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Laboratory and Field Investigation of Temperature Differential in HMA Mixtures Using an Infrared Camera

FINAL REPORT

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DISCLAIMER

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CHAPTER I: INTRODUCTION

Segregation, in general, of hot mix asphalt (HMA) has been one of the most common and costly problems in the highway industry for many years. Several years of research have been spent to determine the causes and effects of segregation in HMA, but the problem still lingers in many pavements.

An ideal HMA pavement has a uniform combination of coarse aggregate, fine aggregate, and binder. However, if this uniform mixture becomes segregated, the graded aggregates are separated and there becomes a concentration of coarse aggregate in some areas of the pavement, and a concentration of fine aggregate in other areas. If left untreated, segregation in a pavement may lead to other problems such as low density, raveling, potholes, and ultimately, the accelerated failure of the pavement.

Segregation can occur for many reasons and at several locations in the construction process. Any time HMA is manipulated, moved or transferred in anyway, the risk of segregation is present. Some of the most common causes of segregation during construction are improper truck loading, improper truck dumping, and poor paver operation. One of the most important concepts concerning segregation that has surfaced in recent years is that of temperature segregation.

Temperature segregation, also called temperature differential damage (TDD), was first proposed by a graduate student at the University of Washington in the late 1990s (1). While studying cyclic segregation (or end load segregation) of HMA, he concluded that it was actually a problem related to varying temperature of the HMA within the transport trucks. The theory was that within a haul truck, the HMA material closest to the exterior walls of the truck's bed cooled off very rapidly during transport. The material towards the center and in the interior of the HMA mass tended to maintain a higher temperature. When the total mass of mix was dumped into a paver, the cool material near the exterior walls generally fell to the extreme left and right sides of the paver hopper in the hopper wings. As the hopper was emptied, the material in the wings was usually the last to exit the hopper. The result was that a large mass of cool material was introduced into the new pavement. The material had become more difficult to compact and did not consolidate as well behind the paver screed, thus leaving a very open textured, low-density pavement (1).

Though a pavement which has exhibited traditional material segregation may also have had TDD, the opposite is not always the case. TDD has occurred where there has been no visual sign of material segregation. During the University of Washington’s study, samples that were taken from pavements, exhibiting temperature segregation, did not always demonstrate significant gradation variations from the uniform areas (1). However, the non-uniform (segregated) areas demonstrated higher air voids and lower density than was acceptable. Furthermore, other studies have shown that temperature segregated areas were not always visually apparent during construction, and may appear several months after construction has been completed (2). Since temperature segregation does not always exhibit the traditional concentration of coarse and fine materials, and is not always easily noticeable, traditional means of locating and having the problem fixed may not work.

Because of these problems, it was necessary to find a tool that would identify temperature segregation immediately during the construction process, so that the problem could be rectified. One of the tools that have been recognized to be effective in identifying temperature segregation is an infrared camera. By using an infrared camera, pictures of HMA can be taken throughout the construction process, including the HMA at load out, in the truck during transport, in the truck prior to dumping, in the paver hopper, behind the screed prior to compaction, and during compaction. The use of an infrared camera could identify areas of differential temperature during the construction process, and identify which processes work best to avoid or rectify temperature segregation.

This research study was divided into two phases. In the first phase, an extensive literature review was conducted to identify causes and cures of traditional segregation as well as what was known about temperature segregation. Also, at this time, infrared cameras were investigated to determine which type should be used for this particular application. The second phase of the study included an in-depth field study of temperature segregation as well as its causes and potential cures.

By studying temperature variability and segregation, common HMA production and construction practices could be modified so as to avoid or minimize this problem. The South Carolina Department of Transportation (SCDOT) should benefit from this study by using the information gathered to either modify current specifications, if necessary, or develop a manual of best practices to prevent TDD. This could potentially result in major cost savings due to an improvement in the quality of HMA pavements (e.g., more consistent physical characteristics, longer service life, lower maintenance costs, and increased safety to the traveling public).

The data for this study was primarily gathered from field observations and testing. Some testing, such as nuclear density testing, was performed in the field, while testing of core samples was performed in the lab for several projects. This report should be used as a guide by the SCDOT and contractors in addition to an informational tool for solving temperature variability and segregation problems. As pavements from this study are observed long term, the report should be updated as new information presents itself.

