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Thermal Segregation Influence on Current Asphalt Mixtures

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Stephen Sebesta, Jinho Kim, Ross Taylor, and Sheng Hu

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16. Abstract
Thermal segregation during the construction of asphalt mixtures can result in the formation of low-density areas and a subsequent decrease in pavement life. Although the methods for measuring thermal segregation have remained largely unchanged, significant advancements have been made in asphalt mixture types and design methods over the past decade. This study assessed the significance of thermal segregation with current asphalt mixes, validated existing criteria, and established modified criteria as necessary. The study also resulted in guidance on identifying and addressing recurring thermal segregation issues, ensuring that thermal profile requirements align with modern asphalt mixes and construction practices. Results from this study showed that based on current practices, more than two thermal profiles with severe thermal segregation could be considered recurring. This study also showed that thermal segregation does induce higher air voids in current mixes, which results in poorer rutting and reduced crack life properties. Analysis suggested that the influence of thermal segregation-induced air voids could take as much as 10 years off the pavement life, although the actual influence of thermal segregation on field performance can vary significantly depending on many factors. In practice, thermal segregation-induced air voids may impact performance but may allow the pavement to still reach its design life. Results from this study showed that the current 25°F temperature differential is still valid as a threshold to define thermal segregation. Results from this study also revealed that the current methods for evaluating thermal profile need further development to include affected area and absolute placement temperature.

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Thermal Segregation, Asphalt Density, Thermal Profile, Paver-Mounted Thermal Profiler, Temperature Differential

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THERMAL SEGREGATION INFLUENCE ON CURRENT ASPHALT MIXTURES

by

Stephen Sebesta
TTI Research Scientist
Texas A&M Transportation Institute

Jinho Kim
Associate Transportation Researcher
Texas A&M Transportation Institute

Ross Taylor
Research Specialist III
Texas A&M Transportation Institute

and

Sheng Hu
TTI Research Engineer
Texas A&M Transportation Institute

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College Station, Texas 77843-3135

DISCLAIMER

This research was sponsored by the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The researcher in charge of the project was Stephen Sebesta.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
AV	Air Void
CAM	Crack Attenuating Mixture
COV	Coefficient of Variation
CSJ	Control Section Job
DC	Dielectric Constant
DG	Dense-Graded
ESALs	Equivalent Single Axle Loads
FN	Flow Number
GPR	Ground-Penetrating Radar
Gr	Rice Gravity
HMA	Hot Mix Asphalt
IDEAL-CT	Indirect Tensile Asphalt Cracking Test
JMF	Job Mix Formula
NDT	Nondestructive Testing
OEM	Original Equipment Manufacturer
OT	Overlay Test
pcf	Pounds per Cubic Foot
PFC	Permeable Friction Course
PMTP	Paver-Mounted Thermal Profiler
RMC	Routine Maintenance Contract
SHRP 2	Strategic Highway Research Program 2
SMA	Stone Matrix Asphalt
SP	Superpave
SS	Special Specification
STA	Station
TBPFC	Thin Bonded Permeable Friction Course
TOM	Thin Overlay Mixtures
TSI	Thermal Segregation Index
TxDOT	Texas Department of Transportation
TxME	Texas Mechanistic-Empirical Flexible Pavement Design and Analysis System

CHAPTER 1. INTRODUCTION

1.1. BACKGROUND AND OBJECTIVES

Thermal segregation during asphalt mixture construction can lead to the formation of low-density areas. These low-density areas generally exhibit reduced pavement life. While the general methods for measuring thermal segregation have remained relatively unchanged since their implementation, asphalt mixture types and design methods have undergone significant modifications in the last 10 years. This project evaluated the significance of thermal segregation with current generation asphalt mixes used in Texas and the historical thermal profile data to provide guidance on determining the frequency at which thermal segregation becomes a recurring issue. The main objectives of this project included:

- Evaluate the significance of thermal segregation on current generation asphalt mixes.
- Summarize and document the current literature on hardware systems, specifications, and new research for thermal segregation.
- Gather and summarize input from stakeholders on the strengths and weaknesses of current thermal profiling methods and specifications.
- Perform analysis to identify what level of thermal segregation is typical in current paving operations.
- Perform field and laboratory testing on construction projects to evaluate how thermal segregation relates to mixture properties with current generation mixes.

1.2. REPORT ORGANIZATION

This report is organized into eight chapters and two appendices:

- Chapter 1 provides a brief overview of the project's background and objectives, along with an outline of the report's organization.
- Chapter 2 presents a comprehensive review of current national literature to examine the existing methods and specifications for thermal profile requirements.
- Chapter 3 documents the strengths and weaknesses of the current thermal profile specification and test procedure based on input from stakeholders.
- Chapter 4 reviews and analyzes historic thermal profile data to benchmark the overall and mix-specific levels of moderate and severe thermal segregation.
- Chapter 5 presents field results from demonstration projects.
- Chapter 6 evaluates mixture volumetrics, presents performance-related testing, and discusses pavement performance modeling to document potential consequences of different levels of thermal segregation.
- Chapter 7 presents results from 13 site visits to projects of known age and with thermal profile information available from the time of construction.
- Chapter 8 presents conclusions and recommendations from the research project.
- Chapter 9 presents value of research from the project.
- Appendix A lists questions for industry feedback on current thermal profiling methods and specifications.

- Appendix B presents questions for owner feedback on current thermal profiling methods and specifications.

CHAPTER 2. LITERATURE REVIEW

This chapter summarizes the current literature on hardware systems, specifications, and new research for thermal segregation. Since thermal segregation was identified in the 1990s to correlate with in-place mixture properties (*1*, *2*), particularly the density of asphalt mixtures, there have been many developments in asphalt mix design methods and types of mixtures placed. Additionally, there has been a notable increase in the availability of hardware and software systems for measuring and calculating thermal segregation, along with the development of comprehensive specifications by the Texas Department of Transportation (TxDOT).

Researchers reached out to equipment manufacturers to ascertain the capabilities of different systems that can facilitate continuous thermal profiling, along with the key features associated with each system. They identified and obtained nine agency specifications for thermal profiling to analyze how different user groups define, report, and provide incentives and/or disincentives based on thermal segregation. The researchers also conducted an extensive literature search spanning the past 5 years in databases such as Transport Research International Documentation, Compendex, and Geobase to gather relevant literature on thermal segregation, thermal profiling, and asphalt mixture uniformity and construction quality.

2.1. SYSTEMS FOR CONTINUOUS THERMAL PROFILE

Currently, the Moba PAVE-IR, Vogele RoadScan, and Caterpillar thermal mapping camera represent the most developed hardware systems for continuous thermal profilers (*3*–*5*). Topcon offers a thermal mapper product as part of its Pavelink system. However, during the initial literature review, it was found that the product was not yet commercially available. As of the time of this report, this system appears to be available in the market (*6*).

Figure 1 shows representative views of key hardware from these manufacturers for each system. Table 1 summarizes the key characteristics of each system.

PAVE-IR

RoadScan

Thermal Mapping Camera

Thermal Mapper

Figure 1. Representative Views of Thermal Profile Test Systems (*3*–*6*).

Table 1. Key Characteristics of Hardware Systems.

System	Moba PAVE-IR	Vogele RoadScan	Caterpillar Thermal Mapping Camera	Topcon Thermal Mapper
Approximate cost	$32,000	$25,000–$40,000	Not available	No further information was available at the time of the literature review
Compatible with any make of paver	Yes	No, Vogele Dash 3 pavers only	Not available	
Sensor type	Infrared spot radiometer	Infrared camera	Infrared camera	
Measurement width	Up to 13 m	10 m	Up to 30 ft	
Measurement resolution	1 ft × 1 ft	25 × 25 cm	Not available	
AASHTO PP 80 compliant	Yes	Yes	Yes	
Tex-244-F compliant	Yes	No	Not available	

Note: AASHTO = American Association of State Highway and Transportation Officials.

Each of the thermal profile systems in Table 1 fit into a growing movement of intelligent construction and digital construction process optimization and documentation. Some manufacturers offer proprietary packages for paving applications to interconnect plant, trucking, and job site information. However, with an increasing number of states considering thermal profiling and more manufacturers contemplating the provision of equipment, there has been a growing interest in integrating continuous thermal profile outputs into the Veta (*7*) post-process data tool. Specifically, hardware manufacturers hesitated to take on the additional role of software developers, primarily due to the lack of standardization of analysis requirements across the states. Therefore, the newer market entrants may comply with AASHTO PP 80 but may not adhere to the current Tex-244-F specifications.

The **PAVE-IR** system represents the first commercial system developed and introduced to the industry for full-coverage thermal mapping. Unique features of this system include the ability to retrofit to any make/model of the paver, auto mat edge or configurable selective monitoring scanning modes, and automatic generation of reports tailored to TxDOT's requirements.

The **RoadScan** system represents an original equipment manufacturer (OEM) integration of continuous thermal profiling into the manufacturer's paving equipment. This type of integration has the potential to simplify the field setup but comes with the trade-off that the system is proprietary to the specific make of paver. If the end user desires it, RoadScan can be integrated into a proprietary digital paving optimization and documentation package from the manufacturer. This integration can offer daily summaries of paving parameters, logistics, efficiency, and placement temperature.

The **thermal mapping camera** represents another OEM system for thermal scanning. A review of current information suggests this system is designed primarily with the AASHTO PP 80 specification in mind. Multiple attempts over time to obtain further information from the manufacturer were unsuccessful.

The **thermal mapper** represents another option for the interconnected plant, trucking, and job site digital construction documentation. This system is not proprietary to any specific manufacturer's paving equipment. During the literature search efforts, the thermal mapping component of this system was not available, and multiple attempts over time to obtain further information from the manufacturer were unsuccessful. However, as of this report date, information suggests this system may now be commercially available and provides support for Veta files (*6*).

2.2. AGENCY SPECIFICATIONS

Researchers identified 10 agencies with continuous thermal profile specifications. Specifications exist for AASHTO, Alaska, Georgia, Kentucky, Maine, Minnesota, Missouri, New Jersey, Ohio, and Texas DOTs. Researchers specifically sought to identify how user groups define, report, and provide incentives and/or disincentives based on thermal segregation.

2.2.1. Definition of Thermal Segregation

All except two specifications categorize thermal segregation according to the temperature differential ranges in Table 2.

Table 2. Temperature Differentials Typically Used to Define Thermal Segregation (*8–15*).

Range	Category
0–25°F	Low (good)
25 < range ≤ 50°F	Moderate
> 50°F	Severe

One agency (*16*) uses only two categories with a threshold temperature differential of 25°F. This agency developed a thermal segregation index (TSI), which represents a composite index of the variability of surface temperatures and the transverse variability of surface temperatures (*17*). This agency reports that the range statistic was not adequately capturing longitudinal streaks (*18*). Table 3 shows the agency's TSI categories.

Table 3. TSI Categories (*17*).

TSI Values	Thermal Segregation Category
TSI of less than 30.0	Low
TSI of 30.0 or greater and less than 50.0	Moderate–Low
TSI of 50.0 or greater and less than 70.0	Moderate–Severe
TSI of 70.0 or greater	Severe

2.2.2. Reporting Thermal Segregation

In all the specifications reviewed for continuous thermal profiling, a segment length of 150 ft was consistently used. It was commonly required to collect temperature data from within 10 ft behind the paver screed plate (*8*, *11*, *12*). One state required data collected from within 3 to 12 ft behind the paver screed (*17*). Variations exist in the data included for use in determining the temperature differential. Table 4 summarizes the data identified in the literature used by each specification.

Table 4. Profile Data Used for Determining Thermal Segregation.

Agency	Min. Valid Temp. (°F)	Include Paver Stops[a]	Omit Areas within 2 ft of Edge	Calculation of Thermal Segregation
AASHTO	180	No	No	98.5 - 1 percentile
Alaska	All locations reading non-ambient temperatures	Yes	No	98.5 - 1 percentile
Georgia	176[b]	No[b]	No	98.5 - 1 percentile[b]
Kentucky	176[b]	No[b]	No	98.5 - 1 percentile[b]
Maine	176[b]	No[b]	No[b]	98.5 - 1 percentile[b]
Minnesota	180	No	No	TSI
Missouri	180	No	No	98.5 - 1 percentile
New Jersey	170	No	Yes	98.5 - 1 percentile
Ohio	180	No	No	98.5 - 1 percentile
Texas	176[b]	No	Yes	98.5 - 1 percentile

[a] *Paver stop* is defined as the area 2 ft behind and 8 ft in front of a location where the paver stopped for more than 1 minute.

[b] The specification does not clearly designate requirements for this parameter. The entry in Table 4 is based on the current state of the practice for default approaches.

2.2.3. Incentives/Disincentives Based on Thermal Segregation

Approaches for using continuous thermal profiles range from information only (as a method to foster quality control) to adjustments in pay. Almost all existing specifications pay for the actual collection of the data by lump sum. Some specifications reduce this payment if the thermal coverage (the percentage of the required paving area tested and reported) falls below a specified percentage (*8*, *10*, *11*, *17*).

Three specifications in the literature take the general approach of requiring corrective action or investigation when thermal segregation exists. Figure 2 summarizes these approaches.

Georgia — When temperature differentials exceed 25°F

- Take immediate action to control the placement operation.
- Operations subject to suspension if corrective action fails to provide subsequent profiles with temperature differentials ≤ 25°F.

Kentucky — For severe readings over 3 consecutive segments

- Investigate the cause.
- Also applies for severe readings over 4 or more segments in a day.

Maine — If 2 or more profiles in a day have severe thermal segregation

- Notify in writing of proposed corrective action.

Figure 2. Corrective Action and Investigation Disincentives (*10*, *11*, *16*).

Five specifications in the literature included price adjustments based on the category of thermal segregation in each profile. These incentives/disincentives varied widely, from $5 to $75 incentive and from $5 to $40 disincentive, per profile. Table 5 summarizes the incentives based on the temperature differential range. In Table 5, the wide range exists in pay adjustment from incentive to disincentive because the specification that included a $75 incentive did not include a pay disincentive; rather, that specification required density profiles and repairs for any result with moderate or severe thermal segregation (*9*).

Table 5. Incentives/Disincentives Used for Thermal Segregation (*8*, *9*, *12*, *14*).

Range	Category	Incentive/Disincentive	Average
0–25°F	Low (good)	$5–$75 incentive	$26.75
25 < range ≤ 50°F	Moderate	No pay adjustment	No pay adjustment
> 50° F	Severe	$5–$20 disincentive	$10.67

For the specification using the TSI, incentives/disincentives ranged from $40 incentive to $40 disincentive on a linear scale (*17*).

The literature suggests Washington State, where the thermal segregation phenomenon was first identified, requires material transfer devices for any mix in or partially in the top 0.3 ft of the pavement structure; any thermal profile testing is at the discretion of the engineer and uses handheld devices (*19*, *20*). Washington's specification performs a cyclic density test if temperature differentials exceed 25°F and assesses a $500 cyclic density adjustment for any 500-ft section with two or more density readings below 90 percent of the theoretical maximum (*19*).

2.3. RESEARCH LITERATURE

Throughout the 2010s, work investigating and fostering digital construction technologies, including thermal segregation and thermal profiling topics, continued. The Strategic Highway Research Program 2 (SHRP 2) initiated an implementation assistance program to foster agency exposure and buy-in to thermal profiling technologies. Other researchers evaluated the influences of thermal segregation on warm-mix asphalts, and some work evaluated the mechanical properties of segregated mixes. Within this body of literature, some authors identified threshold criteria for segregation categories.

2.3.1. SHRP 2 Activities

SHRP 2 completed 10 demonstration projects with 10 agencies from 2015 to 2017. From field measurements, SHRP 2 reported the following (*21*):

- As the coefficient of variation (COV) of mat temperature increased, the COV of mat density increased.
- Aggressive quality control programs by the contractor—defined as using a density gauge to ensure that mat density was achieved before moving to the next roller section in real time—decreased the sensitivity of density COV to temperature COV.
- When using the thermal profiler for quality control to help decide adjustments to the paving process, the air void (AV) standard deviation and percent defective decreased; thus, the contractor and agency risk lowered (Figure 3).
- Using a thermal profiler does not automatically result in better pavement performance. The contractor must take corrective action when thermal segregation is observed.

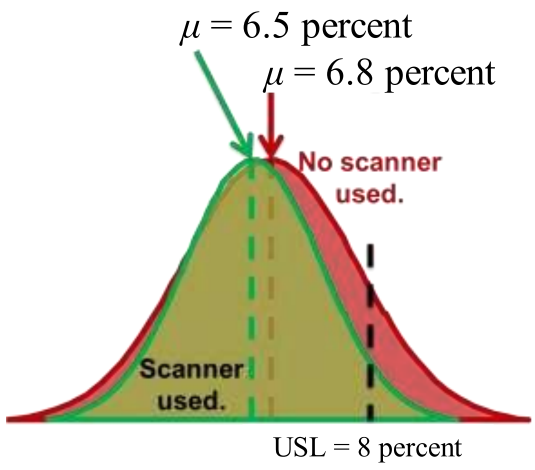


Figure 3. Statistical Distribution of AVs Tightens When Using Thermal Profiling (*21*).

2.3.2. Other Research Activities

The recent body of knowledge and study of thermal segregation includes some evaluations of the impacts of thermal and/or gradation segregation on laboratory and field performance, in some cases focused specifically on warm-mix asphalt. Historical information (not referenced in this report) generally agrees well with information from the more recent literature:

- Temperature segregation has a negative impact on density, and the cold spots are generally more crack-susceptible and have poorer fracture properties (*22–27*). Even with warm-mix asphalt, temperature segregation influences density, high-temperature stability, low-temperature cracking, and tensile strength (*27*).
- Using remixing material transfer vehicles can be key to reducing segregation (*22*, *28*, *29*).
- Applying more compaction effort can mitigate the impacts of thermal segregation (*24*).
- Coarser mixes are more prone to aggregate segregation (*30, 31*). However, not all thermal segregation is aggregate segregation (*27*).
- Paver stops have been found to cause thermal segregation (*26*), resulting in areas of localized roughness (*28*). Paver stops should be kept to less than 4 minutes (*26*).
- There is no complete consensus on the utility of thermal profiling. A study reported that field-cored temperature-segregated samples did not show statistically lower density. While temperature-segregated samples generally exhibited lower fracture resistance, the correlation between temperature differential and the change in fracture resistance was not strong (*32*).

2.3.3. Segregation Thresholds

Some alternative thresholds for thermal segregation can be found in the literature. Two documents classified high severe segregation at temperature differentials of 43°F (*24*) and 38°F (*26*). Based on changes in AV content, one study proposed medium-level segregation beginning at a temperature difference of 14.4°F and high-level segregation beginning at a temperature difference of 32.4°F (*27*).

2.4. SUMMARY AND CONCLUSIONS FOR LITERATURE REVIEW

The literature offers valuable insights into equipment, methods, and incentives/disincentives that can inform TxDOT's efforts to update its thermal profiling requirements. Figure 4 provides a comprehensive summary of the literature's findings in each of these areas and highlights how these findings can influence the considerations for updating specifications or test procedures.

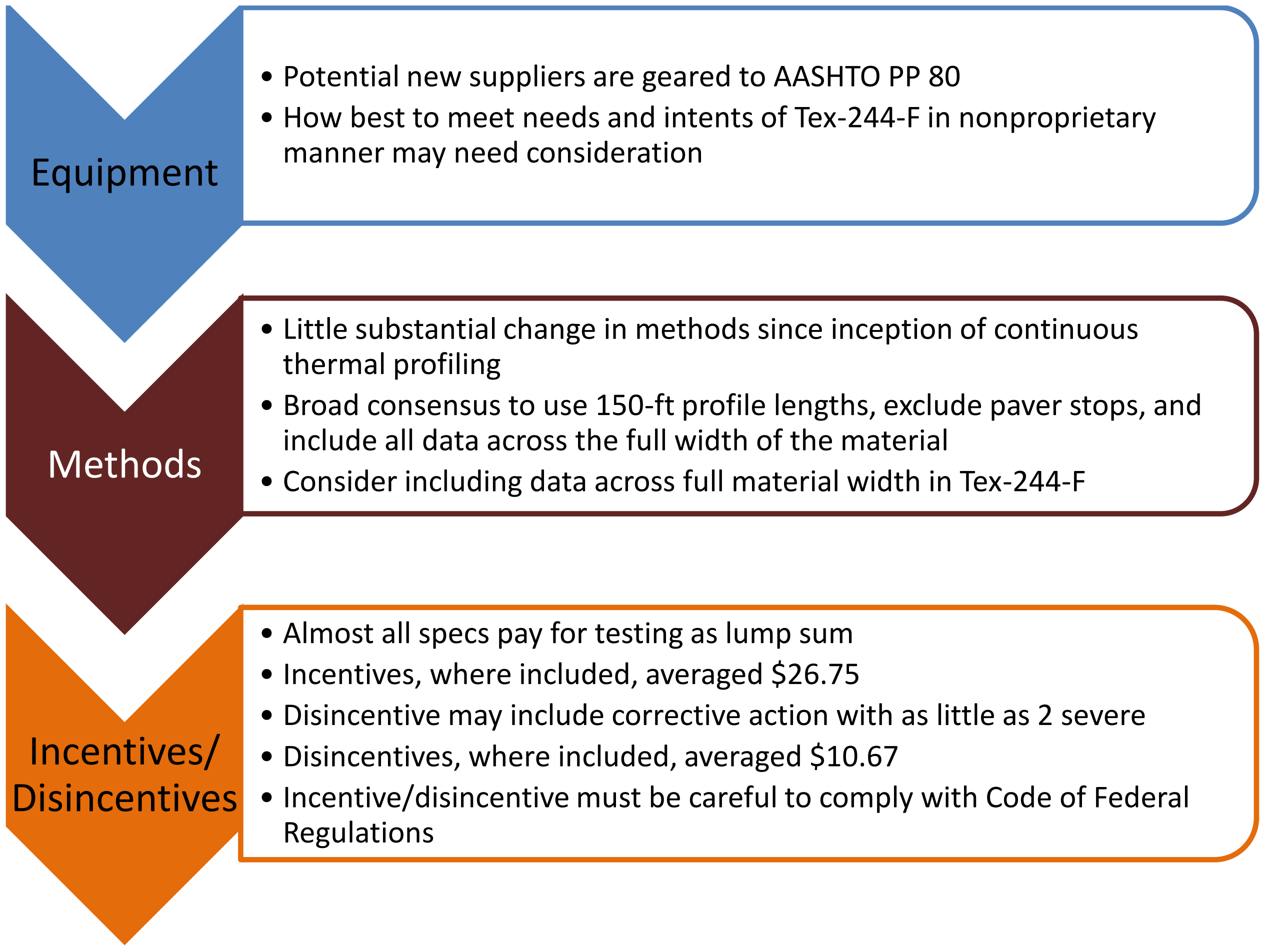


Figure 4. Summary Findings from Literature for Thermal Profiling.

2.4.1. Equipment

More manufacturers are entering the market with equipment capable of conducting continuous thermal profiles. These manufacturers primarily specialize in hardware systems and offer their own software packages, often without customization for specific state requirements. However, potential new equipment suppliers and AASHTO PP 80 aim to integrate all test data and post-processing into Veta. Therefore, finding the most effective way to meet the requirements and objectives of Tex-244-F in a nonproprietary manner may require careful consideration.

2.4.2. Methods

The methods for continuous thermal profiling have generally remained unchanged since the technology was introduced over a decade ago. The main difference highlighted in the literature compared to Test Method Tex-244-F is that most agencies incorporate all temperature data across the entire width of the pavement mat. In summary:

- Broad consensus exists to use 150-ft profile lengths.
- Other agency specifications exclude paver stops from the thermal profile analysis.

- Other agency specifications incorporate all temperature data across the entire width of the pavement mat.
- With one exception, existing specifications categorize thermal segregation based on the temperature differential calculated from the 98.5–1 percentile.
- With one exception, existing specifications use the temperature differential to categorize thermal segregation as follows:
    - Low: 0–25°F.
    - Moderate: 25 < range ≤ 50°F.
    - Severe: > 50°F.

The literature suggests that consideration should be given to incorporating the temperature data across the entire width of the pavement mat in Tex-244-F.

2.4.3. Incentives/Disincentives

Varied approaches exist in the literature on incentives or disincentives for thermal profiling. Outside of Texas, almost all specifications for continuous thermal profiling include a pay item for the actual performance of the test. Regarding the thermal profile result, the literature presents two main approaches: implementing a corrective action disincentive or applying a pay adjustment based on the category of thermal segregation indicated in each profile.

According to the literature, corrective action can be triggered by as few as two or more severe readings in a day or three consecutive severe readings, providing a basis for interpreting "recurring thermal segregation" as stated in TxDOT's specifications.

In terms of pay incentives/disincentives, the literature indicates a range of $5 to $75 per profile, with $75 being an outlier. The suggested pay schedule in AASHTO PP 80 includes a $20 incentive for profiles without thermal segregation and a $20 disincentive for each profile with severe thermal segregation.

Compliance with Federal Highway Administration requirements for independent validation of the contractor-provided data will be a significant topic to consider when discussing pay adjustments. This aspect must be carefully addressed in any proposed updates to TxDOT specifications.

CHAPTER 3. IDENTIFY AND DOCUMENT CURRENT STRENGTHS AND WEAKNESSES

This chapter presents findings obtained through stakeholder input on the strengths and weaknesses of existing thermal profiling methods and specifications. To gather this information, the researchers developed a questionnaire and sought feedback from both industry stakeholders and TxDOT districts. The industry stakeholder questionnaire was distributed online through coordination with the Texas Asphalt Pavement Association. TxDOT's Materials and Tests Division distributed a separate set of questions to the TxDOT districts.

The input received played a crucial role in identifying the key aspects of current thermal profiling practices and specifications that are viewed as strengths or weaknesses. The following sections present a comprehensive analysis of these findings.

3.1. INDUSTRY FEEDBACK

Appendix A presents the questions from the industry stakeholder questionnaire. Researchers received nine responses. Figure 5 illustrates that most respondents (56 percent) indicated they use a paver-mounted thermal profiler (PMTP), and about 67 percent reported reviewing thermal profile results one or more times a day. These results suggest a reasonable implementation level of the paver-mounted thermal imaging system. The results also indicate that, generally, contractor staff check the data daily. However, nearly 30 percent of the time, the data are only reviewed a few times a week or less.

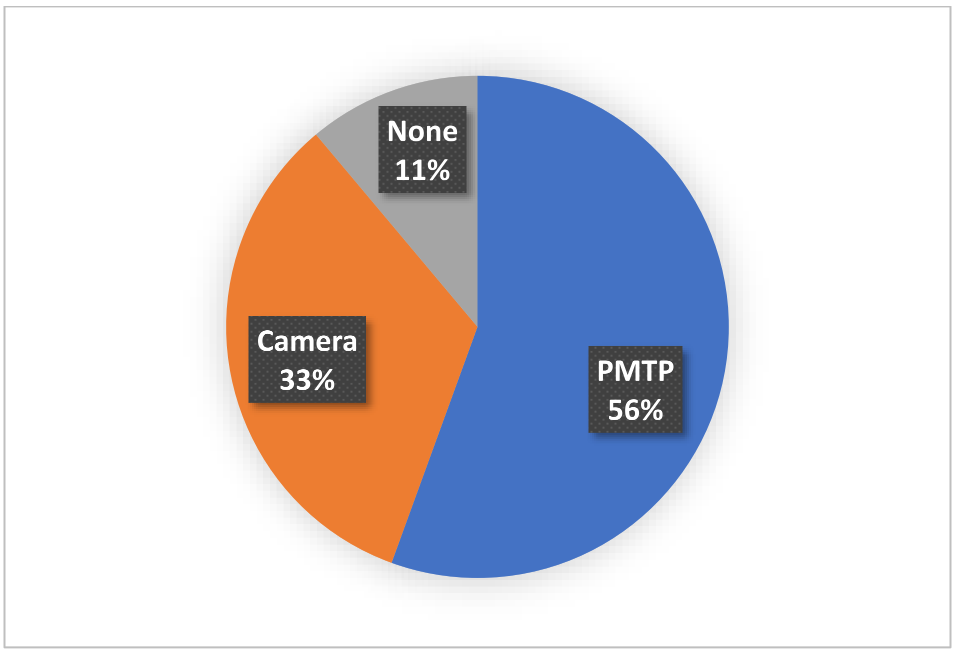


Figure 5. Thermal Profile System Usage.

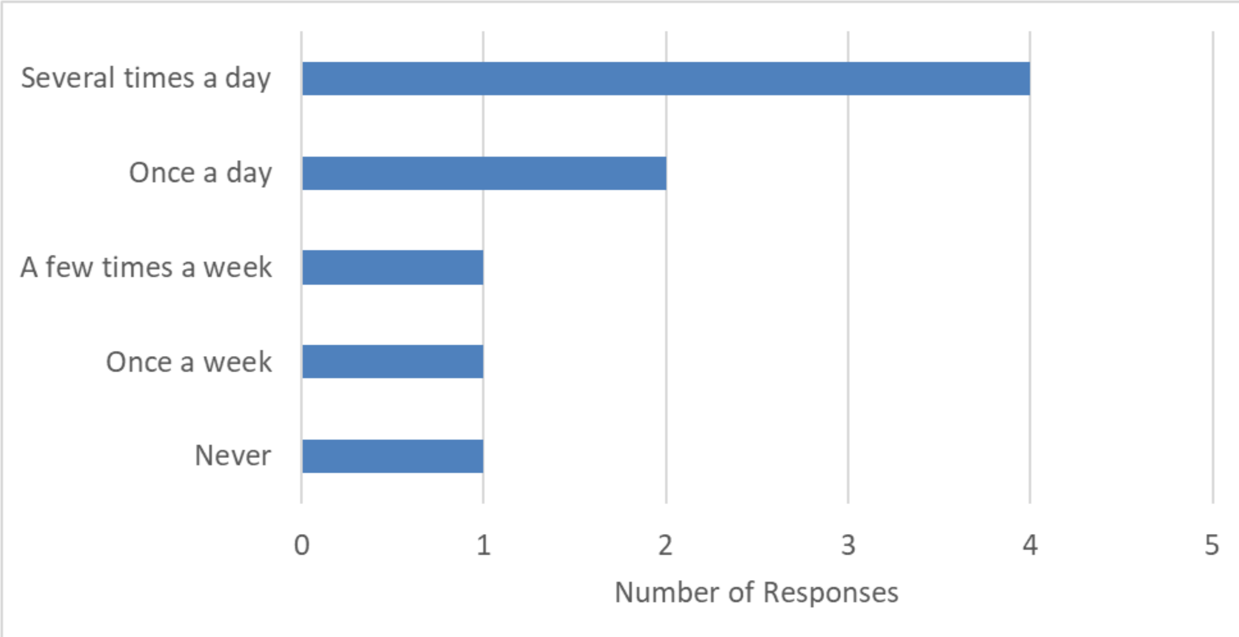


Figure 6. Frequency of Thermal Profile Data Review.

Figure 7 shows that 45 percent of respondents indicated current methods allow paving with <10 percent severe thermal segregation. However, 33 percent of respondents indicated a higher percentage of severe thermal segregation is likely with current practices, and 22 percent did not select a response. These results suggest that the real or perceived ability to minimize severe thermal segregation within the current state of the practice probably varies substantially.

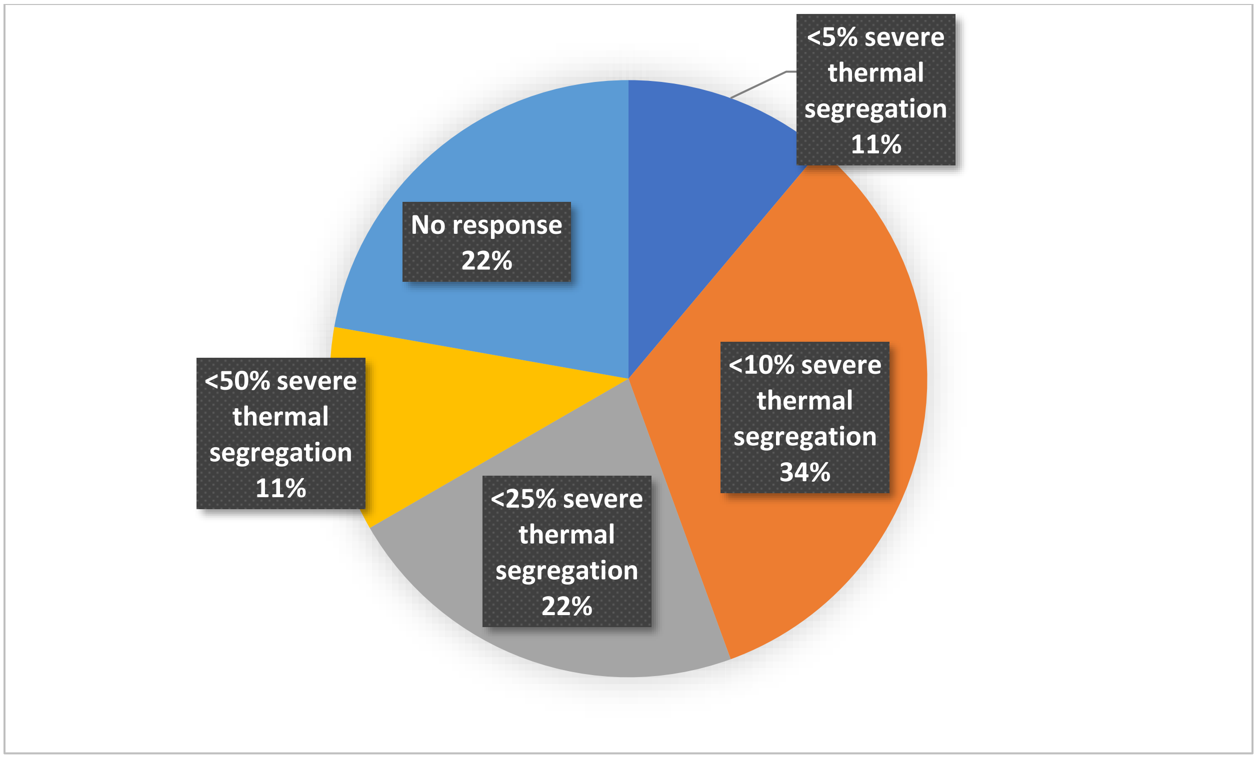


Figure 7. Reported Amount of Severe Thermal Segregation with Current Practices.

Industry responses also included feedback on the definition of recurring thermal segregation. Table 6 presents representative definitions and highlights the existence of various interpretations among practitioners. In row A, the definition links the presence of recurring thermal segregation to corresponding failing density profiles. Row B aligns closely with current TxDOT specifications, offering a relatively open-ended definition of "recurring." Row C considers two consecutive profiles as constituting "recurring" when tested with a thermal camera, but when tested with a thermal profiling (PAVE-IR) type system, a more flexible approach is adopted by defining recurring as a "pattern."

Table 6. Industry Definitions of Recurring Thermal Segregation.

A	Clear pattern of end-load appearing thermals that cross-correlate with longitudinal density profile out of tolerance.
B	Thermal segregation in a recurring pattern during a single paving period.
C	More than two back-to-back profiles with severe thermal segregation with the thermal camera. With the PAVE-IR system, it would be a pattern of severe thermal segregation.

Industry responses reported the following practices to minimize thermal segregation. These practices are in reasonable agreement with the information found in the literature:

- Operate the plant consistently and supply material uniformly.
- Use similar truck types and tarp trucks.
- Use a material transfer vehicle when possible.
- If using windrows, overlap the windrows and do not make long windrows.

- Pave continuously and at a consistent speed, keeping the hopper at a consistent level.
- Use experience, recognize, and react to issues.

Figure 8 summarizes the reported impacts of using a paver-mounted thermal profiling system on paving operations. While Figure 8 suggests some (45 percent) positive views that the PMTP promotes better awareness of the paving operation and helps enhance quality, 33 percent of respondents reported neutral to negative impacts on operations from the use of a PMTP.

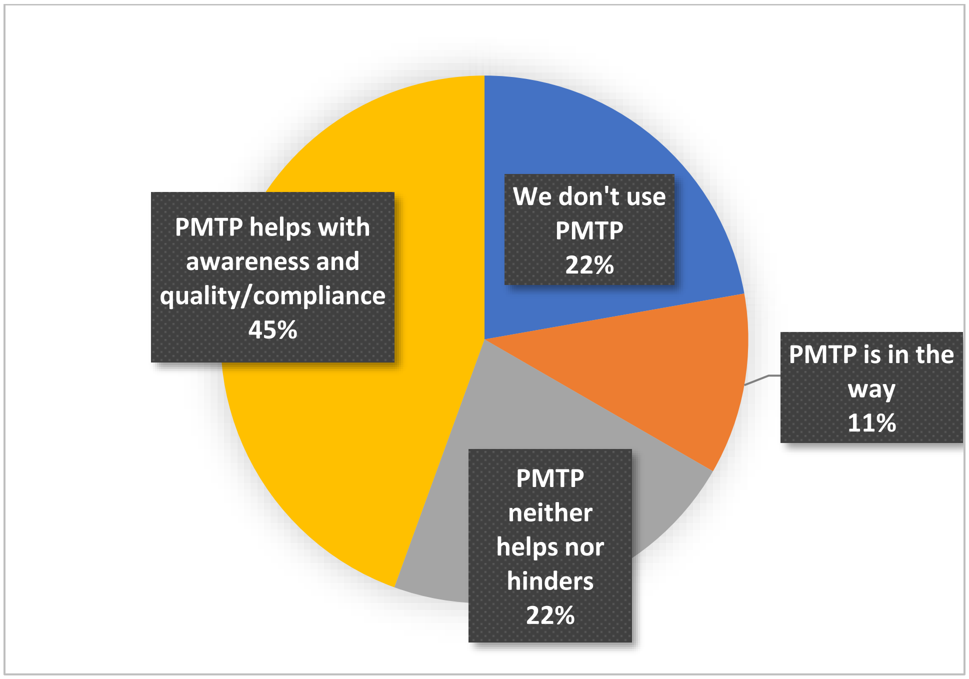


Figure 8. Reported Impact of PMTP on Paving Operations.

Industry responses reported that the benefits of Tex-244-F and TxDOT's thermal profile specifications include promoting placement uniformity, fostering better communication, not requiring density profiles, and allowing paving at colder temperatures. One industry response indicated getting better density and better ride when running the thermal profile system.

Regarding opportunities for updates to the thermal profile methods and specifications, the consensus from industry respondents indicated the following areas for improvement:

- Interpretation of the specification needs greater clarity.
- The method to process the data needs review.
- The definitions of moderate and severe thermal segregation need review.
- Better training on performing the test and interpreting the data is needed.
- More interaction between the contractor and TxDOT based on the thermal profile results is needed.

3.2. TXDOT FEEDBACK

Appendix B presents the questions distributed to the TxDOT districts. Researchers received 20 responses representing 12 TxDOT districts. Figure 9 illustrates the location of the 12 districts from which recorded responses were received.

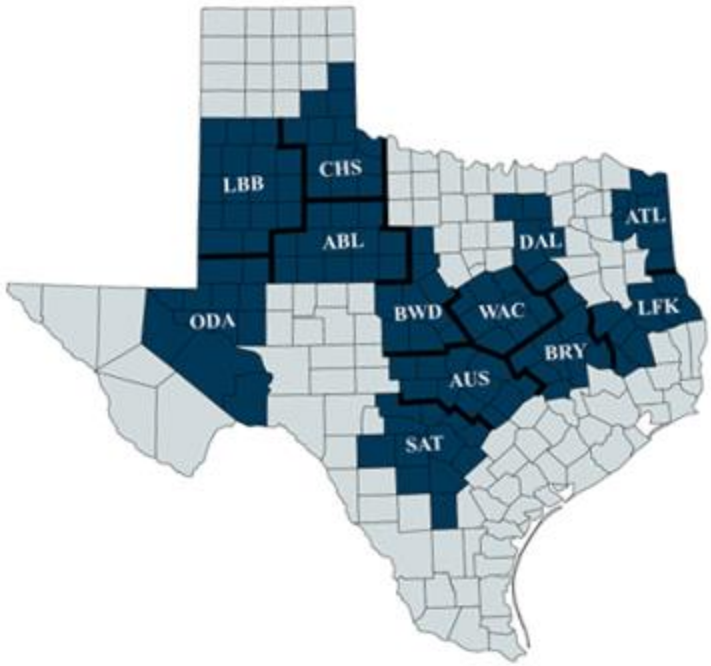


Figure 9. Districts with Recorded Responses for Thermal Profile.

Figure 10 illustrates that an overwhelming majority of responding districts prefer the PMTP system for performing the thermal profile. Figure 11 shows that the location of maintaining thermal profile results varies widely. The predominant mechanism identified was electronic copies, especially considering respondents who selected "other" indicated thermal profile results were maintained electronically with project files or Projectwise.

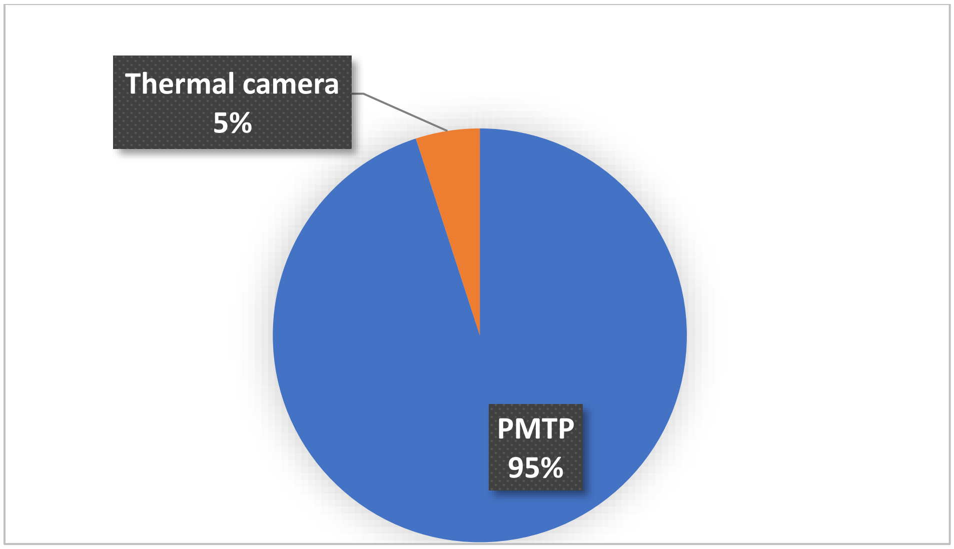


Figure 10. Preferred Method of Thermal Profile Reported by TxDOT Districts.

