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Field Evaluation of Temperature Differential in HMA Mixtures

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16. Abstract

Segregation is a common occurrence in hot mix asphalt (HMA) construction. The two types of segregation encountered are gradation segregation and thermal segregation. This investigation report involves mainly thermal segregation, which occurs when areas of the HMA mat are significantly colder than other areas. Various investigations have determined that cold areas within the asphalt mat during construction tend to show a corresponding decrease in finished pavement density, which could have a detrimental effect on pavement life. This investigation report outlines the effort to gain insight on the long term effects of thermal segregation on the life of a pavement surface. Instances of thermal segregation were identified during HMA construction using an infrared camera and the locations of these instances were noted using GPS coordinates. Then these locations were monitored every six months to develop a timeline for any temperature differential damage that occurred. The data and conclusions reached are outlined in this report.

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CHAPTER 1

INTRODUCTION

Segregation is a common occurrence in hot mix asphalt (HMA) construction. Due to improper handling, transportation, and construction practices, segregation can be present in any category of HMA construction. This segregation is significant because it can shorten the life of a pavement. For this reason many studies have been done to determine the causes of segregation in HMA construction.

There are two main types of segregation in HMA paving. First is gradation segregation, which occurs when the fine aggregate and coarse aggregate in the HMA mix have separated leading to the presence of fine and coarse areas in the HMA mat after construction. This gradation segregation generally occurs during transportation of the HMA mix or due to improper transference of the mix from the plant to the dump truck or the dump truck to the paver.

Gradation segregation is important because it can lead to areas of coarse texture and areas of fine texture within the pavement. These coarse areas are high in air voids. A study performed by Shatnawi and Van Kirk (1993) showed that high air voids reduce the pavement strength, trap water and accelerate the rate of deterioration of the roadway. The fine areas are also a problem. The same study found that excessive fines can decrease the stripping resistance of good mixtures (Shatnawi and Kirk, 1993). Also, a study by Cross and Brown (1993) showed that the coarser areas have lower asphalt contents and are therefore more prone to raveling. If (due to gradation segregation) the gradation of the mixture in a particular area of the pavement is not the optimum designed for the application in the field, low strength, decreased stripping resistance, and raveling are all examples of the premature failures of the HMA mat that can be anticipated.

Identification of gradation segregation is fairly simple. As a general rule, gradation segregation can be seen after the pavement has cooled off. Often, the segregation can be seen in a reoccurring pattern corresponding to the last portion of asphalt mix in each truck. This is known as end of the load segregation. Identification is not as simple when dealing with temperature segregation.

Temperature or thermal segregation refers to the situation in which there are cold spots in the HMA mat behind the paver during the rolling phase of construction. This phenomenon was first discovered in 1996 by Steve Read at the University of Washington when studying gradation segregation (Brock and Jakob, 1997). It has been studied by various industry and government organizations ever since.

There are several factors that can lead to temperature segregation. Poor paving practice, improper paver operation, poor transportation and transfer technique, and even long haul distances can all lead to a HMA mat containing severe cold spots behind the paver. Even gradation segregation, due to the coarser areas allowing more air flow around the mix before compaction, can lead to colder spots on the HMA mat. Weather also plays a role in determining the severity of the temperature segregation present in a pavement. As the weather gets colder during HMA construction, it becomes even more important that proper paving and hauling techniques are followed to produce a consistent mix temperature.

The study by Steve Read shows that the presence of temperature segregation can reduce the life of an HMA overlay to approximately half of the 12 to 15 years expected (Brock and Jakob, 1997). Cold spots behind the paver are harder to consolidate leaving pockets of low density with high air voids. These areas are likely to deteriorate rapidly leading to premature cracking, raveling, rutting, and other signs of distress leading to costly early repairs and rehabilitation.

Identification of temperature segregation requires more effort than gradation segregation, because it is not a visible to the naked eye. Also, thermal segregation can occur anywhere in the mat. It sometimes occurs in correlation with gradation segregation, but this is not always the case. For these reasons, identification of thermal segregation requires the use of a tool that allows the user the see the temperature of the HMA mat behind the paver.

SCDOT inspectors currently have infrared temperature devices that allow them to determine the surface temperature at specific places behind the paver. This however, does not provide a complete picture of the surface temperatures of the entire mat making it difficult to identify thermal segregation. Now a commonly used tool used to identify thermal segregation is the infrared camera. These cameras, made by various manufacturers, take infrared digital pictures of the HMA mat which can then be downloaded to a computer and viewed and manipulated to determine various pieces of surface temperature information. These cameras also have viewing screens that allow the user to see the temperatures of the mat on the jobsite. This makes it convenient to identify thermal segregation during the paving and to take steps immediately to eliminate it.

The purpose of this research study was to study the causes and effects of thermal segregation. First, several paving projects were visited during construction. The paving operation was followed with an infrared camera while specific locations of thermal segregation were noted. This allowed the observation of the paving practices that cause thermal segregation that are common in today's paving operations. Also, using a handheld GPS unit, the locations of the segregated areas were marked so they could be found again. These sites were visited approximately every six months to monitor their performance and check for temperature differential damage. The purpose was to detail the effects of thermal segregation over the lifetime of the pavement and to determine if the life of the pavement was affected.

By analyzing the temperature data from this study, the SCDOT should be able to determine specific paving practices that are leading to thermal segregation in this state. Also, by monitoring the pavements, some understanding should be gained about how detrimental thermal segregation is based upon how long it takes for distress in the pavement to become apparent in relation to the severity of the thermal segregation.

Objectives of the Study

The major objective of this study was to investigate the long term effects of thermal segregation on a pavement surface. This objective was accomplished through the following series of specific objectives:

1. The infrared camera that would be used to identify thermal segregation was chosen by obtaining information about cameras from different manufacturers and choosing the camera most suited to this study.

2. A handheld GPS unit that would be used to mark the specific locations of thermal segregation was purchased.
3 Several paving projects were visited to observe the paving operations. If available, three sites of each of the following major HMA types were to be monitored:

   A. Surface Type A
   B. Surface Type B
   C. Surface Type C
   D. Surface Type CM
   E. Intermediate Type A
   F. Intermediate Type B
   G. Intermediate Type C
   H. Open Graded Friction Course

   Specific sites of thermal segregation were noted and marked with the handheld GPS Unit so they could be located easily in the future.
4. The thermal pictures and GPS coordinates of each location of thermal segregation were downloaded and incorporated into reports. These reports show all of the pictures, list a cause for the segregation (if known), show the GPS coordinates, and show some spot temperatures in some of the coldest and hottest areas. Along with these spot temperatures was the tabulation of the maximum, minimum, and average pavement temperatures contained within each infrared picture. Also included in each report was an information sheet listing pertinent information including the paving contractor, weather conditions, equipment used, pavement type, and travel time from the plant.
5. Each location was visited every six months. The specific locations of thermal segregation were observed to look for distress. The condition of each location was noted and pictures were taken if premature distress was evident. This data was added to the reports

CHAPTER 2

SELECTION OF THE THERMAL CAMERA AND GPS UNIT

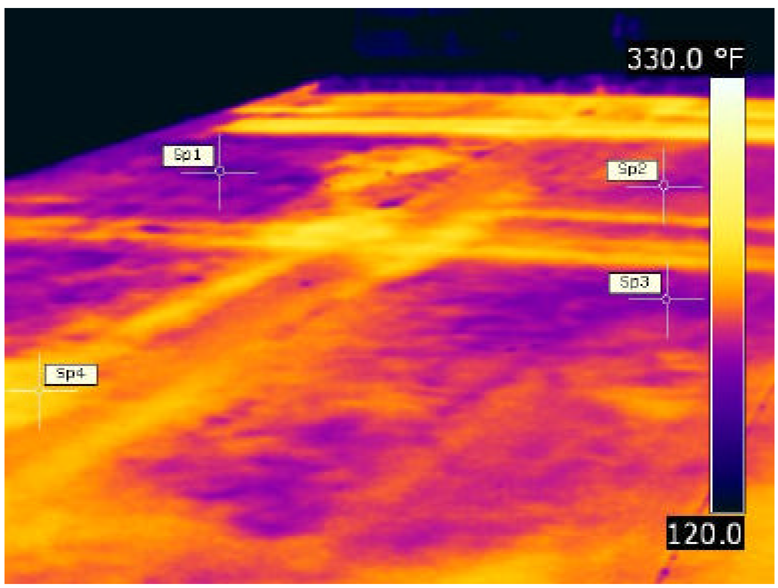
Effective identification of thermal segregation requires the use of an infrared thermal camera. This camera needs to measure surface temperatures accurately. It must have a viewfinder that displays thermal images so the operator can identify the thermal segregation as it occurs in the field. It must also be able to store and download digital images to a computer to be used and analyzed later. It should also allow the production of a report document utilizing the infrared images.

In an investigation entitled "Laboratory and Field Investigation of Temperature Differential in HMA Mixtures Using an Infrared Camera," Amirkhanian and Putman (2006) chose the ThermaCam PM695, manufactured by Flir Systems Incorporated, as their infrared camera. This camera is no longer manufactured, so a new camera had to be purchased.

For this investigation, the ThermaCam EX 320 was chosen. This camera is accurate to ± 3.6°F or within 2% of the actual measurement. The unit also has a digital display that allows the user to see the infrared view, allowing the identification of thermal segregation in the field. It stores up to 80 jpeg images that can be transferred through a USB cable to a computer. Figure 1 shows an example of pictures taken with the camera in the field.

The infrared camera is supplied with a software package called "ThermaCAM Reporter," which works in conjunction with Microsoft Word. This software first allows the user to design report templates for displaying thermal pictures and pertinent information regarding the pictures. Once the template is formed the pictures can be inserted, forming a report. Then the pictures can be manipulated: changing the temperature scale, the color scheme, etc. The temperatures of specific points within the pictures can be displayed. Also, different information can be added such as: asphalt mix information, weather information, and paving information. The final product is a Microsoft Word document report that can be converted to a PDF document if desired. An example of the reports generated for this investigation can be seen in Appendix C.

(A)



(B)

Figure 1: Example thermal image of (A) an asphalt truck backed up to paver with mix still in the bed and (B) thermal segregation in mat behind the paver before compaction.

It is not practical to physically mark each location of thermal segregation in the field. Therefore, it is necessary to mark the locations in some other way. This necessitates the use of a handheld GPS device which can be used to record the GPS coordinates of each location. The unit selected for this investigation is the Garmin

GPSmap 60CSx. This unit has a coordinate accuracy such that any location given should be within 15 feet of the actual location, which is adequate for this application.

Once the coordinates are recorded in the field, the GPS unit can be attached to a computer using the supplied USB chord and the coordinates can be downloaded to the computer. This is done using the accompanying software package that comes with the GPS unit called “MapSource.” This software records sets of coordinates as separate files that can be opened and will display the different waypoints on a map. These coordinates can also be uploaded back to the handheld GPS unit when a visit of the project is needed.

CHAPTER 3
DATA COLLECTION AND ANALYSIS

The purpose of this study is to gain some insight on the effects of temperature segregation during construction on the life of an asphalt pavement. The research evaluated the techniques and circumstances that led to and prevented thermal segregation during construction. The effects of this temperature segregation on different asphalt types were evaluated by identifying specific locations of thermal segregation and monitoring the conditions of these locations over time.

Test Sites

The test sites for this investigation were chosen based upon the asphalt mix type used in construction. The main mixes considered were Surface Types A, B, C, and CM, Intermediate Types A, B, C, and Open Graded Friction Course.

Surface Type A is the Superpave surface mix typically used on interstates and in intersections prone to rutting. It is a 100 gyration mix indicating a very tightly compacted asphalt mix. This mixture contains relatively coarse aggregate and uses PG 76-22 liquid asphalt. The coarser aggregate and stiffer liquid asphalt make the pavement stiffer and stronger to withstand the high levels of truck traffic present on the interstates and loadings of intersections prone to rutting.

Surface Type B is the Superpave surface mix typically used on high volume primary routes. It has the same gradation requirements of Surface Type A, but only uses PG 64-22 liquid asphalt and is only a 75 gyration mix. This mix is not as strong as the Surface A mix making it unsuitable for the increased loading found on interstates.

Surface Type CM is the Superpave surface mix typically used on low volume primary roads. It is also a 75 gyration mix and uses PG 64-22 liquid asphalt, but uses a finer aggregate gradation.

Surface Type C is the Superpave surface mix typically used on secondary roads. It is a 50 gyration mix that uses PG 64-22 liquid asphalt and has the same gradation as Surface CM. This mix is not as strong as the other surface mixes because it does not have to support the heavy loadings that would be present on an interstate or primary route.

Open Graded Friction Course (OGFC) is a special asphalt mix used on South Carolina interstates. It has a very porous texture with many open voids, which allows water to drain off of the surface of the road. This mix uses PG 76-22 liquid asphalt and utilizes polyester fibers to keep the liquid asphalt from draining down in the pavement. OGFC is the riding surface, placed on top of Surface A on many interstates and is used to reduce or eliminate accumulation of water on the surface during a rainstorm. This reduced accumulation improves visibility by reducing water spray and decreases the chances of hydroplaning.

Intermediate Type A is a 100 gyration mix using a coarse aggregate and PG 76-22 liquid asphalt. This mix is used for intersections prone to rutting. Intermediate Type B is a 75 gyration mix using the same gradation as Intermediate A, and PG 64-22 liquid asphalt. Intermediate B is used for Interstates and high volume primary routes. Intermediate Type C is a 50 gyration mix, using a finer gradation than Intermediates A and B, and using PG 64-22 liquid asphalt. It is used for low volume primary and secondary roads.

Appendix D shows tables of the different properties of each HMA mix used for this investigation. Appendix E shows a list of the test sites identified for this investigation, dates of paving and identification, pavement type, and the location or county in which the segment is located.

Information Gathered On-Site

Appendix F shows the information sheet used for all paving segments identified during this investigation. The information collected includes the following.

A. SCDOT file number
B. Highway identification
C. Date of paving
D. Paver brand and model name
E. Material transfer vehicle brand and model name, if used
F. Directions to the segment
G. Mix type
H SCDOT asphalt job mix formula
I. General weather description

J. Ambient air temperature at the job site during paving
K. Travel time from the plant to the jobsite
L. Compaction information if available

Identification of Thermally Segregated Mat Locations.

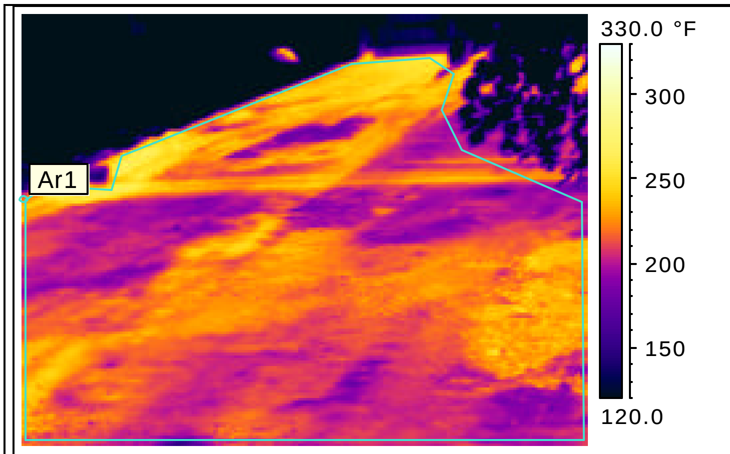
To identify specific locations of thermal segregation, jobsites were visited during construction. The infrared camera was used to follow the paver and find the cold spots in the mat. Pictures of these spots were taken with the camera and the locations were noted with the GPS unit. Pictures were only taken before the rollers rolled the pavement. This is the best time to note the segregation as the water from the rollers will cool the surface of the mat and possibly give the appearance of more or less thermal segregation than is actually present. Also, the cause of each instance was noted if known.

