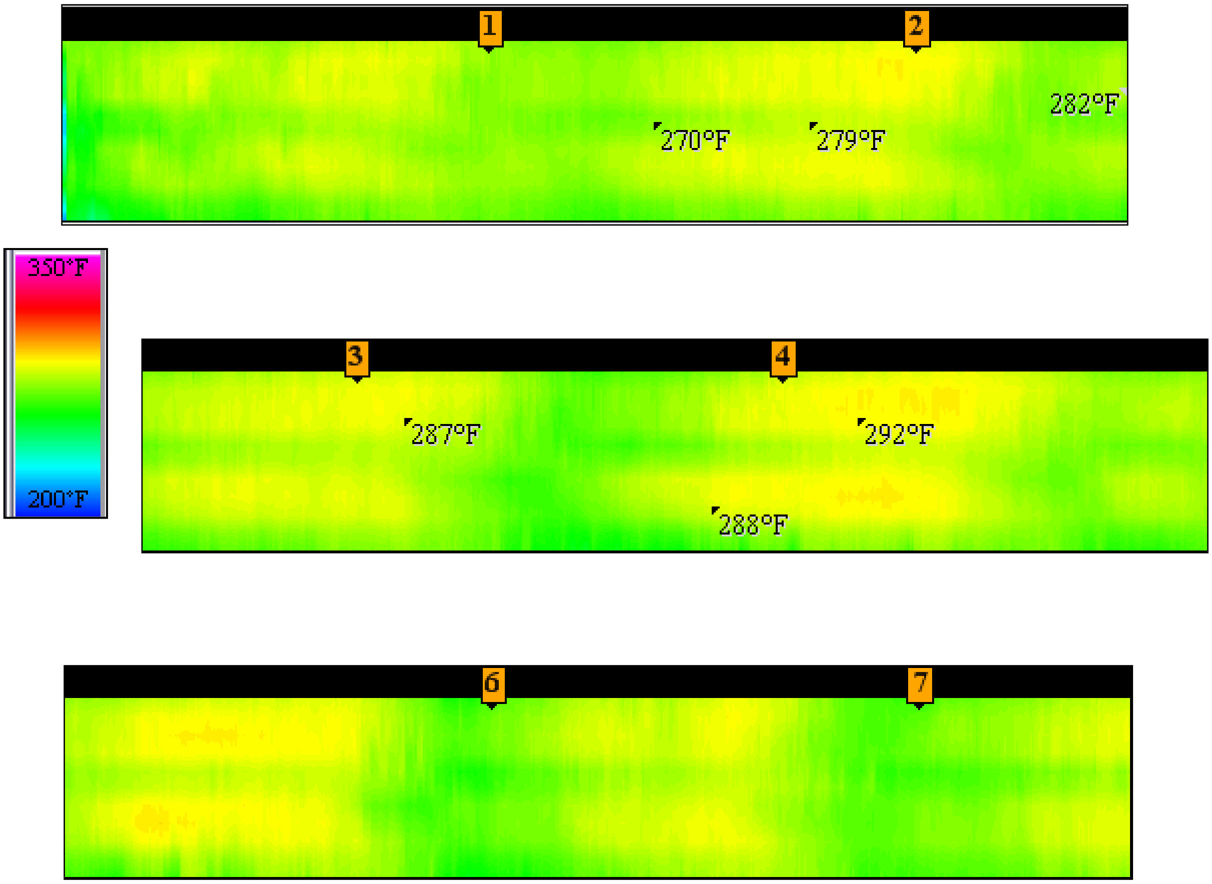


Figure 3.10. Thermal profile from Route 3.

Table 3.6. SM-12.5D Measured Placement Temperatures at Core Locations on Route 3

Core Number	1	2	3	4	5	6
IR Temperature (°F)	270	279	282	286	288	292

From the core results, Figure 3.11 presents a scatter plot of in-place air voids after all compaction versus measured temperature at time of placement. Within the range of measured placement temperatures, the data show that compaction was insensitive to temperature. This could be the resultant of the WMA technology employed combined with the narrow range of placement temperatures. Figure 3.11 shows the Route 3 project had much less thermal variability than the project on US-29. On Route 3, the temperature range of cores from lowest to highest spanned only 22°F, while the US-29 results in Figure 3.3 show the temperature range spanned 88°F.

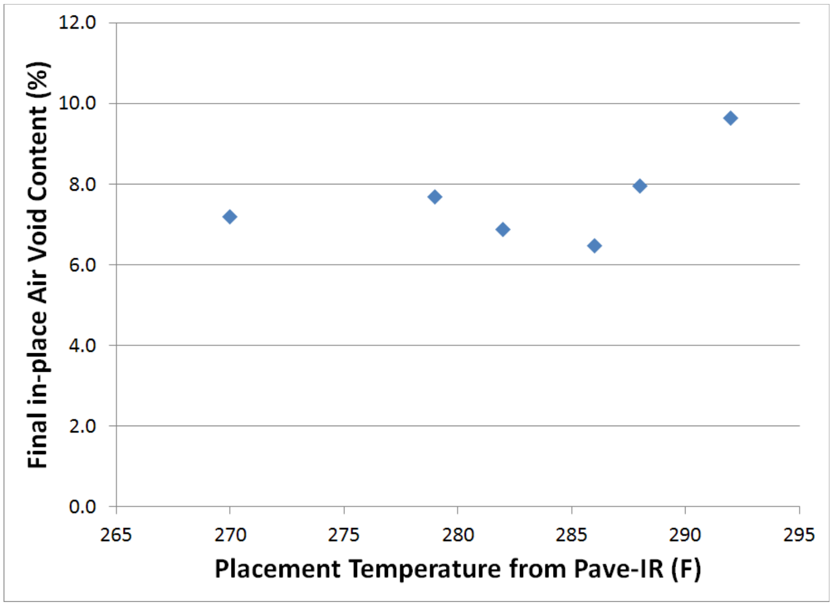


Figure 3.11. Scatter plot of air voids versus placement temperature from Route 3.

GPR Survey Result

After the contractor completed finish rolling, the researchers collected GPR data at three different transverse offsets (both wheel paths and the centerline) from 38.239008 N, 78.14980 W to 38.23826 N, 77.147274 W using both a 1 GHz air-coupled system and a prototype 2.5 GHz system from GSSI. After collecting these radar passes, researchers selected six locations for focused coring to calibrate the GPR measurements to in-place density. Table 3.7 shows the GPR-measured surface dielectric values from the core locations and the corresponding lab-determined core air void content. The JMF-reported Rice gravity of 2.673 g/cc was used in calculation of lab air voids.

Table 3.7. GPR-Measured Core Dielectric Values on Route 3

Core	1	2	3	4	5	6
ε from 1 GHz	6.3	6.1	6.3	6.5	6.2	5.9
ε from 2.5 GHz	5.58	5.26	5.29	5.48	5.02	5.00
Lab Air Voids (%)	7.2	7.7	6.9	6.5	8.0	9.6

Figure 3.12 presents the observed calibration between the radar-measured dielectric value and core air voids using the data from Table 3.7. Both systems provided reasonable calibrations; the somewhat lower fit of the calibration with the 2.5 GHz system may be due to that system's smaller measurement footprint (as compared to the 1 GHz system) combined with some imprecision of the exact core locations within each radar run, since, on this project, spot GPR readings over selected core locations were precluded by impending weather.

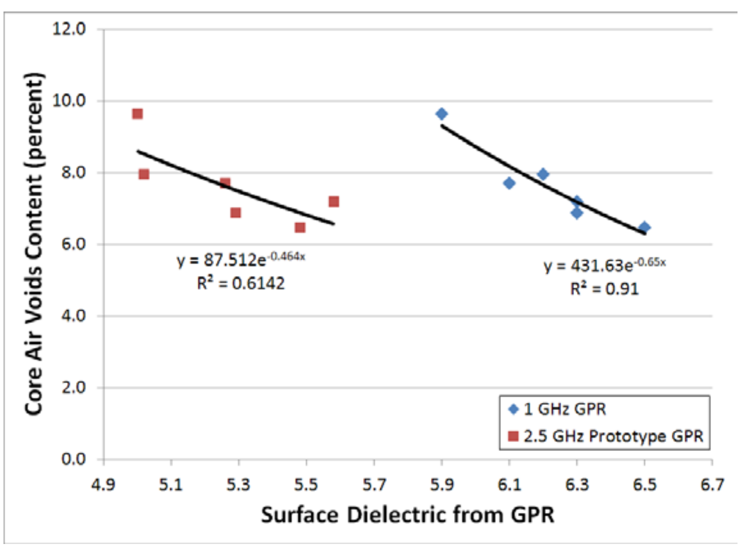


Figure 3.12. Calibration of air voids to GPR from Route 3.

Using the calibrations in Figure 3.12, researchers predicted the in-place air void content at each measurement location in the three GPR runs, resulting in about 2200 points of air void estimation with the 1 GHz system and almost 4500 points of air void estimation with the prototype 2.5 GHz system. These predictions yielded the statistics in Table 3.8.

Table 3.8. Summary Air Void Statistics from GPR on Route 3

Statistic	1 GHz	Prototype 2.5 GHz
Average	7.5	7.5
Standard Deviation	0.7	0.4
Min	5.9	6.4
Max	12.1	9.1

Using the large quantity of air void measurements, Figure 3.13 presents the expected statistical distribution of air voids in the test section. The data listed in Table 3.8 and illustrated in Figure 3.13 show that

- Both GPR systems estimated the same mean air void content value.
- The statistical distributions compare favorably, with the 1 GHz system predicting slightly more variability than the 2.5 GHz system.
- Both systems estimated that similar percentages of the mat area met VDOT's desired maximum air void content of 7.8%. This percentage was 83% with the 1 GHz system and 78% with the prototype 2.5 GHz system.