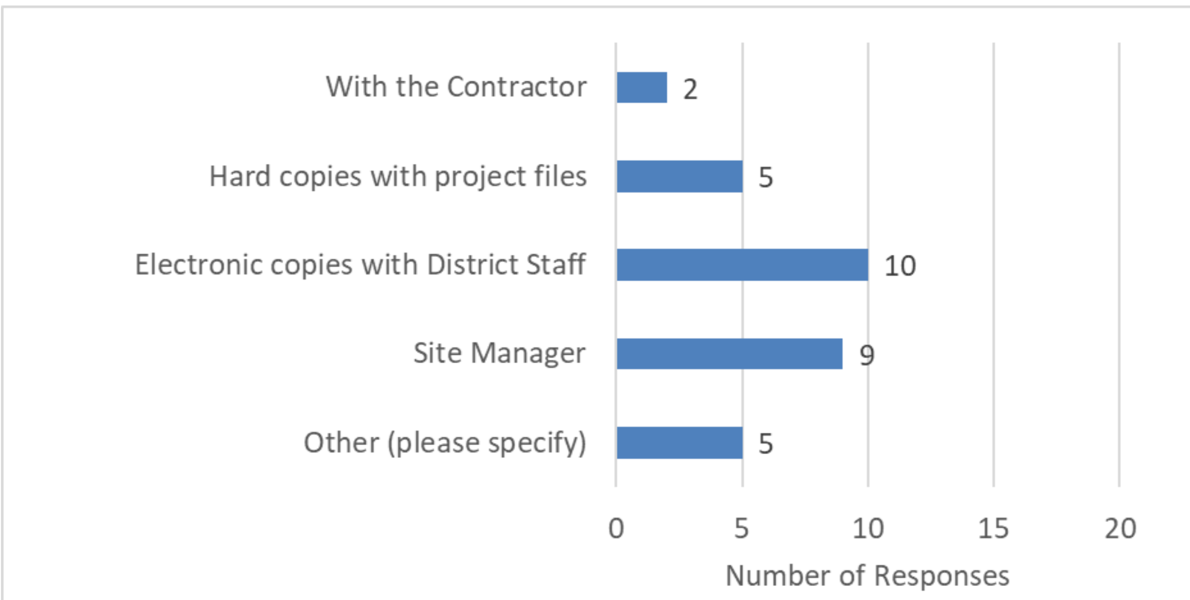


Figure 11. Location of Maintaining Thermal Profile Results.

Figure 12 presents the frequency that TxDOT respondents review thermal profile results. The data in Figure 12 show that 35 percent of respondents reported reviewing the thermal profile data a few times a week or less, while 65 percent reported reviewing results at least once a day.

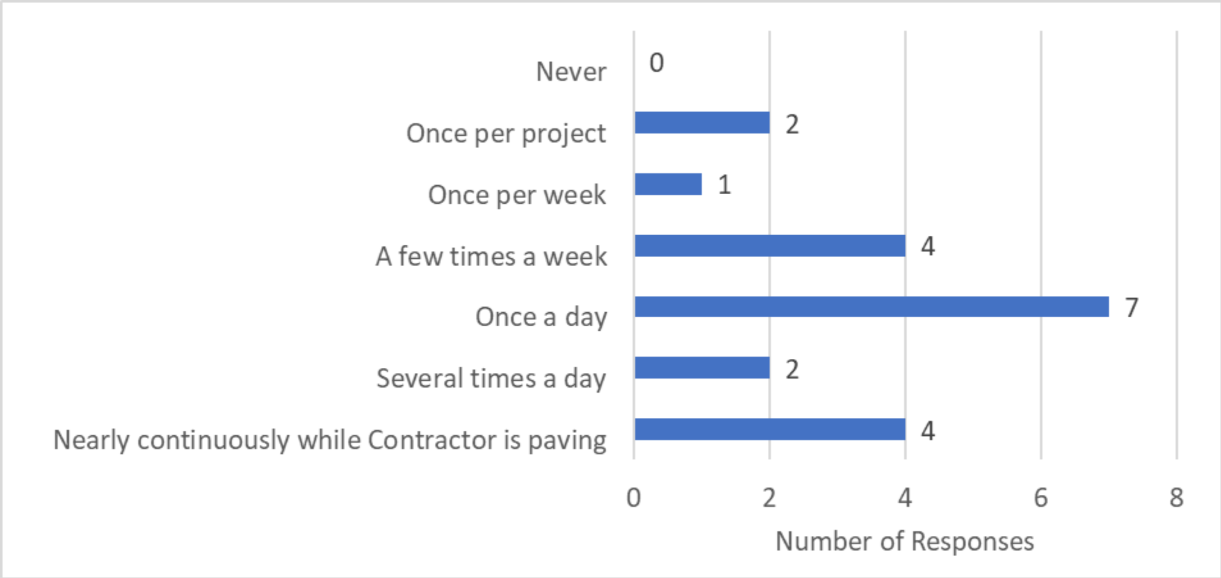


Figure 12. Frequency of Owner Reviewing Thermal Profile Results.

TxDOT responses also included feedback on what constitutes recurring thermal segregation. Table 7 presents a synopsis of the general responses and the number of responses that fall into each category. In general, the TxDOT responses suggest a stringent (more than one occurrence) or rather low threshold (several times a day, or at least three occurrences per sublot) for the number of thermal profiles with thermal segregation constituting a recurring issue.

Table 7. Owner Definitions of Recurring Thermal Segregation.

Category	General Definition	Percent of Responses
A	More than 1 occurrence	44
B	Multiple, several times a day, or at least 3 occurrences per sublot	44
C	A continuous problem	12

Figure 13 illustrates that slightly more than half of TxDOT respondents indicated their district had experienced problems with thermal segregation. Examination of the underlying data (since some districts provided responses from multiple staff members) shows 6 of the 12 districts generally reported experiencing problems with recurring thermal segregation, which aligns well with Figure 13's summary of individual responses.

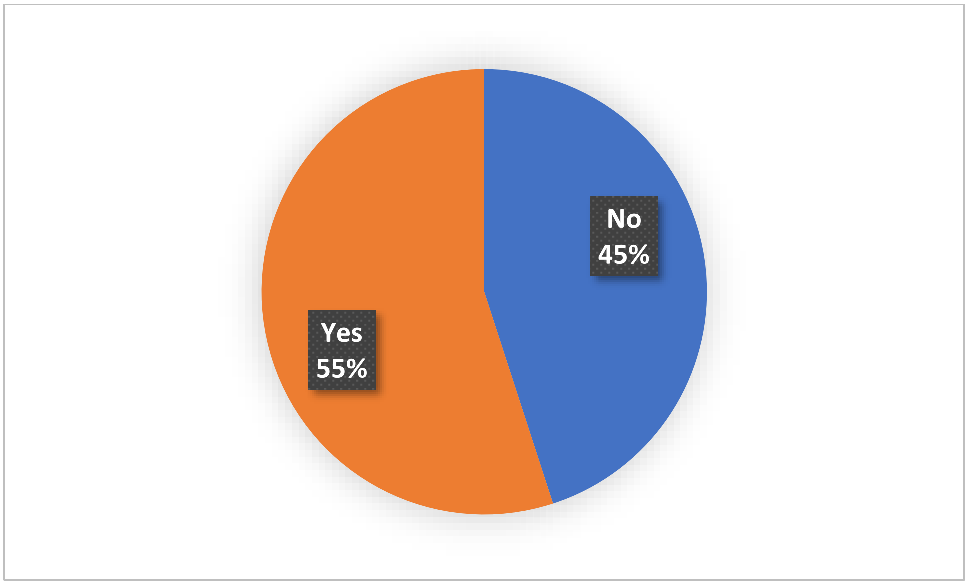


Figure 13. Percentage of Owner Responses Indicating Problems with Recurring Thermal Segregation.

Figure 14 presents the reported actions taken when a project has recurring moderate or severe thermal segregation. Figure 14 shows process changes are the most common action, followed by suspension of paving. Of the three other actions reported, two could essentially be considered process changes, and the other depends on the severity of the problem.

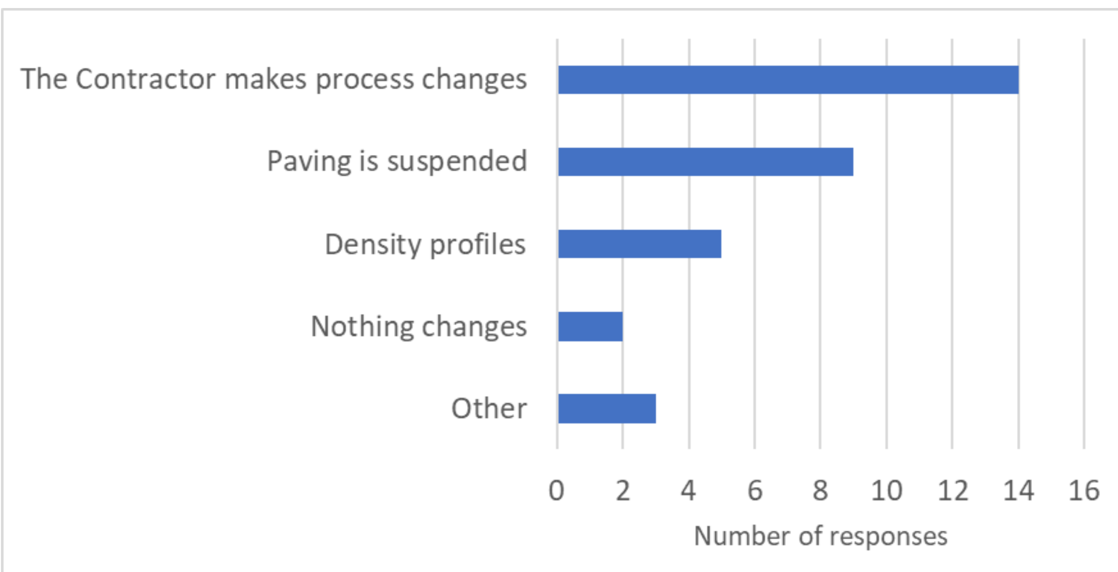


Figure 14. Actions Taken with Recurring Moderate or Severe Thermal Segregation.

Figure 15 presents the reported common causes of thermal segregation. Paver stops and long haul distances were the most frequently reported causes. Common causes of thermal segregation listed as "other" included:

- Uneven heating of the screed, screed plates out of adjustment, or heaters not working.

- First few loads at the start of the day.
- Wind.
- Lack of trucks.
- Lack of insulated trucks.

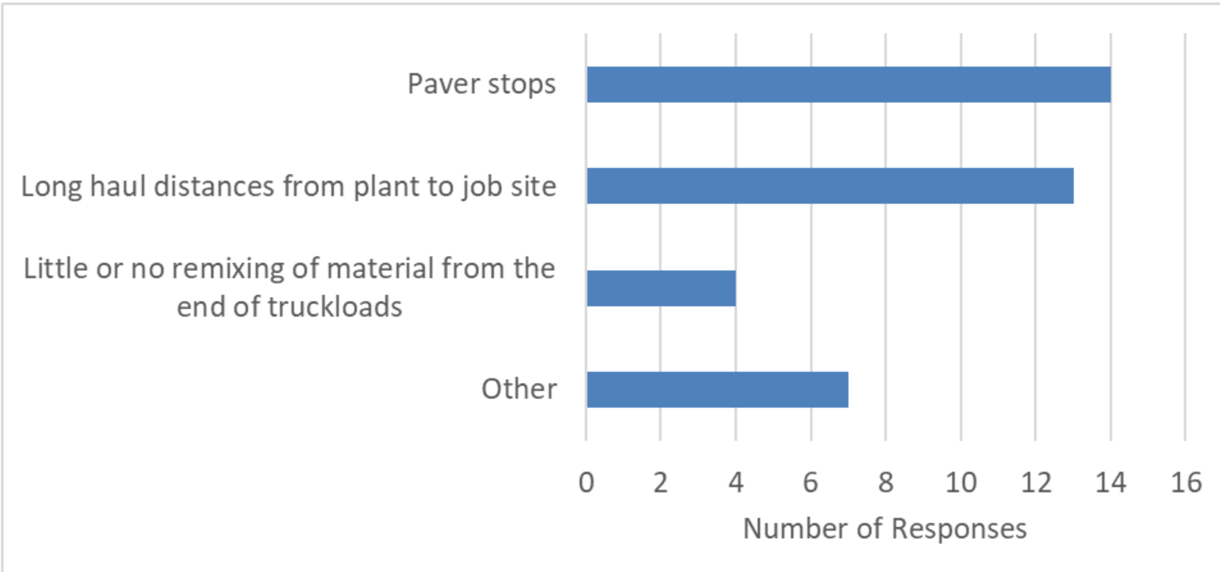


Figure 15. Common Causes of Thermal Segregation.

Figure 16 shows the reported benefits of TxDOT's current thermal profiling approach. Most responses focused on promoting placement uniformity, better jobsite communication and workmanship, and expanded allowable environmental conditions. Only six respondents, or 20 percent, reported contractors attaining better density as a benefit. Other benefits cited included allowing TxDOT to see results from the entire project and longer pavement life.

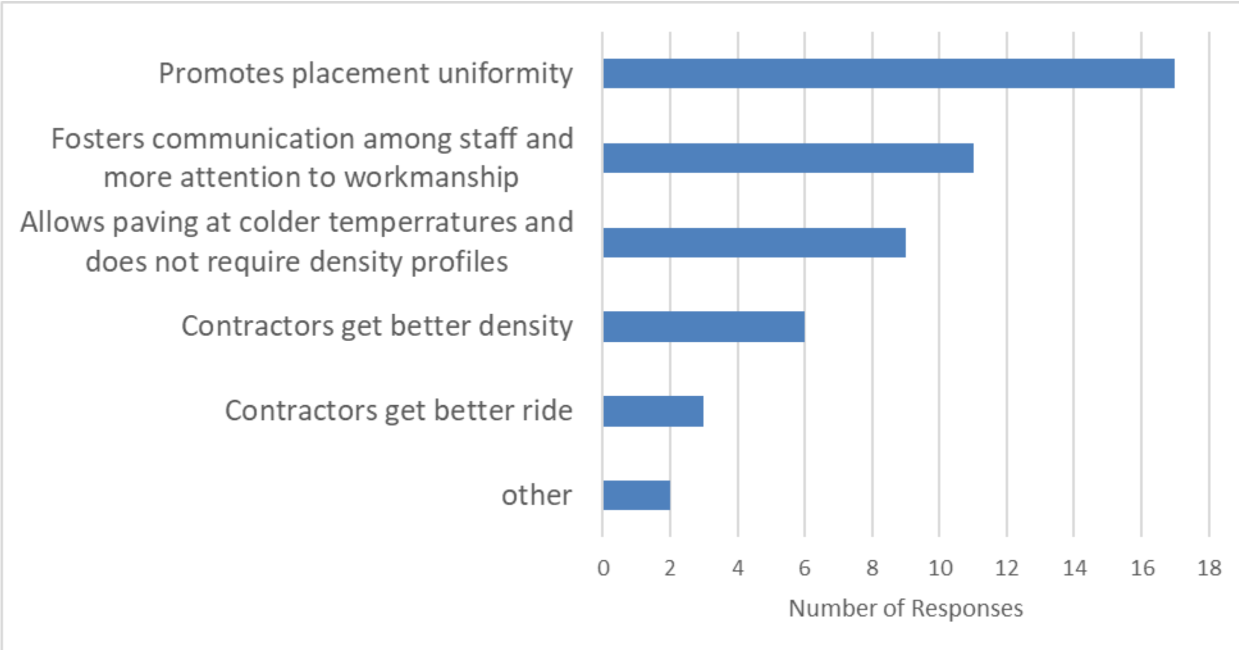


Figure 16. Benefits of Thermal Profile from TxDOT Perspective.

Regarding areas needing improvement with current methods:

- Better training on how to perform the test and use the data was the most frequently reported need.
- Respondents also indicated that more interaction between the contractor and agency based on the thermal profile results is needed.
- Slightly more than one-third of respondents noted that the thermal camera should be disallowed.
- 25 percent of respondents indicated that interpretation of the specification needs greater clarity.
- 20 percent of respondents indicated that the method to process the data needs review.
- Other needs cited included better guidance on actions to take when recurring thermal segregation exists, a better definition of the baseline temperature when using a thermal imaging system, a need to assess penalties for moderate and severe thermal segregation, and a recommendation to mandate material transfer devices.

3.3. SUMMARY OF FEEDBACK ON STRENGTHS AND WEAKNESSES

The industry and TxDOT responses on the strengths and weaknesses of current thermal profile methods and specifications support the following observations and conclusions:

- **Hardware for Thermal Profiling**: A slim majority of industry respondents prefer the paver-mounted thermal imaging system, while TxDOT overwhelmingly prefers the paver-mounted system.
- **Data Review**: About one-third of respondents, whether from industry or from TxDOT, reported reviewing results a few times a week or less. Without further exploration, it is

unclear whether this frequency is due to the nature of the individual respondent's role or if this observation suggests some lack of engagement in the thermal profile test results.

- **Frequency of Thermal Segregation**: Industry input on the level of compliance possible with current thermal profile requirements using current paving practices varies widely. Although 45 percent of respondents indicated current methods allow paving with <10 percent severe thermal segregation, 33 percent stated that a higher percentage of severe thermal segregation is likely with current practices, and 22 percent did not select a response. No clear consensus exists, which may not be surprising since the level and frequency of thermal segregation may depend on paving practices, equipment, level of experience, and/or other factors that could vary across the industry.
- **Meaning of Recurring Thermal Segregation**: Interpretation of recurring thermal segregation varies widely. Industry interpretations tended to be a bit open-ended and, in one case, even contingent on the simultaneous presence of a failing density profile. In contrast, 88 percent of TxDOT feedback categorized three profiles with thermal segregation as recurring, and 44 percent of owner responses defined recurring thermal segregation as more than one profile with thermal segregation. The results suggest a potentially significant discrepancy in how TxDOT views recurring thermal segregation and how the industry views recurring thermal segregation.
- **Practices to Minimize Thermal Segregation**: The consensus among respondents, whether from the industry or TxDOT, was that consistent plant operation, efficient trucking operations, and a continually steady pace of the paving train all contribute to reducing thermal segregation. The use of material transfer vehicles was not mentioned as frequently as anticipated by the researchers; it was cited by only 20 percent of TxDOT respondents and 44 percent by industry respondents.
- **Benefits of Current Thermal Profile Specifications**: Across both industry and owner responses, several common benefits of TxDOT's current thermal profiling specifications were highlighted, including promoting placement uniformity, fostering better communication, eliminating the need for density profiles, and enabling paving at colder temperatures. Additionally, although to a lesser degree, respondents indicated improvements in density and ride quality.
- **Areas for Improvement**: Both industry and TxDOT responses indicated various areas that need to be addressed for potential specification updates. Industry input emphasized the importance of clarifying the interpretation of the specification, reviewing the data processing methods, reviewing the definitions of moderate and severe thermal segregation, providing better training on how to perform the test and use the data, and enhancing interaction between contractor and agency based on the thermal profile results. TxDOT responses, while also acknowledging these areas, placed greater emphasis on the need for improved training on how to perform the test and use the data, as well as fostering greater stakeholder interaction in cases of thermal segregation. Furthermore, slightly over one-third of TxDOT respondents indicated that thermal cameras should be disallowed.

CHAPTER 4. BENCHMARK OCCURRENCE OF THERMAL SEGREGATION WITH CURRENT MIXES

This chapter presents a benchmark analysis based on existing data collected through a paver-mounted thermal imaging system. The analysis aimed to identify what level of thermal segregation is normal in current mixes. The evaluated mixes include Superpave (SP)-B, SP-C, SP-D, permeable friction course (PFC), thin overlay mixture (TOM)-C, Type D hot mix, thin bonded permeable friction course (TBPFC), crack attenuating mixture (CAM), and stone matrix asphalt (SMA)-D. Researchers also evaluated all thermal profile results where paver stops were included in the calculation of temperature differential to identify how inclusion of paver stops may impact the results.

Table 8 summarizes the thermal profile data used in the benchmarking analysis and shows that of the mix types with data available to the researchers, the quantity of results from the SP-C mix is much greater than the thermal profile data available from other mixes.

Table 8. Available Full-Coverage Thermal Profile Data for Benchmarking.

Mix Type	Number of Projects	Number of Pulls	Total Number of 150-ft Thermal Profiles
SP-C	24	387	13,806
PFC	4	43	1892
TOM-C	2	36	1442
Type D	2	32	1163
TBPFC	1	9	390
SP-B	1	7	199
SP-D	1	3	50
CAM	1	2	150
SMA-D	3	30	1626
Total	**39**	**549**	**20,718**

4.1. THERMAL SEGREGATION BY MIX TYPE

Researchers reviewed and then pooled the thermal segregation results according to mix type to generate a cumulative distribution frequency by mix type. Figure 17 presents the output, which shows:

- The amount of thermal segregation, defined as temperature differentials exceeding 25°F, ranged from about 20 to 80 percent, with results from most mix types showing 20 to 40 percent of profiles exhibiting thermal segregation.
- The amount of severe thermal segregation, defined as temperature differentials exceeding 50°F, ranged from 0 to about 25 percent, with results from most mix types showing results between 1 and 10 percent severe thermal segregation.
- SP-D results in Figure 17 show the most segregation by far compared to any other mix type. However, the SP-D results in Figure 17 only represent one project. Researchers

believe results from that mix in Figure 17 may not reflect the expected outcome typically observed for that mix type if more data were available.

- The amount of moderate thermal segregation was similar, around 20 to 30 percent, for the SP-C, PFC, TOM-C, Type D, TBPFC, and SMA-D mixes. Of these mixes, the PFC and SMA-D results showed the least percentage of severe thermal segregation, and the TOM-C and Type D mixes showed the most severe thermal segregation. However, results from all these mixes showed less than 10 percent severe thermal segregation.

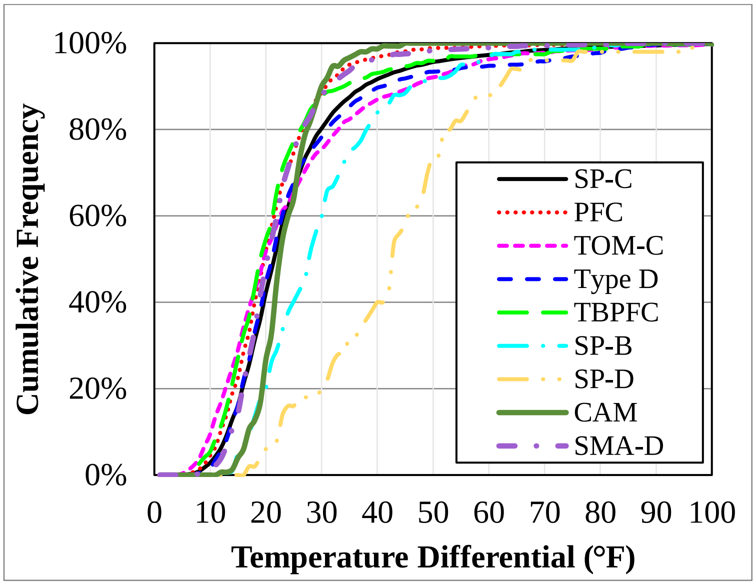


Figure 17. Temperature Differential Distributions by Mix Type.

Based on the underlying data from Figure 17, Table 9 summarizes the thermal profile results across the mixture types. From the results in Figure 17 and Table 9, Figure 18 illustrates the general rate of occurrence of thermal segregation by mix type. Figure 18 does not include a placeholder for the SP-D mix because researchers believe that the available results for that specific mix type, obtained from a single project, do not adequately represent the expected occurrences if data were available from a broader range of construction projects where this mix type is used.

Table 9. Summary of All Thermal Profile Results.

Mix Type	Moderate 25°F < Differential ≤ 50°F		Severe > 50°F	
	Number	Percent	Number	Percent
SP-C	4102	29.7	610	4.4
PFC	467	24.7	21	1.1
TOM-C	387	26.8	115	8
Type D	306	26.3	77	6.6
TBPFC	75	19.2	16	4.1
SP-B	104	52.3	16	8
SP-D	29	58	13	26
CAM	55	36.7	0	0
SMA-D	386	23.7	27	1.7

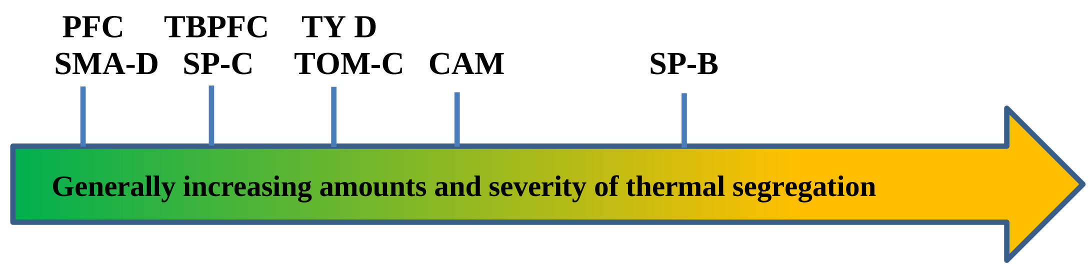


Figure 18. Observed Occurrence of Thermal Segregation by Mix Type.

4.2. THERMAL SEGREGATION FROM ALL MIXES COMBINED

From the results of over 20,000 thermal profiles represented across the historical data from different mix types, Figure 19 shows the combined distribution frequency. The data show:

- 67.2 percent of profiles have no thermal segregation.
- 28.5 percent of profiles have moderate thermal segregation.
- 4.3 percent of profiles have severe thermal segregation.

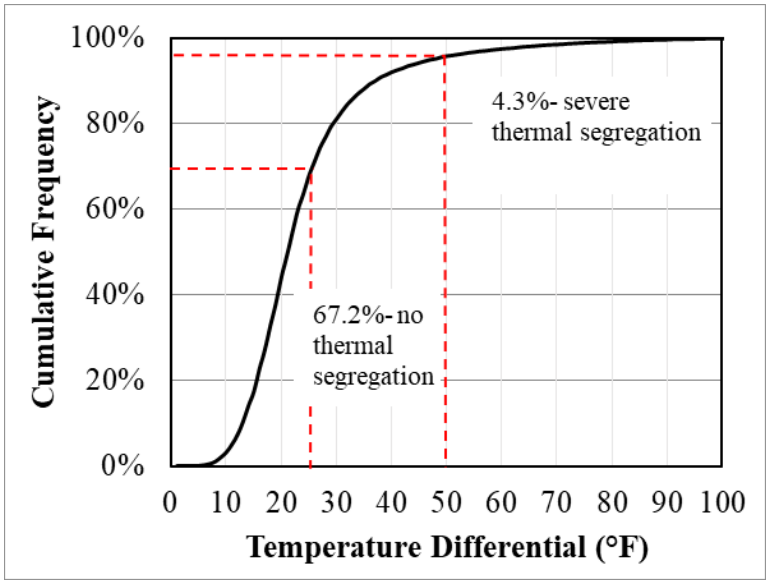


Figure 19. Distribution of Thermal Profile Result from All Data.

4.3. IDENTIFYING THERMAL SEGREGATION BENCHMARKS

Figure 17 and Table 9 indicate that the distributions of thermal profile results may differ across mix types. In the underlying data, results could vary significantly even within a given mix type. For example, thermal profile results from pulls representing SP-C mix show moderate thermal segregation ranging from 0 to 70 percent. Considering the inherent variability within mixes, as well as the potential variations in day-to-day operations during paving projects, researchers propose adopting a benchmarking approach that can be applied consistently across all mix types. Table 10 outlines potential approaches that can be used to develop these benchmarks.

Table 10. Potential Approaches to Set Benchmarks.

Approach	Source Data	Comment
Set benchmark weighting each mix type equally.	Summary of all profile results (Table 9).	Averages the percentages of moderate and percent severe across all mix types.
Set benchmark weighting mix type according to the number of observations.	Distribution of thermal profile results from all data and all mixes (Figure 19).	Identifies the actual percentages of observed moderate and severe thermal segregation from all data. Mix types with more underlying data have more influence on the outcome.
Set benchmark from statistical analysis of results from individual pulls.	Analysis of profile results from pulls. Quantifies the variability in moderate and severe thermal segregation and uses that variability to define the benchmark.	Analysis of results from paving pulls may best mimic how the profile results are currently reported and reviewed in practice. Can account for typical variability in identifying benchmark reference points.

Using Table 10, the outcomes from the first two approaches are:

- Weight each mix type equally: 33.0 percent moderate; 6.7 percent severe thermal segregation.
- Weight mix types according to the number of observations: 28.5 percent moderate; 4.3 percent severe thermal segregation.

The first two potential benchmarking approaches produce similar outcomes. One concern with the first two approaches is that in practice, half of the results should be below, and half above, the average value. Consequently, relying solely on the average value as the benchmark reference point could set a stringent threshold for what is considered normal, leading to a situation where field results fail to meet the benchmark around half of the time.

To address this concern, researchers propose the third approach outlined in Table 10, which offers multiple benchmark reference points. Researchers analyzed results from all 549 pulls of existing thermal profile data, including the percentages of moderate and severe thermal segregation observed in each pull. The researchers also performed a benchmark analysis that incorporated paver stops in the calculation of temperature differentials to identify the impact this change in data processing would have on results. Table 11 demonstrates that the inclusion of paver stops significantly increases the reported amount of severe thermal segregation:

Table 11. Thermal Segregation by Mix Type with and without Paver Stops.

Mix Type	Moderate 25°F < Differential ≤ 50°F		Severe Differential > 50°F	
	Without Paver Stops	With Paver Stops	Without Paver Stops	With Paver Stops
SP-C	29.7	30.4	4.4	14.8
PFC	24.7	25.4	1.1	9.7
TOM-C	26.8	31.0	8	24.3
Type D	26.3	28.0	6.6	17.3
TBPFC	19.2	24.1	4.1	7.9
SP-B	52.3	*	8	*
SP-D	58	56.0	26	28.0
CAM	36.7	61.3	0	13.3
SMA-D	23.7	24.8	1.7	13.8
Overall	**28.5**	**29.3**	**4.3**	**14.5**

* Not available with paver stops because data were provided in PDF version already processed in accordance with the current Tex-244-F.

By developing the statistical distribution of these results, depicted in Figure 20, researchers define various benchmark reference points. Using Figure 20 as a basis, Table 12 and Table 13 present recommended reference points for moderate and severe thermal segregation, respectively. These tables can be used to gauge how thermal segregation results from a particular paving pull align with typical industry operations. For example, from Table 12 and Table 13, the most uniform 10 percent of paving pulls should have no more than 8 percent moderate thermal segregation and no severe thermal segregation based on Tex-224-F.

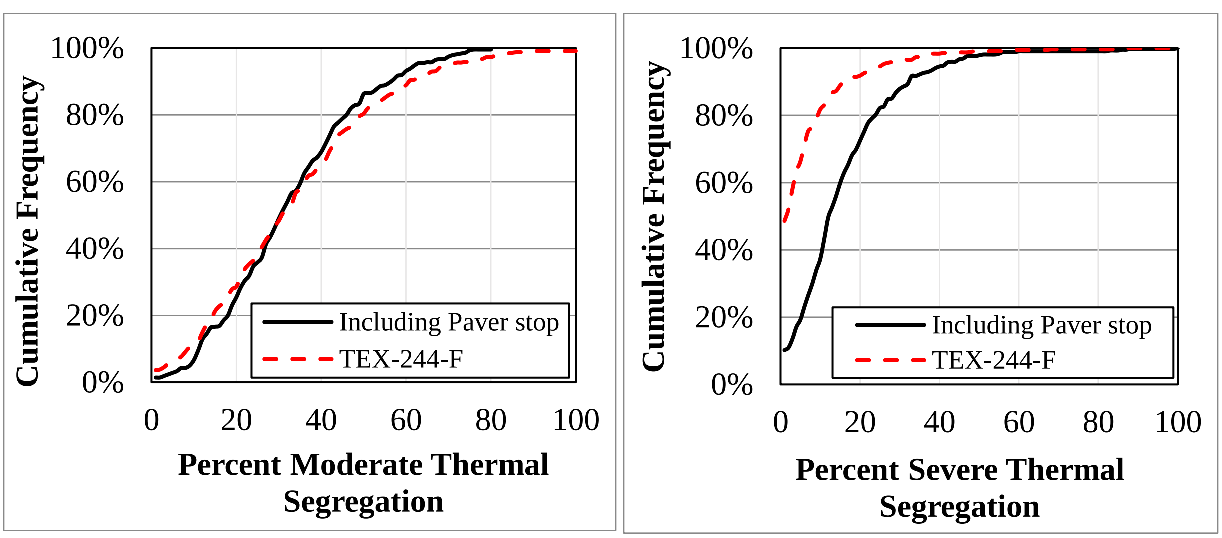


Figure 20. Distributions of Moderate (Left) and Severe (Right) Thermal Segregation with and without the Inclusion of Paver Stops.

Table 12. Reference Points for Moderate Thermal Segregation with and without Paver Stops.

Frequency of Occurrence	Without Paver Stops Included		With Paver Stops Included	
	Percentage Moderate Thermal Segregation	Max Number of Profiles with Moderate Thermal Segregation in a Pull	Percentage Moderate Thermal Segregation	Max Number of Profiles with Moderate Thermal Segregation in a Pull
5%	≤ 3%	1	≤ 10%	4
10%	≤ 8%	3	≤ 12%	4
20%	≤ 14%	5	≤ 19%	7
50%	≤ 30%	11	≤ 31%	11
70%	≤ 42%	16	≤ 41%	15
80%	≤ 49%	18	≤ 46%	17
90%	≤ 60%	22	≤ 57%	21
95%	≤ 70%	26	≤ 63%	23

Table 13. Reference Points for Severe Thermal Segregation with and without Paver Stops.

Frequency of Occurrence	Without Paver Stops Included		With Paver Stops Included	
	Percentage Severe Thermal Segregation	Max Number of Profiles with Severe Thermal Segregation in a Pull	Percentage Severe Thermal Segregation	Max Number of Profiles with Severe Thermal Segregation in a Pull
5%	None	0	0	0
10%	None	0	≤ 1%	0
20%	None	0	≤ 6%	2
50%	None	0	≤ 13%	5
70%	≤ 5%	2	≤ 20%	7
80%	≤ 8%	3	≤ 24%	9
90%	≤ 15%	6	≤ 33%	12
95%	≤ 25%	9	≤ 42%	16

4.4. EFFECT OF INCLUDING PAVER STOPS

Figure 20 shows that the inclusion of paver stops has minimal effect on the anticipated levels of moderate thermal segregation. However, the distribution of severe thermal segregation is noticeably shifted toward higher values when paver stops are included. Based on the information in Figure 20, Table 12 and Table 13 can be used to gauge how thermal segregation results from a particular paving pull align with typical industry operations. For example, from Table 12 and Table 13:

- When paver stops are excluded in accordance with current Tex-244-F, the most uniform 20 percent of paving pulls should have no more than 14 percent moderate thermal segregation and no severe thermal segregation.

- If the test procedure were modified to include paver stops, the most uniform 20 percent of paving pulls should have no more than 19 percent moderate thermal segregation and no more than 6 percent severe thermal segregation.

Table 12 and Table 13 use an expected value of 37 individual 150-ft thermal profile segments per pull for calculating the maximum number of acceptable profiles in a typical pull in each category of thermal segregation. In practice, the number of thermal profile segments contained within any given pull will vary and depend on many factors; therefore, researchers recommend the percentages of thermal segregation in Table 12 and Table 13 as better-suited guides for benchmark analysis across a broad cross-section of paving projects.

4.5. SUMMARY AND CONCLUSIONS FROM BENCHMARKING

Based on a comprehensive analysis of 39 paving projects, encompassing nine mix types and over 20,000 original individual 150-ft thermal profiles, it can be anticipated that an average of approximately 5 percent severe thermal segregation occurs during typical paving operations when measured in accordance with current Tex-244-F. This percentage corresponds to approximately two profiles with severe thermal segregation within the length of a typical paving pull.

If the current Tex-244-F test procedure were modified to include paver stops in the thermal profile analysis, about 14 percent severe thermal segregation could be expected on average in a typical paving pull, translating to about five profiles with severe thermal segregation.

While an expected value provides a useful metric, that value may not capture the variability in paving operations. To address this, researchers recommend using benchmarking reference points that provide a more comprehensive evaluation. Figure 21 and Figure 22 illustrate reference points that are better suited for benchmarking paving operations. Figure 21 presents the benchmarking points derived from the current test method, which excludes paver stops, while Figure 22 presents benchmarking reference points obtained by including paver stops in the thermal profile analysis.

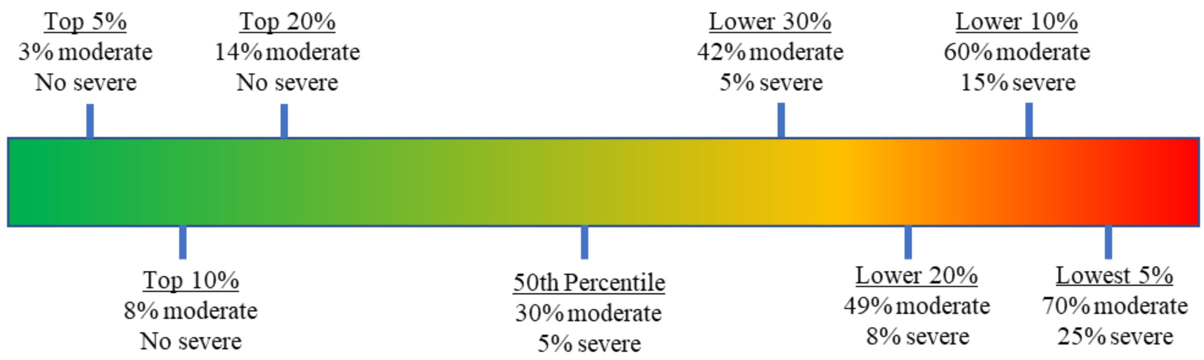


Figure 21. Thermal Profile Benchmarks from Current Tex-244-F (Excludes Paver Stops).

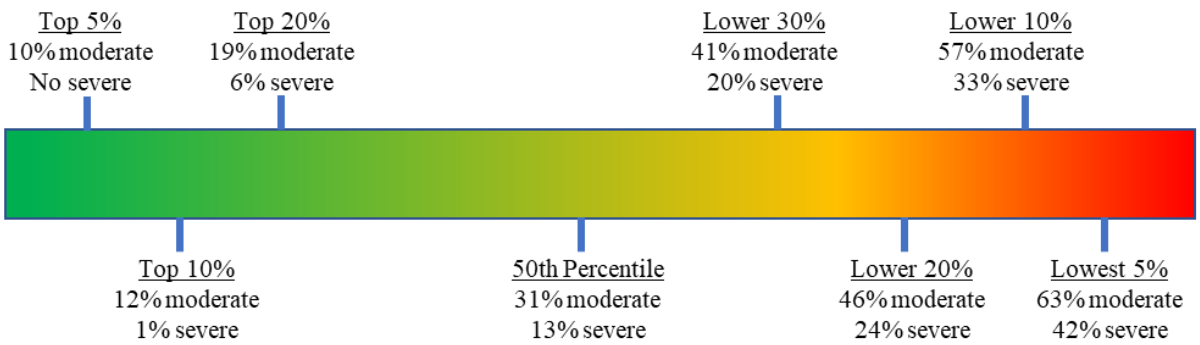


Figure 22. Thermal Profile Benchmarks from Including Paver Stops.

If specification updates move toward incorporating maximum allowable thresholds for thermal segregation, Table 14 provides an overview of the rate of conformity that can be expected based on the benchmarking data and analysis. Table 14 shows that:

- If paver stops are excluded, and a maximum of 10 percent severe thermal segregation is allowed, actual paving operations should meet the criteria about 84 percent of the time.
- If paver stops are included, and a maximum of 10 percent severe thermal segregation is allowed, the expected conforming rate drops to 37 percent.

From a feasibility perspective, researchers recommend that thresholds be established to align with an expected conformity rate of at least 70 percent.

Table 14. Expected Rate of Conformity for Different Maximum Allowed Amounts of Severe Thermal Segregation.

Max. Allowed % Severe Thermal Segregation	Expected Rate of Conformity	
	Paver Stops Excluded	Paver Stops Included
5	70%	19%
10	84%	37%
15	90%	59%
20	92%	72%
25	95%	82%
30	96%	87%
40	99%	94%

Table 14 presents expected rates of conformance based on existing practices and may not necessarily reflect the level of thermal segregation deemed acceptable by the owner.

CHAPTER 5. DEMONSTRATION PROJECTS

This chapter presents the results and findings of the researchers' investigations on the impact of thermal segregation on various commonly used mixture types in construction projects. The researchers performed field testing on SP-C, dense-graded (DG)-D, SP-D, and SMA-D projects. They performed field nondestructive testing (NDT), including thermal profile investigation and ground-penetrating radar (GPR) analysis. Additionally, field cores were collected based on the NDT results, and loose mix samples were taken from each project for further lab testing.

The researchers used the data from these demonstration projects to determine how thermal segregation impacts the in-place density in the field. They also visited two of these projects for post-construction performance evaluation. In the laboratory, loose mix samples from the projects were analyzed to investigate the influence of potential changes in mix density due to thermal segregation on performance-related properties. Chapter 6 presents the comprehensive laboratory results.

5.1. SP-C ON US 69

Coordinating with the TxDOT Lufkin District, researchers collected thermal profile data over approximately 50 stations on US 69. Following finish rolling, researchers selected an approximately 1500-ft long zone to perform focused testing to evaluate the meaning of thermal segregation on the newly placed and compacted mat. This focused testing included conducting an NDT survey of the mat area with a multiple channel GPR system, selecting spot test locations to represent normal and thermally segregated points over the hot mix asphalt (HMA) mat, and then collecting 6-in. diameter cores directly over each spot location for lab testing.

The field results revealed that while severe thermal segregation was not observed in this project, about 50 percent of the profiles exhibited moderate thermal segregation. In the lab, the researchers analyzed each core's AV content. The cores obtained from thermally segregated locations generally displayed elevated AV content.

5.1.1. Project Location, Mix Type, and Paving Operations

The demonstration project was located on US 69, just south of Zavalla, Texas, for Control Section Job (CSJ) 0200-03-021. Researchers performed testing on the project on October 28, 2021. This project placed a 1.5-in. lift of TxDOT Item 344 SP-C mix. Table 15 presents the design job mix formula (JMF) and the Lot 2 JMF, which was the current production lot on the day of testing.

Table 15. SP-C Mix Design for US 69.

Sieve Size	Design JMF Cumulative % Passing	Current JMF Cumulative % Passing
1"	100.0	100.0
¾"	100.0	100.0
½"	92.4	92.0
⅜"	80.2	82.0
#4	48.6	47.0
#8	29.6	29.6
#16	23.4	23.4
#30	19.9	19.9
#50	16.3	16.3
#200	5.0	5.6
Binder originally specified		PG 70-22
Substitute binder		PG 64-22
Design asphalt content, %		4.9
Current JMF asphalt concrete (AC), %		4.9
Recycled binder, %		0.78
Ratio of recycled to total binder, %		15.8
Design number of gyrations		50
Design rice gravity (Gr)		2.440
Lot 2, DOT2 rice gravity		2.464
Target lab-molded density, %		96.0

The mix was produced in Lufkin and hauled about 30 mi to the jobsite in tarped belly dump trucks. On site, the trucks maintained a windrow typically 50–100 ft long, from which an SB2500e transferred the mix into an RP-190E paver. The paver laid a mat 15 ft wide. Figure 23 shows the paving operation.

Figure 23. Paving Operation on US 69.

After laydown, a CB564D performed breakdown rolling, typically applying four passes. Intermediate and finish rolling occurred using a Trupac 915 and CB634-D, respectively. On the day of testing, paving started at about 8:30 a.m. and concluded at about 4:00 p.m. Ambient air temperatures ranged from 56 to 75°F, and winds were approximately 20 mph from the west/northwest with gusts up to about 40 mph. Figure 24 and Figure 25 show the air temperature and wind speeds, respectively, as recorded at the Angelina County Airport throughout the day.

Figure 24. Air Temperature during US 69 Paving.