Along with pictures of thermal segregation, pictures with little to no thermal segregation were taken on some of the sites. These were used as control sections to demonstrate the rate of deterioration of pavements without thermal segregation. They were also used to provide a full range of thermal segregation severity to aid in the development of a method to characterize thermal segregation based on the temperature measurement taken in the field. If no pictures were taken with little to no segregation, the areas between the locations where the pictures were taken were used as control sections.

Infrared Image Modification

Once all of the infrared pictures and GPS coordinates were obtained in the field, these data were downloaded. The pictures were compiled and made into separate reports for each worksite. The scale on all of the mat pictures was adjusted to the range of 120°F to 330°F causing all temperatures above this range to show up as white and all temperatures below to show up as black. This is the typical range of temperatures likely to be found in the asphalt mat behind the paver, therefore, most of the surroundings are eliminated from each picture.

The Flir ThermaCam software allows the user to used different shapes to select portion of the thermal pictures, for which it will give the maximum, minimum, and average temperatures. For this investigation, a polygon was selected around most of surface area of the pavement mat. Any area that had other objects overlapping the mat was omitted so that the temperatures of these other objects did not corrupt the actual pavement data. This procedure resulted in the maximum, minimum, and average temperatures for the pavement mat within each picture, which was tabulated for each separate worksite.



Work stoppage.

N33 56 46.7 W80 20 25.0

Object Parameters	Value
Ar1 Max. Temperature	268.4 °F
Ar1 Min. Temperature	150.6 °F
Ar1 Average Temperature	215.1 °F

Figure 2: Example thermal image showing polygon surrounding portion of mat and excluding overlapping objects with resulting temperature data.

Monitoring of Pavement Segments

Once the thermally segregated pavements were identified, they were monitored every six months from the time of construction. The GPS coordinates and the handheld GPS unit were used to visit every location of thermal segregation to look for signs of pavement distress. Signs such as raveling, excessive rutting, cracking, pot holes, gradation segregation, and joint distress were all noted, and pictures were taken whenever they appeared. Records of the findings from each inspection were kept and compiled to provide a time line for the condition of each location.

CHAPTER 4
RESULTS AND DISCUSSION

The goal of this investigation was to gain insight on the relationship between thermal segregation severity at the time of construction and the time it takes for pavement distress to appear. To do so, first, specific sites of thermal segregation were identified. Then, the severity of the thermal segregation was quantified. Then, the pavements containing the thermal segregation were monitored for thermal segregation damage. Finally, the relationship between the thermal segregation severity and the length of time before pavement distress appears was explored.

Monitoring of Test Segments from Previous Research

The previous research by Amirkhanian and Putman (2006), in addition to investigating different correlations and aspects of thermal segregation, identified several pavement segments containing thermal segregation. Segments of each of the asphalt types used in construction at the time were included. Information on these segments was supplied for the current investigation at the onset.

The original intent was to monitor these segments every six months like the segments identified in the current investigation. This long term monitoring would have provided several years of data on the rate of deterioration of thermally segregated asphalt pavements. However, upon visiting these segments, it was determined that there was not sufficient information to accurately and confidently locate the specific locations of thermal segregation within the pavements. This lack of information was primarily due to two factors. The first was imprecise or inaccurate GPS coordinates from an older GPS unit producing less precise location coordinates than the one used in the current investigation. The second was a lack of information identifying the traffic lanes in which the pictures were taken. To avoid the possibility of inaccurate findings from these segments, this objective was abandoned.

Identification of Locations of Thermal Segregation

The original intent of this investigation was to identify 24 pavement segments in which thermal segregation was present at the time of construction. There were to be three segments of each major pavement type: Surface A, B, C, CM, Intermediate A, B, C and Open Graded Friction Course. However, during the course of this study, there were actually 32 pavement segments identified. Only three intermediate segments were identified: two Intermediate B segments, one Intermediate C segment, and no Intermediate A segments. Intermediate asphalt for mainline applications is typically used for new construction. There has been a limited amount of new construction as compared to the amount of rehabilitation of existing pavement. Also, contractors are currently choosing to substitute surface mixes in the place of intermediate mixes due to the surface mix's finer gradation making it easier to place. For these reasons, there was little intermediate mix paving available during the time of this investigation, and only few sections were identified for monitoring. Appendix E outlines the different mix types, number of test segments of each type, and how many specific locations were identified.

Types of Thermal Segregation Observed

During this investigation, several causes or types of thermal segregation were observed. These different types and causes along with techniques that can eliminate or lessen their severity will be discussed later in this report.

Thermal Segregation Characterization

Different methods have been used to characterize thermal segregation in relation to actual temperature measurements. Amirkhanian and Putman (2006) used the difference in temperature of specific spots from the mean temperature of the mat. Song, Abdelrahman, and Asa (2009) characterized thermal segregation as the difference in temperature between specific locations on the mat and their surrounding areas. Brock and Jakob (1997) were concerned with the temperature of the cold spots only, as they developed data relating temperature of asphalt at compaction with rutting susceptibility and fatigue resistance.

This investigation used three measurement strategies to characterize temperature segregation. First, simple minimum temperature within each infrared asphalt mat picture was used. This strategy has advantages and disadvantages. Since compaction becomes more difficult as the asphalt becomes cooler, the location with the minimum temperature would be the most important location on the pavement. Also, because the surrounding pavement temperatures are not considered, the size of the picture should have little effect on the measurement. This however gives no insight to the prevailing temperature of the whole mat, so there's no way to know if the whole mat is rolled at a cooler temperature based on this single measurement.

As temperature segregation can be defined as changes in temperature over relatively small areas, the difference between the maximum and minimum mat temperatures within each infrared picture was considered. Along with the difference between the maximum and minimum, the average mat temperature within each picture was tabulated. The combination of these measurements gives an idea of the temperature of the mat surrounding the cold spot. The disadvantage of this measurement strategy is that it can be manipulated based upon the size of the picture. The measurement becomes more accurate as more of the pavement mat is included in the picture. The incidence of segregation will seem less severe if the camera is zoomed in on just the cold spot. For this reason, it is recommended that infrared pictures of cold spots be taken including as much of the surrounding portion of the asphalt mat as possible. Appendix G shows the tabulation of all the data for each test segment. It shows the maximum temperature, minimum temperature, average temperature, months to significant distress of the pavement, months until temperature differential damage of the pavement becomes apparent, and the number of months of monitoring for each specific location of thermal segregation.

Pavement Distress

The test segments in this investigation were monitored every six months after identification. Monitoring involved checking the test segments for pavement distresses such as raveling, cracking, rutting, potholes and coarse areas that retain water. The areas between the identified cold spots were used as control areas for the project. These control areas helped to determine which instances of pavement distress were due to thermal segregation and which were due to other factors. Distresses such as cracks that travel across the longitudinal joint or through control areas, holes in the control area but not the test area, and raveling or rutting over the entire test segment can probably be attributed to factors other than thermal segregation like normal wear. Also, any distresses caused by thermal segregation should progressively get worse over time. Distresses, such as small holes, that are present in the first inspection, but do not get any worse in subsequent inspections are probably not due to thermal segregation. Any distresses attributed to thermal segregation should be limited to the cold areas detected in the mat, and should show a progression of deterioration over several inspections.

Distress Findings

The original intent of this investigation was to determine the relationship between thermal segregation severity and the time until pavement distress appears. With the test segments from the previous research discarded, only the segments identified during this research could be monitored. Two classifications of pavement distress were tabulated: temperature differential damage and simple deterioration. Temperature differential damage refers to distress caused by thermal segregation. Simple deterioration is distress caused by other factors such as age and subsurface conditions.

There is a somewhat steady progression of total deterioration which is expected as the pavements age. In several of the pavement segments, simple deterioration appears and no temperature differential damage appears showing that it is possible for simple deterioration to occur before temperature differential damage appears.

No significant correlation could be obtained between the temperature data and the length of time before distress was evident. When attempting to obtain a correlation between the difference in the maximum and minimum temperatures within each infrared picture and the length of time until distress appears, an R^2 value of 0.13 was obtained. When the average temperature within each infrared picture was used, an R^2 value of 0.02 was obtained. When the minimum temperature within each infrared picture was used, an R^2 value of 0.15 was obtained. None of these R^2 values indicate any significant correlation. The possible reasons for this lack of correlation are discussed later in this report.

At the time of this report, there were only nine locations that showed evidence of temperature differential damage. Seven of these nine locations are within one segment of OGFC, which will be discussed later. With the lack of temperature differential damage that has become apparent at the time of this report, it becomes impossible to develop a reliable, significant correlation between temperature differential and the time until temperature differential damage becomes apparent. Some of these thermally segregated pavements have been in service for at least three years without major temperature differential damage due to thermal segregation.

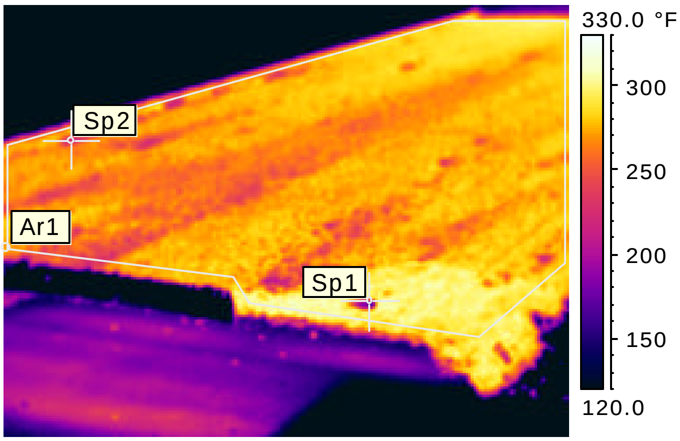
Open Graded Friction Course Distress Findings

During this investigation, a need to emphasize thermal segregation in OGFC was determined. A common major problem encountered with OGFC is localized major raveling. This raveling produces major roughness, additional rocks to damage vehicles, and locations that allow possible ponding of water during rain storms. Often these locations are located right after construction joints and adjacent to bridge decks. Figures 3 and 4 show some of the many examples of this raveling, following cold joints in this state.

Figure 3: Severe Raveling at OGFC Construction Joint on I-26 Eastbound

Figure 4: Severe Raveling at OGFC Construction Joint on I-26 Eastbound

Several segments of OGFC were visited. The first OGFC segment visited was on I-77 in Richland County. Figure 5 shows the infrared picture from the beginning of the paving operation.



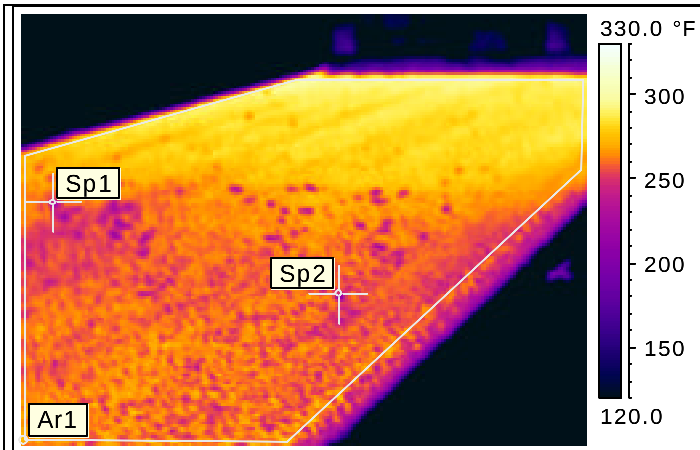
001 – Run Start-Up

N33 57 16.5 W80 57 32.5

Object Parameters	Value
Sp1 Temperature	160.8 °F
Sp2 Temperature	226.6 °F
Ar1 Max. Temperature	309.6 °F
Ar1 Min. Temperature	160.7 °F
Ar1 Average Temperature	273.5 °F

Figure 5 (A): Infrared Image of Beginning of Night's Paving Operation

(OGFC on I-77 in Richland County)



002 – Run Start-Up

N33 57 16.6 W80 57 32.5

Object Parameters	Value
Sp1 Temperature	227.0 °F
Sp2 Temperature	210.5 °F
Ar1 Max. Temperature	298.6 °F
Ar1 Min. Temperature	210.5 °F
Ar1 Average Temperature	266.6 °F

Figure 5 (B): Infrared Image of Beginning of Night's Paving Operation

(OGFC on I-77 in Richland County)

Figures 5 (A) and (B) show a cooler area from the beginning of paving for length of about 20 feet. The causes of this cooler area include:

- Paving delay as paving crew tries to match up with previous paving.
- Hand work including tossing the mix through the air to create a smooth transition from previous paving.
- Delay of the rollers due to time need for the hand working of the mix.

Appendix H shows the progression of the temperature differential damage of the segment shown in figures 5 (A) and (B) and 6 (A) and (B). The main mechanism of failure in these pictures is the raveling of the OGFC. As can be seen in the pictures, distress was evident at six months. At 36 months, a major hole had developed in the pavement surface, which only got worse as the pavement aged.

Figure 6 (A): OGFC Construction Joint Cold Spot After Six Months Service

(OGFC on I-77 in Richland County)

Figure 6 (B): OGFC Construction Joint Cold Spot After 48 Months Service

(OGFC on I-77 in Richland County)

Possible causes of this premature distress include:

- Excessive rolling of the mat to achieve a smooth transition from the bridge deck causing aggregate destruction.
- Thermal segregation.

Similar distress can be found in the OGFC placed at bridge approaches and departures. This distress is generally in the form of severe raveling, and possible causes include the following:

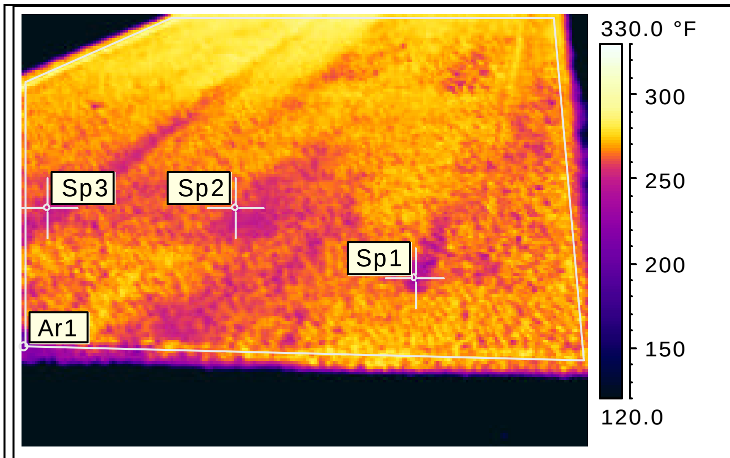
- Thermal segregation.
- Excessive rolling of the mat to achieve a smooth transition from the bridge deck causing aggregate destruction.

Causes of the thermal segregation at these locations include:

- Asphalt in the paver cools down while the paver moves across the bridge.
- Paving delay as the crew tries to match the asphalt with the top of the bridge deck.

- Hand work, including tossing the mix through the air to create a smooth transition from the bridge deck to the pavement surface.
- Delay of the rollers due to waiting for the hand work to be finished.

Figure 7 shows the infrared picture for a bridge departure on the same OGFC project in Richland County.



