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16. Abstract This project conducted work to investigate the performance of asphalt surface mixtures that exhibited thermal segregation during construction. From 2004 to 2009, a total of 14 construction projects were identified for monitoring. Five of these projects did not exhibit thermal segregation, while the remaining projects did exhibit thermal segregation. In all cases, a Pave-IR thermal profiling system collected data during construction. Follow-up surveys using visual examination, ground-penetrating radar, and in some cases focused coring, were used to evaluate whether the locations of thermal segregation showed significant distress. The projects constructed free of thermal segregation have not shown any distress due to segregation. Results from projects constructed with thermal segregation present were mixed. In some cases, traffic action seems to have homogenized the pavement surface. On other projects, evidence of thermal segregation still exists shown by different surface appearance and localized changes in radar data. One project showed evidence of cracking due to segregation. Core results from field projects suggested the segregated locations will be more prone to cracking. This research project's results certainly do not show that thermally segregated locations will definitely fail within three to seven years of service; however, the results do show that instances of thermal segregation may continue to be anomalous locations in the layer, even after subsequent overlays, and exhibit properties that could lead to failures in the pavement structure.					
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# **PERFORMANCE MONITORING PAVEMENTS WITH THERMAL SEGREGATION IN TEXAS**

by

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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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## EXECUTIVE SUMMARY

The Texas Department of Transportation (TxDOT) initiated work beginning in 2000 to study the utility of thermal imaging during hot-mix-asphalt paving for detecting segregation in the asphalt mixture. Based upon promising results, temperature differential thresholds and a thermal profiling procedure in Test Method Tex-244-F were developed. In subsequent project work, researchers developed an automatic method of thermal profiling (called Pave-IR) using a series of infrared sensors attached to the paver and a computer to collect, process, and display the results.

While the initial research work in Texas with thermal segregation focused on whether the mixture properties at thermally segregated locations exceeded the operational tolerances allowed at the time of construction, this research project sought to investigate the pavement condition of projects with thermal segregation after exposure to traffic and environmental cycling. A total of 14 projects were monitored in this project. The projects constructed without thermal segregation range in age from two to seven years, and currently none of them show distress due to segregation.

Projects constructed where thermal segregation was observed during construction also range in age from two to seven years. Field results from these projects are mixed. Most projects did not exhibit any distress at locations of known thermal segregation, and in some cases the ground-penetrating radar (GPR) data suggest traffic action has homogenized the pavement surface. In other cases, evidence of thermal segregation was still evident, generally noted by differences in surface appearance and localized decreases in the surface dielectric from GPR. One project showed evidence of cracking from segregation, although that cracking was not within the limits of the section monitored during construction.

Performance testing cores after some years of service also provided mixed results. The results suggested thermal segregation did not impact the Hamburg results. Overlay test results suggested the thermally segregated locations may exhibit higher susceptibility to cracking; these results though were project-specific.

While not monitored during construction, several projects around the state exist where cyclic segregation likely caused early pavement deterioration. Failures on several forensic investigations have been at least partially attributed to cyclic localized defects in subsurface mixtures. Additionally, several recent projects exist where cyclic cracking and raveling occurred within a few years of construction. Although not monitored at the time of construction, these locations of early failure almost certainly would have shown up as thermal segregation.

The results from this project suggest the eventual manifestation of thermal segregation as pavement distress is a complex phenomenon that could be a function of many factors. This project's results certainly do not show that thermally segregated locations will definitely fail within three to seven years of service. However, the results do show that instances of thermal segregation may continue to be anomalous locations in the layer, even after subsequent overlays, and exhibit properties that could lead to failures in the pavement structure. Due to this finding, and the fact that localized distress in a buried pavement layer is quite costly to fix, the

researchers recommend that TxDOT continue to promote uniform quality in asphalt mixture construction using best practices, including inspections for thermal segregation.

## CHAPTER 1. PROJECT SCOPE AND METHODS

This project sought to evaluate the performance of overlay projects where thermal segregation occurred during construction. TxDOT defines thermal segregation as temperature differentials exceeding 25°F at the time of placement. The current test method for thermal profiling allows the use of a handheld infrared thermometer, a thermal imaging camera, or paver-mounted infrared bar (Pave-IR). Since Pave-IR is the only one of these three methods that can provide 100 percent testing coverage, the research team began identifying projects for monitoring by reviewing thermal profile data from projects tested during the development of Pave-IR. The research team also collected data at the time of construction on numerous additional projects. Combined, this resulted in monitoring 14 projects.

To evaluate performance, the initial thermal profile data often were coupled with a complementary GPR survey with coring at the time of construction. Then, at the end of this research project's performance period, researchers conducted visual and radar surveys of the sections, resulting in sections ranging from two to seven years old. On several construction projects, field cores also were collected to test laboratory properties of segregated and non-segregated locations after several years of service. The research team then used the field performance over time and the core results to analyze the performance of the projects.

Table 1 summarizes the construction projects evaluated, grouped according to whether thermal segregation occurred at the time of construction or not. Chapter 2 of this report presents the results from projects constructed without thermal segregation, while Chapter 3 presents results from projects where thermal segregation occurred during construction. Chapter 4 presents examples of early failures observed on construction projects likely due to segregation, although those projects were not monitored during construction. Chapter 5 presents conclusions and recommendations from this research project.

**Table 1. Projects for Investigation.**

	<b>Pavement I.D.</b>	<b>Mix Type</b>	<b>District</b>	<b>Date Tested</b>
<b>Without thermal segregation</b>	IH 20	1" Superpave	Odessa	May 11, 2004
	IH 10	Type D	Houston	April 2007*
	US 75	Type D	Paris	Dec 3, 2008
	IH 40	Type C	Amarillo	Aug 11, 2009
	US 81	Type C	Fort Worth	Sept 10, 2009
<b>With thermal segregation</b>	BU 290	Type D	Houston	Aug 12, 2004
	US 77	Type C	Yoakum	May 10, 2006
	IH 10	CRM	Odessa	August 2006*
	BU 59	CAM	Lufkin	July 31, 2008
	US 90	CAM	San Antonio	Sept 23, 2008
	FM 2440	Type C	Austin	Oct 2008
	Parmer Lane	Type C	Austin	March 24, 2009
	SH 6	PFC	Bryan	May 13, 2009
US 190	SMA-D	Beaumont	Sept 29, 2009	

\*Thermal profile data collected by Contractor



## **CHAPTER 2. RESULTS FROM PROJECTS WITHOUT SIGNIFICANT THERMAL SEGREGATION**

### **SUMMARY**

Five projects were constructed and monitored that did not exhibit thermal segregation during construction. While distress does exist on some of the projects, no distress observed appears due to uniformity problems with the surface mix. However, on one project, cyclic segregation in subsurface mix seems a likely cause of the deterioration that occurred.

### **IH 20 1 IN. SUPERPAVE, ODESSA DISTRICT, CONSTRUCTED MAY 11, 2004**

On this project, the contractor used belly dump trucks, a Roadtec SB-2500B, and a Vogele 1110WB paver. The haul distance was approximately 50 miles and the trucks were tarped. Texas Transportation Institute (TTI) researchers started testing at station (STA) 578 -29, which is just past the FM 829 bridge, and tested in the eastbound outside lane. Figure 1 shows the start location and the paving train.



**Figure 1. IH 20 1 In. Superpave Site.**

TTI collected 1200 ft of data with the infrared sensor bar by collecting a scan every 2 in., and 2000 ft of data with GPR by collecting a data point every foot. With GPR, TTI performed five passes each at a different transverse offset and then collected stationary readings over four locations that were then cored. Lab results from these cores served to calibrate the relationship between dielectric and in-place air voids.

## Thermal Profile Results

Figure 2 presents the thermal profile results. Due to the breaking up of the data files, the distance scale starts over at zero for each plot. The top plot is 0 to 400 ft, the middle plot is 400 to 800 ft, and the bottom plot is 800 to 1200 ft. When paving started, the ambient air temperature by the paver was 95°F and winds were calm. The thermal profile shows the following:

- There is some noticeable variability in temperatures between trucks, but overall temperature uniformity is good. Temperatures across each transverse scan are very uniform, typically ranging less than 15°F from the min. to max. temperature. Recommendations from prior work suggest temperature uniformity should be within 25°F.
- The 257.8°F cold spot at 780 ft (380 ft into middle plot) is not due to segregation, but resulted from cold water spilling onto the mat when a worker got water from a cooler.

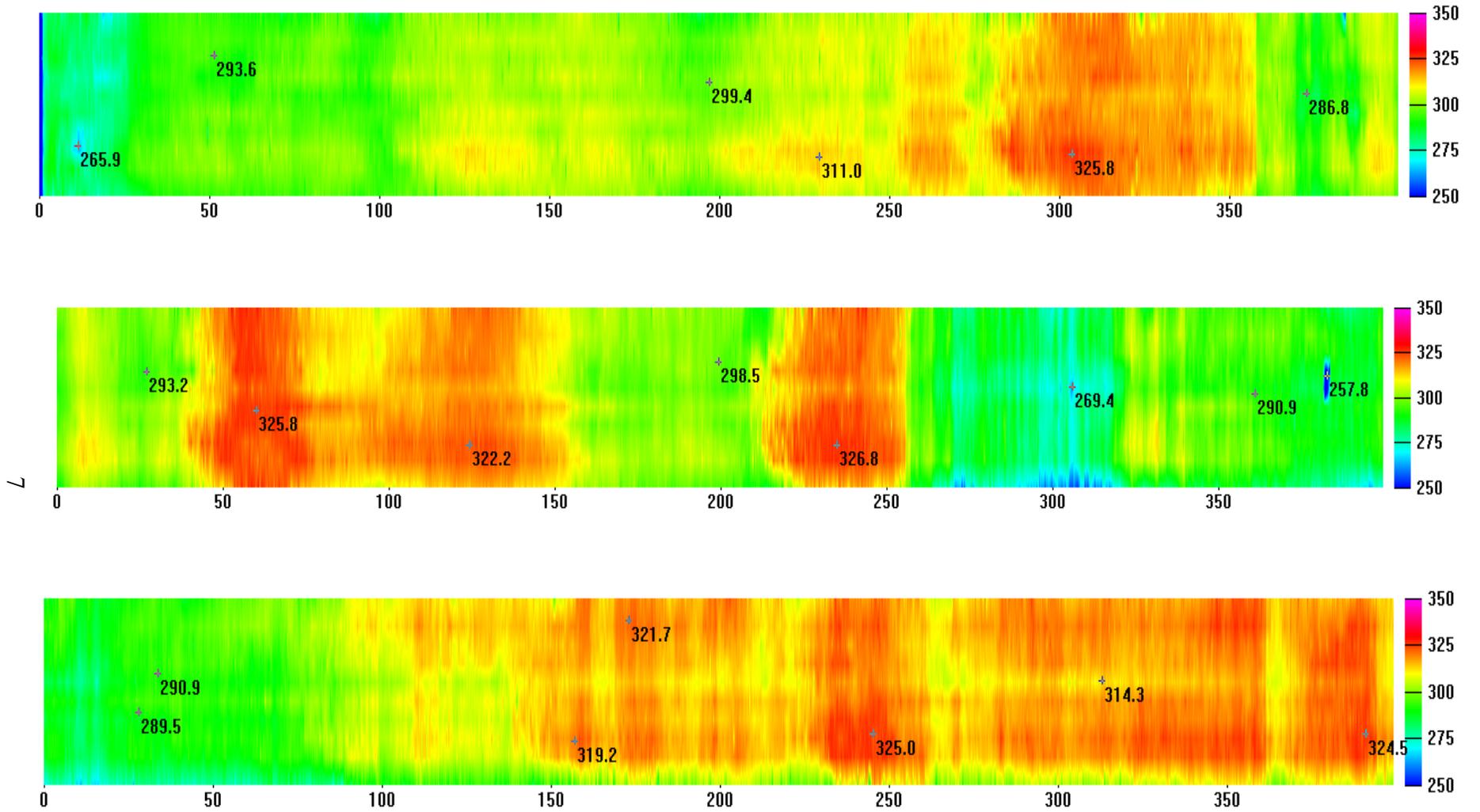


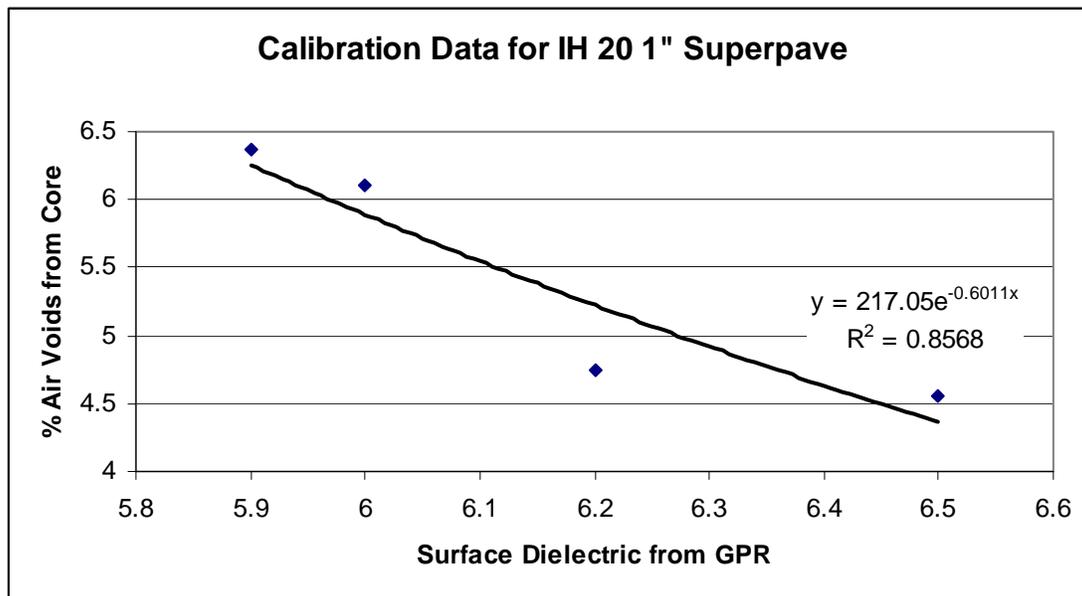
Figure 2. Infrared Data on IH 20 Starting at Station 578 -29.

## GPR Results at Time of Construction

Table 2 summarizes the coring results used to calibrate the relationship between dielectric and air voids. Figure 3 graphically shows the calibration. Based upon the determined relationship, the data from the five GPR runs were converted into a plot of predicted in-place air voids. Figure 4 shows this plot. Additionally the GPR data, with about 10,000 data points, can be used to estimate the percent of the section with air voids within a given range. Figure 5 shows this distribution. Based on the results, 95 percent of the test section is expected to have air voids between 4.6 and 6.2 percent. The minimum predicted air void content is 3.6 percent and the maximum predicted air void content is 7.5 percent.

**Table 2. Summary of Coring Results from IH 20.**

Core	Dielectric	Bulk Density (pcf)	Percent Air Voids
1	6.2	146.6	4.7
2	6	144.5	6.1
3	5.9	144.1	6.4
4	6.5	146.9	4.5



**Figure 3. Calibration of Relationship between Dielectric and Air Voids on IH 20.**

6

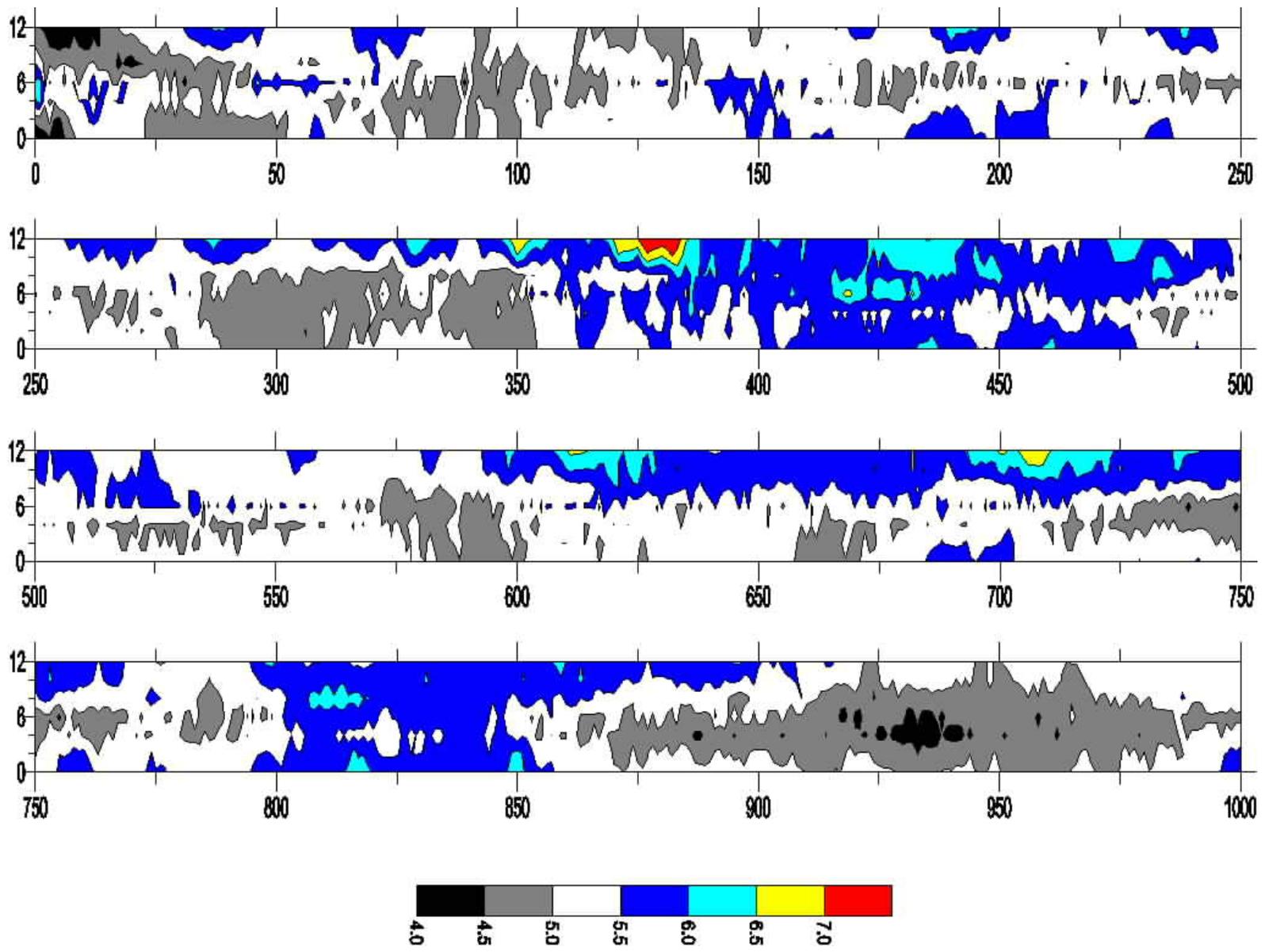


Figure 4. Predicted Air Voids for IH 20 Test Section.

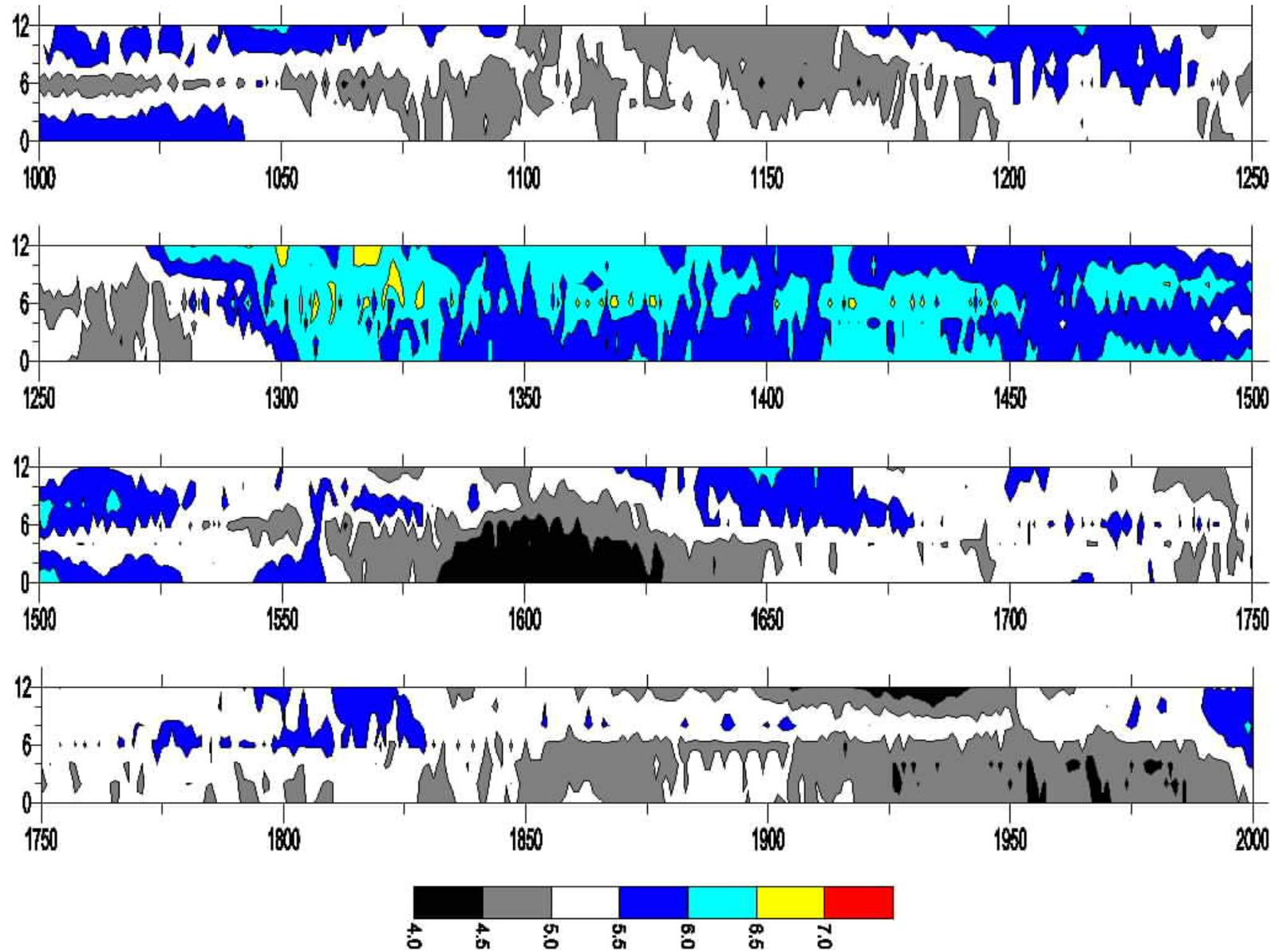
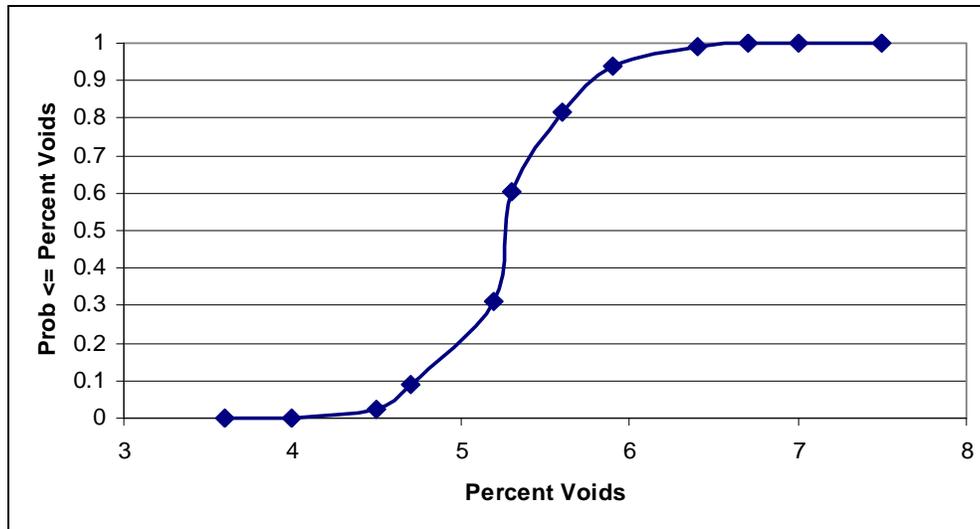


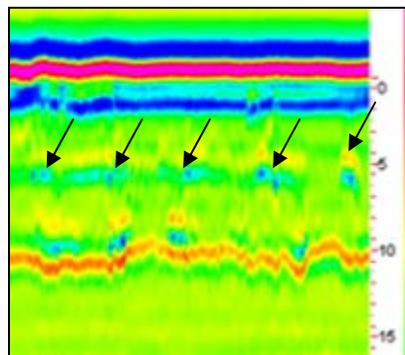
Figure 4. Predicted Air Voids for IH 20 Test Section (continued).



**Figure 5. Distribution of Predicted Air Voids on IH 20 Test Section.**

### **Follow-Up Survey Results on IH 20**

In late 2009, TxDOT reported that this project had some leveling work performed by maintenance forces due to rutting. In 2011, TTI conducted a radar survey over the section; Figure 6 presents an example from these radar data. The data show the surface mix appears good; however, the GPR indicates possible localized problem areas in the subsurface mixture. These areas may be cyclical segregation that could result in distress occurring over time.



**Figure 6. Example GPR on IH 20 after Seven Years of Service.**

### **Conclusions from IH 20**

Data collected during construction on the IH 20 paving project showed good placement and density uniformity. After seven years of service, some problems have occurred throughout the project. Current GPR indicates that some portions of the project may have subsurface defects, which could have contributed to the problem. The performance suggests ensuring quality on lower-layer mixes is just as important as ensuring quality and uniformity on the final surfacing.

## IH 10, HOUSTON DISTRICT, CONSTRUCTED MARCH-APRIL 2007

To collect thermal profiles on this project, TTI trained the contractor on how to install and collect the thermal data with Pave-IR, after which the contractor collected thermal profiles of the entire project. The project limits were from 0.265 mi. east of FM 359 to the Brazos River for a total distance of approximately 4.71 miles.

### Paving Operation

The contractor used both belly and end dump trucks to transport the mix, where it was windrowed then picked up by a Roadtec Shuttle Buggy and transferred to a Blaw Knox PF 3200 paver for placement.

### Thermal Profile Results

Figure 7 shows illustrative data from the thermal profiles. Thermal uniformity overall was good, with the main anomalies being slight variations in mean truck arrival temperatures.

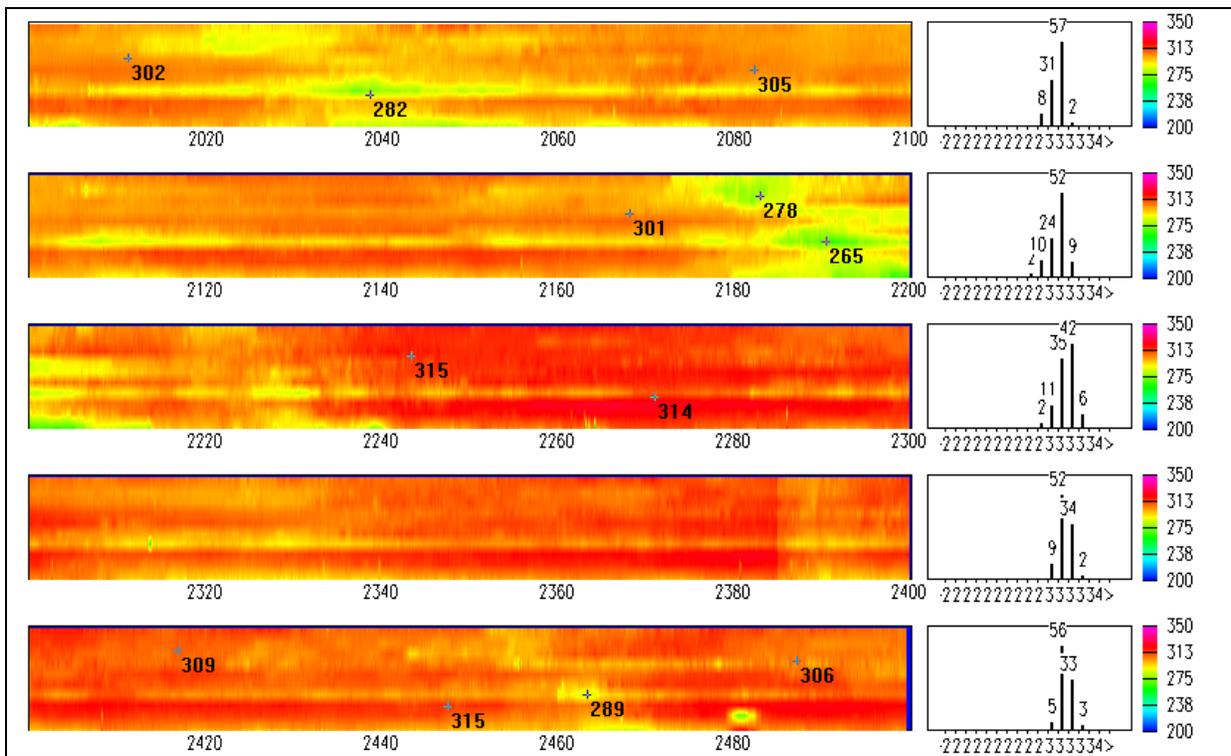


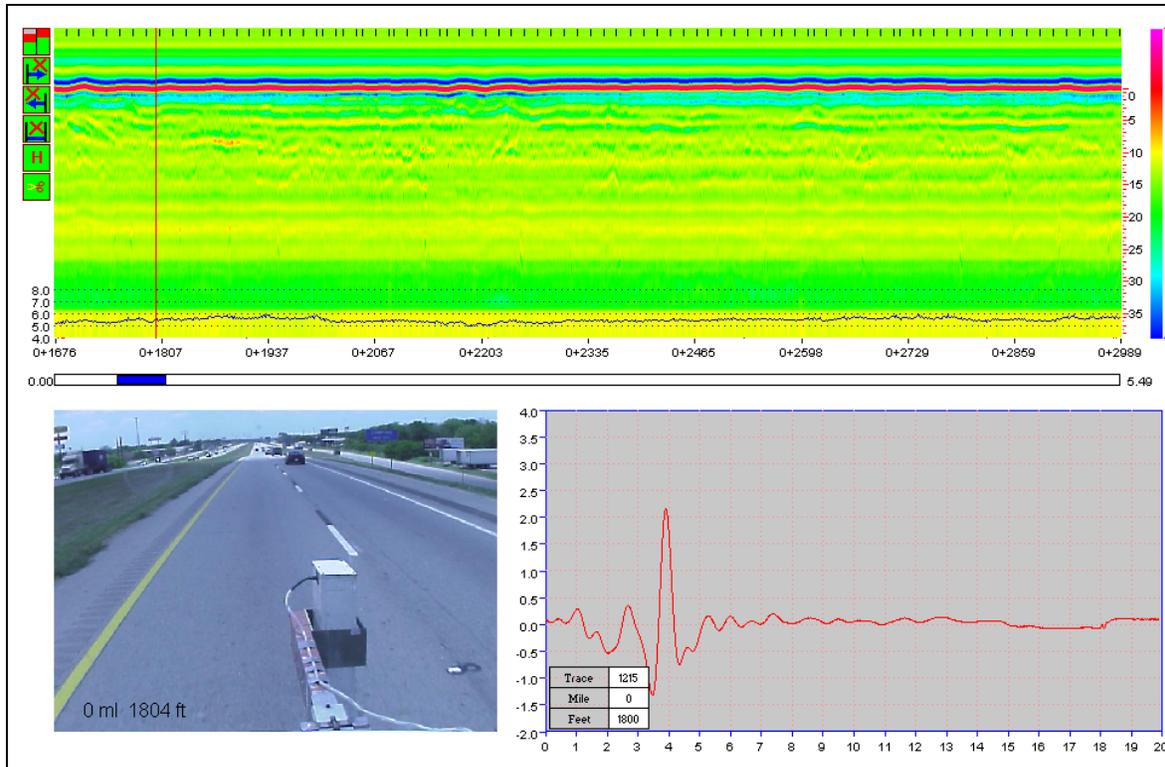
Figure 7. Example Thermal Data from Houston District IH 10.

## **Follow-Up Survey Results on IH 10**

In July 2011, TTI conducted a visual and GPR survey of this project. The only distresses noted were occasional transverse cracks, as Figure 8 illustrates, and occasional longitudinal cracking on the shoulder. The longitudinal cracking was likely due to the subgrade and dry weather pattern that existed at the time of the survey. The GPR survey did not reveal any items of concern, with clean, uniform traces and uniform surface dielectric values. Figure 9 presents an example excerpt from the GPR data collected over the westbound inside lane.



**Figure 8. Example Transverse Cracking on IH 10 after Four Years of Service.**



**Figure 9. Example GPR on IH 10 in July 2011.**

### **Conclusions from IH 10**

The data collected during construction on IH 10 showed excellent thermal uniformity with no major causes of concern. Similarly, after approximately four years of service on the interstate, the mix appears to be performing well.

### **US 75, TYPE D, PARIS DISTRICT, CONSTRUCTED DECEMBER 3, 2008**

On December 3, 2008, researchers from TTI conducted a thermal and GPR survey on the 2-inch thick Type D hot mix asphalt (HMA) placed on US 75 in the Paris District. Although planned as a warm mix asphalt (WMA) project, on this particular day the plant produced the mix as a hot-mix without the WMA additive.

### **Paving Operation**

The contractor produced the mix in Denison and hauled the mix to the site in tarped flow boy trailers. A Roadtec SB-1500 transferred the mix to a Roadtec RP-180-10 paver. Figure 10 shows the paving operation.



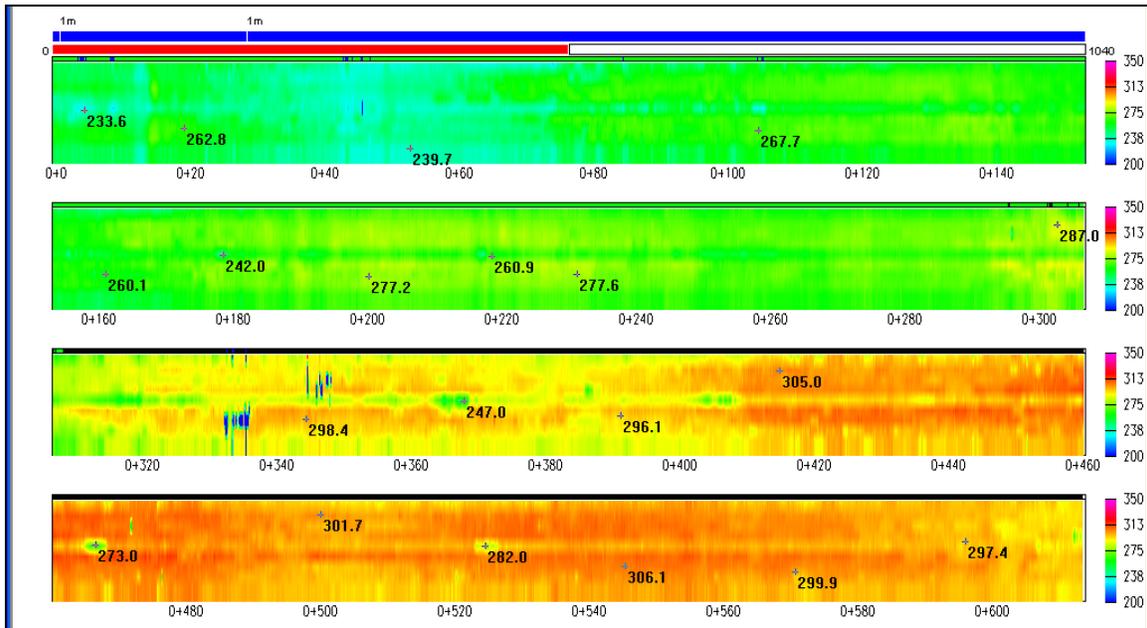
**Figure 10. Paving Operation on US 75.**

### **Thermal Profile Results**

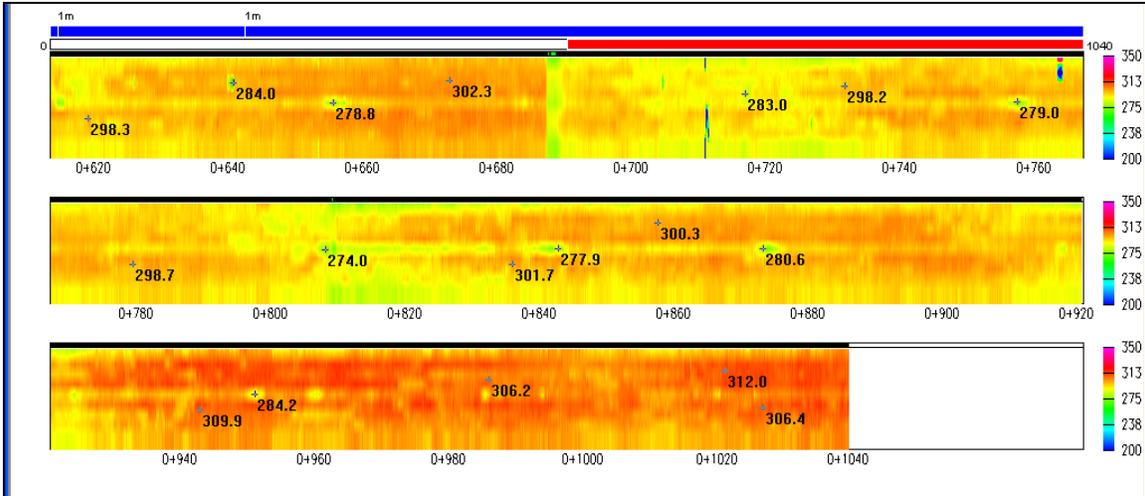
Figure 11 shows a Pave-IR system collecting project data on US 75. In the thermal survey, the “zero” distance point is approximately 15 ft north of the northern end of the bridge deck over Center Road. Figure 12 shows the IR data collected on the first approximately 1000 ft of paving. The data show that the first two truckloads of mix were somewhat cooler than the rest of the loads, with placement temperatures between approximately 230 and 275°F. After those first initial truckloads, the mix placement temperatures appeared to stabilize within a narrow temperature window of approximately 280° to 310°F. Although the thermal profile also shows recurring thermal differentials at approximately 40-ft intervals in the lane centerline, after the first two truckloads the magnitude of these differentials was only between approximately 20° and 30°F, which should not cause concern.