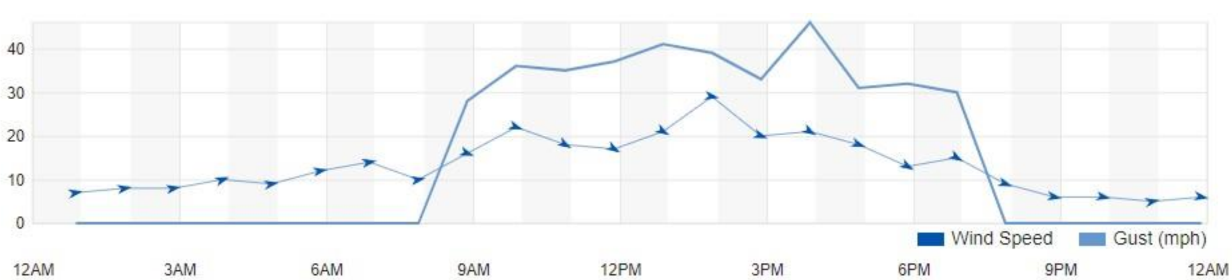


Figure 25. Wind Speeds during US 69 Paving.

5.1.2. US 69 Thermal Profile Results

Thermal profile data were collected from station (STA) 11409+13 to STA 11459. Figure 26 shows the thermal plot, which shows a region of generally higher overall placement temperatures from approximately STA 11442 to 11449. The thermal plot also shows a region of generally lower overall mean placement temperatures from around STA 11454 to 11459. The contractor took additional action in this area by reducing placement temperatures, conducting more spot tests with a non-nuclear density gauge, and applying additional passes with the breakdown roller.

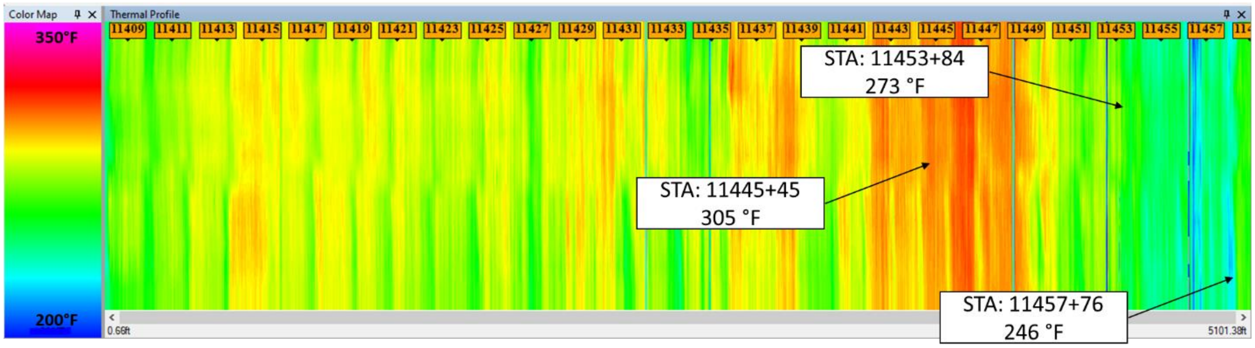


Figure 26. US 69 Thermal Profile.

Table 16 shows the thermal profile summary results, and Figure 27 shows the distribution of measured placement temperatures. These data show that, although a material transfer device was used on this project, about half of the thermal profiles exhibited moderate thermal segregation. The results also show that measured placement temperatures behind the screed ranged from about 240 to 310°F.

Table 16. Thermal Profile Summary Results from US 69.

Number of Profiles	Moderate 25°F < Differential ≤ 50°F		Severe Differential > 50°F	
	Number	Percent	Number	Percent
35	18	51	0	0

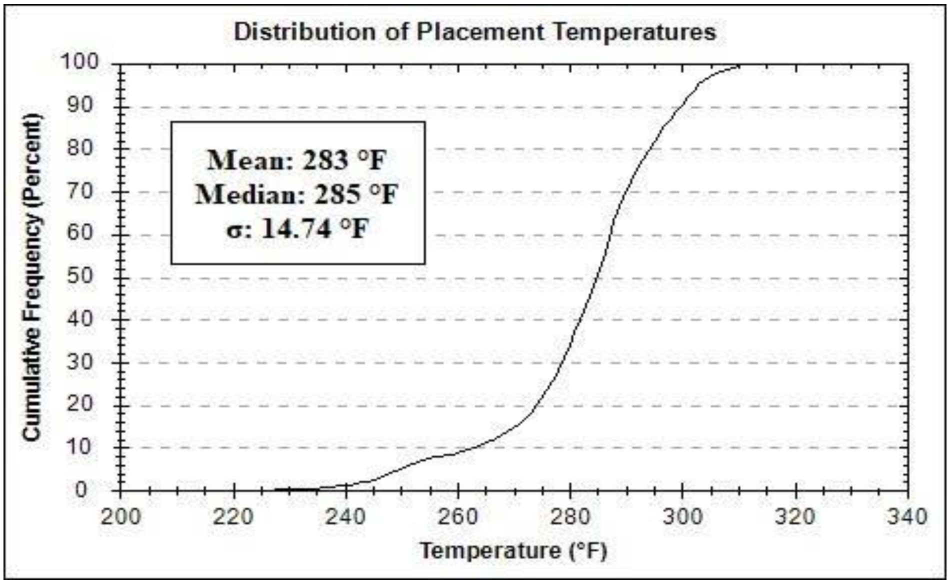


Figure 27. Distribution of Placement Temperatures on US 69.

5.1.3. US 69 Focused Testing Results

For the focused testing used to evaluate the meaning of thermal segregation on the newly compacted mat, researchers further evaluated the section from STA 11444 to 11459 through additional field testing, coring, and lab testing. Table 17 shows the thermal profiles represented from within these station limits. Profiles 25–28 do not exhibit any thermal segregation, while profiles 29–34 exhibit moderate thermal segregation. Profile 35 could be considered extraneous due to the limited data available within that profile, as indicated by the starting and ending station provided in Table 17.

Table 17. US 69 Thermal Profile Results from Focused Demonstration Section.

Profile Number	Begin STA	End STA	Max. Temp (°F)	Min. Temp (°F)	Temp. Differential (°F)
25	11444.01	11445.50	307.4	286.9	20.5
26	11445.51	11447.00	309.9	291.6	18.4
27	11447.01	11448.50	313.7	290.1	23.6
28	11448.51	11450.00	306.7	292.1	14.6
29	11450.01	11451.50	299.1	266.9	32.2
30	11451.51	11453.00	284.4	256.6	27.7
31	11453.01	11454.51	284.4	246.4	38.0
32	11454.51	11456.01	268.5	240.6	27.9
33	11456.02	11457.51	258.8	222.6	36.2
34	11457.51	11459.00	273.0	228.0	45.0
35	11459.01	11459.01	268.5	260.2	8.3

Based on the results shown in Table 17, researchers identified and marked nine core locations that were representative of the observed temperature range. Figure 28 shows the thermal plot along with these selected locations. To gather additional data, researchers conducted GPR readings at each core location before extracting the cores. Figure 29 shows researchers collecting GPR data with a multichannel system.

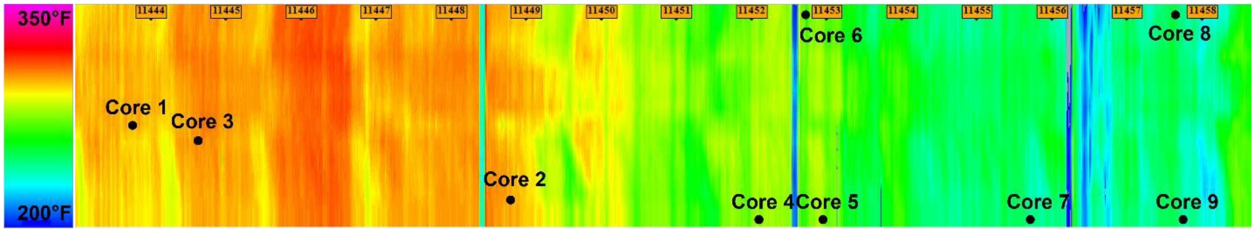


Figure 28. US 69 Thermal Plot with Core Locations.

Figure 29. GPR Survey on the In-Place Mat with Multichannel GPR.

Researchers returned the cores to the lab, where they trimmed and then measured the bulk specific gravity of each core in accordance with Tex-207-F. They calculated the percent AVs of each core using the Gr of 2.464 as reported for Lot 2, DOT production sample 2. Table 18 shows the results from the cores, which contain a range of AVs from 4.4 to 10.8 percent.

Table 18. Core Results from US 69.

Core	STA	Offset (ft)	Temperature at Placement (°F)	Field Dielectric from GPR	Lab-Measured AVs (%)
1	11444+20	7.75	300	5.46	7.0
2	11449+75	5.75	299	5.68	5.8
3	11445+45	7.25	305	5.98	4.4
4	11453+00	0.75	281	5.23	9.2
5	11453+76	0.75	273	5.28	8.9
6	11453+84	14.25	273	4.97	10.8
7	11456+15	0.75	244	5.27	10.2
8	11457+64	14.25	249	5.19	10.2
9	11457+76	7.75	246	5.44	8.4

In Table 18, Cores 7–9 showed much lower temperatures than Cores 4–6, yet the AV content of Cores 7–9 and 4–6 were similar. Researchers attribute this similarity to specific operations observed during the construction process. Within the area represented by Cores 7–9, the overall placement temperature dropped, prompting the contractor quality control staff to conduct extra spot tests with a non-nuclear density gauge. Furthermore, the breakdown roller was instructed to apply more passes in those areas. Thus, Cores 7–9 do not represent the identical operation as the other collected cores. The actions of extra quality control testing and the adjusted breakdown rolling likely contributed to mitigating the impact of the lower mix placement temperature on density.

5.1.3.1. Interpretation of Thermal Segregation

Due to the different compaction processes applied at Cores 7–9, Figure 30 shows the lab-measured AVs versus temperature measured at the time of placement for the identified core groupings. Figure 30 shows:

- For Cores 1–6, which represent a steady-state operation, the temperatures recorded at the time of placement ranged from 273 to 305°F. Within this range, the data reveal a potential variation of up to 6.4 percentage points (10.8 percent–4.4 percent) in the AV content.
- Based on the slope of the regression line, a temperature differential of about 26°F corresponds to an expected density differential of 6 pounds per cubic foot (pcf). This value represents the maximum allowable density range (highest–lowest) according to TxDOT’s density profile requirements for SP-C. This finding is based on a 3.9 percentage point change in AV, equivalent to a 6 pcf change in density based on the reported rice gravity of this particular mix.
- For Cores 7–9, which represented a region of lower overall placement temperatures and increased compaction effort applied during breakdown rolling, the measured placement temperatures ranged from 244 to 249°F, and the AVs ranged from 8.4 to 10.2 percent. These AV contents are all elevated, and since the measured placement temperatures were similar across these three core locations, the AV variation most likely represents random variation.

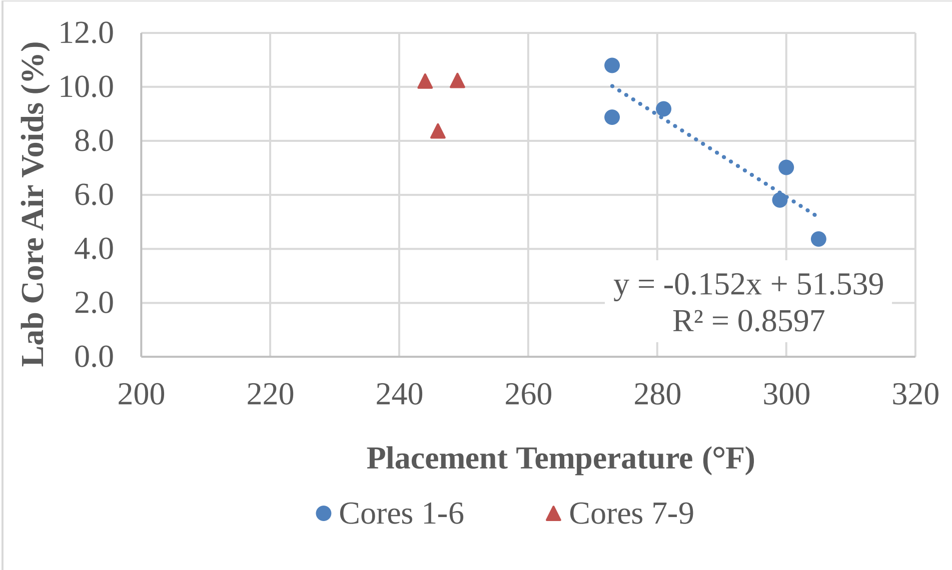


Figure 30. Results from US 69 by Core Grouping.

5.1.3.2. Interpretation of GPR

While the thermal profile tests the placed, uncompacted mat, the GPR tests are conducted after all rolling is completed. Figure 31 presents the core AV contents versus the field-measured surfaced dielectric constant (DC) from GPR using a linear relationship, which produced the best R^2 with these data. Figure 31 shows a good correlation, illustrating the viability of GPR as a potential final quality and uniformity check on the in-place mat density. In contrast to Figure 30, Figure 31 does not require separating the data into core groupings to reflect the different compaction processes because the GPR testing occurs after the completion of all placement operations.

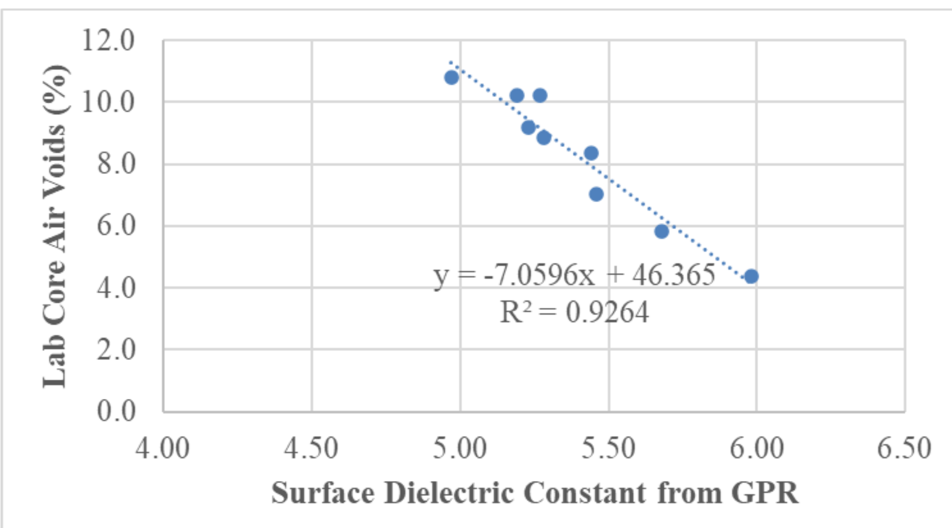


Figure 31. GPR Results from US 69 Cores.

With the correlation depicted in Figure 31, the GPR data can be used to estimate density across the tested mat area. Figure 32 displays the projected cumulative distribution of AVs from STA 11444 to 11459.

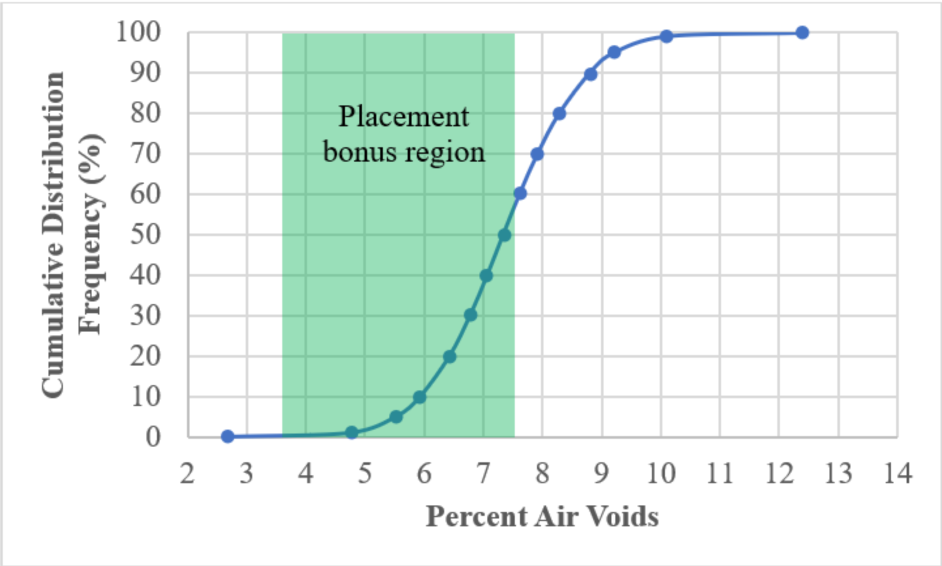


Figure 32. Expected Distribution of AVs on US 69.

The underlying data used to generate Figure 32 consist of over 35,000 data points obtained from 12 distinct GPR passes, each conducted at a different transverse offset. These GPR data produce the following descriptive statistics:

- Mean AV content: 7.4 percent.
- Standard deviation: 1.1 percent.
- Percentage within placement pay factor ≥ 1.0: 56.

Thus, the GPR data and Figure 32 show that for the area tested by GPR, about 56 percent of the mat area is within the placement bonus region for AV content, which is between 3.7 and 7.5 percent AVs for this mix. Based on project records, TxDOT's reported placement densities for Lot 2, Sublot 2, from which the GPR survey was conducted, were 7.4 and 7.2 percent AVs.

Those placement AV contents from TxDOT's random sampling are consistent with the mean and standard deviation generated from the GPR analysis.

With multiple GPR runs available at different transverse offsets, the GPR data can also generate a geospatial plot of expected in-place mat density. Figure 33 presents this output, which shows:

- In general, the poorer-compacted regions were along the mat edges. In particular, the portion of the mat along the bottom of Figure 33 that became the shoulder showed the greatest proportion of elevated AV contents.
- A region of generally higher AVs across the entire mat width exists from STA 11454 to STA 11457. This region of higher voids reasonably aligns with the thermal profiles with the higher temperature differentials in Table 18.

- Near STA 11459, Figure 33 shows a zone of expected high AVs that correspond with the location of thermal segregation observed in Figure 28.

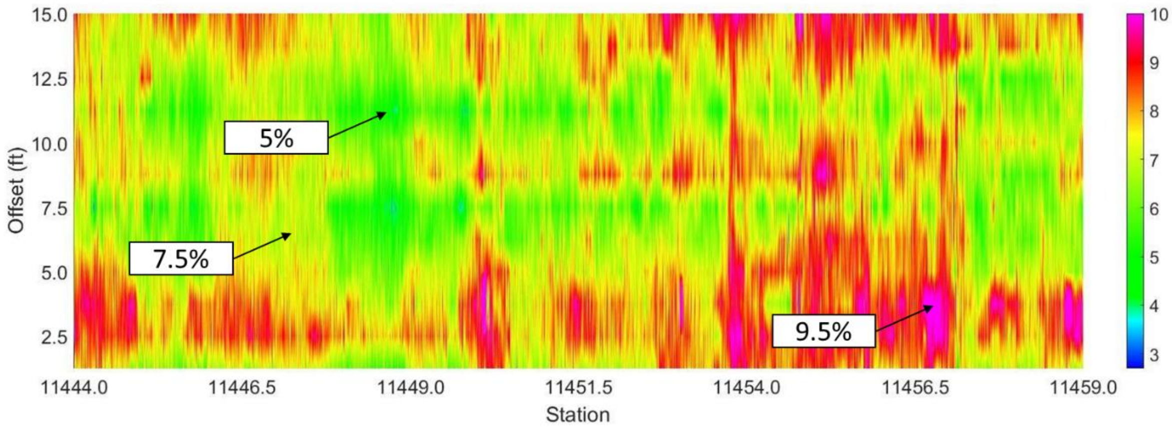


Figure 33. AV Map for US 69.

Figure 33 represents a subset of the paving placed on the specific day of testing and does not necessarily represent past or future anticipated results on other locations along the project.

5.1.4. Conclusions from SP-C on US 69

Results from the thermal segregation demonstration on US 69 show that simply using a material transfer vehicle does not necessarily eliminate thermal segregation or negate the potential influence of thermal segregation on the density of the compacted mat. Results from this project showed about 50 percent of thermal profiles with moderate thermal segregation and density variations of almost 10 pcf. The findings also showed that the cold spots in the thermal results generally exhibited higher AVs, where for a steady-state operation, a 26°F temperature differential would be expected to correspond with a 6 pcf density differential.

The results of this project also demonstrated that contractor intervention by applying more compaction effort upon seeing significant areas of thermal irregularities at the time of placement could potentially reduce the impact of the cold spots on the final in-place AVs. This type of active quality control should be adopted more widely by paving crews.

5.2. DG-D ON US 287

Coordinating with the TxDOT Childress District, researchers conducted a thermal profile demonstration on US 287 to evaluate the meaning of thermal segregation on the newly placed and compacted mat. This testing included selecting spot test locations to represent normal and thermally segregated points over the HMA mat, conducting an NDT survey of the mat area with a multichannel GPR system, and then cutting and collecting 6-in. diameter cores directly over each selected spot location for lab testing.

In the field, this project exhibited minimal thermal segregation. In the lab, researchers measured the AV content of each core. The results showed a good correlation between AVs and temperature measured at the time of placement, with the cold spots becoming higher AVs. The results also showed a strong correlation between AVs and the GPR data, illustrating the potential of the GPR as a quality and uniformity check on the completed mat.

5.2.1. Project Location, Mix Type, and Paving Operations

The demonstration project was located on US 287 near Memphis, Texas, for CSJ 0042-08-058. Researchers performed testing on the project on November 11, 2021. This project placed a 2-in. lift of TxDOT Special Specification (SS) 3076 DG-D mix. Table 19 presents the design JMF and the JMF for Lot 4, which was the current production lot on the day of testing.

Table 19. DG-D Mix Design for US 287.

Sieve Size	Design JMF Cumulative % Passing	Current JMF Cumulative % Passing
¾"	100.0	100.0
½"	98.7	98.7
⅜"	90.8	90.8
#4	64.5	62.5
#8	35.5	37.5
#30	23.5	22.5
#50	15.8	15.8
#200	6.0	6.0
Binder originally specified		PG 70-28
Substitute binder		None
Design asphalt content, %		5.8
Current JMF AC, %		5.8
Recycled binder, %		0.54
Ratio of recycled to total binder, %		9.4
Design number of gyrations		50
Design rice gravity (Gr)		2.430
Lot 4, DOT1 rice gravity		2.447
Target lab-molded density, %		97.0

The mix was produced in Ashtola and hauled about 35 mi to the jobsite in tarped belly dump trucks. On site, the trucks maintained a windrow typically 50–100 ft long, from which a SB2500D transferred the mix into an AP1055E paver. The paver laid a mat 22 ft wide. Figure 34 shows the paving operation.

Figure 34. Paving Operation on US 287.

After laydown, CC6200 VI rollers performed breakdown rolling, typically applying five passes. Two breakdown rollers worked in tandem, with one roller on the area of the mat that would become the lane and the other roller over the area that would become the shoulder. Intermediate and finish rolling used a CP2700 and CB66B roller, respectively. On the day of testing, paving started at about 9:00 a.m. By 11:15 a.m., approximately 1500 ft of pavement had been placed, constituting the section that researchers concentrated on for further evaluation. The contractor continued to place additional mix until approximately 5:00 p.m.

On the day of testing, ambient air temperatures ranged from 42 to 66°F, with light winds at approximately 5 mph from the north and then shifting from the south in the afternoon. Figure 35 and Figure 36 show the air temperature and wind speeds, respectively, as recorded at the Childress Municipal Airport throughout the day.

Figure 35. Air Temperature during US 287 Paving.

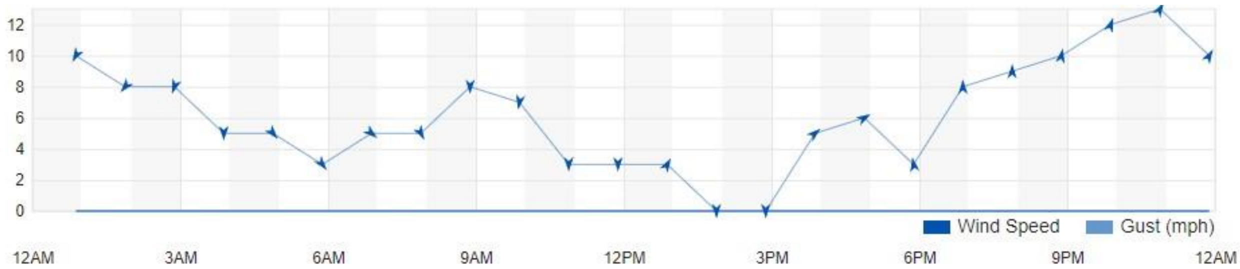


Figure 36. Wind Speeds during US 287 Paving.

5.2.2. US 287 Thermal Profile Results

Thermal profile data for this demonstration project were collected from STA 1968+25 to STA 1954+00. Figure 37 displays the thermal plot, demonstrating overall minimal thermal variations. The notable thermal irregularity is observed between STA 1967 and 1966, where measured placement temperatures were below 250°F.

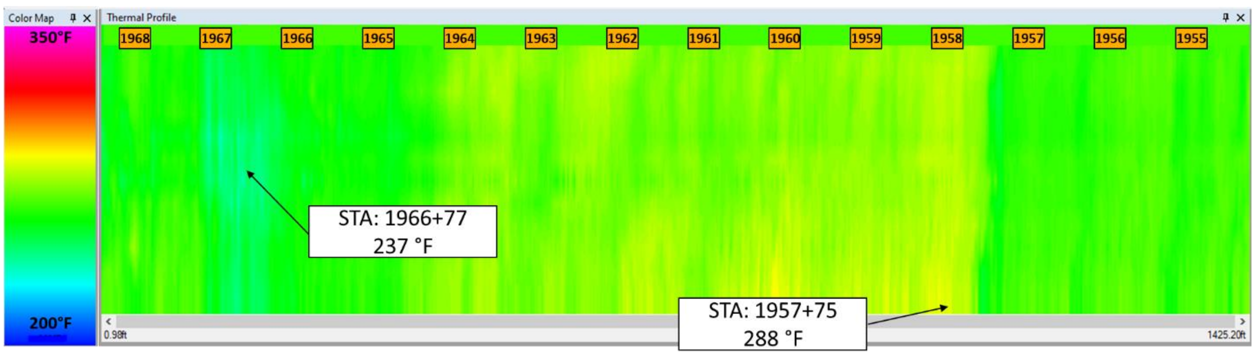


Figure 37. US 287 Thermal Profile.

Table 20 shows the thermal profile summary results generated from the automated analysis in accordance with Tex-244-F, and Figure 38 shows the distribution of measured placement temperatures. These data confirm that the level of thermal segregation observed would be considered minimal, with 20 percent moderate thermal segregation, no severe thermal segregation, and measured placement temperatures behind the screed from about 245 to 285°F.

Table 20. Thermal Profile Summary Results from US 287.

Number of Profiles	Moderate 25°F < Differential ≤ 50°F		Severe Differential > 50°F	
10	Number	Percent	Number	Percent
	2	20	0	0

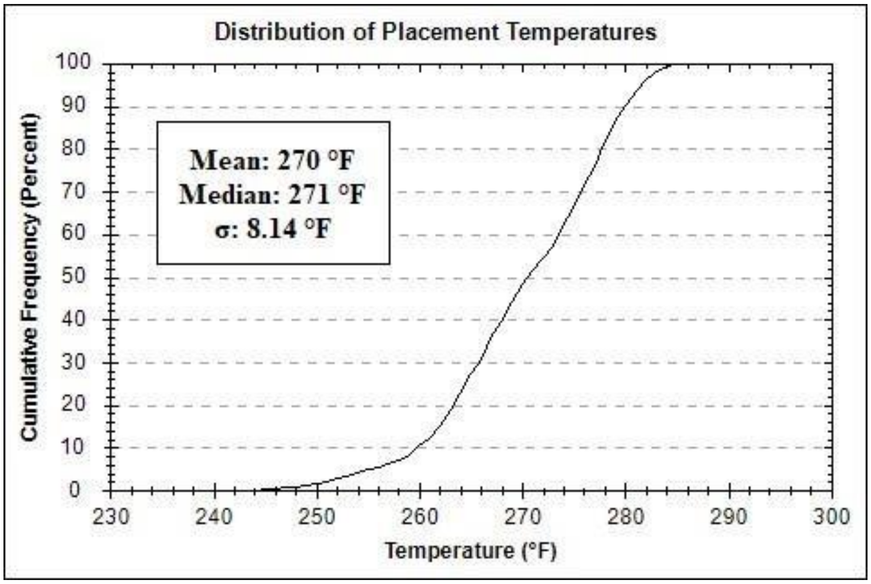


Figure 38. Distribution of Placement Temperatures on US 287.

5.2.3. US 287 Focused Testing Results

To comprehensively assess the impact of thermal segregation on the newly compacted mat, researchers conducted additional field testing, coring, and lab testing on the focused section. Table 21 presents the individual thermal profile results and shows that even the profiles exhibiting moderate thermal segregation had temperature differentials only slightly exceeding the 25°F threshold. Overall, the data in Table 21 indicate a relatively uniform placement operation.

Table 21. US 287 Thermal Profile Results from Demonstration Section.

Profile Number	Begin STA	End STA	Max. Temp (°F)	Min. Temp (°F)	Temp. Differential (°F)
1	1968.24	1966.74	272.5	246.6	25.9
2	1966.73	1965.25	266.2	244.2	22.0
3	1965.24	1963.74	279.1	256.6	22.5
4	1963.73	1962.25	281.8	266.9	14.9
5	1962.24	1960.75	283.6	269.8	13.9
6	1960.74	1959.24	287.2	270.1	17.1
7	1959.23	1957.75	286.9	273.7	13.1
8	1957.74	1956.24	284.0	258.1	25.9
9	1956.23	1954.75	272.8	261.7	11.2
10	1954.74	1954.00	273.6	262.0	11.5

Based on the results in Table 21, researchers field located 11 core locations to represent the temperature differentials observed in the thermal profiles. Figure 39 shows the thermal plot along with these selected locations. Researchers collected a GPR reading at each core location before extracting the core.

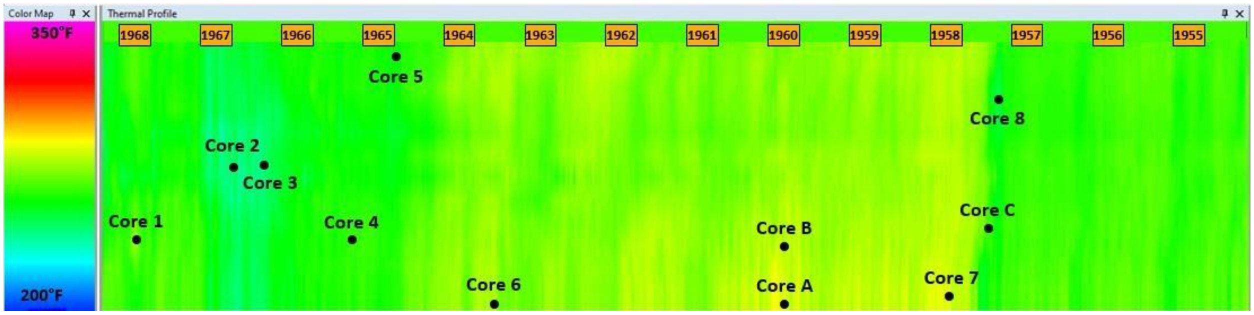


Figure 39. US 287 Thermal Plot with Core Locations.

Researchers returned the cores to the lab, where they trimmed and then measured the bulk specific gravity of each core in accordance with Tex-207-F. They calculated the percent AVs of each core using the Gr of 2.447 as reported for Lot 4, Sublot 1. Table 22 shows the results from the cores, which contain a range of measured AV contents from 2.7 to 9.9 percent. The data in Table 22 show that lower AV contents are generally associated with higher measured temperatures, while higher AV contents correspond to lower measured temperatures. This mix also included 0.4 percent Evotherm, which served as a compaction aid. Table 22 indicates that despite the inclusion of the compaction aid, locations with lower temperatures measured during placement experienced a significant increase in AVs after compaction operations were complete.

Table 22. Core Results from US 287.

Core	STA	Offset (ft)	Temperature at Placement (°F)	Field Dielectric from GPR	Lab-Measured AVs (%)
1	1967+85	9	280	4.55	3.6
2	1966+77	13	237	4.05	8.4
3	1966+54	12	240	4.00	9.9
4	1965+44	9	266	4.45	5.7
5	1964+67	18	255	4.20	7.3
6	1963+90	6	280	4.55	3.6
7	1957+75	7	288	4.55	4.3
8	1957+13	15	253	4.20	7.1
A	1960+00	9	279	4.30	6.0
B	1960+00	6	286	4.70	2.7
C	1967+85	9	280	4.50	5.6

5.2.3.1. Interpretation of Thermal Segregation

Figure 40 shows the lab-measured AVs versus the temperature measured at the time of placement. The results in Figure 40 illustrate the following:

- A good correlation was observed between the measured temperature at the time of placement and lab-measured AV contents. The data suggest that even if the thermal variation is relatively low in terms of temperature differentials within each 150-ft thermal profile segment, the level of compaction and final in-place AVs is still influenced by the absolute temperature of the mix at the time of placement.
- Although the amount and severity of thermal segregation measured in this demonstration project would be considered reasonably low, the measured AV content range was quite high.
- Based on the slope of the regression line, a temperature differential of 34°F corresponds to an expected density differential of 6 pcf, which aligns with the maximum allowable density range (highest–lowest) specified in TxDOT's density profile requirements for DG-D HMA. This finding is based on a 3.9 percentage point change in AV, which equates to a 6 pcf change in density considering the reported rice gravity of this mix.

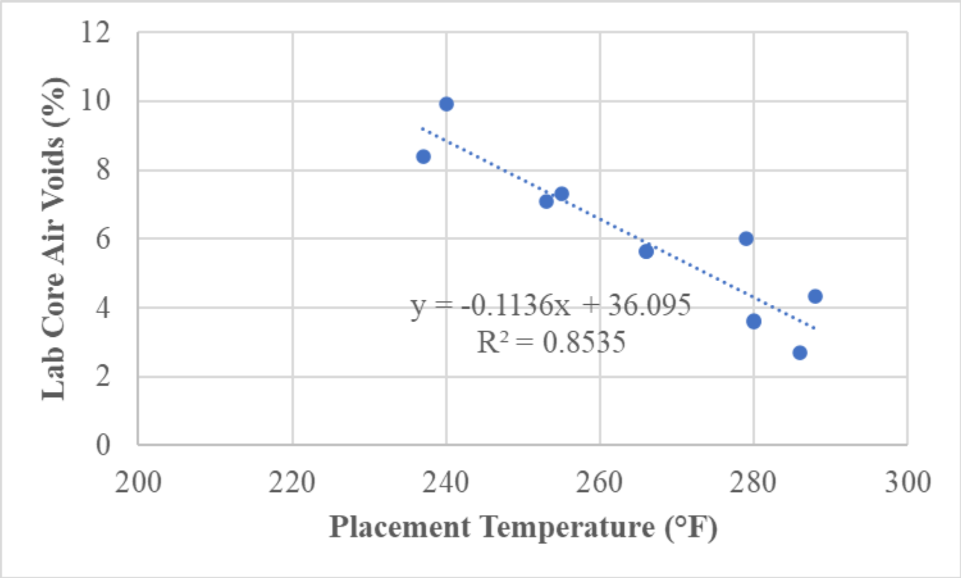


Figure 40. Results from US 287 AVs versus Temperature.

5.2.3.2. Interpretation of GPR

While the thermal profile tests the placed, uncompacted mat, the GPR tests are conducted after all rolling operations have been completed. Figure 41 displays the relationship between core AV contents and the field-measured surface DC obtained from GPR. The figure demonstrates a strong correlation between these two parameters, indicating that GPR has the potential to be used as a final quality and uniformity check for assessing the in-place mat density.

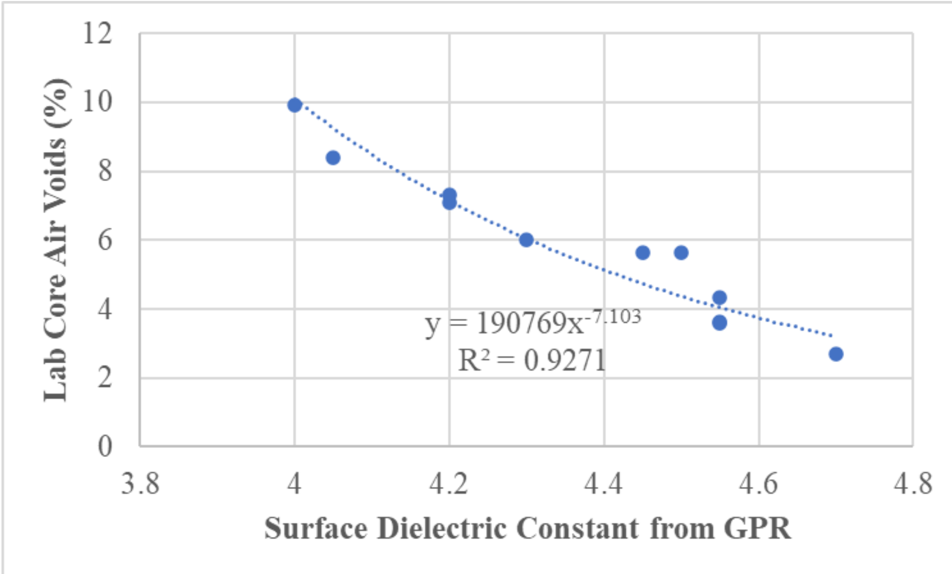


Figure 41. GPR Results from US 287 Cores.

Based on the correlation shown in Figure 41, the GPR data can be used to estimate the density of the tested mat area. Figure 42 presents the expected distribution frequency of AVs over the demonstration area. This distribution frequency is based on the AV prediction model depicted in Figure 41, using over 20,000 individual data points collected across the mat area with multiple passes of the GPR at various transverse offsets.

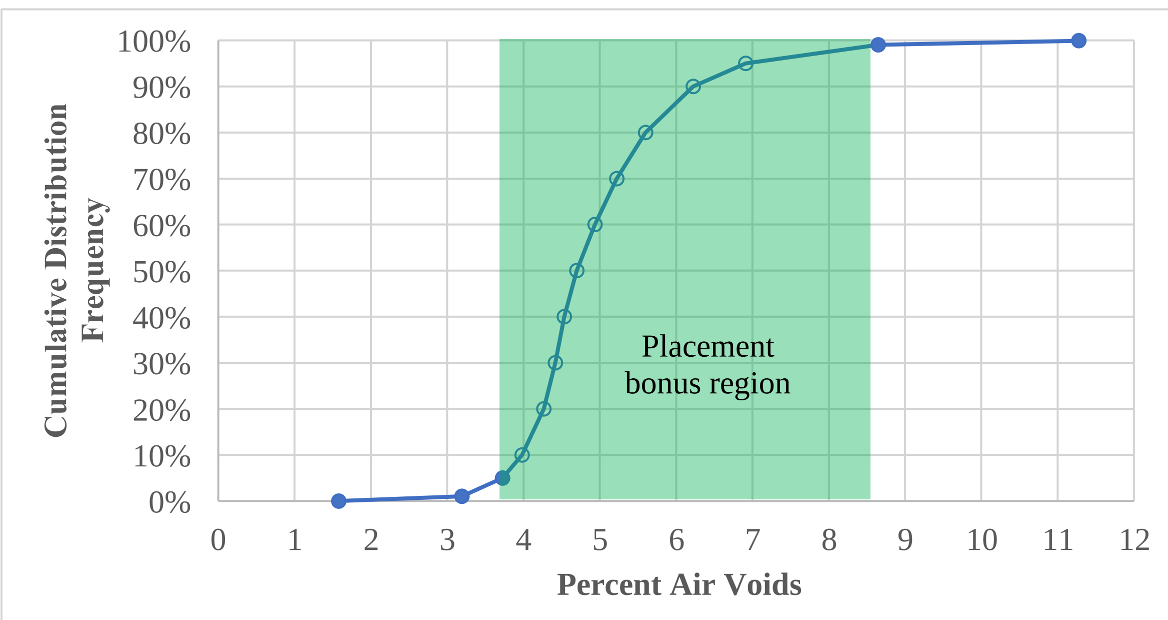


Figure 42. Expected Distribution of AVs on US 287.

The underlying data used to generate Figure 42 produce the following descriptive statistics:

- Mean AV content: 5.0 percent.
- Standard deviation: 1.04 percent.
- Percentage within placement pay factor ≥ 1.0: 93.

Thus, the GPR data and Figure 42 show that for the area tested by GPR, about 93 percent of the mat area is within the placement bonus region for AV content, which is between 3.8 and 8.5 percent AVs for this mix. Based on project records, TxDOT's reported placement densities for Lot 4, Sublot 1, from which the GPR survey was conducted, were 6.7 and 6.0 percent AVs. The average AV content of 6.4 percent from the TxDOT random cores is higher than the 5.0 percent mean AV content estimated from the GPR analysis. This random test result is about 1.3 standard deviations from the mean AVs estimated by GPR, indicating the quality control/quality assurance (QC/QA) result is reasonably consistent with the statistical distribution estimated by the GPR analysis.

With multiple GPR runs available at different transverse offsets, the GPR data can also generate a geospatial plot of expected in-place mat density. Figure 43 presents this output for the demonstration area tested. Figure 43 illustrates:

- Most of the mat area exhibits AV content within the desired range of 3.8 to 8.5 percent.
- The cold spot in Figure 39 became the zone of the highest AVs in Figure 43.
- A small proportion of the mat is expected to have less than 3.8 percent AVs.

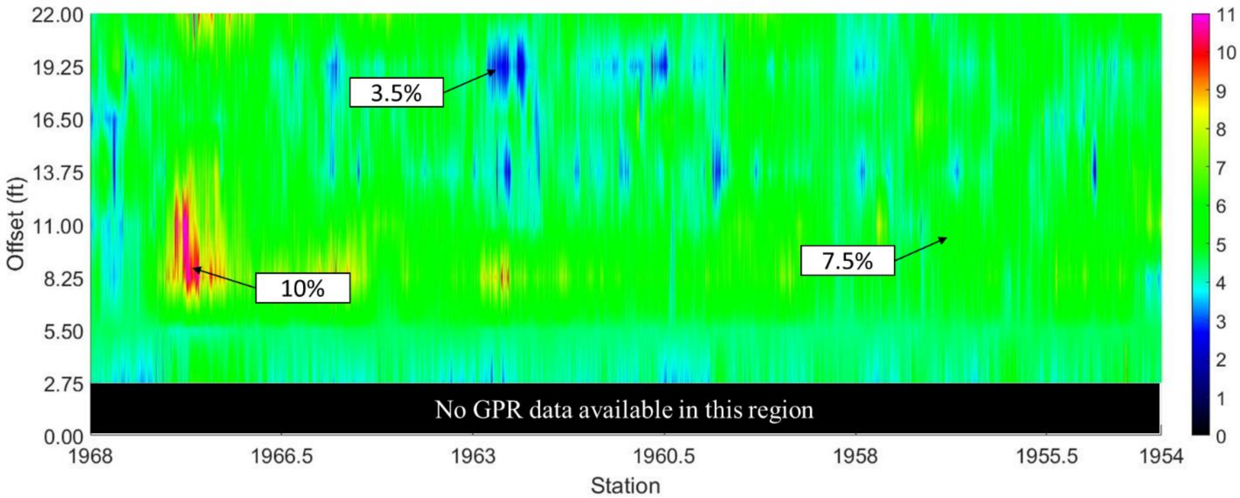


Figure 43. AV Map for US 287.