006 – Bridge Departure

N33 57 18.7 W80 57 26.9

Object Parameters	Value
Sp1 Temperature	232.0 °F
Sp2 Temperature	247.2 °F
Sp3 Temperature	245.5 °F
Ar1 Max. Temperature	292.7 °F
Ar1 Min. Temperature	202.9 °F
Ar1 Average Temperature	267.6 °F

Figure 7: Infrared Image of Bridge Departure (OGFC on I-77 in Richland County)

This location showed slight raveling at only six months; however significant raveling was present at 18 months. After 42 months of service, a hole had developed. The distress is not as severe as the distress at the previously discussed construction joint, but is still causing serious roughness and a location for water to pond. Appendix I shows pictures of the segment over the time of the investigation.

Figure 8: OGFC Bridge Departure Cold Spot After 42 Months in Service

For this investigation, seven segments of OGFC were identified for temperature differential damage observation with a total of 116 individual locations of thermal segregation identified. At the time of this report, only one of these segments demonstrated any significant damage. In that segment, seven locations showed signs of temperature differential damage, and 7 segments showed simple deterioration. Neither simple deterioration nor temperature differential damage demonstrated a correlation between the time when they became apparent and the mat temperature at construction. This segment did demonstrate some correlation between the locations of severe raveling and the locations of cold spots. All locations of major raveling were found inside areas noted to have been thermally segregated, however not all locations noted for thermal segregation showed signs of temperature differential damage. All other areas showed only signs of regular wear on the roadway surface.

Reasons for Poor Correlation

The data obtained in this investigation demonstrated no significant correlation between temperature at compaction and length of time until any distress becomes apparent. In addition to the shear lack of distress data points, this lack of correlation can be attributed to several factors:

- Differences in subsurface conditions and traffic levels
- Differences in the rolling practices between different contractors
- Differences in the number of roller passes by the same contractor on different areas of the same pavement mat
- Different types of thermal segregation
- Lack of repeatability of camera data
- Other factors leading to distress

Traffic Levels and Substructure Conditions

The time needed for distress to appear is heavily affected by traffic levels and substructure conditions which can change from one location to another on a pavement segment and can change from pavement segment to pavement segment. This variability makes correlations between mat temperature during construction and the length of time until distress appears difficult to obtain.

Mat Rolling Practices

Based on the data obtained, it seems that proper rolling practice can negate much or most of the effect of temperature segregation as long as that temperature segregation is not too severe. As deterioration rate of pavements is effected heavily by the finished mat density, the rolling becomes a very important factor in how long the pavement lasts and how long until distress appears. Therefore, different contractors with different rolling techniques would lead to different densities, and thus different asphalt lifespans per given mat temperature at construction.

Also, different areas of the mat receive differing amounts of compactive effort during construction. Ideally, every area of the mat would receive the same number of passes with each roller. This is not the case, however. Some areas of the mat receive more roller passes than others due to overlapping of roller passes and roller operator error. This leads to different densities across the mat, leading to differing lifespans per a given mat temperature.

Different Types of Thermal Segregation

There were several types of thermal segregation encountered during this investigation. These types can be separated into two groups. One type is caused by factors affecting the mix before it is placed. This includes causes such as end of load segregation, segregation from mix that has been allowed to sit in the hopper and get cold, and wing dump segregation. The other type of thermal segregation is caused by factors affecting the mix after it is placed and before it is rolled. This would include causes such as wind cooling, work stoppages, and spillage of water on the mat. There can also be combinations of the two types of segregation.

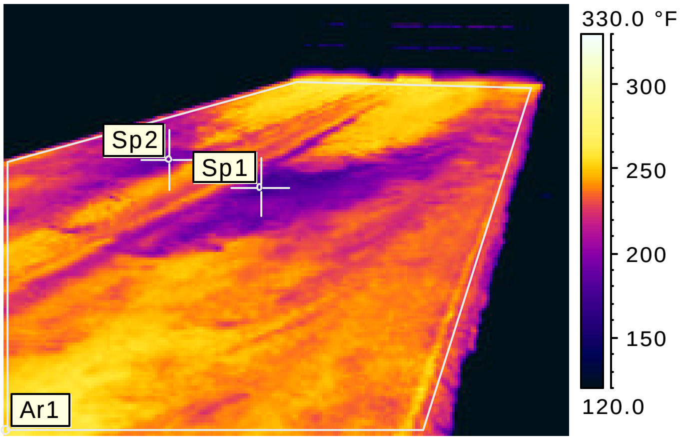
The two types of thermal segregation affect the density of the pavement differently. Segregation caused by factors before placement can affect the mat for the entire depth because the cold material is consolidated into one cold area that can extend the entire depth of the mat. This extended area would have a greater effect on the finished density of the pavement. Segregation caused by factors after placement will not necessarily affect the entire depth of the mat due to the insulating effect of the asphalt. This would cause a lesser effect on the density of the finished pavement.

The infrared camera only sees temperatures on the surface of the mat. Two locations of thermal segregation may look like the same severity, but beneath the surface, one may be much colder than the other. This would lead to inconsistencies in the relationship between mat temperature and density after compaction, which would lead to poor correlation between thermal segregation severity and the time needed for distress to appear.

Lack of Repeatability of Camera Data

There are factors that can affect the temperature data measured by the camera. As discussed earlier the distance and zooming of the camera image with respect to the cold area can affect the measurement data by including more or less of the surrounding mat. This affects average temperatures and the difference between maximum and minimum temperatures.

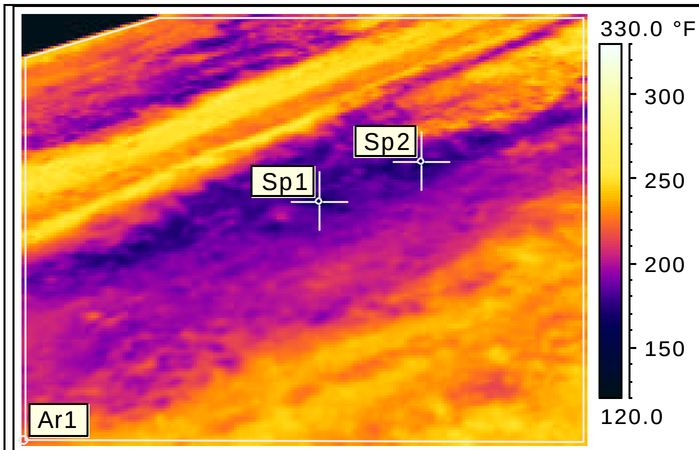
The length of time after the mix is placed by the paver also affects the temperature data. If the picture is taken right behind the paver, there is no information on the actual pavement temperature at the time of compaction. If the picture is taken right before the first roller, wind and differential cooling will have taken place affecting the temperature measurements.



004A – End of Load

N33º56’00.9” W81º12’44.4”

Object Parameters	Value
Sp1 Temperature	171.1 °F
Sp2 Temperature	186.9 °F
Ar1 Max. Temperature	264.8 °F
Ar1 Min. Temperature	169.8 °F
Ar1 Average Temperature	233.9 °F



004B – End of Load

N33º56’00.9” W81º12’44.4”

Object Parameters	Value
Sp1 Temperature	165.6 °F
Sp2 Temperature	159.9 °F
Ar1 Max. Temperature	256.4 °F
Ar1 Min. Temperature	159.9 °F
Ar1 Average Temperature	216.4 °F

Figure 9: Infrared Pictures Demonstrating the Change in Temperature Data

The key to consistent temperature data is to be consistent with the camera positioning used to take the pictures. Consistent camera positioning is not always practical though. Figure 9 shows an example of two infrared pictures taken of one cold spot from different distances, angles and times. The tabulated temperature data for each picture is significantly different. This difference in data would significantly affect any attempt to correlate pavement mat temperatures to the length of time until pavement distress appears.

Other Factors Leading to Distress

There are several factors that cause distress in asphalt pavements. Cracks in underlying pavement layers cause reflective cracking and traffic levels affect the rate of raveling over the pavement. These types of conditions cause the distress of new asphalt pavements as they age. Based upon the data it appears that, with the degree of thermal segregation encountered in this investigation, these factors begin to cause distress before temperature differential damage appears. This was the case with all mix types that showed distress except OGFC.

Reasons for Lack of Temperature Differential Damage (Surface and Intermediate Mixes)

As stated previously, only nine locations demonstrated any temperature differential damage in the course of this investigation, and seven of these locations were OGFC. There are several possible reasons for the lack of temperature differential damage in these cold locations when compared to previous research.

Previous research has shown temperature segregation that was severe enough to show up on the finished mat. This would be caused by very severe temperature segregation or temperature segregation combined with gradation segregation. Figure 10 is an image from a Washington State Department of Transportation investigation. The locations of the segregation are evident and appeared as end of the load segregation. As these textural changes allow an increased probability of moisture damage, temperature differential damage would be more likely in these areas. No cyclical textural changes corresponding to thermal segregation were evident at the time of this report. This could explain some of the lack of temperature differential damage.

Figure 10: Cyclical Pavement Mat Texture Changes Due to Thermal Segregation

Washington Department of Transportation (n.d.)

It is also believed that the paving techniques observed could be partially responsible for the lack of temperature segregation damage. Very few wing dumps were observed during this investigation. Also, a large percentage of paving projects utilized material transfer vehicles (MTV's) during this investigation. Amirkhanian and Putnam (2006) showed that the use of a MTV lessened the severity and frequency of thermal segregation. Of the 32 segments identified during this investigation, 22 used a MTV. Of the coarser mixes, which include Surface A, Surface B, OGFC, and Intermediate B, 20 of the 21 segments used a MTV. This high percentage of MTV usage, especially when using the coarser mixes which would show more negative effects from cold paving temperatures, should cause less severe thermal segregation and lessen the probability of encountering temperature differential damage.

Roller technique could also mitigate the effects of thermal segregation. If there is enough compactive effort on the mat, areas that are slightly cooler, would still obtain acceptable densities. A paving project utilizing Surface C was visited with a TransTech non-nuclear density gauge in an attempt to demonstrate the change in density with varying compaction temperatures. The average temperature along several transverse lines across the pavement was measured and the density was measured at one foot intervals along that line to get the average density. Figure 11 shows the temperature versus density data obtained. The data shows very poor correlation between the temperature at

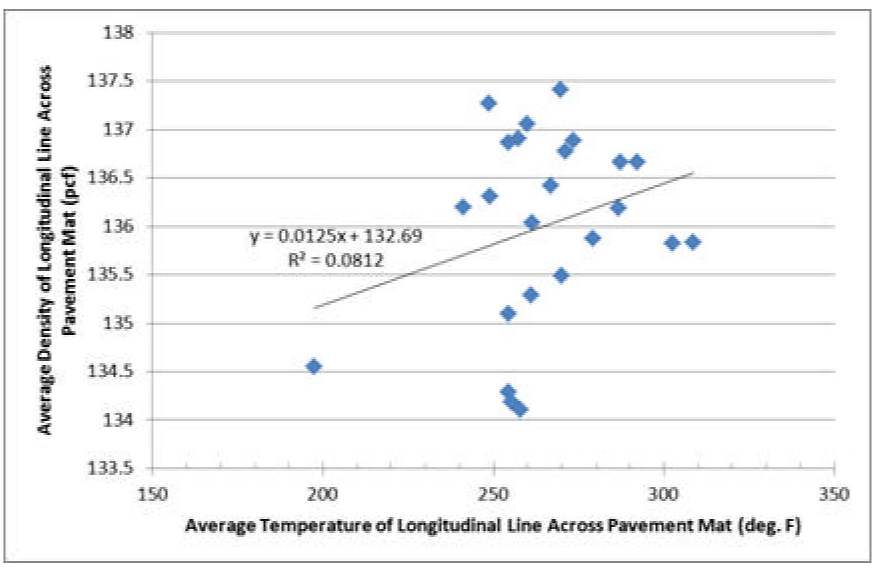


Figure 11: Temperature vs. Density Data From Surface C Paving Project

compaction and the final density of the pavement. The data obtained leads to the conclusion that lower pavement temperatures do not necessarily result in lower densities if quality roller techniques are followed. Therefore, the lower temperatures may not result in premature pavement distress.

Also, many of the instances of thermal segregation noted were caused by factors after the mix had been placed. As the infrared camera only sees the surface temperatures of the mat, these factors such as wind cooling, and cooling caused by work stoppages appear to cause serious instances of thermal segregation. Due to the insulating effect of the asphalt mentioned earlier, the thermal segregation may not be as severe as it appears.

Lastly, the segments may not have been monitored long enough for most of the temperature differential damage to become apparent. Some of the segments have only been monitored for six to 12 months. Longer monitoring (possibly as long as ten years) would be beneficial in gaining understanding about temperature differential damage.

Reasons for Increase in Temperature Differential Damage (OGFC)

As noted before, seven of the nine instances of temperature differential damage were on one segment of OGFC. Also, as discussed before, there are repeated instances of severe raveling at construction joints and around bridged decks were the mix is allowed to cool significantly before it is compacted. There are several possible reasons that thermal segregation has such an effect on OGFC.

First, OGFC utilizes PG 76-22 liquid asphalt which is stiffer than the PG 64-22 that is more commonly used. With the stiffer liquid, compaction is more difficult at higher temperatures. Therefore cooler compaction temperatures could be more detrimental to OGFC than other conventional asphalt pavement types using the PG 64-22 liquid asphalt.

OGFC has an open, coarse texture to allow water to drain through it providing better visibility and traction during rainfall. This provides more surface area for the aggregates in the mix, causing faster cooling and less of an insulating effect than conventional asphalt mixes

Lastly, OGFC is compacted differently than conventional asphalt mixes. Typical asphalt mixes receive several passes with two or three rollers to achieve a certain level of compaction. OGFC is ideally only rolled with one pass of the roller just to seat the mix, and density is not even measured. Therefore, if the mix is cold, it does not seat properly with the stiffer liquid asphalt, and there is no opportunity to compensate with increased rolling of the mix.

Thermal Segregation Types, Causes, and Remedies

Several causes of thermal segregation were encountered during this investigation. These causes can be divided (as discussed earlier) into causes before placement and causes after placement. Figure 12 shows a list of the major causes encountered and how many instances of thermal segregation were attributed to each one. Appendix B shows all of the major types encountered and shows an example infrared picture of each.

Cause of Thermal Segregation Encountered		Number of Pictures
Causes Before Placement		
	End of Load	129
	Cold Mix Due to Waiting During Long Work Stoppages	40
	Handworking	31
	Streaks in the Mix	27
	Start-up, Cold Joint, Etc.	21
	Wing Dump	18
	Mechanical Problems	5
Causes After Placement		
	Work Stoppages	98
	Start-up, Cold Joint, Etc.	21
	Liquids Spilled on Mat	3
	Environmental	2

Figure 12: Types of Thermal Segregation Encountered

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The purpose of this investigation was to gain insight on the effects of thermal segregation. Infrared pictures were taken of specific locations of thermal segregation for all of the mix types available. The mix types included were Surface A, Surface B, Surface CM, Surface C, Intermediate B, Intermediate C, and Open Graded Friction Course. The GPS coordinates of each location were tabulated allowing each location to be visited later. Also, temperature data including minimum temperature, difference between minimum and maximum temperature, and average temperature were tabulated for each infrared image.

Each pavement segment was monitored every six months. All signs of distress for each location were tabulated, including simple deterioration and temperature differential damage, in an attempt gain a correlation between temperature at construction and the length of time until pavement distress appears.

The data obtained was also used to derive implementation guidelines for the use of the infrared camera in asphalt paving specifications. Also, techniques for minimizing and reducing the severity of thermal segregation were suggested.

Conclusions

Based on the results of this study involving temperature segregation in asphalt pavements, the following conclusions were made:

- Due to a heavy reliance on factors such as subsurface conditions and traffic levels, little to no significant correlation between asphalt temperature at construction and length of time until simple pavement deterioration became apparent.