**Figure 11. Pave-IR Collecting Thermal Profile on US 75.**

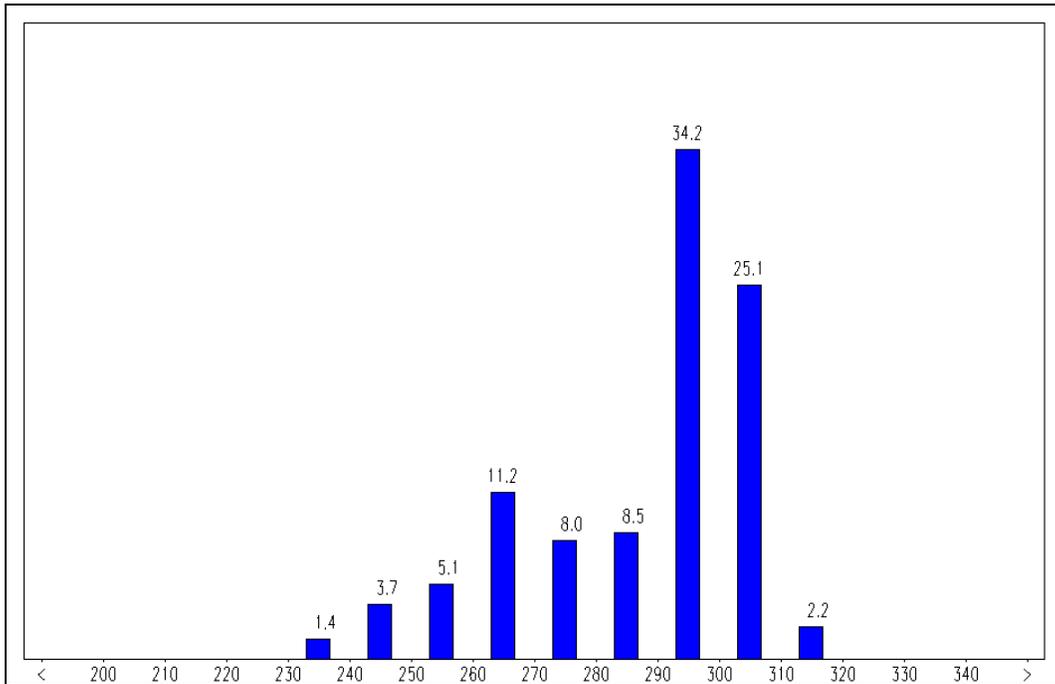


**Figure 12. Thermal Profile at Start of US 75 Paving on 12-3-08.**



**Figure 12. Thermal Profile at Start of US 75 Paving on 12-3-08 (continued).**

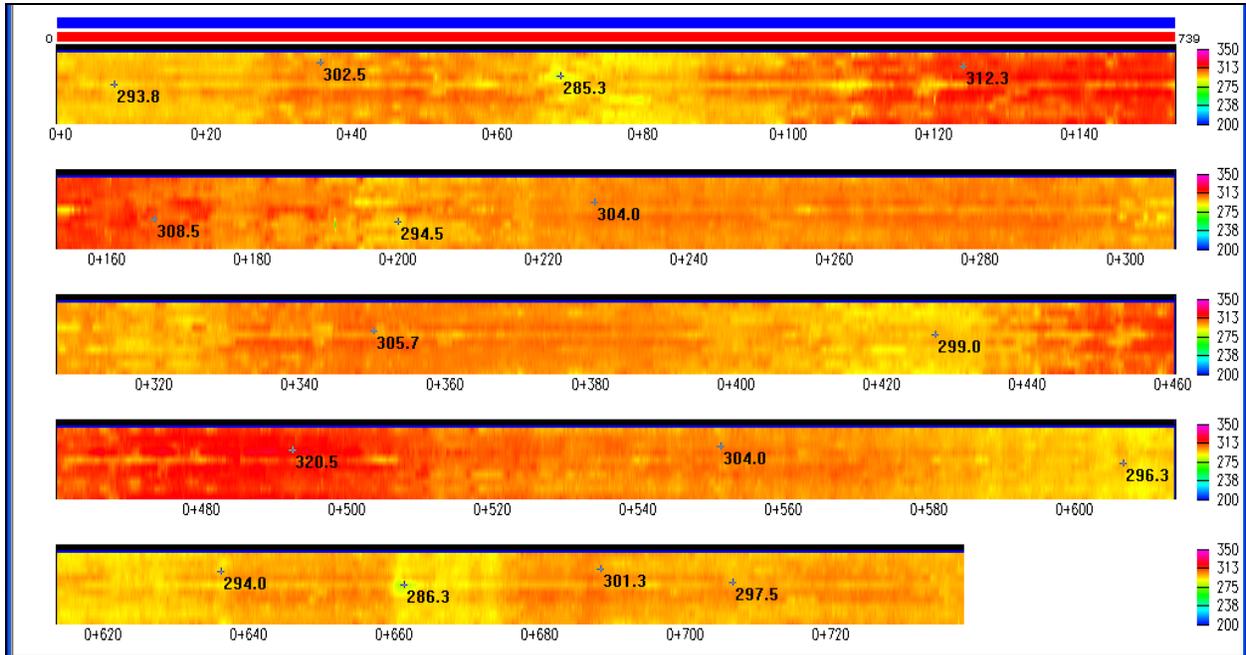
Figure 13 presents a histogram representing the temperature distribution of the section profiled with Pave-IR. The impact of the cooler first truckloads is clearly evident with the histogram skewed to the left. However, if the impact of the first two truckloads is excluded, the paving train shows excellent thermal uniformity.



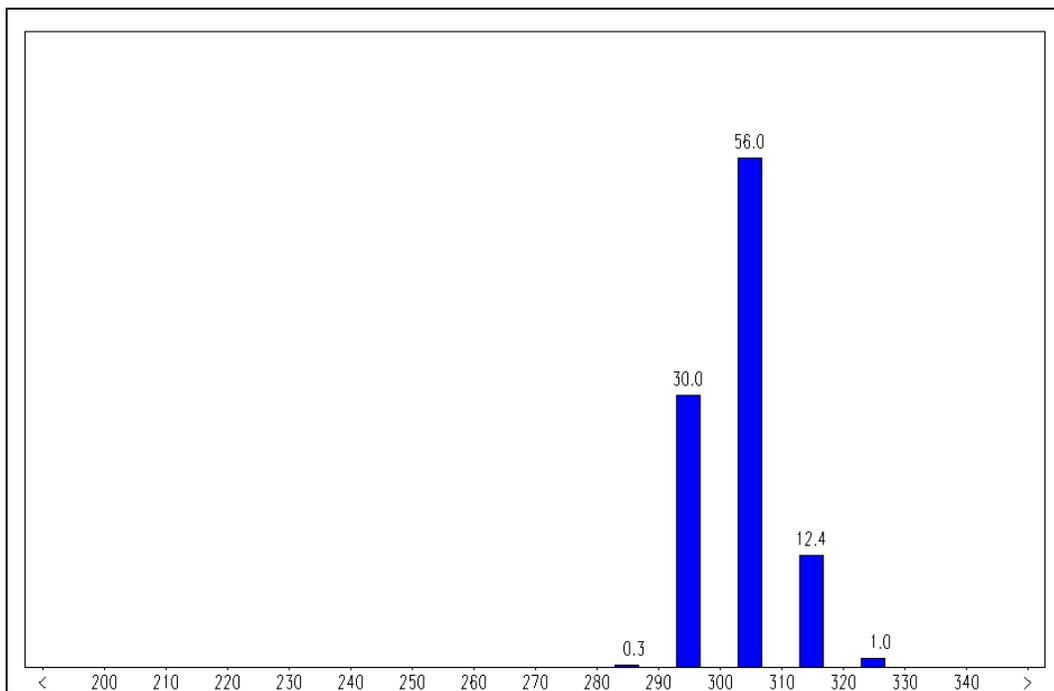
**Figure 13. Temperature Histogram for Start of US 75 Paving Run.**

For comparison purposes, another set of thermal profile data was collected beginning on US 75 southbound (SB) beginning across from W. Dulin Street and continuing until the contractor neared the stopping point for the day. This profile covered approximately 710 ft of paving and is shown in Figure 14. At this point, the contractor's operation appeared to have stabilized with placement temperatures falling into a narrow range of 290° to 320°F. Figure 15

presents the histogram of the temperatures recorded in this second thermal profile data set, further illustrating the narrow band of placement temperatures produced.



**Figure 14. Second Thermal Profile Collected on US 75 Type D HMA.**

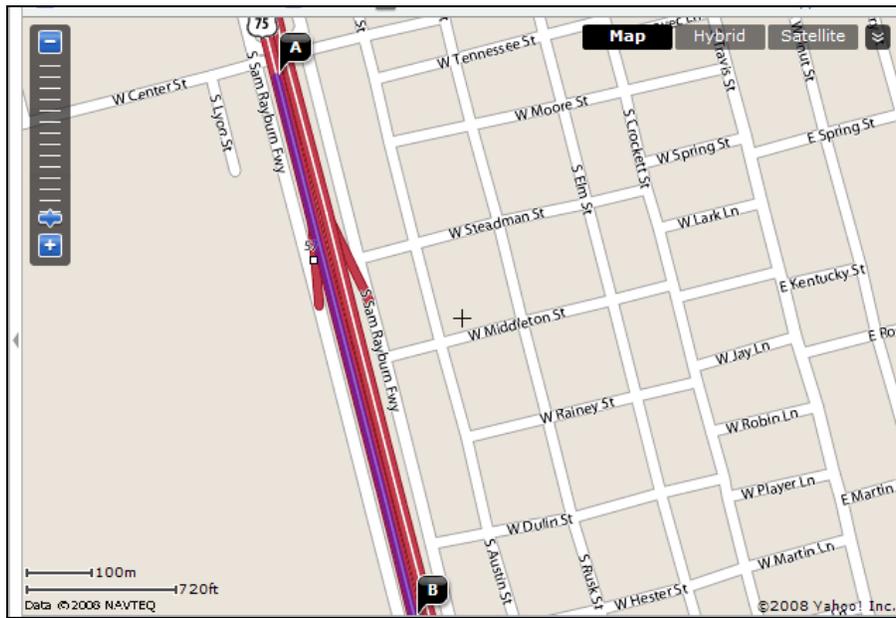


**Figure 15. Histogram of Measured Temperatures on Second US 75 Thermal Profile.**

## GPR Results at Time of Construction

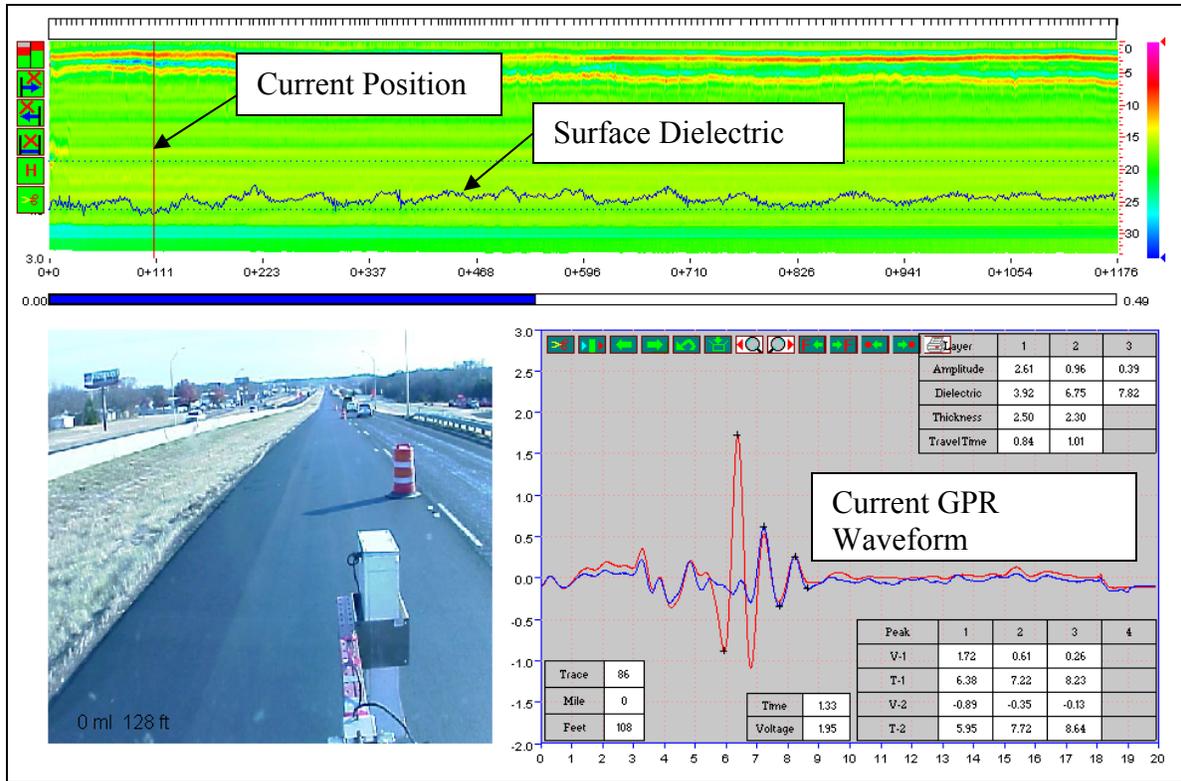
To perform a final quality check on the compacted mat, TTI performed two GPR runs at different transverse offsets over the finished mat. The first GPR run traversed between the lane centerline and outside wheel path; the second run collected data approximately over the inside wheel path. Figure 16 shows the location limits of the GPR data, which began and ended at the following GPS coordinates:

- Begin: Lat: 33.6283 Long: -96.6136.
- End: Lat: 33.6214 Long: -96.6115.



**Figure 16. Limits of GPR Survey on US 75 SB after Construction.**

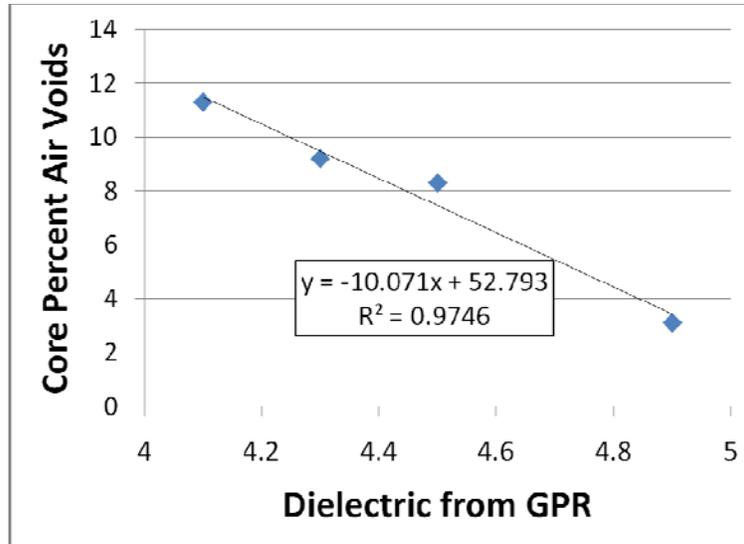
Figure 17 shows an excerpt from one of the GPR runs. At the location shown, the surface dielectric is rather low compared to the rest of the data. Based upon data review in the field, TTI selected four core locations to calibrate the GPR to density. TxDOT collected and tested the cores for air void content. Table 3 shows these data, and Figure 18 shows the calibration between the GPR data and HMA density. Although the air voids are typically predicted from the dielectric value using an exponential function, with this data set a much better fit exists by using a linear function.



**Figure 17. Excerpt from GPR Survey on US 75.**

**Table 3. Calibration Data to Correlate GPR to HMA Air Void Content on US 75.**

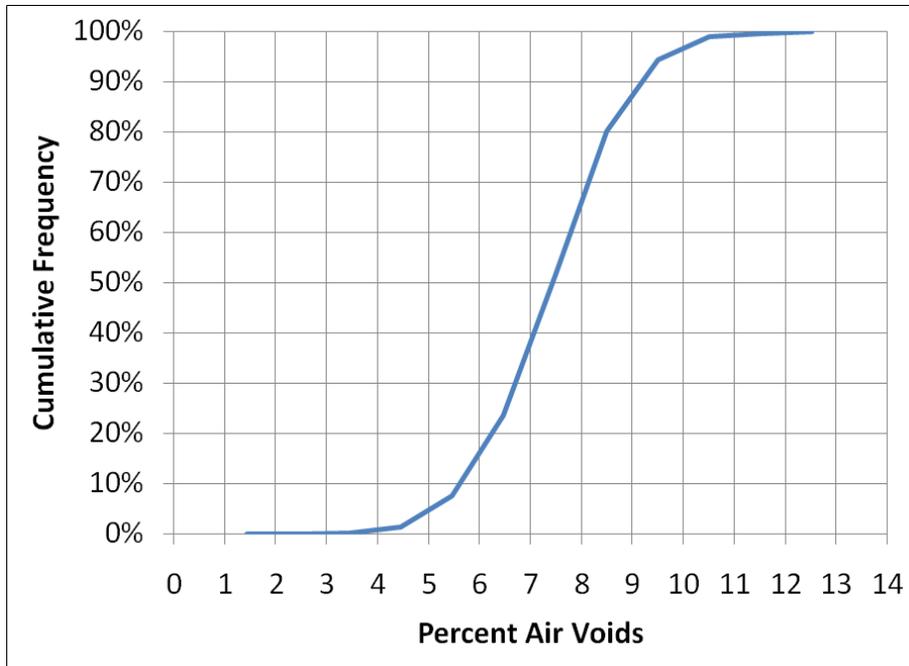
Core	Location	Dielectric from GPR	Core Percent Air Voids
1	108 ft in Run 1	4.3	9.2
2	990 ft in Run 2	4.5	8.3
3	1298 ft in Run 2	4.9	3.1
4	1538 ft in Run 1	4.1	11.3



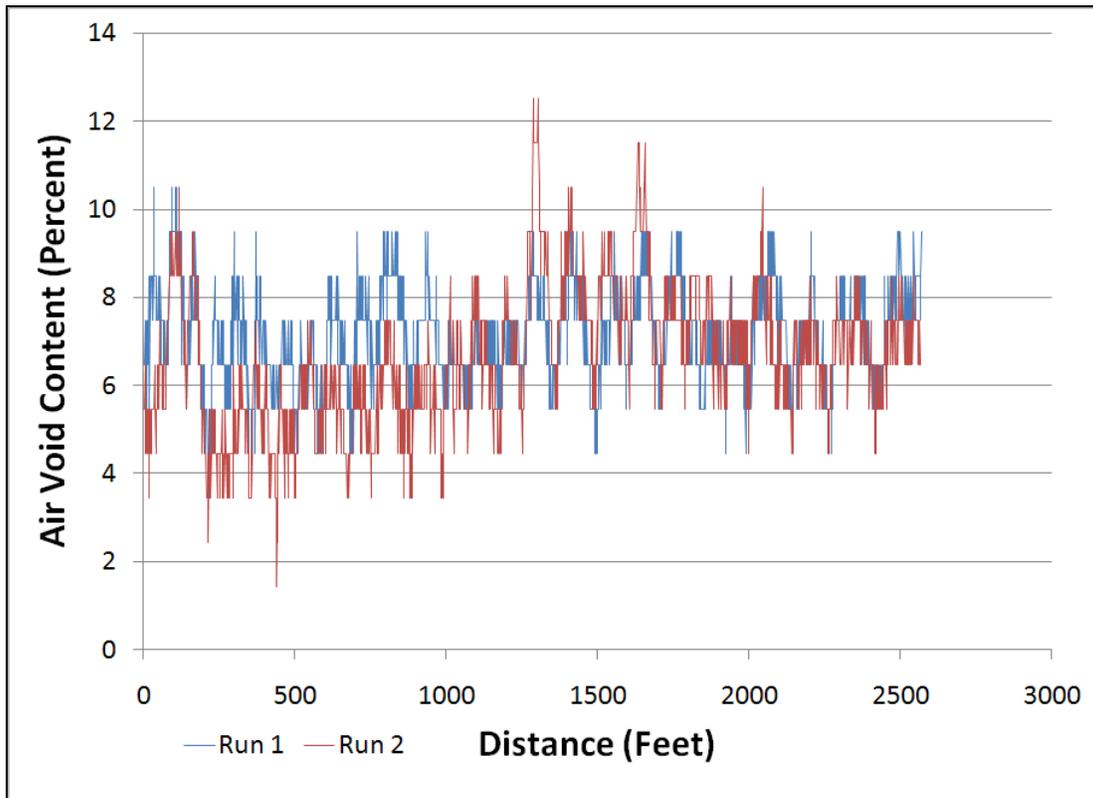
**Figure 18. Correlation between GPR and HMA Density for US 75.**

Using the calibration in Figure 18, TTI transformed each of the GPR measurements into an air void content. Between the two GPR runs, this amounts to several thousand measurements. Performing these in-place air void predictions from each of the collected GPR traces allows for the development of the air void distribution expected in the test area, as Figure 19 shows.

According to the governing TxDOT specification on this project, the contractor receives a placement pay factor of 1.00 or greater for air voids between 4.7 and 8.5 percent. From Figure 19, the GPR data suggest approximately 77 percent of the section would qualify for a pay factor of 1.00 or greater. The data also suggest approximately 3.5 percent of the section has air voids greater than or equal to 10 percent. Figure 20 shows the air void predictions with distance for both GPR runs, which suggest the locations with unacceptable air void content exist primarily at distances between 95 and 121 ft, 1288 to 1310 ft, 1407 to 1418 ft, and 1632 to 1661 ft into the GPR runs.



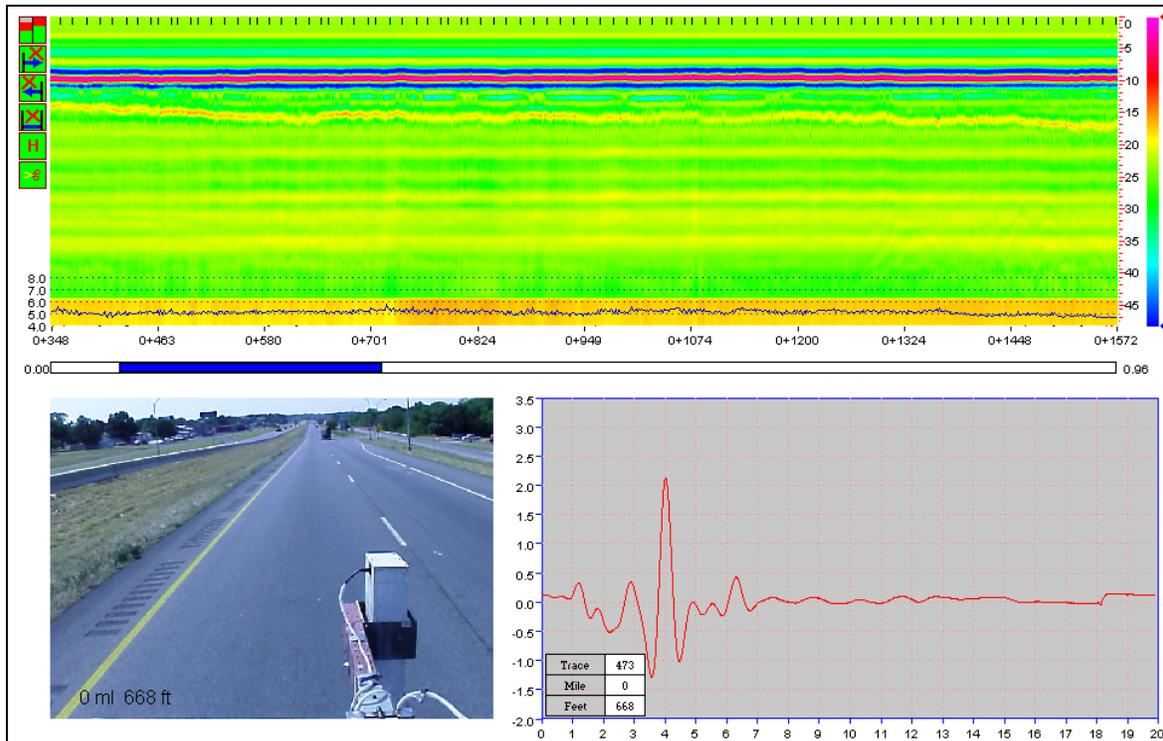
**Figure 19. Expected Distribution of Air Voids in US 75 Section Surveyed by GPR.**



**Figure 20. Predicted Air Voids with Distance from GPR Runs on US 75.**

## Follow-Up Survey Results

In August 2011, TTI conducted a visual and GPR survey of this US 75 project and noted no distresses. The GPR data similarly look good, with no odd reflections and a uniform surface dielectric. Figure 21 presents an excerpt of the GPR data from the section.



**Figure 21. Example GPR Data on US 75 in August 2011.**

## Conclusions from US 75

The results from US 75 suggest good uniformity existed during placement, with no significant thermal segregation during placement. Similarly, after approximately four years of service, the pavement was performing well with no distress observed.

## IH 40, TYPE C, AMARILLO DISTRICT, CONSTRUCTED AUGUST 11, 2009

TTI researchers conducted a thermal profile and GPR survey on Type C hot mix asphalt placed on IH 40 on August 11, 2009, in TxDOT's Amarillo District.

## Paving Operation

The contractor placed the Type C mix in the eastbound inside lane and used tarped belly dump trucks to transport the mix approximately 45 miles from the plant to the jobsite. For placing the mix, the contractor used a Roadtec Shuttle Buggy SB 2500C to transfer the mix into a Roadtec RP 190 paver, as Figure 22 shows. The contractor used a Cat CB 634D as the breakdown roller, a Cat PS 360C for the intermediate roller, and a Cat CB 534C as the finish roller.



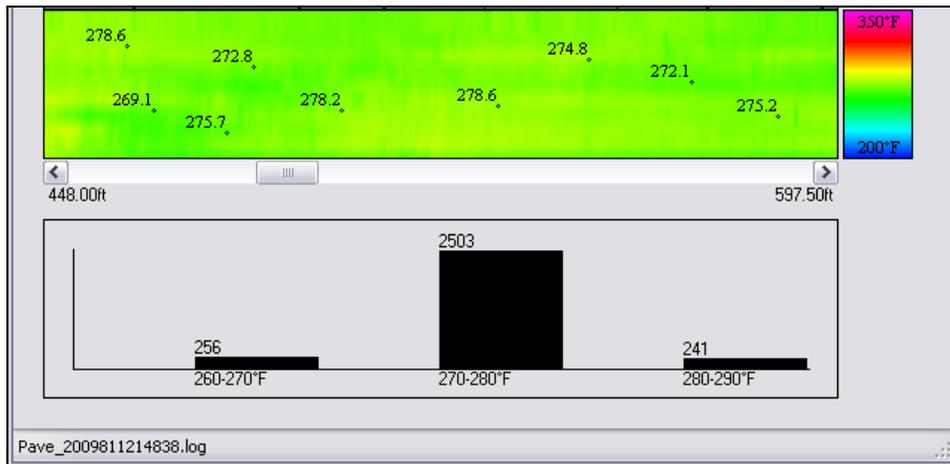
**Figure 22. Paving Operation on IH 40.**

### **Thermal Profile Results**

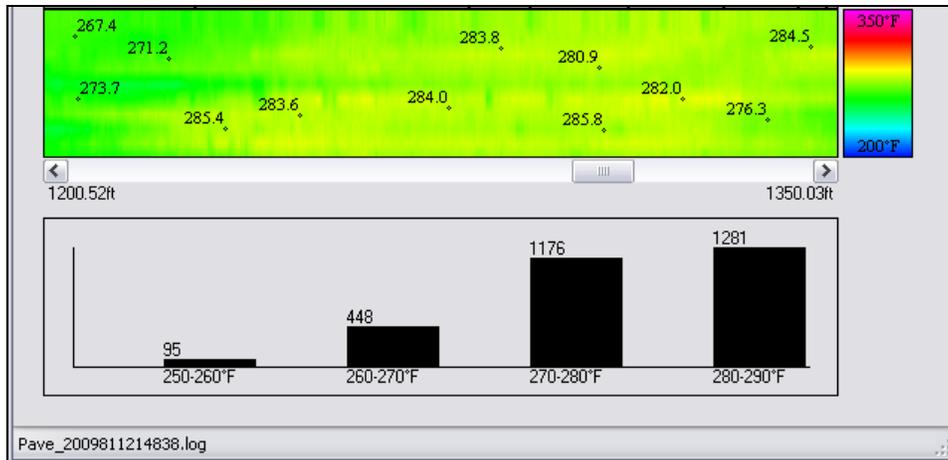
Figure 23 shows Pave-IR collecting thermal profile data on IH 40. The section investigated was the top lift of the mix with PG 64-28 binder and no RAP. This section began at STA 1056 -24 and ended at STA 1068 +15. Within 150 ft segments, the thermal differential typically ranged from 20 to 30°F, as Figure 24 illustrates. Occasional segments exist with differentials within 40°F, as Figure 25 shows. These segments with larger temperature differentials appear due to increases in the mean mix temperature, and not necessarily segregation. Additionally, Figure 26 presents the thermal profile from the entire pull, indicating minimal thermal variations. The data show that a 40-degree window (from 250° to 290°F) contained 97 percent of measured placement temperatures, as illustrated in Figure 27.



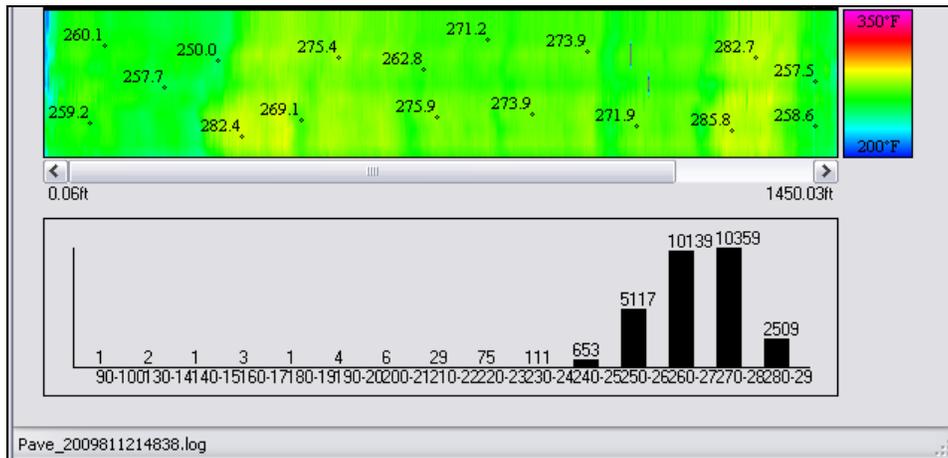
**Figure 23. Pave-IR Installed and Collecting Thermal Profile on IH 40.**



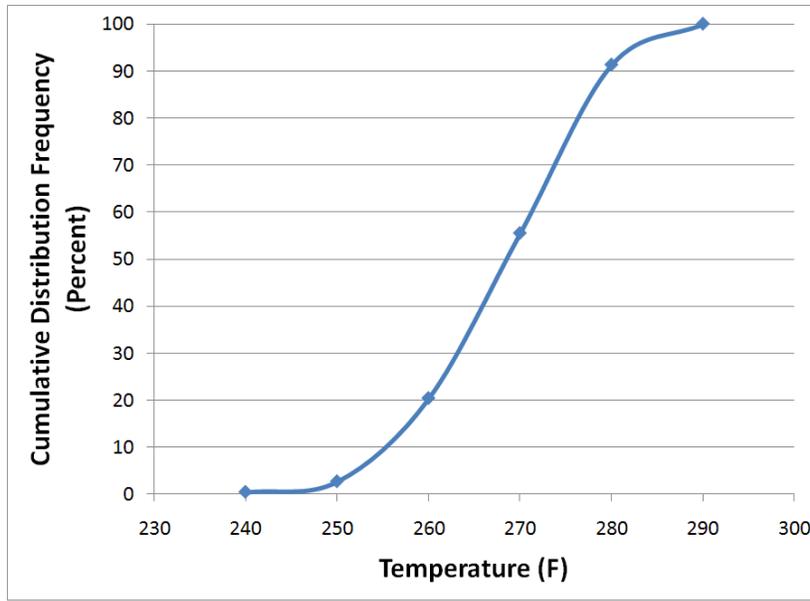
**Figure 24. Example Typical Thermal Profile from IH 40 Type C HMA.**



**Figure 25. Increase in Mean Arrival Temperature Resulting in Increased Temperature Differential within 150 Ft Segment on IH 40 Type C HMA.**



**Figure 26. Thermal Profile of Entire Pull from IH 40 Type C HMA with PG 64-28 and No RAP.**



**Figure 27. Cumulative Distribution Frequency of Placement Temperatures on IH 40 TYPE C HMA.**

### GPR Results at Time of Construction

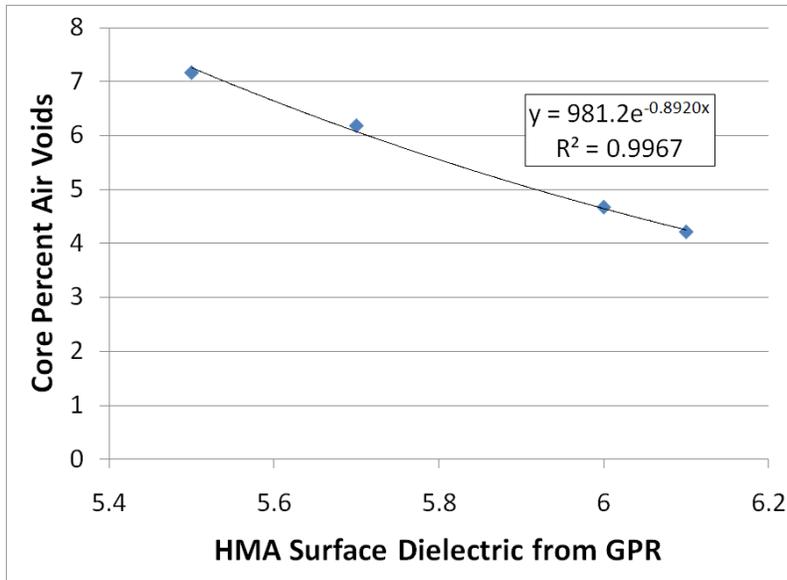
As a quality assurance check on the completed mat, TTI conducted a GPR survey using its 1 GHz air-coupled GPR system. TTI collected GPR data at 1-ft spacing over both wheel paths and the mat centerline. Due to ongoing construction operations, only approximately 970 ft of the section was profiled with GPR. After collecting the three GPR passes, researchers selected and marked locations for coring to represent the spectrum of observed surface layer dielectric values. These cores serve to calibrate the GPR-measured surface dielectric to the HMA air void content.

Table 4 presents the data collected to calibrate the GPR to air voids. The observed dispersion of measured dielectric values was small, indicating good uniformity, and the measured density range (highest to lowest) was 4.5 pcf. For reference, TxDOT specifications allow a maximum density range of 6.0 pcf for Type C mix. From these data, the relationship shown in Figure 28 calibrated the GPR to in-place mixture air voids.

**Table 4. Data to Calibrate GPR to Density on IH 40 Type C HMA.**

Core #	$\epsilon$ from GPR	Core Lab Density (pcf)	Core Percent Air Voids <sup>1</sup>
1	6.1	145.6	4.2
2	6.0	144.9	4.7
3	5.7	142.6	6.2
4	5.4	141.1	7.2

<sup>1</sup>Based on QC/QA reported  $G_r$  of 152.0 pcf; QC/QA Cores averaged 5.8 percent air voids.

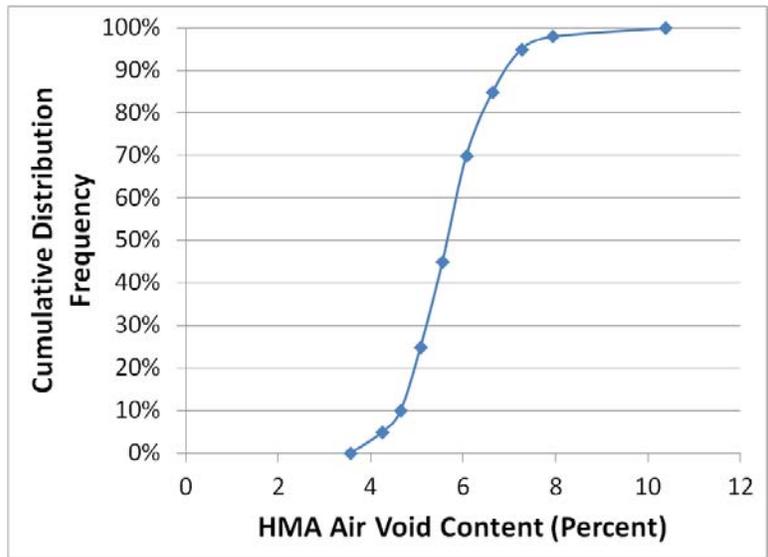


**Figure 28. Calibrating GPR to HMA In-Place Air Voids on IH 40.**

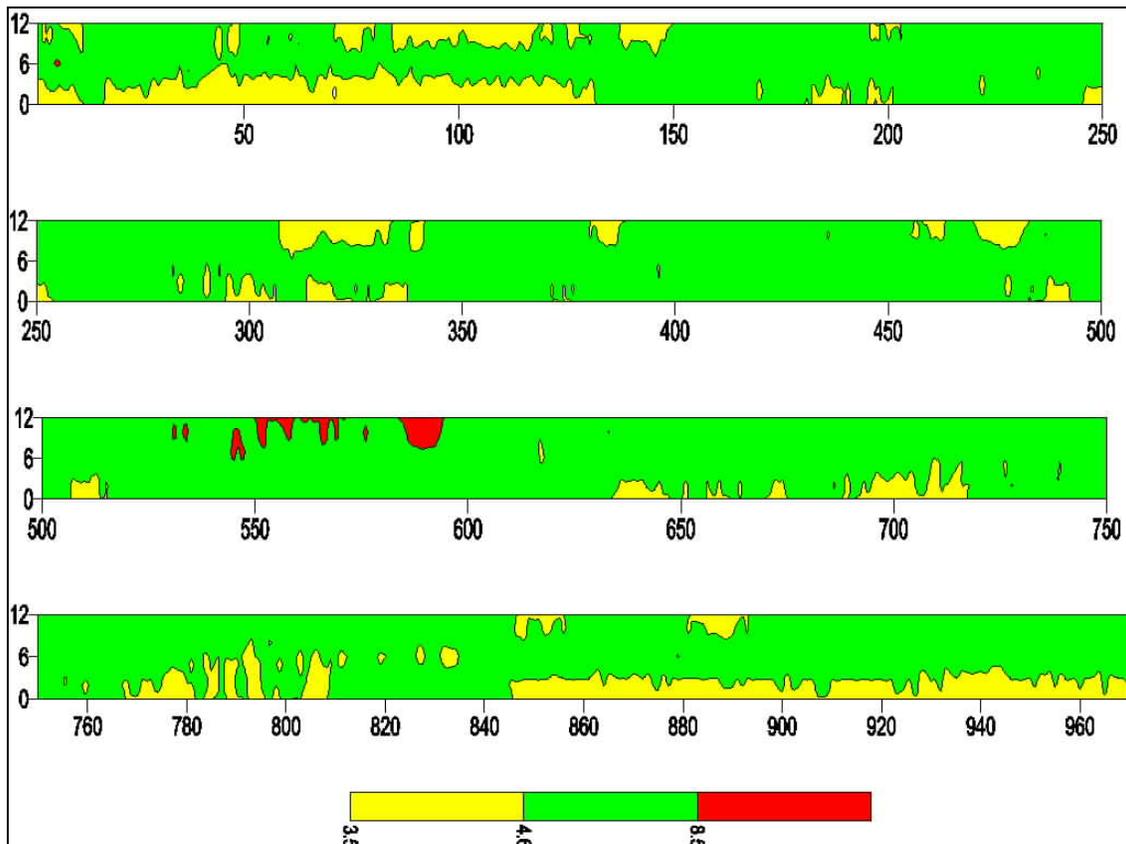
Using the calibration from Figure 28, each radar trace was converted to an air void measurement, yielding over 2100 measurements spatially over the HMA mat with summary statistics, as shown in Table 5, and distribution frequency as illustrated in Figure 29. The data show approximately 87 percent of the mat area is within the placement bonus region between 4.7 and 8.5 percent air voids. The individual air void predictions at known spatial locations on the mat also allow development of the contour map, as Figure 30 illustrates. In the location in Figure 30 with air voids exceeding 8.5 percent, the thermal data did not show any noticeable anomalies. It is, therefore, suspected that the higher air voids (from 550 to 600 ft) may have been the result of issues with the rolling operation.