Objectives of the Study

The major objective of this study was to investigate variation in asphalt mix temperatures using an infrared camera at various locations in the paving process and its effects on pavement segregation and physical properties. The specific objectives of the proposed study included the following:

1. Conducting an extensive literature review to determine causes and cures of traditional and temperature segregation.

2. Reviewing various models of infrared cameras to determine which performance characteristics are necessary for temperature variability studies.

3. Observing various HMA construction operations throughout the state of South Carolina in a randomized fashion for temperature variability and segregation. The following mixtures paved by various contractors were to be monitored:

    a. Surface Type 1 (4 Contractors)
    b. Surface Type 3 (4 Contractors)
    c. Surface Type 1C (4 Contractors)
    d. Superpave 12.5 mm Surface (4 Contractors)

    Where available, the following pieces of paving equipment, from various manufacturers were evaluated for each of the four mix types:

    a. Traditional Paver with Conveyor Transfer from Hopper
    b. Paver with Auger Transfer from Hopper
    c. Material Transfer Device (MTD)

    Data concerning haul distance and ambient and surface temperatures were also collected.

4. Identifying temperature variability and segregation in the observed pavements and evaluating the uniform and non-uniform areas for the following properties:

    a. Percent Binder Content,
    b. Percent Air Voids,
    c. Percent Voids in Mineral Aggregate,
    d. Percent Voids Filled with Asphalt,
    e. Gradation, and
    f. In-place Nuclear Density.

5. Identifying construction equipment and practices that either increased or decreased the potential for temperature variability and segregation.

6. Identifying SCDOT mix types that were prone to temperature variability and segregation.

Based on the SCDOT's request, another objective was added after the completion of the previous objectives.

7. Observing several projects of various mix types and document all cold spots on paving projects and record their GPS location. The following mixes were observed:

    a. Surface Type 1C
    b. 12.5 mm Superpave
    c. 19.0 mm Superpave
    d. Open-Graded Friction Course (OGFC)
    e. Base course
    f. Binder course

    In addition, the SCDOT requested that the following pieces of paving equipment, if available, be evaluated for each of the four mix types (surface, binder, base, and OGFC):

    a. Traditional Paver with Conveyor Transfer from Hopper
    b. Paver with Auger Transfer from Hopper
    c. Material Transfer Device (MTD)

After observing several projects, the SCDOT also requested to eliminate Objective 4 of the proposal due to many reasons (e.g., too many cores needed to obtain a statistically valid data set for each project, etc.). During the course of this project, every attempt was made to satisfy the objectives of the proposal. However, due to many reasons (e.g., weather, not paving a particular mix that season, etc.), there were a few objectives that could not be satisfied. For example, only a portion of Objective 3 was completed including:

a. Surface Type 3 (1 Contractor)
b. Surface Type 1C (6 Contractors)
c. Superpave 12.5 mm Surface (1 Contractor)

In addition, only the following pieces of paving equipment were evaluated for each of the three mix types:

a. Traditional Paver with Conveyor Transfer from Hopper
b. Material Transfer Device

For each project, the contractor and/or the SCDOT inspector for that job was notified. The photos were taken at various stages of each project (e.g., truck bed, behind paver, after compaction, etc.). Several pieces of information regarding each project were recorded and noted, including: equipment types and models used; mixture type; haul distance; ambient temperature; surface temperature; and the weather condition. An example of the data collection sheet used is shown in Figure 1.

After gathering all of the information, all appropriate data was analyzed using the SAS statistical analysis software package (3). Conclusions and recommendations were made based on these findings and are included in this report.

Temperature Differential Damage Data Collection Sheet							
Inspector			Date			Time	
Location				Weather Conds.			
Equipment Selection							
Asphalt Plant:							
Asphalt Spreader:		Cedar Rapids		Mat.Trans. Device:		No	
Compaction Equipment:		1			3		
		2			4		
Construction Technique							
Comments:							
Asphalt Spreader Observation Locations							
Observation	1	2	3	4	5	6	7
Location							
Observation	8	9	10	11	12	13	14
Location							
Haul Truck Observation							
Observation	1	2	3	4	5	6	7
Haul Time (M)							
Observation	8	9	10	11	12	13	14
Haul Time (M)							
Cold Spot Observations							
Observation	1	2	3	4	5	6	7
Density							
Observation	8	9	10	11	12	13	14
Density							
Observation	15	16	17	18	19	20	21
Density							
Contractor Cores							
Observation	1	2	3	4	5	6	7
Density							
Observations	8	9	10	11	12	13	14
Density							
Random Cross Section of Pavement							
Observation	1	2	3	4	5	6	7
Location							
Observation	8	9	10	11	12	13	14
Location							

Figure 1: Sample data collection sheet.