- As evidenced by several of the segments identified in this investigation, simple deterioration can begin to become apparent before temperature differential damage in surface and intermediate mixes with the typical severity of thermal segregation found during this investigation.

- The Flir ThermaCAM EX320 used for this investigation was able to accurately and precisely measure temperature values on all pavements including OGFC.

- OGFC can be severely affected by thermal segregation and damage can appear in as little as six months after construction, however, temperature data does not indicate a specific correlation between temperature at construction and the length of time until temperature differential damage becomes apparent.

- OGFC running through a cold MTV and paver along with hand working of the mix and paving delays associated with paving from a cold joint can lead to serious temperature differential damage in the form of major raveling.

- Increased usage of MTV's on coarser, higher volume mixes seems to have lessened the severity of temperature segregation in asphalt as evidenced by the lack of temperature segregation combined with or leading to cyclical pavement surface texture changes as found in previous research.

- The techniques used to take the infrared images, including the distance from the subject area, the angle to the subject area, and the length of time after the paver has passed the subject area, have a significant effect on the temperature measurement values.

- The most common cause of thermal segregation found during this investigation was end of the load thermal segregation, which was occasionally combined with segregation cause by dumping the wings of the paver. The second most common was from work stoppages.

- Based upon monitoring of specific locations of thermal segregation identified in this investigation. Pavements can be in service longer than three years without temperature differential damage becoming apparent.

Recommendations

Based on the findings of this investigation, the following recommendations have been made concerning thermal segregation and temperature differential damage:

- The SCDOT should continue to monitor the identified test segments to gain insight about the timeline of temperature differential damage with respect to thermal segregation severity.

- The SCDOT should strongly encourage the use of a MTV for all paving with OGFC and Surfaces A, B, and CM, which tends to minimize the instances and reduces the severity of end of load thermal segregation.

- When paving with OGFC, contractors should implement the following techniques when paving from a cold construction joint or paving a bridge approach or departure:

- Match paver as close as possible to previous paving to minimize necessity to do hand work of the mix.
- Do not toss mix through the air, which causes accelerated cooling of the mix and cold areas.
- Do any preparation or hand work of the mix quickly, and allow the rollers to roll this area quickly to minimize cooling of the mix before rolling.

- The SCDOT should consider implementing OGFC construction specifications based upon information gathered from the use of the infrared camera. Suggested guidelines for the implementation of this specification for OGFC are shown in Appendix A.

- As the infrared camera only sees the surface temperature of the asphalt mix, some research would be beneficial to determine the relationship between the rate of surface cooling and the rate of interior cooling of the asphalt mix at paving work stoppages. This would give guidance as to how detrimental thermal segregation due to work stoppages is in asphalt pavements.

- Research studying only OGFC cold spots (specifically cold spot at construction joints and bridge decks) could be beneficial as it would give insight into a possible minimum temperature for a mill and replace specification for OGFC construction.

- Paving contractors should attempt to observe the following recommendations to minimize thermal segregation for all mix types:

    - Continue to use a MTV whenever practical to reduce end of the load thermal segregation.
    - Match the paver speed with the haul truck arrival rate such that there are no paving delays due to waiting for trucks. This would also minimize the time that trucks wait at the site which would help to minimize cooling of the mix in the truck.
    - Continue to avoid wing dumping between truck loads to minimize thermal segregation at the end of each load.
    - Avoid hand working of the mix as much as possible. When hand working is necessary, avoid tossing of the mix as tossing the mix leads to accelerated cooling.
    - To combat environmental cooling effects, keep rollers as close as possible to the paver.

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Appendix A: Suggested Implementation Guidelines for an Open Graded Friction Course Specification Based on Findings with an Infrared Camera

Given the findings of this investigation and the evidence from past paving projects around the state of South Carolina, it is evident that premature distress is a common problem when paving with Open Graded Friction Course, especially when paving from cold construction joints or bridge approaches and departures. The findings of this investigation give evidence that some of this premature distress is a result of thermal segregation during construction. For this reason, additional specifications could be beneficial, and implementation guidelines for these possible specifications are listed below.

1. To prevent the possibility of damaging the pavement through excessive compaction, only one roller pass per roller should be allowed on the OGFC mat.

2. To minimize heat loss of the mix before rolling, tossing of the mix should be prohibited.

3. To minimize the effects of environmental effects that lead to cooling, such as wind, the OGFC should be compacted within three minutes of the time it is deposited by the paver.

4. Infrared camera usage should be considered for all OGFC paving within 20 feet of a cold joint or bridge deck, as these are locations that have demonstrated the most common premature distress.

5. The infrared camera is recommended, anywhere the inspector suspects a problem with low mix temperatures.

6. Based on the OGFC data, a minimum allowable mix temperature of 200°F before compaction is suggested. This would eliminate 50 percent of the cold areas that demonstrated premature distress in this investigation. Also, the OGFC paving project in Spartanburg County demonstrated quality paving techniques and displayed very little thermal segregation. All of the infrared images included minimum pavement temperatures above 200°F. This demonstrates that a quality paving operation should be capable of maintaining unrolled mat temperatures above 200°F. More research would be beneficial to refine this suggested minimum temperature.

7. Some judgment is required when enforcing a minimum mat temperature. Rejection or penalty should not be based on one individual location. Nor should judgement be based upon foreign material that falls on the mat. Rejection or penalty should be based upon an actual area within the mat that is cooler than its surroundings.

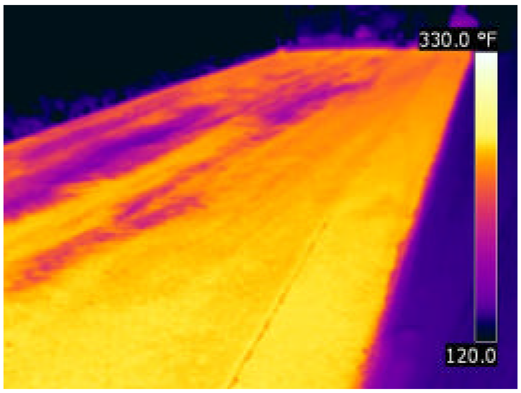
8. Temperature measurements within approximately two to four inches of the edge of the asphalt mat should be excluded because that area cools faster and it can be difficult to distinguish between the mat and its surroundings in this area.

9. All pictures should be taken before the first pass of a roller, as the roller cools the surface of the asphalt mix.

Appendix B: Types of Thermal Segregation Encountered During This Investigation

The following is a list of the major types of thermal segregation encountered during this investigation and an example picture of each.

- **End of Load**



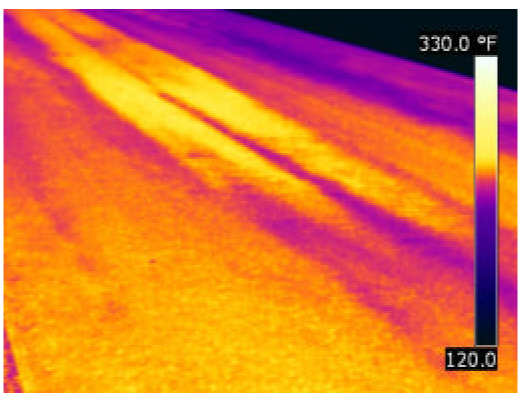
Causes:

- Mix forms crust of cold mix during transport to the job site.

Reduction Strategies:

- Be sure to use tarps on beds of transport trucks.
- Use MTV that remixes the mix to produce uniform mat temperature.

- **Cold Mix Due to Waiting During Long Work Stoppages**



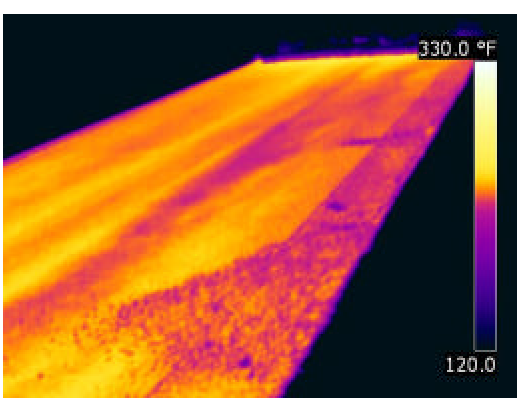
Causes:

- Mix cools in paver hopper when subject to long work stoppages

Reduction Strategies:

- Reduce the number of work stoppages.

- **Hand Working**



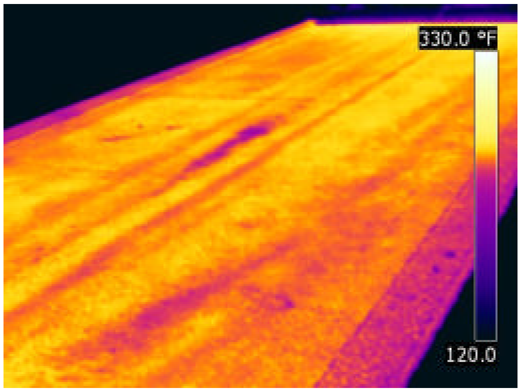
Causes

- Hand working is necessary due to mars in the pavement mat behind the paver
- The mix cools when tossed through the air

Reduction Strategies

- Minimize instances such as the paver running to low and foreign material in the mix that necessitates hand working.
- When hand working is necessary, minimize tossing of the mix.

- **Streaks in the Mix**



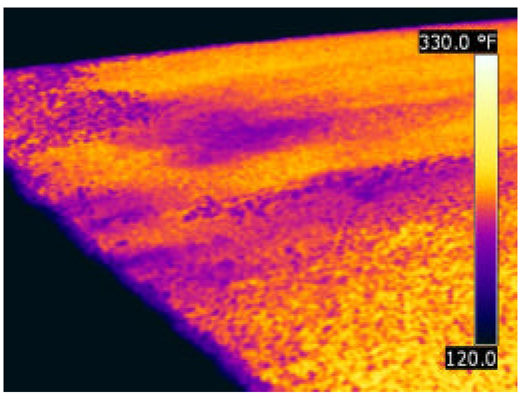
Causes:

- Possibly caused by the operation of the paving machine.
- Can also be caused by textural differences in different areas of the mat.

Reduction Strategies:

- Be sure all parts of the paver are working properly.
- Roll quickly so areas with textural differences don't have time to cool.

- **Start-Up (Cold Joint and Bridge Decks)**



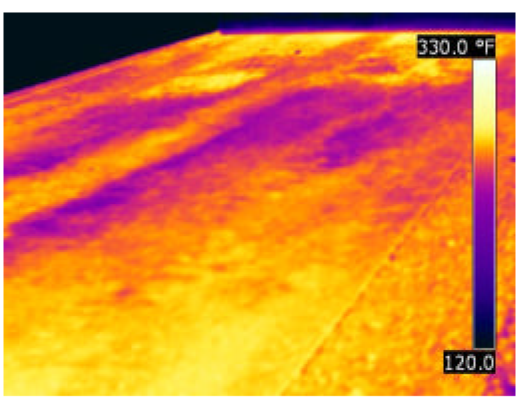
Causes:

- Delayed rolling due to time needed for hand working of mix to match previous paving.
- More cooling due to tossing of the mix during handworking.
- Mix cooling in the paver while crossing bridge.

Reduction Strategies:

- Be sure that any asphalt mix is rolled within three minutes of placement.
- Do not toss the mix through the air when hand working.
- Move as quickly as possible across the bridge.

- **Wing Dump**



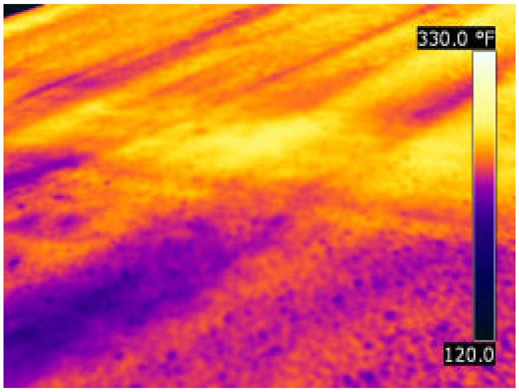
Causes:

- Cold mix builds up and cools in the wings of the paver and is deposited in the mat after the wing dump.
- Often this occurs with end of the load segregation.

Reduction Strategies

- Do not dump the wings until the end of paving and discard this mix.

- **Mechanical Problems**



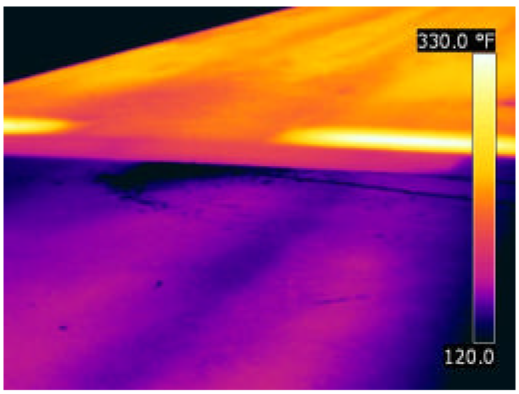
Causes:

- Generally shows up as work stoppages while paving crew works to fix the malfunction.

Reduction Strategies:

- Perform proper maintenance on equipment at specified intervals.
- Mechanical malfunctions will occur. They should be fixed as quickly as possible.

- **Work Stoppage**



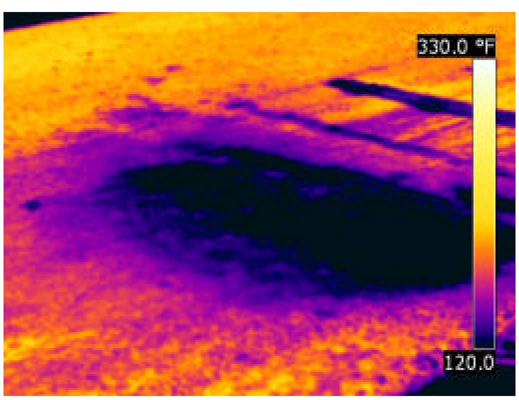
Causes:

- Typically occur when the paving operation has to stop to wait on haul trucks to arrive with the asphalt mix.

Reduction Strategies:

- Run paver slow enough that trucks can arrive before the paver runs out of mix and has to stop.
- Utilize a MTV and keep it full so that if there is a slight delay in the arrival of the haul truck, the paving operation can continue.

- **Liquid Spilled on Mat**



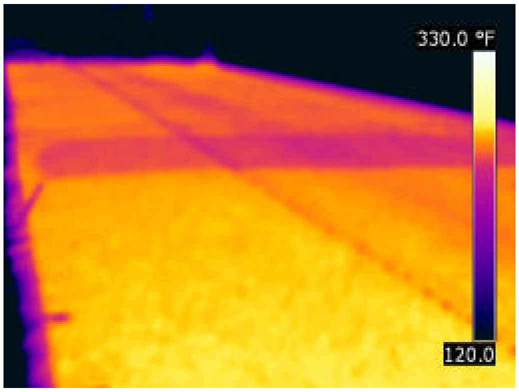
Causes:

- Operators on the paving machine spill drinks and other liquids on the mat behind the paver.
- During refilling, the water tanks on the rollers are overfilled allowing the water to run out onto the pavement mat.

Possible Solutions:

- Do not spill drinks or any liquids on the mat.
- Do not overfill water tanks on the rollers

- **Environmental Effects**



Causes:

- Unavoidable effects such as wind and shadows cause differential cooling on the surface of the pavement mat.