**Table 5. Summary Statistics of Air Voids on IH 40 Type C HMA, PG 64-28, No RAP.**

<b>Mean</b>	5.54
<b>Standard Deviation</b>	0.91
<b>Minimum</b>	3.56
<b>Maximum</b>	10.38



**Figure 29. Cumulative Distribution Frequency of Predicted In-Place Air Voids on IH 40 Type C HMA.**



**Figure 30. Expected Air Void Content on IH 40 Type C HMA.**

## **Follow-Up Survey Results**

In April 2011, TTI visited the project site and did not observe any distress except for some transverse reflection cracking. No pavement distress, such as raveling, rutting, or fatigue cracking was observed.

## **Conclusions from IH 40**

During construction, the data collected showed good thermal uniformity with temperature differentials typically between 20° and 30°F. Occasional occurrence of higher temperature differentials seemed more resultant from increases in the mean mixture temperature. At the time of construction, the in-place mat density was good, with approximately 87 percent of the mat area expected within the bonus region.

After slightly more than two years of service on the interstate, no distress related to segregation issues exists. The only distress present is transverse reflective cracks.

## **US 81, TYPE C, FORT WORTH DISTRICT, CONSTRUCTED SEPTEMBER 10, 2009**

On this project, the contractor paved the southbound outside lane, and data collection began at station 1019 and ceased at station 1088. The beginning GPS coordinates were 97.566950 W, 33.210710 N; and the ending coordinates were 97.561840 W, 33.197150 N.

## **Paving Operation**

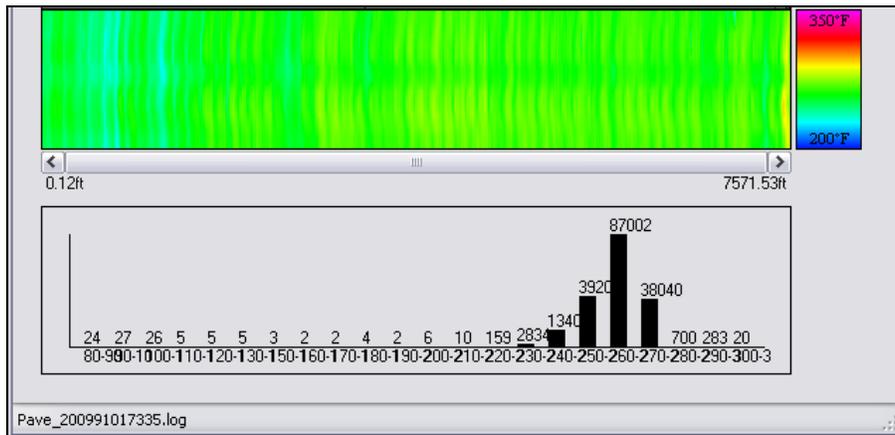
Flow boy trucks hauled the mix approximately 20 miles to the site where they offloaded into a Roadtec Shuttle Buggy SB2500D. The Shuttle Buggy transferred the mix to a Terex Cedarapids CR 252 paver. The remainder of the paving train consisted of a Sakai SW900 breakdown roller, a Sakai GW750-2 intermediate roller, and a Sakai SW 652 finish roller. Figure 31 shows the paving train.



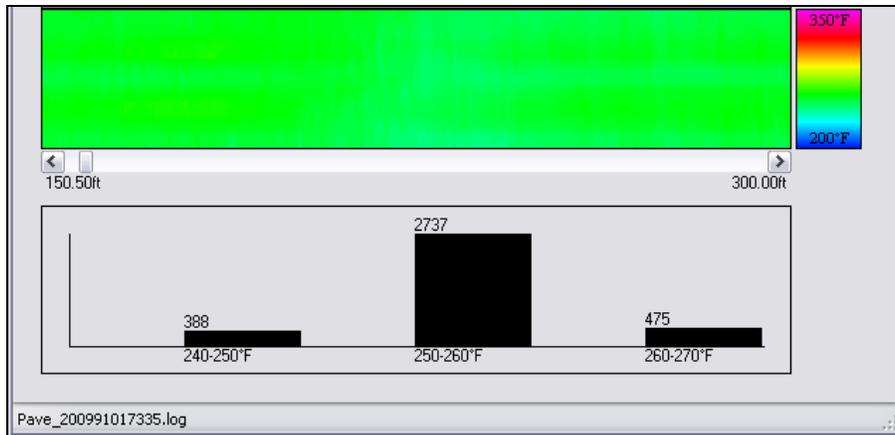
**Figure 31. Paving Operation on US 81.**

### Thermal Profile Results

Figure 32 shows the thermal profile from the entire pull, and Figure 33 presents a representative 150 ft segment. The profiles show that within 150 ft profile segments the thermal differentials typically ranged from 20° to 30°F and rarely exceeded 25°F.

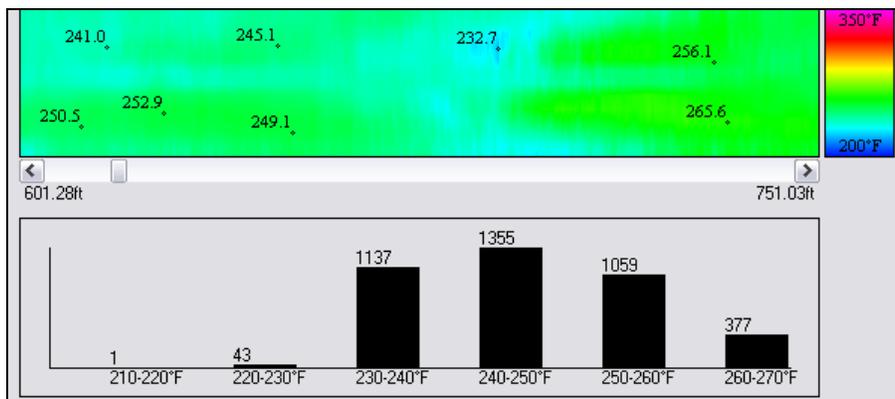


**Figure 32. Thermal Profile of Entire Pull on US 81.**



**Figure 33. Typical Thermal Profile on US 81.**

Figure 34 presents the most severe location of thermal differentials observed on the US 81 project. This location has a temperature differential of 36°F; only two other profiles were observed with temperature differentials exceeding 30°F.



**Figure 34. Location of Most Severe Temperature Segregation on US 81.**

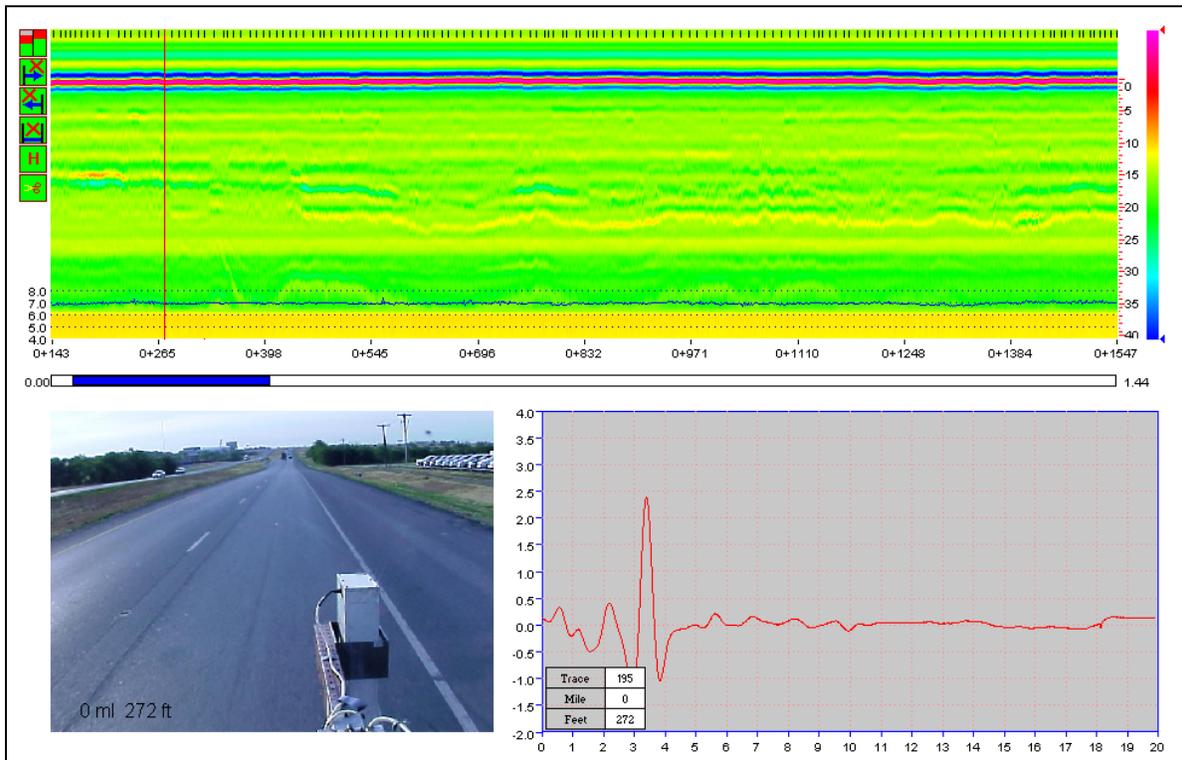
### Follow-Up Survey Results

TTI performed a visual and GPR survey on the US 81 section in August 2011. The section exhibited some roughness, which was probably due to the subgrade, and had five locations of low-severity potholes, as Figure 35 shows.



**Figure 35. Localized Distress on US 81.**

Figure 36 shows example radar data from the section. The radar data are clean with very uniform surface dielectric, and no odd radar traces exist at the locations with the distress. A review of the thermal profiles also did not reveal any anomalies at the locations. Additionally, the problem areas observed were almost in the centerline, as Figure 35 shows. Due to these observations, researchers ruled out segregation as a potential cause for the observed distress.



**Figure 36. Example GPR Data from US 81.**

## **Conclusions from US 81**

In general, the US 81 project showed good thermal uniformity. When the initial data were collected, the primary purpose was to demonstrate the thermal profiling system, so no GPR data were obtained at the time of construction. However, the thermal uniformity at time of construction was excellent. A follow-up survey after approximately two years under traffic revealed a few locations of distress. Based upon a review of the thermal profile, however, GPR, and visual observations, segregation was ruled out as a potential cause.

## **CONCLUSIONS**

Results from the five projects constructed without thermal segregation that the research team monitored show that construction free of segregation prevents distress due to localized problem zones in the mat, but understandably does not prevent all distress from occurring. Reflection cracks and distress likely due to deterioration in a segregated underlying HMA layer were observed.

## **CHAPTER 3. RESULTS FROM PROJECTS WITH THERMAL SEGREGATION**

### **SUMMARY**

Nine projects were constructed and monitored that did exhibit thermal segregation during construction. Performance of these projects was mixed, with the data suggesting traffic action homogenized the surface on some projects, while on other projects evidence of segregation clearly still existed years after construction. One project showed cracking due to segregation. Laboratory tests of pavement cores several years after construction suggested that thermally segregated locations may be more prone to cracking, although during the performance period monitored most thermally segregated locations observed at the time of construction only remained identifiable through a visually different surface appearance and localized anomalies in radar surveys.

### **BU 290, TYPE D, HOUSTON DISTRICT, CONSTRUCTED AUGUST 12, 2004**

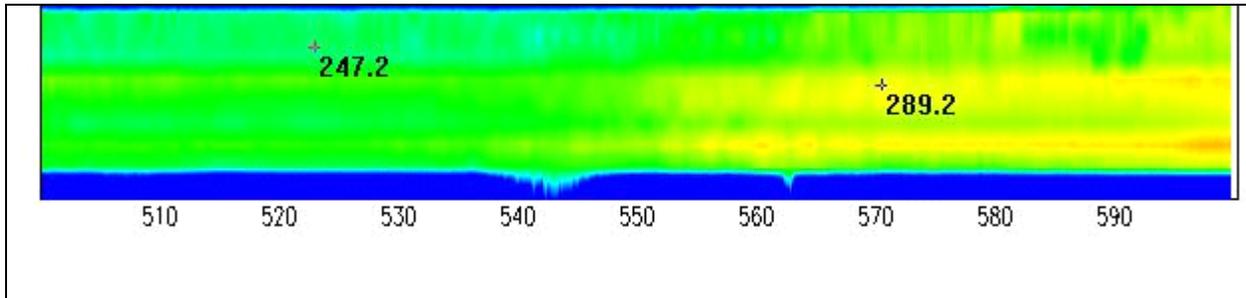
On this project, the contractor used end dump trucks to transfer mix into a Roadtec SB 2500C and a Blaw Knox PF 3200 paver. The contractor started paving just west of the FM 359/Business 290 intersection shown in Figure 37. TTI collected approximately 1215 ft of thermal data with an infrared bar system on the outside eastbound lane, and approximately 870 ft of GPR data. GPR data were initiated east of FM 359, and the zero point on the GPR data was 6.5 ft east of the Business 290 sign. This GPR start location was at approximately 345 ft into the infrared data file.



**Figure 37. Start of Business 290 Eastbound Section.**

### **Thermal Profile and GPR Results at Time of Construction**

Figure 38 shows an excerpt from the IR data, and Table 6 presents results from cores collected on the project at the time of construction. Figures 39 and 40 illustrate that both IR and GPR correlated well with the compacted mat density.

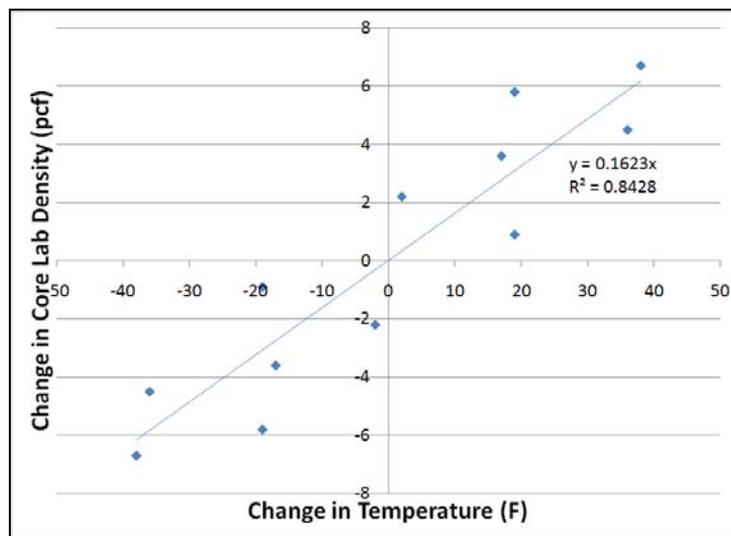


**Figure 38. Example Infrared Data on BU 290 Type D.**  
*Note: blue cold regions at edge of mat are from IR sensors off the mat.*

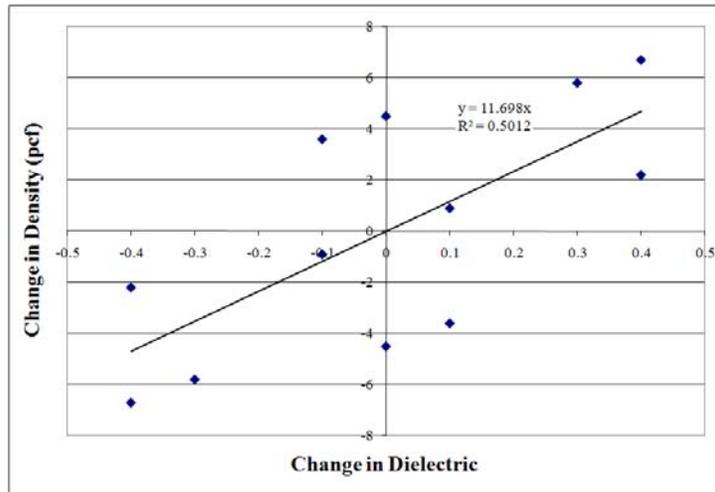
**Table 6. Core Results from BU 290 Type D.**

Core	Temperature (°F)	$\epsilon$ from GPR	Core Percent Air Voids from Lab*
1	282	5.2	10.8
2	263	5.1	11.3
3	301	5.5	7.0
4	299	5.1	8.6

*\*Based on Rice Gravity of 152.9 pcf.*



**Figure 39. Relationship between Infrared and Air Voids on BU 290 Type D.**



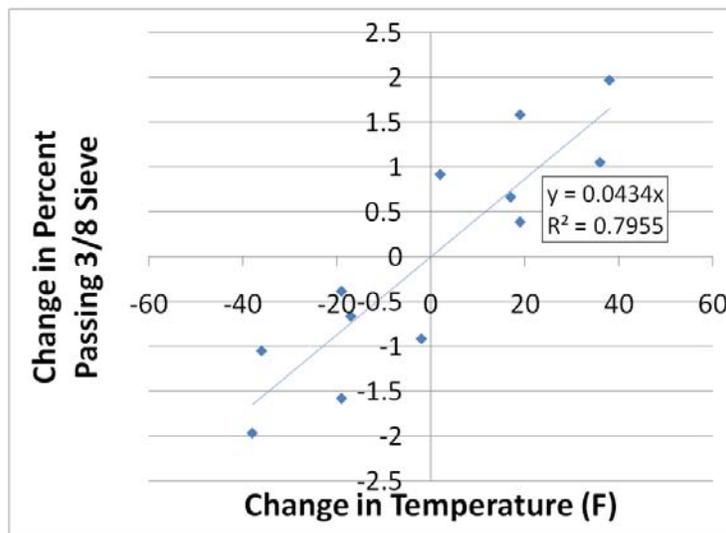
**Figure 40. Relationship between GPR and Air Voids on BU 290 Type D.**

Table 7 presents the gradation results obtained on the field cores. Figures 41 and 42 illustrate that both the infrared and GPR correlated with gradation. As temperature and dielectric values increased, the mix became finer.

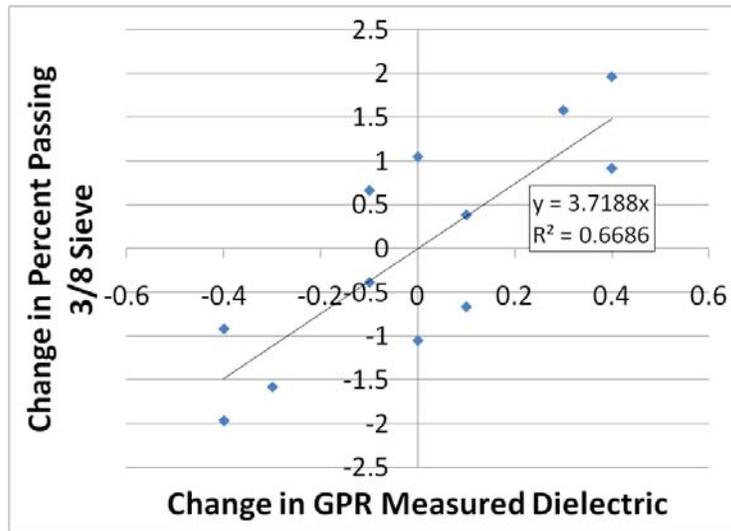
**Table 7. Gradation Results from BU 290 Type D Cores.**

Core	1 in.	½ in.	3/8 in.	#4	#10	#40	#80	#200
1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2	99.8	100.0	99.7	99.3	99.8	100.0	99.7	99.3
3	93.0	92.7	94.6	93.7	93.0	92.7	94.6	93.7
4	67.0	68.2	70.2	66.6	67.0	68.2	70.2	66.6

*Results are percent passing.*



**Figure 41. Change in Temperature and Percent Passing 3/8 in. on BU 290 Type D.**



**Figure 42. Change in Dielectric and Percent Passing 3/8 in. on BU 290 Type D.**

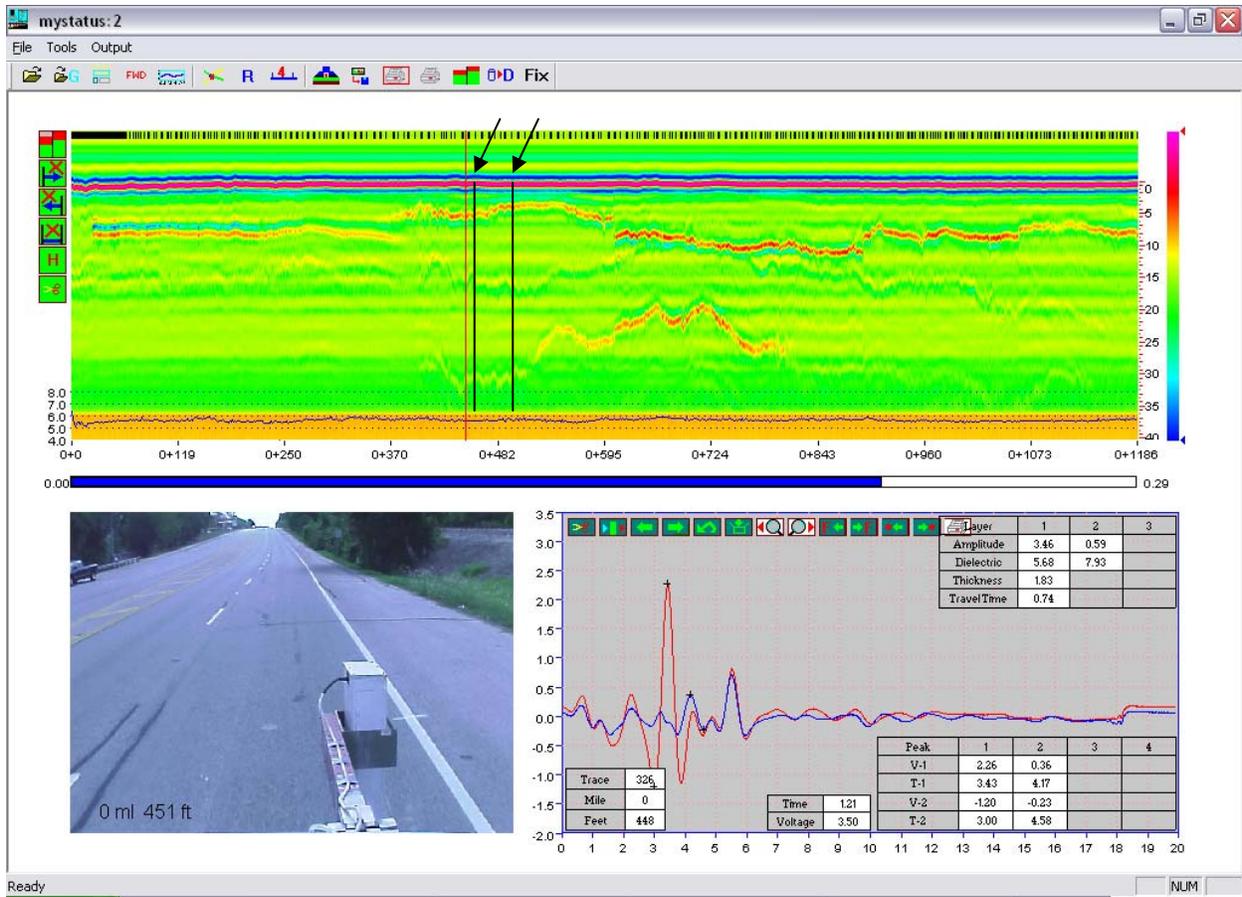
### Follow-Up Survey Results

TTI performed a follow-up visual and GPR survey on the section in July 2011. The section exhibited transverse and reflection cracking and some longitudinal cracking, as Figure 43 illustrates.



**Figure 43. Transverse and Longitudinal Cracking on BU 290.**

Figure 44 illustrates the GPR data collected on the section. The GPR data do not show any unusual traces at the segregated locations identified during construction. Additionally, Figure 45 shows photos as of July 2011 at the locations that exhibited greater than 10 percent air voids at the time of construction. Based upon the radar and condition data, at this time no distress in the field appears due to these segregated locations.



**Figure 44. GPR Data on BU 290 after Seven Years of Service.**  
*Note: segregated areas identified during construction annotated with arrows.*



**Figure 45. Thermally Segregated Locations on BU 290 after Seven Years of Service.**

To investigate the mixture properties after years of service, TTI collected three cores from a segregated location (as identified during construction) and three cores from a non-segregated location (as identified during construction). These cores corresponded to the locations of cores 2 and 3 from Table 7. Researchers tested these cores in the overlay and Hamburg test. Table 8 presents the results, which showed essentially no difference in mixture performance properties. The main difference observed was slightly higher air void contents in the cores collected from the location observed as segregated at the time of construction. However, immediately after construction, that location had over 10 percent air voids; the air void content of the cores collected from that location after years of service was approximately 7.8 percent.

**Table 8. Overlay and Hamburg Results on BU 290 after Seven Years of Service.**

Core Location*	Core Air Voids (%)	Overlay Test Results			Hamburg Test Results (mm rut depth)			
		Trimmed Air Voids (%)	Cycles to Failure	Peak Load (lbf)	5000	10000	15000	20000
2-A	7.45	7.71	3	1073	<i>Not applicable</i>			
2-B	7.84	<i>Not applicable</i>			-2.58	-4.29	-6.36	-9.90
2-C	8.01	<i>Not applicable</i>			<i>Not applicable</i>			
3-A	5.52	5.44	3	1337	<i>Not applicable</i>			
3-B	6.50	<i>Not applicable</i>			-2.78	-3.38	-4.49	-10.38
3-C	6.28	<i>Not applicable</i>			<i>Not applicable</i>			

\*Matches with locations of cores 2 and 3 from Table 7.

### Conclusions from US 290

Although a few segregated locations of over 10 percent air voids were observed at the time of construction, after seven years of service no unusual distress was identified at those locations. Current cores from the segregated zones identified during construction were between 7 and 8 percent air voids, so densification under traffic occurred. Comparing performance test results (overlay and Hamburg test) from these current pavement cores to current cores from the non-segregated zones revealed no notable difference. It appears that during trafficking, on this project the segregated zones densified into what would be considered a “normal” air void content range and exhibited performance properties comparable to the mix identified as non-segregated at the time of construction. In both cases, the Hamburg results were acceptable and the overlay test results were poor, with specimens from both segregated and non-segregated zones failing in three cycles.

### US 77, TYPE C, YOAKUM DISTRICT, CONSTRUCTED MAY 10, 2006

On this visit to the US 77 project, thermal data were collected from STA 22+360 to approximately STA 22+900. The GPR survey at the time of construction was conducted between stations 22+372 and 22+887. A follow-up survey conducted in July 2011 revealed transverse and longitudinal cracking on the project, plus some evidence of cyclical segregation and related raveling and cracking.

## Paving Operation

The Type C mix was produced in New Braunfels, Texas, and hauled in tarped belly dump trucks with an average haul distance of 112 miles. The binder was PG 76-22. A Lincoln 660 AXL windrow elevator transferred the mix into a Barber Green BG 260C paver. Figure 46 shows the paving operation. At the time of testing, the ambient air temperature was 85°F and wind speeds ranged from 3 to 10 mph.

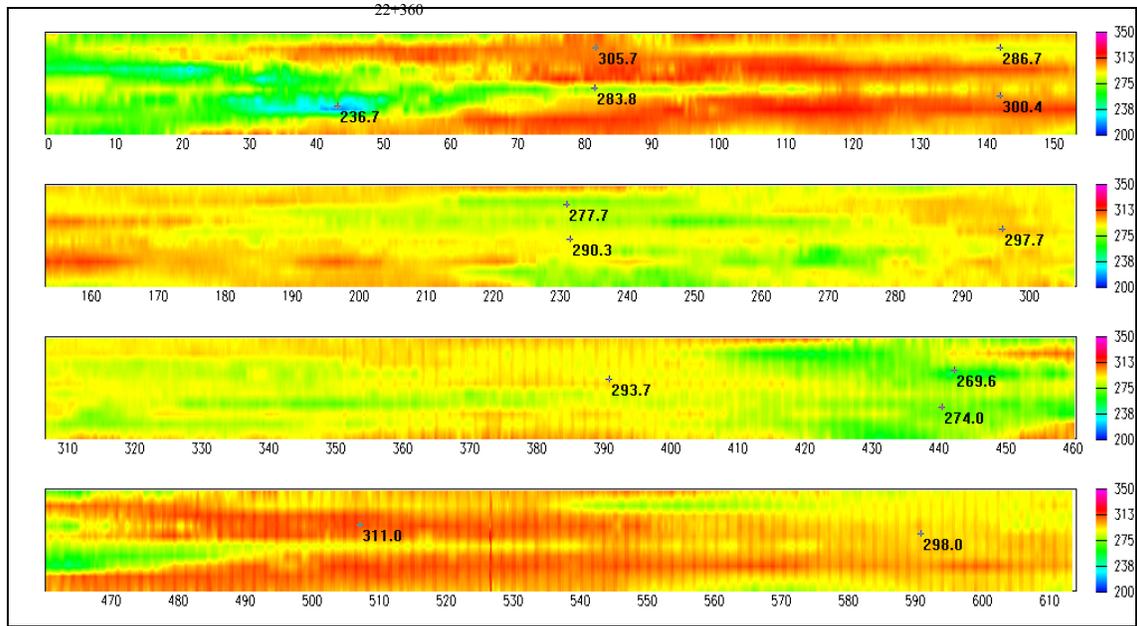


**Figure 46. Paving Operation on US 77 Northbound, May 10, 2006.**

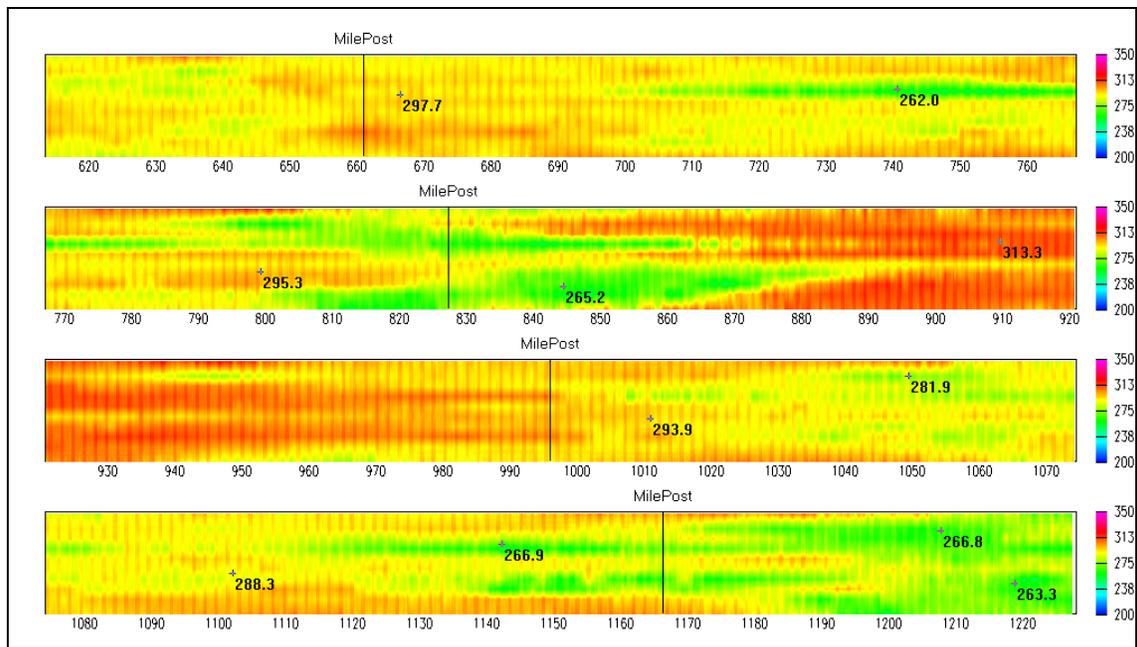
## Thermal Profile Results

Figure 47 shows the thermal plot for the project. Due to problems with the distance measuring device, the thermal data were collected in the time mode. To reference the data to the project, markers were inserted in the data at the stations. Additionally, locations of paver stops and starts were denoted by a marker labeled “stop.” Examination of the thermal data show:

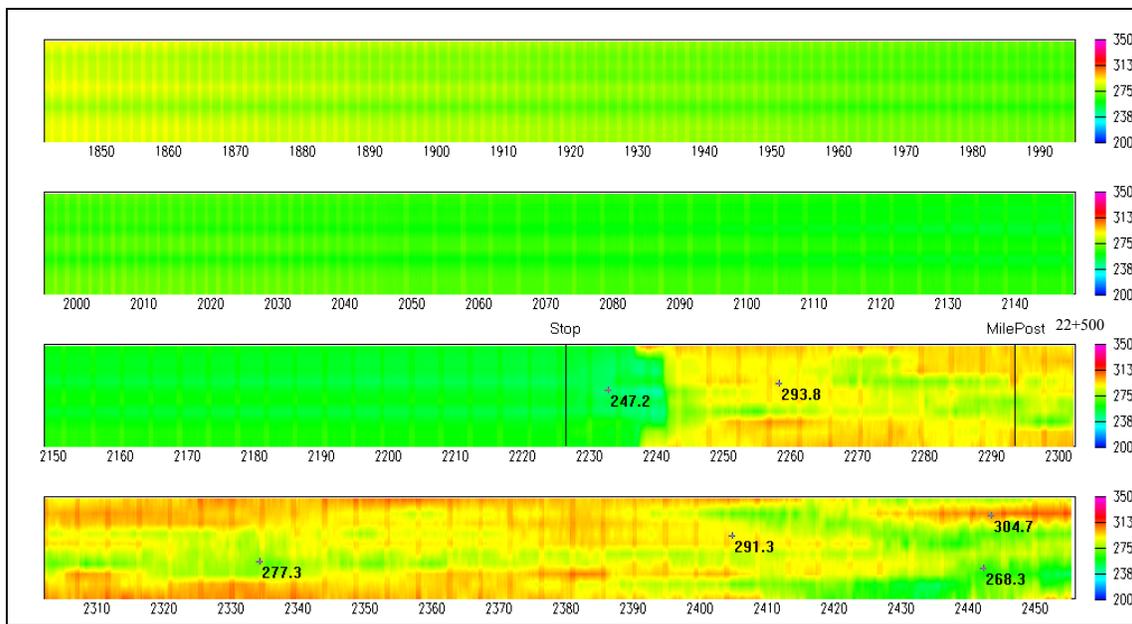
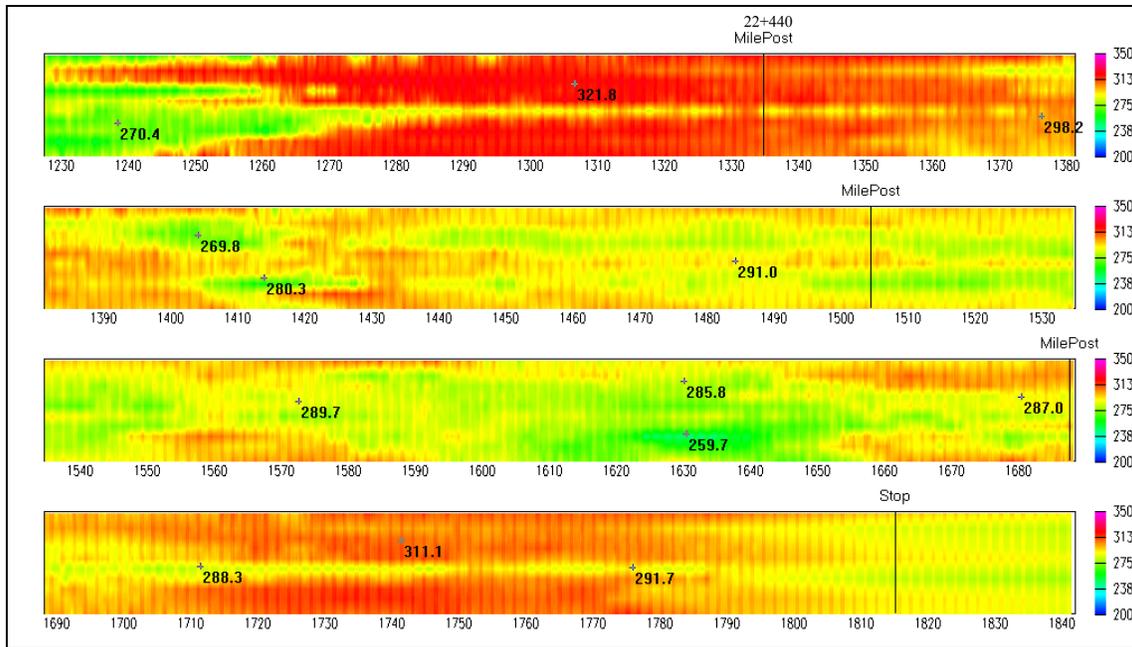
- Thermal uniformity of the mix within each truckload was very good.
- Truck arrival temperatures were consistent, with placement temperatures (excluding truck-end cold spots) typically between 280° and 310°F.
- Clear patterns of truck-end temperature differentials exist from STA 22+360 to STA 22+560. The temperature differentials at these truck-end locations were typically between 25° and 40°F. It is unknown if these trucks were insulated or not.