CHAPTER II: LITERATURE REVIEW – TEMPERATURE SEGREGATION

Temperature segregation, also known as temperature differential damage (TDD), also known as thermal segregation, has been identified as a significant construction related problem since the mid 1980s, and is more common than originally projected (1, 4, 5). In this chapter, the following topics will be covered:

- Definition and Formation of TDD,
- TDD Identification and Measurement,
- Asphalt Pavement Performance Impact,
- TDD Prevention and Cures, and
- Summary of TDD.

Definition and Formation of TDD

Temperature differential damage is a form of segregation that occurs during the construction of hot mix asphalt (HMA) pavement. This type of segregation is the product of placing significantly cooler amounts of HMA into the pavement mat. These materials, when placed in the pavement, can range in size and shape, and can significantly vary in temperature (1, 4, 5). This varying range in temperature, when compounded by a slow compaction effort, can result in portions of the pavement not reaching the target density.

The cooler HMA placed into the pavement mat is the result of a cooler crust that forms on the top of the loose asphalt mix during transport from the plant to the job site. This cooler crust insulates the interior HMA from losing heat uniformly, and grows in thickness proportional to the time that is involved during transport. When the HMA is loaded into the paver, both the hot and cool materials are remixed together. The time the HMA spends in the paver is insufficient to effectively remix both the cooler asphalt and the hot asphalt to a uniform temperature throughout the truckload (1). Figure 2 highlights the cooler crust and the hot asphalt mixture.

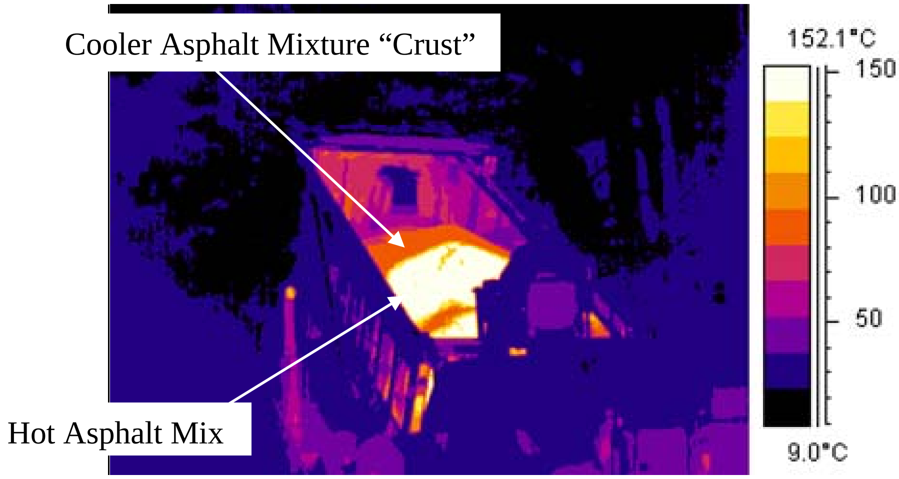


Figure 2: Temperature variations in haul truck.

TDD Identification and Measurement

In most cases, TDD can be difficult to identify. The areas in a pavement that are most prone to TDD are at the switch of haul trucks or "end of load segregation" (Figure 3). This type of segregation can either be the result of TDD or aggregate segregation. This makes distinguishing between aggregate segregation and TDD difficult, because both types of segregation affect the pavement's air void content, density, and surface mat texture (1, 4, 5).