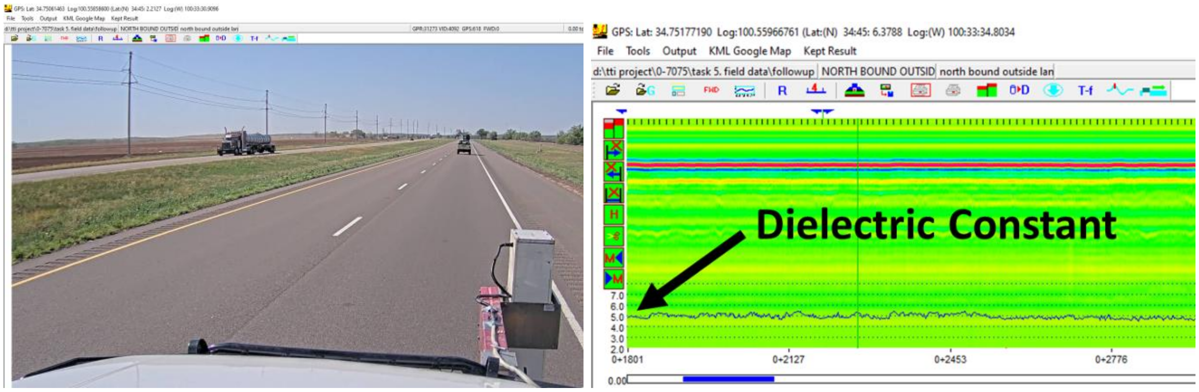
Figure 43 represents a subset of the paving placed on the specific day of testing and does not necessarily indicate past or future anticipated results on other locations along the project.

5.2.4. US 287 Post-Construction Site Visit

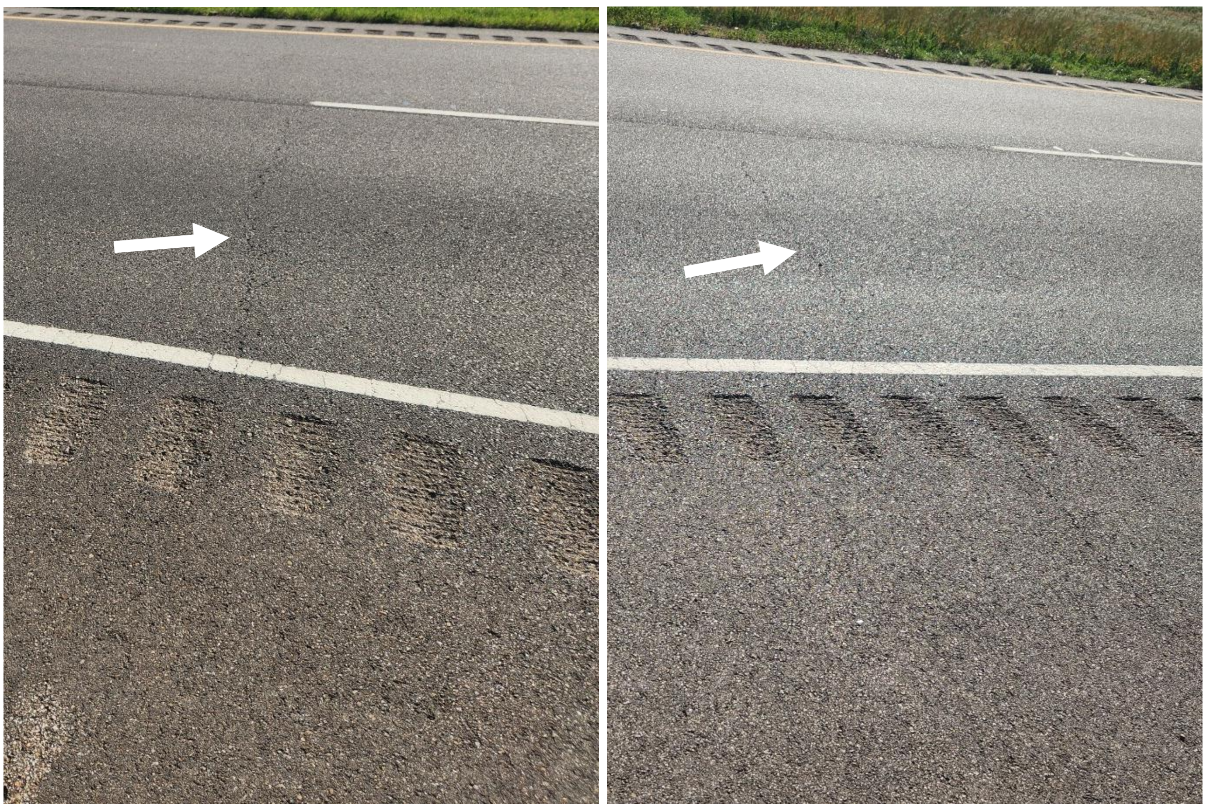
Researchers conducted a post-construction site visit on April 19, 2023, approximately 1.5 years after the project's completion, to assess the presence of any distresses and determine if they correlate with thermal segregation during construction. The visit involved several activities, including an air-launched GPR survey within specified limits (Figure 44), a visual condition survey, digital video collection, and photography of representative locations. Additionally, researchers documented the location of any observed distresses using distance offsets, GPS coordinates, or other suitable methods to align with known thermal profile data.

Figure 44. GPR and Visual Condition Survey Using Digital Video Equipment.

During the construction of this project, 20 percent of the thermal profiles exhibited moderate thermal segregation. Figure 45a illustrates the follow-up GPR survey when the project was approximately 1.5 years old. The survey revealed the presence of transverse cracking, as shown in Figure 45b. However, no correlation was found between the temperature differential at the time of construction and the location of these transverse cracks.



(a)



(b)

Figure 45. (a) GPR and (b) Post-Construction Condition on US 287.

During the post-construction site visit, researchers examined whether the surface DC measured by the 1-GHz air-coupled GPR could correlate with the thermal profile data obtained during the time of construction. However, due to the difference in data coverage (line scan for GPR versus longitudinal and transverse offsets for thermal profiles), evaluating the correlation was not straightforward. Figure 46 presents the plot of the DC measured by the GPR along with the differential temperature and the placement temperature. The results in Figure 46 indicate the absence of clear trends or correlations among these variables.

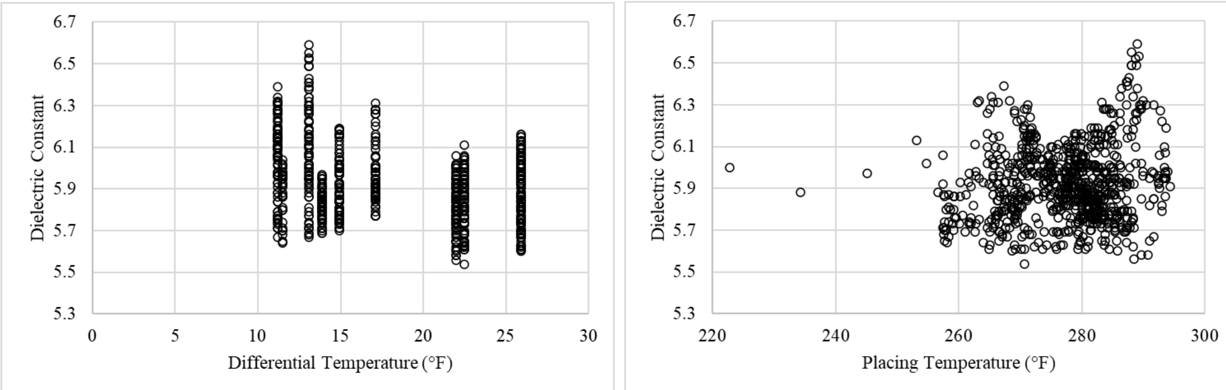
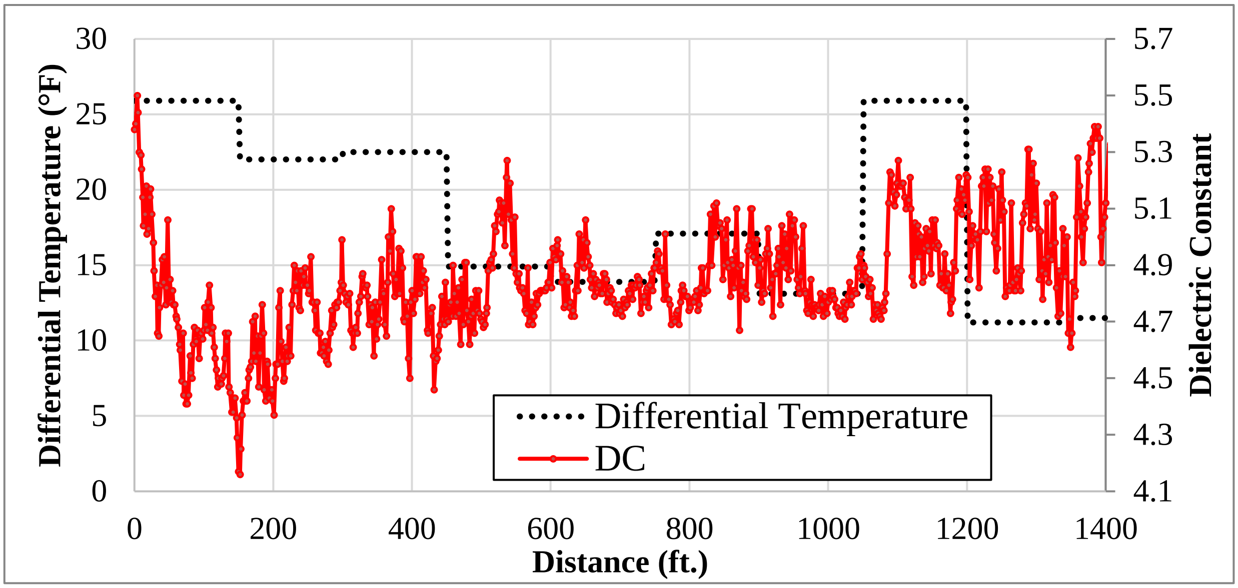
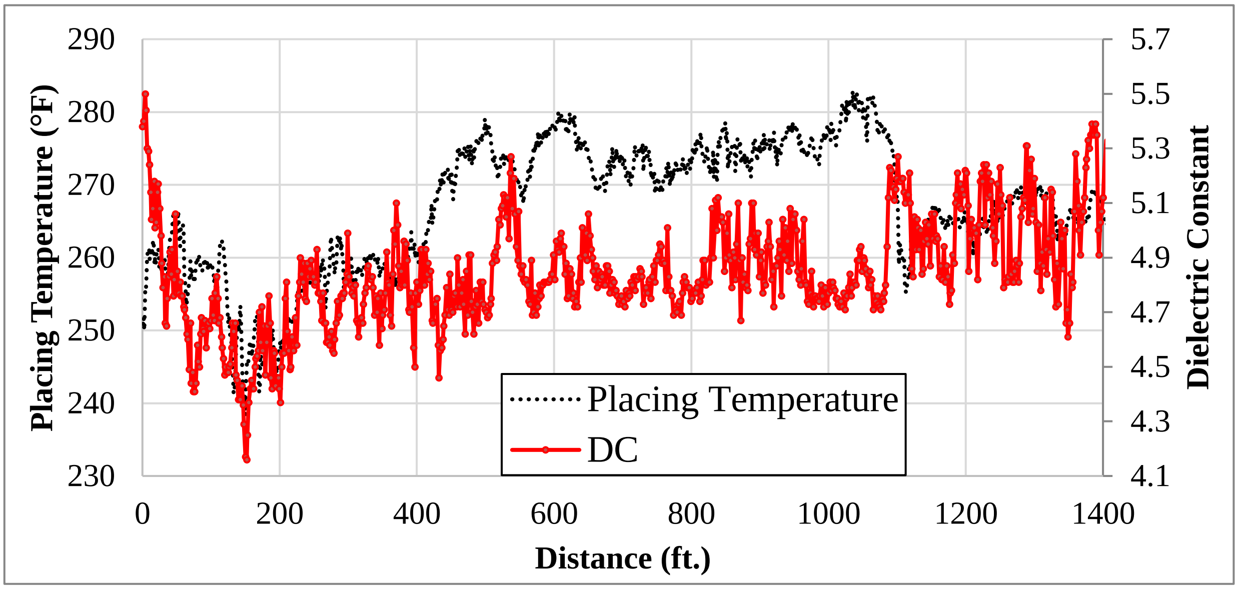


Figure 46. DC versus Differential (Left) and Placement (Right) Temperature on US 287.

Figure 47 shows the DC from the 1-GHz system and thermal profile information plotted with distance. In Figure 47(a), some indication exists that higher DCs existed where temperature differentials were lower (from 0 to 400 ft), and lower DCs existed where temperature differentials were higher (from 1200 to 1400 ft). Figure 47(b) similarly suggests some level of tracking may exist between the DC and the absolute placement temperature. However, these data overall do not show clear evidence of a strong correlation between the GPR and thermal data over the entire demonstration project area.



(a)



(b)

Figure 47. DC versus (a) Differential Temperature and (b) Absolute Placement Temperature on US 287.

5.2.5. Conclusions from DG-D on US 287

The placement operation on US 287 exhibited a low percentage of thermal segregation and generally reasonably low temperature differentials in the thermal profiles. In the demonstration section, only two profiles exhibited moderate thermal segregation, and the temperature differentials in those profiles barely exceeded the 25°F threshold. Across the entire demonstration section, measured placement temperatures ranged from about 245 to 285°F, and measured core AV contents ranged from 2.7 to 9.9 percent.

The results from US 287 show that even when using a compaction aid in the mix, employing a material transfer vehicle, and placing the mix with minimal thermal segregation as measured by the 150-ft long thermal profile analysis from Tex-244-F, the eventual in-place density of the mix is sensitive to the absolute temperature of the mix at the time of placement. Results from this project showed that as the measured placement temperature decreased, the in-place AVs after compaction increased. The results showed that a 34°F temperature differential would be expected to correspond with a 6 pcf density differential with this mix and operation.

This demonstration project illustrates that in addition to the 150-ft long thermal profile analysis method currently used in Test Method Tex-244-F, the mix's overall temperature uniformity along longer paving lengths can also impact the final product. More uniformity throughout the entire operation will produce more uniformity in the final product. On this specific project, while the results clearly showed an influence of thermal variations on final mat density, the findings also showed that the contractor placed the mix with what would be considered reasonable uniformity. This project's high level of placement uniformity resulted in a favorable final product, with over 90 percent of the compacted mat area having AVs within the desired placement bonus range.

Despite the presence of some transverse cracking distress approximately 1.5 years after construction, there was no correlation found between these distresses and thermal anomalies during the time of construction. Furthermore, no clear correlation was observed between the temperature differential or the absolute temperature at the time of construction and the measured DC value during the post-construction site visit.

5.3. SP-D ON US 183

In collaboration with the TxDOT Brownwood District, researchers conducted a thermal profile demonstration on US 183 to assess the potential influence of thermal segregation on the in-place mat density. This testing included selecting spot test locations to represent normal and thermally segregated points over the HMA mat, conducting an NDT survey of the mat area with a multichannel GPR system, and then cutting and collecting 6-in. diameter cores directly over each selected spot location for lab testing.

During field evaluations, researchers observed recurring moderate thermal segregation. In the laboratory, the AV content of each core was measured. However, the results revealed a poor correlation between AVs and temperature measured during placement. Researchers attribute this weak correlation, at least partially, to inconsistent breakdown rolling practices. On the other hand, a strong correlation between AVs and the GPR data was observed, highlighting the potential of GPR as a quality control tool for assessing the entire mat.

5.3.1. Project Location, Mix Type, and Paving Operations

The demonstration project was located on US 183 near Rising Star, Texas, for CSJ 0127-02-148. Researchers performed field testing on December 17, 2021. The project placed a 1.5-in. lift of SS 3077 SP-D mix. Table 23 presents the design JMF and the JMF for Lot 11, which was the current production lot on the day of testing.

Table 23. SP-D Mix Design for US 183.

Sieve Size	Design JMF Cumulative % Passing	Current JMF Cumulative % Passing
¾"	100.0	100.0
½"	99.4	99.6
⅜"	93.5	94.1
#4	56.3	60.9
#8	34.5	38.1
#16	22.4	25.9
#30	17.0	19.3
#50	13.7	14.1
#200	3.4	3.4
Binder originally specified		PG 76-22
Substitute binder		None
Design asphalt content, %		5.3
Current JMF AC, %		5.6
Design number of gyrations		50
Design rice gravity (Gr)		2.448
Lot 11, DOT1 rice gravity		2.426
Lot 11, DOT2 rice gravity		2.444
Target lab-molded density, %		96.0

The mix was produced in Gorman and hauled about 22 mi to the jobsite in tarped flow-boy and end dump trucks. On site, the trucks dumped directly into an E1650 transfer device, which transferred the mix into an AP1055F paver. The paver laid a mat 16.5 ft wide. Figure 48 shows the paving operation.

Figure 48. Paving Operation on US 183.

After laydown, an HD 140i roller performed breakdown rolling, typically applying three passes. Intermediate and finish rolling used a CW34 and CB13 roller, respectively. On the day of testing, paving started at about 9:00 a.m. Ambient air temperatures ranged from 62 to 75°F, with winds initially around 10 mph and gusts to 30 mph later that day. Figure 49 and Figure 50 show the air temperature and wind speeds, respectively, as recorded at the Brownwood Municipal Airport throughout the day.

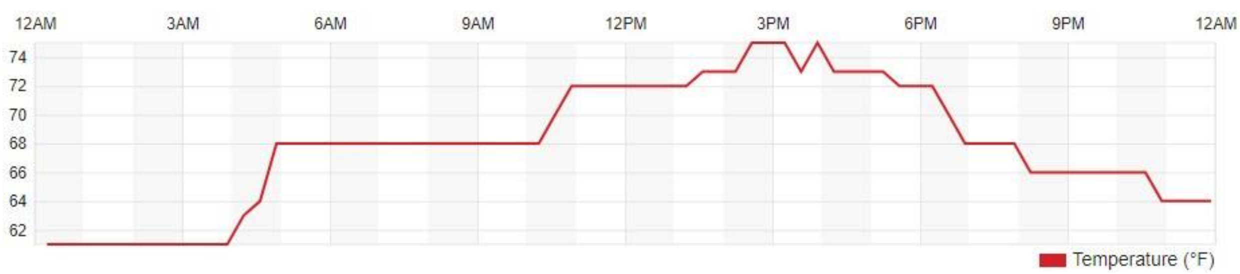


Figure 49. Air Temperature during US 183 Paving.

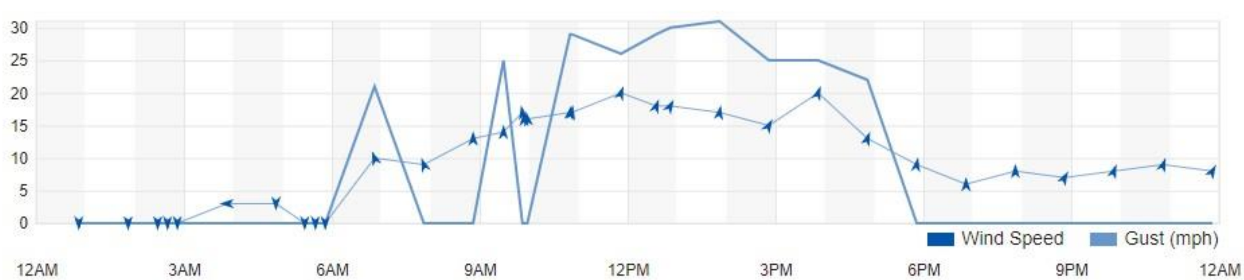


Figure 50. Wind Speeds during US 183 Paving.

5.3.2. US 183 Thermal Profile Results

Thermal profile data used in this demonstration were collected from approximately STA 620 to 587. Figure 51 shows the thermal plot and illustrates recurring thermal patterns.

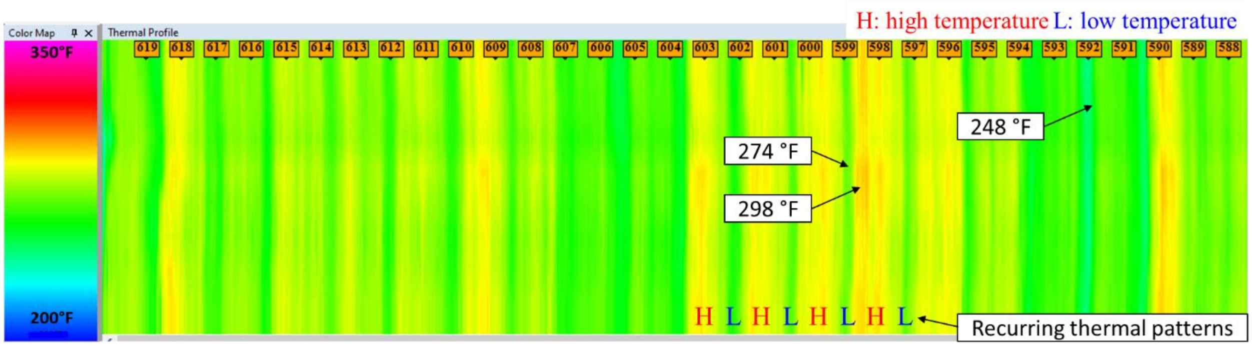


Figure 51. US 183 Thermal Profile.

Table 24 shows the thermal profile summary results generated from the automated analysis in accordance with Tex-244-F and demonstrates a high percentage of recurring moderate thermal segregation. Figure 52 shows measured placement temperatures behind the screed from about 250 to 290 F.

Table 24. Thermal Profile Summary Results from US 183.

Number of Profiles	Moderate 25°F < Differential ≤ 50°F		Severe Differential > 50°F	
	Number	Percent	Number	Percent
23	13	57	0	0

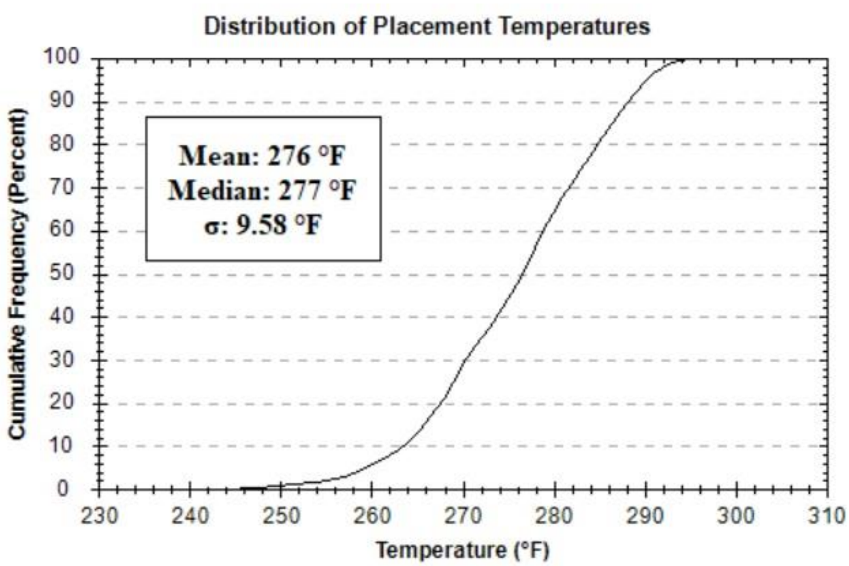


Figure 52. Distribution of Placement Temperatures on US 183.

5.3.3. US 183 Focused Testing Results

For the focused testing used to evaluate the potential influence of thermal segregation on the newly compacted mat, researchers further evaluated the section from STA 606 to 589 through additional testing and coring. Table 25 presents the individual thermal profile results from within these stations. Table 25 shows that the profiles with moderate thermal segregation generally had temperature differentials around 30°F.

Table 25. US 183 Thermal Profile Results from Demonstration Section.

Profile Number	Begin STA	End STA	Max. Temp (°F)	Min. Temp (°F)	Temp. Differential (°F)
10	606.74	605.25	274.6	252.9	21.8
11	605.24	603.74	275.9	256.5	19.4
12	603.73	602.25	293.5	255.0	38.5
13	602.24	600.74	293.0	259.7	33.3
14	600.73	599.25	293.5	269.2	24.3
15	599.24	597.75	296.4	270.9	25.6
16	597.74	596.24	290.5	270.0	20.5
17	596.23	594.75	291.7	262.0	29.7
18	594.74	593.24	285.8	254.5	31.3
19	593.23	591.75	273.2	245.5	27.7
20	591.74	590.25	275.7	248.2	27.5
21	590.24	588.74	296.6	266.5	30.1

Based on the results in Table 25, researchers field located 13 core locations to represent the temperature differentials observed in the thermal profiles. Figure 53 shows the thermal plot along with these selected locations. Researchers collected a GPR reading at each core location before extracting the core.

Figure 53. US 183 Thermal Plot with Core Locations.

Researchers returned the cores to the lab, where they trimmed and then measured the bulk specific gravity of each core in accordance with Tex-207-F. They calculated the percent AVs of Cores 1–6 using the Gr of 2.426 based on the Lot 11, Sublot 1 reported value. They calculated the percent AVs of Cores 7–13 using the Gr of 2.444 based on the Lot 11, Sublot 2 reported value. Table 26 shows the results from the cores, which contain a range of measured AV contents from 5.2 to 10.8 percent.

Table 26. Core Results from US 183.

Core	STA	Offset (ft)	Temperature at Placement (°F)	Field Dielectric from GPR	Lab-Measured AVs (%)
1	605.42	12	254	5.283	10.3
2	604.24	8	273	5.472	8.3
3	603.06	8	294	5.425	10.2
4	599.59	8	295	5.676	8.6
5	598.83	8	274	5.468	7.9
6	598.36	8	298	5.581	8.4
7	594.33	8	285	5.407	9.2
8	592.10	10	251	5.327	10.7
9	591.99	12	244	5.337	10.8
10	591.07	4	270	5.723	7.4
11	590.41	8	249	5.397	8.3
12	589.89	8	298	5.954	5.4
13	589.89	4	295	6.035	5.2

5.3.3.1. Interpretation of Thermal Segregation

Figure 54 shows the lab-measured AVs versus the temperature measured at the time of placement. The results in Figure 54 show a poor correlation between the temperature measured during placement and the lab core AVs. This observation contradicts the prevailing understanding of how thermal segregation typically impacts the final in-place HMA density.

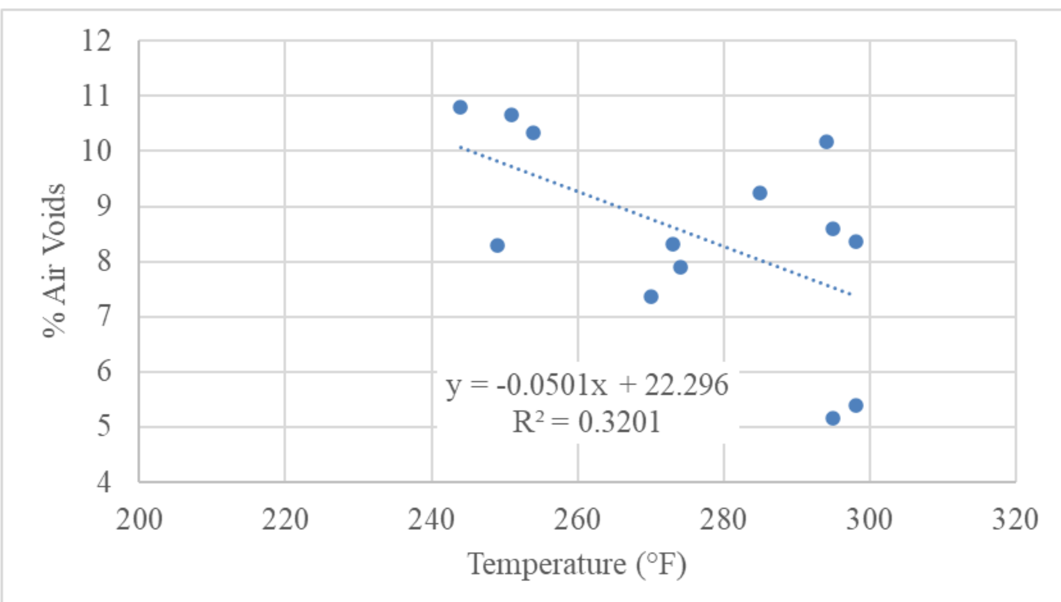


Figure 54. Results from US 183 AVs versus Temperature.

Researchers believe the poor correlation in Figure 54 is due, at least in part, to erratic breakdown rolling patterns on this project. While on site, researchers noted that the breakdown roller seldom kept up with the paving operation. This significant delay in conducting breakdown rolling adversely affects the final density, regardless of the temperature at the time of placement. Researchers hypothesize the erratic breakdown rolling pattern helps explain why certain locations on the roadway, with similar measured placement temperatures of around 300°F, exhibited AVs ranging from around 5 percent to between 8.5 percent and 10 percent.

5.3.3.2. Interpretation of GPR

While the thermal profile tests assess the condition of the placed, uncompacted mat, the GPR tests are conducted after all rolling operations have been completed. Figure 55 presents the core AV contents versus the field-measured surface DC from GPR. Figure 55 shows a good correlation, illustrating the viability of GPR as a final density and uniformity check on the completed mat.

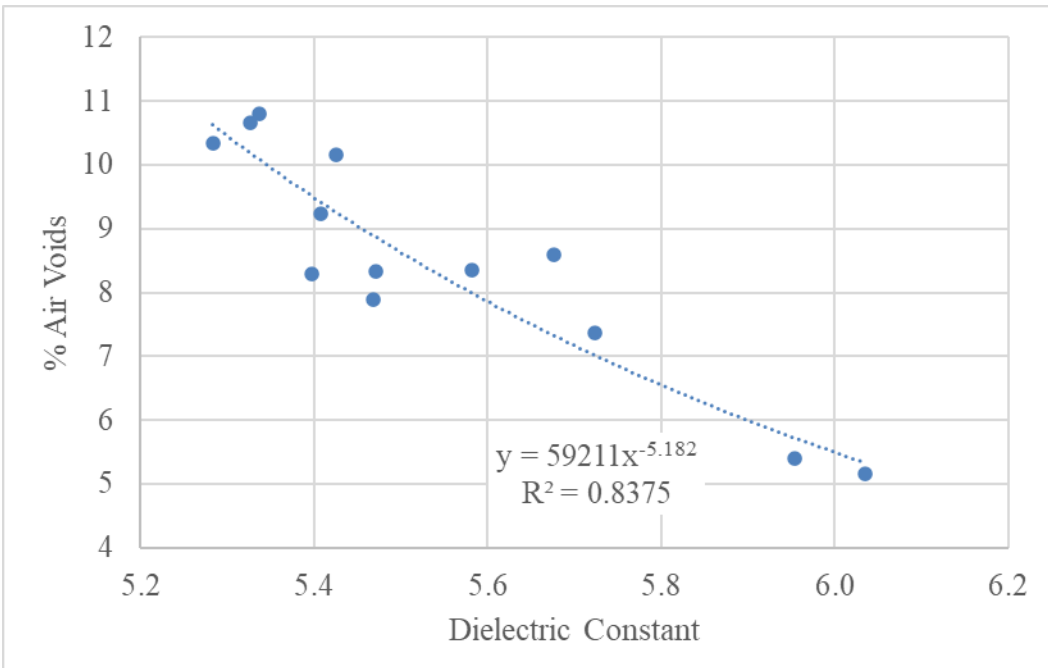


Figure 55. GPR Results from US 183 Cores.

With the correlation in Figure 55, the GPR data can be used to estimate density over the tested mat area. Figure 56 presents the expected distribution frequency of AVs over the area of focused testing. This distribution frequency is based on the AV prediction model shown in Figure 55 and over 40,000 individual data points collected over the mat area with the GPR at different transverse offsets.

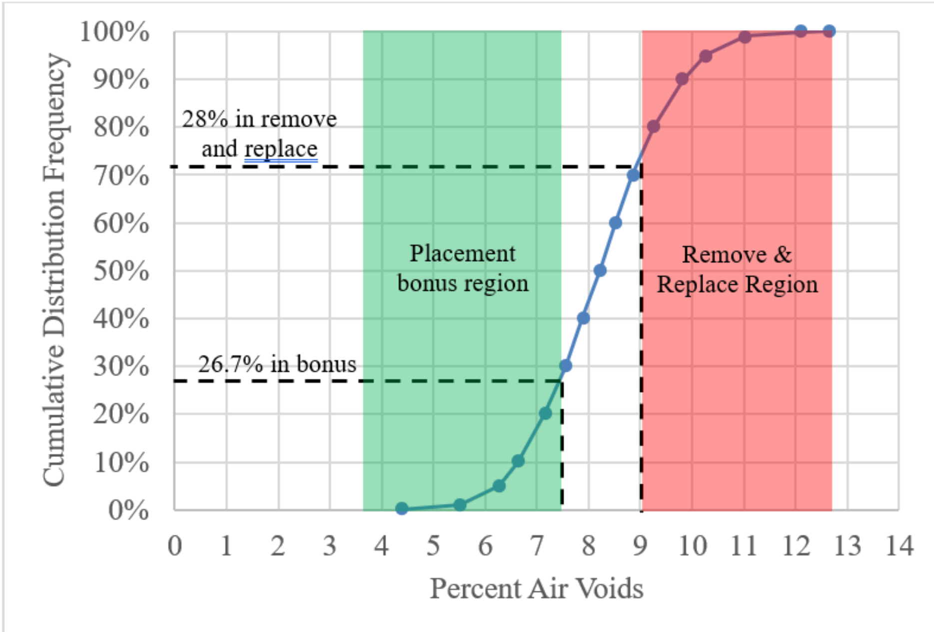


Figure 56. Expected Distribution of AVs on US 183.

The underlying data used to generate Figure 56 produce the following descriptive statistics:

- Mean AV content: 8.4 percent.
- Standard deviation: 1.26 percent.
- Percentage within placement pay factor $\geq$ 1.0: 26.7.

Thus, the GPR data and Figure 56 show that for the area tested by GPR, about 27 percent of the mat area is within the placement bonus region. These data also show that about 45 percent of the tested area is in placement penalty and about 28 percent is expected to have AVs requiring removal and replacement.

Based on project records, TxDOT's reported placement density for Lot 11, Sublot 1 was 8.6 percent, and the random QC/QA location placement density for Lot 11, Sublot 2 was 8.7 percent. These QC/QA results are consistent with the average value provided by the GPR analysis. However, the GPR analysis captures the expected variability, which the random QC/QA results do not capture. The GPR data suggest significant density concerns exist within the focus test area of this project.

With multiple GPR runs available at different transverse offsets, the GPR data can also generate a geospatial plot of expected in-place mat density. Figure 57 presents this output for the demonstration area tested. Figure 57 illustrates:

- A significant percentage of the mat area exhibits high AVs.
- A cyclic pattern of low density seems to exist.
- Approaching STA 591, the severity of low density seems to lessen.

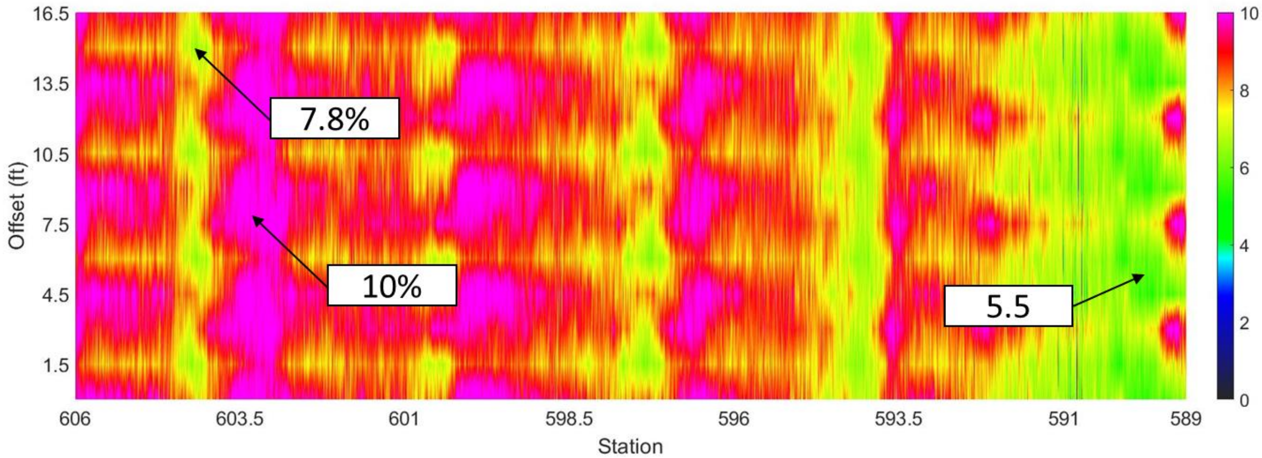


Figure 57. AV Map for US 183.

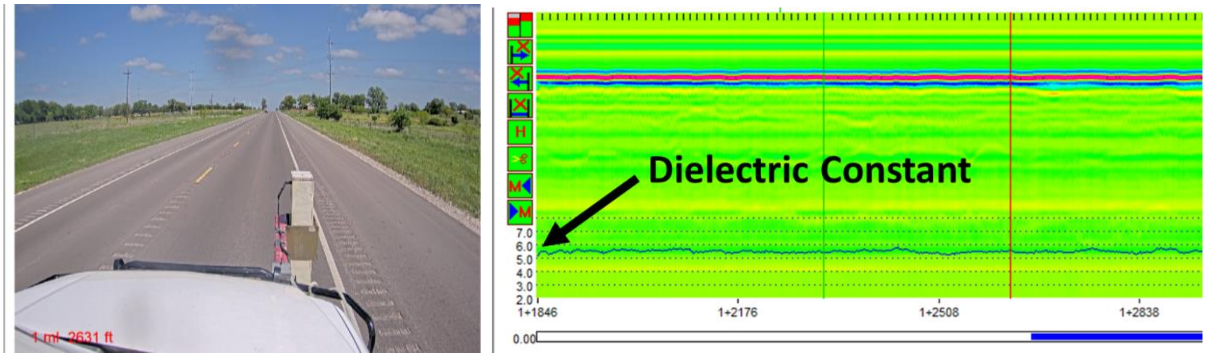
Researchers evaluated the spacing between cycles of moderate thermal segregation in the thermal profile (Figure 51) and the spacing between high AV cycles in Figure 57. The spacings do not align. Researchers hypothesize the spacing of high AV cycles in Figure 57 corresponds with the breakdown rolling pattern. The breakdown roller struggled to keep up with the paving train until approaching STA 589 since the paving train stopped at that station.

Figure 57 represents a subset of the paving placed on the specific day of testing and does not necessarily indicate past or future anticipated results on other locations along the project.

5.3.4. US 183 Post-Construction Site Visit

Researchers conducted follow-up field testing on April 19, 2023. The primary purpose of this post-construction site visit was to assess the presence of any distress and investigate whether the locations correlated with thermal segregation during the construction phase. The visit involved several activities, including an air-launched GPR survey within specified limits, a visual condition survey, digital video collection, and photography of representative locations. Additionally, researchers documented the location of any observed distresses using distance offsets, GPS coordinates, or other suitable methods to align with known thermal profile data.

Figure 58(a) shows an excerpt from the 1-GHz air-coupled GPR survey. No significant distress was observed at the post-construction site, as shown in Figure 58(b).

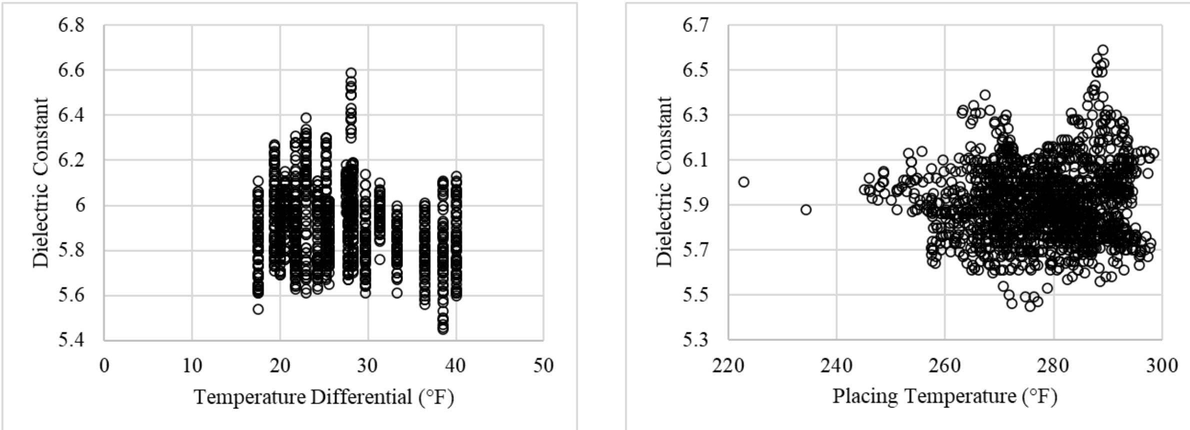


(a)

(b)

Figure 58. (a) GPR and (b) Post-Construction Condition on US 183.

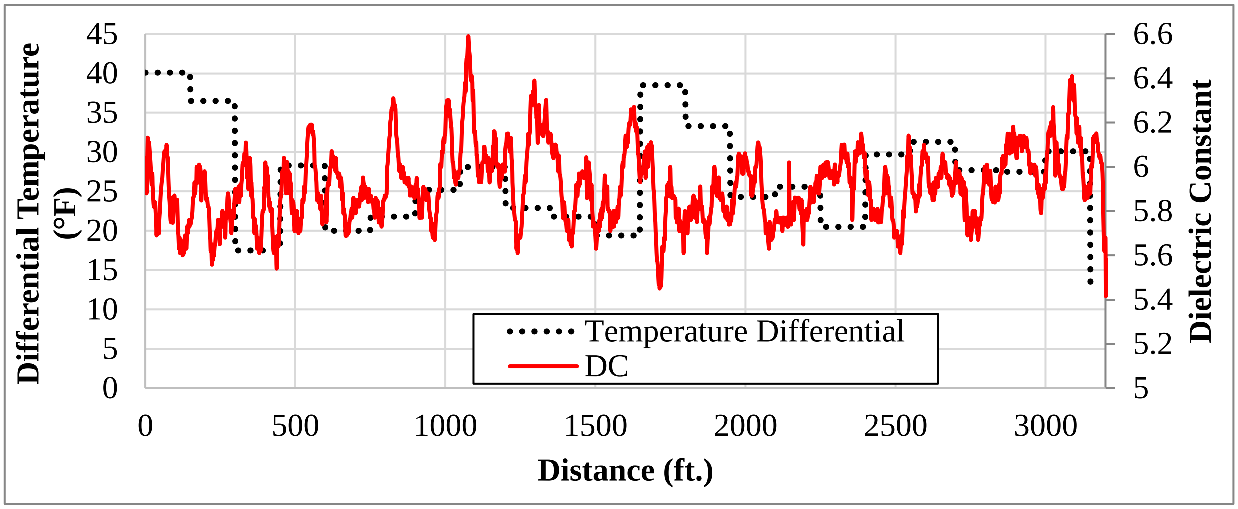
Figure 59 presents the 1-GHz air-coupled GPR line scan of the pavement's DC, carried out approximately 17 months after construction, with the differential and placement temperature from the thermal profile data. Figure 59 shows the GPR data did not consistently correlate with the thermal data. Although it is somewhat possible to match the longitudinal path of GPR with the locations measured for thermal segregation, it can be challenging due to the transverse testing coverage of the thermal profile.