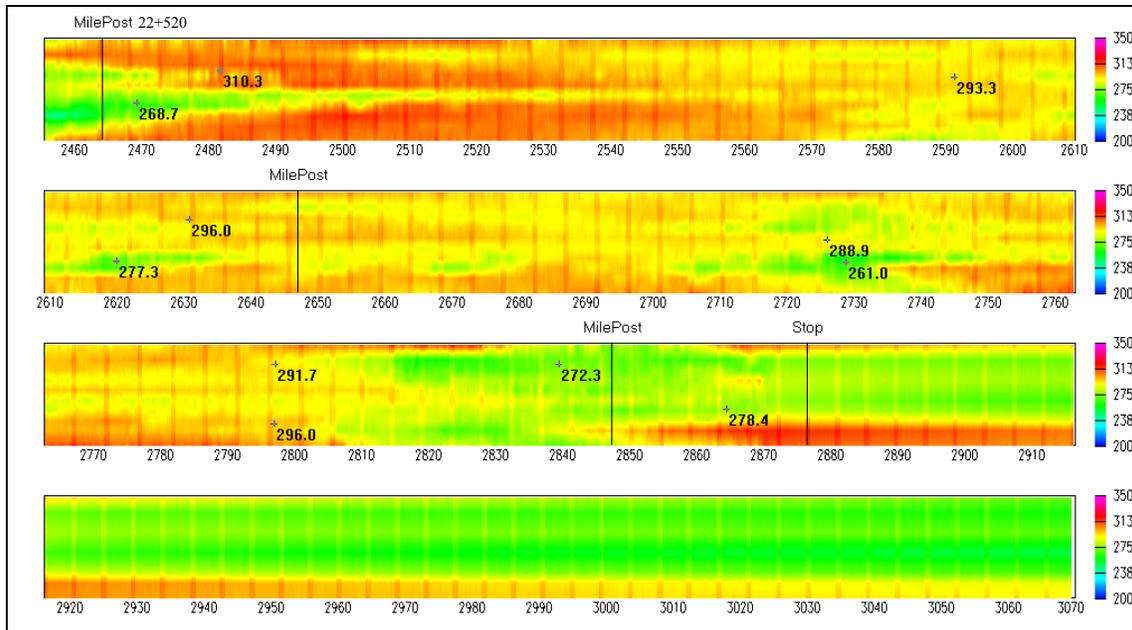


**Figure 47. Thermal Plot of US 77.**

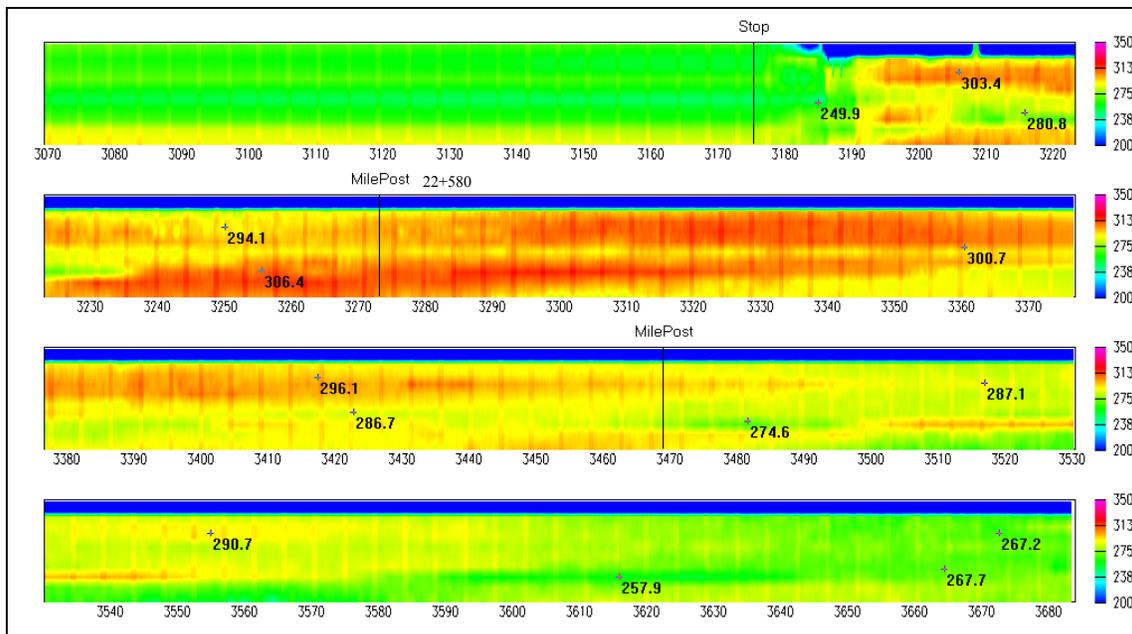


**Figure 47. Thermal Plot of US 77 (continued).**



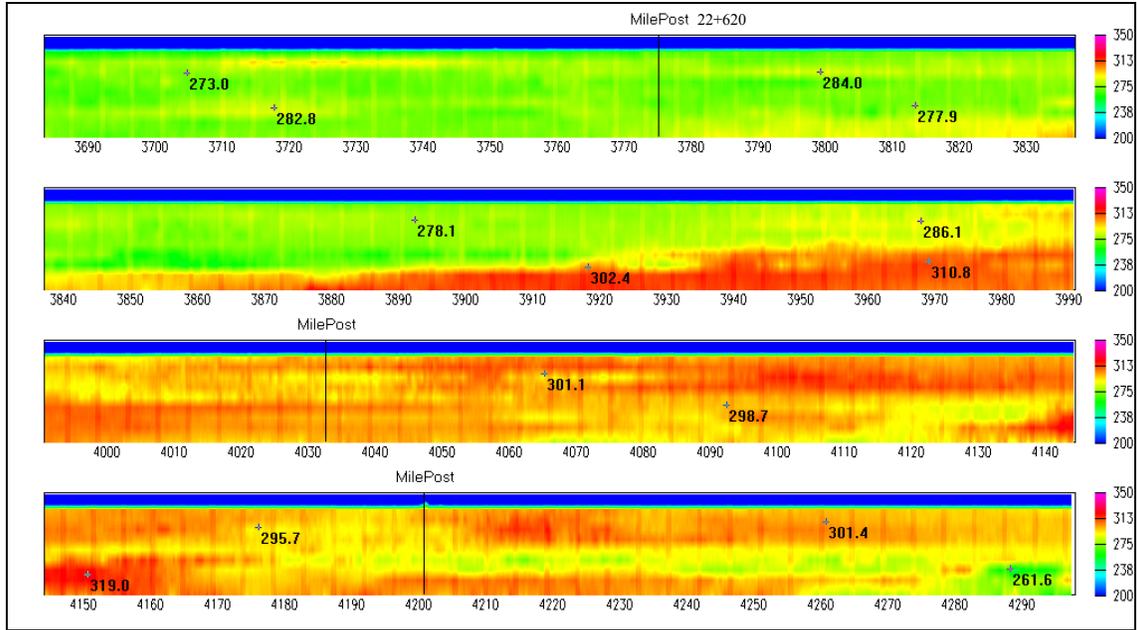


**Figure 47. Thermal Plot of US 77 (continued).**



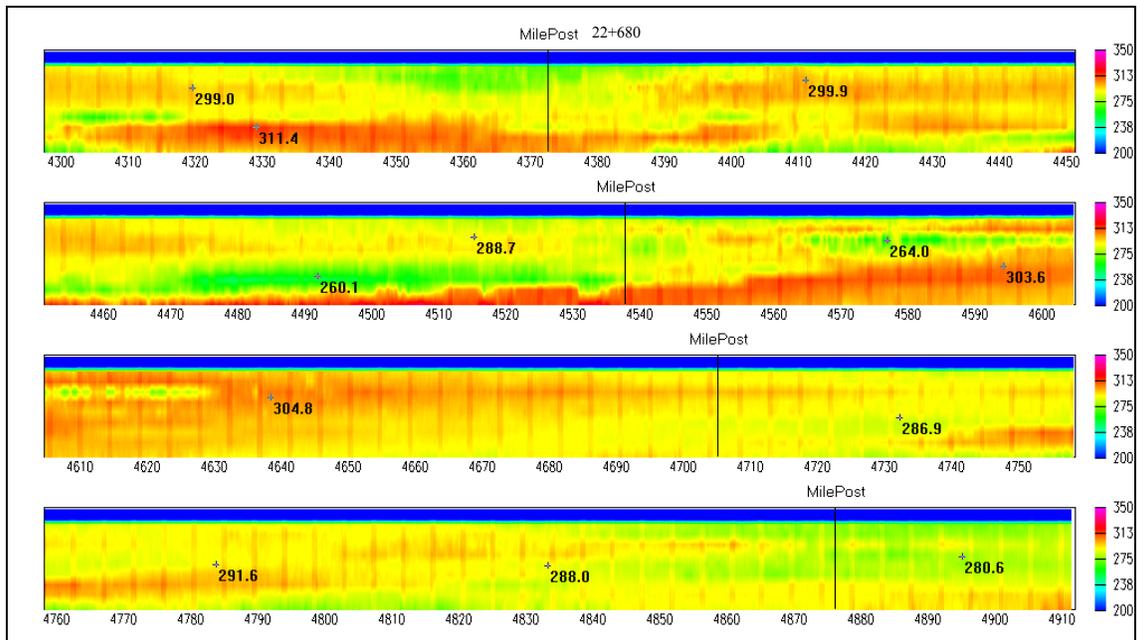
**Figure 47. Thermal Plot of US 77 (continued).**

*Note: blue region at top of profile plots is from an outer sensor off the mat.*



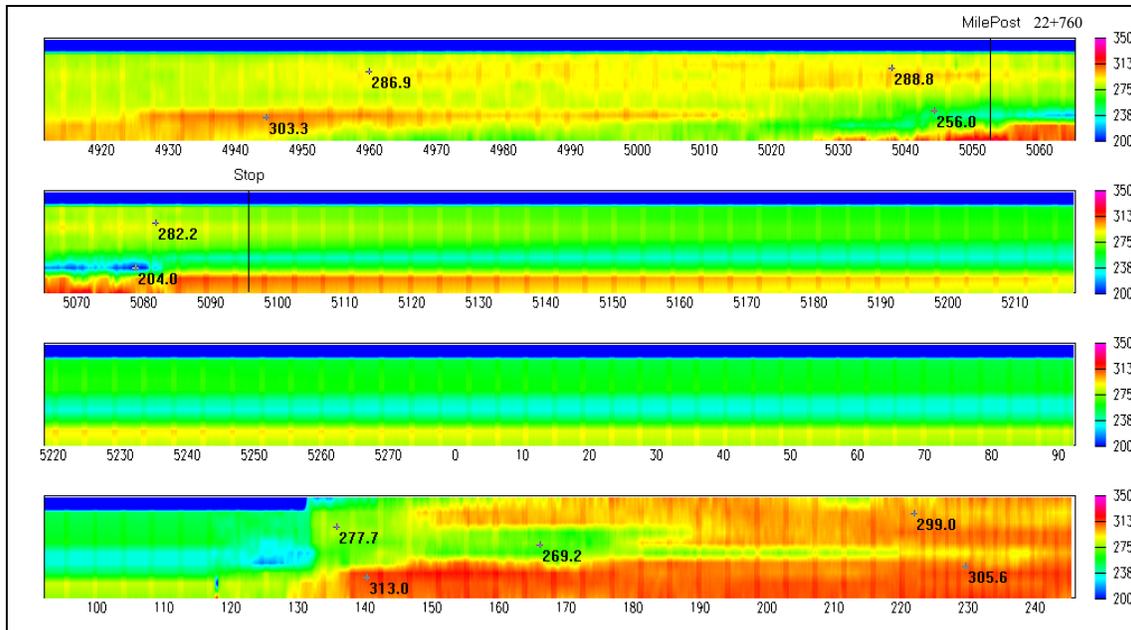
**Figure 47. Thermal Plot of US 77 (continued).**

*Note: blue region at top of profile plots is from an outer sensor off the mat.*



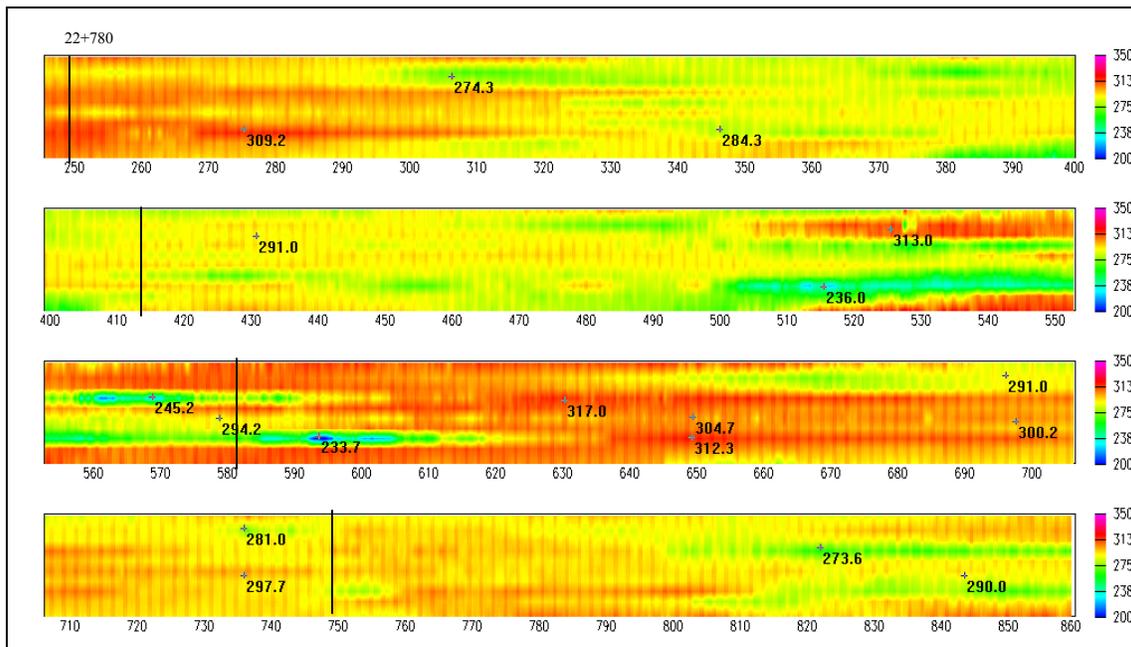
**Figure 47. Thermal Plot of US 77 (continued).**

*Note: blue region at top of profile plots is from an outer sensor off the mat.*

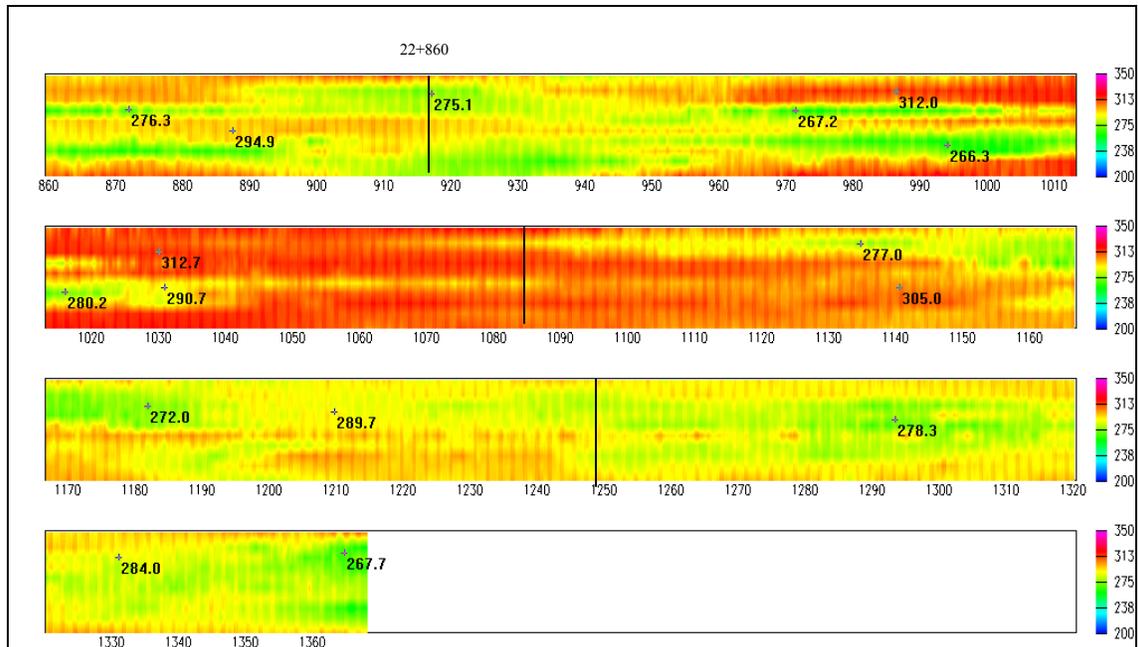


**Figure 47. Thermal Plot of US 77 (continued).**

*Note: blue region at top of profile plots is from an outer sensor off the mat.*



**Figure 47. Thermal Plot of US 77 (continued).**



**Figure 47. Thermal Plot of US 77 (continued).**

### GPR Results at Time of Construction

After completion of the thermal survey and all rolling operations on the tested section, five GPR passes (each at a different transverse offset) were performed over approximately 1700 ft of the test section as a quality assurance measure. After a field evaluation of the GPR data, TTI selected five locations for correlating the in-place air voids to GPR. Table 9 shows the lab-measured densities from the cores.

**Table 9. Core Results from US 77 Project at Time of Construction.**

<b>Core Number</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>
<b><math>\epsilon</math> from GPR</b>	5.8	5.8	5.9	5.5	5.3
<b>Lab Bulk Density (pcf)</b>	136.8	138.6	140.6	136.5	133.5
<b>Percent Air Voids</b>	10.4	8.9	7.6	10.3	12.3

Based upon GPR readings over the core locations and the laboratory results, the relationship shown in Figure 48 calibrated the GPR data to predict the in-place air void content of the mat. With this calibration, each of the GPR field readings were converted into a predicted air void content value to develop the distribution of air voids shown in Figure 49. This distribution indicates that approximately 85 percent of the tested mat is expected to have air voids ranging between 6.5 and 9 percent.

Figure 50 shows another product from the GPR survey: the surface plot of expected in-place air voids. This figure is generated from the calibrated relationship between dielectric and air voids and the known transverse spacing of each of the five GPR passes.

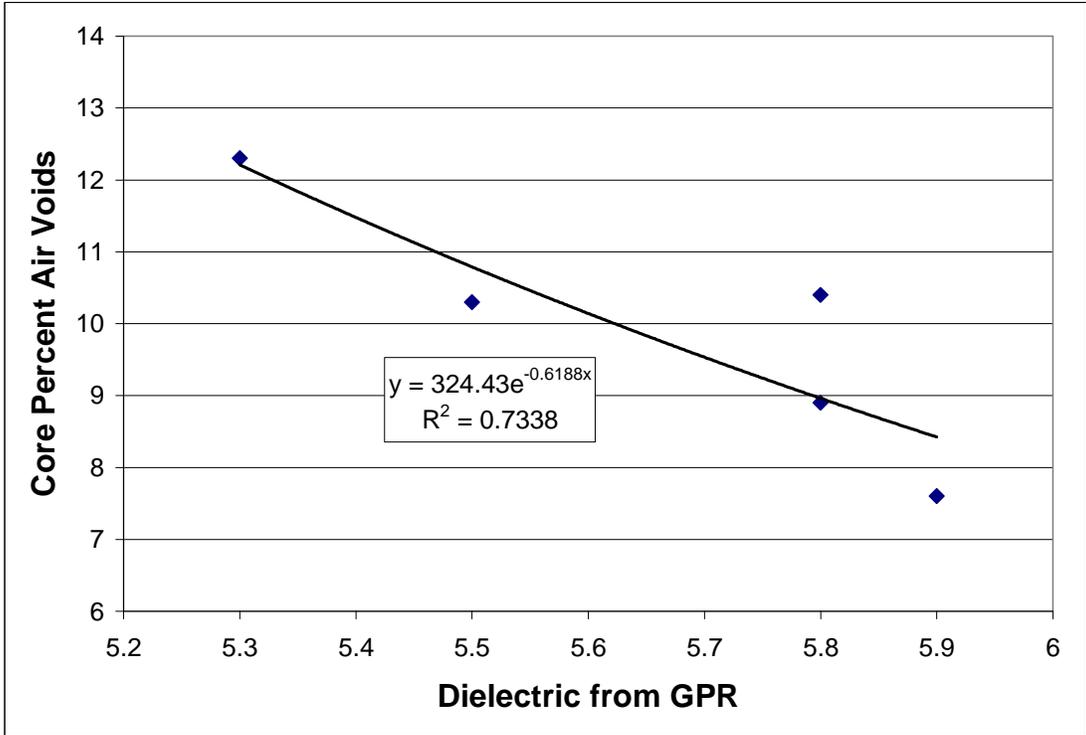


Figure 48. Calibration of Air Voids to Dielectric on US 77.

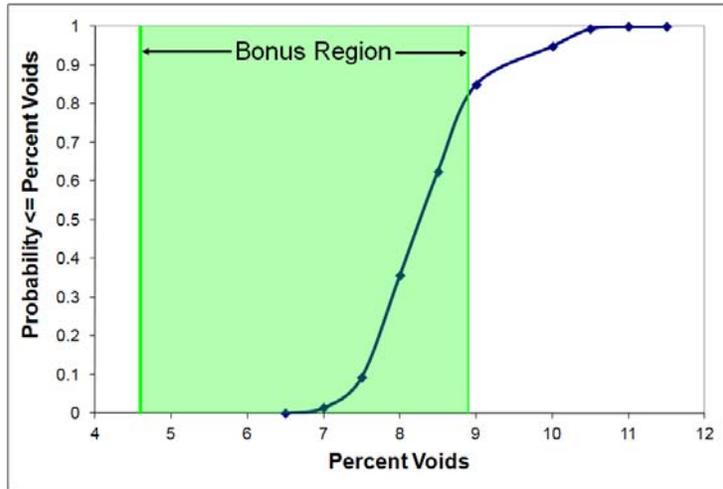


Figure 49. Expected Distribution of In-Place Air Voids on US 77 Section at Time of Construction.

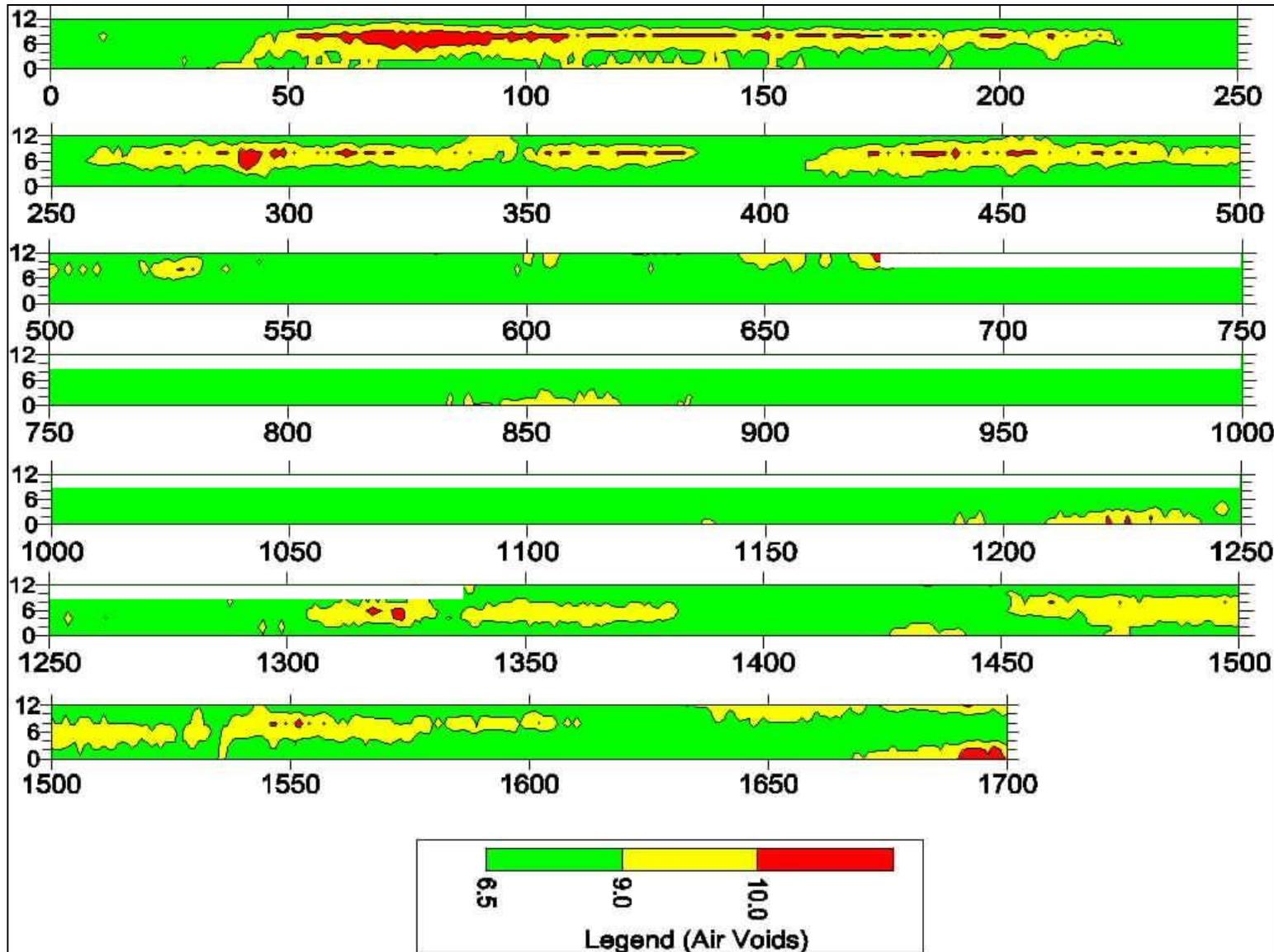


Figure 50. Surface Plot of Expected In-Place Air Voids on US 77 Northbound Test Section.

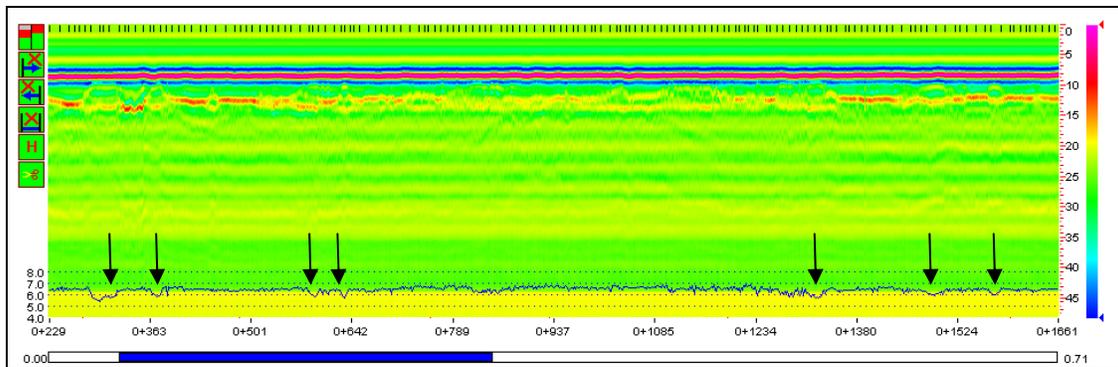
Note: distance in feet from STA 22+372.

## Follow-Up Survey Results

TTI conducted a visual and GPR survey on this section of US 77 in July 2011, approximately five years after construction. The pavement exhibited some longitudinal and transverse cracking, as Figure 51 illustrates. Additionally, the visual and GPR survey shows clear signs of truck-end segregation. Figure 52 presents the GPR data, which show cyclical dips in the surface dielectric value. Many of these cyclical dips correspond to locations of high air voids shown in Figure 49 identified at the time of construction.

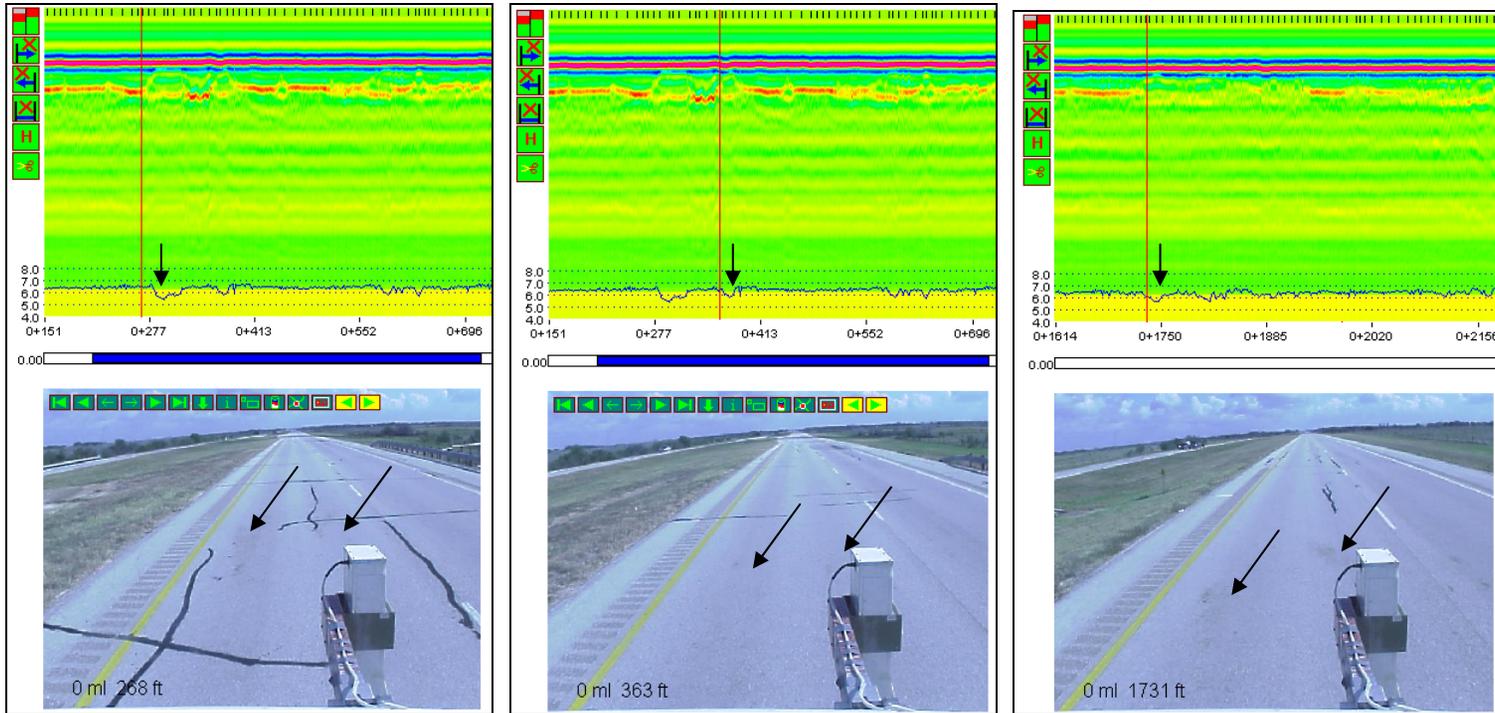


**Figure 51. US 77 Section after Five Years of Service.**



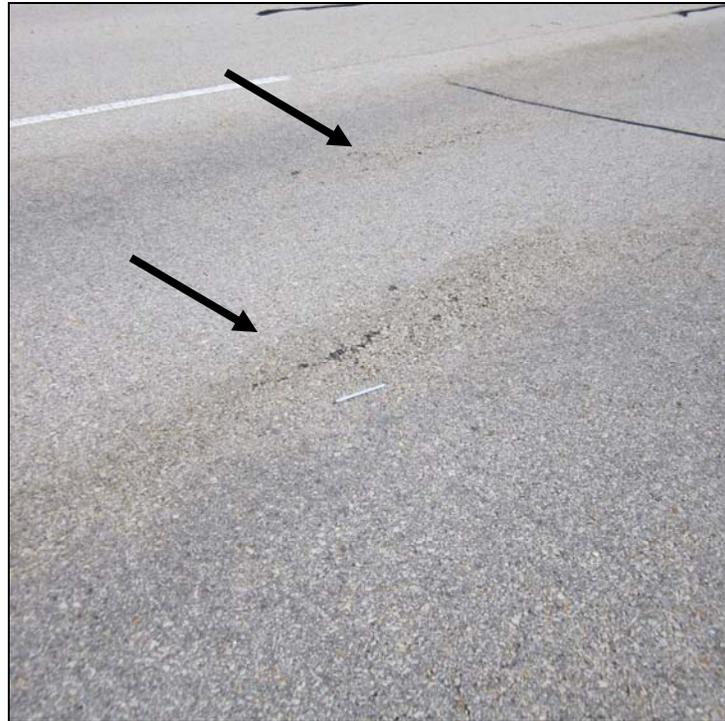
**Figure 52. GPR on US 77 after Five Years of Service.**

Figure 53 illustrates the current condition of some of these segregated locations. Although difficult to distinguish in Figure 53, all locations show signs of a coarser texture. At one location, a crack originates over the segregated location in the inside wheel path. However, since longitudinal cracking exists project-wide, this occurrence may not necessarily be due to the segregation.



**Figure 53. Cyclically Segregated Locations on US 77 after Five Years of Service.**

Elsewhere on the US 77 project, other locations of segregation were observed, as Figure 54 illustrates. Although these locations were not surveyed at the time of construction, Figure 54 illustrates classic cases of cyclical segregation, exhibiting a coarser surface texture, raveling, and cracking. Additionally, some locations of patching exist on the project, and at one location, these patches were centered about 150 ft apart, typically the distance between truckloads. Figure 55 shows this location.



**Figure 54. Segregated Location on US 77.**



**Figure 55. Patching on US 77.**

## Conclusions from US 77 Section

On this US 77 project, cyclical segregation was identified at the time of construction with temperature differentials typically between 25° and 40°F. Within-truck uniformity was very good. The GPR survey at the time of construction indicated approximately 85 percent of the constructed mat area would qualify for a bonus.

After five years of service, evidence of the cyclical segregation still exists—both visually and through the radar survey. While no significant distress due to segregation was positively identified in the section surveyed at the time of construction, elsewhere in the project some locations did exist where cracking was clearly initiating in a segregated zone. One location of patching exists where the distance between patches was consistent with the distance between truckloads, so it is possible some failures may have occurred and been patched due to segregation.

Given the widespread longitudinal cracking on this project, even though segregation and some distress due to segregation exist, it was not clear if the presence of segregation significantly impacted the service life of this overlay.

## IH 10 CRM, ODESSA DISTRICT, CONSTRUCTED AUGUST 2006

On this project, TTI trained the contractor on how to install and collect data with the thermal profiling system. The contractor performed thermal profiling on nearly the entire project, for a total of approximately 19 miles of data. The project limits were from reference marker 306+0.69 to 298+0.752.

### Paving Operation

Figures 56 and 57 show the paving operation. The material was supplied to the project in belly dump trucks. A Cedarapids windrow elevator transferred the mix into a Terex/Cedarapids 562 paver.



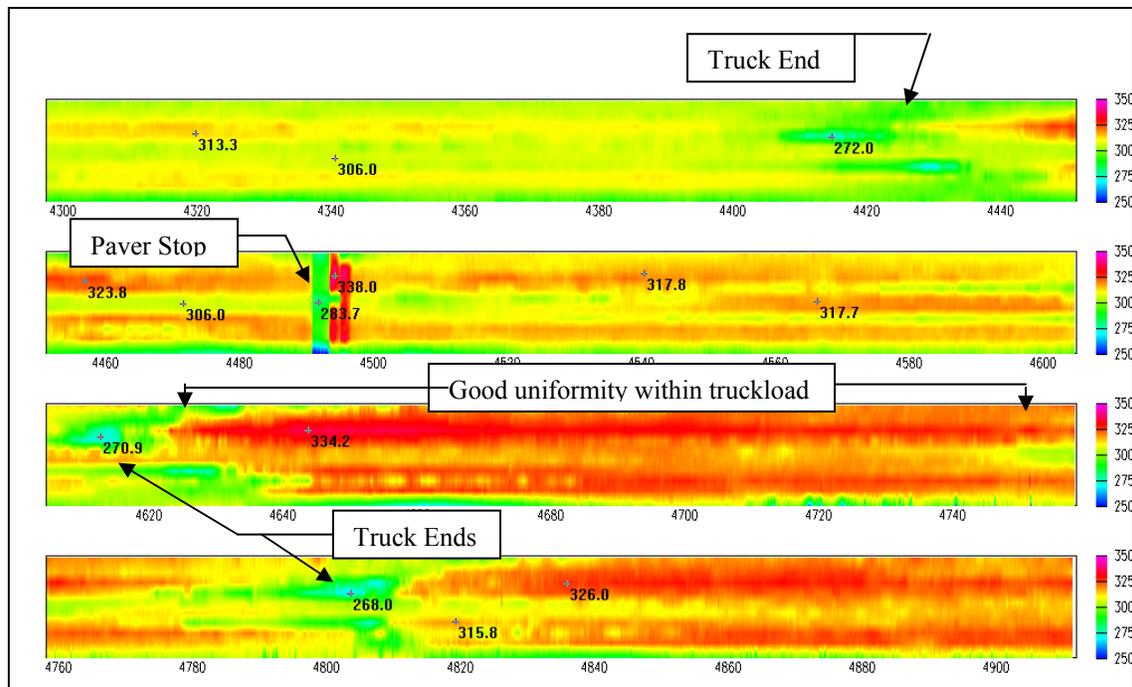
**Figure 56. Belly Dump and Windrow Operation on IH 10 CRM.**



**Figure 57. Paver with IR Bar Installed on IH 10 CRM.**

### Thermal Profile Results

Figure 58 shows a representative surface plot of mat placement temperatures and illustrates good uniformity within truckloads, a location where the paver stopped, and locations of truck-end thermal segregation. Figure 58 shows a hot spot immediately following the location of a paver stop. This pattern is due to burners on the paver operating while the paving train was stationary.