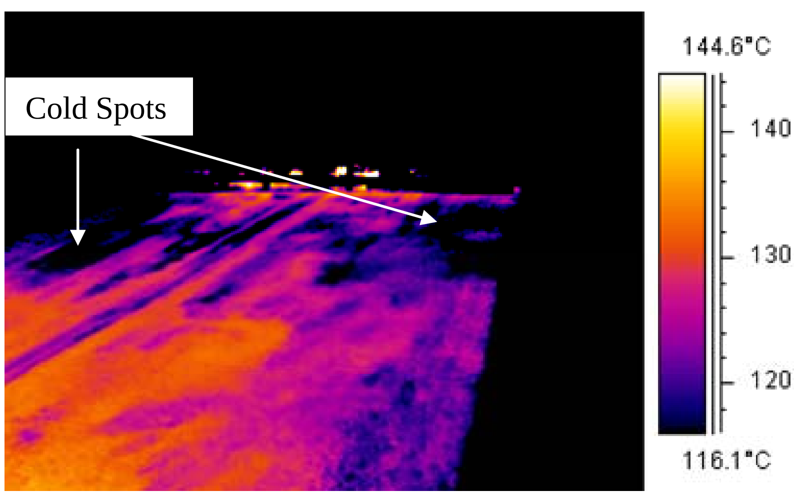


Figure 3: End of load temperature segregation.

One of the most successful ways to determine if TDD is occurring in a pavement is to observe the fresh laid HMA before compaction begins. Brock and Jakob placed thermometers across the width of the pavement to determine if temperature differentials existed (6). The Washington State Department of Transportation (WSDOT) improved on this method with the use of a thermal camera. The thermal camera can take a picture of the fresh laid pavement, which can then be analyzed using computer software to calculate the average mat temperature. From this, portions of the pavement having substantial temperature differentials can be identified (1, 4, 5). The affected portions are usually in the form of small circular spots or long columns that are parallel to the length of the pavement (Figure 3). These forms of temperature differentials are referred to as “cold-spots” and “cold runs”, respectively (1, 5).

Asphalt Pavement Performance Impact

As previously stated, the effects of TDD on a HMA pavement are similar to those caused by segregation, and at this time there have been few studies on this topic which have produced a relationship between TDD and long-term pavement performance. However, some studies and experiences have revealed that TDD can result in a decreased pavement fatigue life. In one such study, WSDOT reported a 50% decrease in pavement fatigue life due to TDD, mainly because of a reduction in the density of the hot mix asphalt pavement (1).

The density that is achieved in the field directly affects the performance of a flexible pavement. When desired compaction is achieved, the result is a pavement that has adequate shear strength to fulfill its service life. The introduction of a temperature differential into the asphalt paving process can either decrease the window for compaction to take place, or in severe cases, compaction might not take place at all. According to one study, the possibility of non-compaction is due to the fact that once an asphalt mixture drops to 174°F, the process of compaction to eliminate air voids is no longer effective. When a portion of the fresh pavement mat has a temperature that is significantly less than the average mat temperature, the time frame for compaction is less than the rest of the pavement mat (1).

The loss in shear strength due to decreased density is not the only characteristic being affected. The decrease in density results in a higher air void content, which results in a pavement that is more susceptible to moisture damage, raveling, rutting, and the overall decrease of durability of an asphalt pavement (1).

Even though there have been only a few studies conducted to determine the long-term effects of TDD, it is possible that TDD does affect the long-term pavement performance. However, many researchers have indicated that TDD produces results similar to that of asphalt pavements that have been exposed to aggregate segregation (e.g., raveling, rutting, moisture damage, potholes, etc.) (7).

TDD Prevention and Cures

TDD is considered a construction related problem due to the fact that heat loss is inevitable during the placement of asphalt concrete in the field (8). This loss of heat, however, can be overcome by construction crews that use good paving practices. In this part of the report a description of how construction crews can reduce the occurrence of TDD resulting from the paving process is discussed.

Haul Time

It is hypothesized that the haul time has a direct relationship with TDD. Therefore, reducing the haul time would be one of the options to minimize or eliminate TDD. One method, which would reduce the haul time, is the appropriate release of haul trucks from the asphalt plant. This would limit the time that the loose asphalt spends in queue at the job site (1, 4, 5). The appropriate release of haul trucks can be determined by using computer simulation or other forms of statistical scheduling where a balance point can be determined.

Asphalt Paver

The reduction of TDD in an asphalt pavement is also possible by operating the asphalt paver appropriately. The paver operations that influence TDD are the paving speed and management of the wings of the hopper. The paving speed of the asphalt paver must be kept constant. Figure 4 shows the difference in temperature across the pavement mat when the asphalt paver is allowed to come to a halt for an extended period of time. This portion of the pavement directly behind the paver is usually not compacted until the asphalt paver restarts the paving operation. This results in a decreased amount of time for the compaction effort. The paver must be kept moving at a constant speed, ensuring that no portion of the pavement is exposed to a reduction in the compaction time (1).