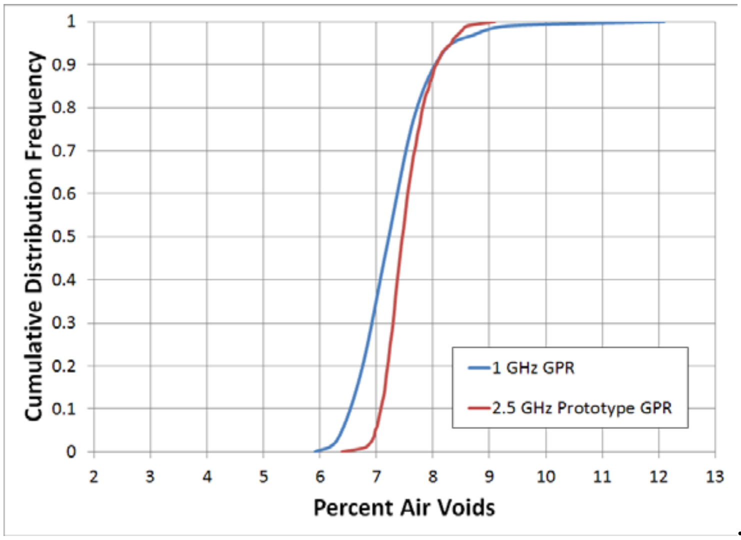


Figure 3.13. Expected distribution of air voids on Route 3 from GPR. Note: VDOT desired density is ≤7.8% air voids.

With the known offsets of each GPR run, the radar data can also be presented as a geospatial contour plot. Figure 3.14 presents this plot for Route 3 from the 1 GHz radar system, and Figure 3.15 presents this plot from the prototype 2.5 GHz system. These plots further illustrate the portions of the mat area that met the less than 7.8% air void criteria and the somewhat increased variability predicted from the 1 GHz system. The higher air void zone centered around 400 ft into the test section may be due to a roller breakdown that slowed down the compaction operations until a new roller was delivered.

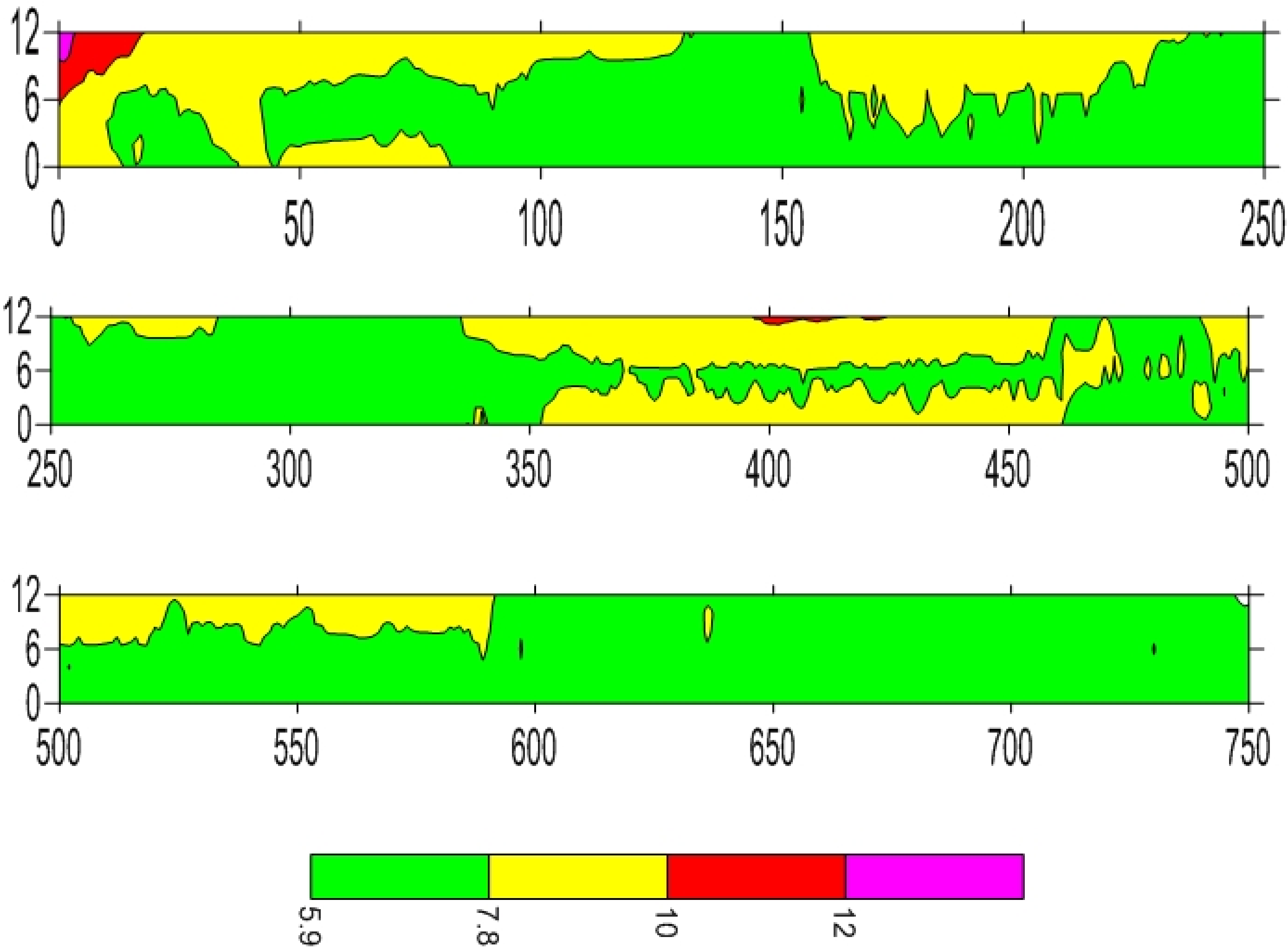


Figure 3.14. Geospatial distribution of air voids on Route 3 from 1 GHz GPR.

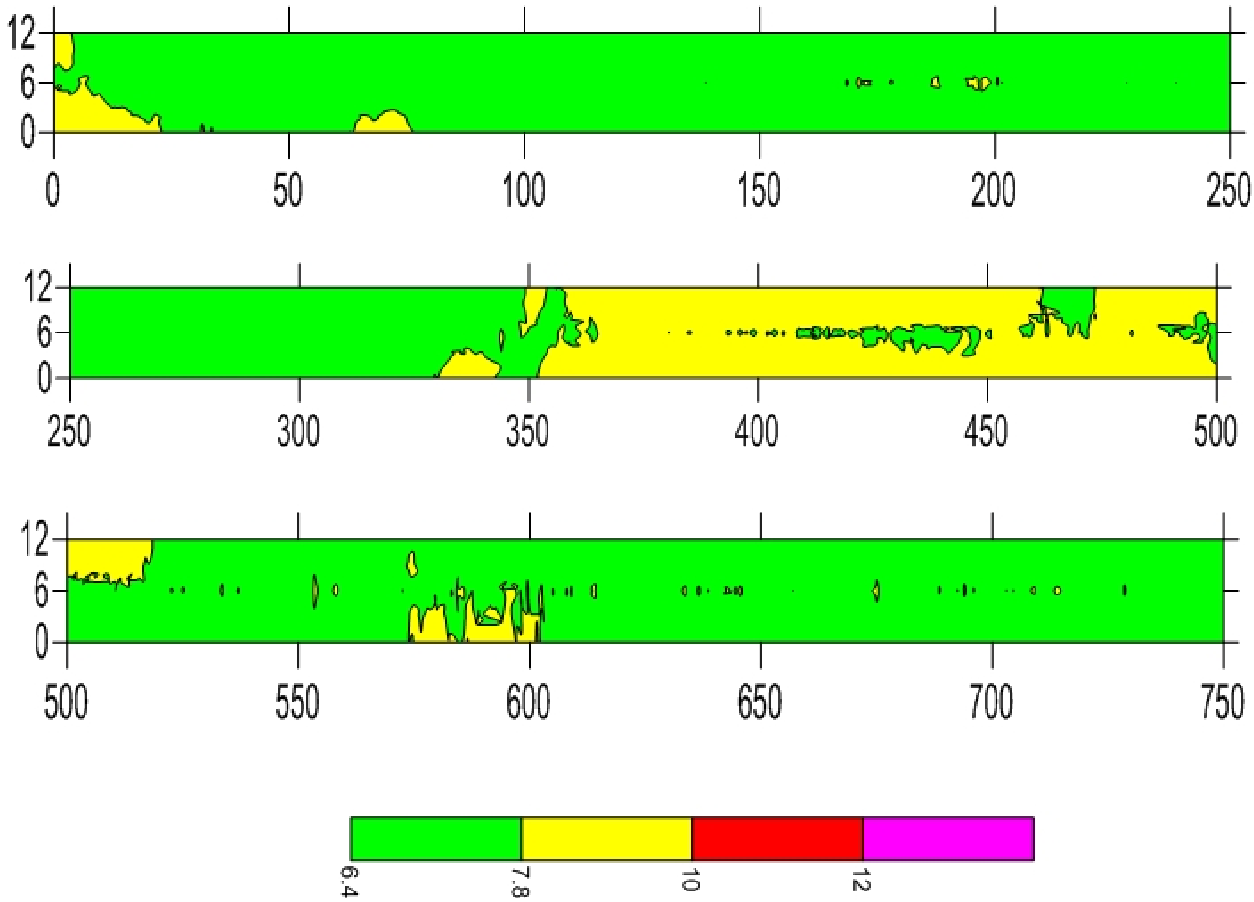


Figure 3.15. Geospatial distribution of air voids on Route 3 from 2.5 GHz GPR.

Conclusions from Route 3 Pilot Project

The nondestructive tests on Route 3 showed quite good uniformity. Both the thermal profile and radar provided quantitative estimates of uniformity and showed the following:

- Thermal uniformity was good. Although truck exchanges were visible in the thermal profile, temperature differentials rarely exceeded 30°F.
- The paver was idle only about 12% of the time during the pull. Few paver stops occurred.