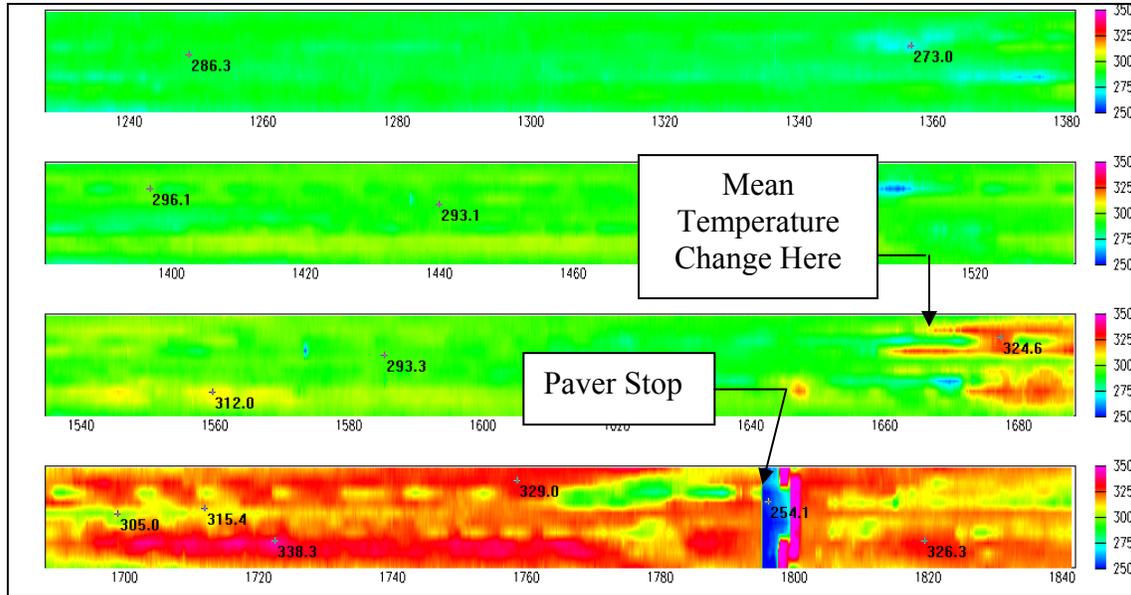


**Figure 58. Representative Temperature Surface Plot.**

*Note: data from Lot 3.*

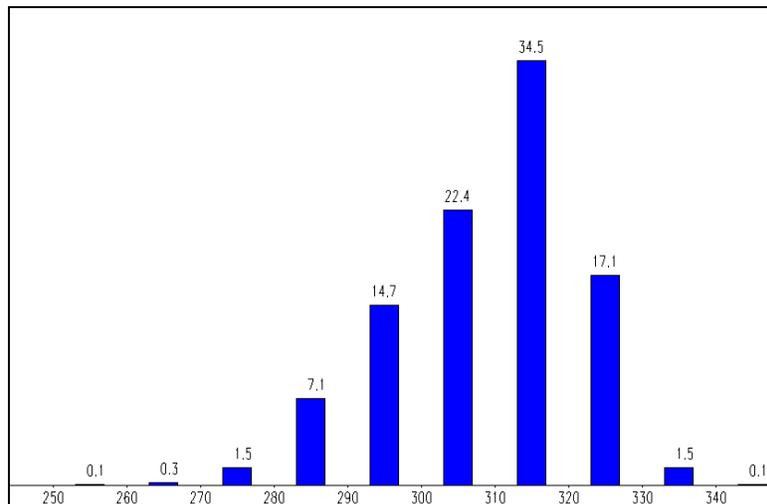
Figure 59 illustrates a location where a shift in the mean truckload temperatures occurred. The green areas are in the range 280° to 300°F, whereas in the last segments the temperatures are

generally above 320°F. This figure also shows a location of a paver stop; the short blue area represents cooling mix under the paver; the adjacent strong red strips across the mat probably represent the area beneath the burners.



**Figure 59. Transition Point in Mean Truckload Temperatures.**  
*Note: data from Lot 1.*

Figure 60 illustrates a representative histogram of measured mat placement temperatures. This is a summary of all the surface temperature data collected in Lot 1. A review of all data collected shows the majority of mat placement temperatures typically ranged between 280° to 330°F. The numbers at the top of each column are the percentage of the area in each temperature range; for example, 34.5 percent of the entire placement for this lot was between 310° and 320°F.



**Figure 60. Representative Histogram of Mat Placement Temperatures from IH 10 CRM.**  
*Note: data from Lot 1.*

## Detailed Evaluation of Lot 2 Data

Infrared data were collected on eight lots placed on this project. File lengths ranged from 4812 ft for Lot 8 to 3 miles and 1036 ft for Lot 1. The lot where the most dramatic changes in pavement temperature were observed was Lot 2, which was collected on August 11, 2006. In this lot, several instances of multiple truckloads arriving at significantly reduced temperatures occurred. TTI verified with TxDOT that these were valid data.

For Lot 2, the total paving length was measured as 2 miles and 919 ft. In that lot, the paver stopped 19 times, with eight of the stops equal to or longer than 10 minutes. In one instance (at 1 mi. and 3660 ft) that paver stopped for 66 minutes. After this paver stop, the pavement segment from 1 mi. + 3660 ft to 1 mi. + 5220 ft seemed to have been placed at an average temperature of between 220 to 250°F, well below the target temperature range.

Figures 61 and 62 show examples of the temperature profile from the possible problem locations. In Figure 61, the paver stop at 1 mi. + 3660 ft, and the surface temperature of the mat when the paving train resumed was 159°F, while under the burners that surface temperature was 450°F.

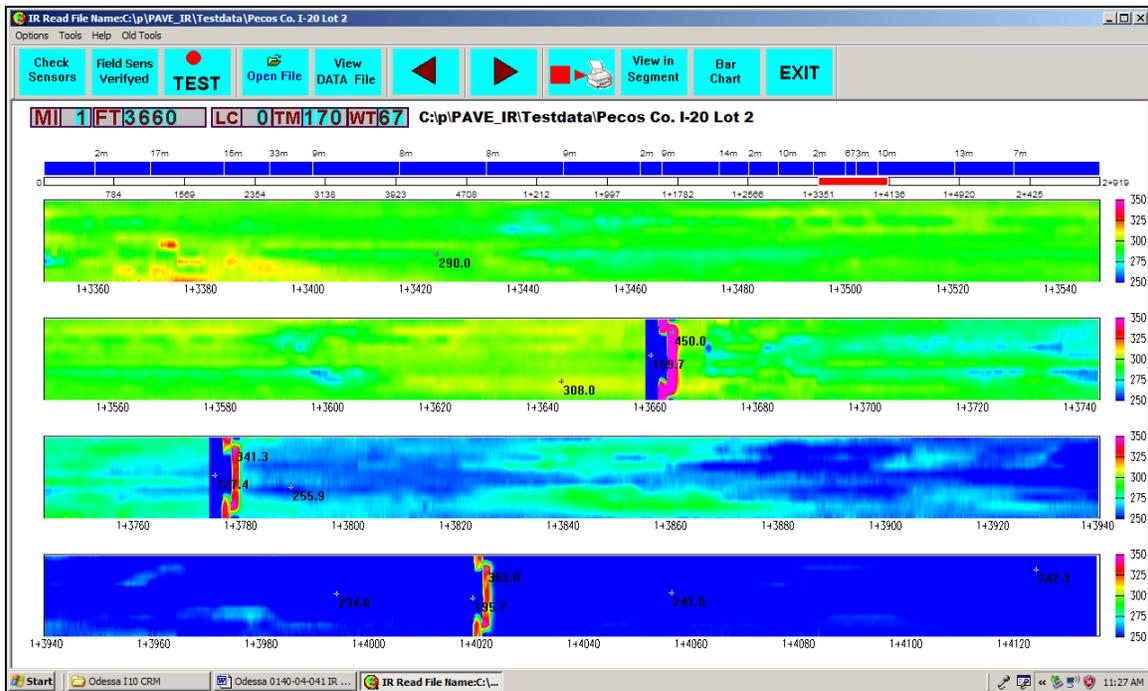
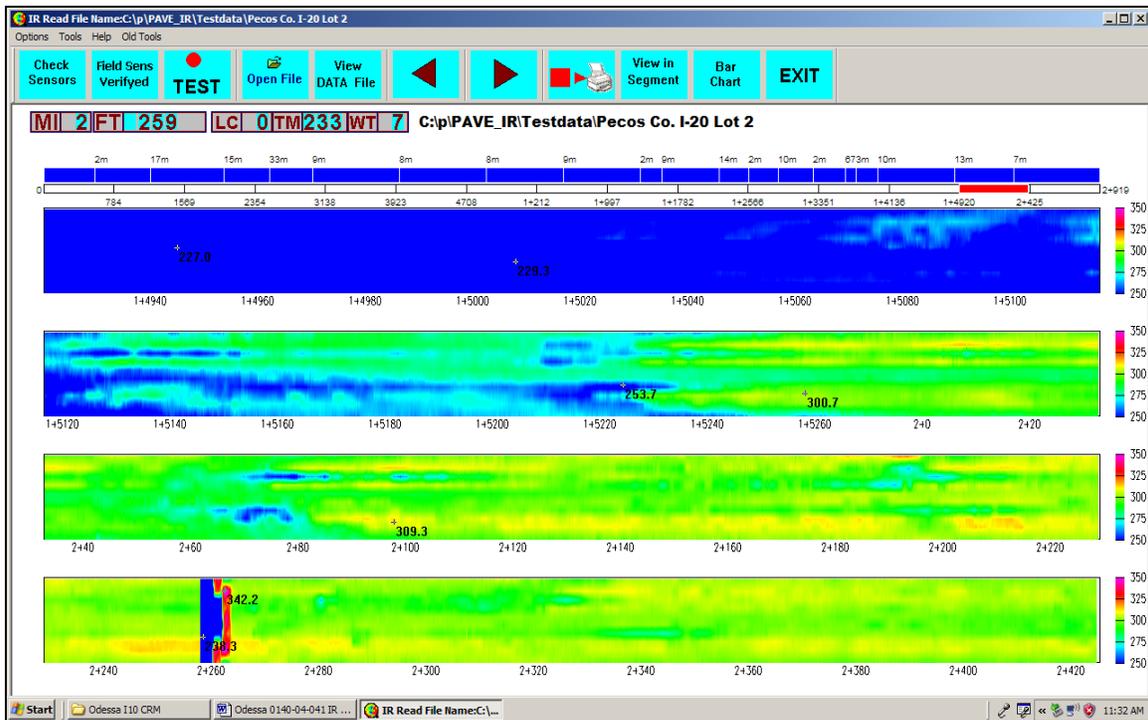


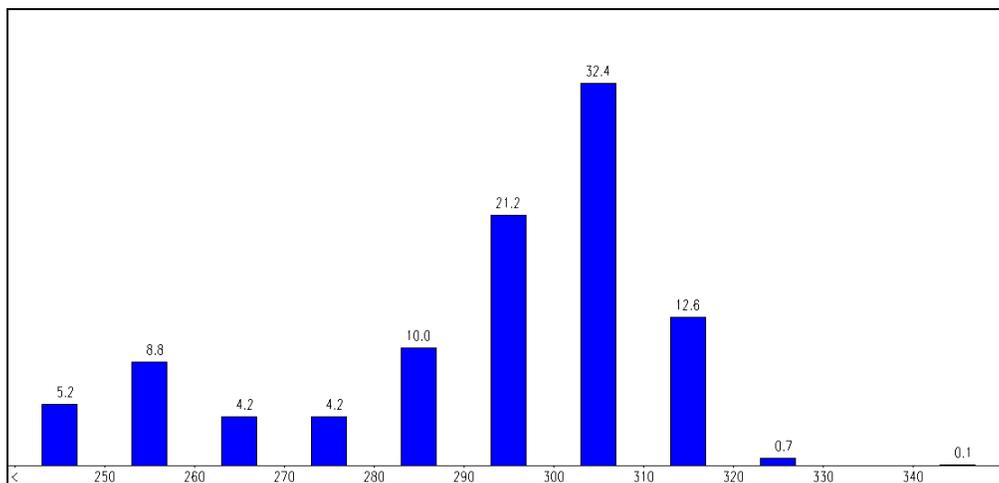
Figure 61. Potential Problem Area in Lot 2 on IH 10 CRM.

Figure 62 shows the end of the cold section where normal surface temperatures were restored after 1 mi. and 5220 ft. Lot 2 was by far the most extreme lot from all the data collected. Most of the other lots showed reasonably uniform placement temperatures. The most obvious temperature issue with the other lots was caused by frequent paver stops.



**Figure 62. End of Cold Truckloads in Lot 2 on IH 10 CRM.**

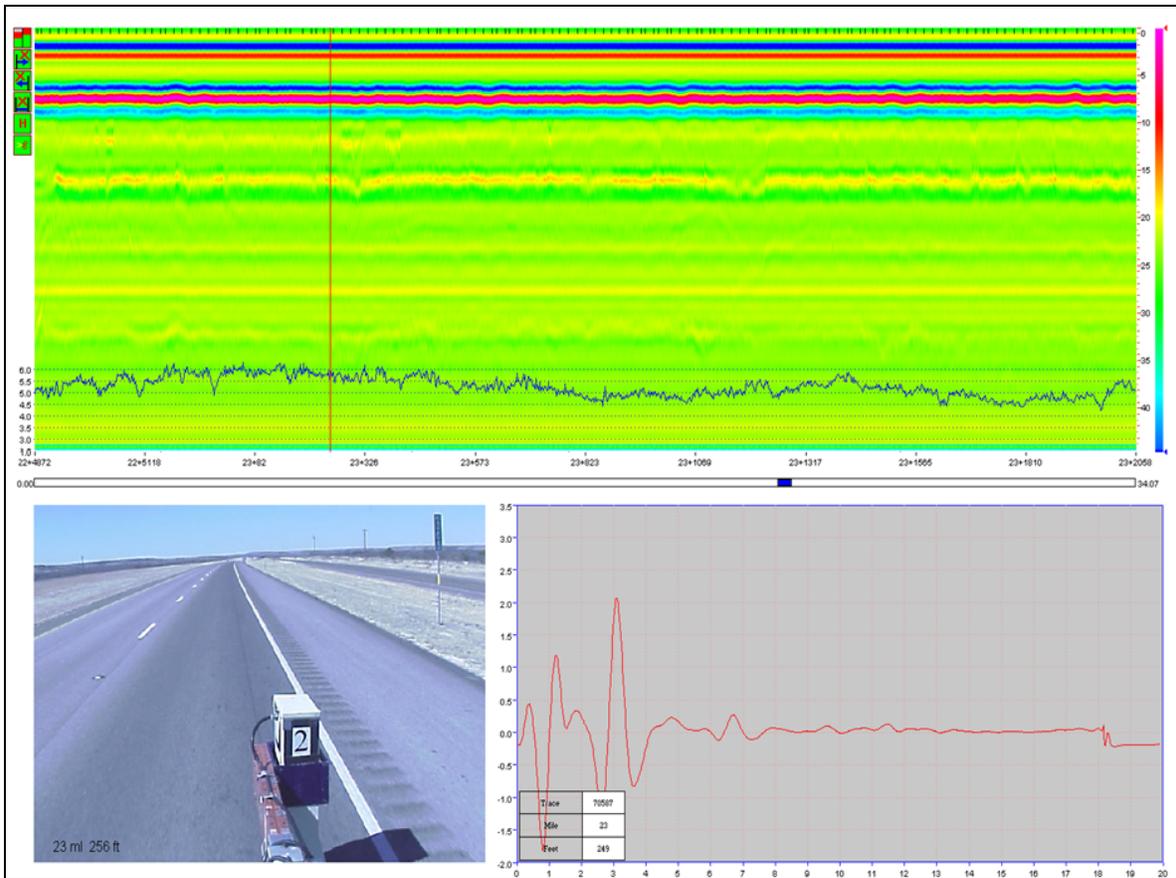
Figure 63 shows the distribution of temperature for the entire Lot 2. This distribution is considerably different from the distribution for Lot 1 shown earlier in Figure 60. In Lot 1, only 2 percent of the mat was less than 280°F; in Lot 2, over 22 percent of the mat was placed at less than 280°F.



**Figure 63. Histogram of IH 10 CRM Lot 2 Placement Temperatures.**

### Follow-Up Survey Results

In 2011, TTI conducted a visual and GPR survey on this section. Figure 64 shows representative GPR data.



**Figure 64. Example GPR on IH 10 CRM after Five Years of Service.**

### **Conclusions from IH 10 CRM Project**

At the time of construction, the within-truckload thermal uniformity was typically good. The most common pattern of thermal segregation was due to truck ends, where the temperature differentials typically ranged between 25° and 50°F. After approximately five years of service, the section still appears to perform well.

### **BU 59 CAM, LUFKIN DISTRICT, CONSTRUCTED JULY 31, 2008**

On July 31 and August 1, 2008, TTI conducted a thermal survey and observed construction of the Crack Attenuating Mixture (CAM) placed on Business 59 in the Lufkin District. This was a 1-inch thick overlay placed in town intended to resist reflection cracking from the existing pavement.

### **Paving Operation**

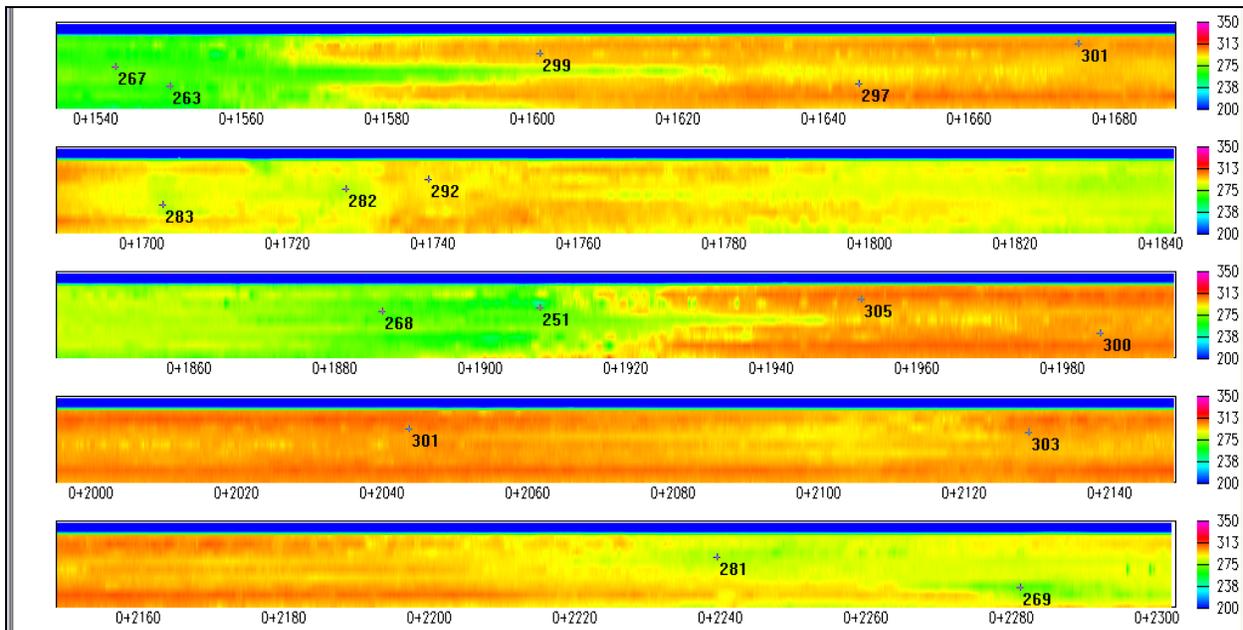
The contractor used belly dump trucks to place the mix in windrows. A Lincoln 660 windrow elevator and a Blaw Knox PF-3200 paving machine then placed the CAM. Figure 65 shows the paving operation. The contractor's primary compaction roller was a CAT CB-634D. The contractor used an Ingersoll Rand DD130 for the finish roller.



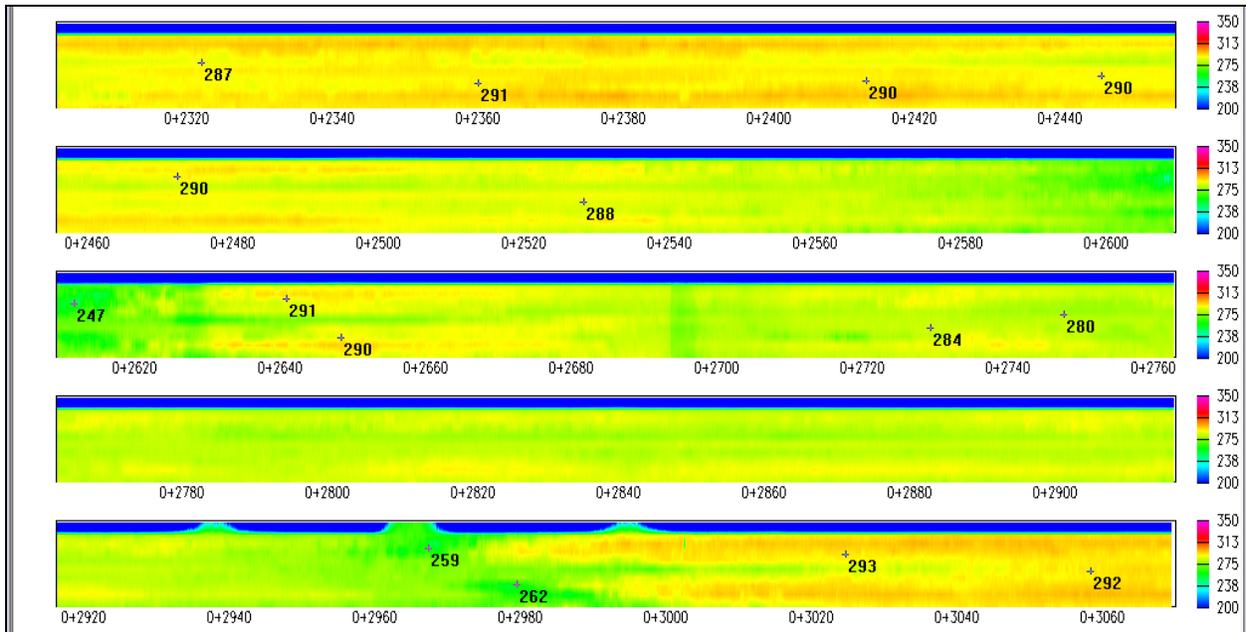
**Figure 65. CAM Paving Operation on Business 59.**

### Thermal Profile Results

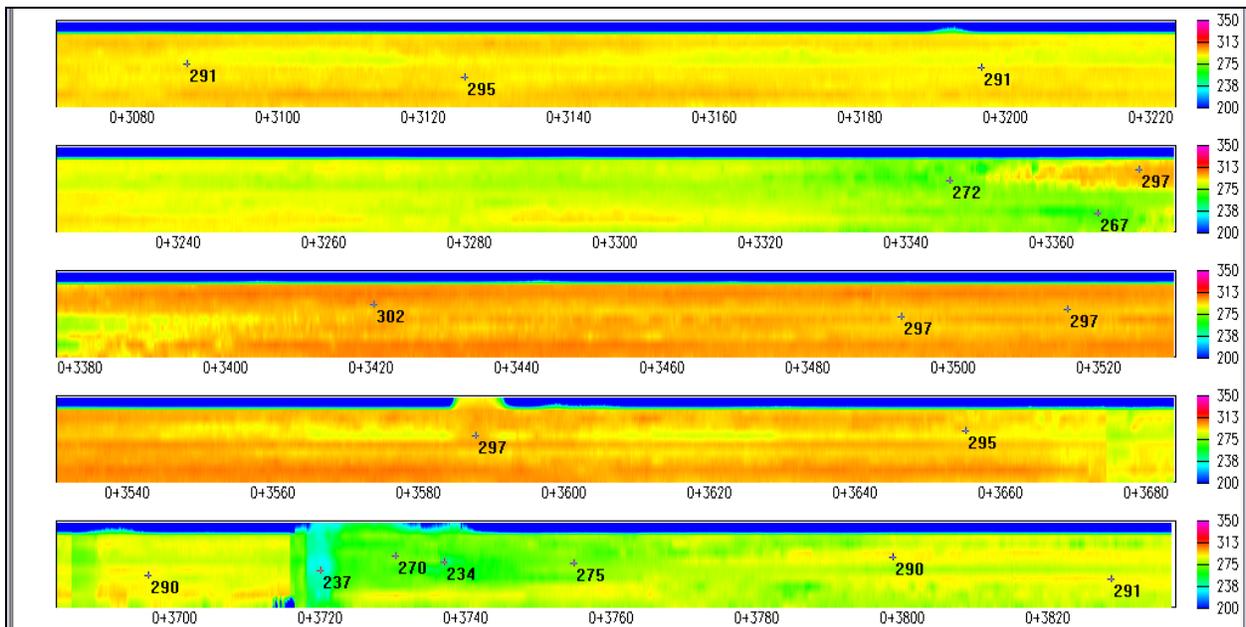
TTI performed a thermal survey on the southbound inside lane, beginning at the northern project limit and continuing to station 45+09. Figure 66 shows excerpts from the thermal profile, which revealed good uniformity within truckloads, some variations in the mean placement temperature from individual trucks, and some truck-end thermal differentials typically around 30°F.



**Figure 66. Thermal Profile of CAM on US 59 Southbound Inside Lane.**



**Figure 66. Thermal Profile of CAM on US 59 Southbound Inside Lane (continued).**



**Figure 66. Thermal Profile of CAM on US 59 Southbound Inside Lane (continued).**

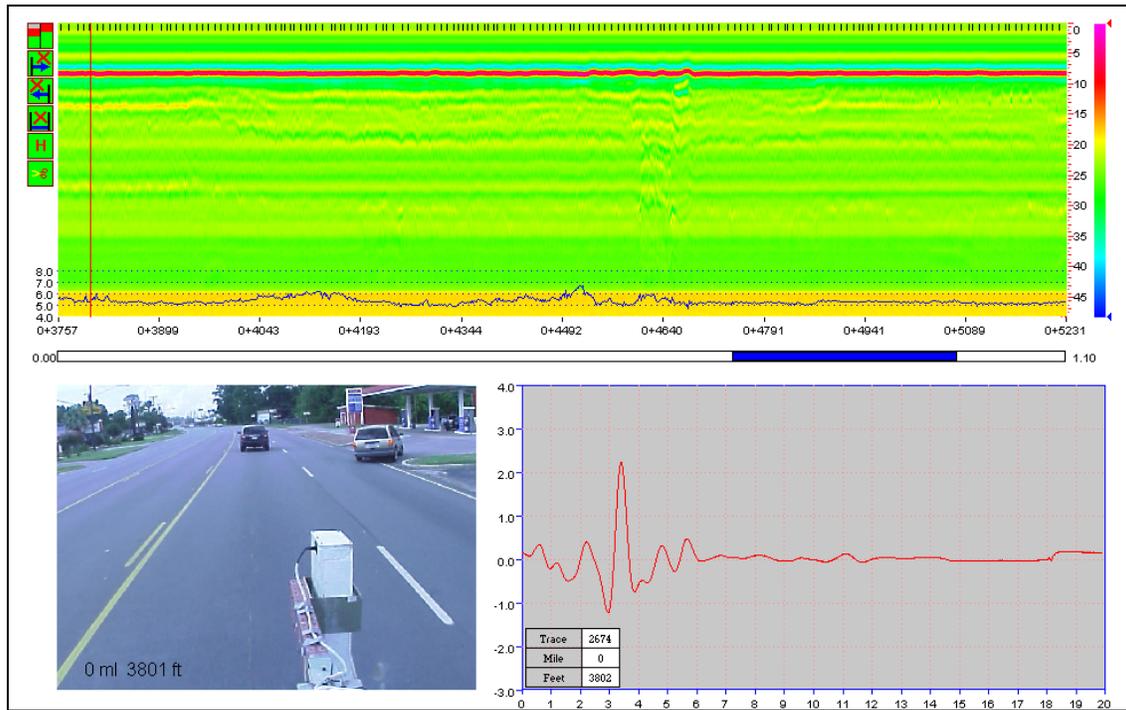
### Follow-Up Survey Results

In July 2011, TTI conducted a follow-up visual and GPR survey on the section. The only distresses observed were reflection cracking and some locations of corrugations. Figure 67 provides visual examples of these distresses.



**Figure 67. Distresses Observed on BU 59 after Five Years of Service.**

Figure 68 shows example GPR data from the section. The GPR data are clean and have some notable variations in the surface dielectric. However, no distress appears apparent at these locations, and the locations of corrugations in the pavement do not seem to consistently match any changes in the dielectric from the GPR.



**Figure 68. GPR Data on BU 59 after Five Years of Service.**

### Conclusions from BU 59 Project

After five years of service, the CAM section did not exhibit any distress clearly due to segregation. At the time of construction, most truck-end temperature differentials were around 30°F, so although some thermal segregation was observed at the time of construction, its

magnitude was not severe. The primary distress present was reflection cracks due to the pavement below the overlay.

## **US 90 CAM, SAN ANTONIO DISTRICT, CONSTRUCTED SEPTEMBER 23, 2008**

### **Paving Operation**

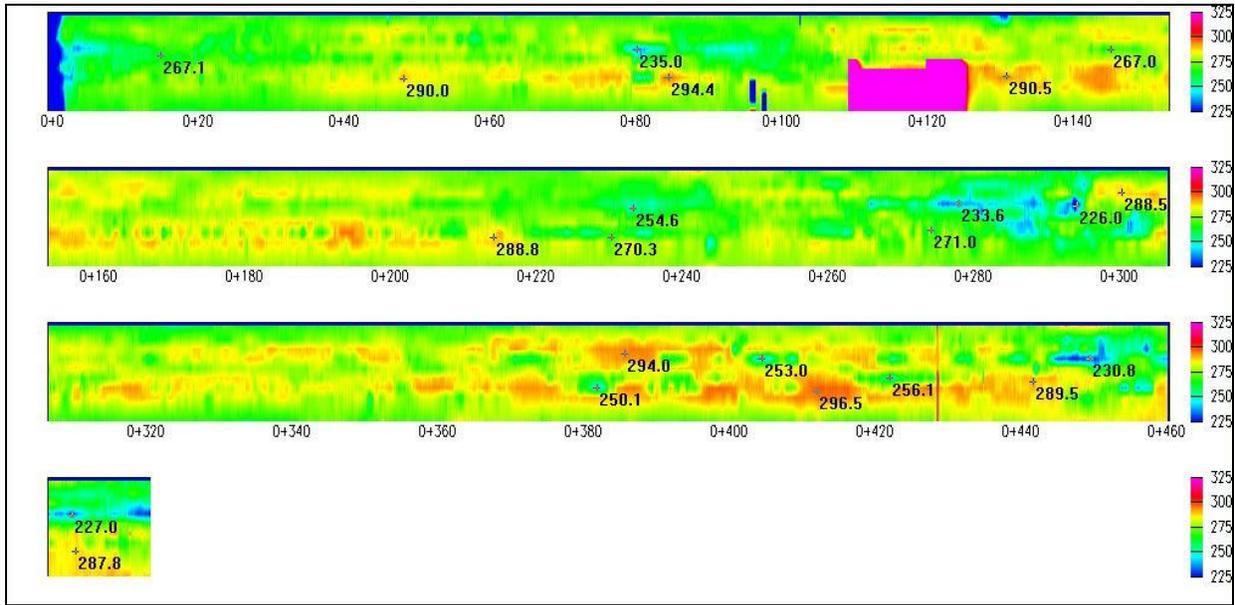
At this CAM project, the contractor end-dumped the mix into a Barber Green BG-260C paver. Compaction was accomplished with Dynapac CC 722 and CC 522V rollers, and an Ingram pneumatic roller. Figure 69 shows the operation.



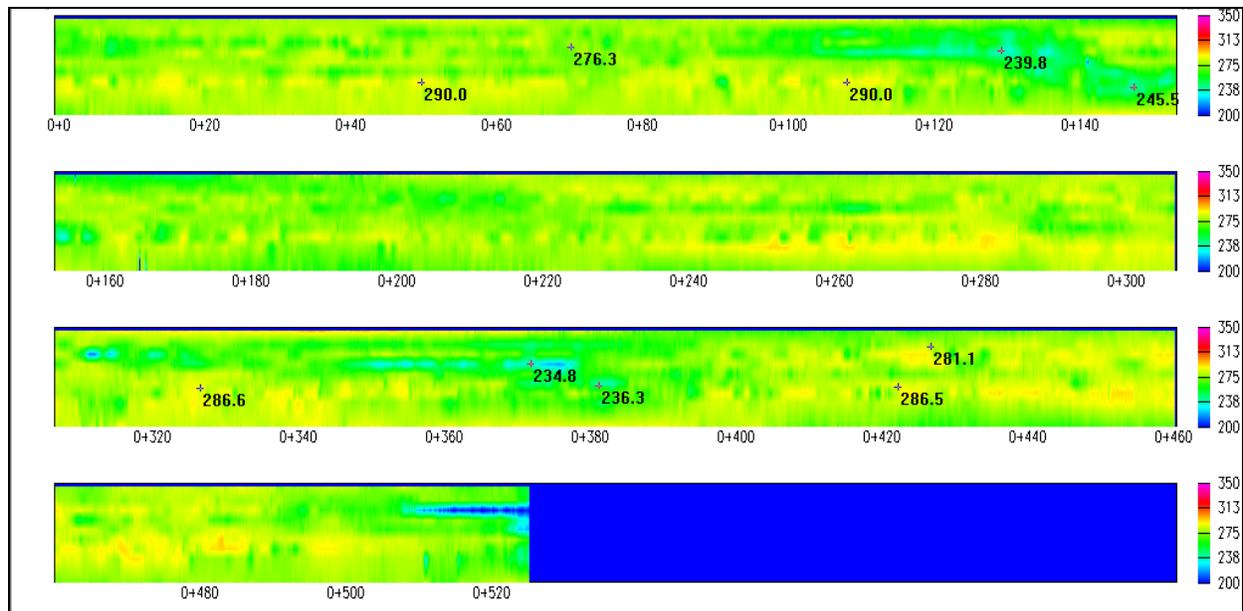
**Figure 69. Paving Operation on US 90 CAM Mix.**

### **Thermal Profile Results**

TTI collected a thermal profile beginning at N 29 12.820, W 99 55.612; and ending at N 29 12.751, W 99 55.425. On this project, numerous locations of thermal segregation were observed with temperature differentials around 50°F. Figures 70 and 71 show the thermal profile. Oftentimes these cold locations were also visibly evident, as Figure 72 illustrates.



**Figure 70. Thermal Profile from US 90 CAM.**



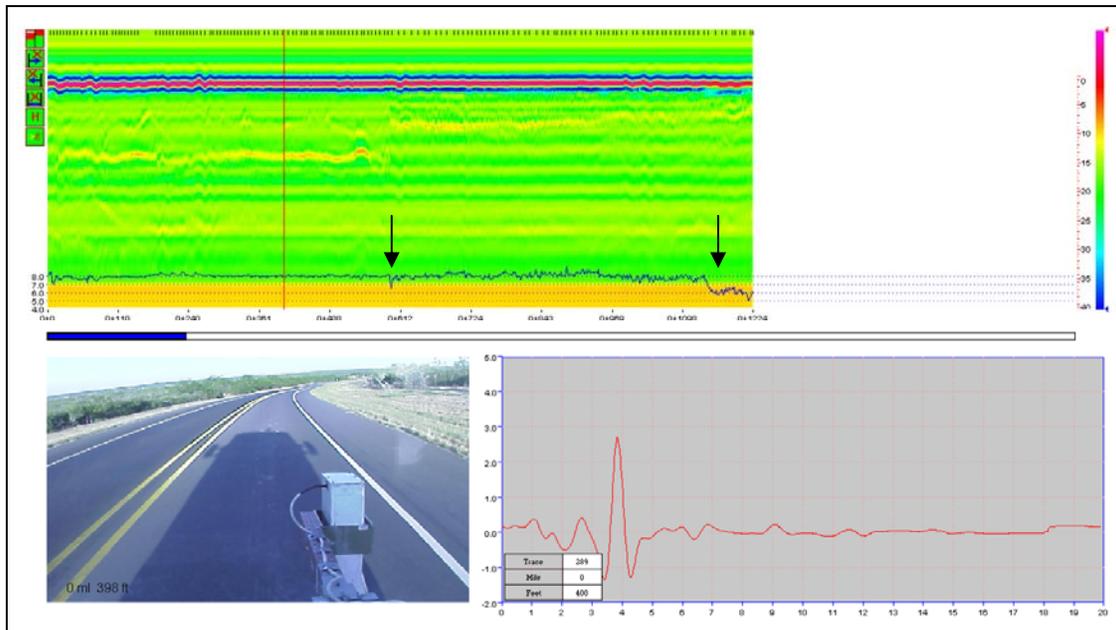
**Figure 71. Second Data File of Thermal Profile on US 90.**



**Figure 72. View of Cold Spot on US 90 CAM.**  
*Note: corresponds with 520 ft in Figure 57.*

### Follow-Up Survey Results

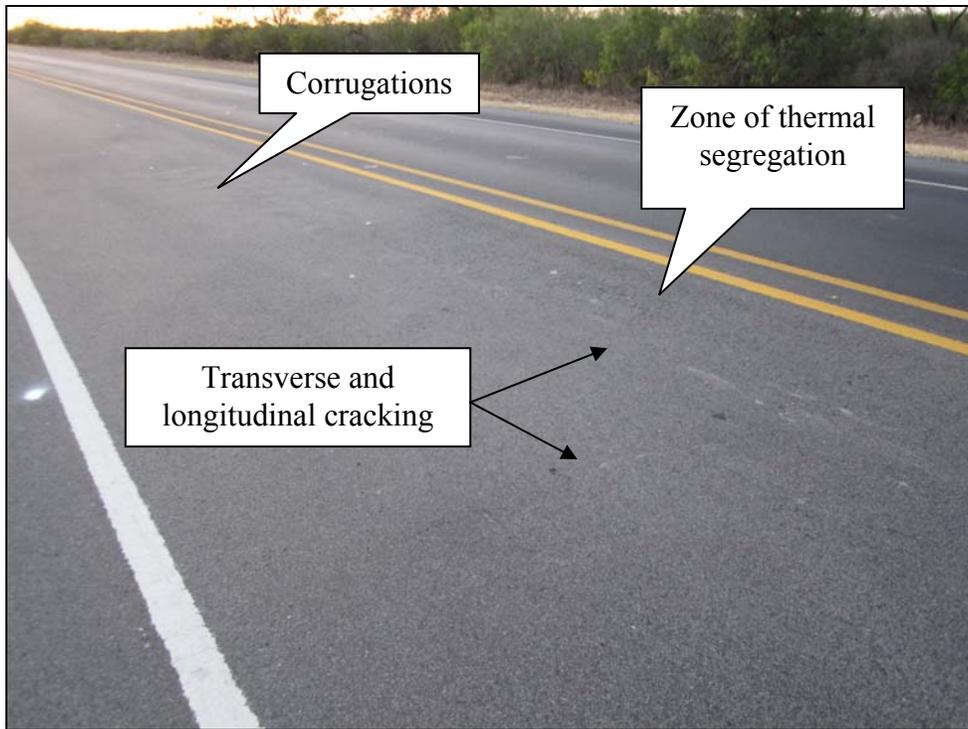
In July 2011, TTI conducted a follow-up visual and GPR survey. Figure 73 shows the GPR data, which show a significant drop in the dielectric in the middle and at the end of the evaluated section. Visually, some locations of coarser surface texture, and some corrugations, were observed. Figures 74 and 75 show the thermally segregated locations selected for coring.



**Figure 73. US 90 CAM after Three Years of Service.**



**Figure 74. US 90 Thermally Segregated Locations.**  
*Note: corresponds to ~450 ft in Figure 70.*



**Figure 75. Corrugations, Cracking, and Thermal Segregation on US 90 CAM after Three Years of Service.**  
*Note: follow-up coring performed at location of arrow, which corresponds with 525 ft in Figure 71.*

In addition to the cores selected from the thermally segregated areas, coring also was performed at a normal location corresponding with approximately 355 ft in Figure 70. Table 10 presents these core results. The core results show some significant changes in density at the most severely thermally segregated location, but poor performance in all cases in the overlay test.