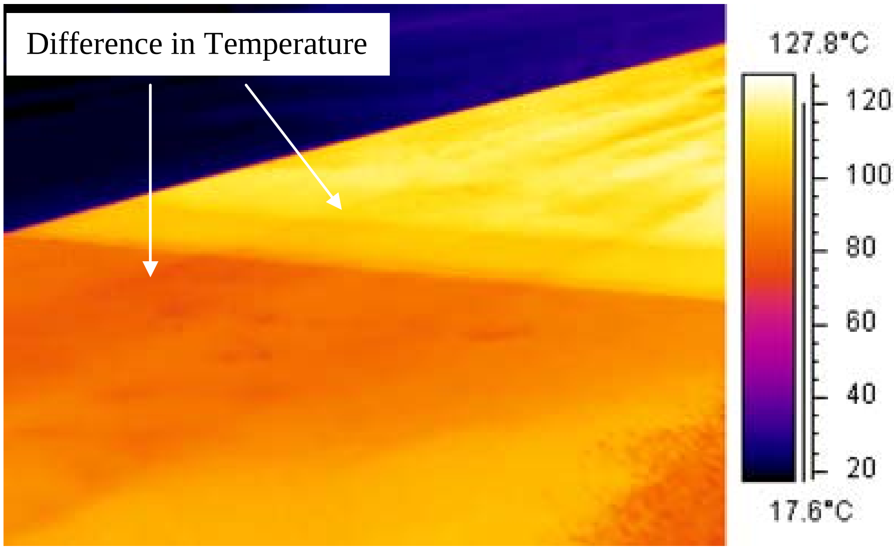


Figure 4: Difference in temperature due to paving delay.

The operation of the paver wings is also critical when trying to reduce the occurrence of TDD in an asphalt pavement mat. When material falls into the wings of the hopper in an asphalt paver, it is exposed to ambient temperature for an extended duration and, therefore, loses additional heat, which can lead to temperature segregation. The heat loss is increased if this material is exposed to the elements for a long time. The practice of dumping the hopper wings should be avoided due to the potential for thermal segregation. However, if the wings must be dumped, then they should only be dumped when there is a sufficient amount of material in the hopper to absorb the cooler wing material into the hotter mix.

Compaction

Diligence in the compaction of the HMA is critical to reducing the effects of TDD. Therefore, as long as compaction takes place in a timely manner, the effects of TDD can be minimized. One method to help ensure timely compaction is to set the paver speed so that the compaction equipment can keep up with the paving operation (1).

Equipment Selection

The equipment that is used in the construction of HMA pavements is very critical in the prevention of TDD. A few pieces of equipment that will be covered in this portion of the report are haul trucks and material transfer devices.

Haul Trucks

The selection of haul trucks used to transport the hot mix asphalt to the construction site, and the method by which the asphalt is loaded into the paver are very important. There are three types of haul trucks that can be used to accomplish this task. The first is the standard haul truck that delivers the loose HMA to the paver by dumping the mix out the rear of the truck directly into the paver hopper. This type of system requires a steady stream of hot asphalt moving into the paver (1). This is the most common method used in South Carolina to transport the HMA mix.

A second type of truck, although not commonly used in South Carolina, is the belly dump truck that delivers the HMA in front of the paver, and dumps the HMA onto the existing pavement. The asphalt paver then collects the mix by using a conveyor belt that is attached to the front of the hopper. Experiences with this technique have yielded an increase in production of 35-40% by keeping the paver constantly moving (9). A few problems with this system that have been brought to light by opponents is that the piles must be made correctly so that aggregate segregation does not occur. The second problem is that the asphalt is being dumped onto the cooler existing pavement surface where more heat is lost (9). Both problems have merit, but the outcome is dependent upon the skills of the construction crew. A good crew can increase the production by keeping the paver continuously moving, which in turn allows for an increase in time for the compaction effort. Research has shown that the loose HMA that is deposited on the pavement surface should not be affected by the elements because few states allow asphalt paving during cold weather (9).

The third type of haul truck is a live bottom truck/trailer that contains a conveyor at the bottom of the trailer. The slat conveyor pulls the HMA from the truck bed and discharges it into the hopper without elevating the bed (9). This type of truck is also not commonly used in South Carolina.