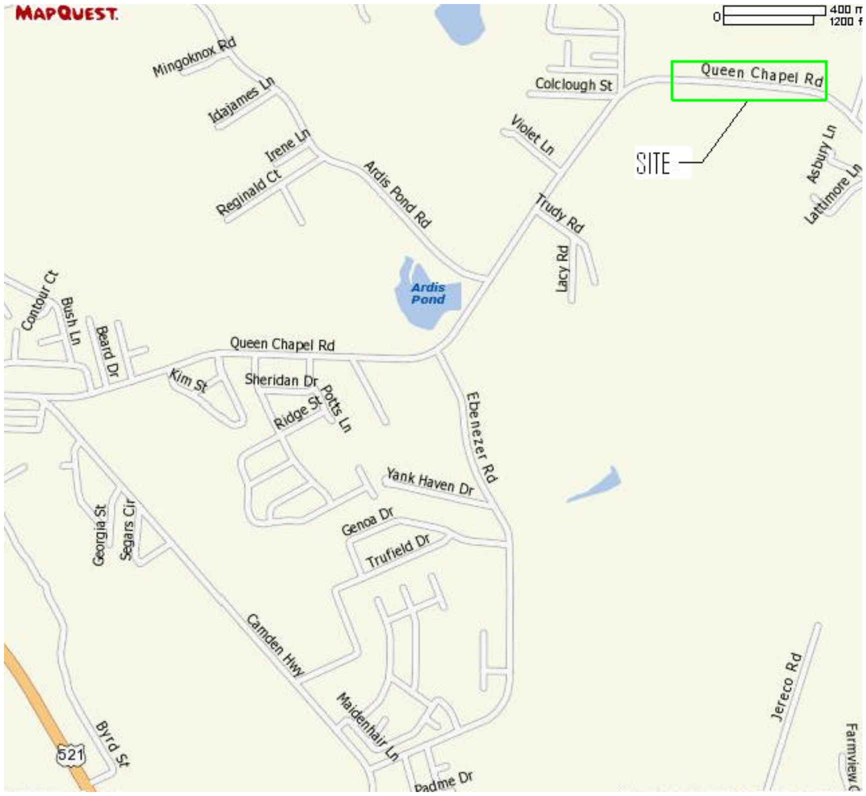
Reduction Strategies:

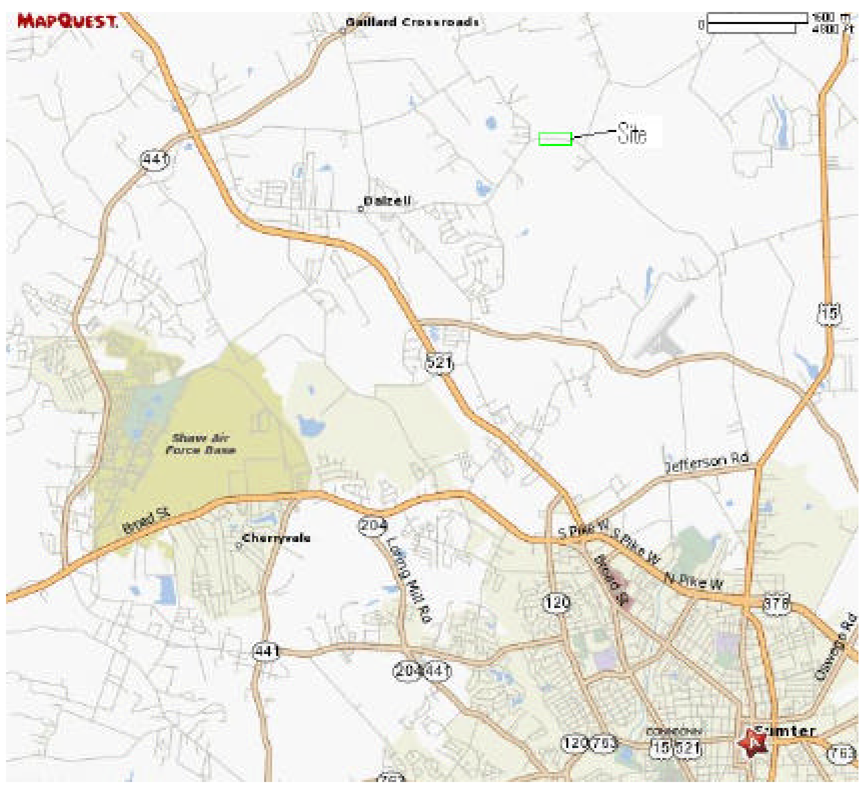
- Roll mat as quickly as possible so environmental effects have less time to produce differential cooling. This had the added benefit of reducing the likelihood of motorist driving across the unrolled mat.

Appendix C: Sample Asphalt Paving Infrared Thermal Segregation Report

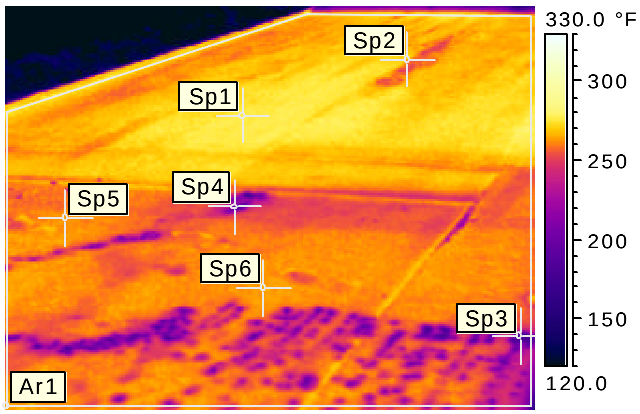
This is an example of the reports formed for every test section used in this investigation. It shows the infrared picture, temperature data, the GPS coordinates of the location, and the reason (if known) for the thermal segregation. It also shows information such as the date the pictures were taken, and some project information along with the mix type, ambient temperature and the identity of the road.

SCDOT	Thermographic Inspection of: Surface C Placed on Queen Chapel Road in Sumter County	Date: 8/19/09 File No.:31.038325 Job Mix No.: Ambient Temp.: 87ºF Mix Type: Surface C





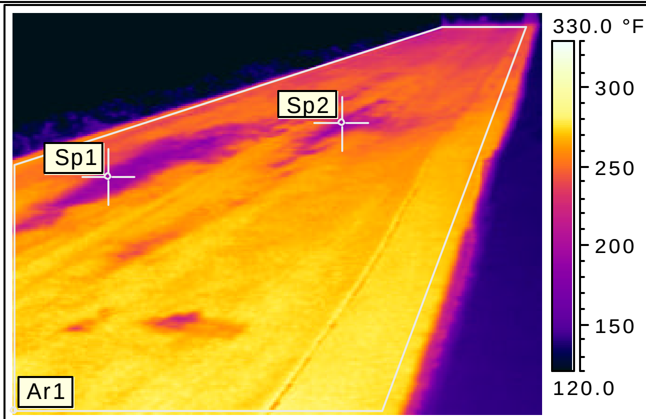
SCDOT	**Thermographic Inspection of:** **Surface C Placed on Queen Chapel Road in Sumter County**	**Date: 8/19/09** File No.:31.038325 Job Mix No.: Ambient Temp.: 87ºF Mix Type: Surface C



001 – Work Stop

N34º01'45.6" W80º23'05.3"

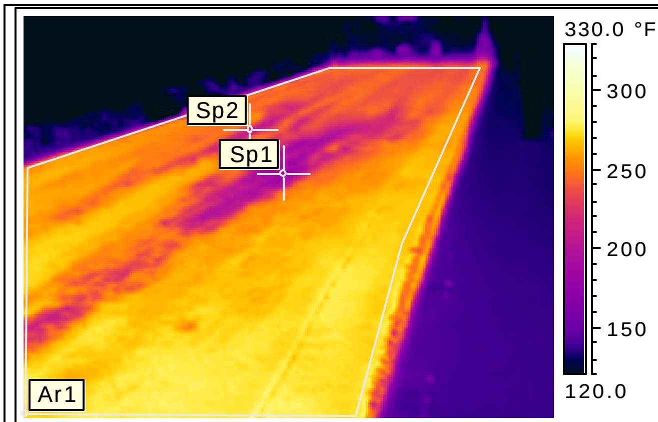
Object Parameters	Value
Sp1 Temperature	277.1 °F
Sp2 Temperature	257.7 °F
Sp3 Temperature	177.0 °F
Sp4 Temperature	179.4 °F
Sp5 Temperature	262.3 °F
Sp6 Temperature	265.3 °F
Ar1 Max. Temperature	281.6 °F
Ar1 Min. Temperature	164.2 °F
Ar1 Average Temperature	260.0 °F



002 – End of Load

N34º01'45.6" W80º23'04.9"

Object Parameters	Value
Sp1 Temperature	186.7 °F
Sp2 Temperature	189.4 °F
Ar1 Max. Temperature	285.4 °F
Ar1 Min. Temperature	182.1 °F
Ar1 Average Temperature	261.8 °F

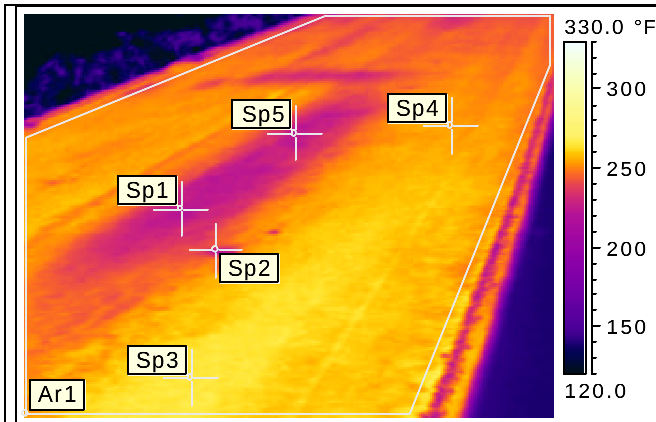


003 – End of Load

N34º01'45.4" W80º23'02.4"

Object Parameters	Value
Sp1 Temperature	183.4 °F
Sp2 Temperature	205.4 °F
Ar1 Max. Temperature	284.0 °F
Ar1 Min. Temperature	183.4 °F
Ar1 Average Temperature	258.0 °F

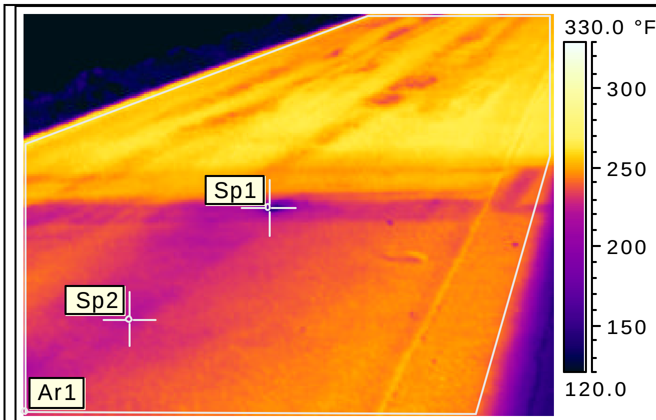
SCDOT	**Thermographic Inspection of:** **Surface C Placed on Queen Chapel Road in Sumter County**	**Date: 8/19/09** File No.:31.038325 Job Mix No.: Ambient Temp.: 87ºF Mix Type: Surface C



004 – Cold Spot

N34º01'45.3" W80º23'02.0"

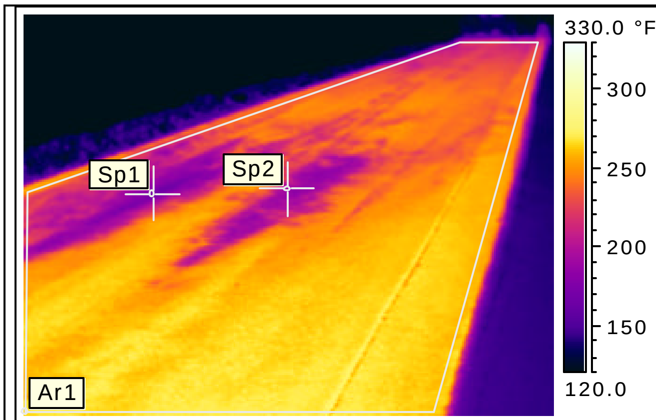
Object Parameters	Value
Sp1 Temperature	222.4 °F
Sp2 Temperature	218.7 °F
Sp3 Temperature	264.0 °F
Sp4 Temperature	253.8 °F
Sp5 Temperature	224.3 °F
Ar1 Max. Temperature	268.3 °F
Ar1 Min. Temperature	218.2 °F
Ar1 Average Temperature	251.9 °F



005 – Work Stop

N34º01'45.1" W80º23'00.2"

Object Parameters	Value
Sp1 Temperature	143.0 °F
Sp2 Temperature	222.2 °F
Ar1 Max. Temperature	267.5 °F
Ar1 Min. Temperature	138.5 °F
Ar1 Average Temperature	244.4 °F

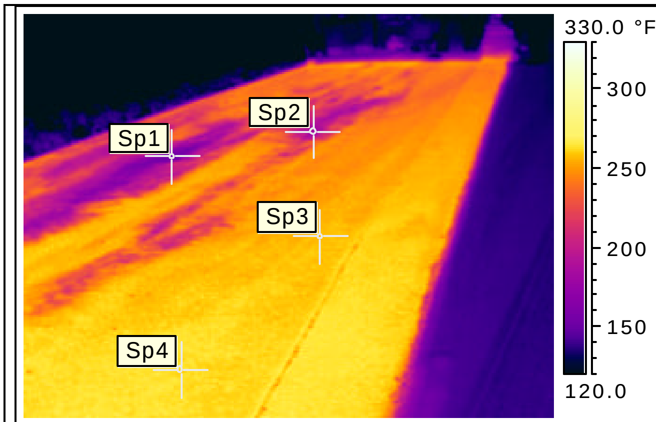


006 – End of Load

N34º01'45.1" W80º22'59.7"

Object Parameters	Value
Sp1 Temperature	167.7 °F
Sp2 Temperature	185.2 °F
Ar1 Max. Temperature	277.6 °F
Ar1 Min. Temperature	165.6 °F
Ar1 Average Temperature	247.4 °F

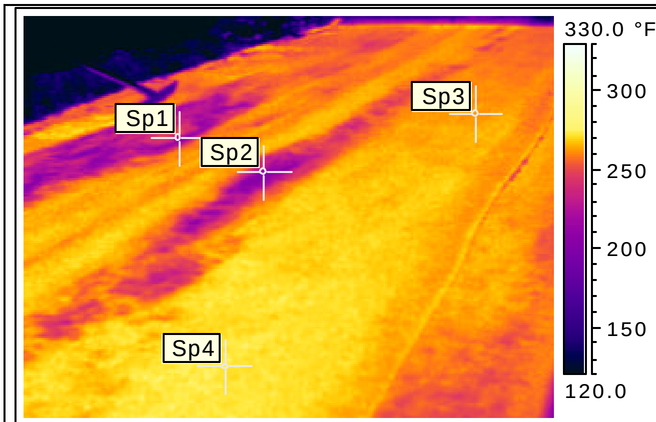
SCDOT	**Thermographic Inspection of:** **Surface C Placed on Queen Chapel Road in Sumter County**	**Date: 8/19/09** File No.:31.038325 Job Mix No.: Ambient Temp.: 87ºF Mix Type: Surface C



007 – End of Load

N34º01’45.0” W80º22’57.2”