**Table 10. Core Results from US 90.**

<b>Location</b>	<b>Percent Density</b>	<b>Overlay Test Peak Load (lb)</b>	<b>Overlay Test Cycles to Failure</b>
Normal	100.6	812	11
1	98.0	978	4
2	87.7	833	3

### **Conclusions from US 90 Project**

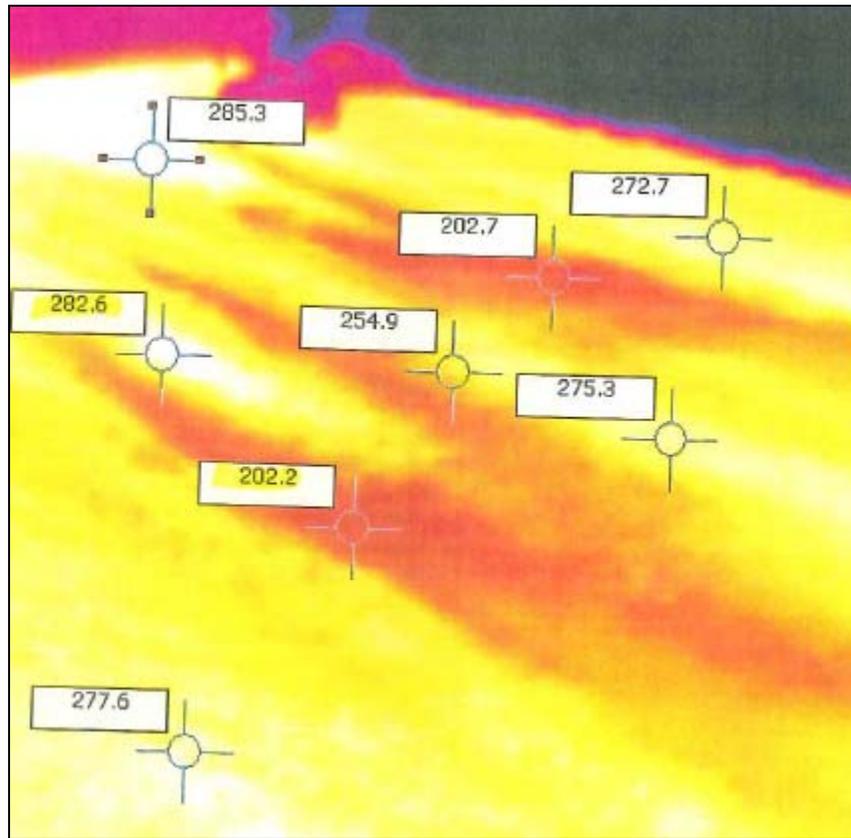
At the time of construction, cyclical thermal segregation occurred on this project, and these locations were sometimes visible by different surface texture during construction. After about three years of service, only one location prominently stood out upon inspection. Follow-up coring found that location had over 12 percent air voids. However, all cores collected on the project exhibited poor performance in the overlay test. Some transverse cracking, longitudinal cracking, and corrugations exist in the section monitored. While these distresses occurred in one of the known regions of thermal segregation, these distresses also were present at a few other locations that lacked thermal segregation at the time of construction. At this time, the only definite indicator of the thermal segregation on the project is the difference in surface texture appearance.

### **FM 2440 TYPE C, AUSTIN DISTRICT, CONSTRUCTED FALL 2008**

Based on reported segregation problems and numerous failing density profile results on FM 2440 in Lee County, TTI performed a GPR survey and limited coring program in December 2008 to capture an idea of the variability of compaction on the project at the time of construction. A follow-up survey in 2011 was performed to examine the pavement condition.

### **Thermal Profile Results**

TxDOT's Austin District staff performed thermal profiling on this project with an infrared camera. The results indicating thermal segregation and failing density profiles prompted a request for follow-up radar and coring surveys. Figure 76 shows an example thermal picture from the project.

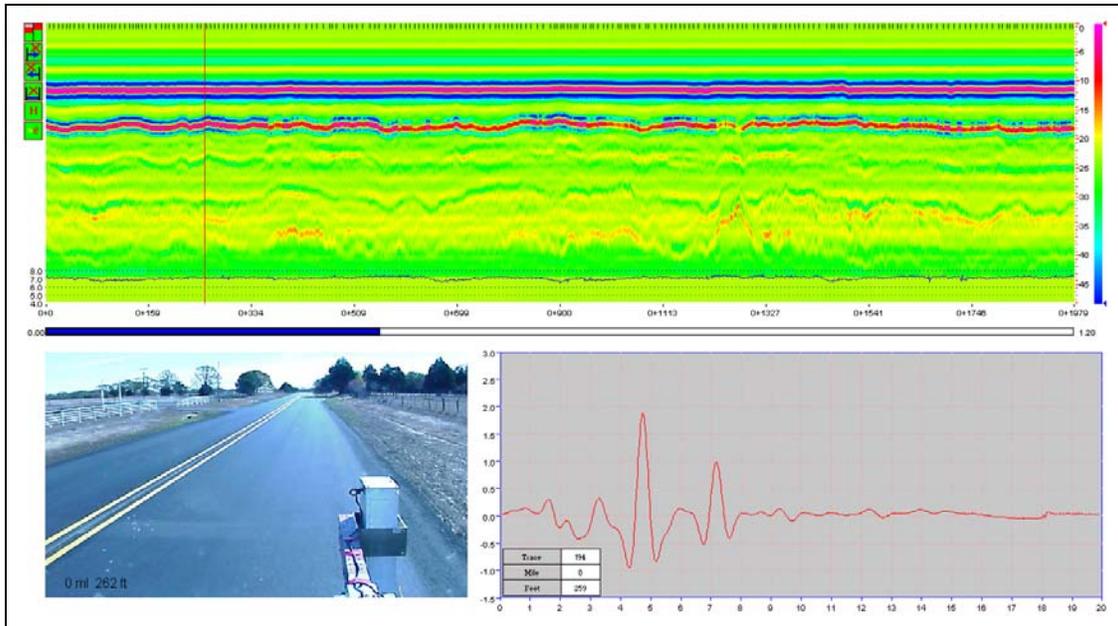


**Figure 76. Example Thermal Picture on FM 2440.**

*Note: courtesy of TxDOT.*

### **GPR Results near Time of Construction**

The GPR survey employed four passes each at a different transverse offset on a section approximately 1.2 miles long. The beginning and ending GPS coordinates were 30.20290495 N -96.96591655 W, and 30.19522483 N -96.94862899 W, respectively. The survey covered approximately from station 237 to 299. Figure 77 presents an excerpt of the GPR survey data.



**Figure 77. Example GPR on FM 2440 Shortly after Construction.**

Based upon the results, core locations were selected and tested, as shown in Table 11. In selecting core locations, TTI made efforts to specifically select cores representing a range from the worst to best compacted locations in the area surveyed.

**Table 11. FM 2440 Core Results.**

Core	Distance (ft) to Core from Start Location	Dielectric from GPR	Density (pcf)	Percent Air Voids*	Hamburg Rut Depth (mm) after 20,000 cycles**	Overlay Test Result	
						Initial Load	Cycles to Failure
1	53	6.7	143.3	5.3	8.1	Not Tested on Overlay Test	
2	86	6.2	139.1	8.1			
3	1279	6.9	144.6	4.4	Not tested in Hamburg	927	52
4	4545	6.7	143.4	5.2		Not Tested	
5	4561	6.2	137.7	9			
6	655	6.1	135.8	10.3		681	38

\*Before trimming for overlay test using the project Rice value of 2.425. Air voids after trimming for Cores 4 and 6 were 4.7 and 9.6 percent, respectively.

\*\*Binder was PG 70-22 and only required 15,000 cycles.

The core testing allowed correlation of the GPR to the air void content, as Figure 78 illustrates. Using this correlation, researchers converted the trace from each GPR reading to an air void prediction, and used that data to generate predicted air void distributions for the section surveyed. Figure 79 shows this distribution in the cumulative frequency format, encompassing information from over 11,000 data points collected spatially over the mat area surveyed.

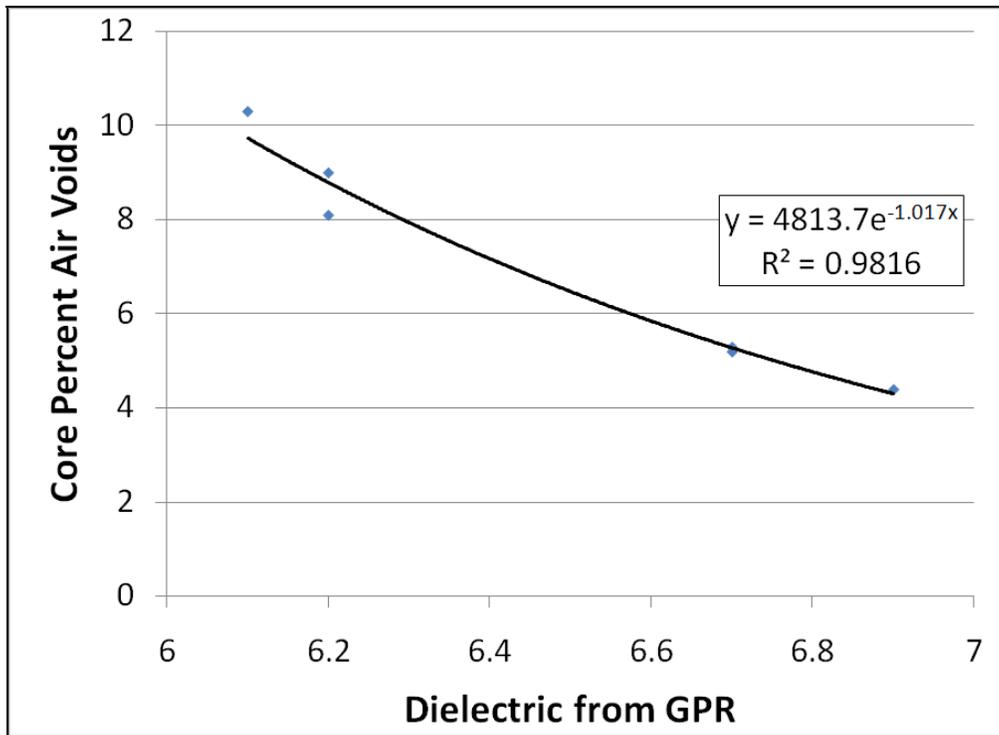


Figure 78. Calibrating GPR to Air Voids on FM 2440.

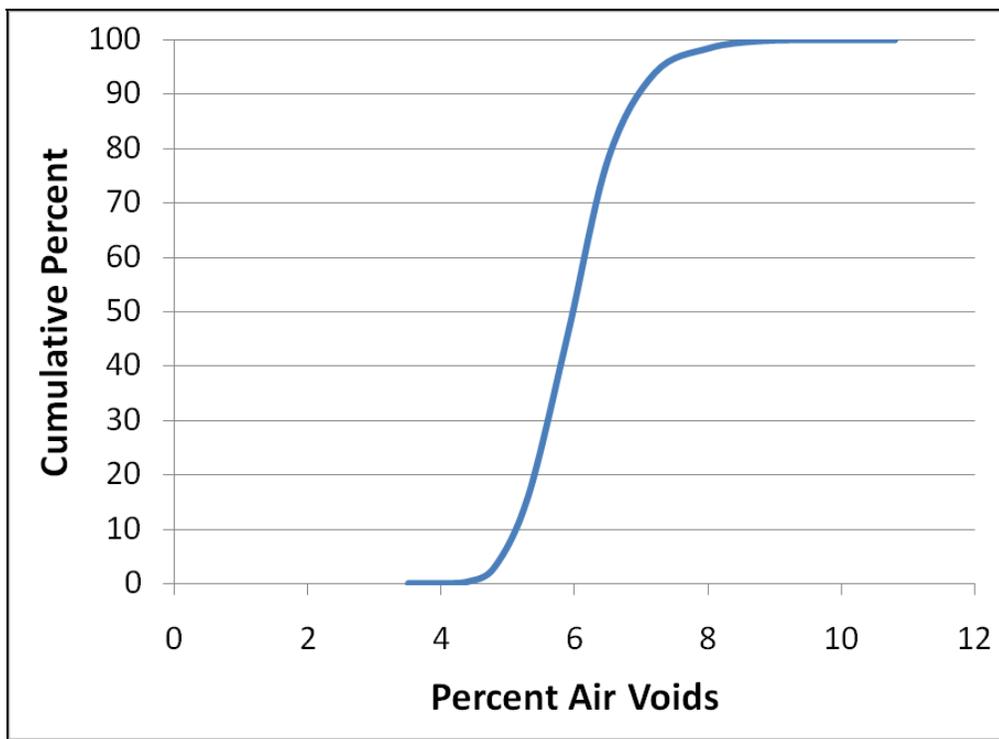


Figure 79. Cumulative Frequency Distribution of Expected Air Void in Surveyed Mat Area.

Although the expected distribution of air voids shown in Figure 78 does not raise many concerns, visual localized segregation was observed at many locations throughout the project, as Figure 80 shows. Although these cyclic segregated areas will not make up a large portion of the mat area, they can result in maintenance headaches for TxDOT due to the early failure that may occur at these locations. Therefore, the GPR data were further examined for evidence of cyclic spikes in air void content. The GPR data do show noticeable patterns. For example, Figure 81 graphs predicted air void content with distance for both the second and third GPR runs. Noticeable peaks in air void content exist at approximately 300-ft intervals over the first 1000 ft, then at an average spacing of 150 ft from 1450 to 2000 ft. Figure 82 zooms in on the first 2000 ft and further illustrates these patterns using data from the second GPR run. Also, Figure 82 combines the information from all the GPR runs into a surface contour plot of the predicted in-place air void content with thresholds in the color scale chosen from critical points in the Item 341 Placement Pay Adjustment Factors table. Figure 83 illustrates the cyclical low-density areas spatially on the pavement mat from station 237 to 257.



**Figure 80. Visually Observed Segregation on FM 2440 after Construction.**

*Note: photo courtesy of TxDOT.*

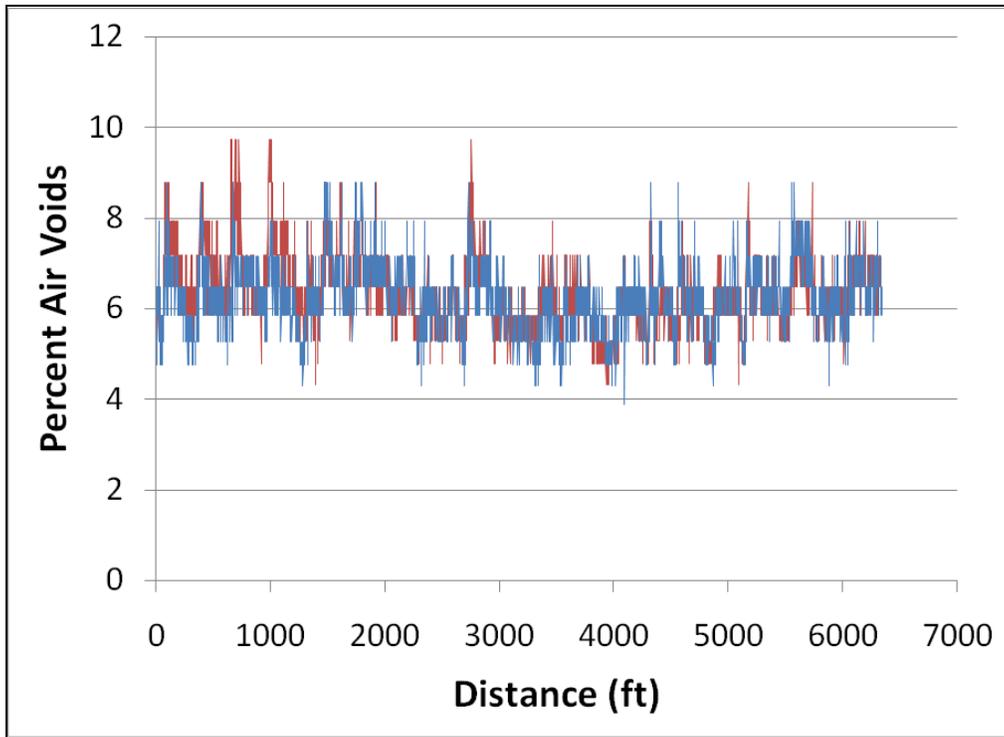


Figure 81. Predicted Air Voids with Distance for GPR Runs 2 and 3 on FM 2440.

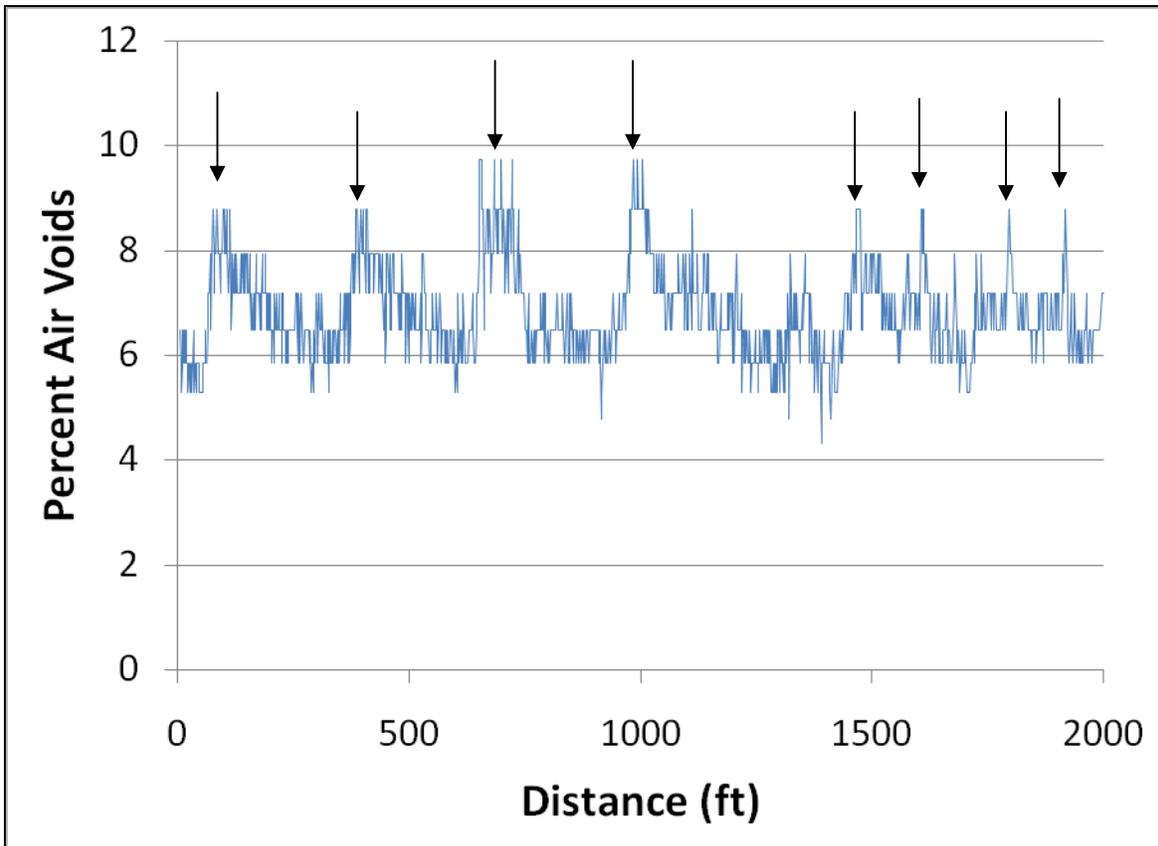
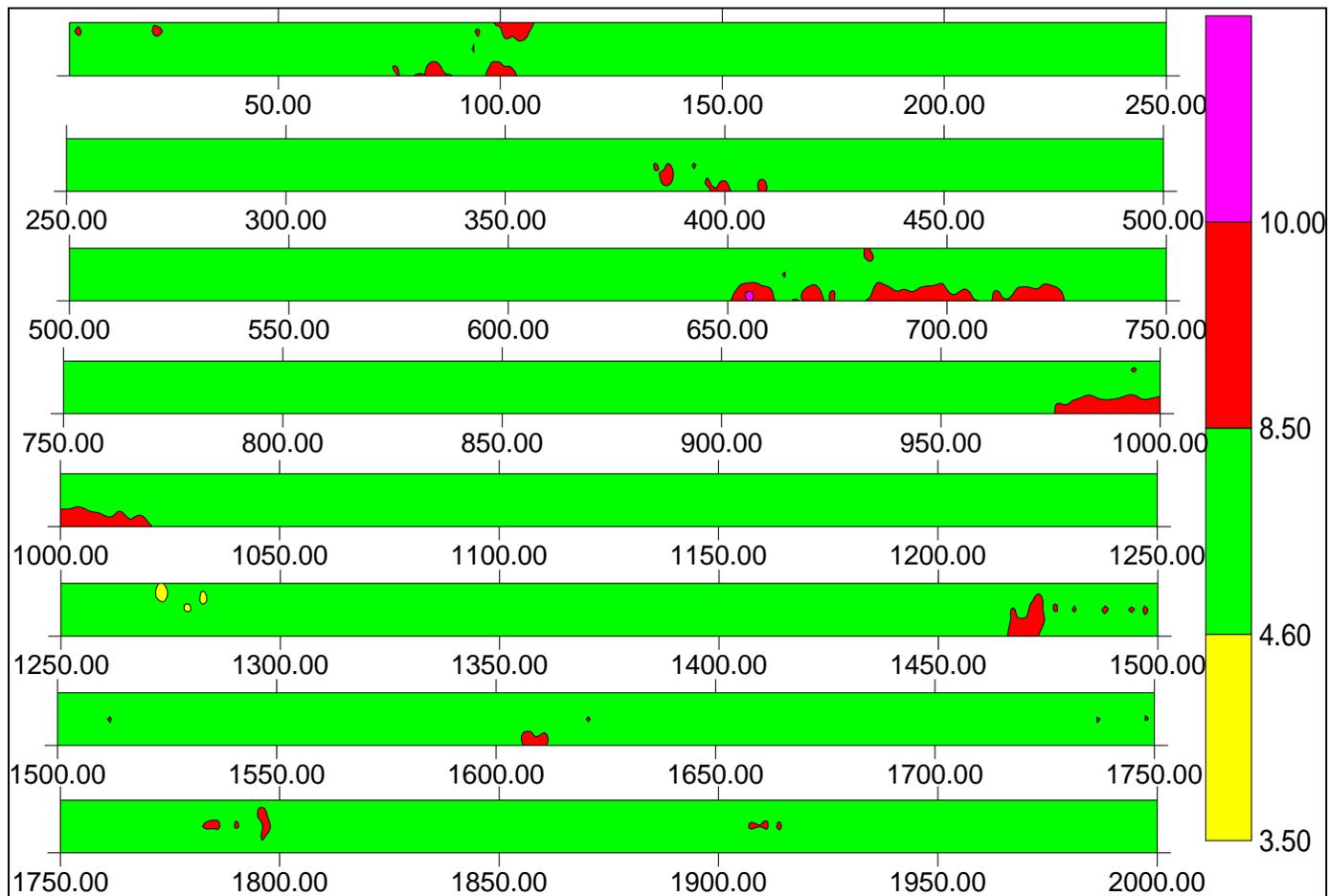


Figure 82. Cyclic Peaks in Air Voids with Distance in Second GPR Pass on FM 2440.



**Figure 83. Surface Plot of Predicted In-Place Air Voids on FM 2440.**

*Note: starting position is 30.20290495 N -96.96591655 W, or approximately at Station 237.*

## Follow-Up Survey Results

TTI performed a follow-up visual and GPR survey on this section in July 2011. Longitudinal cracking, likely due to the subgrade, was the only distress noted. Figure 84 shows example GPR data from the section evaluation. Contrasting Figure 84 with Figure 77 indicates the dielectric plot in the current data does not vary as much as the dielectric plot observed shortly after construction. This may mean traffic action has smoothed out some of the density irregularities that existed immediately after construction.

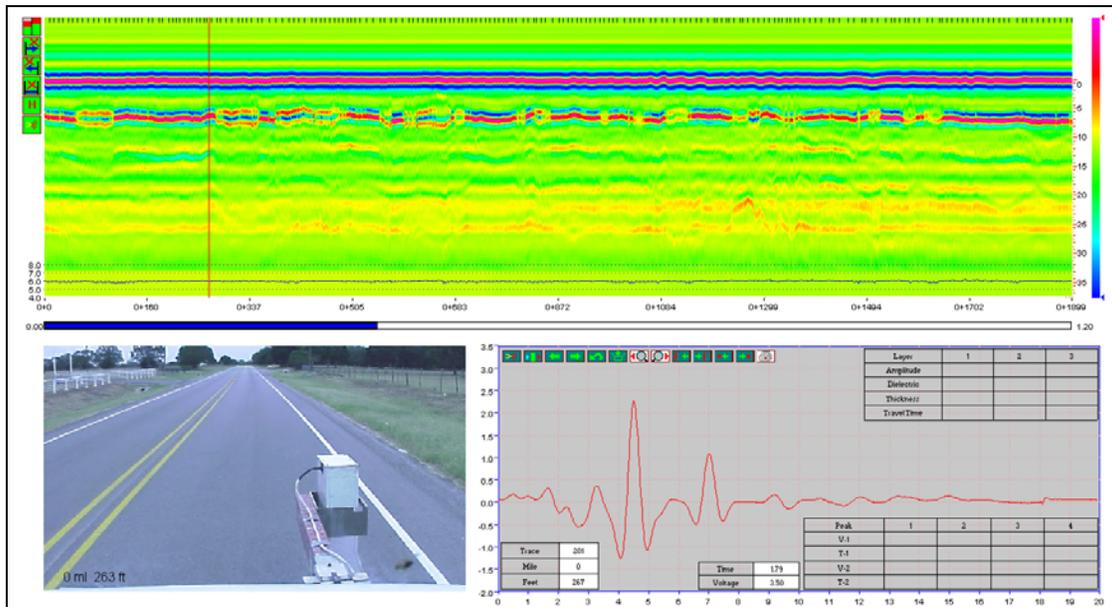


Figure 84. FM 2440 after 3 Years of Service.

## Conclusions from FM 2440 Project

An analysis of the GPR, coring, and laboratory testing performed on FM 2440 shortly after construction revealed cyclic segregation existed. The total area impacted with air voids greater than 8.5 percent was a small portion (approximately 0.8 percent) of the mat area surveyed. Representative pavement cores passed the Hamburg test, but did poorly in the overlay test. This mix may be prone to reflection and possibly fatigue cracking.

After approximately three years of service, no distress due to segregation was observed in the section monitored. The only distress was longitudinal cracking due to the subgrade. Additionally, based upon the current GPR data, it appears traffic action may have helped homogenize the density irregularities that were observed at the time of construction.

## PARMER LANE, TYPE C, AUSTIN DISTRICT, CONSTRUCTED MARCH 24, 2009

### Paving Operation

The Type C mix was produced in Buda and hauled in belly dump trucks to the project site. A Roadtec SB 2500D transferred the mix into a Barber Green paver. Figure 85 shows the transfer device and paver placing the HMA.



**Figure 85. Paving Operation on Parmer Lane.**

### **Thermal Profile Results**

The thermal survey began at 30.42574588 N, -97.71588790 W, and ended at 30.42156534 N, -97.70664239 W. The section was the eastbound left lane on Parmer Lane. Figure 86 shows the thermal profile, and Figure 87 shows a histogram of all the measured temperatures. Some observations and comments from the profile data include:

- Sensor one was occasionally off the mat (for example, from the start location to a distance of 80 ft) up through the first 920 ft.
- Twelve paver stops exist ranging in duration from 1 minute to 35 minutes. Most of the stops were 5 minutes or less; one location was 13 minutes and the longest paver stop lasted 35 minutes. At that location, the mat surface temperature had cooled to approximately 195°F.
- Noise exists in the data when the computer was plugged into the paver generator. The impact of the noise on the profile can be seen by comparing the first 770 ft in Figure 86 to the data from 770–1530 ft.
- Four locations of centerline cold spots exist. These locations are at approximately 282, 320, 625–660, and 2125–2135 ft. The location at 320 ft is known to be from water spilled from the water jug. The other three locations represent true cold spots in the paving operation.
- The temperature differential across each transverse scan is typically less than 20°F. This observation was confirmed with a handheld spot radiometer.
- With the exception of locations of paver stops and a few other anomalous spots, temperature differentials in the longitudinal direction are typically around 30°F or less.
- Approximately 95 percent of the mat surveyed had placement temperatures between 270° and 320°F, as Figure 87 shows. However, the noise in the data from the method of powering the laptop likely inflated this range; the actual 95 percent interval of placement temperatures is more likely within a 40°F range.

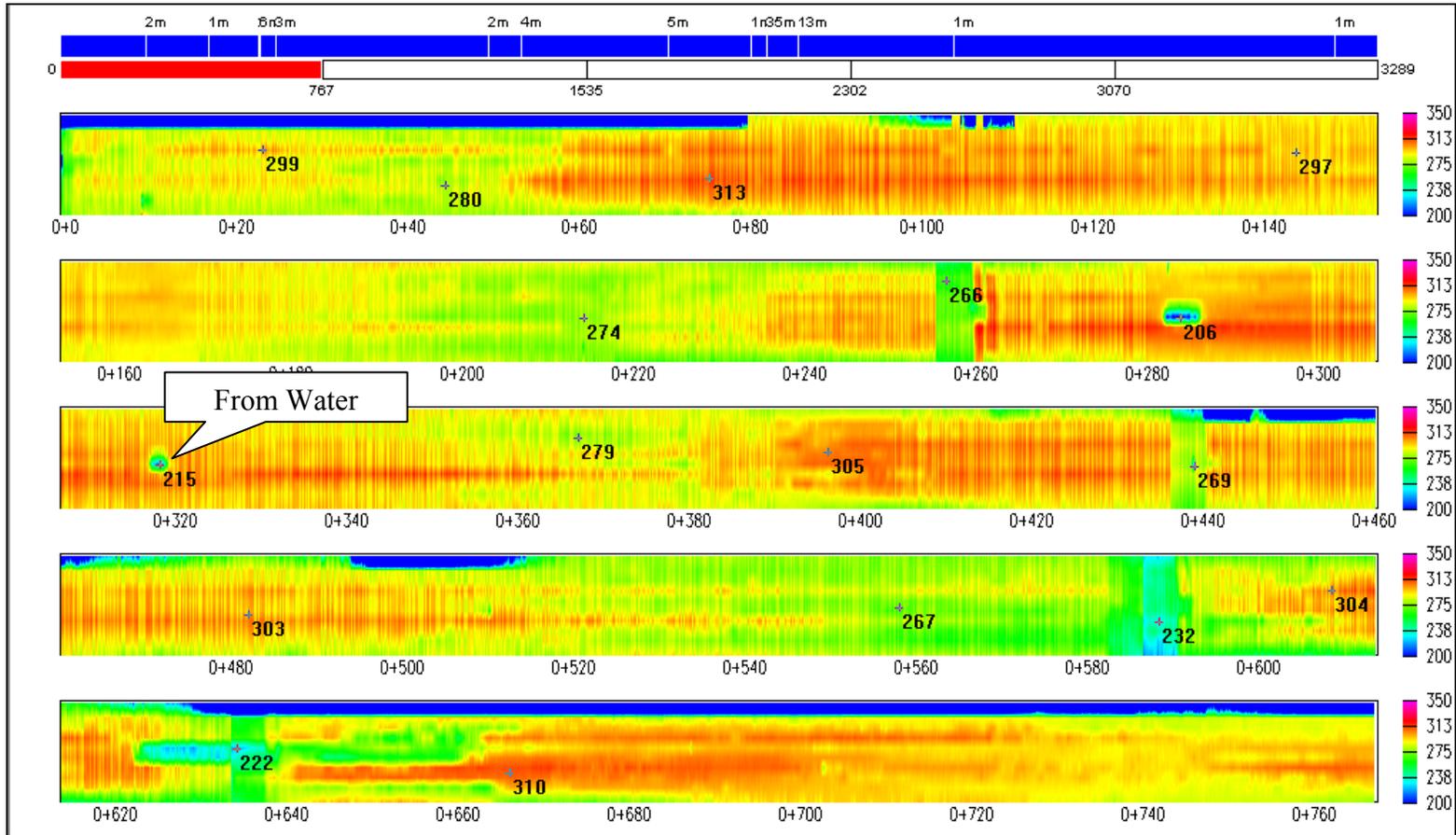


Figure 86. Thermal Profile on Parmer Lane.

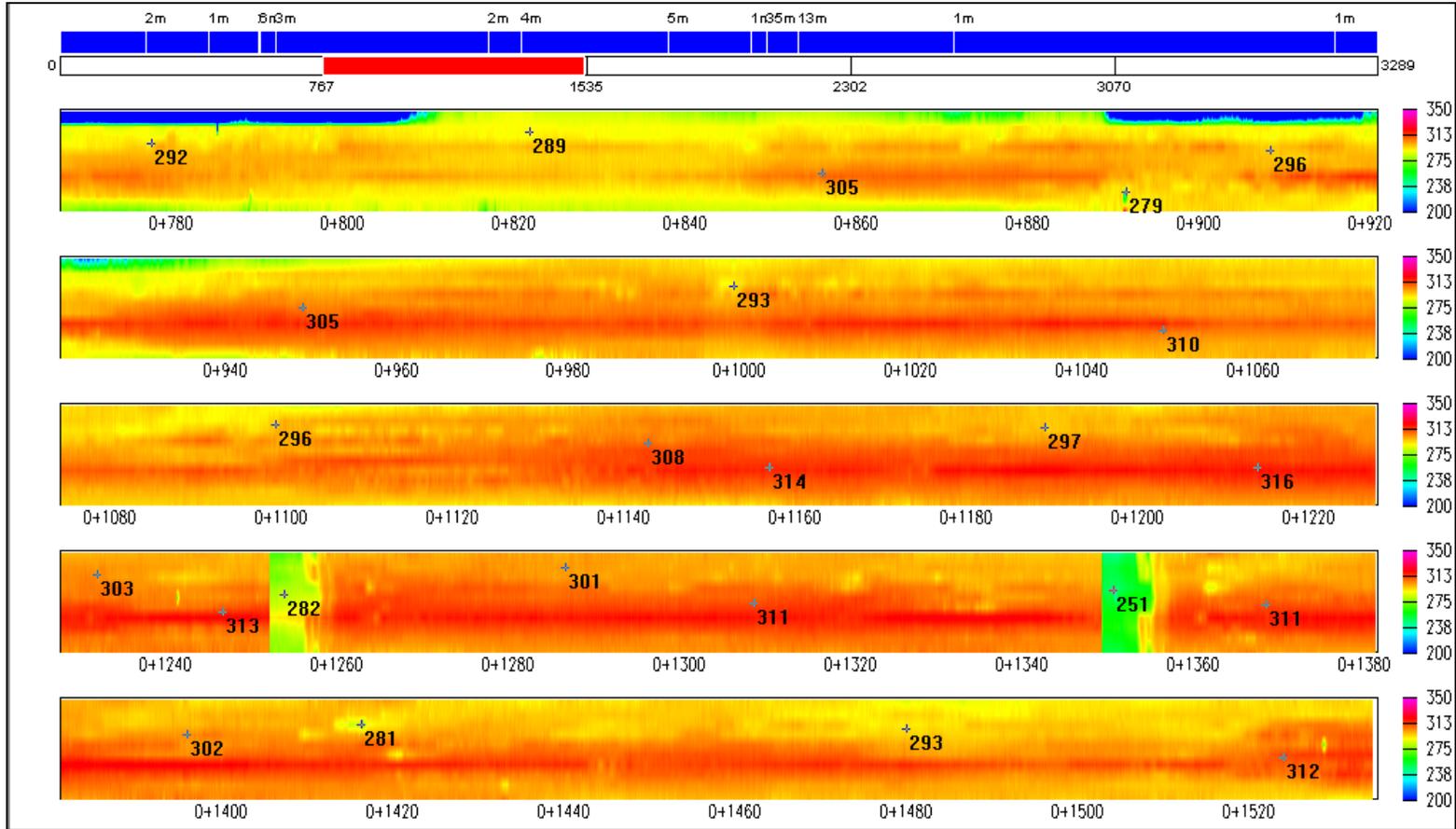


Figure 86. Thermal Profile on Parmer Lane (continued).

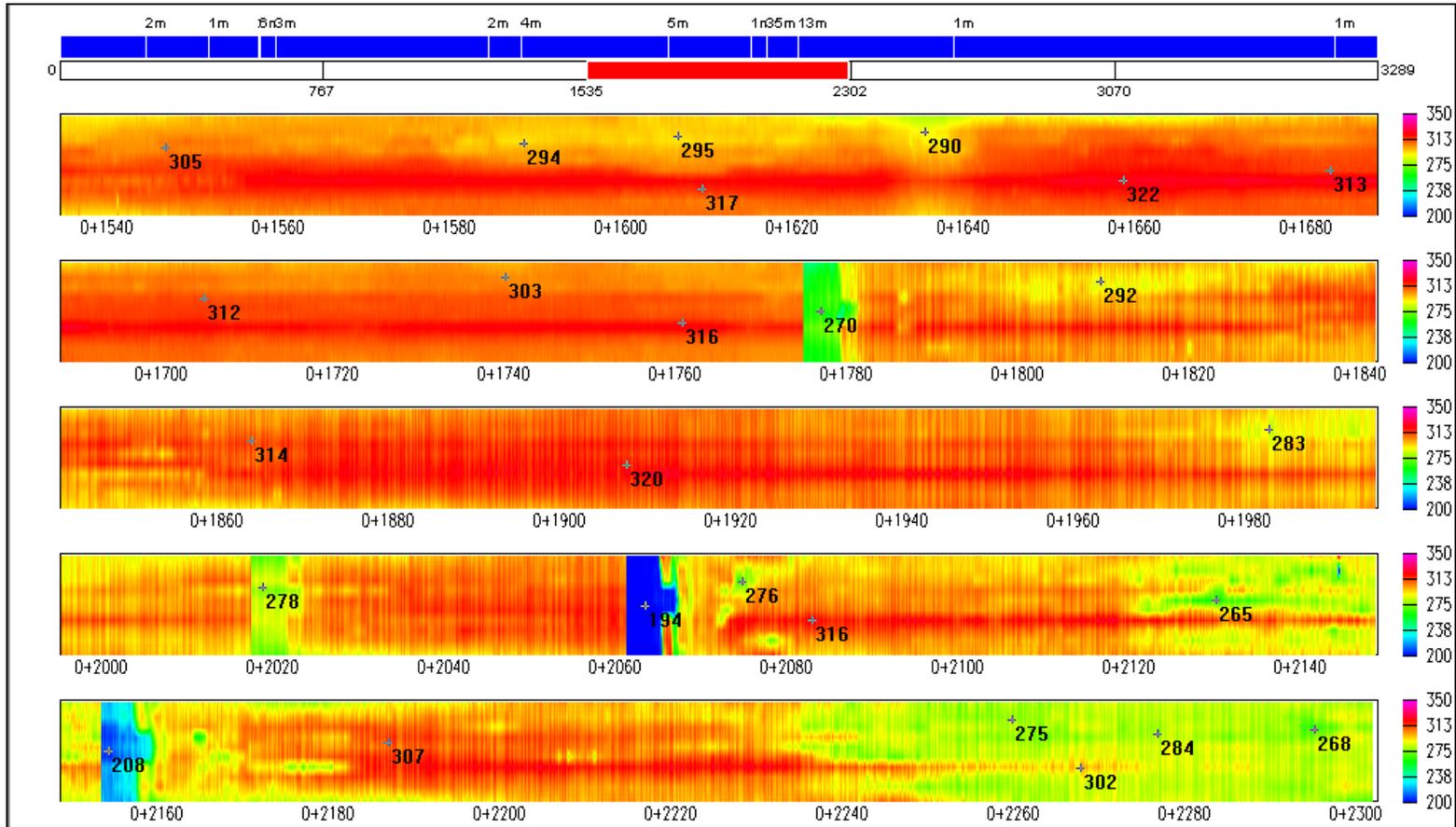


Figure 86. Thermal Profile on Parmer Lane (continued).