Material Transfer Device (MTD) /Material Transfer Vehicle (MTV)

A MTD and MTV are both pieces of equipment that can be used to help improve the quality of the pavement. The MTD is a piece of equipment that is pushed by the paver. It can be loaded by dump trucks, and has surge capacity so that the paving process does not have to stop and wait on trucks to keep the paver full of HMA (9). The MTD can also aid as a cushion between the paver and the haul truck. This keeps the problem of the paver and the truck bumping to a minimum, which can cause jostling of the screed resulting in irregularities in the pavement.

The MTV works exactly like the MTD with exception to the fact that the MTV moves on its own. The MTV can move in front of the paver and be loaded by haul trucks. The HMA is remixed using a triple auger system. This system allows for more mixing time so that the HMA has a uniform temperature in addition to reduction in aggregate segregation in an HMA pavement (9). After the HMA has been remixed, it is transported to the asphalt paver by a conveyor belt where it is fed directly into the paver hopper. Experiences with these pieces of equipment by both the Connecticut DOT and Washington DOT have resulted in a reduction in TDD and uniform mat temperatures (5, 10). Figure 5 shows how the use of a MTV produces a uniform pavement temperature.

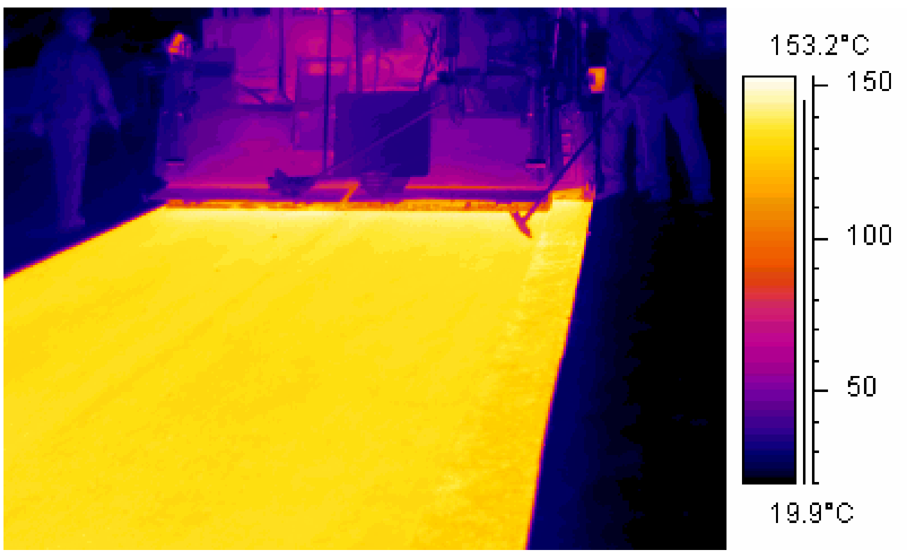


Figure 5: Thermal profile of a pavement where a MTV was utilized.

Summary of TDD

Temperature differential damage is caused by the top portion of a loose asphalt load cooling off during transport from the plant to the job site. This cooler material, when loaded directly into the asphalt paver hopper, does not spend sufficient time in remixing to produce a HMA that is uniform in temperature. The result is a pavement that is not uniform in temperature across the pavement mat. These cooler spots located in the pavement range in both size and temperature, and if not compacted in a timely manner, result in poor pavement performance.

The major problem with TDD is that it is hard to detect because the symptoms are similar to that of aggregate segregation. One of the most effective methods to determine if TDD exists is the use of a thermal camera. A thermal camera is a tool that allows the user to take a picture of the pavement surface and, after analyzing it, determine the extent of temperature segregation.

Once TDD is identified, there are many methods to reduce the occurrence of temperature segregation. The first method that can be used to reduce TDD is to reduce the amount of time that the loose asphalt mix spends in queue at the job site. The cool asphalt forms at the top of the mix during transport, so it is of the utmost importance to get the loose asphalt placed as soon as it gets to the job site. The second method is to use a MTV or MTD in the paving operation, allowing for the loose asphalt to have a longer remixing cycle that is not present in the conventional asphalt paver. This additional time allows for the entire mix to be reheated to a uniform temperature. The last method to prevent TDD from affecting a paving project is to use good paving practices. The effects of TDD can be compounded, or negated, due to the practices that the equipment operators use in the field. Some of the practices that are the most important are the selection of paver speed and the wing operation. The speed should be set so that the compaction equipment can keep up with the paver so that timely compaction occurs. The wings of the paver also need to be dumped into the hopper at the end of each truckload, with a sufficient amount of material in the hopper so that asphalt in the wings can be remixed with warmer material.