- Within the placement temperatures observed, the final in-place air voids did not seem sensitive to temperature. This could have resulted from the warm-mix technology employed, or it could be simply because significant thermal irregularities did not occur.
- The average in-place air void content on the section tested was expected to be 7.5%.
- Approximately 78% to 83% of the tested mat area was expected to have air voids less than 7.8%. This estimate was based on the 2.5 GHz prototype GPR and 1 GHz GPR, respectively. Overall, the analysis of uniformity agreed well between the two different radar systems.

UPDATES TO 2.5 GHZ GPR BASED ON FIRST PILOT PROJECTS

Based on the results from the first two SHRP 2 pilot projects, the research team worked with GSSI to make updates to the prototype 2.5 GHz radar system tailored for asphalt mixture uniformity measurement. Specifically, GSSI investigated the sources of potential system issues and developed a second-generation radar system that addressed the overheating and electronic drift issues. The last pilot project conducted in this SHRP 2 pre-implementation used this second-generation 2.5 GHz system.

PILOT PROJECT ON SR-220

On September 6 and 7, 2013, the research team conducted pilot implementation of thermal profiling and ground-penetrating radar on SR-220 in coordination with PennDOT. This pilot implementation served to illustrate how these technologies could be used in quality control applications for evaluating a paving process and measuring the uniformity and density of the mat with near full-coverage testing. The project team used a Moba Pave-IR system to collect the thermal profiles and a new second-generation 2.5 GHz air-coupled system from GSSI for the

GPR analysis. The research team also evaluated the project with a 1 GHz air-coupled GPR system for comparison.

Job Mix Formula

The contractor placed a 1-inch lift of SP 6.33 warm mix on SR-220. The mix used PG 76-22 binder and was produced at a batch plant approximately 10 mi from the project site. The mix used the foam process and only used virgin asphalt binder. Table 3.9 shows the job mix formula.

Table 3.9. Job Mix Formula for SP 6.33 on SR-220

Sieve Size	**Composite Formula**
⅜″	100
¼″	95
No. 4	87
No. 8	55
No. 16	35
No. 30	24
No. 50	16
No. 100	9
No. 200	6
% AC	6.9

Paving Operation

The contractor transported the mix in bobtail trucks, which offloaded into a Roadtec SB 2500D to transfer the mix into a Volvo PF6170 paver. Figure 3.16 shows the paving train. Two Sakai SW850 rollers performed both breakdown and intermediate rolling, while a SW880 performed finish rolling. The contractor paved a 12 ft wide lane with a 4 ft wide inside shoulder for a total width of 16 ft.

Figure 3.16. Paving operation on SR-220.

Thermal Survey Result

Thermal profiles were collected from 41.19852 N, 77.29294 W to 41.20911 N, 77.26202 W, for a total length of 9,360 ft of paving. The duration of paving was 5 hours and 48 minutes, resulting in an average paving speed of 26.9 ft/min. The paver stopped nine times during the pull, resulting in a total paver idle time of about 7%. While truck exchanges were visible in the thermal profile, the temperature differentials were typically between 18°F and 28°F, which indicates good thermal uniformity. The average placement temperature was 292°F, with a standard deviation of 9.2°F.

Figure 3.17 shows an excerpt representing 5,000 ft of paving from the pull. The most significant thermal segregation occurred between 7,800 and 8,100 ft into the pull, where an increase in mean mixture temperature occurred. Thermal segregation caused by such increases in mean placement temperature generally is not as much a cause for concern as other types of thermal segregation patterns, such as truck-end segregation or random segregation.

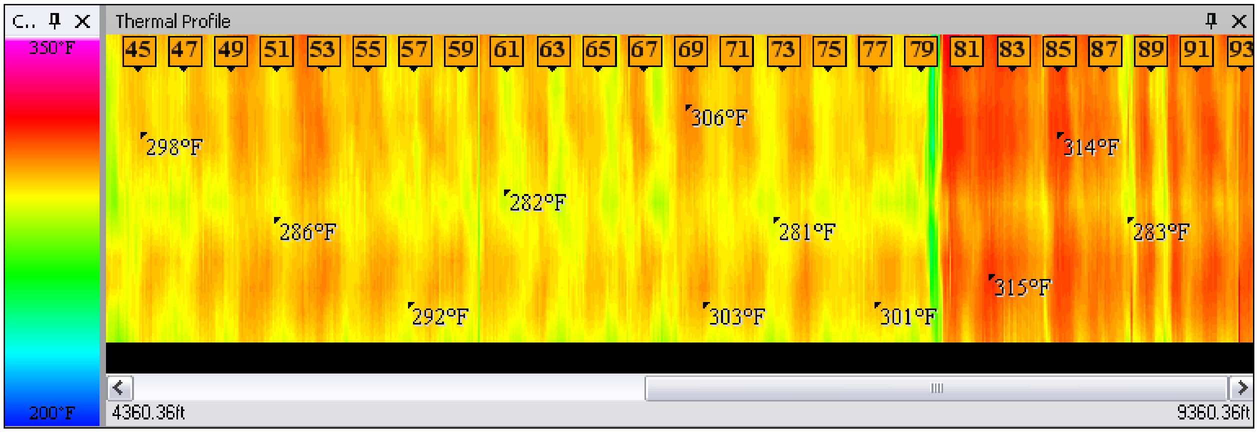


Figure 3.17. Excerpt of thermal profile for SP 6.33 placed 09/06/2013 on SR-220.

Figure 3.18 shows the thermal profile from the last 1,000 ft of the pull, which was the section focused on for follow-up GPR and coring analysis, resulting in a focus test section 1,000 ft long starting at 41.20811 N, 77.26550 W. An arbitrary station of 100 was assigned at the start point of the section. Temperature annotations in Figure 3.18 illustrate the typical range of observed placement values within the 1,000 ft section; additionally, the thermal signature from paver stops is evident at stations 104.62, 106.07, and 109.31. The mixture temperature of the zones at these paver stops was between about 263°F and 273°F on the paving train resuming.

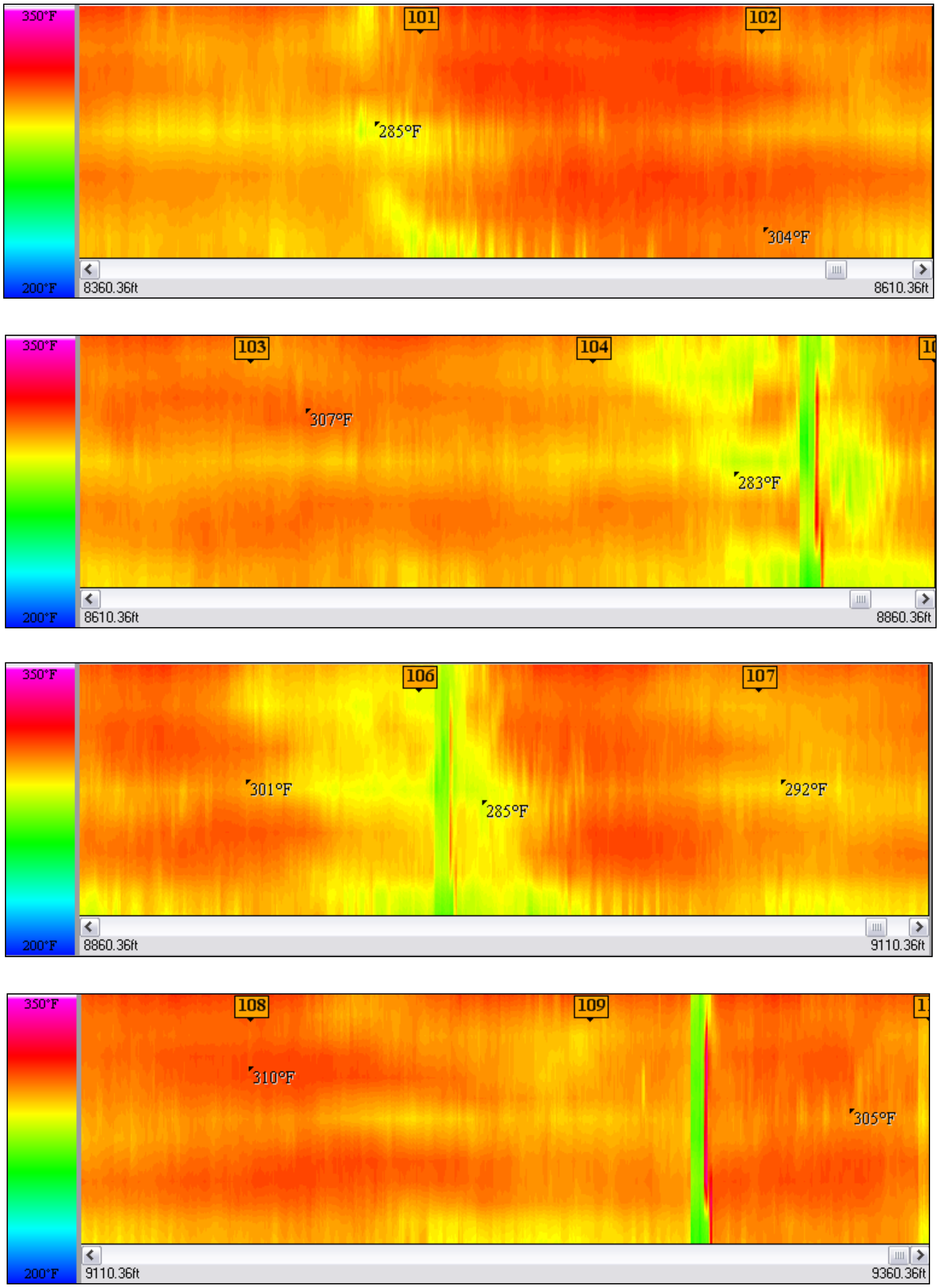


Figure 3.18. Thermal profile from last 1,000 ft of SR-220 placed 09/06/2013.