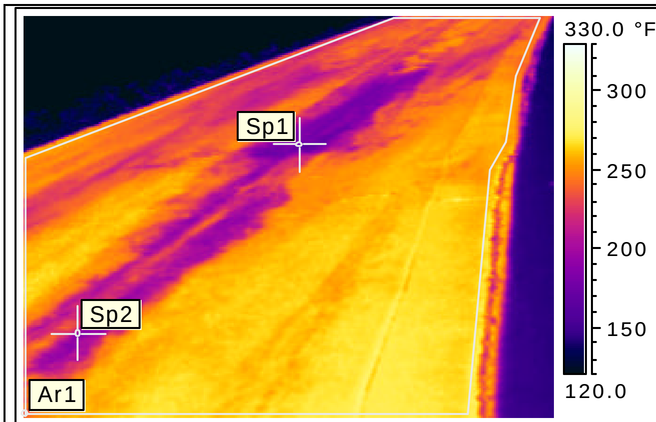
Object Parameters	Value
Sp1 Temperature	152.1 °F
Sp2 Temperature	182.3 °F
Sp3 Temperature	258.4 °F
Sp4 Temperature	260.2 °F
Ar1 Max. Temperature	268.5 °F
Ar1 Min. Temperature	149.0 °F
Ar1 Average Temperature	247.6 °F



008 – End of Load

N34º01’44.8” W80º22’55.4”

Object Parameters	Value
Sp1 Temperature	208.5 °F
Sp2 Temperature	202.5 °F
Sp3 Temperature	261.8 °F
Sp4 Temperature	272.5 °F
Ar1 Max. Temperature	276.2 °F
Ar1 Min. Temperature	201.3 °F
Ar1 Average Temperature	261.4 °F

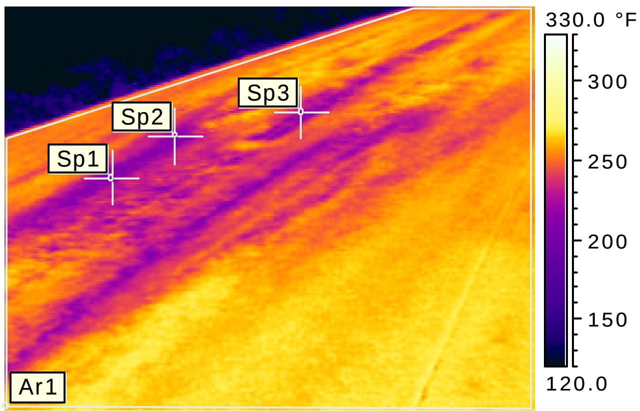


009 – End of Load

N34º01’44.6” W80º22’54.7”

Object Parameters	Value
Sp1 Temperature	161.4 °F
Sp2 Temperature	184.9 °F
Ar1 Max. Temperature	276.6 °F
Ar1 Min. Temperature	161.4 °F
Ar1 Average Temperature	246.6 °F

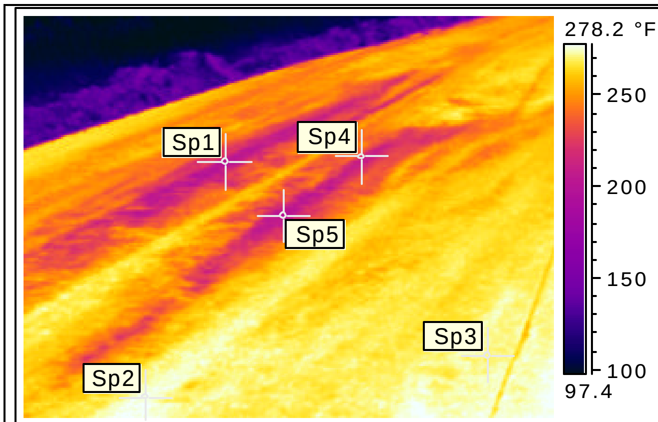
SCDOT	**Thermographic Inspection of:** **Surface C Placed on Queen Chapel Road in Sumter County**	**Date: 8/19/09** File No.:31.038325 Job Mix No.: Ambient Temp.: 87ºF Mix Type: Surface C



010 – End of Load

N34º01'43.8" W80º22'52.0"

Object Parameters	Value
Atmospheric Temperature	68.0 °F
Sp1 Temperature	210.7 °F
Sp2 Temperature	209.0 °F
Sp3 Temperature	213.4 °F
Ar1 Max. Temperature	275.9 °F
Ar1 Min. Temperature	207.6 °F
Ar1 Average Temperature	253.4 °F



011 – End of Load

N34º01'42.5" W80º22'49.6"

Object Parameters	Value
Sp1 Temperature	202.5 °F
Sp2 Temperature	277.1 °F
Sp3 Temperatu re	270.5 °F
Sp4 Temperature	211.2 °F
Sp5 Temperature	201.3 °F
Ar1 Max. Temperature	281.0 °F
Ar1 Min. Temperature	198.1 °F
Ar1 Average Temperature	255.6 °F

Appendix D-1: South Carolina Surface Mix Requirements (From SC-M-402)

HMA Surface Courses						
Designation	**Type A**	**Type B**	**Type CM**	**Type C**	**Type D**	**Type E**
Old Designation	*12.5 mm Superpave*	*Surface Type 1C*	*Surface Type 1D*	*Surface Type 1 & 3*	*Surface Type 4*	*Thin Lift Seal Course*
System Application	Interstate / Intersections	High Volume Primary	Low Volume Primary	Secondary	Low Volume Secondary	Seal Course
Gradation Requirements						
1”	100.0	100.0	----	----	----	----
¾”	98.0 – 100.0	98.0 – 100.0	100.0	100.0	100.0	----
½”	90.0 – 100.0	90.0 – 100.0	97.0 – 100.0	97.0 – 100.0	97.0 – 100.0	----
3/8”	72.0 - 90.0	72.0 - 90.0	83.0 – 100.0	83.0 – 100.0	90.0 – 100.0	100.0
No. 4	44.0 - 62.0	44.0 - 62.0	58.0 – 80.0	58.0 – 80.0	70.0 – 95.0	90.0 – 100.0
No. 8	23.0 – 43.0	23.0 - 43.0	42.0 – 62.0	42.0 – 62.0	50.0 – 82.0	70.0 – 100.0
No. 30	10.0 – 25.0	10.0 - 25.0	20.0 – 40.0	20.0 – 40.0	20.0 – 50.0	36.0 – 70.0
No. 100	4.0 - 12.0	4.0 - 12.0	5.0 – 20.0	5.0 – 20.0	6.0 – 20.0	4.0 – 28.0
No. 200	2.00 - 8.00	2.00 - 8.00	2.00 – 9.00	2.00 – 9.00	2.00 – 10.00	2.00 – 10.00
Required Job Mix Criteria						
Gyrations	100	75	75	50	50	50
Binder Limits, %	4.5 - 6.0	4.5 - 6.0	5.0 - 6.8	5.0 - 6.8	5.0 - 6.8	6.0 - 7.0
Binder Grade	PG 76-22	PG 64-22	PG 64-22	PG 64-22	PG 64-22	PG 64-22
Air Voids, %	3.0 – 4.0	3.0 – 4.0	3.5 – 4.5	3.5 – 4.5	4.0 – 9.0	NR
VFA, %	70.0 – 80.0	70.0 – 80.0	70.0 – 77.0	70.0 – 77.0	60.0 – 70.0	NR
Design D/A Ratio	0.60 - 1.20	0.60 - 1.20	0.60 - 1.20	0.60 - 1.20	0.60 - 1.20	NR
Min. Stability – 6” (lbs.)	No Requirement (NR)					2500
ITS Testing Required?	Yes	Yes	Yes	Yes	No	No
Rutting Susceptibility (max mm)	3.0	5.0	5.0	NR	NR	NR
Liquid ASA Permitted	No	No	No	Yes	Yes	Yes
Required Aggregate Criteria						
Local Sand Allowed?	No	No	No	Yes	Yes	No
Crushed Coarse Aggr. Required? (% fractured faces)	Yes (90% min)	Yes (90% min)	Yes (90% min)	Yes (70% min)	No	NR
Coarse Aggr. Max. % Passing No.200	1.50	1.50	1.50	1.50	1.50	NR
LA Abrasion (B), max %	55.0	55.0	55.0	60.0	60.0	60.0
Sodium Sulfate Soundness, max %	15.0	15.0	15.0	15.0	NR	NR
Crusher Run / Asphalt Sand Allowed?	No	No	No	Yes (25% max)	Yes (50% max)	No
Absorption, max. %	1.5	1.5	1.5	1.5	NR	1.5
Limestone Allowed? (CA / Screenings)	No / No	No / Yes	No / Yes	No / Yes	Yes / Yes	No
Slag Allowed?	No	No	No	Yes	Yes	No
RAP	Yes	Yes	Yes	Yes	Yes	Yes (-4)

Appendix D-2: South Carolina Intermediated Mix Requirements (From SC-M-402)

HMA Intermediate Courses			
Designation	**Type A**	**Type B**	**Type C ***
Old Designation	*19.0 mm for Intersections*	*19.0 mm / Binder T-1*	*Binder Type 2*
System Application	Intersections	Interstates / High Volume Primary (> 15% Truck Traffic)	Low Volume Primary / Secondary / Build up / Leveling / Patching
Gradation Requirements			
1”	100.0	100.0	100.0
¾”	90.0 – 100.0	90.0 – 100.0	90.0 – 100.0
½”	75.0 – 90.0	75.0 – 90.0	80.0 – 95.0
3/8”	64.0 – 80.0	64.0 – 80.0	68.0 – 87.0
No. 4	38.0 – 54.0	38.0 – 54.0	45.0 – 68.0
No. 8	22.0 – 36.0	22.0 – 36.0	30.0 – 46.0
No. 30	8.0 – 22.0	8.0 – 22.0	12.0 – 29.0
No. 100	3.0 - 10.0	3.0 - 10.0	4.0 – 13.0
No. 200	2.00 - 8.00	2.00 - 8.00	2.00 – 8.00
Required Design Criteria			
Gyrations	100	75	50
Binder Limits, %	4.0 – 5.5	4.0 – 6.0	4.0 - 6.0
Binder Grade	PG 76-22	PG 64-22	PG 64-22
Air Voids, %	3.0 - 4.0	3.0 - 4.0	3.5 - 4.5
VFA, %	70.0 – 80.0	70.0 – 80.0	70.0 – 77.0
Design D/A Ratio	0.60 - 1.20	0.60 - 1.20	0.60 - 1.20
Min. Stability (lbs.)	No Requirement (NR)		
ITS Testing Required?	Yes	Yes	Yes
Rutting Susceptibility (max mm)	3.0	5.0	NR
Liquid ASA Permitted	No	No	Yes
Required Aggregate Criteria			
Local Sand Allowed?	No	No	Yes
Crushed Coarse Aggregate Required? (% fractured faces)	Yes (90% min.)	Yes (90% min.)	No
Coarse Aggr. – max. % Passing No. 200	1.5	1.5	NR
LA Abrasion (B), max. %	55.0	55.0	60.0
Sodium Sulfate Soundness, max %	No Requirement (NR)		
Crusher Run / Asphalt Sand Allowed?	No	No	Yes (50% max)
Absorption, max. %	1.5	1.5	NR
Limestone Allowed? (CA / Screenings)	No / No	No / Yes	Yes / Yes
Slag Allowed?	Yes	Yes	Yes
RAP	Yes	Yes	Yes

Appendix E: Test Segment Information

Road Name	County	Pavement Type	Date Identified	City (In/Near)	Number of Locations
I-26 Westbound	Newberry	Surface A	5/13/2008	Near Newberry	12
I-26 Eastbound	Spartanburg	Surface A	10/19/2009	Near Spartanburg	12
I-95 Northbound	Clarendon	Surface A	11/9/2009	Near Manning	11
I-95 Southbound	Clarendon	Surface A	6/9/2010	Near Manning	16
I-20 Eastbound	Aiken	Surface A	10/25/2010	Near Aiken	7
SC Hwy 64 Westbound	Colleton	Surface B	10/2/2007	Near Walterboro	12
SC Hwy 33 Southbound	Orangeburg	Surface B	5/12/2008	In Orangeburg	12
SC Hwy 9 Northbound	Lancaster	Surface B	9/5/2008	In Lancaster	9
Frink Street	Lexington	Surface B	5/28/2009	In Cayce	14
SC Hwy 601 Southbound	Kershaw	Surface B	7/27/2009	Near Lugoff	16
SC Hwy 29 Northbound	Spartanburg	Surface B	3/15/2010	In Spartanburg	13
I-20 Eastbound	Aiken	Surface B (Int.)	4/12/2010	Near Aiken	5
Alexander Street	Lexington	Surface CM	8/19/2009	In West Columbia	15
Old Barnwell Road	Lexington	Surface CM	11/5/2009	In Cayce	12
SC Hwy 178	Orangeburg	Surface CM	4/21/2011	In Bowman	16
Queen Chapel Road	Sumter	Surface C	8/19/2009	Near Sumter	11
Belfast Road	Newberry	Surface C	11/6/2009	Near Newberry	15
Calhoun Road	Calhoun	Surface C	3/23/2010	Near St. Matthews	9
Hood Road	Fairfield	Surface C (WM)	7/6/2010	Near Ridgeway	8
S-43-1428	Sumter	Surface C	9/16/2010	In Sumter	15
Springvale Road	Kershaw	Surface C	4/4/2011	Near Lugoff	14
North Brailsford Road	Kershaw	Surface C (WM)	5/3/2011	Near Camden	8
I-77 Northbound (Right Lane)	Richland	OGFC	10/2/2007	In Richland	18
I-26 Eastbound (Left Lane)	Spartanburg	OGFC	4/28/2010	Near Spartanburg	13
I-26 Eastbound (Right Lane)	Berkley	OGFC	7/8/2010	In Summerville	14
I-185 Northbound (Left Lane)	Greenville	OGFC	8/24/2010	Near Greenville	15
I-77 Northbound (Right Lane)	Richland	OGFC	11/1/2010	In Columbia	22
I-20 Eastbound (Right Shoulder)	Aiken	OGFC	4/11/2011	Near Aiken	15
I-20 Eastbound (Right Lane)	Aiken	OGFC	4/20/2011	Near Aiken	19
Robertson Boulevard	Colleton	Intermediate B	3/9/2011	In Walterboro	8
Robertson Boulevard	Colleton	Intermediate B	3/11/2011	In Walterboro	22
John Smith Road	Jasper	Intermediate C	3/9/2011	In Hardeeville	18

Appendix F: Thermal Segregation Test Segment Information Sheet

File #: __________ Highway ID: __________ Date: __________

Project Location Description:

Paver: __________

MTD: __________

Contr. __________

Pavement Type: __________

Job Mix Number: __________

General Weather Description: __________

Ambient Air Temperature: __________

Travel Time From Plant: __________

Compaction Information - __________

Pay For Lot: __________

Plant Report: __________

Core Information: __________

Appendix G: Thermal Segregation Data Tabulation

	Picture #	Max. Temp. (°F)	Min. Temp. (°F)	Avg. Temp. (°F)	Max. - Min.	Months to Det.	Months to TDD	Months Monitored
Surface A on I-26 in Newberry County	1	279.5	236.6	267.9	42.9	NA	NA	42
	2	285.1	224.4	267.8	60.7	NA	NA	42
	3	279.2	177.3	262.4	101.9	NA	NA	42
	4	318.8	201.9	262	116.9	NA	NA	42
	5	287.7	244.7	264.8	43	NA	NA	42
	6	297.8	224.2	271.1	73.6	6	NA	42
	7	287.3	254.5	269.8	32.8	NA	NA	42
	8	300.7	175.4	233.4	125.3	NA	NA	42
	9	289.5	262.4	215	27.1	NA	NA	42
	10	300.7	246.5	281.9	54.2	NA	NA	42
	11	318.7	207.4	256.9	111.3	30	NA	42
	12	310.2	218.7	284.5	91.5	30	NA	42
Surface A on I-26 in Spartanburg County	1	276	139.4	201.4	136.6	NA	NA	24
	2	269.5	203.3	229.7	66.2	NA	NA	24
	3	241.3	172.2	229.1	69.1	NA	NA	24
	4	274.7	237.2	261	37.5	NA	NA	24
	5	265.3	214.1	238.4	51.2	NA	NA	24
	6	280	190.5	239.6	89.5	NA	NA	24
	7	272.8	212.8	241.2	60	NA	NA	24
	8	262.8	213.1	243.4	49.7	NA	NA	24
	9	274.2	163.4	258	110.8	NA	NA	24
	10	282.1	214.7	258.1	67.4	NA	NA	24
	11	278.6	221	261.3	57.6	NA	NA	24
	12	285.9	207.8	261.1	78.1	NA	NA	24
Surface A on I-95 in Clarendon County	1	302.8	226.8	280.1	76	NA	NA	24
	2	296.3	265.8	279	30.5	NA	NA	24
	3	305.7	271	286.5	34.7	NA	NA	24
	4	317.7	283.7	303.8	34	NA	NA	24
	5	289.3	247.4	275.6	41.9	NA	NA	24
	6	277.7	245.6	264.6	32.1	NA	NA	24
	7	279.5	254.3	265.4	25.2	NA	NA	24
	8	281.2	240	268.6	41.2	NA	NA	24
	9	286	164.8	222.5	121.2	NA	NA	24
	10	285.1	251.6	271	33.5	NA	NA	24
	11	295.2	270.2	286.2	25	NA	NA	24
Surface A Placed on I-95 in Clarendon County (Near Manning)	1	325	174.2	239.2	150.8	NA	NA	18
	2	293.3	237	274.2	56.3	NA	NA	18
	3	300.7	229.9	277.3	70.8	NA	NA	18
	4	291.3	203.9	255.1	87.4	NA	NA	18
	5	298.9	231.3	269.3	67.6	NA	NA	18
	6	324.5	217.1	261.9	107.4	NA	NA	18
	7	303.2	243.2	286.1	60	NA	NA	18
	8	311	204.5	291.9	106.5	NA	NA	18
	9	296.2	242	276.9	54.2	NA	NA	18
	10	311.9	247.6	289.6	64.3	NA	NA	18
	11	295.9	238.4	275.8	57.5	NA	NA	18
	12	298.8	226.8	272.2	72	NA	NA	18
	13	300.4	220.2	268.6	80.2	NA	NA	18
	14	302.6	229.3	270.5	73.3	NA	NA	18
	15	301	225.6	276.6	75.4	NA	NA	18
	16	293.3	203.3	264.2	90	NA	NA	18
Surface A on I-20 in Aiken County	1	273.3	239.9	255.2	33.4	NA	NA	12
	2	268.1	198.3	241	69.8	NA	NA	12
	3	284.5	241.8	259.4	42.7	NA	NA	12
	4	275.4	252	266.9	23.4	NA	NA	12
	5	281.3	254.9	271.5	26.4	NA	NA	12
	6	274.6	244.1	257.6	30.5	NA	NA	12
	7	274.1	216.6	251.9	57.5	NA	NA	12

	Picture #	Max. Temp. (°F)	Min. Temp. (°F)	Avg. Temp. (°F)	Max. - Min.	Months to Det.	Months to TDD	Months Monitored
Surface B on SC Hwy 64 Near Walterboro	1	231.5	175.4	215.4	56.1	6	6	48
	2	222.2	159.7	200.7	62.5	6	6	48
	3	226.7	156.6	211.4	70.1	36	NA	48
	4	247.6	224.4	236	23.2	NA	NA	48
	5	253.5	218	236.9	35.5	NA	NA	48
	6	260.7	235.6	250.2	25.1	48	NA	48
	7	265.2	238.3	255.5	26.9	48	NA	48
	8	264.1	235.3	255	28.8	42	NA	48
	9	260.9	198.5	248.3	62.4	6	NA	48
	10	264.5	207.3	251.1	57.2	42	NA	48
	11	276	224.8	257	51.2	36	NA	48
	12	274.9	219.5	258.4	55.4	36	NA	48
Surface B on SC 33 in Orangeburg County	1	255.9	234.8	246	21.1	24	NA	42
	2	256.4	213.7	242.3	42.7	24	NA	42
	3	257.5	238	247.7	19.5	36	NA	42
	4	258.5	235.9	247.3	22.6	24	NA	42
	5	261.2	230.9	243.7	30.3	24	NA	42
	6	249.2	215.2	231.3	34	24	NA	42
	7	245.9	217.5	231.6	28.4	36	NA	42
	8	259.5	235.2	248.5	24.3	36	NA	42
	9	265.9	231	246.1	34.9	36	NA	42
	10	256.1	235.3	245.8	20.8	24	NA	42
	11	254.5	234.9	242.7	19.6	36	NA	42
	12	252.5	221.9	238	30.6	36	NA	42
Surface B on SC 9 in Lancaster County	1	265.8	174.2	239.2	91.6	NA	NA	36
	2	258.5	218.3	241.4	40.2	NA	NA	36
	3	277.7	189.8	266.8	87.9	NA	NA	36
	4	278.5	217.9	250.1	60.6	NA	NA	36
	5	273.2	249.5	261.4	23.7	30	NA	36
	6	285.6	242.7	277	42.9	30	NA	36
	7	278	219.2	258.1	58.8	NA	NA	36
	8	283.4	233.5	259.6	49.9	30	NA	36
	9	272.7	199	251.5	73.7	30	NA	36
Surface B on Frink Street in Lexington County	1	280.3	187.7	260	92.6	NA	NA	30
	2	278.8	212.9	258.5	65.9	18	NA	30
	3	270.7	219.2	251.4	51.5	24	NA	30
	4	269.3	227.9	254.3	41.4	24	NA	30
	5	282.7	215.6	261.5	67.1	24	NA	30
	6	276.2	222.5	253.3	53.7	12	NA	30
	7	289.2	215.3	260.3	73.9	24	NA	30
	8	287.2	244	271.7	43.2	NA	NA	30
	9	275.1	185.6	255	89.5	NA	NA	30
	10	281.1	233.2	268	47.9	NA	NA	30
	11	281.7	198.7	267.1	83	24	NA	30
	12	280.6	246.2	269	34.4	NA	NA	30
	13	277.4	193.4	246.8	84	NA	NA	30
	14	283.6	194.4	272.8	89.2	NA	NA	30
Surface B on Highway 601 in Kershaw County	1	266.4	168.7	230.2	97.7	NA	NA	24
	2	294.1	213.6	258.5	80.5	NA	NA	24
	3	273.2	233.9	257.1	39.3	NA	NA	24
	4	267.3	226.8	241.7	40.5	NA	NA	24
	5	269.9	213.8	241	56.1	NA	NA	24
	6	288.1	227	260.1	61.1	NA	NA	24
	7	281.5	213.4	249.6	68.1	NA	NA	24
	8	282.8	230.5	267.6	52.3	NA	NA	24
	9	275.4	183.7	246	91.7	NA	NA	24
	10	273.6	229.9	254.5	43.7	NA	NA	24
	11	280.7	234.9	260.2	45.8	NA	NA	24
	12	289.3	234.2	258.8	55.1	NA	NA	24
	13	275.5	229.6	257.7	45.9	NA	NA	24
	14	281.5	133.5	262.5	148	NA	NA	24
	15	273.1	230.3	252.4	42.8	NA	NA	24
	16	266.7	229.8	252.3	36.9	NA	NA	24

	Picture #	Max. Temp. (°F)	Min. Temp. (°F)	Avg. Temp. (°F)	Max. - Min.	Months to Det.	Months to TDD	Months Monitored
Surface B on Highway 29 in Spartanburg County	1A	269.4	194.9	253	74.5	12	NA	18
	1B	269.9	222.7	258.2	47.2	NA	NA	18
	2	255.1	222.3	244.6	32.8	NA	NA	18
	3	264.5	231.6	250	32.9	NA	NA	18
	4	267.1	234.4	251.1	32.7	NA	NA	18
	5	277.1	216.7	260.8	60.4	NA	NA	18
	6	275.7	184.6	259	91.1	NA	NA	18
	7	254.6	171.1	235.1	83.5	NA	NA	18
	8	262.3	205.2	237.2	57.1	NA	NA	18
	9	285.3	171.6	216.2	113.7	NA	NA	18
	10	248.8	206	228.9	42.8	NA	NA	18
	11	236.1	172	220.2	64.1	NA	NA	18
	12	247.6	204	231.9	43.6	NA	NA	18
	13A	266.9	184.8	252.1	82.1	NA	NA	18
	13B	265.3	219.7	256.1	45.6	NA	NA	18
Surface B on I-20 in Aiken County	1	262.8	123	213.8	139.8	NA	NA	18
	2	259.2	165	238	94.2	NA	NA	18
	3	254.3	179.3	237.2	75	NA	NA	18
	4	244.2	214	233.8	30.2	NA	NA	18
	5	269.1	204.4	225	64.7	NA	NA	18
Surface CM on Alexander Street in Lexington County	1	296	214.1	274.7	81.9	NA	NA	24
	2	296.3	226.9	269.1	69.4	NA	NA	24
	3	296.4	221.6	282.7	74.8	NA	NA	24
	4	279.1	182.6	258.3	96.5	NA	NA	24
	5	284.5	190.2	266.9	94.3	NA	NA	24
	6	287	213.1	265	73.9	NA	NA	24
	7	290.1	240.3	274.9	49.8	NA	NA	24
	8	292.2	223	272.5	69.2	NA	NA	24
	9	294.9	220.1	270	74.8	NA	NA	24
	10	296.7	236.7	273.5	60	NA	NA	24
	11	294.8	214.7	272.4	80.1	NA	NA	24
	12	302.3	288.8	249.2	13.5	NA	NA	24
	13	302	180.8	256.5	121.2	NA	NA	24
	14	297.9	195.8	275.3	102.1	NA	NA	24
	15	289.6	230.5	270.5	59.1	NA	NA	24
Surface CM on Old Barnwell Road in Lexington County	1	279.7	193.7	236.1	86	NA	NA	24
	2	257.2	163.8	228.7	93.4	NA	NA	24
	3	270.9	172.5	231.9	98.4	NA	NA	24
	4A	264.8	169.8	233.9	95	NA	NA	24
	4B	256.4	159.9	216.4	96.5	NA	NA	24
	5	274.2	212.6	246.5	61.6	NA	NA	24
	6	270.4	168.4	234.8	102	NA	NA	24
	7	257.9	117.4	198.6	140.5	NA	NA	24
	8	262.1	168.3	226.1	93.8	NA	NA	24
	9	270.2	175	240.6	95.2	NA	NA	24
	10	269.4	170.4	244.5	99	NA	NA	24
	11	258.8	133.5	217.4	125.3	NA	NA	24
	12	274	174.7	242.9	99.3	NA	NA	24

	Picture #	Max. Temp. (°F)	Min. Temp. (°F)	Avg. Temp. (°F)	Max. - Min.	Months to Det.	Months to TDD	Months Monitored
Surface CM Placed on Hwy 178 in Bowman in Orangeburg County	1	279.5	189.3	250.2	90.2	NA	NA	6
	2	271.9	169.6	224.8	102.3	NA	NA	6
	3	271.6	159.1	219.3	112.5	6	NA	6
	4	270.5	178.2	240.2	92.3	NA	NA	6
	5	283.6	231.2	268.1	52.4	NA	NA	6
	6	259.3	190.1	233.1	69.2	NA	NA	6
	7A	268.7	184.9	228.8	83.8	6	NA	6
	7B	267.4	190.3	225.1	77.1	6	NA	6
	8	279.5	199.2	258.9	80.3	NA	NA	6
	9	274.5	190.8	247.6	83.7	NA	NA	6
	10	235.4	142.2	191.1	93.2	NA	NA	6
	11A	254.1	162	231	92.1	NA	NA	6
	11B	261.2	153.4	219.4	107.8	NA	NA	6
	12	266.3	192.2	242.9	74.1	NA	NA	6
	13A	267.3	160.5	234.1	106.8	NA	NA	6
	13B	266.5	163.1	226.5	103.4	NA	NA	6
	14	287.3	219	266.2	68.3	NA	NA	6
	15	263.2	177.9	237.8	85.3	NA	NA	6
	16A	266.5	124.3	221.5	142.2	NA	NA	6
	16B	266.6	163.2	216.4	103.4	NA	NA	6
Surface C on Queen Chapel Road in Sumter County	1	281.6	164.2	260	117.4	24	NA	24
	2	285.4	182.1	261.8	103.3	6	NA	24
	3	284	183.4	258	100.6	6	NA	24
	4	268.3	218.2	251.9	50.1	6	NA	24
	5	267.5	138.5	244.4	129	6	NA	24
	6	277.6	165.6	247.4	112	6	NA	24
	7	268.5	149	247.6	119.5	6	NA	24
	8	276.2	201.3	261.4	74.9	6	NA	24
	9	276.6	161.4	246.6	115.2	6	NA	24
	10	275.9	207.6	253.4	68.3	6	NA	24
	11	281	198.1	255.6	82.9	NA	NA	24
Surface C on Belfast Road in Newberry County	1	267.6	191.5	236.7	76.1	NA	NA	24
	2	274.5	153.4	249.4	121.1	NA	NA	24
	3	263.9	190.3	241.1	73.6	NA	NA	24
	4	293.7	174.2	262.2	119.5	NA	NA	24
	5	288.9	199.6	258.3	89.3	NA	NA	24
	6	261.7	200.3	239.4	61.4	NA	NA	24
	7	271.8	198.7	244.4	73.1	NA	NA	24
	8	287.2	195.4	270.4	91.8	NA	NA	24
	9	294.3	210.6	265.9	83.7	NA	NA	24
	10	283.9	201.8	257.8	82.1	NA	NA	24
	11	284.6	230.2	261.3	54.4	NA	NA	24
	12	287.7	214.5	263.4	73.2	NA	NA	24
	13	282	211.3	248.2	70.7	NA	NA	24
	14	276.4	190.9	247.8	85.5	NA	NA	24
	15	282.9	201.3	267.6	81.6	NA	NA	24
Surface C on Calhoun Road in Calhoun County	1	248.6	152.3	202.5	96.3	NA	NA	18
	2	258	200.4	240.5	57.6	NA	NA	18
	3	249.2	206.4	234	42.8	NA	NA	18
	4	249.4	167	211.8	82.4	NA	NA	18
	5	260.4	215.4	240.2	45	NA	NA	18
	6	260.2	212.4	243	47.8	NA	NA	18
	7	262.3	225.1	245.8	37.2	NA	NA	18
	8	278.7	241.3	261.6	37.4	NA	NA	18
	9	269.1	202.5	251.8	66.6	NA	NA	18