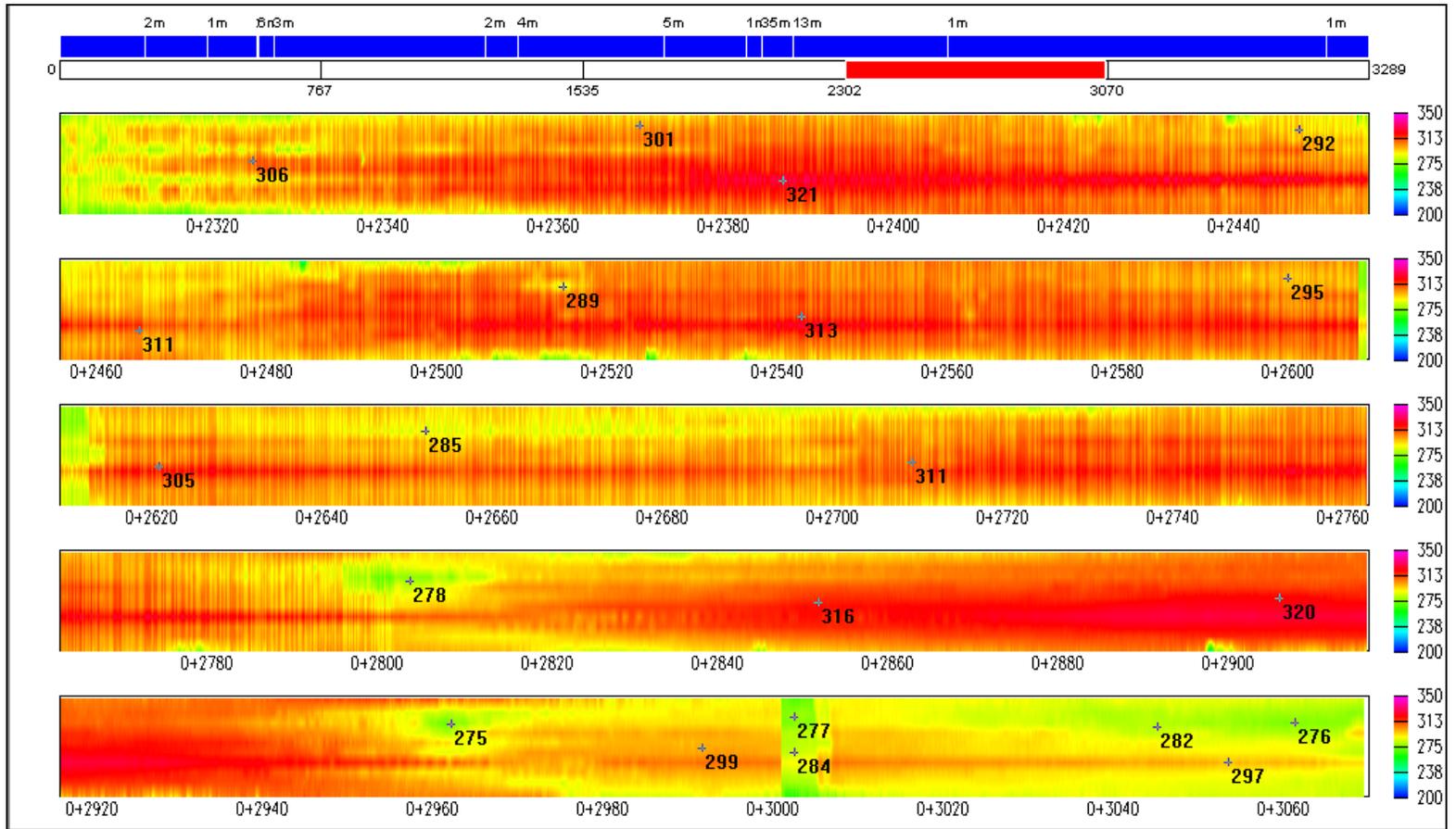


Figure 86. Thermal Profile on Parmer Lane (continued).

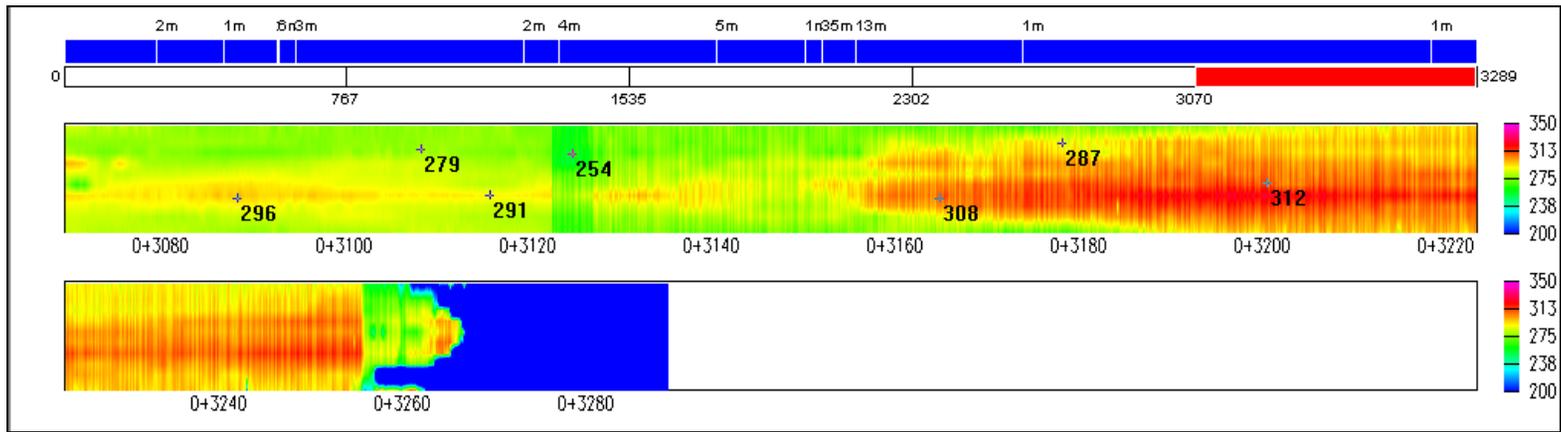
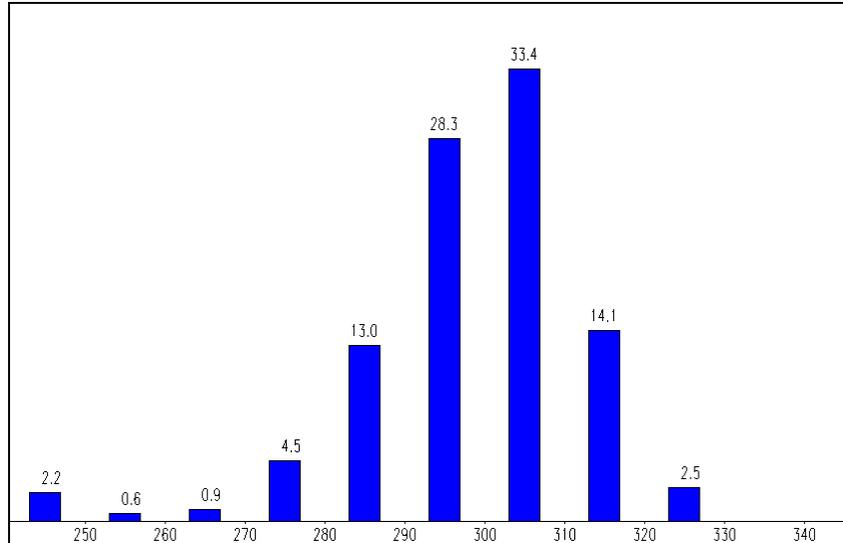


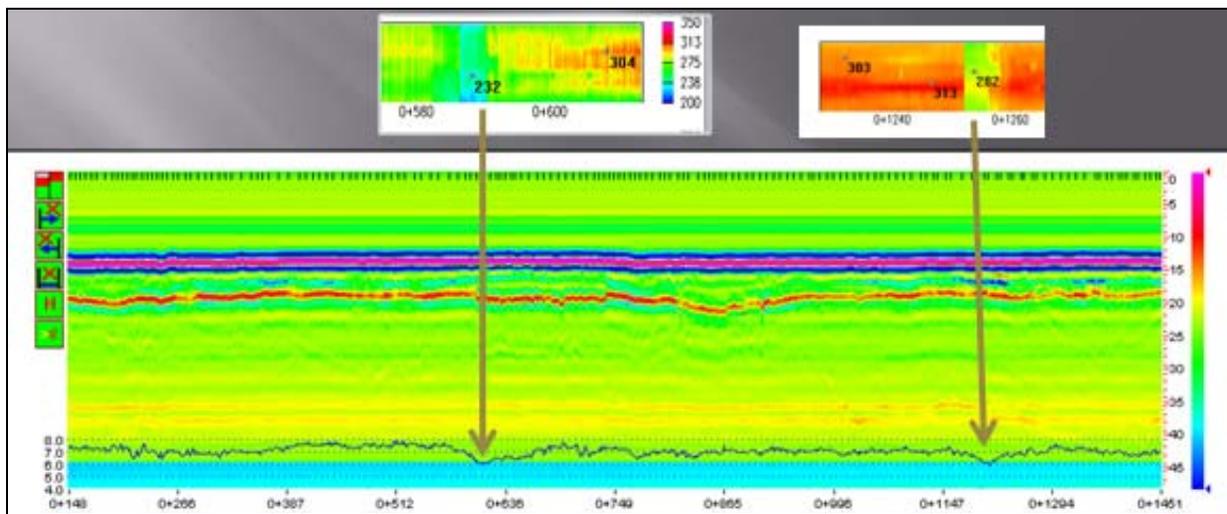
Figure 86. Thermal Profile on Parmer Lane (continued).



**Figure 87. Histogram of Measured Temperatures on Parmer Lane.**

### GPR Results at Time of Construction

On April 23, 2009, TTI collected GPR over the section. An initial review of the data showed some sizeable dips in the GPR-measure surface dielectric value. Some of these low dielectric locations occurred at locations of paver stops. However, not all paver stops showed up in the GPR data as low dielectric locations. Figure 88 shows an example of two paver stops and corresponding low surface dielectric values.



**Figure 88. Low Dielectric Locations at Paver Stops on Parmer Lane.**

### Follow-Up Survey Results

In July 2011, TTI performed a follow-up visual and GPR survey on the section. The section appears in good condition with no distress noted. The only observations noted were locations of coarser surface texture between 625 and 680 ft. The location at 625 ft matches the centerline thermal streak in Figure 86. Patterns of paver stops at 2060 and 2154 ft also were observed and match paver stops observed in the thermal profile. Figures 89 and 90 show these

streak and paver stop locations. At the streaks, only a coarser surface texture was noted. At the locations of the paver stops, the outline of the paver bull plate was still visible in the pavement.



(a) 628 ft

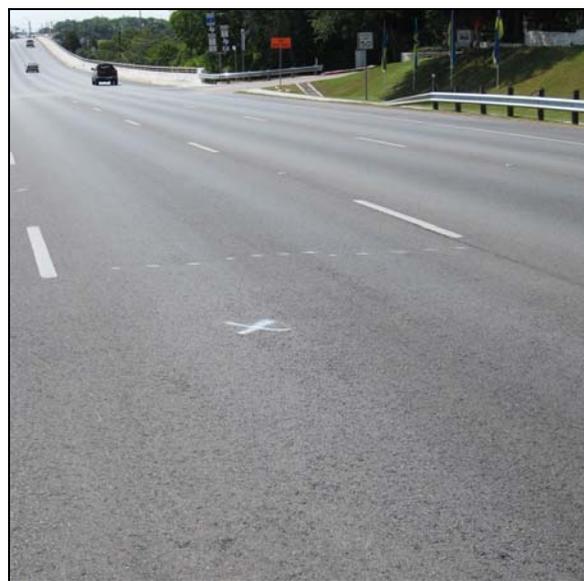


(b) 679 ft

**Figure 89. Streak on Parmer Lane after Two Years of Service.**



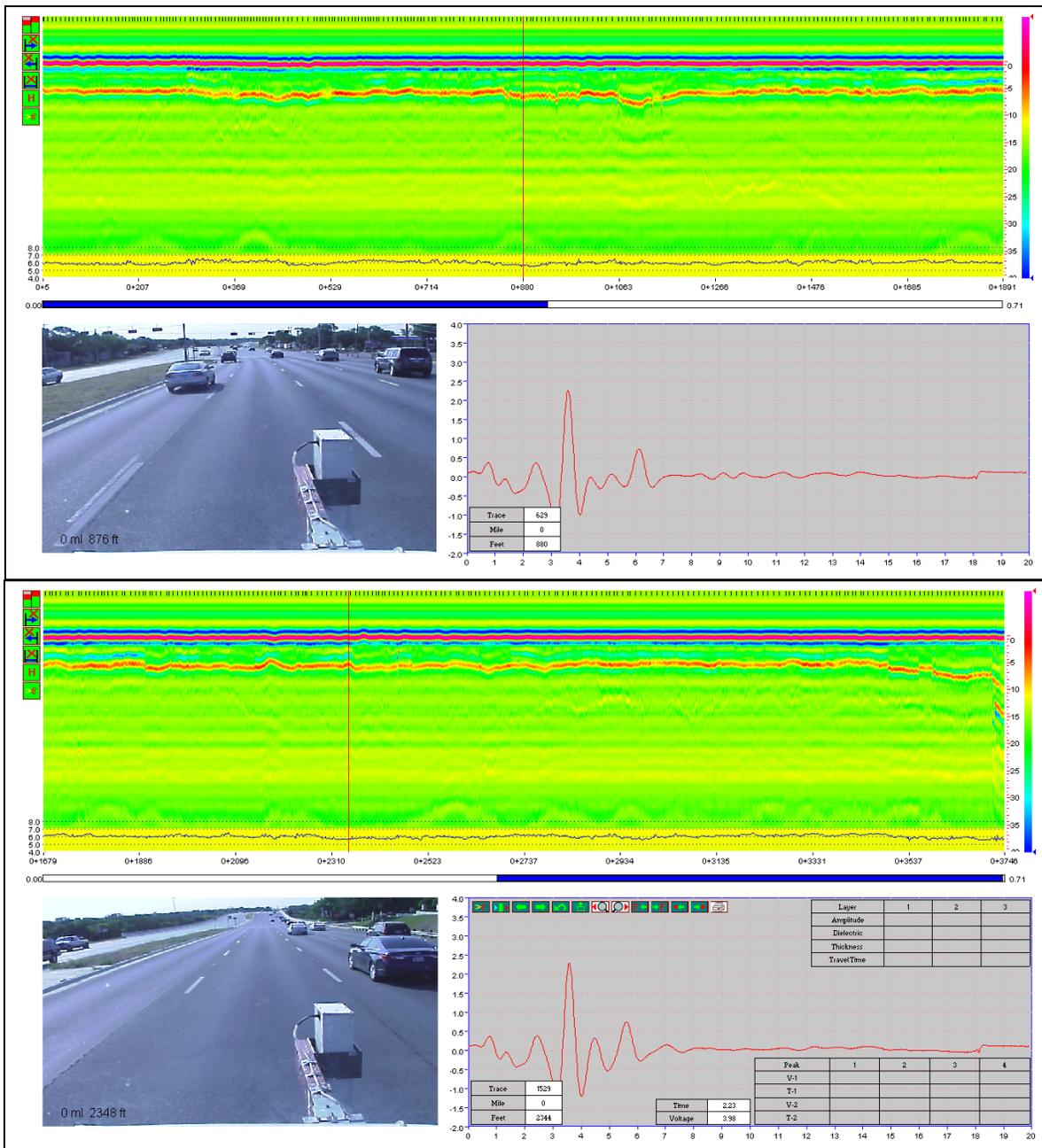
(a) 2060 ft



(b) 2154 ft

**Figure 90. Paver Stops on Parmer Lane after Two Years of Service.**

Figure 91 shows GPR data on Parmer Lane after two years of service. As compared to Figure 77, the surface dielectric does not vary as much as was observed immediately after construction.



**Figure 91. GPR on Parmer Lane after Two Years of Service.**  
*Note: start of pull is at 292 ft in this GPR file.*

To evaluate in the lab the performance measures of the anomalous locations against a normal location, the spots marked in Figures 89 and 90 were cored for laboratory density, overlay, and Hamburg tests. Two additional cores at 1079 and 1779 ft into the pull were cored. The location at 1079 represents a normal location, and the location at 1779 ft was another paver stop region. Table 12 presents the results from these cores. In general, the locations observed as thermally segregated at the time of construction had higher air voids. All the samples passed the

Hamburg test. The overlay results show a correlation of increasing peak load with decreasing air voids (i.e., the mix is stiffer at lower air voids). The locations with thermal anomalies at the time of construction exhibited reduced cycles to failure in the overlay test. However, all of the cores exhibited relatively low cycles to failure.

**Table 12. Core Results from Parmer Lane.**

Core Location *	Comment	Core Air Voids (%)	Overlay Test Results			Hamburg Test Results (mm rut depth)			
			Trimmed Air Voids (%)	Cycles to Failure	Peak Load (lbf)	5000	10000	15000	20000
628 ft.	Thermal and visual streak	9.4	9.3	2	868	<i>Not tested in Hamburg</i>			
		8.3	<i>Not tested in O.T.</i>			-2.78	-3.3	-3.88	-4.46
		8.0							
679 ft.	Visual streak	7.6	7.9	47	926	<i>Not tested in Hamburg</i>			
		8.5	<i>Not tested in O.T.</i>			-2.52	-3.1	-3.71	-4.45
		8.6							
1079 ft.	Normal location	7.5	7.9	37	717	<i>Not tested in Hamburg</i>			
		8.3	<i>Not tested in O.T.</i>			-1.27	-1.97	-2.59	-3.01
		8.5							
1779 ft.	Paver stop	6.8	5.7	4	1323	<i>Not tested in Hamburg</i>			
		7.2	<i>Not tested in O.T.</i>			-2.16	-2.59	-3.17	-3.39
		7.0							
2060 ft.	Paver stop	9.5	9.2	26	731	<i>Not tested in Hamburg</i>			
		6.9	<i>Not tested in O.T.</i>			-2.68	-4.96	-6.44	-7.16
		6.7							
2154 ft.	Paver stop	10.0	11.4	2	573	<i>Not tested in Hamburg</i>			
		9.4	<i>Not tested in O.T.</i>			-3.09	-3.72	-4.3	-4.3
		9.3							

### Conclusions from Parmer Lane Project

The thermal profile results on Parmer Lane showed reasonable thermal uniformity. However, some locations of paver stops showed significantly reduced temperatures, and a few other locations existed that would be deemed as having thermal segregation. These locations were streaks in the mat. After slightly more than two years of service, no significant distress exists on the projects. Some streaks of coarser surface texture were observed, and patterns of the paver stops remain in the mat at some locations. Current GPR data suggest the surface dielectric has smoothed slightly since the time of construction. This observation suggests traffic action may help homogenize the surface layer density.

Cores collected after two years of service showed all test locations passed the Hamburg test. In general, the cores collected from locations of known thermal anomalies exhibited reduced cycles to failure in the overlay test. While none of the cores performed extremely well in the overlay test, this observation suggests the zones of thermal anomalies may be more prone to cracking.

## SH 6, PFC, BRYAN DISTRICT, CONSTRUCTED MAY 13, 2009

On May 13, 2009, TTI collected thermal profile data with Pave-IR on the SH-6 PFC surface course in the Bryan District. Although paving the northbound inside lane, the mix was placed traveling southbound. The start location was approximately at Station 550.42. The total distance paved according to the distance encoder on Pave-IR was approximately 19,080 ft.

### Paving Operation

The contractor performed the paving using primarily flow-bow haul trucks with some end-dump bobtails also used to transport the mix. A Roadtec SB-2500D transferred the mix to an IR/Blaw Knox PF-5510 paver. Figure 92 shows the paving train.



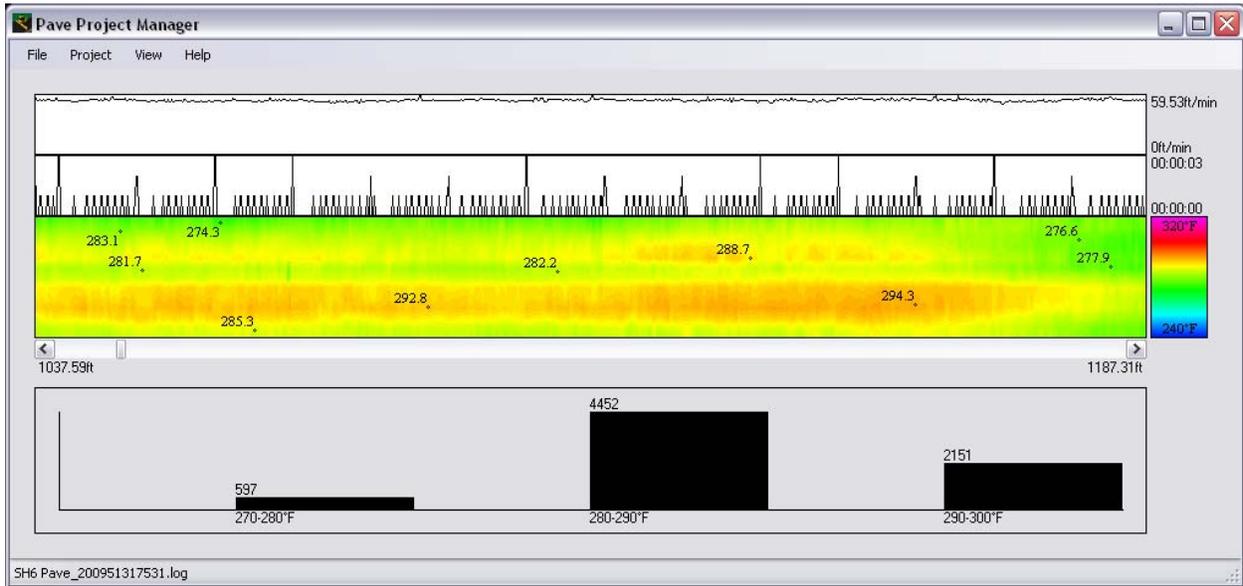
**Figure 92. Paving Train on SH 6 PFC.**

### Thermal Profile Results

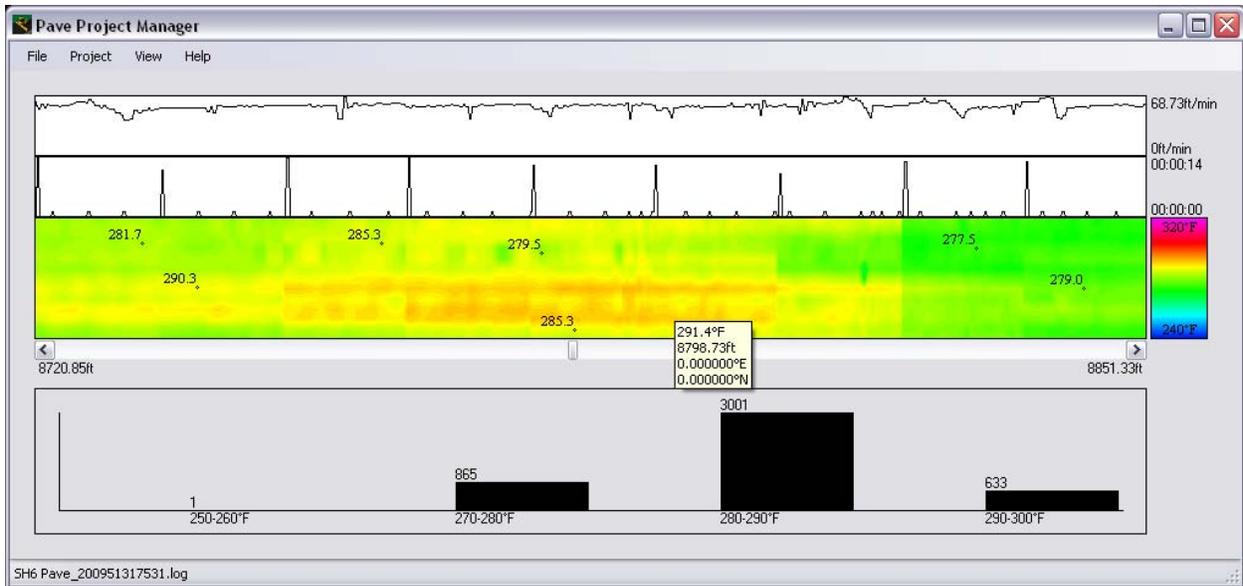
Figure 93 shows the Pave-IR unit used to collect the thermal profile. This unit employs 12 sensors spaced approximately 1 ft apart and was set to collect data at 3-in. distance intervals. Within 150-ft. segments, the thermal differentials typically ranged from 20° to 30°F, as Figure 94 illustrates; with occasional segments with differentials within 40°F, as Figure 95 shows. The cumulative distribution frequency of placement temperatures, presented in Figure 96, shows approximately 90 percent of placement temperatures were between 250° and 295°F.



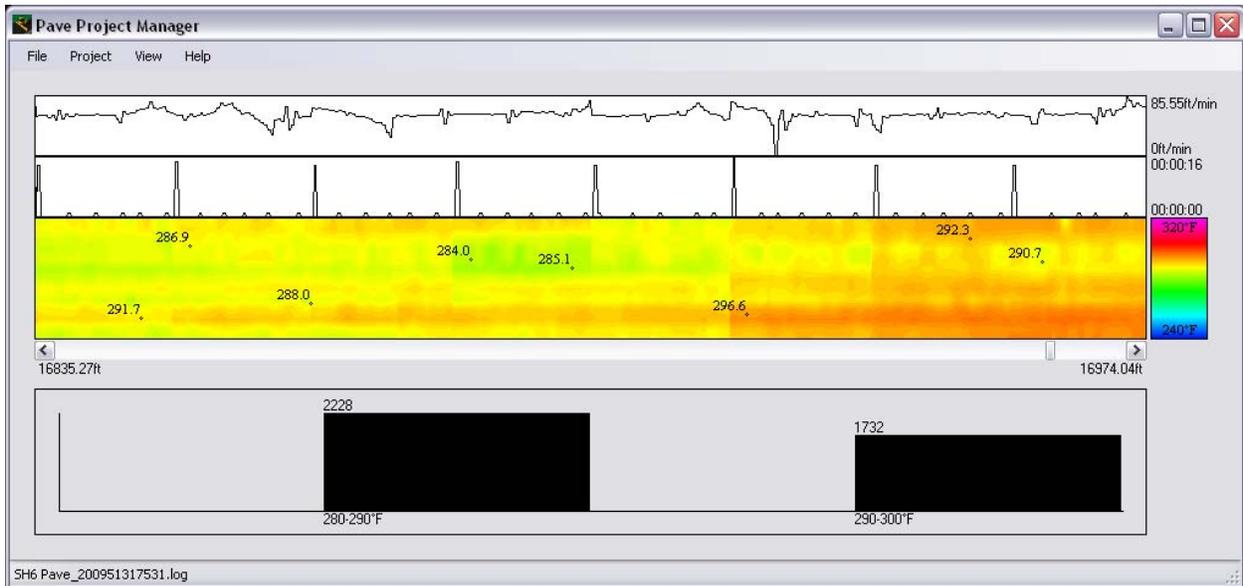
**Figure 93. Pave-IR Collecting Thermal Profile on SH 6.**



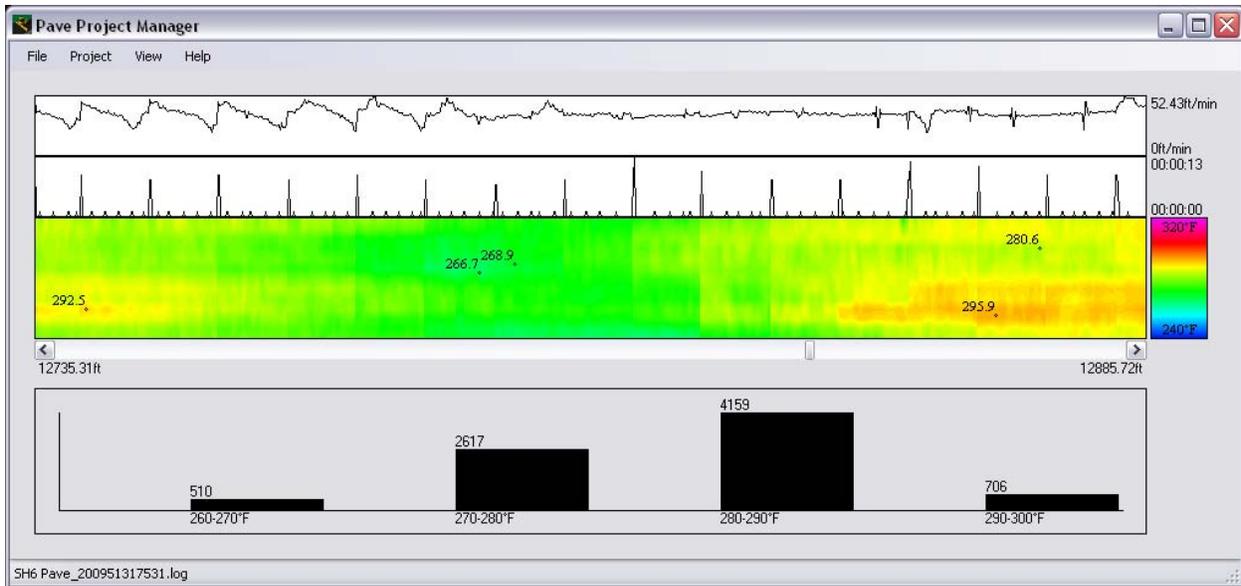
**Figure 94. Example Thermal Profile on SH 6 PFC.**



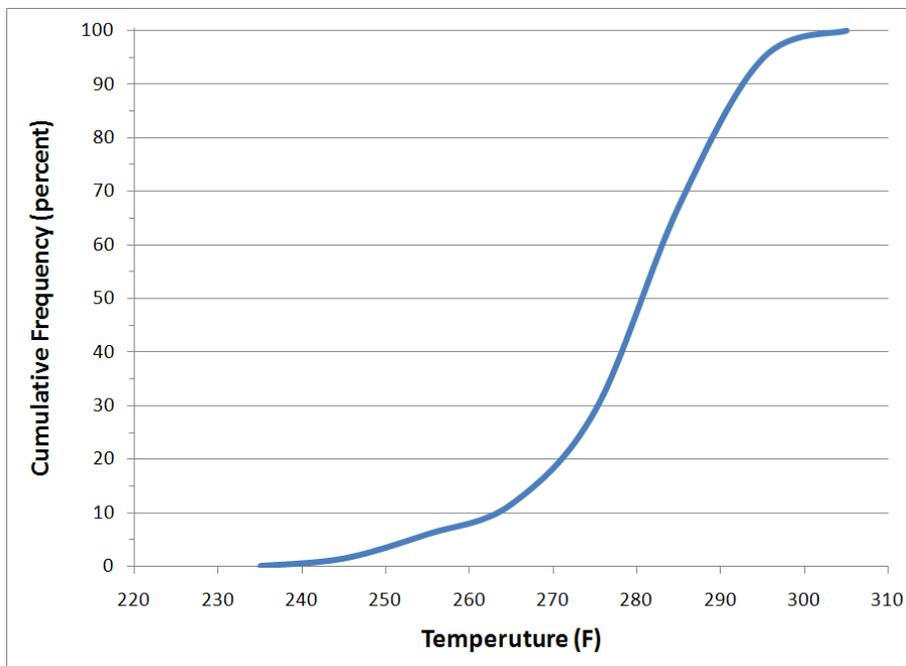
**Figure 94. Example Thermal Profile on SH 6 PFC (continued).**



**Figure 94. Example Thermal Profile on SH 6 PFC (continued).**



**Figure 95. Example Thermal Profile on SH 6.**



**Figure 96. Cumulative Frequency Distribution of Placement Temperatures on SH 6 PFC.**

The most anomalous location occurred as the paving train approached the first (northernmost) bridge deck. Figure 97 shows these data. Reportedly, the plant experienced some problems that resulted in this anomalous location. Figure 97 shows mix from approximately 1047 ft north of the bridge deck to the bridge deck not meeting the minimum desired placement temperature of 260°F. This location was from approximately Station 488.86 to the bridge deck. Additionally, the first approximately 67 ft south of the bridge deck did not exceed 260°F.

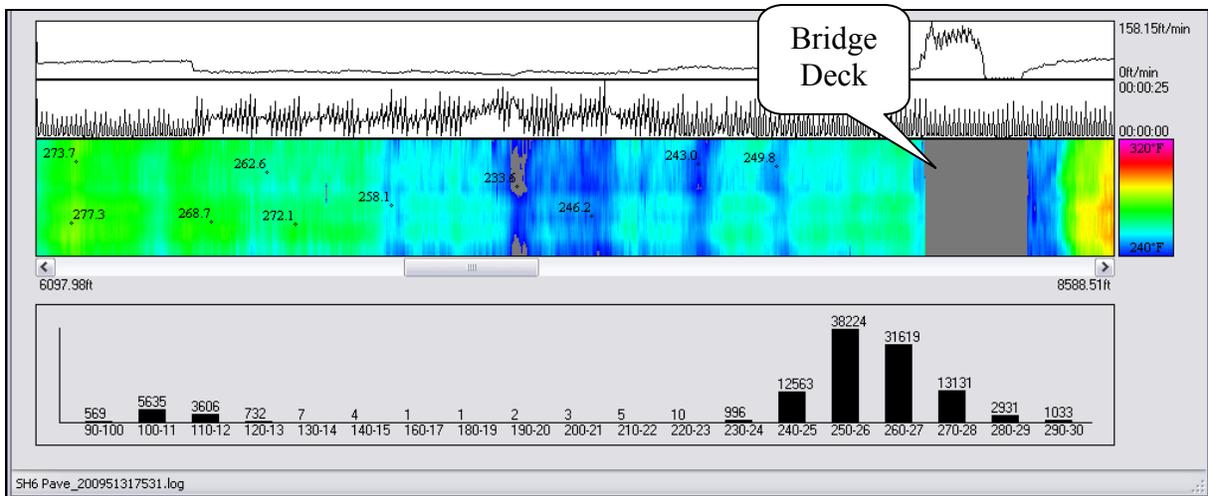


Figure 97. SH 6 Thermal Problems as Approaching First Bridge Deck.

### Follow-Up Survey Results

Although TxDOT does not currently apply thermal profiling to PFC mixtures, TTI performed a follow-up survey in July 2011. In particular, this survey focused on examining whether any problems existed at the location shown in Figure 97 with the thermal irregularities. Figure 98 contrasts the current GPR data from a representative portion of the project with the section of thermal irregularity at the time of placement. No visual or GPR indicators exist to suggest the zone with the thermal irregularity is substantially different than the normal section. Visually, no distress was observed, and the GPR shows no difference in surface dielectrics between the two zones.

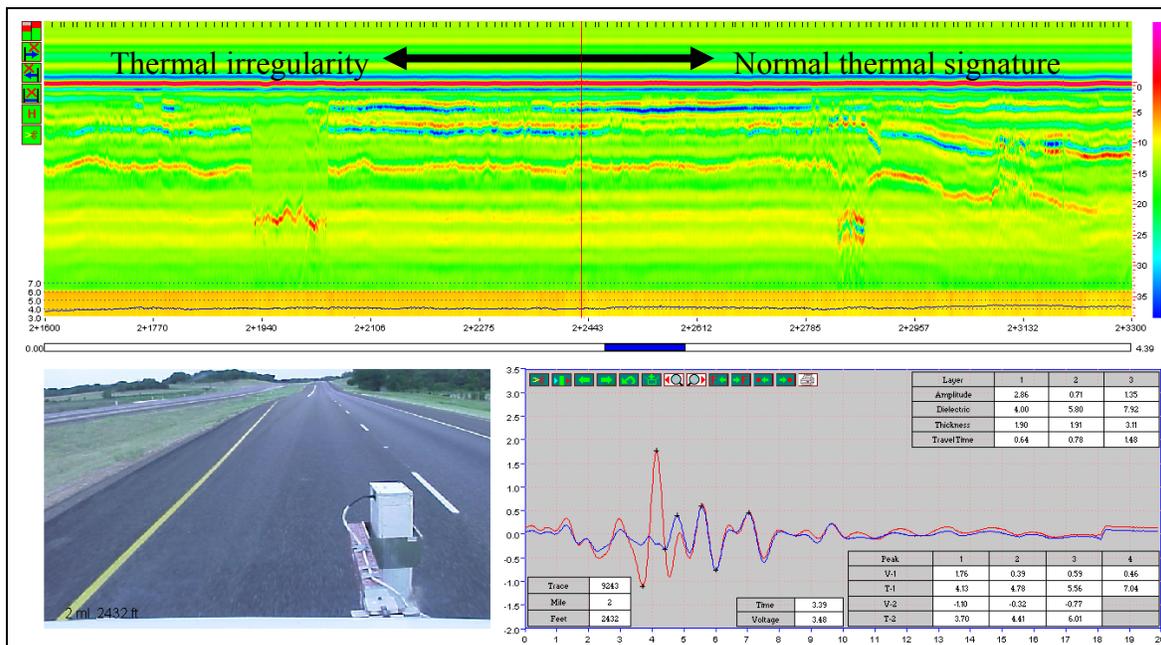


Figure 98. Representative GPR from SH 6 after Two Years of Service.

## Conclusions from SH 6 PFC

On this PFC project, a sizeable section about 1100 ft long was placed at temperatures below the specified minimum placement temperature due to reported problems at the plant. After approximately two years of service, a visual and GPR survey did not reveal any problems in this section.