GPR Survey Result

On the morning of September 7, 2013, the TTI team collected GPR data at six different transverse offsets on the last 1,000 ft of the pull that was placed 1 day prior. The transverse offsets were at 2, 4, 6, 8, 10, and 14 ft from the outside mat edge, yielding five passes in the lane and one pass in the shoulder. The contractor maintained the lane closure on the section so that no traffic had occurred on the section between placement and radar testing. The team relied primarily on the new second-generation 2.5 GHz air-coupled radar system shown in Figure 3.19. A unique advantage of this radar system is that the surface dielectric values are calculated in real time and available in the field immediately on completing data collection without the need for any user post-processing. Data were also collected with a 1 GHz radar system for comparison.

Figure 3.19. Collection of GPR data on SR-220 with real-time data processing.

The project team used the data from these radar passes while still in the field to select six locations for focused coring to calibrate the GPR measurements to in-place density. Table 3.10

shows the GPR-measured surface dielectric values (ε), lab-determined air void content, transverse offset from the outside mat edge, and longitudinal distance from the start of the 1000 ft section for the cores collected. The JMF-reported Rice gravity of 2.447 g/cc was used in calculation of lab air voids.

Table 3.10. GPR-Measured Core Dielectric Values on SR-220

Core	1	2	3	4	5	6
ε from 1 GHz	4.65	4.60	4.89	4.86	5.11	4.38
ε from 2.5 GHz	4.81	4.65	5.08	4.77	5.22	4.43
Lab Air Voids (%)	7.2	9.0	4.8	6.3	4.4	10.3
Offset (ft)	2	2	6	6	6	6
Distance (ft)	200.6	549.0	199.9	551.1	707.4	977.1

Figure 3.20 presents the observed calibration between the radar-measured dielectric value and core air voids using the data from Table 3.10. Both GPR systems showed an excellent correlation to the core laboratory air void content. Using this calibration, researchers predicted the in-place air void content at each measurement location in each of the GPR runs, resulting in about 6,000 points of estimation with the 1 GHz system and about 12,000 points of air void estimation with the 2.5 GHz system. These predictions yielded the statistics in Table 3.11.

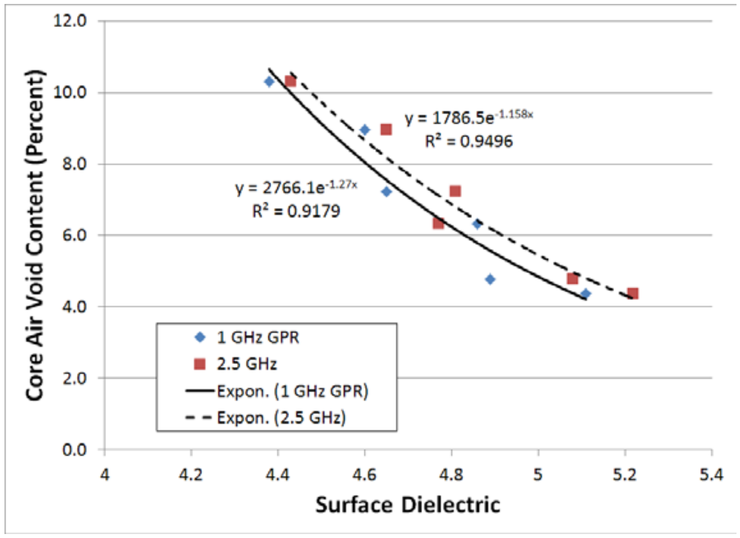


Figure 3.20. Calibration of air voids to GPR from SR-220.

Table 3.11. Summary Air Void Statistics from GPR on SR-220

Statistic	1 GHz	2.5 GHz
Average	6.9	7.2
Standard Deviation	1.4	1.1
Min	3.8	4.2
Max	12.0	13.3

Using the large quantity of air void measurements, Figure 3.21 presents the expected statistical distribution of air voids in the 1,000 ft test section. The data listed in Table 3.11 and illustrated in Figure 3.18 show that

- The two radar systems estimated similar mean air void content.
- The statistical distributions were similar, with the 2.5 GHz system estimating slightly less project variability than the 1 GHz system.

- Both GPR systems predicted a similar portion of the mat met PennDOT's desired compaction range of 3% to 8% air voids. The 1 GHz system estimated 77% met the target compaction, while the 2.5 GHz system estimated 80% met the target compaction.

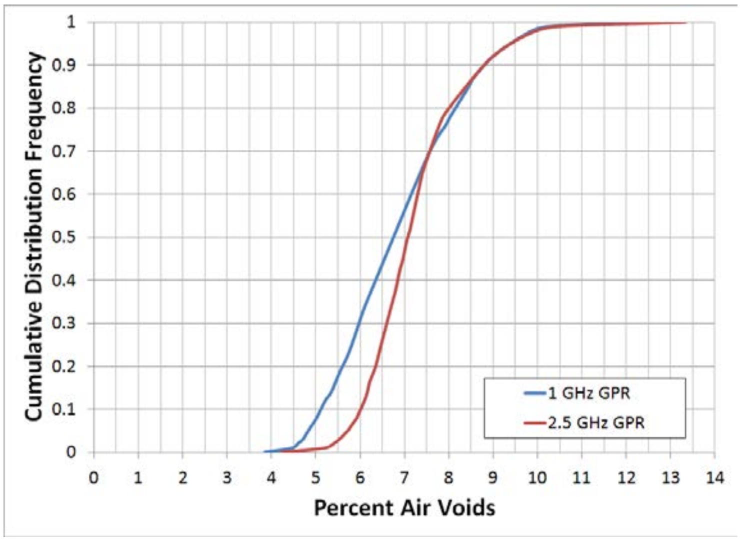


Figure 3.21. Expected distribution of air voids on SR-220.

One concern with the 1 GHz data from SR-220 was the overlay lift thickness. The planned compacted lift thickness was 1 inch, and Table 3.12 shows that cores collected ranged between about 1 and 1.5 inches. The surface echo from the 1 GHz system has a zone of influence to about 1.5 inches deep, so the research team suspected that results from that system were being influenced by the scratch course that existed immediately below the SP 6.33 mm mix.

Table 3.12. Core and GPR-Measured Lift Thickness from SR-220

Core	1	2	3	4	5	6
Core Height (in.)	1.01	1.32	1.14	1.42	1.39[a]	1.35[a]
Height from 2.5 GHz GPR (in.)	1.07	1.36	1.14	1.47	1.53	1.52

[a] Thickness reported may be short due to difficulty in identifying interface and subsequent saw cutting.

Since the data in Table 3.12 suggest that the new 2.5 GHz radar system provided good estimates of overlay thickness, Figure 3.22 illustrates the estimated thickness from the 2.5 GHz system along with the measured surface dielectric from the 1 GHz system and 2.5 GHz system for comparison. The data indicate the lowest dielectric areas from the 1 GHz system were generally located at the locations of lowest overlay thickness (around 1 inch thick), while the surface dielectric values from the 2.5 GHz system show no such correlation. The research team concluded that the results from the 1 GHz system on SR-220 may be somewhat skewed by influence from the lower lift.

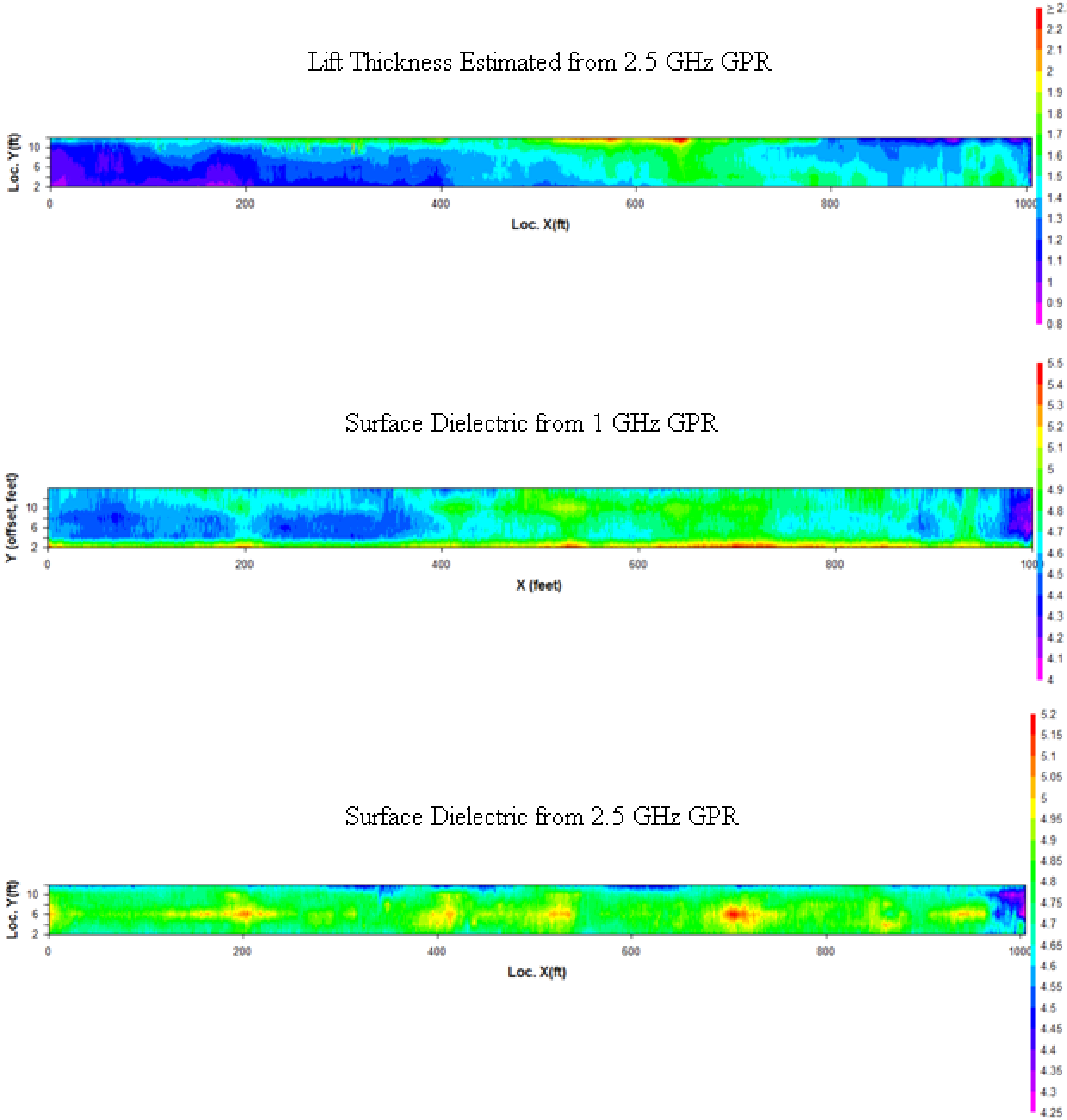


Figure 3.22. Lift thickness and surface dielectrics from SR-220.