CHAPTER III: SELECTION OF THERMAL CAMERA

This chapter covers the selection of the camera for this project, and how the thermal camera works from a technical standpoint. A brief set of instructions on how to use the Flir ThermaCam PM695 camera is included in Appendix A.

Selection of the Flir ThermaCam PM695

To determine the best thermal camera for this project, the research team along with members from the SCDOT determined certain criteria required for the ideal thermal camera for this application. The criteria determined for the camera included the camera configuration, capabilities of the system to analyze the data, technical support, durability, and portability of the camera.

The first criterion for the selection of the thermal camera was the camera configuration. First and foremost, the camera had to be able to measure the temperature of asphalt correctly. The Flir ThermaCam PM695 can be configured to measure the temperature of a typical HMA. The camera was set up with this configuration, by the manufacturer, and it is accurate within a range of ± 2%.

The second criterion was that the data collected by the camera could be analyzed in an office environment or on the jobsite. The ThermaCam PM695 met both of these criteria. The camera has several attachments that could be used in the field to study the collected data. In addition, the analysis could be accomplished in an office using a computer; therefore, enabling the technician to generate reports.

The third criterion was the availability of technical support. The Flir Company met this requirement by supplying a representative on multiple occasions to help train the members of the research team. Classes on the operation of the camera were also available periodically.

The fourth criterion was the durability of the camera. This camera represents a sizable investment for the SCDOT. To insure that the return is high for this investment, the camera has to be durable to survive the conditions faced in the field. The Flir ThermaCam PM695 met this criterion by being waterproof and shockproof. Being waterproof reduces the concern of the camera being ruined because of exposure to the environment (e.g., rain). The shockproof feature is also necessary in that an accidental drop will not damage the camera.

The final criterion was that it had to be portable. The Flir ThermaCam PM695 fit this criterion by weighing in at approximately 5.5 lbs. The camera was also equipped with straps so that it could be carried over the shoulder. This feature is necessary when long distances have to be covered by foot to capture the surface condition of a pavement.

Thermal Camera Operation

There are several concepts necessary to understand the operation of the thermal camera including the electromagnetic spectrum, blackbody radiation, and infrared semi-transparent concepts. The electromagnetic spectrum is divided arbitrarily into a number of wavelength regions called bands, distinguished by the methods used to produce and detect the radiation. There is no fundamental difference between radiations in the different bands of the electromagnetic spectrum except the wavelength. Thermography makes use of the infrared spectral band. At the short-wavelength end, the boundary lies at the limit of visual perception, in the deep red. At the long wavelength end, it merges with the microwave radio wavelengths, in the millimeter range.

The second part is blackbody radiation. Simply, a blackbody is an object that absorbs all radiation imposed on it at any wavelength. This concept is explained by Krichhoff's Law, which states that a body capable of absorbing all radiation at any wavelength is equally capable in the emission of radiation.

The final part is the infrared semi transparent materials. This concept deals with how an object gives off radiation when heated. This principle allows for the determination of correction factors that can be assigned to different materials, because in reality, all materials are different with respect to how they give off radiation. The correction factor of the material, when coupled with the measured reflected radiation, is all that is needed to determine the temperature of the object.

CHAPTER IV: PROCEDURES AND EXPERIMENTAL DESIGN

An experimental design was implemented to determine the effects of many variables (e.g., different pavers, time of day, mix type, etc.) on temperature differential damage (TDD). The resulting plan was to isolate certain variables so that their individual effect on TDD could be measured. This chapter explains the resulting experimental setup that was used to collect the measurements needed to satisfy the objectives of the research project.

Project Information

The first step in the experimental process was to determine what variables needed to be considered and studied. The following variables were collected for each project.

a. Job location,
b. Weather conditions (e.g., temperature),
c. Daytime versus nighttime paving,
d. Type of asphalt paver,
e. Type of material transfer device,
f. Types of compaction equipment used,
g. Haul time,
h. Qualitative comments on the contractor's workmanship (e.g., kept up with the paver, dumped wings after each load, etc.), and
i. Daily plant report (e.g., QC reports).