## US 190, SMA, BEAUMONT DISTRICT, CONSTRUCTED SEPTEMBER 29, 2009

On September 29, 2009, on US 190 near Woodville, Texas, TTI researchers used a Pave-IR system to collect thermal profile data on US 190 near Woodville, TX. They used TTI's 1 GHz system for the GPR data collection. A follow-up survey was conducted in July 2011.

### Paving Operation

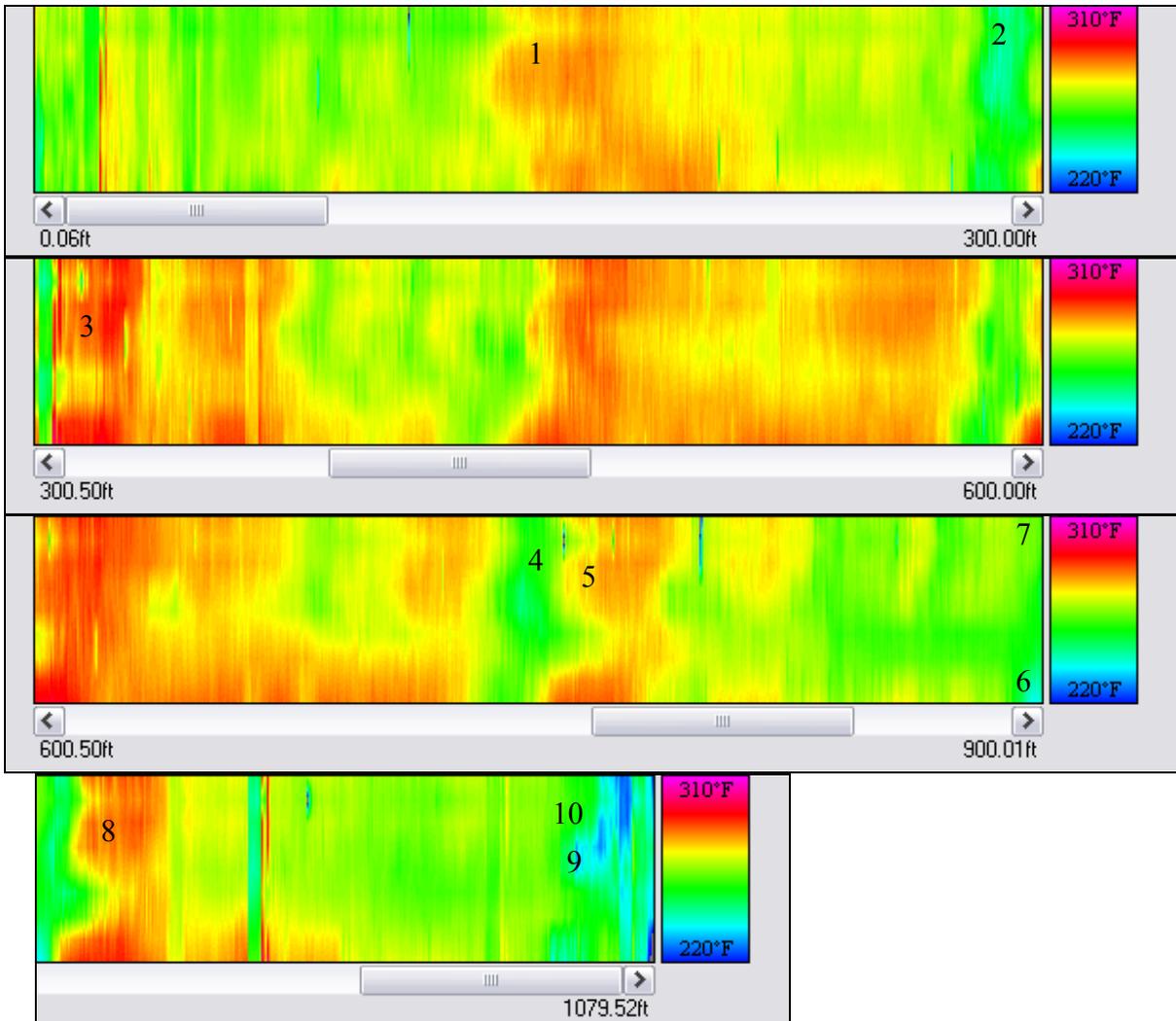
The contractor produced the mix in Livingston, Texas, resulting in a haul distance of approximately 30 miles, and used belly dump trucks and a Lincoln 660 AXL windrow elevator to convey mix into an Ingersoll Rand PF 3200 paver. The contractor overlapped the truck windrows by approximately 30 ft and paved the eastbound inside lane from station 166+11 to 177+80. Heavy rains at the plant resulted in cutting the workday short. Figure 99 shows the paving operation.



**Figure 99. Paving Operation on US 190.**

### Thermal Profile Results

Figure 100 shows the thermal profiles from the project. The thermal data show reduced temperatures at the truck ends with temperature differentials typically around 30°F. Ten locations were marked for further investigation, as annotated in Figure 100.



**Figure 100. US 190 Thermal Profile.**

*Note: numeric annotations are the ten core locations at time of construction.*

### GPR Results at Time of Construction

After the contractor completed finish rolling, the researchers collected GPR data over both wheel paths and the centerline with TTI's 1 GHz system. Figure 101 shows the GPR data collection in progress.



**Figure 101. 1 GHz GPR Data Collection on US 190.**

After collecting the GPR data, the research group performed a field and a laboratory sequence on the 10 core locations. In the field, researchers collected nuclear density readings with a Troxler 3450, using a 60-second count time. In the laboratory, researchers determined the bulk specific gravity of the cores, followed by permeability with the constant head method and then used the Overlay Test for a performance evaluation. Lab testing concluded with asphalt content by ignition oven and gradation determination. Table 13 presents the density data, permeability, and asphalt content results merged with the temperature and GPR measurements, and Table 14 presents the gradation results. The cores did not reach the failure criteria in the overlay test.

**Table 13. Core Density and Overlay Test Results with Field Data from US 190.**

Core	Field IR Temp. (°F)	Field $\epsilon$ from GPR	Field Nuclear Density (pcf)	Lab Density (pcf)	Lab Percent Air Voids*	Permeability (cm/s)	Asphalt Content (%)
1	290	4.9	133.8	139.8	7.2	3.493 E-05	5.6
2	250	4.5	127.0	140.7	6.6	2.662 E-04	5.6
3	300	4.9	136.1	143.7	4.6	No Flow	5.8
4	265	5.0	132.1	135.8	9.9	4.742 E-05	6.1
5	292	4.6	130.2	139.8	7.2	2.237 E-04	5.8
6	245	5.4	136.9	145.7	3.3	No Flow	6.0
7	274	4.9	133.2	131.4	12.8	1.31 E-07	5.8
8	300	4.8	131.9	142.1	5.7	1.688 E-04	5.5
9	239	4.8	132.2	138.9	7.9	2.138 E-05	6.0
10	265	4.8	129.9	135.3	10.3	5.535 E-04	6.4

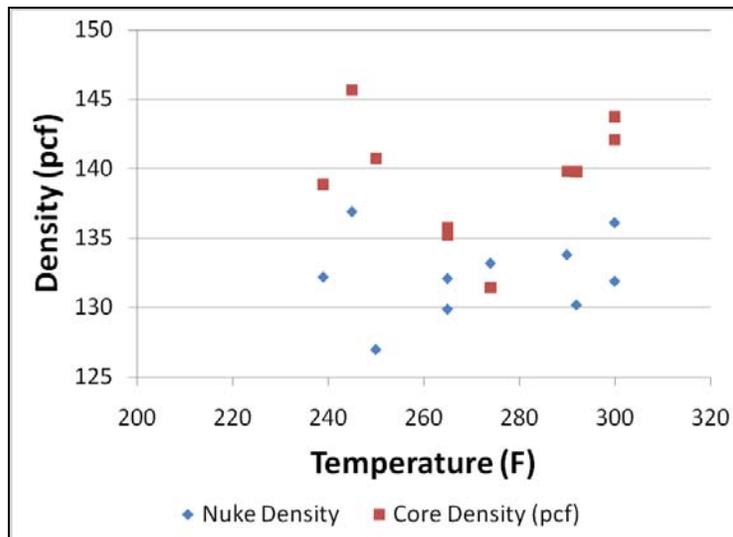
\*Based on TxDOT QC/QA-determined maximum theoretical specific gravity of 150.7 pcf.

**Table 14. Core Gradation Results from US 190\*.**

Core	2	3	4	5	6	7	8	9	10	JMF
¾"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
½"	86.1	89.6	88.4	89.2	89.7	<b>91.7</b>	85.6	89.1	87.6	86.0
<b>3/8"</b>	61.2	<b>69.7</b>	<b>65.7</b>	<b>65.5</b>	<b>68.9</b>	<b>67.8</b>	63.0	<b>66.7</b>	64.7	57.5
<b>No. 4</b>	26.3	<b>32.0</b>	28.8	27.1	29.0	28.9	26.6	29.1	29.9	23.5
<b>No. 8</b>	20.0	<b>24.4</b>	21.7	20.5	21.2	20.8	19.9	22.2	23.4	23.6
<b>No. 16</b>	<b>15.6</b>	19.9	17.6	16.6	17.1	16.6	16.4	17.8	18.9	19.0
<b>No. 30</b>	13.3	17.3	15.2	14.3	14.7	14.1	14.1	15.0	16.3	15.6
<b>No. 50</b>	11.4	15.3	13.3	12.6	12.9	12.2	12.3	12.7	14.3	12.8
<b>No. 200</b>	8.1	11.8	10.1	9.5	9.6	9.1	9.0	8.5	10.7	10.5

\*Percent passing. Results for core 1 not available due to sample handling accident.  
 Note: entries in bold are outside of the JMF percent passing operational tolerances.

With the core data complete, researchers analyzed the IR and GPR data in conjunction with the core results to investigate the significance of the NDT readings. Historically, thermal cold spots typically show up as low density locations in the mat. However, Figure 102 illustrates that on this project the temperature data did not correlate to the in-place density.



**Figure 102. Lack of Correlation between Temperature and Density on US 190.**

Figure 103 illustrates that on this project, although the GPR-measured surface dielectric correlated well with field nuclear density readings, neither the GPR nor the nuclear gauge correlated with the laboratory-measured core densities. More research needs to be conducted to determine why the GPR did not correlate with the lab densities. It is unknown if the mix type, the presence of fibers, or the rain at the plant contributed to the lack of tracking between the GPR and core densities.

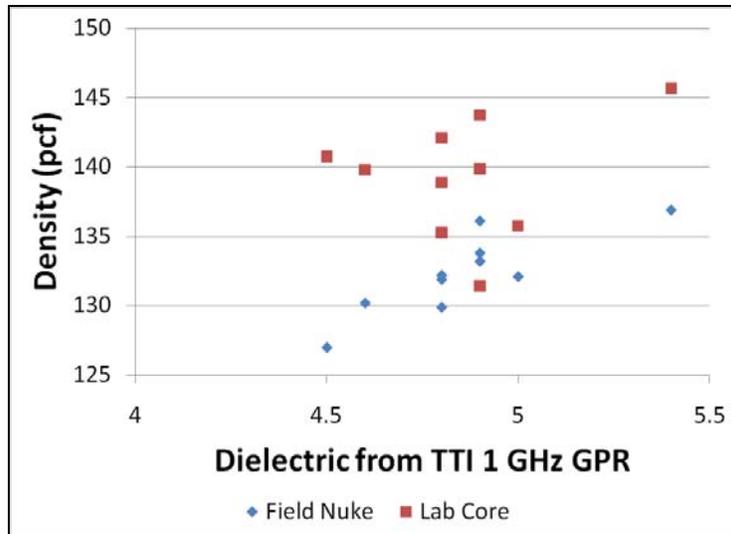


Figure 103. Lack of Correlation between GPR and Lab Density on US 190.

### Follow-Up Survey Results

In July 2011, TTI conducted a follow-up visual and GPR survey on this section. Visually, no distress was noted. Figure 104 presents the GPR data over the section approximately two years after construction. With the exception of the first 70 ft, and the location in the immediate vicinity of the construction joint at the end of the pull, the GPR data are uniform with no indication of concerns.

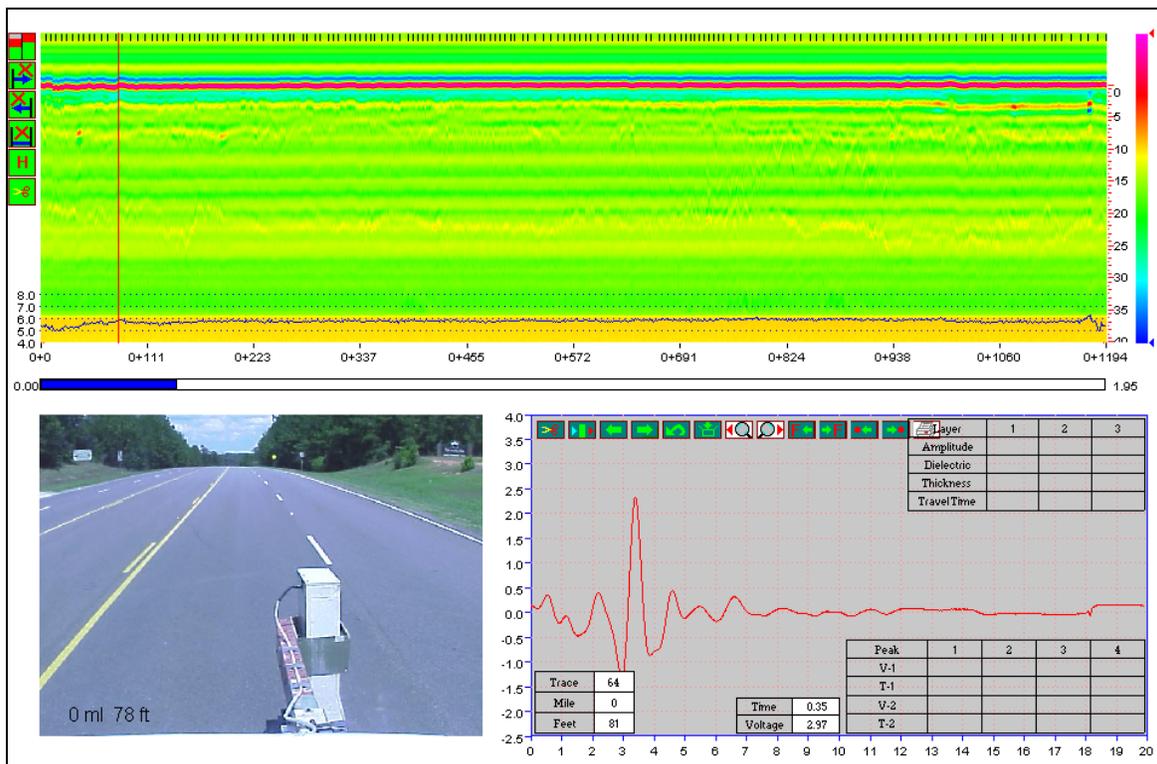


Figure 104. US 190 GPR after Two Years of Service.

## **Conclusions from US 190 Project**

On this project, although at the time of construction some moderate thermal segregation was observed with temperature differentials typically around 30°F, after two years of service no evidence of concerns exists on the project. The section does not have any distress, and current radar data indicate a uniform surface mix.



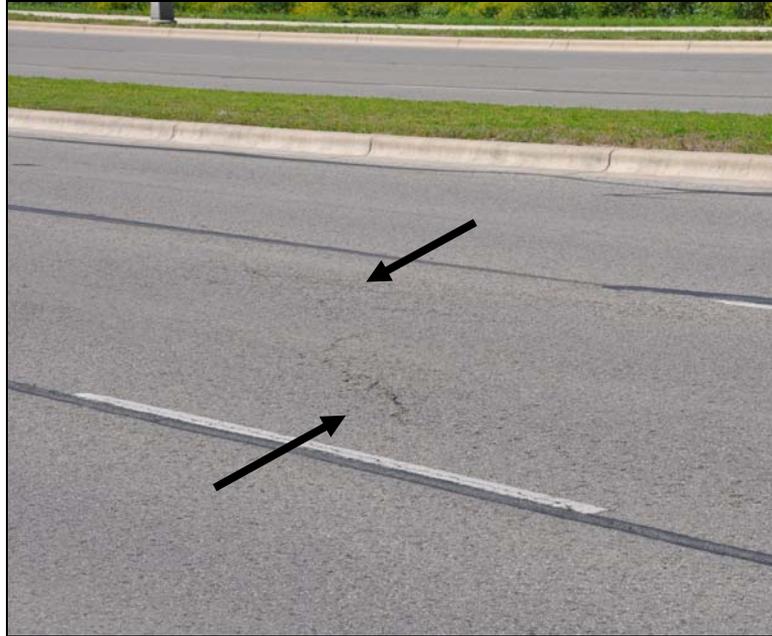
## **CHAPTER 4. OBSERVATIONS FROM PROJECTS NOT MONITORED DURING CONSTRUCTION**

### **SUMMARY**

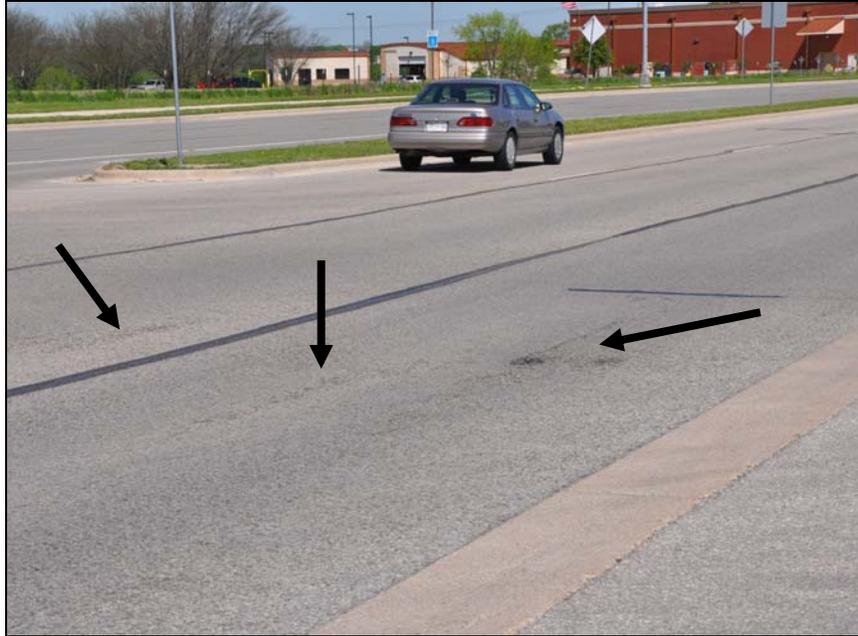
During the course of this research project, the research team gathered reports of and observed several projects with cyclical pavement failures. Even though these projects were not monitored for thermal segregation during construction, they illustrate the magnitude of premature deterioration that can occur when overlays are placed with segregation. One example project also illustrates the importance of segregation-free subsurface mixtures, since field results suggest these buried segregated zones can translate to premature deterioration in the final surface, even if that final surface is segregation-free.

### **A.W. GRIMES**

This project experienced significant cyclical segregation that resulted in pavement deterioration beginning soon after construction. The segregated zones in the mat are visible as areas of coarser-appearing surface texture, and many of these zones already exhibit cracking and raveling. Figures 105 and 106 present examples of the cyclical distress occurring on this project. In some locations, severe raveling exists, as Figure 107 illustrates.



**Figure 105. Example Cyclical Cracking on A.W. Grimes.**



**Figure 106. Example Cyclical Distress with Raveling and Cracking on A.W. Grimes.**



**Figure 107. Severe Raveling on A.W. Grimes.**

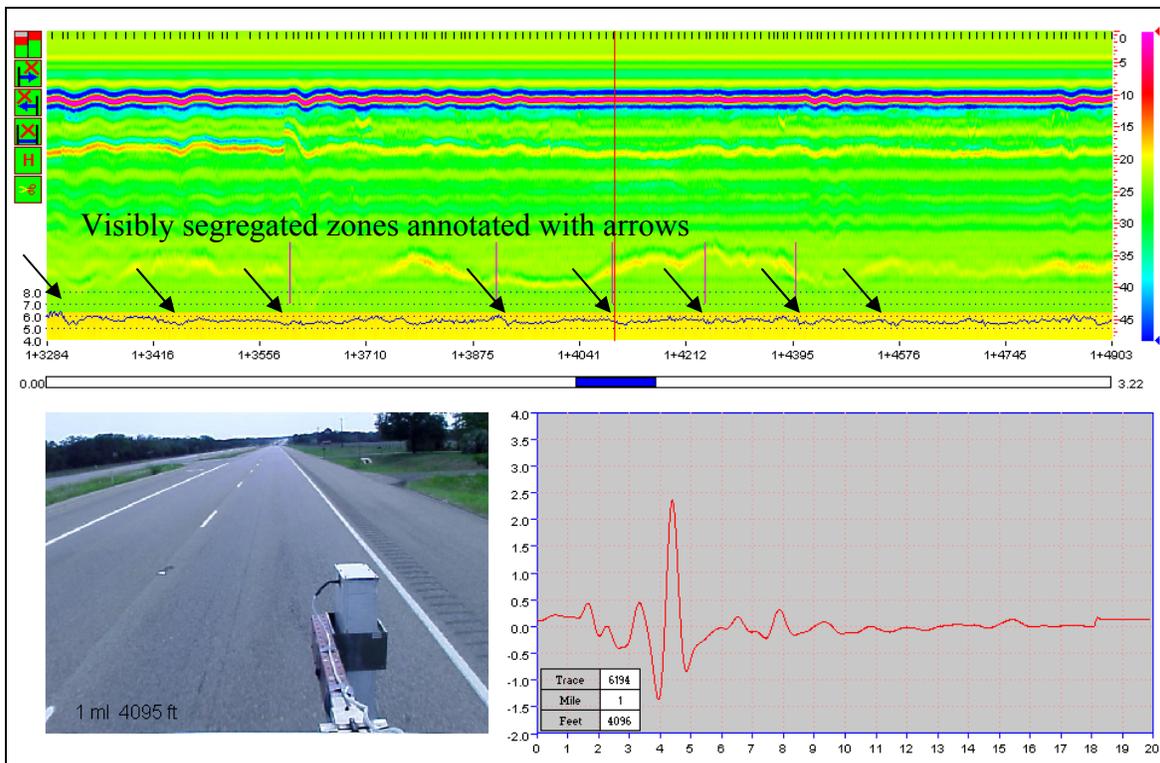
## **SH 21**

On this project, sections of cyclical segregation exist where the segregated zones appear as more open areas in the mat. In many cases, these zones began cracking within a few years after construction. Figure 108 shows examples of the distress occurring in the segregated zones.



**Figure 108. Examples of Cyclical Distress on SH 21.**

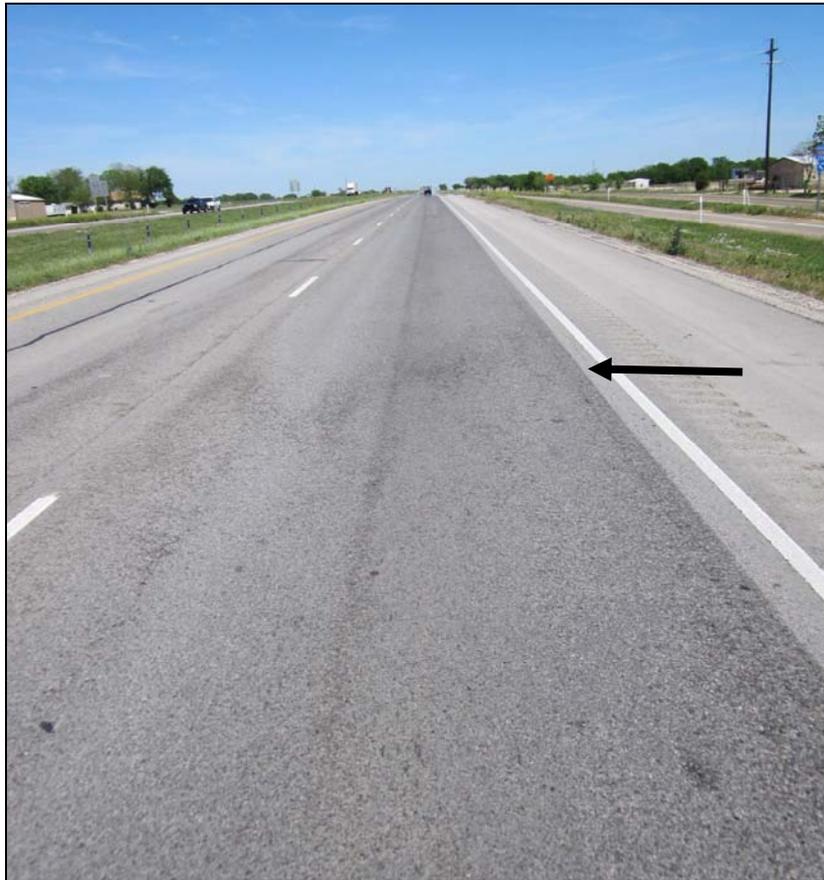
Figure 109 shows example GPR from this SH 21 project. The radar data show systematic drops in the surface layer dielectric corresponding to the segregated zones. These are the zones experiencing early failure. Had the construction been completed without segregation, the pavement condition would not have deteriorated as rapidly.



**Figure 109. Example GPR on SH 21 with Cyclical Distress.**

## IH 35W

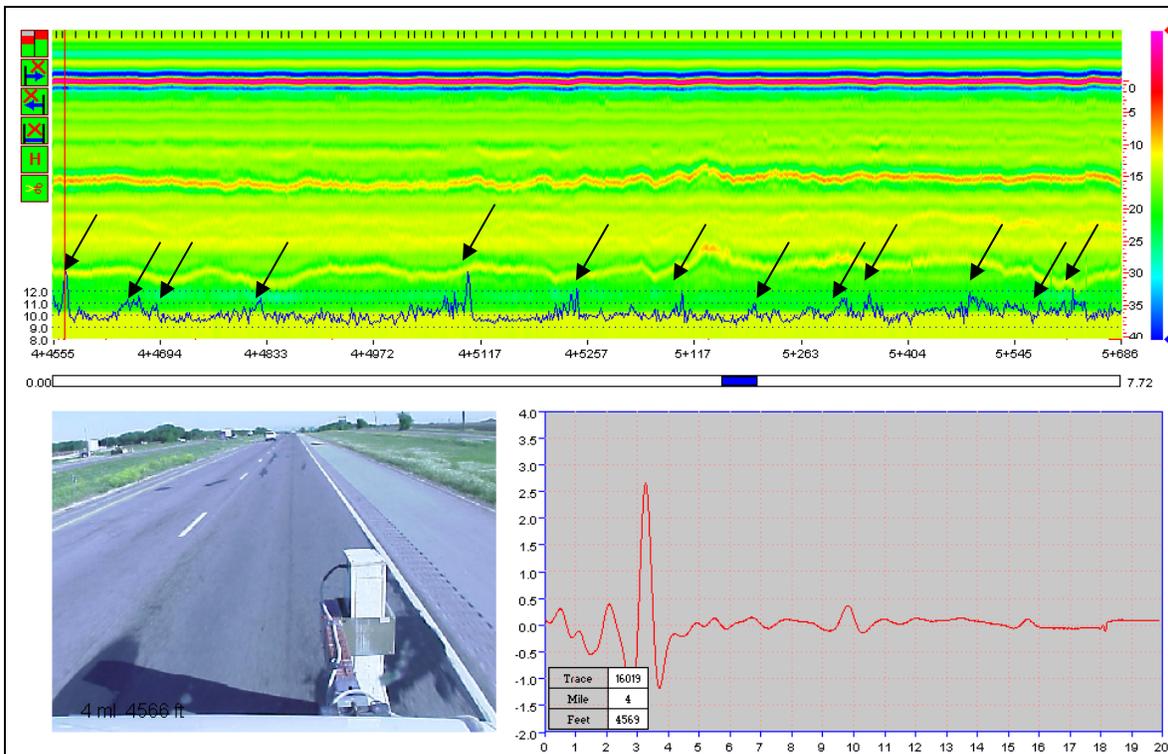
This section on IH 35W from SH 81 to US 67 exemplifies classic segregation distress in the field. Throughout the section, cyclical zones exist that are visibly more open; many of these zones exhibit raveling and cracking. Figures 110 and 111 show examples of the pavement, and Figure 112 illustrates GPR data from the section. The GPR data actually show spikes in the surface dielectric at the segregated zones, meaning these regions have trapped water. This trapping of water and traffic action results in the cyclical distress observed in the pavement surface.



**Figure 110. Zone of Cyclic Segregation on IH 35W.**



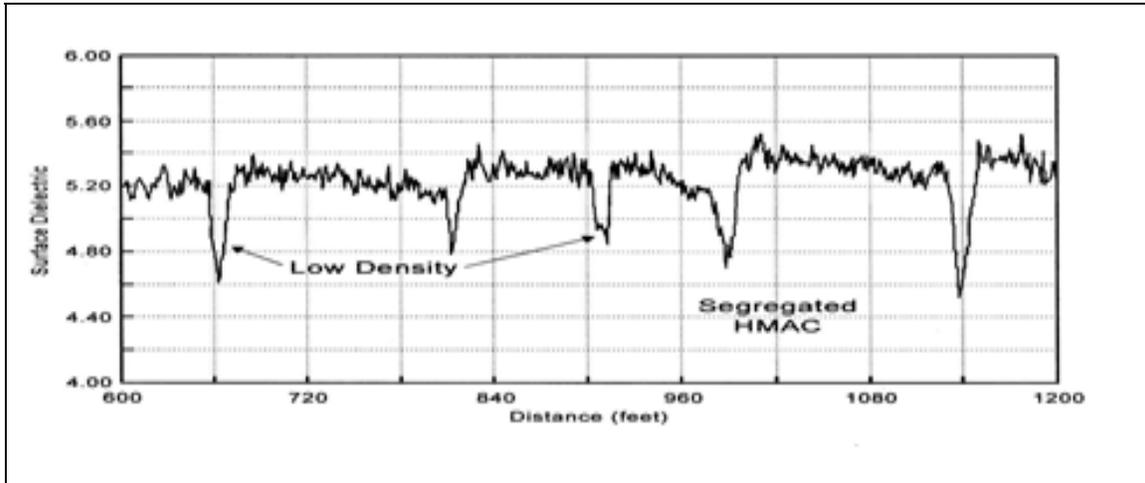
**Figure 111. Raveling and Cracking Failures in Segregated Zones on IH 35W.**



**Figure 112. Cyclic Failures with Raveling and Cracking on IH 35W in GPR.**

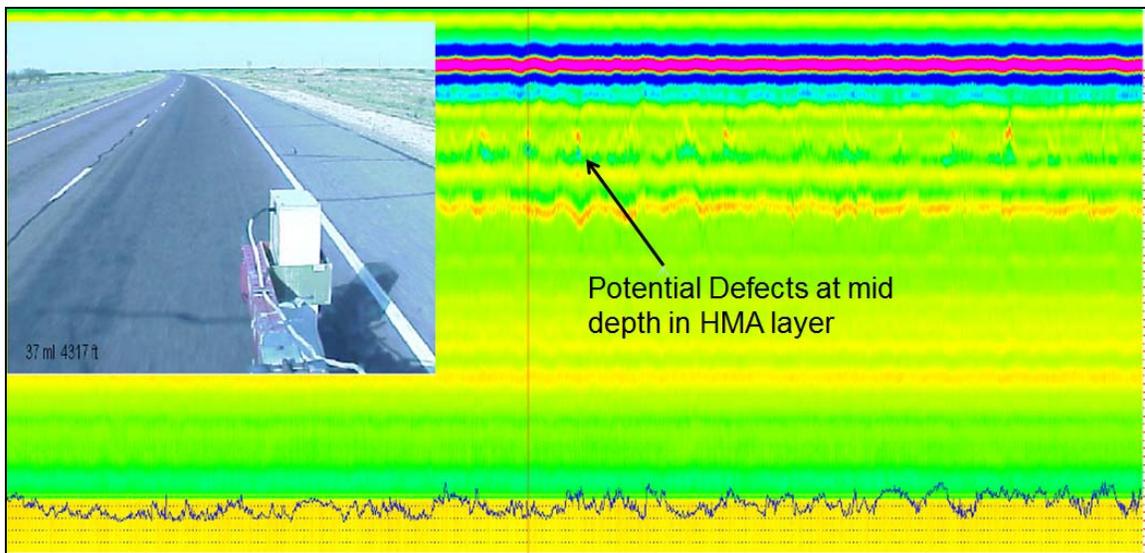
## IH 20

One of the first demonstrations using GPR to identify thermal segregation was on a section of asphalt base material on IH 20 west of Odessa in 2002. Figure 113 shows the surface dielectric from the GPR data, clearly showing cyclical zones of low density in the mat.



**Figure 113. Surface Dielectric for a Section of HMA Base Material on IH 20.**

At the time of construction, the segregated layer was not an immediate concern since it was to be overlaid with at least 4 inches of additional HMA. This section of highway has performed well for 10 years, and it was resurveyed in 2011 as part of the IH 20 corridor analysis that TTI conducted. Currently, this section has periodic transverse cracking and some longitudinal cracking. Figure 114 presents example GPR data from the section, which show some periodic negative reflections from mid-depth in the HMA layer. In most cases, the surface cracks coincided with the defects observed in the GPR data at mid-depth in the HMA layer.



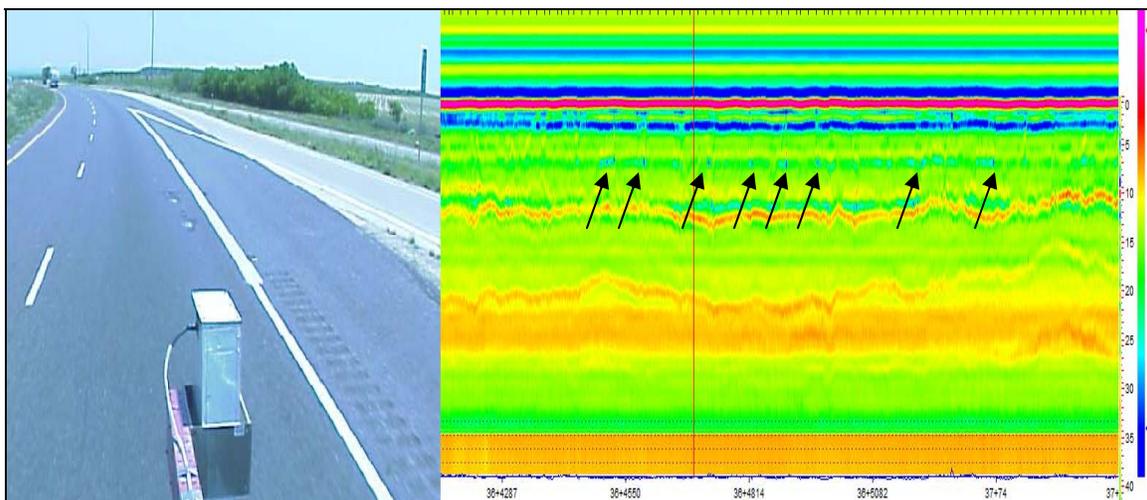
**Figure 114. GPR Data from IH 20 near Reference Marker 87.**

As part of the corridor analysis, this section was cored, and Figure 115 shows an example core collected directly over a transverse crack. The lower layer of the core completely deteriorated during the coring process. However, cores taken at locations free of cracking were solid.



**Figure 115. Core Taken from TRM 87 on IH 20.**

The GPR signature shown in Figure 114 was also observed in other locations of IH 20. Figure 116 shows an excerpt of radar data from TRM 148 to 159, which also exhibited periodic areas with a similar GPR display. This section has received a seal and a PFC surfacing, but as Figure 116 shows, localized suspect areas at mid depth exist in the HMA layer about 6 inches below the surface.



**Figure 116. IH 20 near TRM 157 Eastbound.**

*Note: areas highlight zones of suspected segregation in subsurface HMA.*

Based on these observations, field performance of these pavements suggests that buried thermal segregation may be a more significant problem than originally thought. With time and the probable ingress of moisture, these areas could continue to deteriorate. These localized

failure zones will become a major maintenance problem, since repairs to only the upper surface layers will not address the defect buried at mid-depth in the HMA layer. In the worst-case scenario, the problem in the lower HMA layers could continue to deteriorate to such a stage that rehabilitation of the section will require the complete replacement of all the HMA layers.

## **CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS**

### **CONCLUSIONS FROM PROJECTS FREE OF THERMAL SEGREGATION**

The results from the projects monitored suggest that construction free of thermal segregation certainly precludes defects from non-uniformity, although such construction does not mean pavement deterioration will not occur due to other factors. Additionally, the results observed suggest deterioration in a uniformly constructed surface layer can occur due to segregation in subsurface mixtures. Other state departments of transportation have also reported this occurrence illustrating the importance of uniform quality in asphalt-mixture construction, since the problem zones from segregation can result in failures years after subsequent overlay, resulting in a deeper-rooted problem that is more costly to address.

### **CONCLUSIONS FROM PROJECTS WITH THERMAL SEGREGATION**

The results from projects monitored where thermal segregation was observed at the time of construction were mixed. With projects ranging in age from two to seven years, most projects did not exhibit distress at locations of known thermal segregation. On some projects, the GPR data suggested traffic action may have homogenized the pavement surface density. However, on several projects, evidence of thermal segregation still existed, generally noted by differences in surface appearance and localized decreases in the surface dielectric from GPR. Performance testing cores after some years of service indicated thermal segregation did not impact the Hamburg results but may result in a higher susceptibility to cracking. Field observations of sections with cyclic subsurface segregation indicated those subsurface zones contribute to eventual pavement deterioration.

In essence, the results from projects with segregation lead to the conclusion that the presence of thermal segregation at the time of construction does not guarantee failure within two to seven years. However, the results do show that thermally segregated locations may remain anomalies in the mat that deteriorate due to cracking when on the surface, or contribute to failures of subsequent overlays once covered. The presence of thermal segregation at the time of construction results in a higher risk of pavement deterioration within those segregated zones, even if the segregation is covered with another overlay.

### **RECOMMENDATIONS**

Based on the conclusions from this project, TxDOT should continue to promote construction of asphalt-mixture layers free from significant thermal segregation. Constructing layers free of thermal segregation should be an objective for both surface and subsurface mixtures. The thermal profiling requirement in TxDOT's construction specifications should continue to be used, as this requirement is designed to promote construction free of segregation.

Future research work should be directed toward understanding the variation in performance of projects constructed with thermal segregation. When or how different mixtures deteriorate due to segregation may be a function of mixture properties, binder properties, climate,

moisture susceptibility of the base layer, or other variables. At this time, it is not clear why some projects constructed with segregation experience dramatic early failures, while others constructed with segregation perform for many years with no appreciable changes in the segregated zones. Understanding these factors may enable the calculated design of mixtures with performance properties less sensitive to segregation.