Since the lift thickness of the overlay may have influenced the 1 GHz radar traces, further analysis on SR-220 was conducted only with the 2.5 GHz results. PennDOT's target in-place air void content for this mixture was between 3% and 8%. Figure 3.23 shows about 80% of the total mat area met PennDOT's desired compaction and also shows that, when only the travel lane area was analyzed, about 92% of that lane's area met the desired compaction.

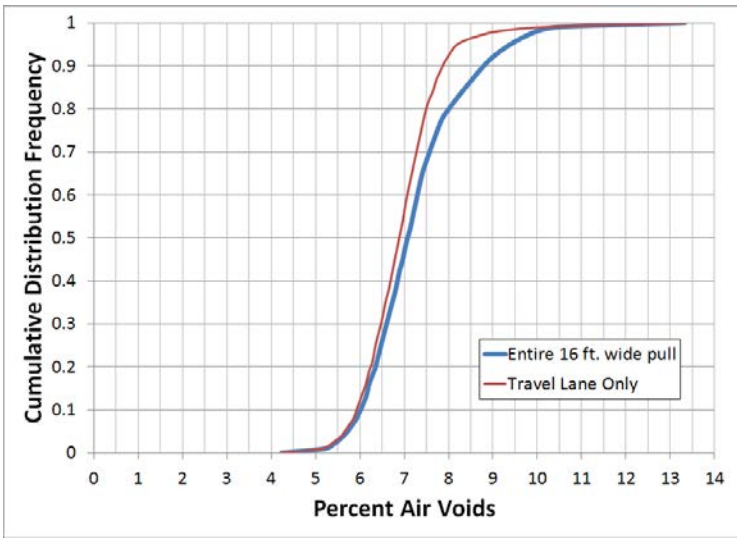


Figure 3.23. Expected entire pull and travel lane distribution of air voids on SR-220 from 2.5 GHz GPR.

With the known offsets of each GPR run, the radar data can also be presented as a contour plot. Figure 3.24 presents this plot for SR-220 from the 2.5 GHz radar system. The data show regions where air voids exceeded 8%, generally at transverse offsets between 12 and 16 ft. These regions were in the shoulder area, which was also the unconfined edge. To a lesser extent, some regions of air voids exceeding 8% also occurred at the inside longitudinal joint.

Regarding the shoulder area, consideration should be given to an altered rolling pattern to try to better meet compaction targets across the entire mat width. On SR-220, a complicating issue is that the inside shoulder has a different slope than the lane, so special care and/or an additional roller may be necessary to make sure compaction effort gets adequately applied to the shoulder area. Regarding the outside edge, the project team observed the roller spanning the longitudinal joint at times when rolling in this vicinity. If possible, such practice should be avoided.

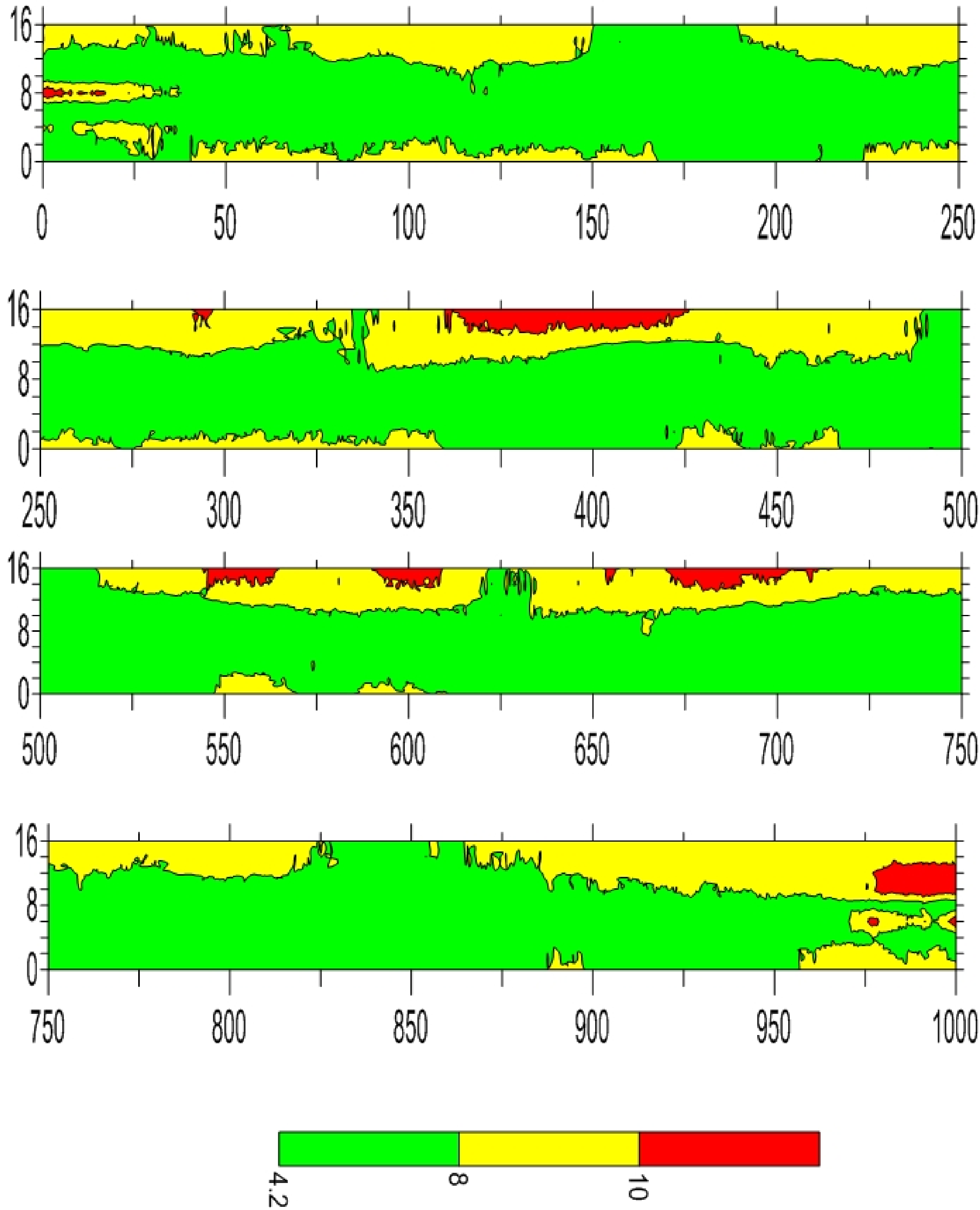


Figure 3.24. Expected geospatial distribution of air voids on SR-220.

Conclusions from SR-220 Pilot Project

The data from SR-220 showed

- Thermal uniformity was good. Although truck exchanges were visible in the thermal profile, temperature differentials rarely exceeded 30°F.
- The contractor successfully kept the paving train moving. The paver was idle only about 7% of the time during the pull. The average paving speed was 26.9 ft/min.
- The average in-place air void content on the section tested was expected to be 7.2%, with a standard deviation of 1.1%.
- Approximately 80% of the section tested was expected to meet PennDOT's target in-place air void content of 3% to 8%.
- The pull included a 4 ft inside shoulder. The lowest density areas tended to be in this shoulder. When the shoulder was eliminated from the analysis, the data showed approximately 92% of the travel lane meets the target in-place density range.

To improve this operation, the data suggest that some modification to rolling patterns to try to achieve better compaction at the shoulder (which in this case was also the unconfined edge) may be warranted.

The pilot project on SR-220 also revealed several important findings about the NDT technologies used for evaluating uniformity:

- The second-generation 2.5 GHz radar worked well and did not exhibit system issues that had been encountered with the first prototype.
- The real-time signal processing with the 2.5 GHz system greatly improves the efficiency of evaluating project uniformity.

- Many overlays currently constructed are thinner than 2 inches. The 2.5 GHz system is ideally suited to these types of overlays and can evaluate the surface uniformity without influence of lower layers.
- The 2.5 GHz system showed promising results for measuring in-place thickness. While such analysis currently requires user post-processing, the suggested accuracy from preliminary results suggests that this capability should be further explored.

CHAPTER 4

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

This SHRP 2 project piloted two nondestructive techniques for measuring uniformity and segregation in new asphalt mixture construction. Both technologies, thermal profiling and ground-penetrating radar, tested essentially 100% of the new surfaces and provided rapid feedback on the quality of construction. The thermal profile, conducted on three pilot projects by a Pave-IR system, provided real-time feedback measuring thermal segregation. In addition, the thermal profile as piloted also documented the paver speed, paver idle time, and location and duration of paver stops. The thermal profile pilots conducted showed:

- The Pave-IR system readily installs to field equipment and is straightforward to operate by contractor and DOT staff.
- The ability of the thermal profile to also measure paving speed and idle time is a value-added feature as compared to other methods of thermal profiling.
- The current temperature criteria for defining moderate and thermal segregation are temperature differentials of 25°F and 50°F, respectively. However, the widespread use of WMA technologies as compaction aides may require further work to determine if these current tolerances are too strict.