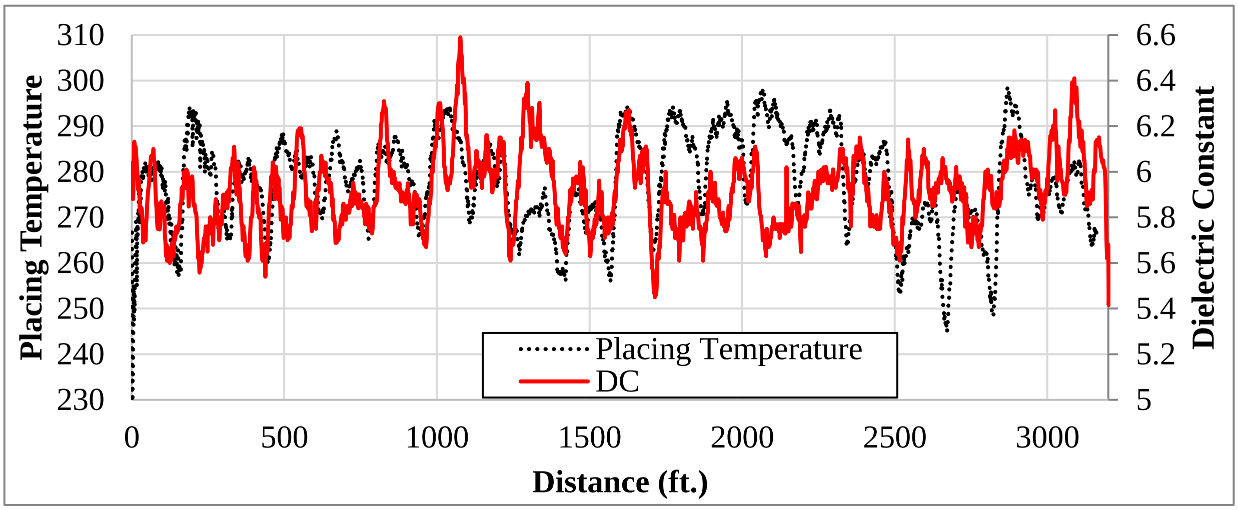
(a) (b)

Figure 59. DC versus Differential (Left) and Placement (Right) Temperature on US 183.

Figure 60 illustrates the thermal and GPR data results along with the corresponding distance for the evaluated section. The correlation between the DC values and the differential temperatures was found to be non-straightforward, as shown in Figure 60(a). As shown in Figure 60(b), DC values did not consistently exhibit a correlation with the absolute placement temperature. Certain locations indicated a positive correlation, while others showed a negative correlation. Any potential general trends between the thermal data and GPR could be further obscured by the documented erratic breakdown rolling pattern during the construction phase. Although the correlation between the absolute value of DC and the absolute placement temperature was not strong, there appeared to be a tendency for the DC value to increase with higher placement temperatures in certain areas of the project.



(a)



(b)

Figure 60. DC versus (a) Placement and (b) Differential Temperature from GPR Investigation on US 183.

5.3.5. Conclusions from SP-D on US 183

The placement operation conducted on US 183 exhibited recurring moderate thermal segregation, with over 50 percent of thermal profiles indicating such thermal segregation. In these profiles, the temperature differential observed was typically around 30°F. Additional testing revealed a poor correlation between the thermal profile and in-place mat density. Researchers attribute this poor correlation to inconsistencies in the breakdown rolling pattern since the breakdown roller faced challenges in maintaining a steady state synchronized with the mat placement. Additionally, the breakdown roller frequently lagged the mat placement, leading to further complications in achieving consistent density.

GPR analysis showed a good correlation between the GPR data and AV content in the completed mat. The GPR analysis indicated significant density concerns within the focus test area. Approximately 45 percent of the tested area was found to be in the placement penalty range, and around 28 percent of the tested area was found to be in the range for removal and replacement.

The results from US 183 highlight the limitations of relying solely on thermal segregation as a measure of paving operation quality. While thermal profiles provide valuable insights into uniformity at the time of laydown, they do not encompass all factors that influence the final pavement outcome. In this demonstration project, the thermal profile results did not meet benchmarks, but it was determined that inadequate rolling patterns were the primary contributor to low density. The data also demonstrated the potential of GPR as a valuable tool for evaluating the final density of the in-place mat after all rolling operations are completed.

During the post-construction field investigation, no significant distress was found. Furthermore, no clear correlation was observed between the temperature differential or the absolute temperature at the time of placement and the post-construction surface DC values. While placement temperature is known to impact density, it was concluded that other factors also play a role in determining the outcome. Although the correlation between the absolute DC values and the absolute placement temperatures was not strong, there was a tendency for the DC value to increase with higher placement temperatures in certain areas of the project.

5.4. SMA-D ON SH 6

Coordinating with the TxDOT Bryan District, researchers conducted a thermal profile demonstration on SH 6 to evaluate the meaning of thermal segregation on the newly placed and compacted mat. This testing included selecting spot test locations to represent normal and thermally segregated points over the HMA mat, conducting an NDT survey of the mat area with a multichannel GPR system, and then cutting and collecting 6-in. diameter cores directly over each selected spot location for lab testing.

This project exhibited a high percentage of severe thermal segregation in the field. In the lab, researchers measured the AV content of each core. The results showed a good correlation between AVs and temperature measured at the time of placement, with the cold spots becoming higher AVs. The results also showed a strong correlation between AVs and the GPR data, illustrating the potential of the GPR as a quality and uniformity check on the completed mat.

5.4.1. Project Location, Mix Type, and Paving Operations

The demonstration project was located on SH 6, just north of Bryan, Texas, for CSJ 0049-07-064. Researchers performed testing on the project on December 11, 2022. This project placed a 2-in. lift of Item 346 SMA-D mix. Table 27 presents the design JMF and the Lot 3 JMF, which was the current production lot on the day of testing.

Table 27. SMA-D Mix Design for SH 6.

Sieve Size	Design JMF Cumulative % Passing	Current JMF Cumulative % Passing
1"	100.0	100.0
¾"	100.0	100.0
½"	87.5	87.5
⅜"	67.1	67.1
#4	31.1	31.1
#8	20.9	20.0
#16	16.2	16.2
#30	13.0	13.0
#50	10.5	10.5
#200	9.0	9.0
Binder originally specified		PG 76-22
Substitute binder		None
Design asphalt content, %		6.4
Current JMF AC, %		5.0
Recycled binder, %		0.5
Ratio of recycled to total binder, %		15.0
Design number of gyrations		50
Design rice gravity (Gr)		2.330
Lot 3, DOT2 rice gravity		2.441
Target lab-molded density, %		96.0

The mix was produced in Lorena, Texas, and hauled about 65 mi to the jobsite in tarped belly dump and flow-boy trucks. On the jobsite, belly dump transports windrowed the entire transport, and flow-boy transports placed the entire transport into multiple small piles along the pavement surface until the transport was emptied. The mix was then picked up with an E1650 material transfer device and placed into the AP1055F paver. The paver produced a mat 13 ft wide. Figure 61 shows the paving operation.

Figure 61. Paving Operation on SH 6.

After laydown, a CB64B roller performed breakdown rolling, typically applying five passes per side plus one central pass to complete the pattern. There was no intermediate rolling, and a second CB64B roller performed finish rolling without vibration. On the testing day, paving started at about 9:00 p.m. The demonstration section ended at about 12:00 a.m. Ambient air temperatures that day ranged from 60 to 70°F, and winds were approximately 10 mph from the east/southeast. Figure 62 and Figure 63 show the air temperature and wind speeds, respectively, as recorded at the Hearne Municipal Airport throughout the day.

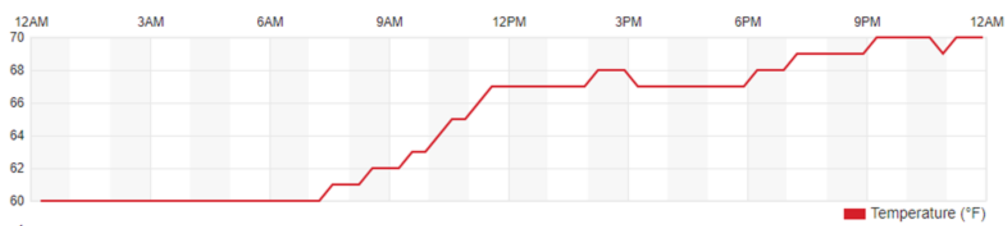


Figure 62. Air Temperature during SH 6 Paving.

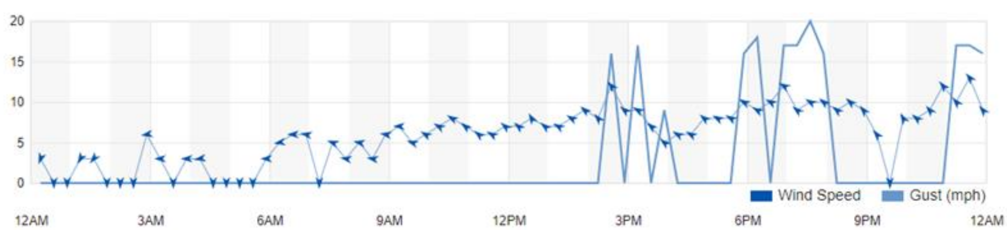


Figure 63. Wind Speeds during SH 6 Paving.

5.4.2. SH 6 Thermal Profile Results

The demonstration section covered about 1100 ft of paving, and the contractor set the thermal profiling system to start at station 1, which was not the actual project station. Figure 64 shows the thermal plot, which shows cyclical patterns of placement temperatures.

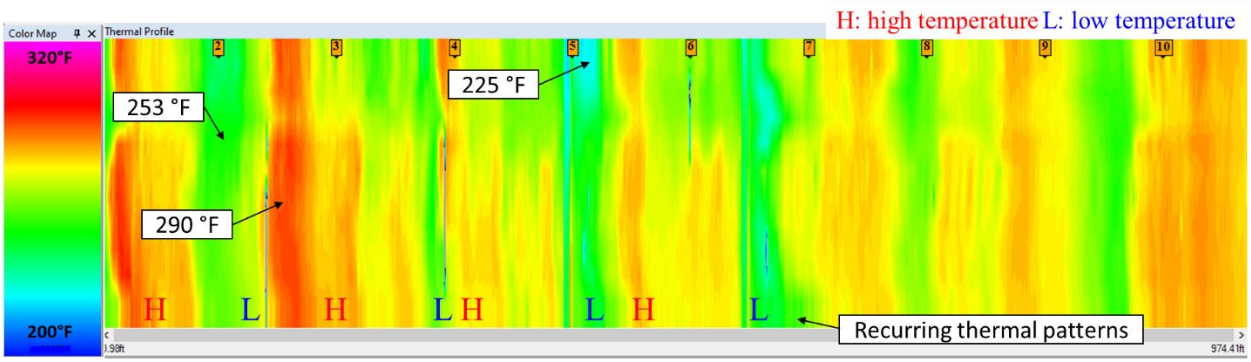


Figure 64. SH 6 Thermal Profile.

Table 28 shows the thermal profile summary results, and Figure 65 shows the distribution of measured placement temperatures. These data reveal that in this project, despite using a material transfer device, over 40 percent of profiles exhibited moderate thermal segregation, and over 40 percent exhibited severe thermal segregation. The results also show that measured placement temperatures behind the screed ranged from about 230 to 290°F.

Table 28. Thermal Profile Summary Results from SH 6.

Number of Profiles	Moderate 25°F < Differential ≤ 50°F		Severe Differential > 50°F	
	Number	Percent	Number	Percent
7	3	43	3	43

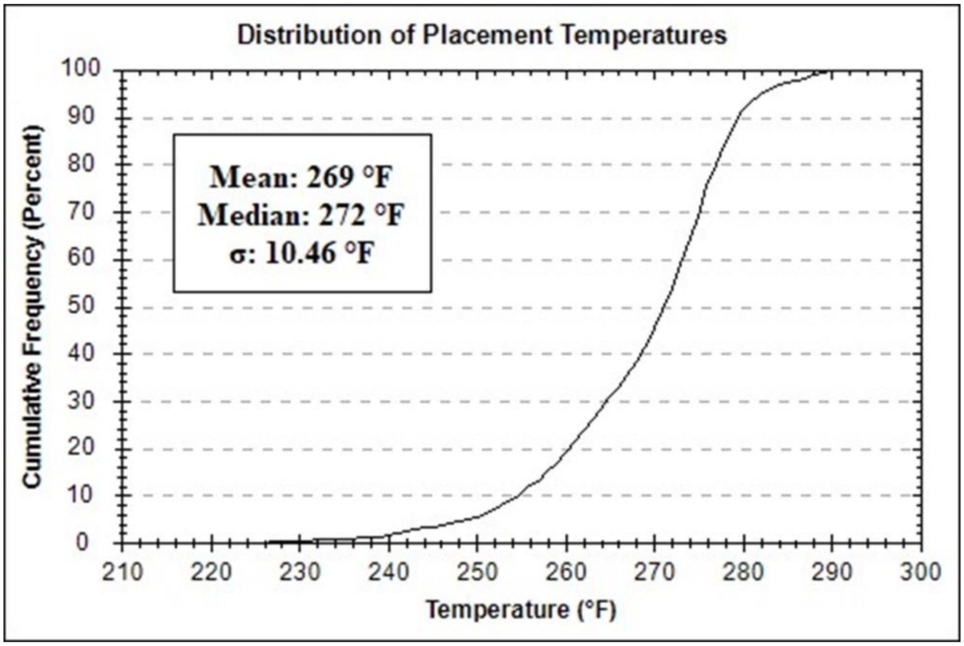


Figure 65. Distribution of Placement Temperatures on SH 6.

5.4.3. SH 6 Focused Testing Results

For the focused testing used to evaluate the meaning of thermal segregation on the newly compacted mat, researchers further evaluated the section through additional field testing, coring, and lab testing. Table 29 presents the individual thermal profile results.

Table 29. SH 6 Thermal Profile Results from Demonstration Section.

Profile Number	Begin STA	End STA	Max. Temp (°F)	Min. Temp (°F)	Temp. Differential (°F)
1	1.01	2.51	291.2	239.2	52.0
2	2.52	4.00	290.7	247.3	43.4
3	4.01	5.51	278.8	226.2	52.6
4	5.52	7.00	279.7	229.5	50.2
5	7.01	8.50	279.3	252.0	27.4
6	8.51	10.01	280.9	251.4	29.5
7	10.02	10.74	284.4	274.3	10.1

Based on the results shown in Table 29, researchers identified nine core locations from the thermal profiles to represent the temperature differentials observed. Figure 66 shows the thermal plot along with these selected locations. Researchers collected a GPR reading at each core location before extracting the core.

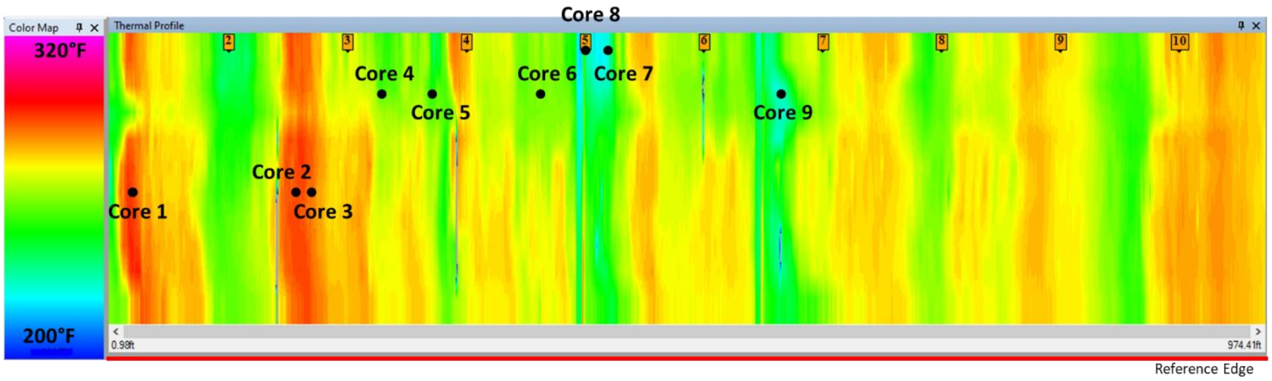


Figure 66. SH 6 Thermal Plot with Core Locations.

Researchers returned the cores to the lab, where they trimmed and then measured the bulk specific gravity of each core in accordance with Tex-207-F. They calculated the percent AVs of each core using the Gr of 2.441 based on laboratory testing. Table 30 shows the results from the cores, which contained a range of measured AV contents from 5.2 to 8.5 percent. A scan of the data in Table 30 suggests that, in general, the lower AV contents correspond with locations of the higher measured temperature, and the higher AV contents correspond with locations of the lower measured temperature.

Table 30. Core Results from SH 6.

Core	Distance (ft from starting point)	Offset (ft)	Temperature at Placement (°F)	Field Dielectric from GPR	Lab-Measured AVs (%)
1	16.7	5	292	5.235	5.2
2	152.6	5	289	5.212	7.0
3	165.4	5	291	5.287	6.3
4	252	7.5	266	4.965	6.6
5	323.8	7.5	266	4.95	6.5
6	375	7.5	260	4.857	7.6
7	409.4	11	219	4.639	8.4
8	421.5	11	226	4.806	8.5
9	564.9	7.5	229	4.881	5.6

5.4.3.1. Interpretation of Thermal Segregation

Figure 67 shows the laboratory-measured AV content versus placement temperature. A specimen can be damaged during construction, coring, or storage, leading to unusual laboratory test values. To account for this possibility, researchers decided to exclude Core 9 (represented by the blue data point in Figure 67) from the analysis since it was identified as a clear outlier. The decision to exclude Core 9 was made due to observed asphalt binder surplus staining on the surface. With this exclusion, the correlation coefficient between temperature and AV content was found to be 0.76, indicating a strong relationship between these two variables. The slope of the line in

Figure 67 shows that a temperature differential of over 100°F would be necessary to exceed the allowable density range of 6 pcf for this mix. This finding is based on a 3.9 percentage point change in AV equating to a 6 pcf change in density for the reported rice gravity of this mix. This observation is considered highly unusual, especially considering that the PG 76-22 binder was used in this mix.

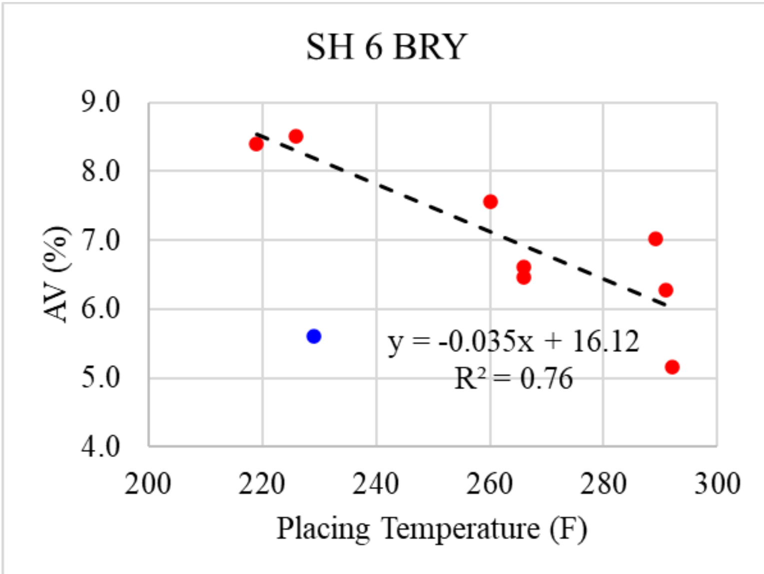


Figure 67. Results from SH 6 by Field Core.

5.4.3.2. Interpretation of GPR

While the thermal profile tests the placed, uncompacted mat, the GPR tests are conducted after all rolling is completed. In Figure 68, the core AV contents are compared to the field-measured surface DC obtained from GPR using a linear relationship. This linear relationship, which excluded Core 9 (the blue data point in Figure 68) due to its identification as a suspected outlier, produced the best R^2 value with the available data. The figure illustrates that increasing the AVs led to a decrease in the DC, indicating a good correlation between the GPR measurements and the AV content.

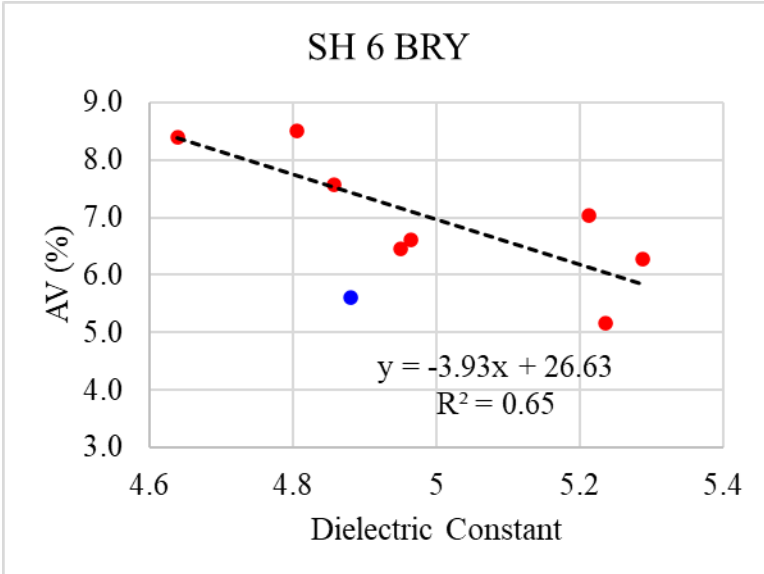


Figure 68. GPR Results from SH 6 Cores.

5.4.4. Conclusions from SMA-D on SH 6

The thermal profile summary results obtained from this demonstration section indicate a significant amount of moderate and severe thermal segregation, as evidenced by the temperature differentials. The measured placement temperatures ranged from 230 to 290°F. The cores taken from the field exhibited varying AV contents, with lower AV contents showing a correlation with higher measured temperatures. The field core test results illustrate a correlation between lab-measured AVs and temperature at the time of placement, except for clear outliers. Additionally, the results demonstrate a strong correlation between core AV contents and the field-measured surface DC using GPR. This correlation highlights the potential of GPR as a reliable method for assessing the quality and uniformity of the in-place mat density.

5.5. SP-C ON SH 105

Coordinating with the TxDOT Bryan District, researchers conducted a thermal profile demonstration on SH 105 to evaluate the meaning of thermal segregation on the newly placed and compacted mat. This testing included selecting spot test locations to represent normal and thermally segregated points over the HMA mat, conducting an NDT survey of the mat area with a multichannel GPR system, and then cutting and collecting 6-in. diameter cores directly over each selected spot location for lab testing.

In the field, this project exhibited minimal thermal segregation. In the lab, researchers measured the AV content of each core. The thermal profile results, although limited, showed that locations representing a region of higher placement temperature had higher AVs, suggesting a lack of correlation between temperature and density from this demonstration project. The NDT survey results showed a strong correlation between AVs and the GPR data, illustrating the potential of the GPR as a quality and uniformity check on the completed mat.

5.5.1. Project Location, Mix Type, and Paving Operations

This demonstration project was located on SH 105 near Navasota, Texas, for CSJ 315-04. Records indicate the work was performed under a routine maintenance contract. Researchers performed testing on the project on November 29, 2022. This project placed a 2-in. lift of SS 3077 SP- C mix. Mix design information was not available to the research team.

The mix was produced in Bryan, Texas, and hauled about 35 mi to the jobsite in tarped belly dump trucks. On site, the trucks windrowed the entire transport, from which an SB2500D transferred the mix into an AP1055E paver. The paver laid a mat 12 ft wide. Figure 69 shows the paving operation.

Figure 69. Paving Operation on SH 105.

After laydown, a CB64 roller performed primary breakdown rolling, typically applying two roller passes approximately 150 ft from the paver. A PS 360C pneumatic and CB64 roller performed intermediate and finish rolling, respectively. Paving operations began at approximately 11:00 p.m. On the night of testing, ambient air temperatures began around 66°F and lowered to 44°F after a cold front passed at approximately 1:00 a.m., with winds of approximately 15 mph from the north with gusts up to 25+ mph. Figure 70 and Figure 71 show temperatures and windspeeds from Easterwood Airport.

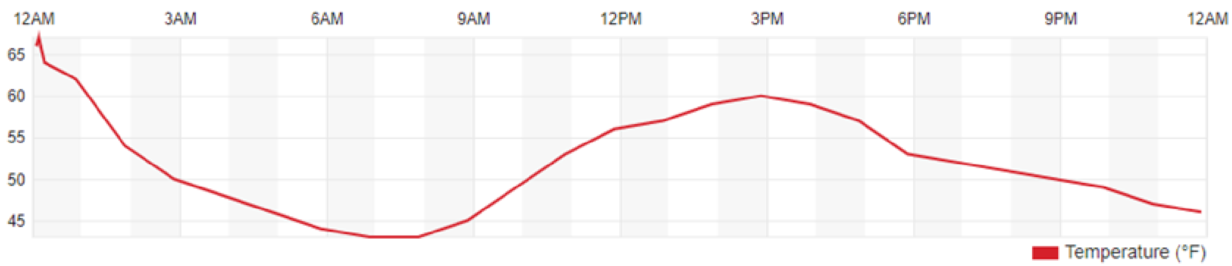


Figure 70. Air Temperature during SH 105 Paving.

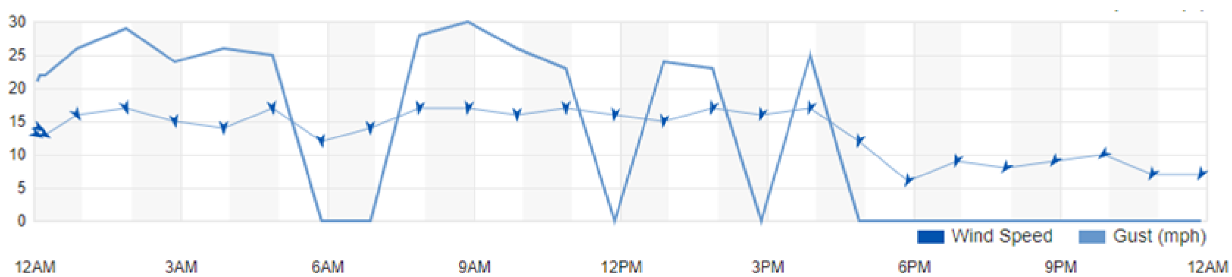


Figure 71. Wind Speeds during SH 105 Paving.

5.5.2. SH 105 Thermal Profile Results

Thermal profile data were collected from STA 771+00 to STA 766+83 for this demonstration project. At that point, the plant broke down, and operations were suspended. Figure 72 shows the thermal plot and illustrates minimal thermal variations.

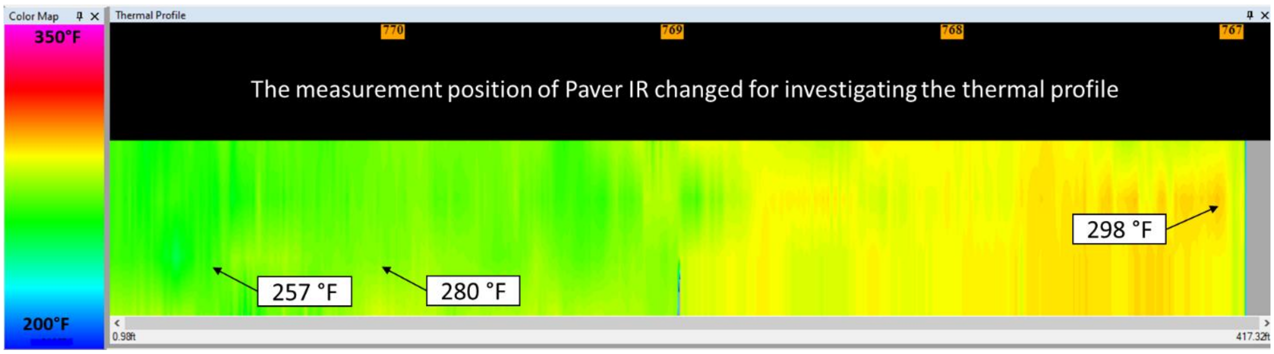


Figure 72. SH 105 Thermal Profile.

Table 31 shows the thermal profile summary results generated from the automated analysis in accordance with Tex-244-F, and Figure 73 shows the distribution of measured placement temperatures. These data confirm that the level of thermal segregation observed would be considered minimal, with 20 percent moderate thermal segregation, no severe thermal segregation, and measured placement temperatures behind the screed from about 255 to 295°F. With the small number of profiles obtained before the plant broke down, it is uncertain whether these results would represent the actual full production operation.

Table 31. Thermal Profile Summary Results from SH 105.

Number of Profiles	Moderate 25°F < Differential ≤ 50°F		Severe Differential > 50°F	
	Number	Percent	Number	Percent
3	1	33	0	0

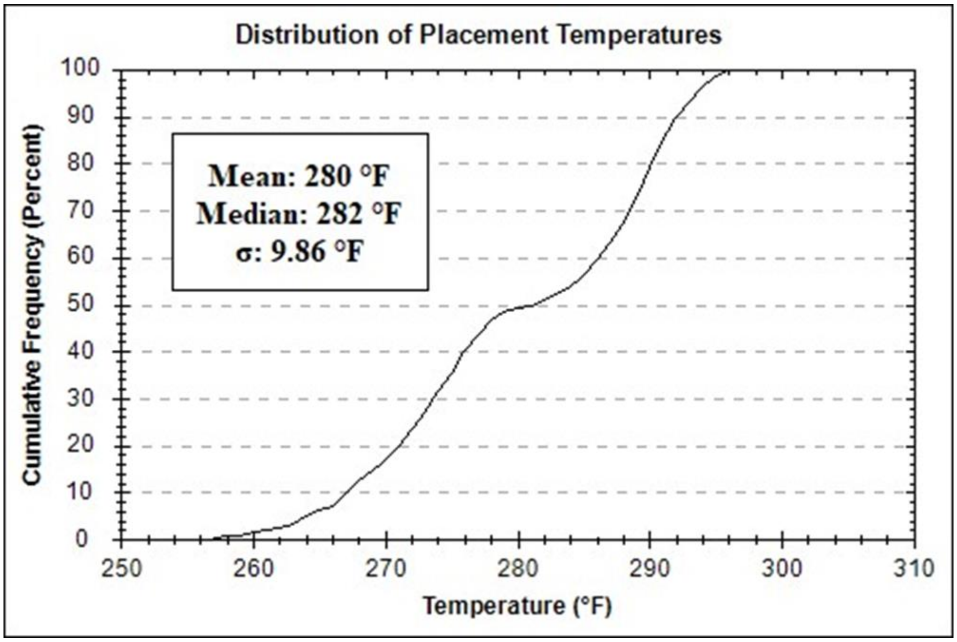


Figure 73. Distribution of Placement Temperatures on SH 105.

5.5.3. SH 105 Focused Testing Results

For the focused testing used to evaluate the meaning of thermal segregation on the newly compacted mat, researchers further evaluated the section through additional field testing, coring, and lab testing. Table 32 presents the individual thermal profile results and shows that even the profiles with moderate thermal segregation had temperature differentials barely exceeding the 25°F threshold. Overall, the data in Table 32 suggest a reasonably uniform placement operation.

Table 32. SH 105 Thermal Profile Results from Demonstration Section.

Profile Number	Begin STA	End STA	Max. Temp (°F)	Min. Temp (°F)	Temp. Differential (°F)
1	770.99	769.49	279.7	257.0	22.7
2	769.48	768.00	293.0	266.4	26.6
3	767.99	766.83	296.8	283.1	13.7

Based on the results shown in Table 32, researchers identified six core locations from the thermal profiles to represent the temperature differentials observed. Figure 74 shows the thermal plot along with these selected locations. Researchers collected a GPR reading at each core location before extracting the core. In this project, the thermal scanner was not properly aligned at the start of the pull, which is why the top portion of Figure 74 includes data off the mat.

Figure 74. SH 105 Thermal Plot with Core Locations.

Researchers returned the cores to the lab, where they trimmed and then measured the bulk specific gravity of each core in accordance with Tex-207-F. They calculated the percent AVs of each core using the rice gravity of 2.733 based on laboratory testing. Table 33 shows the results from the cores, which contained a range of measured AV contents from 5.7 to 10.3 percent. Table 33 does not present temperatures because although temperature estimates could be identified, the misalignment of the thermal scanner resulted in significant uncertainty in determining the actual spot placement temperature.

Table 33. Core Results from SH 105.

Core	STA	Offset (ft)	Field Dielectric from GPR	Lab-Measured AVs (%)
1	770.79	3	4.973	8.2
2	770.55	2	5.058	5.7
3	770.46	3	4.991	6.4
4	770.37	3	5.129	6.1
5	767.43	6	4.566	8.4
6	767.06	6	4.377	10.3

5.5.3.1. Interpretation of Thermal Segregation

The temperature at the core location could not be precisely defined because the thermal scanner was not correctly aligned at the start of the pull. Based on data shown in Figure 74 and Table 33, Cores 5 and 6 were obtained from areas of the mat that were expected to have higher placement temperatures. However, these cores exhibited the highest measured AVs among all the collected cores. Consequently, the data suggested a poor correlation between the measured temperature at the time of placement and lab-measured AV contents.

5.5.3.2. Interpretation of GPR

Figure 75 presents the core AV contents versus the field-measured surface DC from GPR. Figure 75 shows a strong correlation, illustrating the viability of GPR as a potential final quality and uniformity check on the in-place mat density. With the correlation in Figure 75, the GPR data can be used to estimate density over the tested mat area.

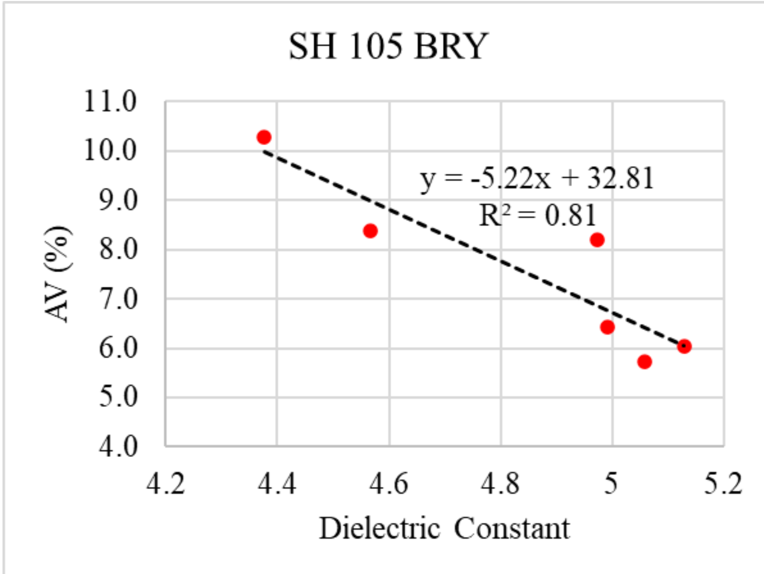


Figure 75. GPR Results from SH 105 Cores.

5.5.4. Conclusions from SP-C on SH 105

The thermal profile data collected for the demonstration project showed minimal thermal segregation, with measured placement temperatures ranging from 250 to 300°F. However, due to the limited number of profiles obtained before the plant broke down, it is uncertain whether these results would represent the actual full production operation. Nevertheless, the data suggest a reasonably uniform placement operation overall.

The thermal scanner was not correctly aligned at the start of the pull. As a result, a poor correlation was observed between the temperature at the time of placement and lab-measured AV contents. This discrepancy may be attributed to the misalignment of the thermal profiler, which affected the ability to precisely define the core locations' placement temperature. Despite the limitations in data availability, the results of this project indicated that the zone with higher placement temperatures exhibited poorer density. This zone was located closer to the area where paving had to be stopped due to the plant breakdown. It is possible that the rolling pattern and time to rolling were altered at these locations, leading to increased AVs and reduced density.

GPR testing showed a strong correlation between core AV contents and the field-measured surface DC, indicating the viability of GPR as a potential final quality and uniformity check on the in-place mat density.

5.6. SUMMARY OF CONCLUSIONS FROM DEMONSTRATION PROJECTS

The demonstration projects in general showed that when operations remain consistent, AVs in the completed mat increase as placement temperature decreases. However, when field operations are erratic (such as rolling patterns changing, plants breaking down, or rollers having difficulty keeping up with paving), the correlation between temperature and density worsens or even becomes nonexistent. These findings highlight that the thermal profile provides only one piece of information at one process stage. Other components of the paving process can influence the overall density and uniformity.

Key findings from the demonstration projects include the following:

- For steady operations, it was observed that as the placement temperature decreased, the AVs in the completed mat increased. Considering TxDOT's allowable range of maximum to minimum density, the current threshold of a 25°F temperature differential appears reasonable for such situations.
- Other factors, such as changes in rolling patterns, have an impact on the results as well. The temperature at the time of placement and its differential represent just one metric within a multistep process.
- In-place AVs of around 10 percent may result from thermal segregation's impact.
- Even with the use of a compaction aid and a material transfer vehicle, the mix's final in-place density is still sensitive to the mix's absolute temperature at the time of placement.
- GPR can provide a valuable tool for evaluating the final, in-place mat density after the completion of all rolling operations. While beyond the scope of this research project, TxDOT should further consider how this GPR tool may apply to evaluating and assuring the quality and uniformity of paving projects.
- During the field performance review conducted approximately 1.5 to 2 years after construction, there was no evidence of distress that could be directly correlated with the locations of thermal anomalies documented at the time of construction. While thermal segregation is generally expected to lead to reduced density in certain areas, this limited review of field performance suggests that the mixes on these projects are not experiencing significant premature failure due to thermal segregation under actual site conditions.

CHAPTER 6. LABORATORY TEST PROGRAM AND TXME ANALYSIS FROM DEMONSTRATION PROJECTS

This chapter presents results from a laboratory program simulating the expected impacts of thermal segregation on mixture density and how the changing density influences performance-related properties. Researchers obtained loose mixes from multiple projects and used them to fabricate cores representing different levels of thermal segregation, including none, moderate, and severe. Then, they performed standard and performance-related laboratory testing on the mixtures to evaluate the influence of thermal segregation on currently specified and performance-related mixture properties. Finally, they used the performance-related tests, along with the Texas Mechanistic-Empirical Flexible Pavement Design and Analysis System (TxME), to analyze the potential impacts of thermal segregation-induced AVs on performance.

6.1. LABORATORY TEST PROGRAM

Researchers selected three different (low, medium, and high) target AV contents for each material to represent the effect of temperature on compaction at the time of placement. Table 34 presents the target AV contents for the lab-compacted specimens. Researchers identified these targets by reviewing the actual range of AVs with different placement temperatures from the demonstration projects presented in Chapter 5.

Table 34. Target AV Contents for Lab Testing Program.

Roadway	District	Mix Type	Target AV Content for Lab Test Program		
			Low	Medium	High
US 69	LFK	SP-C	5%	7%	10–11%
US 287	CHS	DG-D	4%	7%	10%
US 183	BWD	SP-D	5%	7%	10–11%
SH 6	BRY	SMA-D	4.5%	6.5%	8–9%
SH 105	BRY	SP-C	4.5%	7%	9–10%

Table 35 presents details on the lab test program, including specific current mix design tests and performance-related tests.

Table 35. Tests for Laboratory Program.

Test/Activity	Method	Test Description
Rice Gravity	Tex-227-F	Determines the theoretical maximum specific gravity (commonly referred to as “rice gravity”).
Asphalt Content	Tex-210-F Part V	Determines the percentage of asphalt in a paving mixture based on the weight of an asphalt and aggregate mixture.
Sieve Analysis	Tex-200-F	Determines the particle size distribution of aggregate samples using standard U.S. sieves with square openings.
Mold Trial Samples	Tex-241-F	Compacts cylindrical specimens of HMA using the SP gyratory compactor. Prepares specimens for determining the mechanical and volumetric properties of HMA.
Bulk Specific Gravity of Trial Samples	Tex-207-F	Determines the bulk specific gravity of compacted bituminous mixture specimens.
Hamburg	Tex-242-F	Determines the premature failure susceptibility of bituminous mixtures due to weakness in the aggregate structure, inadequate binder stiffness, moisture damage, and other factors, including inadequate adhesion between the asphalt binder and aggregate.
Indirect Tension Asphalt Cracking Test (IDEAL-CT)	Tex-250-F	Determines the cracking tolerance index (CT Index) of compacted bituminous mixtures.
Permeability	ASTM D 5084	Measures the permeability of the compacted asphalt mixture.
Dynamic Modulus and Flow Number (FN)	AASHTO T378	Measures the asphalt mixtures’ dynamic modulus FN using the asphalt mixture performance tester.
Overlay Test (OT)	Tex-248-F	Determines the susceptibility of bituminous mixtures to fatigue or reflective cracking.

6.2. RICE GRAVITY, ASPHALT CONTENT, AND SIEVE ANALYSIS RESULTS

Researchers used Tex-227-F to determine the theoretical maximum specific gravity of the bituminous mixtures, as shown in Table 36. Researchers used Tex-210-F part V to determine the percentage of asphalt, also as shown in Table 36.

Table 36. Rice Specific Gravity and Asphalt Content Results.

Roadway	US 69	US 287	US 183	SH 6	SH 105
Mix Type	SP-C	DG-D	SP-D	SMA-D	SP-C
Rice Specific Gravity	2.469	2.447	2.410	2.441	2.751
% AC	4.3%	5.0%	5.6%	5.0%	4.6%

Table 37 presents the particle size distribution of aggregate samples for US 69, US 287, US 183, SH 6, and SH 105 materials using standard U.S. sieves with square openings determined in accordance with Tex-200-F.

Table 37. Sieve Analysis Results.

Mix Type	US 69	US 287	US 183	SH 6	SH 105
	SP-C % Passing	DG-D % Passing	SP-D % Passing	SMA-D % Passing	SP-C % Passing
¾"	100.0	100	100.0	99.5	100.0
½"	94.9	99.8	99.5	85.6	99.1
⅜"	84.2	93.2	90.0	62.3	82.2
#4	47.8	61.5	58.1	26.9	41.6
#8	29.7	37.4	38.3	17.9	28.1
#16	23.3	N/A	26.8	14.7	21.9
#30	20.00	24.1	20.4	13.0	17.9
#50	16.5	15.1	15.9	11.3	13.2
#200	6.5	7.0	5.3	8.4	5.3

6.3. FABRICATION OF TRIAL SAMPLES

Researchers fabricated trial samples by compacting cylindrical specimens (Figure 76) using the SP gyratory compactor. The specimens for determining the mechanical and volumetric properties of HMA were prepared, and the density of test specimens during their preparation was monitored. Through several attempts, researchers developed compaction parameters for each mix to attain the target AV contents shown in Table 34.

Figure 76. Example Trial Samples.

6.4. HAMBURG RESULTS

The Hamburg wheel tracking test (Tex-242-F) determines the premature failure susceptibility of bituminous mixtures due to weakness in the aggregate structure, inadequate binder stiffness, moisture damage, and other factors, including inadequate adhesion between the asphalt binder and aggregate. Researchers followed the preparation guidelines outlined in Tex-241-F for each Hamburg test specimen. However, a modification was made on the density of the specimens. The specimens were intentionally prepared to have low, medium, and high AV contents, as specified in Table 34. Researchers performed the Hamburg test in duplicate for each mix/AV combination. Figure 77 shows example specimens after this wheel track test.