	Picture #	Max. Temp. (°F)	Min. Temp. (°F)	Avg. Temp. (°F)	Max. - Min.	Months to Det.	Months to TDD	Months Monitored
Warm Mix Surface C on Hood Road in Fairfield County	1	245.9	159.6	227.1	86.3	NA	NA	12
	2	232.3	168.3	210.9	64	NA	NA	12
	3	232.3	173.3	207.5	59	NA	NA	12
	4	249.4	168.7	227.7	80.7	NA	NA	12
	5	251.3	175.9	227.5	75.4	NA	NA	12
	6	254.4	200.9	228.5	53.5	6	NA	12
	7	256.7	228.1	246.6	28.6	6	NA	12
	8	253.1	196.5	237.2	56.6	NA	NA	12
Surface C on Road S-43-1428 in the City of Sumter in Sumter County	1	231.7	147.8	184.5	83.9	NA	NA	12
	2A	272.1	162.3	201.6	109.8	NA	NA	12
	2B	263.1	184.6	215	78.5	NA	NA	12
	3	282.6	202.6	262.1	80	NA	NA	12
	4	283.2	150.4	222.5	132.8	NA	NA	12
	5	272.7	138.4	224.9	134.3	NA	NA	12
	6	281.2	201.3	251.8	79.9	NA	NA	12
	7	280.5	159.5	242.3	121	NA	NA	12
	8A	264.3	158.9	215.8	105.4	NA	NA	12
	8B	257.8	161.3	213.2	96.5	NA	NA	12
	8C	257.9	174.9	214.8	83	NA	NA	12
	9	281.7	143.1	213	138.6	NA	NA	12
	10	354.8	159.1	250.1	195.7	NA	NA	12
	11	275.1	158.7	214.1	116.4	NA	NA	12
	12	257.9	211.4	171.6	46.5	NA	NA	12
	13	261.3	167.1	213	94.2	NA	NA	12
	14	259.8	161.6	214.1	98.2	NA	NA	12
	15	264.6	187.8	235	76.8	6	NA	12
Surface C on Springvale Road in Kershaw County	1	254	187.6	244.8	66.4	NA	NA	6
	2	255.8	232.9	242.3	22.9	NA	NA	6
	3	252	231.8	243.9	20.2	NA	NA	6
	4	249.7	196.8	234.7	52.9	NA	NA	6
	5	263.6	203	247.7	60.6	NA	NA	6
	6	268.3	219	249.8	49.3	NA	NA	6
	7	260.2	225.1	250.1	35.1	NA	NA	6
	8	295.9	240.1	263.6	55.8	NA	NA	6
	9	273.4	250.7	262.8	22.7	NA	NA	6
	10	333.3	103.3	180	230	6	NA	6
	11	263.6	201.9	246.5	61.7	6	NA	6
	12	274.3	240.7	260	33.6	6	NA	6
	13	272	236.8	256.2	35.2	6	NA	6
	14	245.3	154.8	200.8	90.5	6	NA	6
Surface C (Warm Mix)Placed on North Brailsford Road in Kershaw County	1	255.6	172.7	230.9	82.9	NA	NA	6
	2	255.4	152.9	197.1	102.5	NA	NA	6
	3	241.9	158.5	212.5	83.4	NA	NA	6
	4	277.9	200.4	244.2	77.5	NA	NA	6
	5	264.3	200.3	244.8	64	NA	NA	6
	6	270.5	157.7	253	112.8	NA	NA	6
	7	269.6	176	232.5	93.6	NA	NA	6
	8	261.6	140.4	222.9	121.2	NA	NA	6

	Picture #	Max. Temp. (°F)	Min. Temp. (°F)	Avg. Temp. (°F)	Max. - Min.	Months to Det.	Months to TDD	Months Monitored
OGFC on I-77 in Richland County	1	309.6	160.7	273.5	148.9	6	6	48
	2	298.6	210.5	266.6	88.1	6	6	48
	3	310.8	233.2	288.2	77.6	6	6	48
	4	301	204.6	289.5	96.4	6	6	48
	5	292	201.7	257.4	90.3	6	6	48
	6	292.7	202.9	267.6	89.8	6	6	48
	7	295	171.9	268.9	123.1	36	NA	48
	8	283.4	164.5	253.2	118.9	42	NA	48
	9	294.3	218.9	267.8	75.4	18	NA	48
	10	306.9	253.4	290.6	53.5	NA	NA	48
	11	221.6	185.1	204.5	36.5	6	NA	48
	12	304.2	185.2	244.3	119	6	NA	48
	13	298.5	214.7	271.6	83.8	NA	NA	48
	14	291.1	212.2	262.4	78.9	NA	NA	48
	15	288.8	149	215.9	139.8	42	NA	48
	16	290	209	268.7	81	42	NA	48
	17	287.9	227.3	266.8	60.6	NA	NA	48
	18	292.1	119.7	222.5	172.4	6	6	48
OGFC on I-26 in Spartanburg County (Near NC Line)	1	292.7	241.1	269.1	51.6	NA	NA	18
	2	277.3	232.8	264.8	44.5	NA	NA	18
	3	280.4	220.8	261.8	59.6	NA	NA	18
	4	274.3	233.4	254	40.9	NA	NA	18
	5	295	219.6	269.7	75.4	NA	NA	18
	6	291	241.7	271.5	49.3	NA	NA	18
	7	284.8	208.6	270	76.2	NA	NA	18
	8	290.7	207.9	273.5	82.8	NA	NA	18
	9	275.9	237.6	260.9	38.3	NA	NA	18
	10	279.5	249.3	267	30.2	NA	NA	18
	11	278.5	243.6	265.4	34.9	NA	NA	18
	12	291.6	202.4	268.6	89.2	NA	NA	18
	13	286.5	241.3	269.2	45.2	NA	NA	18
OGFC on I-26 in Berkley County	1A	265.7	171.5	221.6	94.2	NA	NA	12
	1B	241.3	163.1	205.4	78.2	NA	NA	12
	2	278.1	213.2	249.4	64.9	NA	NA	12
	3	265.9	227.1	244.4	38.8	NA	NA	12
	4	288.6	217.8	267.5	70.8	NA	NA	12
	5	297.7	250.8	275.8	46.9	NA	NA	12
	6	303.5	244.4	284.4	59.1	NA	NA	12
	7	277.3	225.3	254.3	52	NA	NA	12
	8	296.7	253.4	279.9	43.3	NA	NA	12
	9	288.4	225.6	263.1	62.8	NA	NA	12
	10	288.7	266.7	235.7	22	NA	NA	12
	11	287.9	247.5	269.9	40.4	NA	NA	12
	12	282.1	226.9	263.9	55.2	NA	NA	12
	13	308.7	239.1	270.3	69.6	NA	NA	12
	14A	308.6	189.2	239.5	119.4	NA	NA	12
	14B	306.9	178.9	250.9	128	NA	NA	12
OGFC on I-185 in Greenville County	1	299.9	153.7	218.4	146.2	NA	NA	12
	2	292.3	189.2	249.5	103.1	NA	NA	12
	3	280.9	204.1	248.6	76.8	NA	NA	12
	4	289.3	186.5	265.2	102.8	NA	NA	12
	5	300.1	245.9	275.9	54.2	NA	NA	12
	6	301.9	233.9	268.6	68	NA	NA	12
	7	290.4	246.4	271	44	NA	NA	12
	8	294.1	245.9	282.4	48.2	NA	NA	12
	9	295.2	211.5	273.2	83.7	NA	NA	12
	10	298.9	247.6	277.5	51.3	NA	NA	12
	11	308.1	270.8	290.8	37.3	NA	NA	12
	12	314.8	286.9	302.5	27.9	NA	NA	12
	13	300.4	260.6	291.9	39.8	NA	NA	12
	14	303.2	283.6	294.2	19.6	NA	NA	12
	15	303.7	282.7	293.7	21	NA	NA	12

	Picture #	Max. Temp. (°F)	Min. Temp. (°F)	Avg. Temp. (°F)	Max. - Min.	Months to Det.	Months to TDD	Months Monitored
OGFC on I-77 in Richladn County	1	286	206.5	254.6	79.5	NA	NA	12
	2	311.3	268.5	289.5	42.8	NA	NA	12
	3A	274.4	152.7	210.4	121.7	NA	NA	12
	3B	275.3	149.3	208.4	126	NA	NA	12
	4	283.3	225.4	263.3	57.9	NA	NA	12
	5	288.1	225.9	267.2	62.2	NA	NA	12
	6	307.1	238.9	279.5	68.2	NA	NA	12
	7	321.9	194.1	296.8	127.8	NA	NA	12
	8A	270.8	166	196.7	104.8	NA	NA	12
	8B	272.7	147.1	209.5	125.6	NA	NA	12
	9	272.3	197.5	242.5	74.8	NA	NA	12
	10	295.5	209.7	260.8	85.8	NA	NA	12
	11	313.6	246.5	291.9	67.1	NA	NA	12
	12	303.2	248.2	285.3	55	NA	NA	12
	13	291.9	173.4	220.5	118.5	NA	NA	12
	14	287.6	223.3	266.1	64.3	NA	NA	12
	15	299.5	241.9	271	57.6	NA	NA	12
	16	310.3	247.8	283.1	62.5	NA	NA	12
	17	305.1	263.4	282.9	41.7	NA	NA	12
	18	299.5	250	281.4	49.5	NA	NA	12
	19	318.9	192.1	296.4	126.8	NA	NA	12
	20	304.9	189.9	277.7	115	NA	NA	12
	21	280.3	206.2	247.7	74.1	NA	NA	12
	22	292.9	241.4	275.7	51.5	NA	NA	12
OGFC on I-20 Eastbound (Right Shoulder) in Aiken County	1A	240.2	150	215.1	90.2	NA	NA	6
	1B	238.9	160.2	212.9	78.7	NA	NA	6
	2	260.6	137.2	241.4	123.4	NA	NA	6
	3	279.9	242.7	261.1	37.2	NA	NA	6
	4	295.9	158.5	279.7	137.4	NA	NA	6
	5	277	183.9	248.4	93.1	NA	NA	6
	6	271.4	162.5	231.6	108.9	NA	NA	6
	7	275.6	200.9	242.3	74.7	NA	NA	6
	8	264.7	177.8	238.7	86.9	NA	NA	6
	9	267.3	194.8	241.3	72.5	NA	NA	6
	10	288.8	228.1	265.8	60.7	NA	NA	6
	11	304.7	173.8	253.3	130.9	NA	NA	6
	12	271.8	240.3	255.1	31.5	NA	NA	6
	13	283.8	249.6	265.7	34.2	NA	NA	6
	14	301.1	215.2	290.5	85.9	NA	NA	6
	15	289.6	259.1	277.5	30.5	NA	NA	6
Open Graded Friction Course Placed on I-20 in Aiken County	1	279.3	237.2	264.2	42.1	NA	NA	6
	2	272.3	232.8	259.7	39.5	NA	NA	6
	3	272.8	229.7	249.9	43.1	NA	NA	6
	4	274.2	228.6	254.8	45.6	NA	NA	6
	5	215.4	99.4	161.7	116	NA	NA	6
	6	243.3	108.6	201.7	134.7	NA	NA	6
	7	264.1	218.3	244.6	45.8	NA	NA	6
	8	270.2	214	252.9	56.2	NA	NA	6
	9	281.7	188.7	262.7	93	NA	NA	6
	10	247.2	113.5	168.4	133.7	NA	NA	6
	11	253.3	186.5	232.2	66.8	NA	NA	6
	12	274.7	173.4	255.8	101.3	NA	NA	6
	13	271.2	232.7	259.3	38.5	NA	NA	6
	14	266.8	220.1	249.5	46.7	NA	NA	6
	15	266.6	234	250.4	32.6	NA	NA	6
	16	283.8	185.1	260.7	98.7	NA	NA	6
	17	266.1	173.4	240.2	92.7	NA	NA	6
	18	259.4	149	189.5	110.4	NA	NA	6
	19	265.9	213.9	244.2	52	NA	NA	6

	Picture #	Max. Temp. (°F)	Min. Temp. (°F)	Avg. Temp. (°F)	Max. - Min.	Months to Det.	Months to TDD	Months Monitored
Intermediate B on Robertson Boulevard in Colleton County	1A	232	111.4	167.6	120.6	NA	NA	6
	1B	218.6	105.5	154.9	113.1	NA	NA	6
	2	205.3	110.4	158.3	94.9	NA	NA	6
	3	234.9	154.8	195.6	80.1	NA	NA	6
	4	263.1	198.7	244.4	64.4	NA	NA	6
	5	271.6	176.6	230.8	95	NA	NA	6
	6	255	134.7	190.8	120.3	NA	NA	6
	7	252.1	194.1	240.8	58	NA	NA	6
	8	260.6	200.9	238.3	59.7	NA	NA	6
Intermediate B on Robertson Boulevard in Colleton County	1	273.9	221.1	246.7	52.8	NA	NA	6
	2	267.1	218.4	258	48.7	NA	NA	6
	3	261.4	219.9	242.6	41.5	NA	NA	6
	4	266.8	244	258.1	22.8	NA	NA	6
	5	271	174.2	226.7	96.8	NA	NA	6
	6	265.7	215	236.4	50.7	NA	NA	6
	7	273.2	207.6	239.8	65.6	NA	NA	6
	8	274	181.4	248.8	92.6	NA	NA	6
	9	264.6	166.6	228.2	98	NA	NA	6
	10	273.1	213.7	238.2	59.4	NA	NA	6
	11	280.2	233	258.4	47.2	NA	NA	6
	12	263.3	223.8	246.7	39.5	NA	NA	6
	13	309.3	225.6	247.8	83.7	NA	NA	6
	14	249.7	197.3	227.2	52.4	NA	NA	6
	15	272.7	150.7	242.3	122	NA	NA	6
	16	263.9	162.2	243.9	101.7	NA	NA	6
	17	250	177.5	222.1	72.5	NA	NA	6
	18	252.4	172.3	224.9	80.1	NA	NA	6
	19	251.3	158.7	218.4	92.6	NA	NA	6
	20	244.2	145.2	227.9	99	NA	NA	6
	21	311	216.2	239.9	94.8	NA	NA	6
	22	283.4	227.9	248.3	55.5	NA	NA	6
Intermediate C on John Smith Road in Jasper County	1A	273.3	215.5	250.4	57.8	NA	NA	6
	1B	263.4	191.7	238.2	71.7	NA	NA	6
	2	277	215.4	248.2	61.6	NA	NA	6
	3	289.3	220.2	264	69.1	NA	NA	6
	4	280	197	253.3	83	NA	NA	6
	5	290.6	245.8	277.5	44.8	NA	NA	6
	6	281.3	215.2	260.8	66.1	NA	NA	6
	7	290.8	236.8	277.1	54	NA	NA	6
	8	279.6	219	260.1	60.6	NA	NA	6
	9A	280.2	209.7	259.3	70.5	NA	NA	6
	9B	278.8	193.4	248.7	85.4	NA	NA	6
	10	283.1	201.8	265	81.3	NA	NA	6
	11	277.2	228.2	257.5	49	NA	NA	6
	12	275	193.6	247	81.4	NA	NA	6
	13	275.3	199	247	76.3	NA	NA	6
	14	265.8	186.6	237.5	79.2	NA	NA	6
	15	268.4	195.9	249.1	72.5	NA	NA	6
	16	267.5	195.5	250.7	72	NA	NA	6
	17	278.2	216.7	253.3	61.5	NA	NA	6
	18	287.9	209.4	261.9	78.5	NA	NA	6

Appendix H: OGFC Construction Joint Temperature Differential Damage Progression Pictures

OGFC Construction Joint Cold Area After Six Months

OGFC Construction Joint Cold Area After 12 Months

OGFC Construction Joint Cold Area After 18 Months

OGFC Construction Joint Cold Area After 24 Months

OGFC Construction Joint Cold Area After 36 Months

OGFC Construction Joint Cold Area After 42 Months

OGFC Construction Joint Cold Area After 48 Months

Appendix I: OGFC Bridge Departure Temperature Differential Damage Pictures

OGFC Bridge Departure Cold Area After 18 months.

OGFC Bridge Departure Cold Area After 36 Months

OGFG Bridge Departure Cold Area After 42 Months

OGFC Bridge Departure Cold Area After 48 Months