With ground-penetrating radar, uniformity and segregation analysis on a final in-place product can be realized. In this project, analysis was conducted on three pilots using a 1 GHz air-coupled system and a first- and second-generation 2.5 GHz system specifically tailored for evaluating asphalt mixture construction. The pilots conducted with GPR showed

- The second-generation 2.5 GHz radar system significantly advanced the state of the practice for evaluating asphalt mixture construction. This system provides an easily understood operator interface, real-time data processing, and efficient field reporting to rapidly evaluate uniformity and density.
- The 2.5 GHz radar system is well suited to evaluating overlays for uniformity and segregation without measurements being influenced by lower layers. The 1 GHz radar can be influenced by lower lifts depending on lift thickness. Since many overlays are now less than 2 inches thick and some overlays are as thin as ¾ inches, interferences from lower lifts when using the 1 GHz system may be encountered.
- The calibration of radar systems to in-place asphalt mixture density remains project specific. With time, mix-specific calibration factors may be available.
- The second-generation 2.5 GHz system showed promise for also measuring the in-place thickness of the asphalt mixture overlay.

RECOMMENDATIONS ON SPECIFICATIONS

Based on the pilot project results, Appendix A provides a proposed standard specification for continuous thermal profiling of asphalt mixture construction. This general procedure could be used by owner-agencies to assist in implementing thermal profiling into their operations or serve as a starting point for tailoring the specification to specific agency requirements.

With the successful streamlining of GPR accomplished by the development of the new 2.5 GHz radar system, Appendix B provides a proposed standard specification for uniformity assessment of asphalt mixture construction using ground-penetrating radar. This general procedure could be used by owner-agencies to assist in implementing radar into their quality assurance operations.

SUGGESTED RESEARCH

The findings from work conducted indicate the following topics exist for further exploration:

- The influence of thermal segregation on WMA remains unclear. Work investigating the impact of thermal segregation on different WMA technologies and at different temperatures is needed. The parameter defining thermal segregation—generally accepted as the temperature differential—may need reevaluation with WMA. With many projects producing WMA at HMA temperatures, it is unknown if the temperature differential should remain the sole indicator of thermal problems.
- Work is needed to determine if calibrations to measure density with GPR must remain project specific or mix specific. The possibility of developing a catalog of standard calibration factors for different mix designs should be explored.
- The signal stability and temperature sensitivity for the new radar should be determined.
- Exploration of a multiple-channel GPR system tailored to measuring asphalt mixture uniformity should take place. Such a system could further expedite full-coverage evaluation.

APPENDIX A

PROPOSED STANDARD SPECIFICATION FOR CONTINUOUS THERMAL PROFILE OF ASPHALT MIXTURE CONSTRUCTION

1. SCOPE

1.1. The objective of this specification is to determine the placement uniformity of asphalt mixture construction through continuous thermal profiling. The equipment uses infrared temperature measurement technology to measure a longitudinal thermal profile across the pavement width and displays these data as a surface contour plot of asphalt mixture placement temperatures. This specification can be applied for construction quality control and acceptance. The equipment may install directly onto a paver. The equipment shall be able to calculate real-time indices including the number and percentage of profiles with moderate and severe thermal segregation and the temperature differential of each profile. Post-process software shall be able to calculate summary indices, which include the real-time indices plus the distribution of placement temperatures and the location and duration of paver stops exceeding 1 min. This specification is designed to apply to both hot- and warm-mix asphalt mixtures.

1.2. The equipment shall be capable of outputting the contour plot and real-time indices as a temporary display. The equipment shall be capable of outputting the summary indices as a PDF or printed report.

1.3. It is not the intent of this specification to relieve the supplier from the final responsibility to provide an appropriate product for the intended function, nor is it intended to specify all the design details. The objective is to provide a sufficiently detailed specification that the function is clearly defined. It is intended to be sufficiently detailed that the data collected from multiple thermal profilers will be identical.

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards*:

- None

2.2. *ASTM Standards*:

- None

3. TERMINOLOGY

3.1. *Definitions*:

3.1.1. *Contour plot*: a graphic display of data using contour lines. These plots may employ varying degrees of smoothing.

3.1.2. *Index*: a measure or standard. Within the context of this test method, several suitably chosen indices quantify the uniformity of a hot- or warm-mix asphalt construction operation.

3.1.3. *Moderate thermal segregation*: temperature differentials exceeding 25°F and not exceeding 50°F, unless otherwise defined by the owner-agency.

3.1.4. *Real-time indices*: the number and percentage of thermal profiles with moderate and severe thermal segregation and each thermal profile's actual temperature differential.

3.1.5. *Sample interval*: the longitudinal distance between data capture points.

3.1.6. *Severe thermal segregation*: temperature differentials exceeding 50°F, unless otherwise defined by the owner-agency.

3.1.7. *Summary indices*: the combination of real-time indices plus the distribution of placement temperatures and the location and duration of paver stops exceeding 1 min.

3.1.8. *Temperature differential*: the difference between the statistical 98.5 percentile and the statistical 1 percentile within a thermal profile, unless otherwise specified by the owner-agency.

3.1.9. *Thermal profile*: the geospatial makeup of hot- or warm-mix asphalt placement temperatures over a paving distance of 150 ft.

3.1.10. *Thermal profiler*: the combination of equipment and host vehicle to measure the thermal profile. In the context of this test method, the paving machine typically will serve as the host vehicle.

4. GENERAL EQUIPMENT REQUIREMENTS

4.1. *General*: The equipment shall function independently from the paving crew during normal paving operations and may operate either on its own or via the paver's on-board power supply.

Note 1: Initial data collection must be initiated by an operator. After the equipment has been initialized, no operator attendance shall be required for continuous data collection.

4.1.1. The equipment shall be equipped with various sensors, interface hardware, computer hardware, and software that, working together, perform the measurement, recording, and summary display of the thermal profile. The data shall be stored both internally and onto suitable high-density removable storage media during the test. The equipment computer shall have the capability to process the collected data for display of the thermal profile and the percentage of the project with moderate or severe thermal segregation. Supplier-provided post-process software shall be capable of displaying the thermal profile along with stationing, Global Positioning System (GPS) coordinates, and annotations. The post-process software shall also be capable of automatically processing the profile and generating a PDF report output to include the summary indices.

4.1.2. The equipment shall mount on the paver catwalk or other suitable location with minimum disturbance to the paver and in a fashion that the paving crew can conveniently and safely perform its duties.

4.2. *Measuring Thermal Profile*: The thermal profile shall be measured in a manner to obtain at least 12 measurement points across the mat width. Distance traveled during collection of the thermal profile shall be measured using a distance sensor and/or GPS receiver. The run-time software and post-processing software shall be used to combine these measurements to develop a thermal profile result with distance or stationing and GPS location.

4.2.1. The equipment shall be capable of obtaining and storing profile measurement data at selected longitudinal distance intervals. The equipment shall be capable of a sample interval every 6 inches or less at the maximum sustained paving speed.

4.3. *Calculating Temperature Differential*: The temperature differential of each thermal profile shall be computed automatically in both real time and post-processing using the data collected and stored on either internal or external storage media. The temperature differential shall be calculated as follows, unless otherwise specified by the owner-agency:

$$\text{Temperature Differential} = \text{statistical 98.5 percentile} - \text{statistical 1 percentile}$$

4.3.1. The computer shall also be capable of calculating the temperature differential based on a filtered data set, whereby either the operator indicates which temperatures or sensor(s) to ignore, or a supplier-supplied algorithm determines whether specific temperature or sensor data are valid or not. Any supplier-supplied filtering algorithm must be approved by the owner-agency prior to use.

4.4. *Calibration*: The equipment shall have built-in provisions to facilitate the calibration and verification of each infrared temperature sensor(s) signal. These sensor(s) shall be calibrated at intervals not to exceed 12 months in conjunction with a calibration protocol specified and carried out by the supplier or the supplier's authorized designee. These recurrent calibrations shall ensure the accuracy of the data.

5. EQUIPMENT

5.1. *General Requirements*: The thermal profiler shall meet the following requirements:

- The thermal profiler shall use any infrared temperature sensor or combination of infrared temperature sensors to measure a minimum of 12 points across the mat width, with each measurement point at most 13 inches apart.
- The thermal profiler shall use infrared sensor(s) capable of measuring a range of at least from 40°F to 475°F with an accuracy meeting ±1.5% of reading or ±2.7°F, whichever is greater, when the object temperature exceeds 32°F and the ambient temperature is 73°F ± 9°F. The sensor(s) repeatability shall meet ±0.75 percent of reading or ±1.4°F, whichever is greater.
- The thermal profiler shall measure distance and location using a distance sensor and/or GPS, such that longitudinal distance can be measured with sufficient accuracy and resolution to maintain a 6-inch sample interval. The thermal profiler shall support both English and SI units for distance data in incrementing or decrementing mode from a selected starting point and relate

the longitudinal distance to any test point. Optionally, the equipment may also report in station format.

- The thermal profiler shall determine the low and high temperatures within each profile using the statistical 1 percentile and 98.5 percentile, respectively, unless otherwise specified by the owner-agency. The thermal profiler shall use 150 ft as the default length for each profile.
- The thermal profiler shall provide real-time and post-process software capable of developing and analyzing thermal profiles for the entire project.

5.2. *Functional Hardware Modules*: The following minimum specifications shall apply to the thermal profiler:

- Operating ambient temperature range shall be -22°F to 158°F; non-operating temperature range shall be -40°F to 158°F.
- Power consumption of all installed equipment shall not exceed the capacity of the equipment providing operating power. Complete discharge of this system shall not impact the vehicle's regular electrical system.

Note 2: Local environmental conditions may require extending the suggested temperature limits.

5.3. *Functional Software Modules*: The equipment computer shall contain the necessary software modules to perform all tasks required. These functions include:

- Auto execution.
- Program initialization.

- Operation selection.
- Data collection and management.
- Data save.
- Direct data entry.
- Data retrieval.
- Data output.
- Data transfer.
- Data display.
- Equipment calibration.

5.3.1. *Auto Execution*: The equipment computer shall provide an automatic execution function that shall configure equipment components, load the main control program of the computer, and start up all required operations.

5.3.2. *Program Initialization*: The software shall provide a central program initialization function that shall be loaded by the operating software following all other drivers and reserved memory. The initialization program shall perform start-up initialization, activate the data acquisition system, initialize program control parameters and system self-check, and activate a start-up that requires no operator input.