Figure 77. Example Hamburg Test (Tex-242-F).

Results from the Hamburg test on mixes from the US 69, US 287, US 183, SH 6, and SH 105 projects show that increasing AV content significantly increases the rut depth. In all three materials, the rut depth after 20,000 cycles significantly increased when the AVs changed from medium to high. The change in rut depth was not as pronounced when the AVs changed from low to medium. Table 38 shows the summary of the Hamburg test results for each mix/AV combination.

Table 38. Summary of Hamburg Test.

Roadway	Mix Type	AV Target	Actual AV	5000 Passes	10,000 Passes	15,000 Passes	20,000 Passes Rut Depth (mm)	Std. Deviation (mm)
US 69	SP-C	Low	4.55%	3.54	4.13	4.62	5.55	1.01
			4.55%	3.84	4.66	5.17	5.64	0.80
		Medium	6.45%	4.29	5.27	5.99	6.54	0.40
			6.60%	4.15	5.27	6.2	7.20	0.60
		High	9.40%	5.36	6.7	8.11	11.00	1.53
			9.30%	4.62	5.79	7.22	9.40	0.51
US 287	DG-D	Low	4.15%	2.26	2.61	2.83	3.04	0.75
			4.00%	2.12	2.52	2.77	2.97	0.34
		Medium	6.50%	2.93	3.55	4.04	4.53	0.52
			7.00%	3.2	3.76	4.13	4.42	0.47
		High	9.60%	4.05	5.04	5.77	6.39	0.56
			9.60%	4.46	5.42	6.38	7.66	0.21
US 183	SP-D	Low	5.15%	2.87	3.35	3.78	4.31	0.31
			5.05%	2.35	2.77	3.29	3.98	0.92
		Medium	6.65%	2.93	3.52	4.03	4.53	0.22
			6.80%	3.21	3.81	4.26	4.69	0.40
		High	9.80%	6.78	7.99	8.8	9.55	0.82
			9.20%	5.82	6.99	7.86	8.64	0.76
SH 6	SMA-D	Low	4.25%	2.95	3.38	3.58	3.72	0.60
			4.35%	3.24	3.86	4.15	4.38	1.14
		Medium	6.10%	3.35	4.14	4.64	5.02	0.55
			6.50%	3.08	3.59	3.88	4.12	0.38
		High	8.40%	5.4	6.28	6.93	7.44	1.14
			8.10%	5.99	7.01	7.74	8.18	1.63
SH 105	SP-C	Low	4.50%	2.76	3.32	3.7	4.02	0.60
			4.85%	2.79	3.26	3.53	3.74	0.38
		Medium	6.70%	3.66	4.22	4.54	4.78	0.75
			6.75%	4.25	5.13	5.49	5.76	1.30
		High	8.60%	7.41	8.59	9.19	9.75	1.59
			8.10%	6.96	8.14	8.99	9.47	1.59

The results also showed that high AV (9–10 percent void) specimens with the US 69 and US 287 mixes went beyond the stripping inflection point, as shown in Figure 78. These results further illustrate the detrimental impact of low density on expected pavement performance and show that not all mixes are impacted the same. Figure 78 shows that the US 183, SH 6, and SH 105 mixes never exceeded the stripping inflection point, even at the highest AV content. Another observation is that even though higher voids clearly produced more rutting these mixes passed the Hamburg test requirements even at the high AV content.

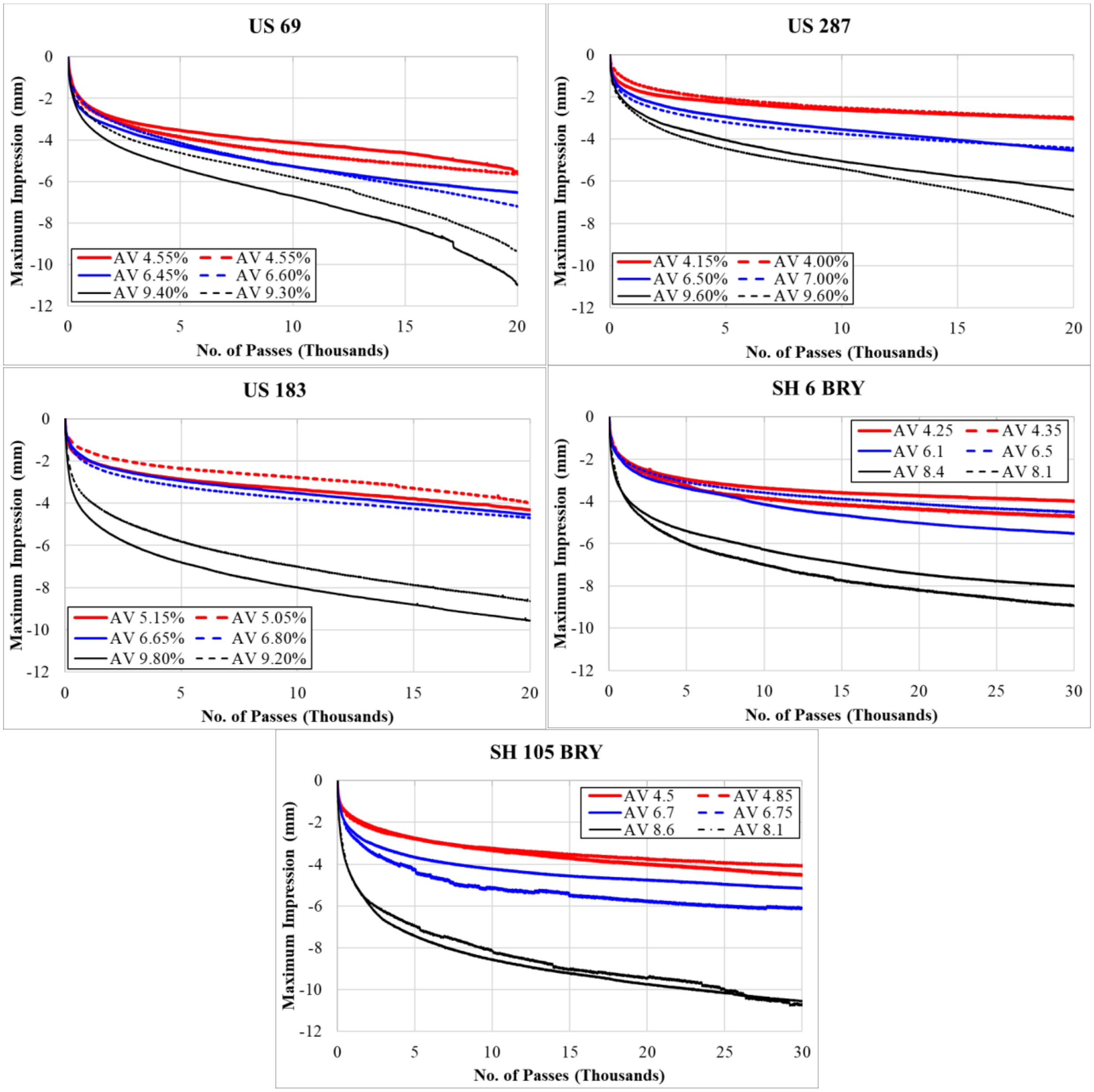


Figure 78. Hamburg Test Results.

6.5. IDEAL-CT RESULTS

The IDEAL-CT, Tex-250-F, determines the cracking tolerance index of compacted bituminous mixtures. Researchers prepared three laboratory specimens for each target AV on the mixes from US 69, US 287, US 183, SH 6, and SH 105. For lab-molded specimens, Tex-250-F requires a specimen diameter of 5.9 in. (150 mm) and a height of 2.4 in. (62 mm) ± 0.1 in. (2 mm), as well as an AV content of 7 ± 0.5 percent. Thus, the different AV contents used in this lab program represent a deviation from the underlying parameters in the development of the IDEAL-CT. Figure 79 shows the test in progress.

Figure 79. Example IDEAL-CT Test.

Researchers placed specimens in a temperature chamber of 77 ± 2°F (25 ± 1°C) before testing to ensure a consistent temperature. The load was applied at a controlled deformation rate of 2 in. per minute until the specimen completely fractured.

Figure 80 shows that increasing AVs decreased strength and fracture energy. The mix from US 183 and SH 105 exhibited comparably higher tensile strength and fracture energy than the other mixes.

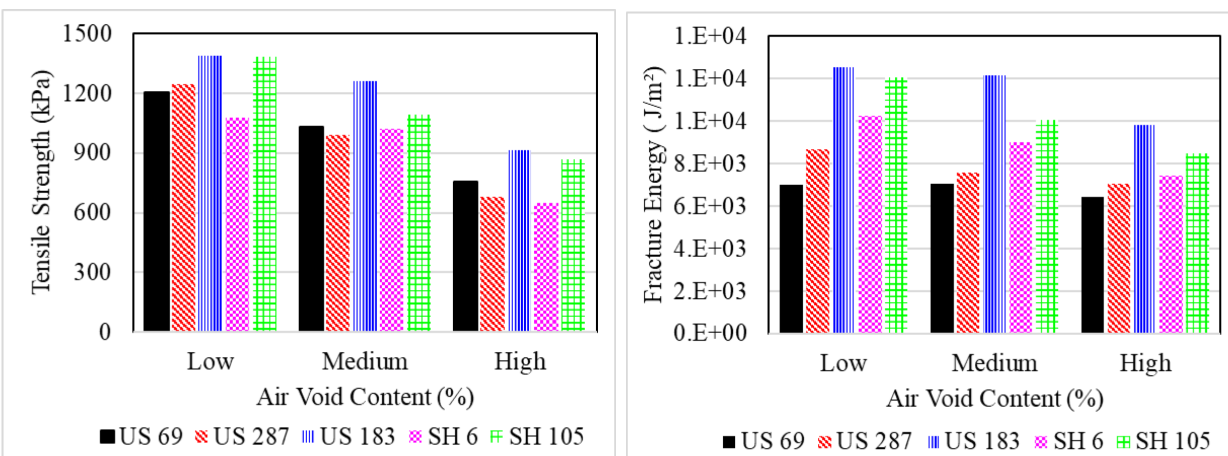


Figure 80. IDEAL-CT Test Results.

6.6. PERMEABILITY RESULTS

Permeability test methods (ASTM D5084) cover laboratory measurements of the hydraulic conductivity (also referred to as the coefficient of permeability) of water-saturated porous materials with a flexible wall permeameter. The hydraulic conductivity of porous materials generally decreases with an increasing amount of air in the pores of the material. The hydraulic conductivity, k, is found as follows:

$$k = \frac{\Delta Q \cdot L}{A \cdot \Delta h \cdot \Delta t} \tag{1}$$

where:
k = hydraulic conductivity, m/s.
ΔQ = quantity of flow for given time interval Δt, taken as the average of inflow and outflow, m^3.
L = length of specimen, m.
A = cross-sectional area of the specimen, m^2.
Δt = interval of time, *s*, over which the flow ΔQ occurs ($t_2 - t_1$).

Rather than fabricating specimens specifically for permeability testing, researchers conducted the permeability test using field cores from the demonstration projects. Figure 81 shows the test configuration applied to water-saturated porous materials containing virtually no air.

Figure 81. Permeability Test (ASTM D 5084).

Table 39 shows the results of the field permeability tests obtained from the US 69, US 287, US 183, SH 6, and SH 105 mixes. The samples selected for testing represented different target AV contents. The thickness of the cores tested varied from 1.2 in. to 2 in.

Table 39. Permeability Test Results.

Roadway	Mix Type	Core ID	AV	Average ΔQ (cm^3)	k (mm/s)
US 69	SP-C	#3	4.4%	10.66	6.1E-04
		#2	5.8%	10.98	5.4E-04
		#1	7.0%	11.61	7.1E-04
		#9	8.4%	11.61	6.7E-04
		#8	10.3%	12.33	7.0E-04
		#6	10.8%	12.22	8.0E-04
US 287	DG-D	#1	3.6%	0.83	6.7E-05
		#6	3.6%	0.22	1.7E-05
		#8	7.1%	11.98	7.8E-04
		#5	7.3%	1.58	1.1E-04
		#2	8.4%	11.69	6.1E-04
		#3	9.9%	12.22	6.9E-04
US 183	SP-D	#12	5.4%	5.51	3.7E-04
		#10	7.4%	2.69	1.7E-04
		#5	7.9%	3.12	2.0E-04
		#8	10.7%	10.73	6.2E-04
SH 6	SMA-D	#1	5.2%	3.05	2.5E-04
		#2	7.0%	9.08	7.6E-04
		#3	6.3%	5.34	4.3E-04
		#4	6.6%	3.41	3.0E-04
		#5	6.5%	0.18	1.4E-05
		#6	7.6%	8.80	7.0E-04
		#7	8.4%	11.63	1.0E-03
		#8	8.5%	12.10	9.7E-04
		#9	5.6%	2.77	2.3E-04
SH 105	SP-C	#1	8.2%	11.08	8.2E-04
		#2	5.7%	5.87	4.6E-04
		#3	6.4%	8.75	6.8E-04
		#4	6.1%	5.95	4.5E-04
		#5	8.4%	10.72	9.4E-04
		#6	10.3%	12.10	9.8E-04

Figure 82 illustrates that, as anticipated, the permeability increases as the AVs increase. However, a few samples deviated from this trend, which researchers attribute to potential irregularities in diameter and thickness caused by field coring constraints.

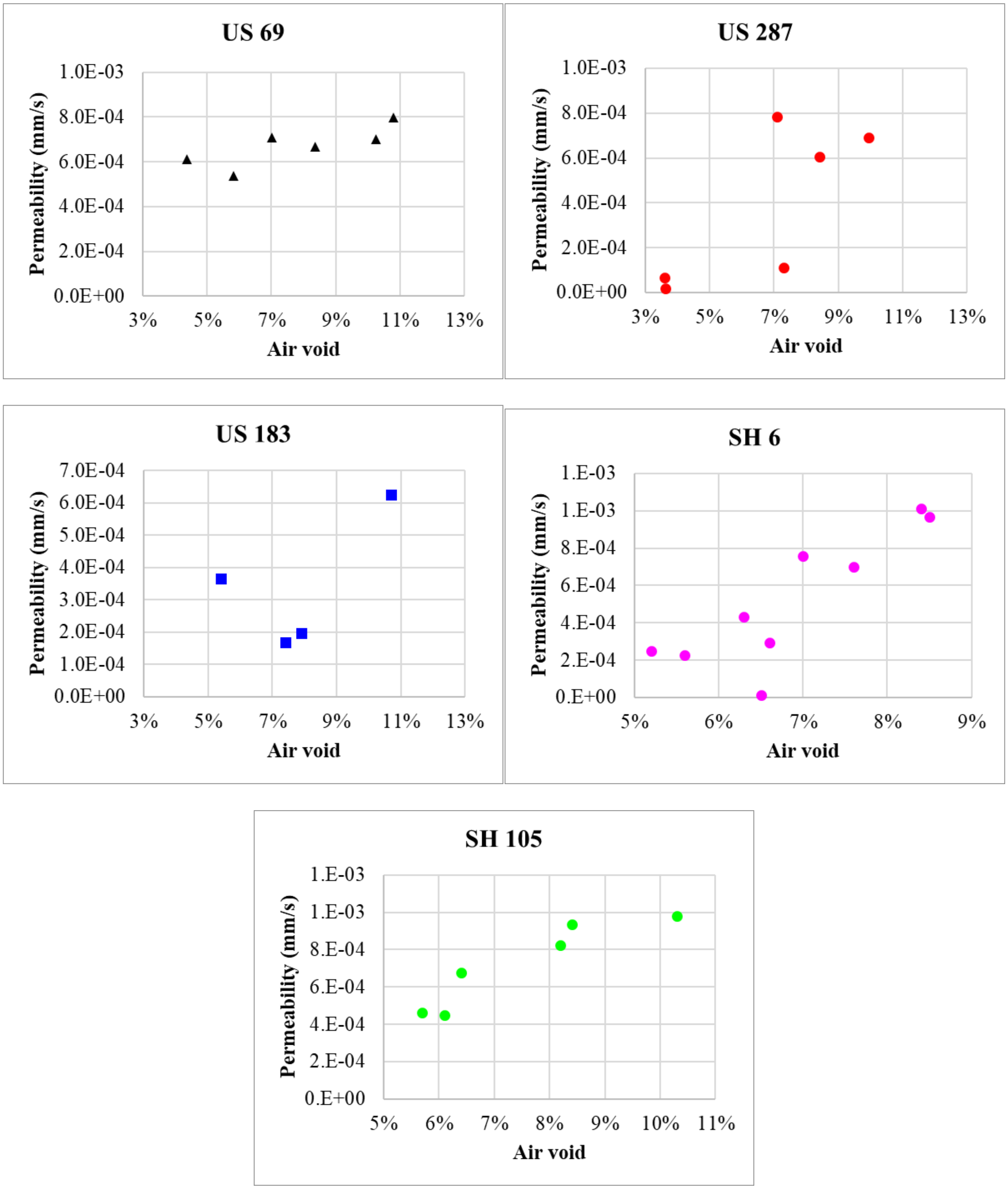


Figure 82. Permeability Test Results from Roadway Cores.

6.7. DYNAMIC MODULUS

The dynamic modulus test can be performed according to AASHTO TP 62: Standard Method of Test for Determining the Dynamic Modulus of Hot Mix Asphalt (HMA) or AASHTO TP 79: Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt

Mixtures Using the Asphalt Mixture Performance Tester (AMPT). The sample size is 4 in. in diameter and 6 in. in height. The master curve and shift factors are developed using the fitted function shown in Figure 83.

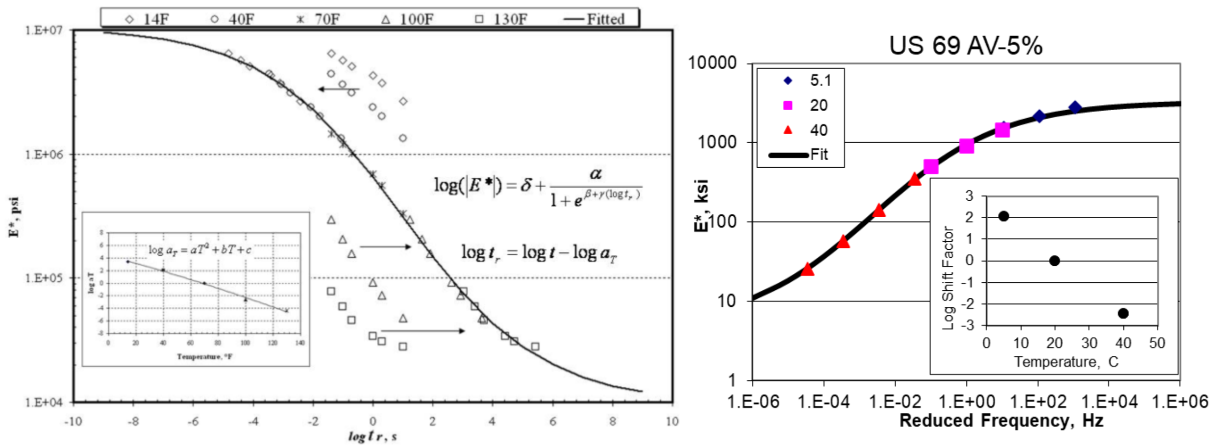


Figure 83. Schematic of a |E*| Master Curve and Shift Factors (Left) with an Example from US 69 (Right).

Table 40 through Table 42 present the dynamic modulus values obtained through the master curve and shift factors approach for each mix and AV content. These dynamic modulus inputs are determined using the National Cooperative Highway Research Program Mastersolver Version 2.2 workbook, which is used in conjunction with the Simple Performance Test System to develop dynamic modulus master curves (*33*).

Table 40. US 183, Level 1 Dynamic Modulus Input Values (ksi).

AV	Temperature (F) \ Hz	25	10	5	1	0.5	0.1
5%	14	3022	2975	2931	2798	2723	2504
	40	2623	2487	2368	2036	1872	1456
	70	1630	1386	1202	802	653	378
	100	569	416	323	174	132	73
	130	133	94	73	43	35	24
7%	14	2880	2824	2773	2622	2539	2300
	40	2439	2294	2169	1831	1667	1268
	70	1451	1221	1050	690	559	323
	100	497	363	282	153	118	66
	130	121	86	67	40	33	22
10%	14	2585	2514	2451	2273	2180	1927
	40	2056	1903	1776	1453	1306	966
	70	1097	908	772	499	403	234
	100	348	255	199	110	85	48
	130	85	61	48	29	24	16

Table 41. US 287, Level 1 Dynamic Modulus Input Values (ksi).

AV	Temperature (F) \ Hz	25	10	5	1	0.5	0.1
4%	14	2851	2764	2689	2474	2363	2064
	40	2220	2040	1892	1521	1355	978
	70	1126	918	772	484	386	218
	100	332	239	184	99	76	42
	130	76	54	42	25	20	14
7%	14	2732	2645	2570	2357	2247	1953
	40	2092	1914	1769	1408	1248	889
	70	1013	818	682	421	333	185
	100	279	199	153	82	63	35
	130	61	44	34	20	17	11
10%	14	2427	2328	2243	2012	1898	1604
	40	1716	1540	1402	1075	938	646
	70	719	568	466	279	219	121
	100	175	124	95	51	40	22
	130	37	27	21	13	11	7

Table 42. US 69, Level 1 Dynamic Modulus Input Values (ksi).

AV	Temperature (F) \ Hz	25	10	5	1	0.5	0.1
5%	14	3142	3096	3054	2930	2863	2668
	40	2720	2591	2479	2170	2018	1629
	70	1686	1453	1276	884	733	444
	100	575	425	333	180	137	72
	130	120	83	64	35	28	18
7%	14	2942	2887	2837	2693	2616	2398
	40	2477	2338	2220	1905	1754	1380
	70	1470	1253	1091	742	611	365
	100	497	367	287	156	118	63
	130	109	76	58	32	25	16
10%	14	2684	2626	2575	2430	2355	2148
	40	2174	2039	1927	1636	1501	1175
	70	1179	995	860	580	477	287
	100	350	258	201	110	84	45
	130	69	48	37	21	16	10

6.8. FLOW NUMBER RESULTS

The FN test is a static uniaxial creep test in which an HMA cylinder is axially loaded, and the total sample compliance versus loading time is measured. The FN test protocol was developed and introduced as a simple performance test to evaluate the rutting susceptibility of asphalt mixtures (*34*). Researchers conducted the FN test using a repeated compressive Haversine loading (1 cycle with 0.1 s loading time and 0.9 s resting time) to measure the vertical accumulated permanent strains as a function of loading cycles.

Researchers followed the guidelines specified in AASHTO T378-17 by using a deviator stress of 600 kPa and a contact stress of 30 kPa. The test was set to terminate at either 10,000 loading cycles or an accumulated 100,000 microstrains, whichever occurred first. For selecting the test temperature, researchers referred to the High Adjusted PG Temperature from LTPP Bind Version 3.1 and chose the climate data from the weather station nearest to the project location. As a result, test temperatures of 154.76, 155.84, and 154.4°F were assigned to the mixes from US 69, US 287, and US 183, respectively. Figure 84 shows the FN test in progress and examples of tested specimens after completion.

Figure 84. FN Test (Left) and Specimens after Testing (Right).

Table 43 presents the FN results obtained from the three different mixes at various AV levels. Table 43 shows both the FN (cycles) and FN index. The data show that FN decreased as AV increased. For reference, the FN from the tested specimens can be compared with the minimum criteria provided in Table 44 (*35*).

Both the FN and FN index parameters indicate that the US 183 mix has the lowest susceptibility to rutting, and the mix from US 69 has the highest FN change according to the increments of AV. These observations agree well with the results observed from the Hamburg test result (Figure 78), which showed the US 183 mix did not pass the stripping inflection point, while the mix from US 69 at the high AVs passed the stripping inflection point at the lowest number of cycles.

Table 43. Summary of FN Test Result.

ID	AV	FN (cycle)	εp(F)=accumulated permanent strain at the onset of tertiary flow	FN index (microstrain/cycle)
US 69	4.7%	135	34,663	256.8
	4.5%	140	33,606	240.0
	6.7%	57	37,287	654.2
	7.0%	48	36,431	759.0
	10.5%	11	35,081	3189.2
	9.6%	18	39,019	2167.7
US 287	4.9%	58	30,392	524.0
	4.7%	62	27,832	448.9
	6.7%	29	31,133	1073.6
	6.6%	20	31,257	1562.9
	9.6%	5	21,697	4339.4
	9.4%	7	32,559	4651.3
US 183	4.7%	182	50,153	275.6
	4.5%	220	45,499	206.8
	6.1%	153	51,687	337.8
	6.5%	138	54,220	392.9
	11.4%	42	67,331	1603.1
	11.1%	48	68,065	1418.0

Table 44. Minimum Average FN Requirements (*35*).

Traffic Level, million ESALs	HMA Minimum Average FN	WMA Minimum Average FN
< 3	—	—
3 to < 10	50	30
10 to < 30	190	105
≥ 30	740	415

Note: ESALs = Equivalent Single Axle Loads.
The minimum average flow numbers for traffic levels less than 3 million ESALs has not been defined.

6.9. OVERLAY TEST RESULTS

The OT (Tex-248-F) is widely used to evaluate bituminous mixtures' susceptibility to fatigue or reflective cracking. Three specimens were prepared and evaluated according to Tex-248-F, except that the specimens were prepared with varying target AV contents according to Table 34.

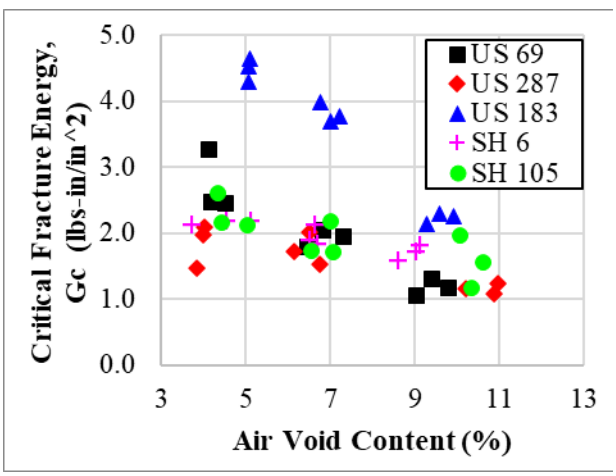
Table 45 shows that the test results vary depending on the AV contents and materials. Overall, the OT results show that maximum load at the first cycle, critical fracture energy, and crack progression rate decrease as the AV increases.

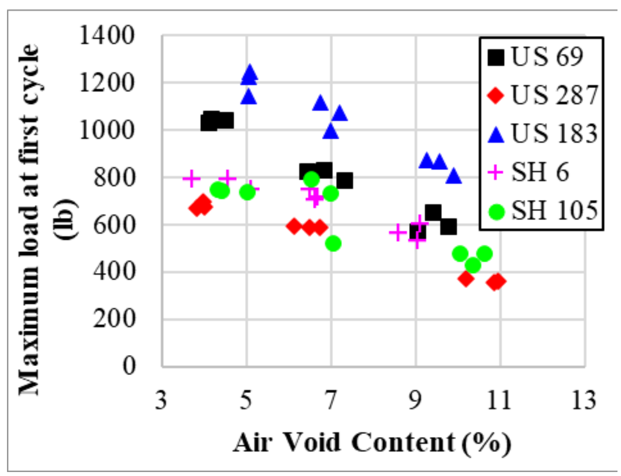
Table 45. OT Results.

ID	AV (%)	Cycle No. to Failure	Crack Progression Rate, |b|	Critical Fracture Energy, Gc (lb-in/in²)	Maximum Load at First Cycle (lb)	Displacement at Maximum Load (in.)	Last Load Reduction (%)	Area (lb-in)
US 69, SP-C	4.5	74	0.625	2.46	1039	0.0143	93.27	11.06
	4.2	19	0.843	2.46	1046	0.0145	94.34	11.07
	4.1	211	0.405	3.27	1028	0.0185	93.23	14.69
	7.3	59	0.568	1.94	784	0.0149	93.75	8.72
	6.5	22	0.920	1.78	823	0.0128	93.51	8.02
	6.8	46	0.655	2.04	831	0.0145	93.30	9.16
	9.8	18	0.988	1.16	590	0.0114	93.79	5.21
	9.1	30	0.816	1.06	570	0.0106	93.47	4.76
	9.4	16	1.035	1.30	651	0.0114	93.77	5.85
US 287, DG-D	3.8	31	0.735	1.47	672	0.0124	93.48	6.60
	4.0	118	0.515	1.98	696	0.0161	93.27	8.92
	4.0	131	0.450	2.10	673	0.0175	93.57	9.43
	6.1	198	0.412	1.72	596	0.0163	93.31	7.73
	6.7	112	0.487	1.52	589	0.0146	93.46	6.86
	6.5	732	0.365	2.02	589	0.0195	92.94	9.09
	10.2	410	0.363	1.15	371	0.0171	92.92	5.18
	11.0	180	0.437	1.24	359	0.0187	93.13	5.56
	10.9	263	0.396	1.08	355	0.0161	92.92	4.85
US 183, SP-D	5.1	252	0.388	4.29	1144	0.0219	93.43	19.30
	5.1	274	0.417	4.53	1223	0.0219	93.16	20.40
	5.1	261	0.457	4.65	1246	0.0217	93.06	20.92
	7.2	144	0.415	3.76	1071	0.0201	93.58	16.94
	7.0	396	0.381	3.69	997	0.0215	93.12	16.61
	6.8	164	0.469	3.98	1118	0.0209	93.15	17.91
	9.6	93	0.509	2.30	870	0.0155	93.38	10.34
	9.3	49	0.652	2.15	870	0.0145	93.23	9.66
	9.9	72	0.575	2.25	807	0.0159	93.33	10.12
SH 6, SMA-D	3.7	153	0.482	2.12	794	0.0158	93.23	9.56
	5.1	82	0.513	2.18	750	0.0169	93.35	9.83
	4.5	124	0.510	2.19	793	0.0161	92.85	9.85
	6.7	187	0.481	1.83	717	0.0147	93.03	8.24
	6.5	390	0.416	1.90	750	0.0150	93.00	8.57
	6.6	294	0.455	2.12	710	0.0173	93.01	9.56
	9.1	211	0.462	1.82	605	0.0173	93.07	8.17
	8.6	185	0.435	1.59	564	0.0165	93.16	7.15
	9.0	352	0.405	1.73	532	0.0183	92.93	7.78

ID	AV (%)	Cycle No. to Failure	Crack Progression Rate, |b|	Critical Fracture Energy, Gc (lb-in/in^2)	Maximum Load at First Cycle (lb)	Displacement at Maximum Load (in.)	Last Load Reduction (%)	Area (lb-in)
US 69, SP-C	4.4	116	0.491	2.15	742	0.0169	93.36	9.69
	4.3	272	0.410	2.60	748	0.0197	93.22	11.70
	5.0	70	0.540	2.13	738	0.0163	93.51	9.57
	7.1	254	0.429	1.70	522	0.0185	93.00	7.66
	7.0	152	0.456	2.18	731	0.0174	93.07	9.82
	6.5	64	0.628	1.73	789	0.0126	93.20	7.78
	10.6	614	0.400	1.57	476	0.0181	92.64	7.04
	10.3	124	0.471	1.17	428	0.0153	93.22	5.25
	10.1	275	0.398	1.96	475	0.0235	93.07	8.83

Figure 85 illustrates the relationship between the critical fracture energy, maximum load at the first cycle, and AV content. However, other results, such as the number of cycles to failure, displacement at maximum load, and last load reduction percentage, exhibit a poor trend with AV content. Researchers attribute this observation, at least in part, to the density of the specimen, which is a significant factor in the OT. The test procedure was originally designed for a target density of 93 ± 1 percent. However, in this lab program, the density was intentionally varied to simulate the expected impacts of thermal segregation on density. As a result, the OT may have limitations in effectively evaluating mixes with varying densities for the purposes of this research.





(a) (b)

Figure 85. OT Results for (a) Critical Fracture Energy, and (b) Maximum Load at the First Cycle.

6.10. TXME ANALYSIS ON THE INFLUENCE OF THERMAL SEGREGATION

While the lab results demonstrate a decrease in performance because of thermal segregation-induced AVs, they do not provide a definitive indication of how time or traffic repetitions to failure will be affected. To estimate the pavement performance under different levels of thermal segregation-induced AVs, researchers used the TxME software (*36*), considering the data obtained from the lab experiments. This approach allowed them to make predictions and assess the potential impact of thermal segregation on pavement performance.

6.10.1. Structure Input

Figure 86 displays the pavement structure input screen from TxME, which encompasses various parameters such as pavement type, location, materials, and layer properties (*36*).

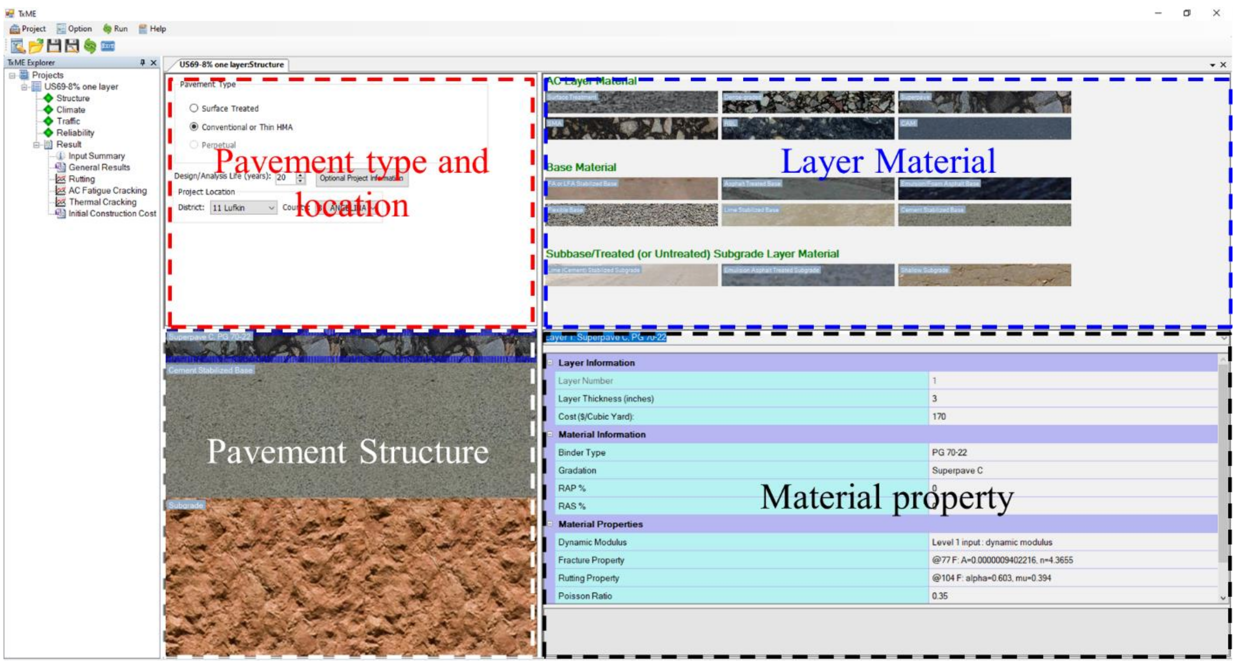


Figure 86. Pavement Structure Information Screen in TxME.

Researchers used TxME to evaluate three projects that were tested with the thermal profile at the time of construction. To assess the effect of thermal segregation, certain assumptions were made on the modulus values of various layers, including the existing AC, flexible base, cement-treated base, and subgrade layers. The assumed modulus values were 150 ksi for the existing AC layer, 35 ksi for the flexible base, 200 ksi for the cement-treated base, and 16 ksi for the subgrade layer. Since there were no available data for the modulus of the existing AC layer, a value of 150 ksi was chosen based on the assumption of an aged condition. While this assumption may not precisely reflect the actual site conditions, it was made to clearly visualize the impact of thermal segregation on the new AC layer. The modulus values for the flexible base, cement-treated base, and subgrade layers were combined with the county defaults specific to each project location.

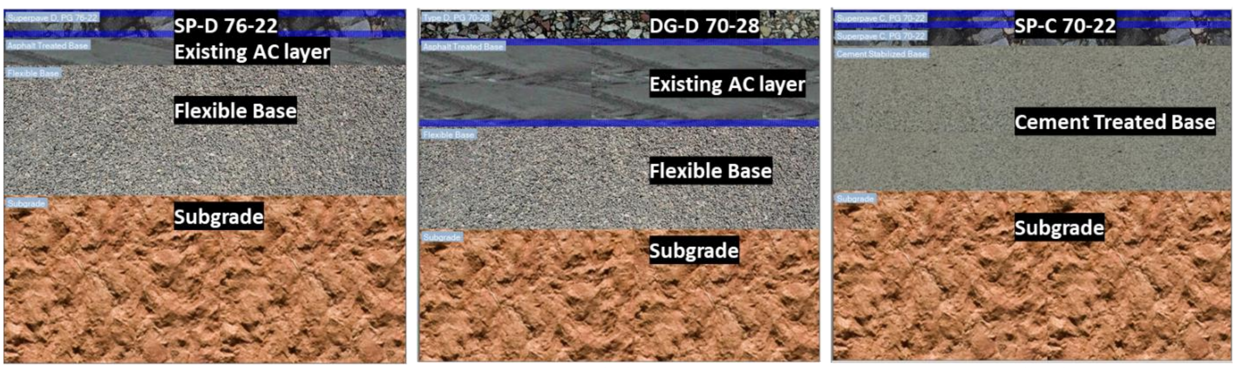
To compare and assess the influence of different AV levels, researchers conducted the analysis for each of the three paving projects using pavement layer property inputs as outlined in Table 46.

Table 46. Pavement Layer Property Input.

Roadway	US 183	US 287	US 69
Material	SP-D	DG-D	SP-C
AC_1 Thickness (in.)	1.5	2	1.5
AC_2 Thickness (in.)	1.5	6	1.5
AC_2 Modulus (ksi)[a]	150	150	AC_1 modulus
Binder Type	76-22	70-28	70-28
Base Thickness (in.)	7	7	12
Base Modulus (ksi)[a]	35	35	200
Subgrade (ksi)[a]	16	16	16

[a] The modulus of the existing AC, flexible base, cement-treated base, and subgrade layer assumed 150, 35, 200, and 16 ksi, respectively.

Figure 87 displays the pavement structures that were analyzed. Researchers used both the plans and GPR data to estimate the total thickness of the HMA layers. The pavement structure for US 183 and US 287 was modeled in TxME as two asphalt layers, a flexible base with a thickness of 7 in., and a subgrade. For US 69, this structure was modeled as two asphalt layers, a 12-in. cement-treated base, and a subgrade.



US 183 **US 287** **US 69**

Figure 87. Pavement Structures on US 183, US 287, and US 69.

The TxME analysis requires the input of material properties, specifically fracture properties and rutting properties, to accurately predict the pavement's performance in terms of cracking and rutting. The process of determining these properties is briefly described below.

6.10.1.1. Fracture Properties

Tex-248-F: Test Procedure for Overlay Test (OT) and its modified version are employed to evaluate the crack resistance of asphalt mixtures, as shown in Figure 88. In the OT, the specimen is glued on two plates; one plate is fixed, and the other moves horizontally. From repeatedly moving horizontally, a vertical crack will develop in the specimen and propagate from bottom to top.

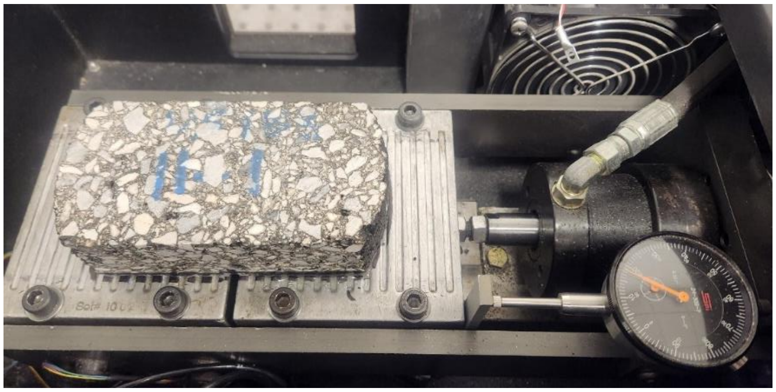


Figure 88. Overlay Test.

The standard OT uses an opening displacement of 0.025 in. to assess the cracking resistance of asphalt mixes. However, for determining the fracture properties A and n of the asphalt mixes, a modified version of the test was employed with a reduced opening displacement of 0.017 in. This adjustment was made to ensure an adequate number of repeated loading cycles for accurate analysis of the fracture properties (*37*). Figure 89 illustrates the relationships between OT cycles to failure (tested at 0.025-in. opening displacement) and fracture properties A and n (tested at 0.017-in. opening displacement) (*38*).

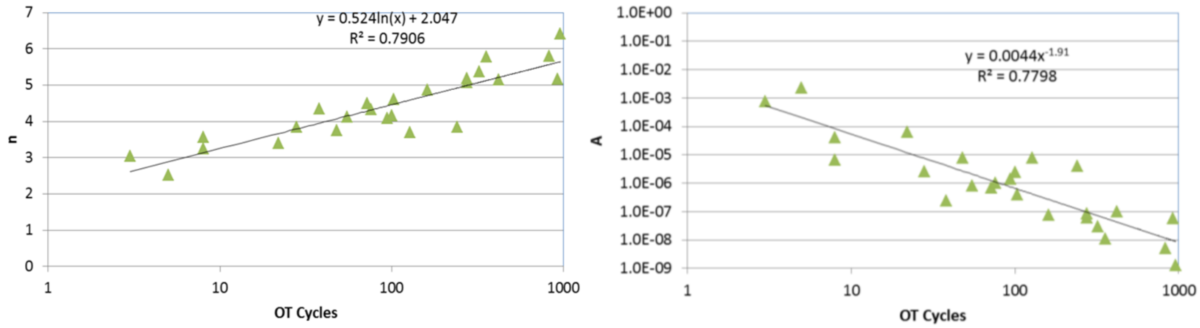


Figure 89. Relationship between OT Cycles with A and n (*38*).

The cycles to failure were measured following the standard OT test procedure, and based on these measurements, the fracture properties A and n were determined for each mixture and AV content using the relationships depicted in Figure 89. Table 47 presents the results.

Table 47. Fracture Property Input.

US 183				US 287				US 69			
AV	**OT Cycle**	**A**	**n**	**AV**	**OT Cycle**	**A**	**n**	**AV**	**OT Cycle**	**A**	**n**
5%	259	1.08E-07	4.96	**4%**	173	2.33E-07	4.75	**5%**	83	9.40E-07	4.37
7%	164	2.59E-07	4.72	**7%**	241	1.24E-07	4.92	**7%**	53	2.26E-06	4.12
10%	21	1.36E-05	3.63	**10%**	308	7.75E-08	5.05	**10%**	7	1.19E-04	3.04

6.10.1.2. Rutting Properties

Rutting properties were measured by conducting repeated load testing using the equipment and data analysis method illustrated in Figure 90. The specimen dimensions remain consistent at 4 in. in diameter and 6 in. in height. The test was conducted under specific conditions, including a target temperature of 40°C, a contact stress of 6.9 kPa, and a deviator stress of 137.8 kPa (*34*). Throughout the repeated loading process, the specimen experienced permanent deformation, allowing for the assessment of rutting properties.