5.3.3. *Operation Selection*: The operation selection function shall display a main menu of computer operation functions that can be performed when selected by the operator. The main menu selections shall be displayed to the operator in a manner clearly indicating their functions. The selection shall be provided via a touchscreen, keypad, computer keyboard, or other input device.

5.3.4. *Equipment Operation Functions*: The equipment computer shall provide a set of operation functions selected by the operator main menu. The equipment operation functions shall provide everything necessary for the operator to perform data collection in a user-friendly manner. It shall not be necessary for the operator to use operating commands directly to perform any of the required functions. The equipment operations as a minimum shall

- Create projects including identification (ID) and data collection properties necessary for adequate documentation and proper data collection.
- Allow editing of project headers.
- Allow deletion of projects from the main menu list of projects. Deletion of projects from the main menu list shall only remove those projects from the display and shall not delete the projects from the internal storage media.
- Display software version information.
- Restore data backup files. This function shall copy all project files on the internal storage media to the removable storage media.
- Support operator-activated initiation of data collection for the selected project.

5.3.4.1. *ID and Data Collection Properties*: The user shall be able to change and save ID and data collection properties for each created project. The equipment shall contain properties similar to those in Table A.1.

Table A.1. ID and Data Collection Properties for Thermal Profile Projects

Project Property	Description
Operator	The name of the person who creates the project.
Roadway ID	The name of the road where the project starts.
Start Location	The description of the section of road where the project starts.
Comment	Additional information of interest to the user.
Lift	The layer number of the mat.
Layer Thickness	The thickness of the mat.
Paving Width	The width of the mat behind the paver.
Sample Interval	The longitudinal distance between data capture points.
Min Temp Display	The minimum temperature of the color scale during data collection.
Max Temp Display	The maximum temperature of the color scale during data collection.
Ignore Sensors	Can be set to yes or no. In case of yes, the sensor omission dialogue is displayed before data collection starts.
Rolling Radius	The distance between the center of the paver wheel where the distance sensor is mounted and the ground. The operator can use the calculation program to automatically determine the

	rolling radius.
Distance Sensor Rotation	Can be set to left or right to indicate which side of the paver the distance sensor is mounted.
Start Station	The number of the nearest station. Select “none” if unknown.
Start Offset	The distance from the paving start point to the nearest station identified as the start station. If the start station is in front of the paver, the offset must be positive. If the start station is behind the paver, the offset must be negative.
Station Distance	The distance between two stations.
Station Sequence	Set to ascending or descending to indicate whether stations are incrementing or decrementing with the direction of paving.
Unit Type	Determines the units of the project.

Note 3: The variables defined in the table above are given only as examples. Specific variables and their definitions may differ among owner-agencies.

5.3.4.2. *Distance Calibration***:** If the system uses a distance sensor, the operational computer software shall allow the operator to perform a distance sensor calibration and use the calculated factor to perform the operational distance measurements. The operator shall only need to enter the distance traveled in feet, meters, kilometers, or miles and not make any calculations to determine the calibration factor. The calibration software shall also allow the operator to save the factor calculated or change the calibration factor to other than the calculated value.

5.3.4.3. *Infrared Temperature Sensor Calibration*: The operational computer software shall allow for calibration of the infrared temperature sensor(s). This calibration shall not be accessible or editable through the main menu, and this calibration shall only be performed by the supplier or its authorized designee. The infrared temperature sensor(s) shall be calibrated on an annual basis.

5.3.4.4. *Roadway Testing*: The operational computer software shall provide all necessary functions for the operator to select and perform roadway testing as required for a specific location. The test software shall activate the testing using the data collection properties stored by the selected project. The position points of each measurement shall be automatically determined using the project property inputs, distance sensor, and/or GPS. The software shall detect abnormal conditions in the status of sensors and report the condition to the operator. The testing software shall as a minimum save temperature values measured by the infrared temperature sensor(s), the position information from the distance and/or GPS sensors, and the time stamp from each recorded measurement. These results must also be automatically transferred to removable media during testing for redundancy of data recording. Data logged in result files shall be encrypted in a manner to prevent tampering or manipulation.

The software shall also display in real time the thermal profile contour plot, total distance, location in terms of station and/or GPS coordinates, paver speed, time, and sensor status. The software shall automatically determine the temperature differential of each thermal profile and allow the operator access to review the summary indices while maintaining continuous thermal profile data collection.

Automated thermal profile testing shall continue until the operator selects to stop data acquisition. On stopping data acquisition, the software shall provide a module to input the correct ending distance or station, should a distance sensor calibration error exist. When used, the software will employ a distance correction and normalize the data to the inputted true distance.

5.3.5. *Equipment Shutdown*: The operational software shall stay active unless the supply of power to the system is removed. The computer shall continuously save project data to minimize data loss in the case of an accidental loss of power during testing.

6. MOUNTING AND INSTALLATION OF EQUIPMENT

6.1. The supplier shall provide all parts and training necessary for the proper installation and use of the equipment. Installation of the new equipment shall include a mounting arrangement that can be easily used by the operator as designated.

6.2. Careful consideration shall be given to the mounting and location of equipment. Mounting of equipment shall be made in a manner to withstand normal vibrations that occur while traveling at the normal operating speeds for the equipment used. The location of equipment shall be accessible to the operator and not impede safety.

6.3. Electronic components shall be restrained where possible with tie-downs or other applicable methods.

7. PROFILER ACCURACY

7.1. *Thermal Profile Precision*: Currently, no precision information exists for this test method.

7.2. *Thermal Profile Bias*: Currently, no bias information exists for this test method.

8. REFERENCES

8.1. Miller, S. R., Doree, A. G., ter Huerne, H. L., and Sluer, B. W. Paving the Way Forward: A Case Study in Innovation and Process Control. Presented at the 4th Annual Eurasphalt and Eurobitume Congress, Copenhagen, Denmark, 2008.

8.2. Read, S. *Construction Related Temperature Differential Damage in Asphalt Concrete Pavements*. University of Washington, Seattle, Wash., 1996.

8.3. Sebesta, S., Saarenketo, T., and Scullion, T. *Using Both Infrared and High-Speed Ground Penetrating Radar for Uniformity Measurements on New HMA Layers.* SHRP 2 Project R06C Final Report, SHRP 2, Washington, D.C. (in publication).

8.4. Sebesta, S., and Scullion, T. Application of Infrared Imaging and Ground-Penetrating Radar to Detect Segregation in Hot Mix Asphalt Overlays. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1861, TRB, National Research Council, Washington, D.C., 2003, pp. 37–43.

8.5. Sebesta, S., and Scullion, T. Infrared Imaging and Ground-Penetrating Radar as QC/QA Tools for Hot Mix Paving in Texas. *Asphalt Paving Technology 2007: Journal of the Association of Asphalt Paving Technologists,* Vol. 76, 2007.

8.6. Stroup-Gardiner, M., and Brown, E. R. *NCHRP Report 441: Segregation in Hot Mix Asphalt Pavements.* Transportation Research Board, National Research Council, Washington, D.C., 2000.

8.7. Ulmgren, N. *Temperature Scanner—An Instrument to Achieve a Homogenous Asphalt Pavement.* Second Euroasphalt and Eurobitumen Congress, Barcelona, 2000, Prog. 0052. UK, p. 6.

8.8. Willoughby, K., Read, S., Mahoney, J. P., Muench, S.T., Pierce, L. M., Thompson, T. R., Uhlmeyer, J. S., Moore, R., and Anderson, K.W. *Construction Related Asphalt Concrete Pavement Temperature Differentials and the Corresponding Density Differentials.* Report WA-RD 476.1, Washington Department of Transportation, Seattle, Wash., July 2001.

APPENDIX B

PROPOSED STANDARD SPECIFICATION FOR DENSITY ASSESSMENT OF ASPHALT MIXTURE CONSTRUCTION USING GROUND-PENETRATING RADAR

1. SCOPE

1.1. This work shall consist of measuring the density and variability of a compacted asphalt mixture overlay.

1.2. The equipment uses ground-penetrating radar (GPR) to measure a longitudinal profile of electrical properties of the asphalt mixture surfacing. This system includes a real-time display that allows the operator to view the measured electrical property and automatically stores and saves the data for later review and reduction into asphalt mixture density and variability statistics.

1.3. This standard practice is intended to be applied for construction quality assurance.

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards*:

- None

2.2. *ASTM Standards*:

- None

3. TERMINOLOGY

3.1. *Definitions*:

3.1.1. *Dielectric constant (ε)*: the electrical property measured by GPR.

3.1.2. *Distance measuring instrument (DMI)*: a sensor attached to a wheel on the host vehicle to calculate distance.

3.1.3. *Ground-penetrating radar*: the combination of equipment and host vehicle used to perform the density assessment.

Note 1: A vehicle or a manually propelled cart will typically serve as the host vehicle.

4. GENERAL GPR REQUIREMENTS

4.1. *General*: The equipment shall function independently from the paving crew.

4.1.1. The equipment shall be equipped with various sensors and interface hardware that will measure, record, and display the dielectric constant. The data shall be stored internally. The density assessment shall take place after all finish rolling, and before any trafficking, of the section. As a minimum, the density assessment shall include at least one wheel path. Also, the agency may specify additional profile lines for more testing coverage. Suggested profile lines for the density assessment include both wheel paths and the centerline.

Note 2: The requirement to perform the density assessment after all finish rolling and before trafficking is to eliminate the risk of weather conditions on the GPR.

4.1.2. Distance traveled during the density assessment shall be measured using a DMI.

4.1.3. The equipment shall be capable of a sample interval of every 6 inches or less.

4.2. *Calculating Air Voids*: The equipment shall be capable of computing air void content using post-process software given A and B of the following equation:

$$Y = Ae^{B\varepsilon}$$

4.2.1. The constants A and B for calculating air voids must be determined for the project.

4.2.2. Determine the constants A and B by collecting the required longitudinal profile(s) and using field review to select at least four locations representing the range of observed dielectric constant. Document the measured dielectric constant at each location and then determine the air void content at each location with an approved method.

Note 3: Coring is recommended for determining air void content.

Use an exponential regression function to determine the constants A and B. Figure B.1 illustrates an example determination of these constants.

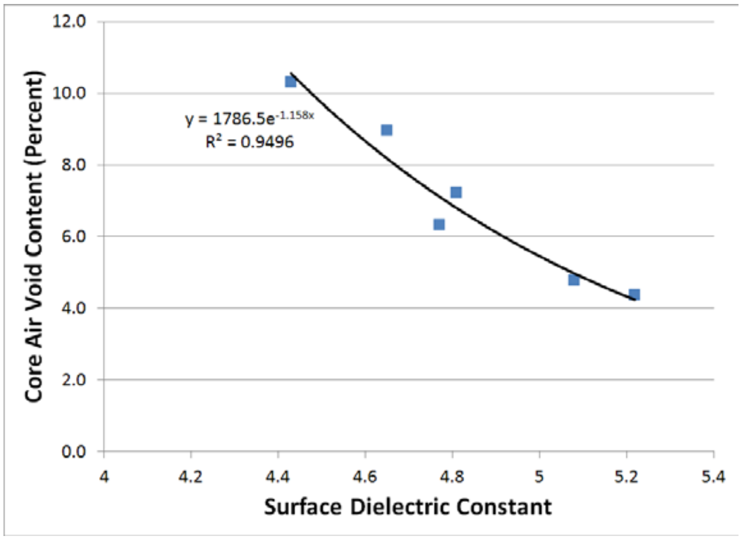


Figure B.1. Example calibration for calculating air voids.

4.3. *Calibration*: The equipment shall have built-in provisions to facilitate the calibration of the ground-penetrating radar antenna prior to each use.

5. HARDWARE

5.1. *General Requirements*:The GPR shall meet the requirements in Table B.1.

Table B.1. GPR Requirements

Full-Width Half Max Time (ns)[a]	0.14
Approximate Coverage Per Measurement (in.^{2})[b]	5
Repeatability (dielectric values)	0.1
Signal-to-noise ratio (S/N) in decibels (dB)	46
Lower Operating Temperature (°C)	-10°C

Upper Operating Temperature (°C)	Not Available
Lower Storage Temperature (°C)	Not Available
Upper Storage Temperature (°C)	Not Available
Ingress Protection (IP) Rating	65
Battery Life	
Antenna (hr)	3.5–4

[a] Full-Width Half Max Time (ns) is the width, in nanoseconds, of the positive portion of the reflection from the metal plate at the amplitude level, where it is 1/2 of the maximum amplitude of the positive peak.

[b] First Fresnel Zone Area.

5.2. The GPR shall provide real-time and post-process software capable of developing the density assessment for the entire project.

5.3. If not powered by battery, power consumption of all equipment shall not exceed the capacity of the host vehicle providing operating power. Complete discharge of this system shall not impact the host vehicle's regular electrical system.

5.4. Equipment or obstructions that could interfere with the GPR are not allowed to be placed so they impede the influence area of the GPR antenna or restrict the accuracy or functionality of the DMI.

6. DATA FILE FORMAT

6.1. The output data shall be formatted so each file's header conforms to Table B.2 and each interval of the longitudinal profile conforms to Table B.3.

Table B.2. GPR Output File Header Information

Item	**Description**
Road Name	The name or some other identification of the road where the measurements were made
Operator	The name of the person using the equipment
Date	Date measurements were made
Longitudinal Distance Start Location	A description of the longitudinal starting location on the road where the measurements were made
Transverse Distance Start Point	The reference point for transverse distances (e.g. longitudinal joint, shoulder)
Comment	Additional information of interest to the user
Lift	The layer number of the mat
Layer Thickness	The design thickness of the mat
Output Sample Interval	The distance increment between reported measurements
Number of Antennas	Number of antennas used (1–3)
Porosity A Value	The A constant used in the equation shown in 4.2 which converts dielectric constant to porosity
Porosity B Value	The B constant used in the equation shown in 4.2

	which converts dielectric constant to porosity

Table B.3. GPR Information Output at Each Longitudinal Measurement Location

Item	**Description**
Longitudinal Distance	Distance relative to longitudinal starting location (ft/m)
Transverse Distance	Transverse distance from the transverse reference location (e.g. shoulder or longitudinal joint). (ft/m)
Latitude[a]	Latitude of measurement (decimal degrees)
Longitude[a]	Longitude of measurement (decimal degrees)
Dielectric	Calculated dielectric value
Porosity	Calculated Porosity (%)
Lift Thickness[a]	Calculated thickness of lift (in./cm)

[a] If unavailable, the field will be empty, but a comma separator will be present.

Note 4: The variables defined in the tables above are given as examples only. Specific variables and their definitions may vary among GPR systems.

6.2. The post-processing software shall readily provide, as a minimum, the average, minimum, maximum, and standard deviation statistics. Figure B.2 shows an example post-process summary screen.

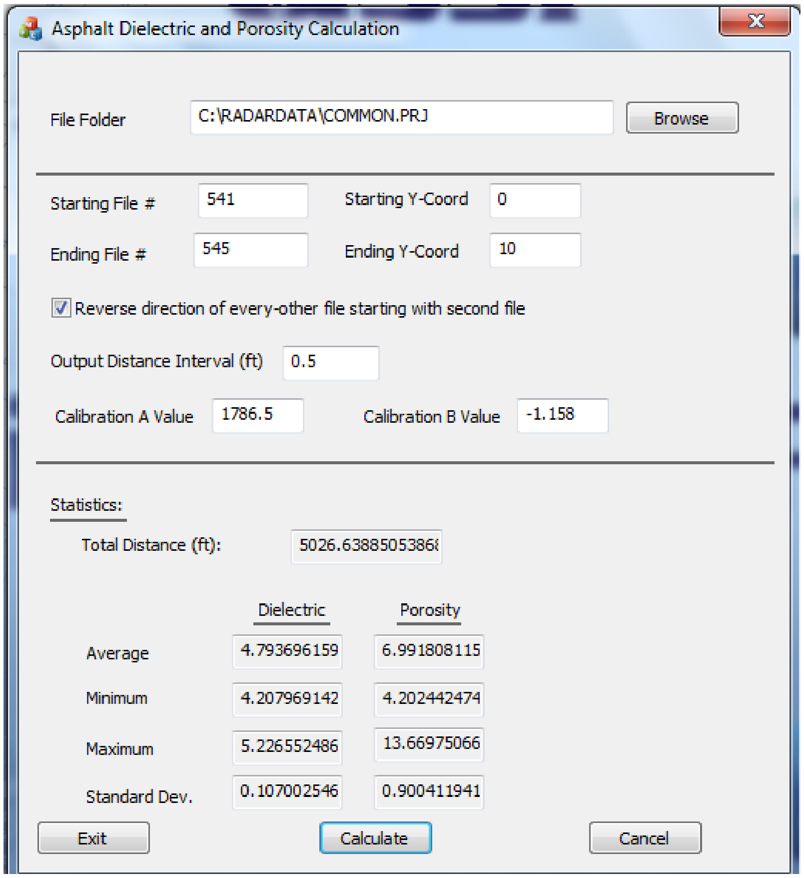


Figure B.2. Example post-process density assessment summary screen.

7. CALIBRATION

7.1. *GPR*: Before each project, calibrate the GPR by performing a metal plate and airwave test sequence.

7.2. *DMI System*: If the system uses a DMI, the operational computer software shall allow the operator to perform a distance sensor calibration and use the calculated factor to perform the operational distance measurements.

8. GPR ACCURACY

8.1. *GPR Precision*: The estimated single operator repeatability for the dielectric constant is 0.1.

8.2. *GPR Bias*: Currently, no bias information exists for this test method.

9. REFERENCES

9.1 Sebesta, S., Saarenketo, T., and Scullion, T. *Using Both Infrared and High-Speed Ground Penetrating Radar for Uniformity Measurements on New HMA Layers.* SHRP 2 Project R06C Final Report, SHRP 2, Washington, D.C., 2013.

9.2. Sebesta, S., and Scullion, T. Infrared Imaging and Ground-Penetrating Radar as QC/QA Tools for Hot Mix Paving in Texas. *Asphalt Paving Technology 2007: Journal of the Association of Asphalt Paving Technologists*, Vol. 76, 2007.

9.3. Sebesta, S., and Scullion, T. Application of Infrared Imaging and Ground-Penetrating Radar to Detect Segregation in Hot Mix Asphalt Overlays. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1861, TRB, National Research Council, Washington, D.C., 2003, pp. 37–43.

9.4. Scullion, T., and Saarenketo, T. Implementation of Ground Penetrating Radar Technology in Asphalt Pavement Testing. In *Proceedings of the Ninth International Conference on Asphalt Pavements*, August 17–22, 2002, Copenhagen, Denmark, p. 16.

9.5. Roimela, P. *The Use of Pavement Radar in Quality Control of Bituminous Pavements.* Tielaitos, Konsultointi, Tielaitoksen selvityksiä 6/1999, Rovaniemi, Finland (English abstract).

9.6. Scullion, T., and Chen, Y. *Using Ground-Penetrating Radar for Real-Time Quality Control Measurements on New HMA Surfaces.* Report 1702-5, Texas Transportation Institute, College Station, Texas, November 1999.

9.7. Saarenketo, T., and Roimela, P. Ground Penetrating Radar Technique in Asphalt Pavement Density Quality Control. *Proceedings of the Seventh International Conference on Ground Penetrating Radar*, May 27–30, 1998, Lawrence, Kans., Vol. 2, pp. 461–466.

9.8. Roimela, P. *Ground Penetrating Radar Surveys in Pavement Quality Control 1996–1997.* Tielaitoksen selvityksiä 4/1998, Rovaniemi, Finland (English abstract).

9.9. Saarenketo, T. Using Ground Penetrating Radar and Dielectric Probe Measurements in Pavement Density Quality Control. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1997, TRB, National Research Council, Washington, D.C., 1997, pp. 34–41.