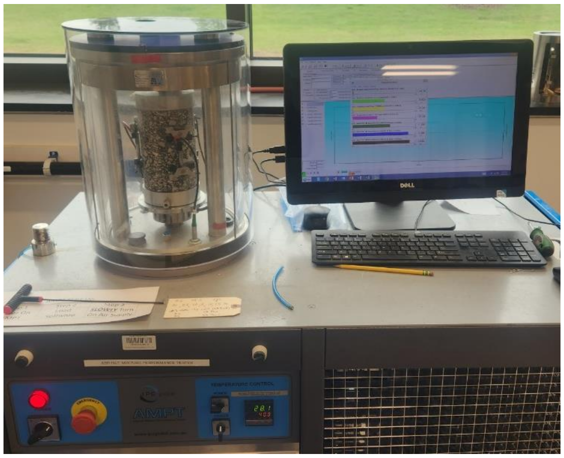


Figure 90. Repeated Load Test Equipment.

Figure 91 illustrates a permanent deformation curve that is employed to determine the rutting parameters alpha (α) and mu (μ). These parameters are essential in assessing the rutting behavior of the material and provide valuable insights into its susceptibility to permanent deformation under repeated loading conditions. By analyzing the permanent deformation curve and incorporating the rutting parameters into TxME, researchers can predict the accumulation of pavement rutting under specific traffic and climate conditions.

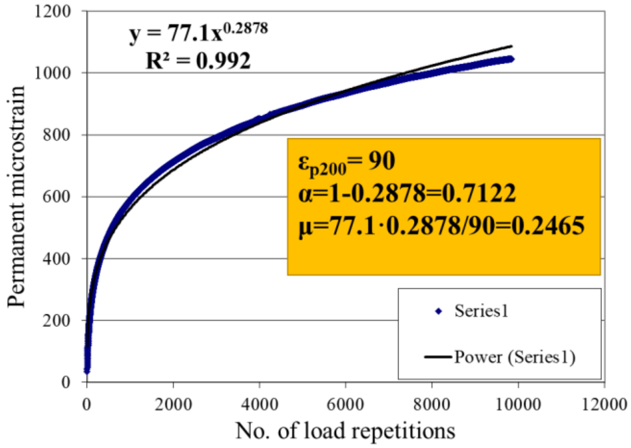


Figure 91. Permanent Deformation Curve and Data Calculation Example.

The viscoelastic parameters α and μ were computed as a function of a log-log plot of the accumulated plastic strain (ε_p) versus the number of load cycles (N) as follows:

$$\varepsilon_p = aN^b \quad (2)$$

$$\alpha = 1 - b;\ \mu = \frac{ab}{\varepsilon_{p200}} \quad (3)$$

Where a and b are the intercept and slope, respectively, of the linear portion of the ε_p-N curve on a log-log scale; α and μ are rutting parameters; and ε_{p200} is the accumulated plastic strain at the 200th load cycle.

Table 48 presents the rutting parameters obtained through the repeated load testing for each AV level in each of the materials.

Table 48. Rutting Property Inputs.

US 183			US 287			US 69		
AV	**Alpha**	**mu**	**AV**	**Alpha**	**mu**	**AV**	**Alpha**	**mu**
5%	0.5837	0.2569	**4%**	0.6904	0.6339	**5%**	0.6025	0.3940
7%	0.5200	0.1972	**7%**	0.6264	0.4679	**7%**	0.5910	0.3922
10%	0.5600	0.3332	**10%**	0.6189	0.5191	**10%**	0.4732	0.3077

6.10.2. Climate

Environmental conditions play a crucial role in pavement performance because they directly impact factors such as moisture content and temperature in unbound materials, ultimately affecting the pavement's load-carrying capacity. In TxME, there are two methods available to incorporate climate information into a project location. Users can choose to assign a specific weather station input or use climatic data interpolation based on the location's coordinates. Table 49 presents the climate input data for this study. Researchers employed the Enhanced Integrated Climatic Model software within TxME to model temperature and moisture profiles in the pavement and subgrade.

Table 49. Climate Input Data.

ID	US 183	US 287	US 69
Mean annual temperature (°F)	64.4	61.8	66.3
Mean annual precipitation (in.)	23.7	23.8	55.3
Number of wet days	102.7	106.5	156.2
Freezing index (°F-days)	209.9	376.2	95.7
Average annual number of freeze/thaw cycles	33.2	50.9	24.6
January (°F)	46.6	41.9	50.1
February (°F)	48.8	44.6	51.1
March (°F)	55.4	51.6	58.2
April (°F)	64.3	61.5	67.8
May (°F)	73.5	71.5	74.3
June (°F)	78.7	78.2	78.9
July (°F)	83.3	83.0	81.1
August (°F)	82.1	81.3	81.8
September (°F)	75.8	73.9	77.0
October (°F)	65.3	62.0	67.8
November (°F)	54.0	50.5	58.2
December (°F)	45.5	41.5	49.3

6.10.3. Traffic Inputs

In TxME, traffic inputs are classified into two levels: Level 1 requires load spectra input, while Level 2 uses ESAL input. For this analysis, the researchers used Level 2 input. They obtained the necessary data from the Texas Statewide Planning Map, which provided estimates of ESALs over a 20-year period. By incorporating this traffic information into TxME, researchers could simulate and evaluate the long-term effects of traffic loading on pavement performance.

Table 50 displays the values employed for calculating the 20-year ESAL values at each location in this analysis. Researchers used three different growth rate assumptions. The first growth rate was obtained from the Statewide Planning Map, which served as the baseline. To account for potential variations in traffic assumptions, researchers introduced two additional growth rates. These growth rates were set at two and three times higher than the current growth rate. By incorporating multiple growth rate scenarios, researchers aimed to assess the sensitivity of pavement performance predictions to different traffic projections.

Table 50. Traffic Inputs—ESAL Values Based on the Growth Rate.

ID	US 183			US 287			US 69		
Begin Average Daily Traffic	2368			13,759			3083		
% of Truck	15.6			43.1			17.7		
Growth Rate	1.6%	3.2%	4.8%	1.1%	2.2%	3.3%	1.3%	2.6%	3.9%
End Average Daily Traffic (vehicles per day)	3215	4345	5844	16,811	20,497	24,940	3948	5039	6413
ESALs (M)	2.7	3.1	3.7	40.9	45.2	50.5	3.8	4.4	5

6.10.4. TxME Analysis Results

Based on the inputs developed for the study, researchers employed TxME to assess the anticipated influence of thermal segregation-induced AVs and traffic on the expected performance of the pavement. By using TxME's predictive capabilities, researchers were able to evaluate the potential effects of these factors and provide insights for optimizing construction practices and addressing potential issues related to thermal segregation.

6.10.4.1. Effect of AVs on Performance

Figure 92 and Figure 93 present the findings from the TxME analysis conducted for US 183 and US 69, respectively. The results demonstrate a clear relationship between AV contents and both rut depth and AC fatigue cracking area, indicating that higher AV contents contribute to increased pavement distress. Notably, the impact of increasing AVs is more pronounced when transitioning from 7 to 10 percent AVs compared to transitioning from 5 to 7 percent AVs. Figure 92 highlights the significant reduction in cracking life when transitioning from medium to high AVs, resulting in a 10-year decrease in pavement durability. In contrast, Figure 93 reveals that thermal segregation-induced AVs, while approximately doubling the rut depth and causing a notable increase in cracking area, do not lead to complete failure based on the specified criteria for rutting or cracking. These contrasting results emphasize the intricate interplay between mix properties, their sensitivity to density changes, and the influence of underlying site conditions and traffic levels, underscoring the potential for diverse impacts arising from thermal segregation in real-world scenarios.

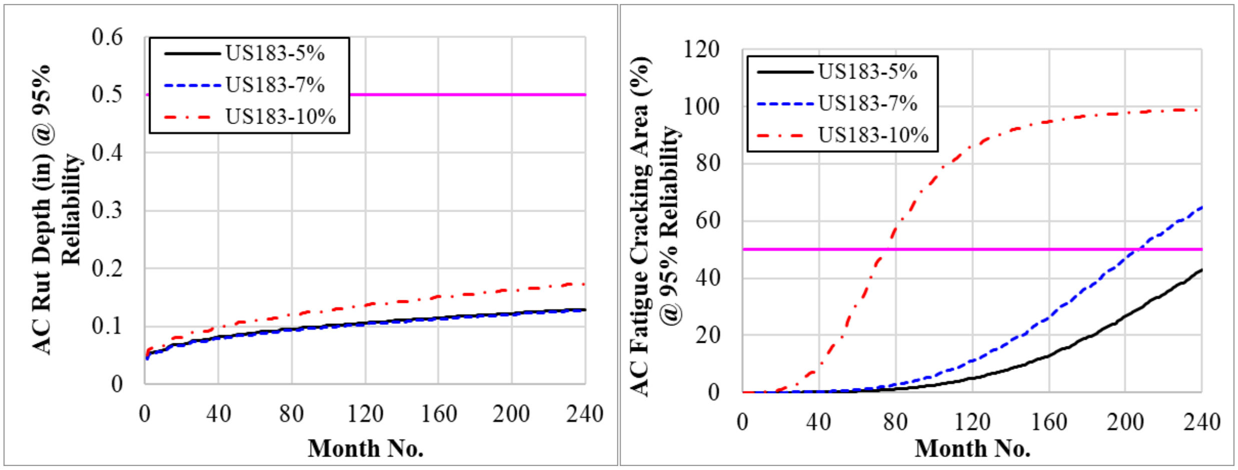


Figure 92. TxME Analysis Results—US 183 for Different AVs.

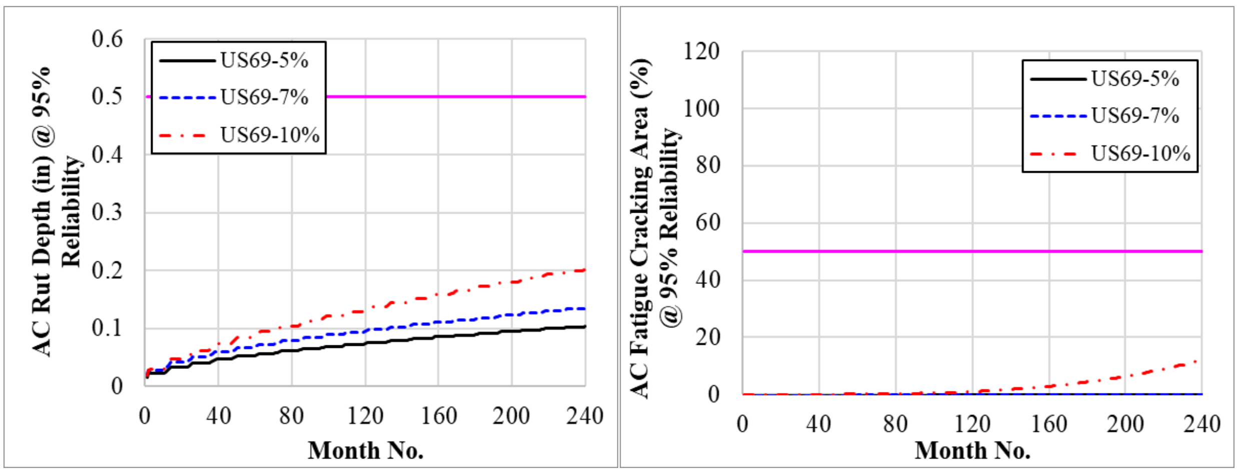


Figure 93. TxME Analysis Results—US 69 for Different AVs.

Figure 94 displays the results obtained from the analysis conducted on US 287. The TxME analysis revealed that as the AVs increased, the rut depth also increased, and transitioning from medium to high AVs resulted in a reduction in the rut life by more than 10 years. Conversely, the area of AC fatigue cracking increased as the AVs decreased. These findings indicate that the impact of AV contents on rutting and fatigue cracking behavior varies and can be influenced by factors such as the existing pavement section, underlying support, mixture properties, traffic level, and other related factors. Of the three pavements analyzed with TxME, US 287 has the highest traffic by far.

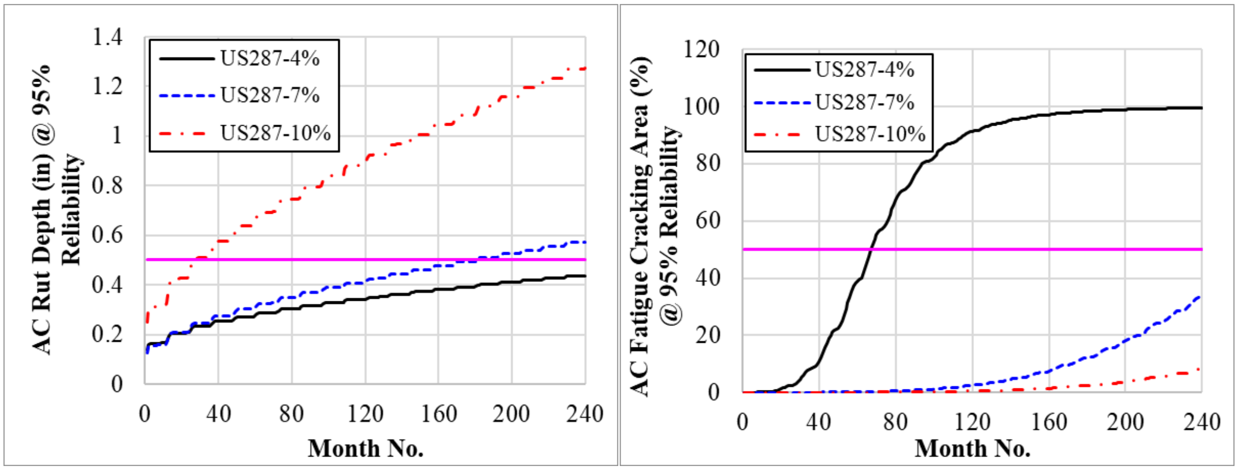
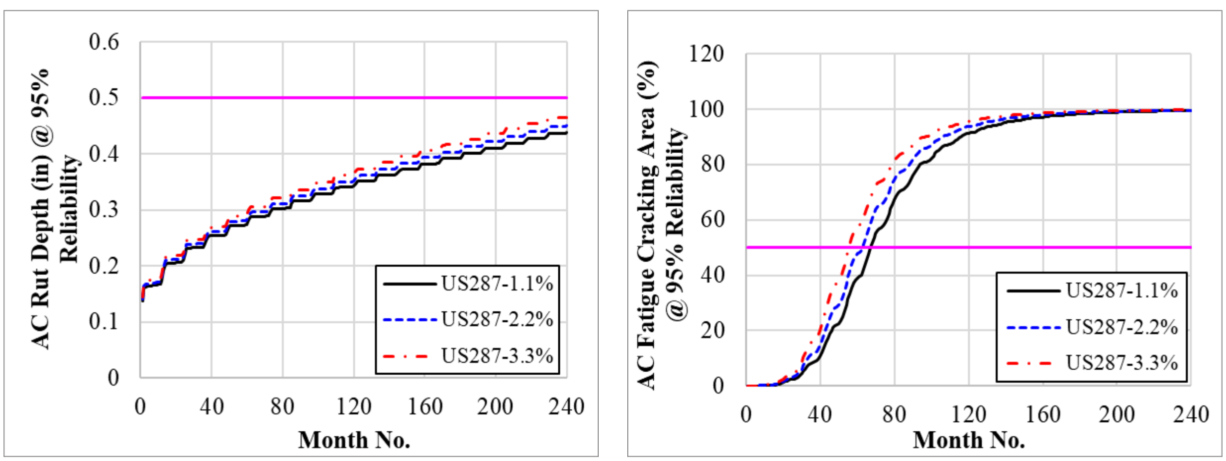


Figure 94. TxME Analysis Results—US 287 for Different AVs.

6.10.4.2. Effect of Traffic on Performance

The sensitivity analysis conducted on traffic volume revealed that the rut depth consistently increased with higher ESALs in all cases, and cracking life slightly decreased, as shown in Figure 95. However, within the range of growth rates assumed, no drastic shifts in expected performance were observed.



(a) (b)

Figure 95. Example of Traffic Growth Rate Sensitivity for Low AV on US 287: (a) AC Rut Depth and (b) AC Fatigue Cracking Area at 1.1, 2.2, and 3.3 Traffic Growth Rate.

6.11. CONCLUSIONS FROM LABORATORY TEST PROGRAM AND TXME ANALYSIS ON DEMONSTRATION PROJECTS

The laboratory testing program on mixes collected from various demonstration projects (US 69, US 287, US 183, SH 6, and SH 105) revealed a consistent trend of decreasing performance characteristics accompanied by increasing AVs. When simulating different levels of AV contents in the lab—representing low, medium, and high AV conditions resulting from poorer compaction due to thermal segregation—researchers observed the following results:

- Increasing AVs resulted in increased rutting, as indicated by the Hamburg and FN tests. The effect was less pronounced when transitioning from low to medium AVs, but the rut depth approximately doubled when transitioning from low to high AVs.
- With some mixes at the higher AV contents, the Hamburg test results went beyond the stripping inflection point.
- Permeability increased with increasing AVs, potentially increasing the risk of moisture damage.
- Increasing AVs resulted in decreasing dynamic modulus.
- Increasing AVs led to decreased crack resistance, as indicated by reduced indirect tensile strengths and reduced fracture energy.
- The OT results showed that maximum load at the first cycle, critical fracture energy, and crack progression rate all decreased with increasing AVs.
- While the lab results demonstrated that thermal segregation-induced AVs have a negative impact on rutting and cracking performance, the specific impact of thermal segregation-induced AVs can vary among different asphalt mixes.

Using lab-measured properties on mixes from three different paving projects, researchers conducted an evaluation using TxME to assess the potential impact of thermal segregation-induced AVs on pavement performance. The findings of the analysis are as follows:

- Increasing AV contents generally leads to higher rut depth and fatigue cracking area. This effect is more pronounced when transitioning from medium (e.g., 7 percent AVs) to high (e.g., 10 percent AVs) levels of AVs.
- The impact of thermal segregation-induced AVs can vary significantly depending on factors such as mix type, sensitivity of mix properties to changes in density, traffic level, and other factors.
- Thermal segregation-induced AVs have the potential to reduce the pavement life by 10 years. However, since these AVs typically manifest as localized defects within a project, the reduced life expectancy would likely present as localized premature failures rather than widespread failure of the entire pavement.
- Even with thermal segregation-induced AVs, the pavement may still reach its design life without reaching rutting or cracking failure criteria.
- Within the investigated ranges of traffic growth rates in this study, it was observed that higher growth rates led to a slight increase in rut depth and a slight decrease in cracking life. Overall, the impact was relatively minimal. However, this conclusion may vary if the analysis is conducted under different pavement structures or climate conditions.

CHAPTER 7. SITE VISITS TO PRIOR CONSTRUCTED PROJECTS

This chapter presents findings from site visits conducted at constructed projects of known age and with available paver-mounted thermal profiling data from the time of construction. This activity sought to identify pavements with several years of service and determine whether thermally segregated locations at the time of placement showed current irregularities or signs of distress. Based on the review of data presented in Chapter 4, researchers selected 13 projects for site visits. The researchers documented the current condition of each project using GPR, a visual condition survey, and digital video. They evaluated whether any current distress aligned with locations of known thermal irregularities or thermal segregation measured at the time of construction.

7.1. FIELD SURVEY METHOD AND INFORMATION

Table 51 provides an overview of the project locations, and Figure 96 visually depicts the distribution of these locations. As seen in Figure 96, the majority of the surveyed projects were concentrated in two specific geographic areas within the state. This clustering of projects occurred due to the research project’s reliance on historical thermal profiled data provided by the industry to identify sites with several years of service. The larger response received from these particular regions prompted the selection of projects in those areas for the site visits.

Table 51. Locations for Current Condition Surveys.

Roadway	District	Let Date	CSJ	Mix Type	Lift Thickness (in.)	Extents	
						Limits from	Limits to
SH 72	CORPUS CHRISTI	Sep-13	0270-09-027	SP-D	1.5	IH 37	Bee County Line
SH 97	SAN ANTONIO	Jan-17	0328-02-043	SP-C	2	Atascosa County Line	LP 181
US 84	TYLER	May-18	0123-03-021	SP-D	2	US 69 in Rusk, N & E	Panola County Line
US 259 (Rusk County)	TYLER	May-18	0138-04-046	SP-C	2.5	US 79 in Henderson, S	CR 344, 3 mi W of FM 348
US 79	TYLER	Jan-19	0246-01-034	SP-C	2	US 259 in Henderson, E	Jarrell Creek, 2.8 mi N of FM 1798
SH 149	TYLER	Jul-18	0393-02-027	SP-C	2	Gregg County Line, E	0.46 mi E of SH 110, near PR 50
SL 390	ATLANTA	Feb-20	1575-05-022	SP-C	4	1.0 mi N of SL 390	0.1 mi of N SH 43
SH 43	ATLANTA	May-19	0208-02-045	SP-C	2	FM 31	Haggerty Creek
FM 9	ATLANTA	Dec-18	0632-04-034	SP-C	2	US 59	FM 451
US 79	ATLANTA	May-19	0247-03-032	SP-C	1.5	FM 2625	Louisiana State Line
US 259 (Upshur County)	TYLER	Jan-19	0392-02-096	SMA-D	2	0.2 mi S of FM 557	SH 155
US 155	ATLANTA	Feb-19	0520-05-050	SP-C	2	US 259	5.0 mi S of US 259
US 271	ATLANTA	May-18	0248-05-064	SMA-D	2	SH 155(S)	FM 726

Figure 96. Locations of Six Counties Selected for Surveys of 13 Constructed Projects.

Table 52 presents a broad overview of the thermal profile results obtained from these projects. SH 72, although exhibiting 58 percent severe thermal segregation, had received a recent seal coat. Thus, little further analysis could be performed on that project. From an overall construction project view, most of the other projects showed relatively low percentages of severe thermal segregation.

Table 52. Thermal Profile Summary of Locations for Condition Evaluation.

Road ID	Total # of 150-ft Profiles	Moderate		Severe		Distress Observation
		Number	Percent	Number	Percent	
SH 72	90	22	24	52	58	Seal coated
SH 97	745	309	41.5	41	5.5	No distress found
US 84	50	29	58	13	5.3	No distress found
US 259 (Rusk County)	445	173	38.9	12	5.4	No distress found
US 79	541	158	29	29	2.7	No distress found
SH 149	190	89	47	10	26	No distress found
SL 390	580	26	4.5	3	0.4	Thermal segregation
SH 43	447	46	10.3	15	0.5	No distress found
FM 9	232	49	21.1	1	0.5	No distress found
US 79	376	49	13	2	3.4	Thermal segregation, patch, pothole, pumping
US 259 (Upshur County)	645	196	30.4	8	1.2	Thermal segregation
US 155	1433	366	25.5	53	3.7	Thermal segregation, patch
US 271	822	217	26.4	12	1.5	Thermal segregation

7.2. RESULTS FROM CONSTRUCTED PROJECTS

Researchers performed a nondestructive GPR survey and a digital video log of each project in Table 52. They also performed site visits to evaluate pavement conditions and identify if thermal anomalies in the thermal profile data corresponded with any locations of current pavement distress. Before the field condition survey, researchers analyzed and identified the thermal profile data to identify potential severe segregation locations, as shown in Figure 97.

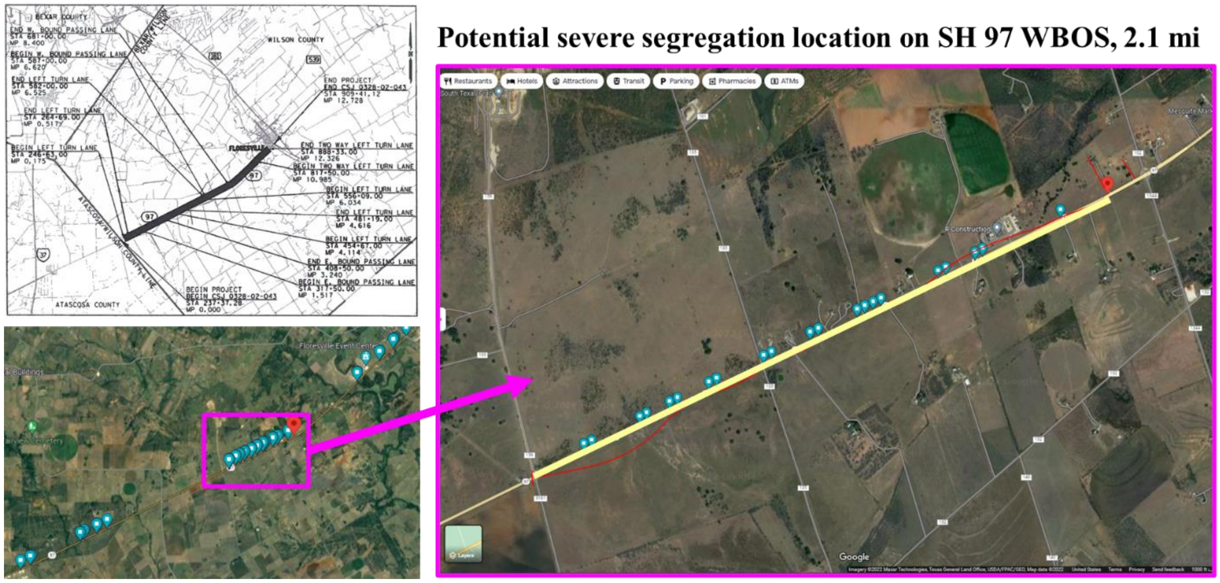
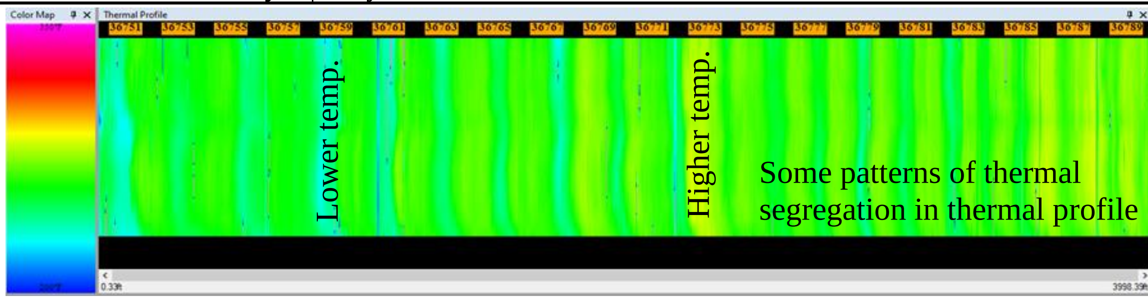


Figure 97. Example Determination for Survey Locations of Interest.

Due to traffic control and time limitations in the field survey, there is a limit to sophisticatedly observing the entire roadway. Therefore, the field survey was conducted in three stages for each project. In the first stage, researchers performed visual observation directly with normal travel speed. In the second stage, GPR and video logs were performed to measure the surface DC and capture images of any distress observations for the whole project. In the last stage, the researchers performed specific documentation at locations of interest identified based on the first two stages and the underlying temperature profile's location.

Figure 98 through Figure 110 present a summary of observations and findings from each project.

Section	**SH 72 (CORPUS CHRISTI), CSJ 0270-09-027**	
Limits	Live Oak, from US 259 to CR 344 (5.761 mi.)	
Letting Date	September 2013	
Overlay Type	1.5" Type D	PG 70-22
Date of condition survey	May 2022	



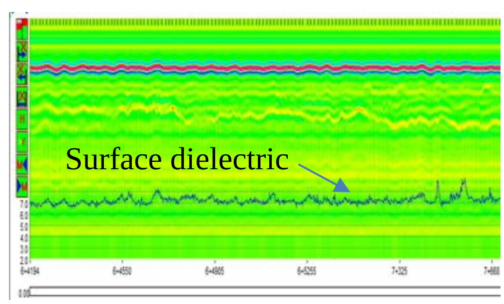
Example Thermal Plot

Thermal Profile Summary

Total # of 150' profiles	Moderate		Severe	
	Number	Percent	Number	Percent
90	22	24	52	58

Example Current Condition Photo 1

Example Current Condition Photo 2



Example Surface Dielectric with Distance

Discussion

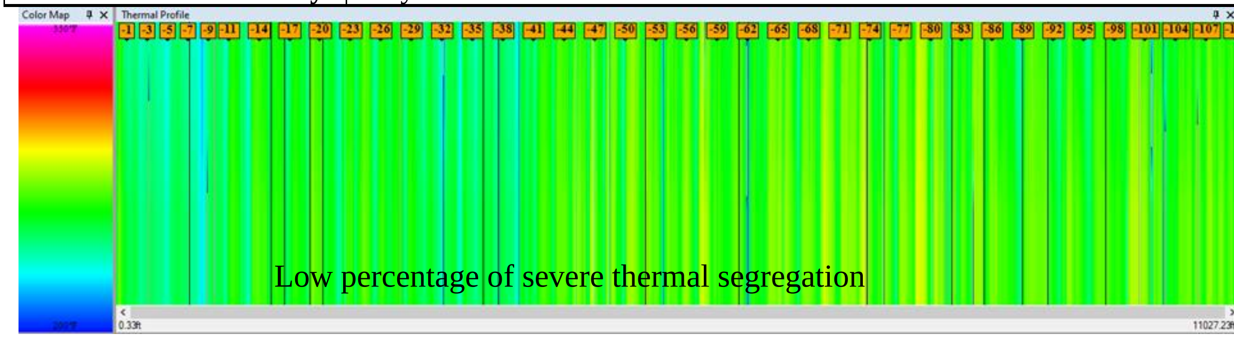
The SH 72 in Live Oak County had already been seal coated. The correlation between the location of thermal segregation known at the time of construction and any distress of the pavement or the appearance of the surface could not be confirmed. The GPR survey did not correlate any trend between surface dielectric and thermal profile.

Summary

The SH 72 in Live Oak County has already been seal coated, so no conclusions could be made.

Figure 98. Summary of Observations and Findings from SH 72.

Section	**SH 97 (SAN ANTONIO), CSJ 0328-02-043**	
Limits	Wilson County, from ATASCOSA C/L to LP 181 (12.7 mi.)	
Letting Date	JAN 2017	
Overlay Type	2" SP-C	PG 76-22
Date of condition survey	May 2022	



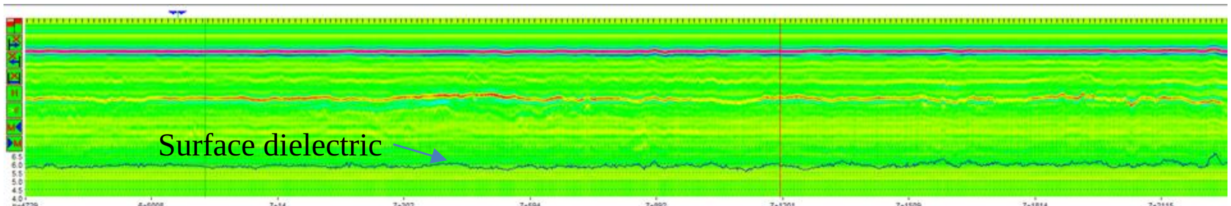
Example Thermal Plot

Thermal Profile Summary

Total # of 150' profiles	Moderate		Severe	
	Number	Percent	Number	Percent
745	309	41.5	41	5.5

Example Current Condition Photo 1

Example Current Condition Photo 2

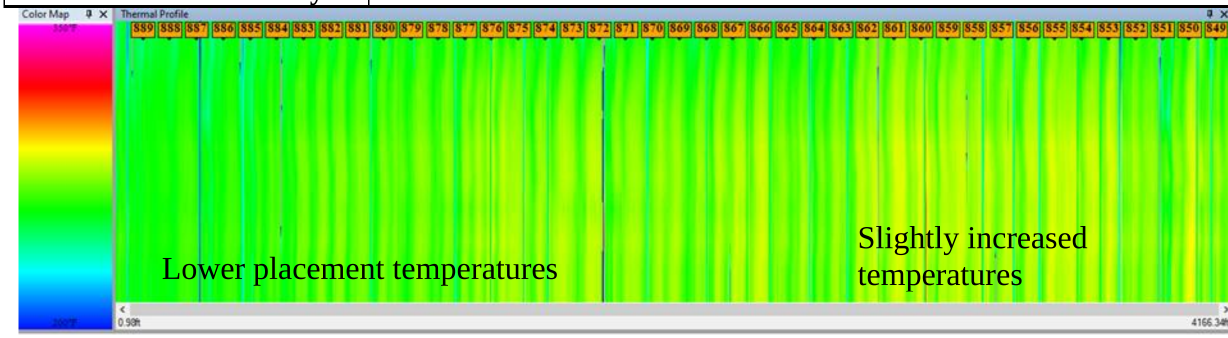


Example Surface Dielectric with Distance

Discussion
In SH 97 in Wilson County, the correlation between the location of thermal segregation known at the time of construction and the distress of the pavement or the appearance of the surface could not be confirmed. No distress was observed for the 41 profiles over the project which classified as severe thermal segregation according to the TEX-244-F. The GPR survey did not correlate any trend between surface dielectric and thermal profile.
Summary
No distress has been observed for the 41 profiles which classified as severe thermal segregation according to the TEX-244-F.

Figure 99. Summary of Observations and Findings from SH 97.

Section	**US 84 (TYL), CSJ 0123-03-021**	
Limits	Cherokee County, from US 69 IN RUSK, N & E to .46 MI E OF SH 110(1.3 mi.)	
Letting Date	May 2018	
Overlay Type	2" SP-C	PG 64-22
Date of condition survey	June 2022	



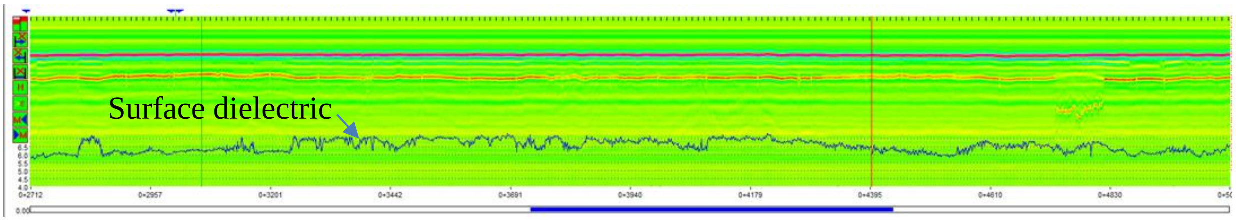
Example Thermal Plot

Thermal Profile Summary

Total # of 150' profiles	Moderate		Severe	
	Number	Percent	Number	Percent
50	29	58	13	26

Example Current Condition Photo 1

Example Current Condition Photo 2



Example Surface Dielectric with Distance

Discussion

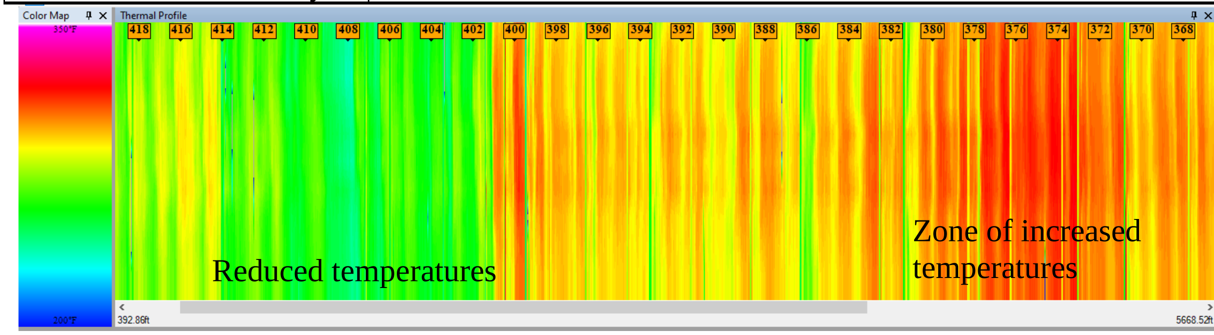
In US 84 in Cherokee county, the correlation between the location of thermal segregation known at the time of construction and the distress of the pavement or the appearance of the surface could not be confirmed. No distress has been observed for the 13 profiles which classified as severe thermal segregation according to the TEX-244-F. The GPR survey did not correlate any trend between surface dielectric and thermal profile.

Summary

No distress has been observed for the 13 profiles which classified as severe thermal segregation according to the TEX-244-F.

Figure 100. Summary of Observations and Findings from US 84.

Section	**US 259 (TYL), CSJ 0138-04-046**	
Limits	Rusk County, from US 79 IN HENDERSON, S to 2.8 MI N OF FM 1798 (7.9 mi.)	
Letting Date	May 2018	
Overlay Type	2.5" SP-C	PG 70-22
Date of condition survey	June 2022	



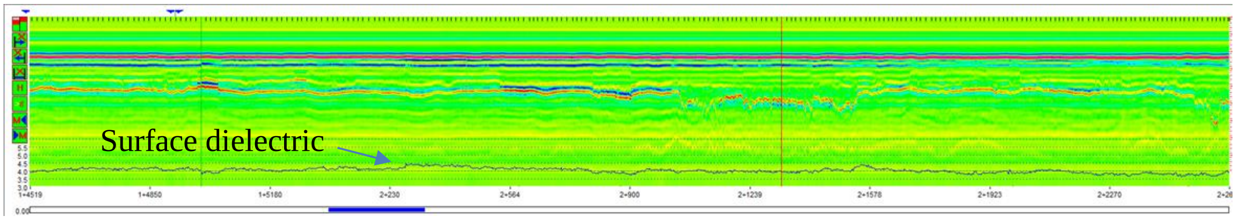
Example Thermal Plot

Thermal Profile Summary

Total # of 150' profiles	Moderate		Severe	
	Number	Percent	Number	Percent
445	173	38.9	12	2.7

Example Current Condition Photo 1

Example Current Condition Photo 2



Example Surface Dielectric with Distance

<u>Discussion</u>	

Discussion

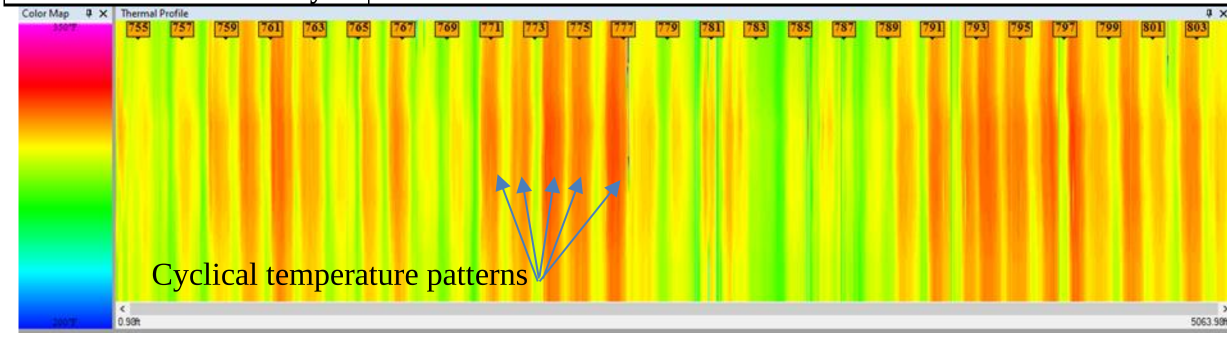
In US 259 in Rusk County, the correlation between the location of thermal segregation known at the time of construction and the distress of the pavement or the appearance of the surface could not be confirmed. No distress was observed for the 12 profiles which classified as severe thermal segregation according to the TEX-244-F. The GPR did not correlate any trend between surface dielectric and thermal profile.

Summary

No distress has been observed for the 12 profiles which classified as severe thermal segregation according to the TEX-244-F.

Figure 101. Summary of Observations and Findings from US 259 (Rusk County).

Section	**US 79 (TYL), CSJ 0246-01-034**	
Limits	Rusk County, from US 259 to CR344, 3 MI W OF FM 348 (5.761 mi.)	
Letting Date	January 2019	
Overlay Type	2" SP-C	PG 64-22
Date of condition survey	June 2022	



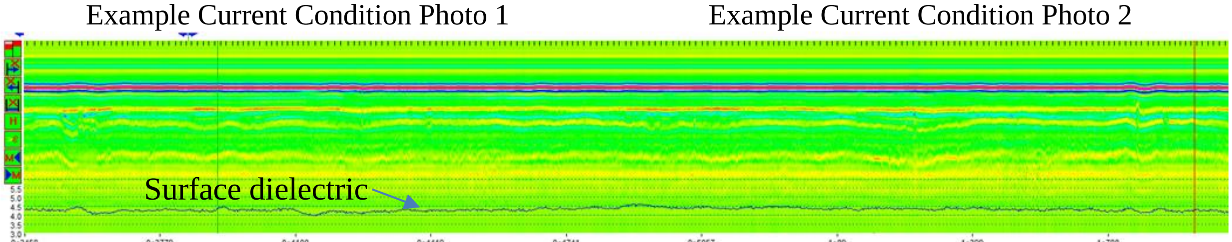
Example Thermal Plot

Thermal Profile Summary

Total # of 150' profiles	Moderate		Severe	
	Number	Percent	Number	Percent
541	158	29	29	5.4

Example Current Condition Photo 1

Example Current Condition Photo 2



Example Surface Dielectric with Distance

Discussion

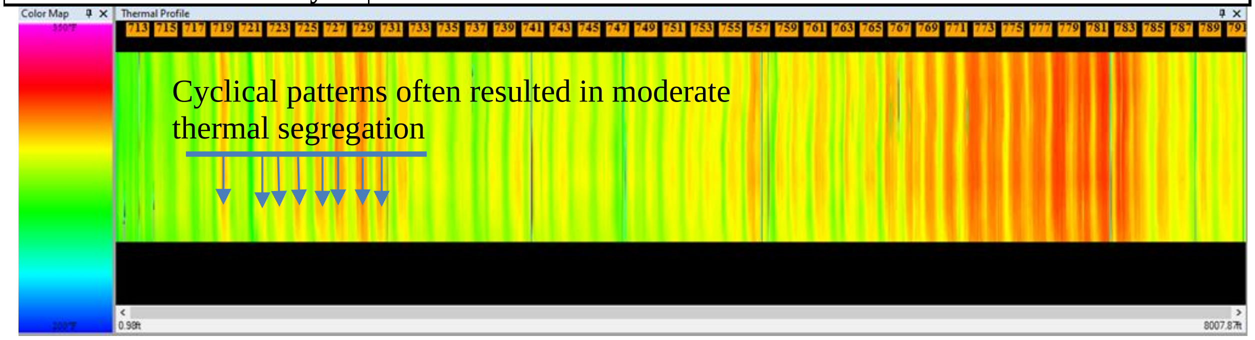
In US 79 in Rusk County, the correlation between the location of thermal segregation known at the time of construction and the distress of the pavement or the appearance of the surface could not be confirmed. No distress has been observed for the 29 profiles which classified as severe thermal segregation according to the TEX-244-F. The GPR survey did not correlate any trend between surface dielectric and thermal profile.

Summary

No distress has been observed for the 29 profiles which are classified as severe thermal segregation according to the TEX-244-F.

Figure 102. Summary of Observations and Findings from US 79.

Section	**SH 149 (TYL), CSJ 0393-02-027**	
Limits	Panola County, from US 79 IN HENDERSON, S to 2.8 MI N OF FM 1798 (7.6 mi.)	
Letting Date	July 2018	
Overlay Type	2" SP-C	PG 70-22
Date of condition survey	June 2022	



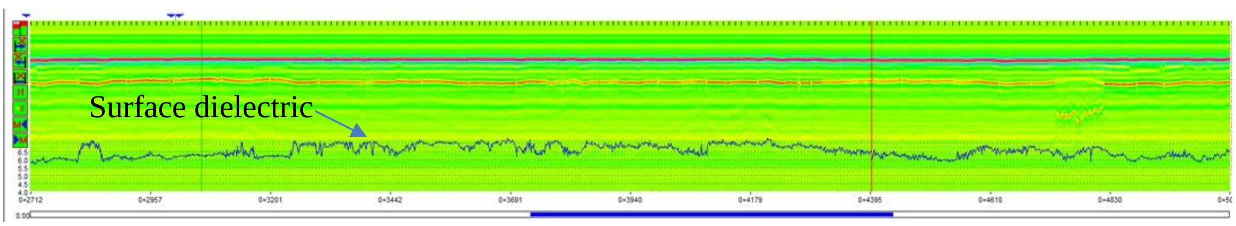
Example Thermal Plot

Thermal Profile Summary

Total # of 150' profiles	Moderate		Severe	
	Number	Percent	Number	Percent
190	89	47	10	5.3

Example Current Condition Photo 1

Example Current Condition Photo 2

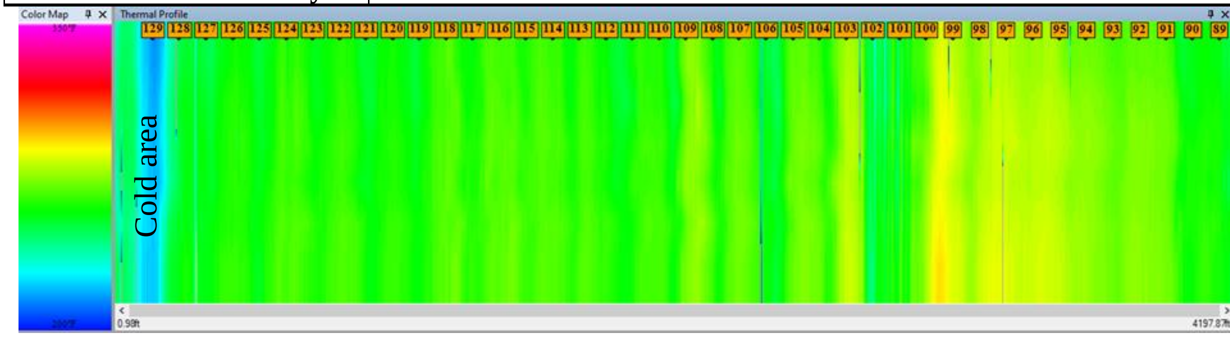


Example Surface Dielectric with Distance

Discussion
In SH 149 in Panola County, the correlation between the location of thermal segregation known at the time of construction and the distress of the pavement or the appearance of the surface could not be confirmed. No distress has been observed for the 10 profiles which classified as severe thermal segregation according to the TEX-244-F. The GPR survey did not correlate any trend between surface dielectric and thermal profile.
Summary
No distress has been observed for the 10 profiles which classified as severe thermal segregation according to the TEX-244-F.

Figure 103. Summary of Observations and Findings from SH 149.

Section	**SL 390 (ATLANTA), CSJ 1575-05-022**	
Limits	Harrison County, from US 59 to 0.1 mi. N of SH 43 (2.511 mi.)	
Letting Date	Feb 2020	
Overlay Type	4" SP-C	PG 76-22
Date of condition survey	June 2022	



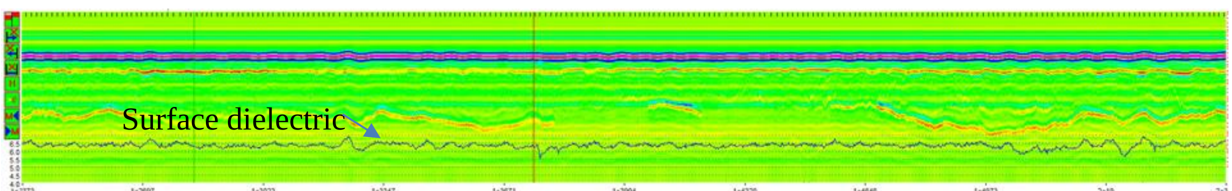
Example Thermal Plot

Thermal Profile Summary

Total # of 150' profiles	Moderate		Severe	
	Number	Percent	Number	Percent
580	26	4.5	3	0.5

Example Current Condition Photo 1

Example Current Condition Photo 2



Example Surface Dielectric with Distance

Discussion

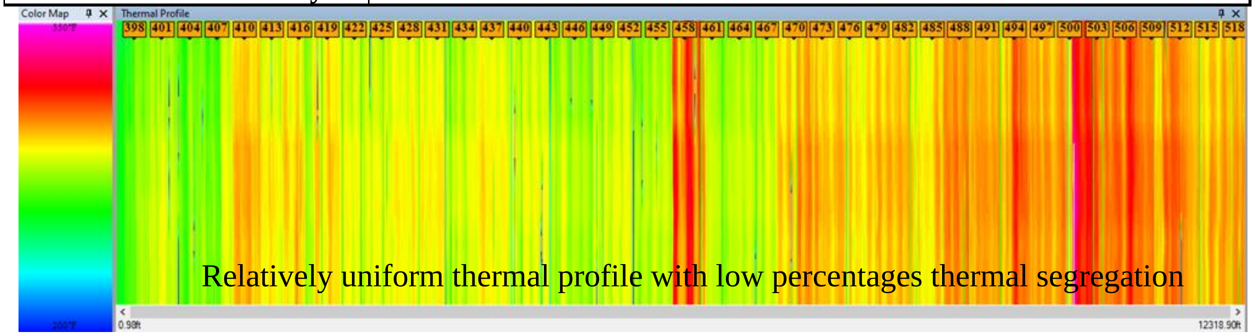
In SL 390 in Harrison County, no distress was observed for the 3 profiles which classified as severe thermal segregation according to the TEX-244-F. The GPR survey did not correlate any trend between surface dielectric and thermal profile. However, pavement distress was observed in a profile where temperatures below 250 °F were dominantly distributed.

Summary

Pavement distress existed at the location of a wide, cold area. However, this area was not classified as thermally segregated according to Tex-244-F because of its relatively uniform (although low) placement temperature.

Figure 104. Summary of Observations and Findings from SL 390.

Section	**SH 43 (ATLANTA), CSJ 0208-02-045**	
Limits	Harrison County, from 1.0 mi. north of SL 390 to Haggerty creek (2.792 mi.)	
Letting Date	May 2019	
Overlay Type	2" SP-C	PG 76-22
Date of condition survey	June 2022	



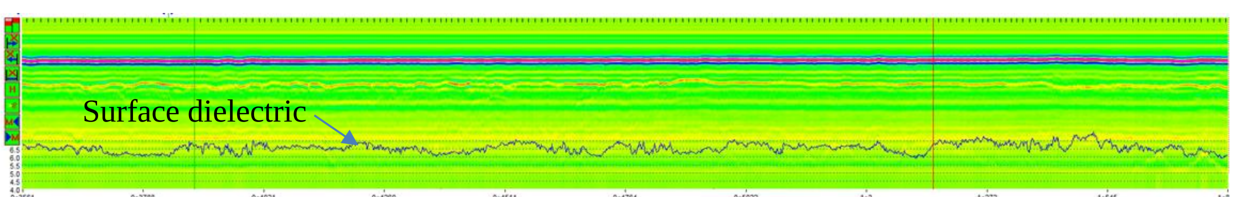
Example Thermal Plot

Thermal Profile Summary

Total # of 150' profiles	Moderate		Severe	
	Number	Percent	Number	Percent
447	46	10.3	15	3.4

Example Current Condition Photo 1

Example Current Condition Photo 2

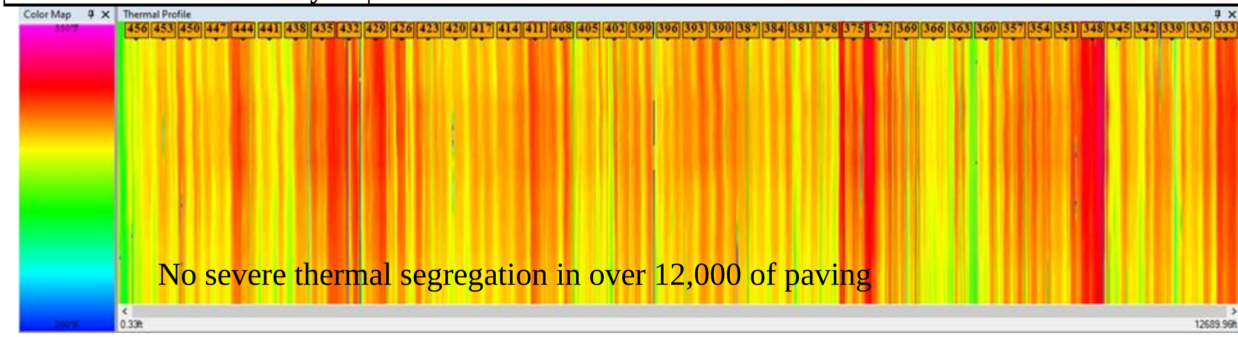


Example Surface Dielectric with Distance

Discussion
In SH 43 in Harrison County, the correlation between the location of thermal segregation known at the time of construction and the distress of the pavement or the appearance of the surface could not be confirmed. No distress was observed for the 15 profiles which classified as severe thermal segregation according to the TEX-244-F. The GPR did not correlate any trend between surface dielectric and thermal profile
Summary
No distress was observed for the 15 profiles which classified as severe thermal segregation according to the TEX-244-F.

Figure 105. Summary of Observations and Findings from SH 43.

Section	FM 9 (ATLANTA), CSJ 0632-04-034	
Limits	Harrison County, from FM 2625 to FM 451 (3.873 mi.)	
Letting Date	Dec 2018	
Overlay Type	2" SP-C	PG 76-22
Date of condition survey	June 2022	



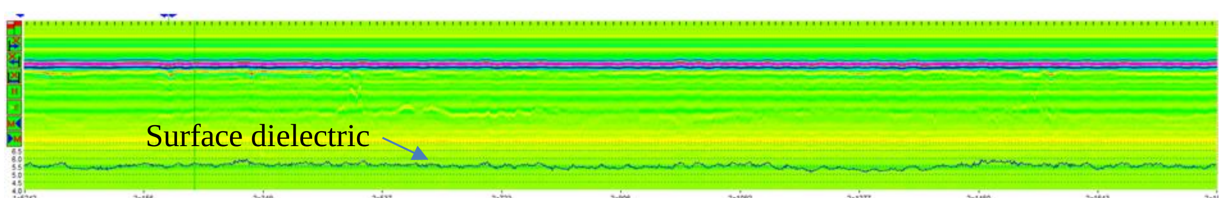
Example Thermal Plot

Thermal Profile Summary

Total # of 150' profiles	Moderate		Severe	
	Number	Percent	Number	Percent
232	49	21.1	1	0.4

Example Current Condition Photo 1

Example Current Condition Photo 2



Example Surface Dielectric with Distance

Discussion

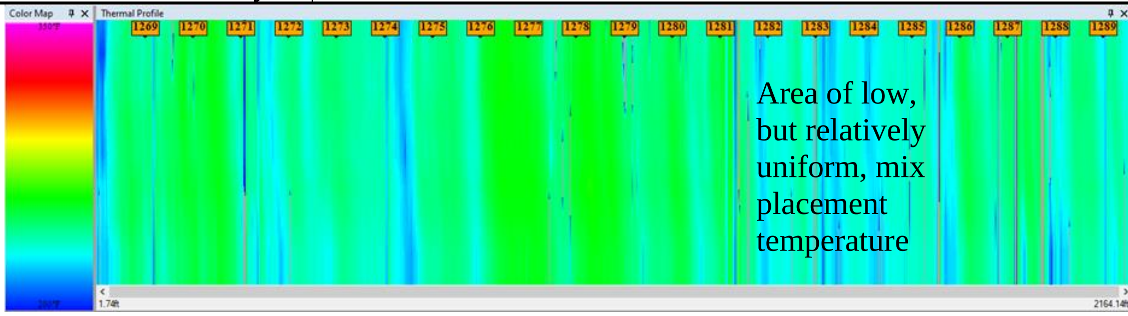
In FM 9 in Harrison County, the correlation between the location of thermal segregation known at the time of construction and the distress of the pavement or the appearance of the surface could not be confirmed. No distress was observed for the 1 profile which classified as severe thermal segregation according to the TEX-244-F. The GPR survey did not correlate any trend between surface dielectric and thermal profile.

Summary

No distress was observed for the 1 profile which classified as severe thermal segregation according to the TEX-244-F.

Figure 106. Summary of Observations and Findings from FM 9.

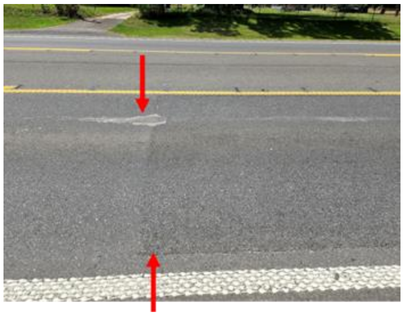
Section	US 79 (ATLANTA), CSJ 0247-03-032	
Limits	Panola County, from FM 31 to Louisiana state line (8.896 mi.)	
Letting Date	May 2019	
Overlay Type	1.5" SP-C	PG 76-22
Date of condition survey	June 2022	



Example Thermal Plot

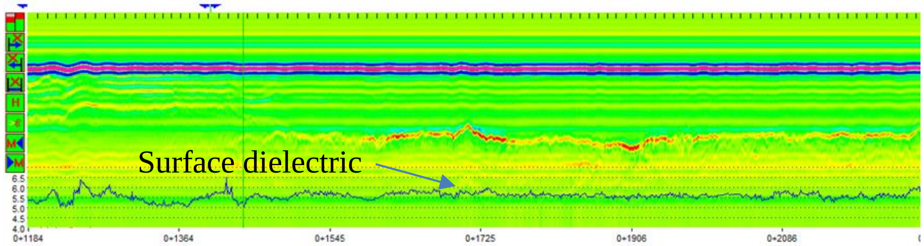
Thermal Profile Summary

Total # of 150' profiles	Moderate		Severe	
	Number	Percent	Number	Percent
376	49	13	2	0.5



Example Current Condition Photo 1

Example Current Condition Photo 2



Example Surface Dielectric with Distance

Discussion

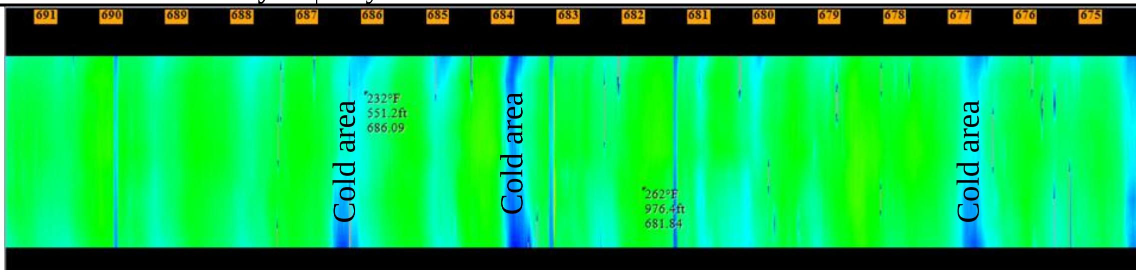
In US 79 in Panola County, the correlation between the location of thermal segregation known at the time of construction and the distress of the pavement or the appearance of the surface could not be confirmed. No distress was observed for the 3 profiles which classified as severe thermal segregation according to the TEX-244-F. The GPR survey did not correlate any trend between surface dielectric and thermal profile. However, several distress types were observed including patching, pothole, and pumping at locations where temperatures below 250 °F were dominantly distributed.

Summary

No distress was observed for the 13 profiles which classified as severe thermal segregation according to the TEX-244-F. Distresses existed where mix placement temperatures were low, but uniform.

Figure 107. Summary of Observations and Findings from US 79.

Section	**US 259 (TYL), CSJ 0392-02-096**	
Limits	Upshur County, from 0.2 MI. S. OF FM 557 to SH 155 (3.370 mi.)	
Letting Date	January 2019	
Overlay Type	2" SMA-D	PG 76-22
Date of condition survey	July 2022	

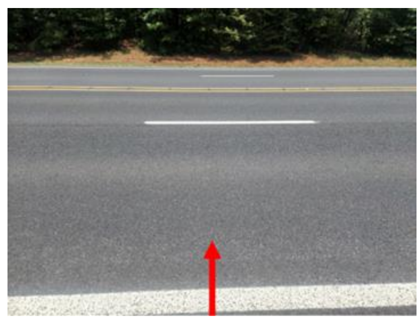


Example Thermal Plot

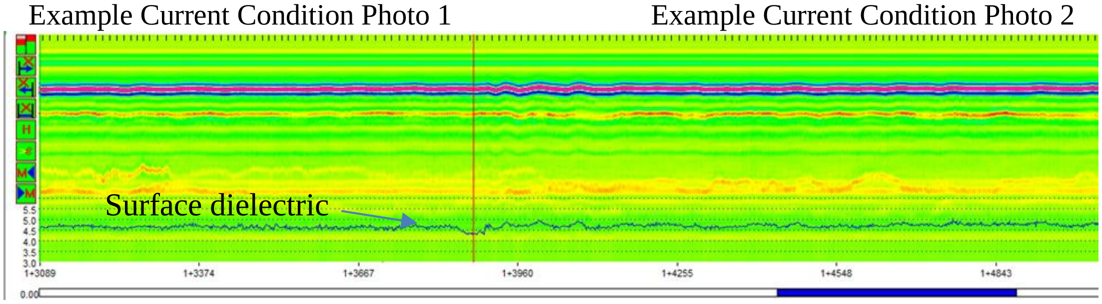
Thermal Profile Summary

Total # of 150' profiles	Moderate		Severe	
	Number	Percent	Number	Percent
645	196	30.4	8	1.2

Example Current Condition Photo 1



Example Current Condition Photo 2

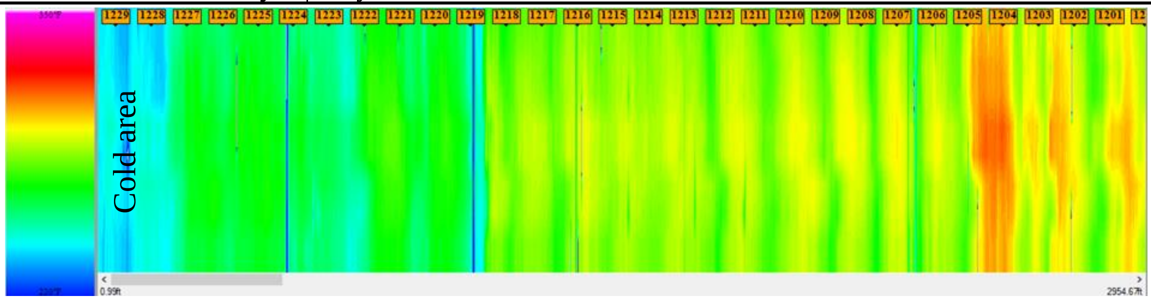


Example Surface Dielectric with Distance

Discussion
In US 259 in Upshur County, the correlation between the location of thermal segregation known at the time of construction and the distress of the pavement or the appearance of the surface could not be confirmed. No distress was observed for the 3 profiles which classified as severe thermal segregation according to the TEX-244-F. The GPR survey did not correlate any trend between surface dielectric and thermal profile. However, evidence of pavement distress was observed in a profile where temperatures below 250 °F were dominantly distributed.
Summary
Pavement distress exists at the location of the wide, cold area. However, this area was not classified as thermally segregated according to Tex-244-F.

Figure 108. Summary of Observations and Findings from US 259 (Upshur County).

Section	SH 155 (ATLANTA), CSJ 0520-05-050	
Limits	Upshur County, from US 259 to 5.0 MI. S. OF US 259 (5.0 mi.)	
Letting Date	Feb 2019	
Overlay Type	2" SP-C	PG 76-22
Date of condition survey	July 2022	



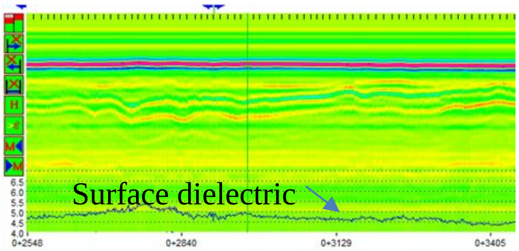
Example Thermal Plot

Thermal Profile Summary

Total # of 150' profiles	Moderate		Severe	
	Number	Percent	Number	Percent
1433	366	25.5	53	3.7

Example Current Condition Photo 1

Example Current Condition Photo 2

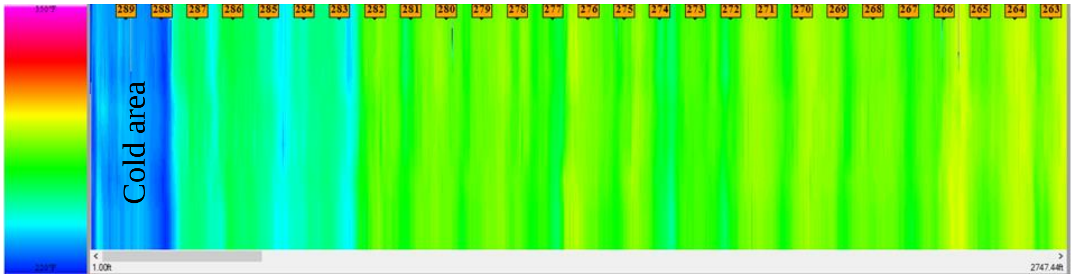


Example Surface Dielectric with Distance

Discussion
In SH 155 in Upshur County, the correlation between the location of thermal segregation known at the time of construction and the distress of the pavement or the appearance of the surface could not be confirmed. No distress was observed for the 53 profiles which classified as severe thermal segregation according to the TEX-244-F. The GPR survey did not correlate any trend between surface dielectric and thermal profile. However, two patched area were observed in a profile where temperatures below 250 °F were dominantly distributed.
Summary
Two patched area exists at the location of the wide, cold area. However, this area was not classified as thermally segregated according to Tex-244-F.

Figure 109. Summary of Observations and Findings from SH 155.

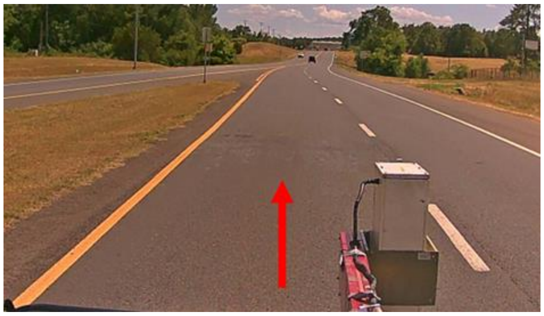
Section	US 271 (ATLANTA), CSJ 0248-05-064	
Limits	Upshur County, from SH 155(S) to FM 726 (7.1 mi.)	
Letting Date	May 2018	
Overlay Type	2" SMA-D	PG 76-22
Date of condition survey	July 2022	



Example Thermal Plot

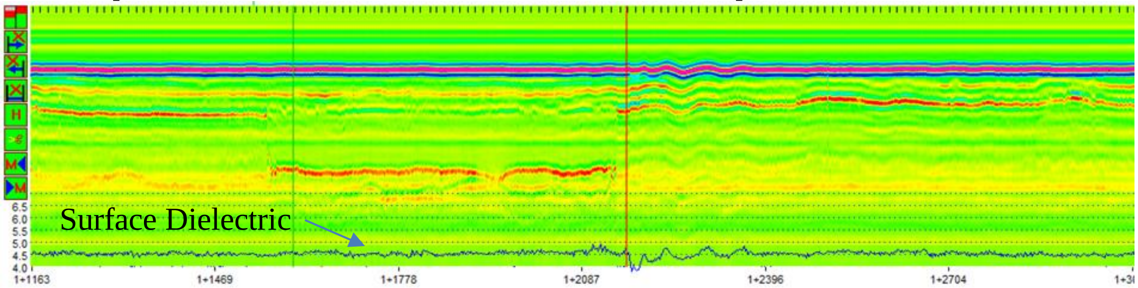
Thermal Profile Summary

Total # of 150' profiles	Moderate		Severe	
	Number	Percent	Number	Percent
822	217	26.4	12	1.5



Example Current Condition Photo 1

Example Current Condition Photo 2



Example Surface Dielectric with Distance

Discussion

In US 271 in Upshur County, the correlation between the location of thermal segregation known at the time of construction and the distress of the pavement or the appearance of the surface could not be confirmed. No distress was observed for the 12 profiles which classified as severe thermal segregation according to the TEX-244-F. The GPR survey did not correlate any trend between surface dielectric and thermal profile. However, thermal segregations were observed in a profile where temperatures below 250 °F were dominantly distributed.

Summary

Pavement distress exists at the location of the wide, cold area. However, this area was not classified as thermally segregated according to Tex-244-F.

Figure 110. Summary of Observations and Findings from US 271.

Summary of Site Visits to Constructed Projects

During their site visits to 13 different projects constructed between 2013 and 2020, researchers examined the known locations of thermal anomalies at the time of construction using thermal profile data. The following results were observed:

- Most projects had around 5 percent or less severe thermal segregation at the time of construction, which aligns with findings from the benchmarking analysis presented in Chapter 4.
- The oldest project, constructed in 2013, had recently undergone a seal coat, preventing the gathering of information on potential pavement distress(es) in the hot mix.
- In general, locations with measured severe thermal segregation at the time of construction did not show any signs of pavement distress.
- Some thermal profiles exhibited relatively low but uniform placement temperatures, which did not meet the criteria for severe thermal segregation according to Tex-244-F. However, pavement distress was observed in several of these locations.

These findings highlight that the current Tex-244-F method captures uniformity but does not distinguish between uniformly good and uniformly bad. For example, Table 53 (a) shows Tex-244-F results with placement temperatures ranging from about 230–250°F, classified as non-thermally segregated. Conversely, Table 53(b) shows profiles with temperatures ranging from about 240 to 275°F, classified as thermally segregated. Despite the relatively uniform temperatures in Table 53(a), these locations may carry a higher risk of significant, widespread density issues compared to the reported thermally segregated locations in Table 53 (b). However, based on the current Tex-244-F procedure, the location of Table 53(a) would not be classified as thermally segregated.

Profile Nr	Beginning Location		Ending Location		Max Temp	Min Temp	Temperature Differential
	Station	GPS in °	Station	GPS in °			
2	-1.51	98.20426648 W, 29.08731891 N	-3.00	98.20471739 W, 29.08712545 N	251.6	237.7	13.9
3	-3.01	98.20471869 W, 29.08712486 N	-4.50	98.20516883 W, 29.08693126 N	252.5	232.7	19.8
4	-4.51	98.20517175 W, 29.08693000 N	-6.00	98.20562464 W, 29.08674283 N	253.9	235.9	18.0

(a)

57	-84.01	98.2290993 W, 29.07671568 N	-85.50	98.22954649 W, 29.07652246 N	280.6	249.6	31.0
58	-85.51	98.22955029 W, 29.07652077 N	-87.00	98.22999665 W, 29.07632376 N	279.9	252.7	27.2
60	-88.50	98.23044637 W, 29.07612347 N	-90.00	98.23089084 W, 29.07592540 N	275.4	239.2	36.2
61	-90.01	98.23089458 W, 29.07592380 N	-91.50	98.2313404 W, 29.07572571 N	275.9	237.7	38.2
62	-91.51	98.2313404 W, 29.07572571 N	-93.00	98.23178449 W, 29.07552568 N	276.4	240.6	35.8
63	-93.01	98.23178919 W, 29.07552365 N	-94.50	98.23223777 W, 29.07533201 N	277.0	242.8	34.2
64	-94.51	98.23223973 W, 29.07533118 N	-96.00	98.23268962 W, 29.07513918 N	273.2	240.4	32.8
66	-97.51	98.23314336 W, 29.07494563 N	-99.00	98.23359681 W, 29.07475861 N	282.9	252.0	31.0

(b)

Table 53. (a) Uniformly Low Temperatures Are Not Reported as Thermally Segregated, in Contrast with (b) Less Uniform but Higher Placement Temperatures.

The field findings and the example in Table 53 highlight the need for further improvements in the thermal segregation analysis procedure outlined in Tex-244-F. The current method, primarily developed to address truck-end or cyclical segregation, may not adequately assess the overall quality of asphalt mixture placement operations. Therefore, it is recommended that additional future work be undertaken to explore updated or modified methods for analyzing and reporting thermal profile data.

CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS

Results and findings from this project support the following conclusions derived from the literature review, feedback on strengths and weaknesses, benchmarking, demonstration projects, laboratory programs, and visits to constructed projects.

8.1. LITERATURE REVIEW

The literature provides valuable insights into equipment, methods, and incentives/disincentives that can inform TxDOT's efforts to update its thermal profiling requirements:

- **Equipment:** Evaluation of potential new suppliers aligning with AASHTO PP 80 is recommended for nonproprietary compliance with Tex-244-F.
- **Methods:** There have been minimal changes in the methods used for continuous thermal profiling since its introduction. A broad consensus exists among industry professionals to use 150-ft profile lengths, exclude paver stops, and include data from the full width of the material. It is recommended that TxDOT consider including data from the full material width in its thermal profiling requirements.
- **Incentives and Disincentives:** Currently, most specifications in the industry offer lump sum payment for testing. Incentives, when included, average $26.75, and disincentives average $10.67. If TxDOT decides to incorporate pay implications with thermal profiling, it is crucial to ensure that any incentive or disincentive measures comply with the Code of Federal Regulations.

8.2. FEEDBACK ON STRENGTHS AND WEAKNESSES

Industry and TxDOT responses on the strengths and weaknesses of current thermal profile methods and specifications support the following observations and conclusions:

- **Equipment of Preference:** There is a division between TxDOT and the industry on the preference for paver-mounted thermal imaging systems.
- **Frequency of Review:** The frequency of reviewing thermal profile results varies widely.
- **Interpretation of Thermal Segregation:** Significant discrepancies exist in the interpretation of recurring thermal segregation between TxDOT and the industry.
- **Importance of Practices:** Consistent plant operation and trucking are recognized as important factors in minimizing thermal segregation, while the use of material transfer vehicles is not universally recognized.
- **Benefits of Current Specifications:** The current thermal profile specifications offer benefits in terms of placement uniformity, communication, elimination of density profiles, and the ability to pave at colder temperatures.
- **Areas for Improvement:** Areas identified for improvement include better training, clarification of interpretation, review of data processing, redefinition of thermal segregation categories, and enhanced stakeholder interaction.

8.3. BENCHMARKING THE OCCURRENCE OF THERMAL SEGREGATION

Through benchmark analysis using data collected with paver-mounted thermal imaging systems, the researchers examined the level of thermal segregation that is typically observed with current asphalt mixes and paving practices. They also analyzed thermal profile results that included paver stops in the calculation of temperature differentials. Based on these evaluations, the following observations and conclusions can be made:

- Approximately 5 percent severe thermal segregation can be expected in typical paving operations.
- A maximum threshold of 10 percent severe thermal segregation allows for an expected rate of conformity of 84 percent without paver stops and 37 percent with paver stops.
- Researchers suggest setting thresholds based on a 70 percent expected rate of conformity. Table 54 summarizes these thresholds for that approximate rate of conformity based on the benchmarking results.

Table 54. Recommended Max Percentage Thermal Segregation.

Thermal Segregation Level	Excluding Paver Stops (%)	Including Paver Stops (%)
Moderate Thermal Segregation	40	40
Severe Thermal Segregation	5	20

8.4. DEMONSTRATION PROJECTS

The demonstration projects revealed that lower placement temperatures were generally associated with increased AVs in the completed mat. Rolling patterns and other factors were also found to significantly influence AVs. Thermal segregation-induced AVs could result in AVs as high as 10 percent, but active quality control testing and additional rolling could mitigate these effects.

The demonstration projects also highlighted that in-place density remained sensitive to the absolute temperature at the time of placement, despite the use of compaction aids and material transfer vehicles. Although not the primary focus of this research project, GPR proved useful for evaluating the final in-place mat density after all rolling operations.

8.5. LAB PROGRAM AND PAVEMENT PERFORMANCE

Laboratory testing on mixes collected from demonstration projects revealed a correlation between increasing AVs and decreasing performance characteristics. When simulating the expected range of low, medium, and high AV contents of these mixes in the lab, the results showed:

- Increased AVs resulted in higher rutting and reduced crack resistance. With some mixes, the higher AV contents went beyond the stripping inflection point in the Hamburg test.
- Permeability increased with higher AVs, increasing the risk of moisture damage.
- OT results demonstrated a decrease in load at the first cycle, a reduced critical fracture energy, and a reduced crack progression rate with increasing AVs.

- The impact of thermal segregation-induced AVs varied among different asphalt mixes.

Using the lab data and measured performance-related properties at different AVs representing different levels of thermal segregation, the TxME analysis conducted on several projects indicated that thermal segregation-induced AVs could reduce the pavement's lifespan by 10 years. However, depending on mix properties, their sensitivity to changes in density, traffic level, and the interaction of these factors, thermal segregation-induced AVs may impact performance but still allow the pavement to meet its design life. In practice, thermal segregation-induced AVs are likely to be localized defects and manifest as localized premature distresses. The TxME analysis suggests that the influence of thermal segregation on field performance can vary significantly depending on various factors.

8.6. CONSEQUENCES OF RECURRING THERMAL SEGREGATION

Researchers visited 13 projects that were constructed between 2013 and 2020. They analyzed thermal anomalies during pavement construction and then visited the sites to assess current conditions. Key findings included the following:

- Minimal severe thermal segregation existed in any of the projects at their time of construction. That observation aligned with the findings obtained from the benchmarking analysis.
- The locations where thermal segregation was detected based on temperature differentials showed little to no distress in the pavement's present condition.
- Some areas of distress were observed, but these areas were found to be more closely associated with low absolute placement temperature rather than temperature differentials. This observation highlights the need to review and update the methods for analyzing thermal profile data since the current Tex-244-F does not report absolute placement temperature information.

8.7. RECOMMENDED SPECIFICATION UPDATES

Based on the data, researchers recommend:

- Retain the current definition of moderate and severe thermal segregation. The current 25°F temperature differential represents a value at which TxDOT's allowable density range may be exceeded.
- Define recurring segregation as no more than two thermal profiles in a pull with severe thermal segregation. Based on existing data from over 20,000 thermal profiles, it has been observed that current practices should usually result in no more than 5 percent severe thermal segregation. Given the length of a typical paving pull, 5 percent thermal segregation translates to slightly less than two profiles.
- Consider incorporating thermal profile requirements in routine maintenance contract (RMC) projects. The temperature differential definition of thermal segregation originated to address cyclical defects in historic paving practices; researchers believe current practices on construction projects have respectably addressed severe cyclic low density. However, these current practices for construction projects have not necessarily made their

way to RMC jobs. Figure 111 shows a relatively recent location exhibiting classic signs of cyclical segregation.

Figure 111. Cyclical Segregation on RMC Project.

8.8. RECOMMENDED TEST PROCEDURE UPDATES

Based on the data analysis, researchers recommend the following:

- Disallow the use of thermal cameras: Consideration should be given to disallowing thermal cameras. Their need for constant attendance exposes operators to occupational hazards, and their level of testing coverage is extremely limited compared to the coverage provided by a thermal imaging system.
- Continue excluding paver stops: The test procedure should continue to exclude paver stops. It is ideal to maintain a continuous paving operation, and the current requirement for extra actions and additional testing when the paver stops should serve as a reasonable incentive to keep the paving train in motion.

- Modify exclusion of side areas for paver-mounted thermal imaging system: The test procedure should be modified to not exclude 2 ft from each side of the paving pull when using a paver-mounted thermal imaging system. The thermal imaging system should test the full mat width and extraneous locations excluded through data processing.

8.9. RECOMMENDED FUTURE WORK

This study's evaluation of thermal segregation has provided valuable insights into the impact of thermal segregation-induced AVs on mixture properties and potential pavement performance. Through a comprehensive assessment in laboratory and field settings, the study has significantly improved understanding of thermal segregation and its implications. While the current temperature differential approach to thermal segregation seems to have reasonably addressed the detection of cyclic low-density problems from historic paving practices to some extent, the current data analysis methods do not quantify the area of problematic locations, nor do they report locations where mix placement is excessively cold but uniform, which can lead to a large area of poor compaction. To improve the evaluation process for thermal segregation and evaluation of overall paving quality, researchers recommend the following:

- Further study and document the timing of compaction to enhance the understanding of the relationship between thermal segregation and density. While thermal profiles provide valuable insights into the temperature differentials within the pavement, they may not directly indicate the initial density of the asphalt product.
- Improve criteria for identifying thermal segregation. First, the current method only provides a uniformity metric without distinguishing between uniformly good and uniformly bad conditions. Second, the current method does not consider the area of thermally segregated locations. A profile with a localized cold spot within otherwise acceptable laydown temperatures will be reported as thermally segregated, identically to a profile with a localized hot spot within otherwise colder than desirable laydown temperatures. The first situation presents the risk of a very localized low-density area, while the second situation is more problematic because it risks a widespread area of poor compaction. However, the current thermal profile method does not distinguish between the two situations. Further work is needed to update the thermal profile analysis criteria to address area and absolute temperature.
- Consider shadow testing nondestructive GPR for uniformity and density assessment in quality assurance and control. While not a focus of this current research, results showed GPR to be a promising tool for evaluating the completed mat after all rolling.

CHAPTER 9. VALUE OF RESEARCH

Table 55 presents value areas and a description of these value areas in context to the project.

Table 55. Benefit Areas of Research.

Value Area	Description
Level of Knowledge	The project demonstrated current generation asphalt mixes still generally exhibit reduced density with thermal segregation. The project demonstrating that existing methods for measuring thermal segregation need improvement to better relate to pavement performance.
Management and Policy	The project established justifiable quantitative definition of recurring thermal segregation that could be included in specifications.
Quality of Life	The project demonstrated that asphalt mixes placed through maintenance contracts do not appear held to the same standard as those in construction lettings, and enhanced pavement performance could be realized by incorporating thermal segregation criteria into larger routine maintenance contracts.
Customer Satisfaction and Environmental Sustainability	The project demonstrated that mix placed at below optimal conditions could be subject to early removal and replacement. Minimizing thermal irregularities at time of placement, combined with other best practices, will result in less repairs. Less repairs over the pavement life mean less usage of raw materials in the future.
Service Life, Reduced Maintenance Costs, Materials and Pavements, and Infrastructure Condition	The project demonstrated that thermal irregularities and thermal segregation at time of construction can induce high air voids that reduce pavement life 10 years. However, the impact can depend on mix properties and the mix sensitivity to changes in density and traffic. The impacted areas also will be a percentage of each project, and strategies to address the premature distress could include (but are not necessarily restricted to) local mill and inlay repairs all the way to full mill and inlay replacement of the mix over the entire project area at a sooner date than anticipated.

For conservativeness, the economic benefit of addressing thermal segregation at time of construction could be estimated as reducing the amount of surface mixes used in maintenance contracts by 5%. For maintenance contracts, TxDOT uses about 261,000 tons of Superpave surface mixes a year at an average cost of $133/ton and about 179,000 tons of dense-graded surface mixes a year at an average cost of $126/ton. Using these assumptions, reducing the amount of surface mixes used for maintenance by 5% would save about $2.86M per year. Over 20 years with a 7% discount rate the net present value of savings would be about $18.6M.

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APPENDIX A. QUESTIONS FOR INDUSTRY FEEDBACK

Your Contact Information

1. What is your name?
2. What organization do you represent?
3. What is your contact email address?

Use of Thermal Profile

4. What thermal profile apparatus do you primarily use on paving projects?
   None
   Thermal camera
   Paver-mounted thermal imaging system
5. How frequently does your staff review thermal profile results?
   Never
   Once per project
   Once per week
   A few times a week
   Once a day
   Several times a day
   Nearly continuously while paving
6. What level of compliance is possible with current methods and specifications?
   < 5% severe thermal segregation
   < 10% severe thermal segregation
   < 25% severe thermal segregation
   < 50% severe thermal segregation
   Other (please specify)
7. How would you define "recurring thermal segregation?"
8. What are best construction practices to ensure compliance with current thermal segregation requirements?
9. What training is required for field crews to perform thermal profile in accordance with Test Procedure Tex-244-F?
10. How does using a paver-mounted thermal profiler impact your operations?
    We don't use a paver-mounted system
    It gets in the way
    It neither helps nor hinders us
    It promotes better awareness of the paving operation and allows us to obtain better quality
    Other (please specify)
11. What is the best aspect(s) of the current Tex-244-F and thermal segregation specifications? (select all that apply)
    They promote placement uniformity
    They foster communication among staff and more attention to workmanship
    They allow paving at colder temperatures and do not require density profiles when using a thermal imaging system
    We get better density when running the thermal profile system

We get better ride when running the thermal profile system Other
(please specify)

12. What key concern(s) need to be addressed in future specification or test procedure updates for thermal profile? (select all that apply)
    Interpretation of the spec needs better clarity
    How to process the data needs review
    The definitions of “moderate” and “severe” thermal segregation need review
    Better training is needed on how to perform the test and use the data
    More interaction needs to take place between Contractor and Agency based on the results
    Other (please specify)

APPENDIX B. QUESTIONS FOR OWNER FEEDBACK

Your Contact Information

1. What is your name?
2. What District do you represent?
3. What is your contact email address?

Use of Thermal Profile

4. What thermal profile method does your District <u>prefer</u>?
   None
   Thermal camera
   Paver-mounted thermal imaging system
5. Where are thermal profile results maintained? (select all that apply)
   We don’t know
   With the Contractor
   Hard copies with project files
   Electronic copies with District Staff
   Site Manager
   Other (please specify)
6. When a Contractor is using a paver-mounted thermal profiler, how frequently does your staff review those thermal profile results?
   Never
   Once per project
   Once per week
   A few times a week
   Once a day
   Several times a day
   Nearly continuously while the Contractor is paving
7. How would you define “recurring thermal segregation?”
8. Has your District experienced problems with recurring thermal segregation? Yes
   No
   I’m not sure
9. What action(s) typically occur in your District when a project has recurring moderate or severe thermal segregation (check all that apply)
   Nothing changes
   The Contractor makes process changes
   Density profiles
   Paving is suspended
   Other (please specify)
10. What are common cause(s) of thermal segregation <u>in your District</u> (select all that apply)
    Long haul distances from plant to job site
    Little or no remixing of material from the end of truckloads
    Paver stops
    Other (please specify)

11. What is the best aspect(s) of the current Tex-244-F and thermal segregation specifications? (select all that apply)
    They promote placement uniformity
    They foster communication among staff and more attention to workmanship
    They allow paving at colder temperatures and do not require density profiles when using a thermal imaging system
    Contractors get better density when running the thermal profile system
    Contractors get better ride when running the thermal profile system
    Other (please specify)
12. What key concern(s) need to be addressed in future specification or test procedure updates for thermal profile? (select all that apply)
    Interpretation of the spec needs better clarity
    How to process the data needs review
    The definitions of "moderate" and "severe" thermal segregation need review
    Better training is needed on how to perform the test and use the data
    The thermal camera should be disallowed and all testing should require a paver-mounted thermal profiler
    More interaction needs to take place between Contractor and Agency based on the results
    Other (please specify)
13. Do you have a current or an upcoming project that will use a thermal imaging system?