Experimental Setup

A random sampling technique was used to obtain the required information to satisfy Objective 3 of this project. However, after gathering data for several projects, based on the SCDOT's request, Objective 7 was added in which the mat temperature was observed during the entire paving process with pictures taken at every instance of an appearance of temperature differential. In the case that a temperature differential was found, the GPS location was recorded so that the SCDOT could evaluate the long term effects of TDD in the future. Several variables were investigated including haul truck information (e.g., haul time); different asphalt pavers; mix types; equipment (e.g., material transfer device); environmental conditions (e.g., ambient temperature, cloud cover, etc.); and compaction efforts.

Stratified Random Sampling

In the case of Objective 3, a stratified random sampling technique was used to obtain the data. For instance, the day's production was divided into sublots and a sample (i.e., an observation) was randomly taken from each sublot. This sampling procedure was used to ensure that no biased observations were made during the collection of the data. Stratified random sampling was chosen because it would ensure the collection of observations throughout the day's production. This type of sampling also allowed the research team to use the contractor's tests for compliance, which could then be used to help study individual variables that might have an effect on TDD.

Haul Truck Inspection

To satisfy Objective 3, three pieces of information were collected for each truck load including:

a. Haul time,
b. The temperature of the asphalt crust, and
c. The temperature of the HMA beneath the crust.

The collection of both temperature observations were to help in determining the differences present on the surface and in the middle of the hot mix asphalt, and support the hypothesis that temperature differentials are formed during the transport of hot mix asphalt to the job site.

The collection of haul time instead of haul distance was determined to be more beneficial to the study, because the loss of heat in a HMA mix is a function of time rather than distance. Haul time, for this research project, was the time from when the truck was loaded until it was deposited into the paver. This information, coupled with the temperature differences in the haul truck, would clarify how haul time affects the surface of the hot mix asphalt during transport.

Effects of Asphalt Pavers on TDD

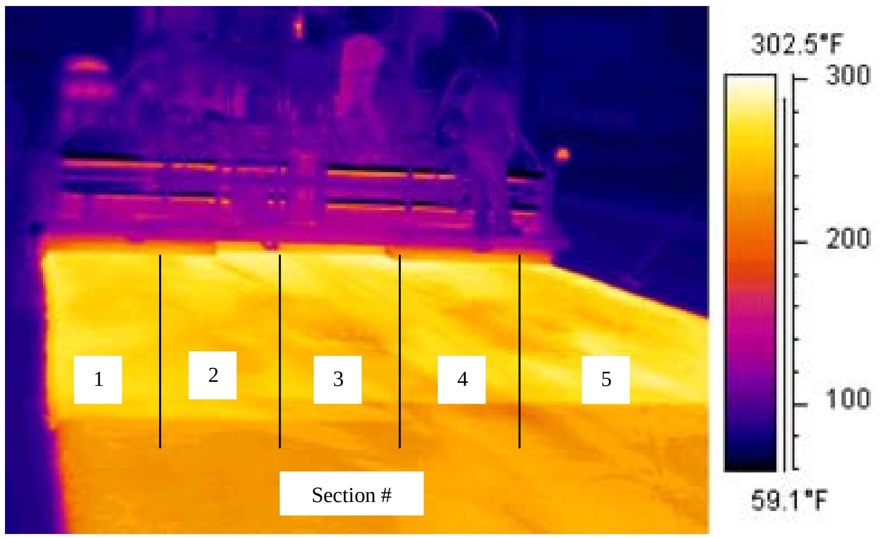
Thermal pictures of the asphalt mix directly behind the asphalt paver were randomly taken throughout the course of the production. Members of the research team evaluated the thermal pictures by using a software package provided by the manufacturer. For this task, a temperature profile, used by the software, was cast along the width of the pavement. The profile calculated the average and standard deviation of the pavement temperature. These values were then used to establish a temperature range (i.e., high and low temperatures) for that particular image.

For each picture taken, the pavement directly behind the paver was divided into five equal sections because this was the easiest way to analyze the data. These five sections represented various locations of the pavement (i.e., the left edge, the right edge, the center, one section to the right of the center, and one section to the left of the center). It is possible that the picture could have been divided into more or less sections. These five sections were visually inspected to determine if any TDD existed. Each observation of cooler material was tallied in the area where it was deposited (e.g. center of the mat). The information was then sorted and graphed so that comparisons could be made. Figure 6 shows this process.

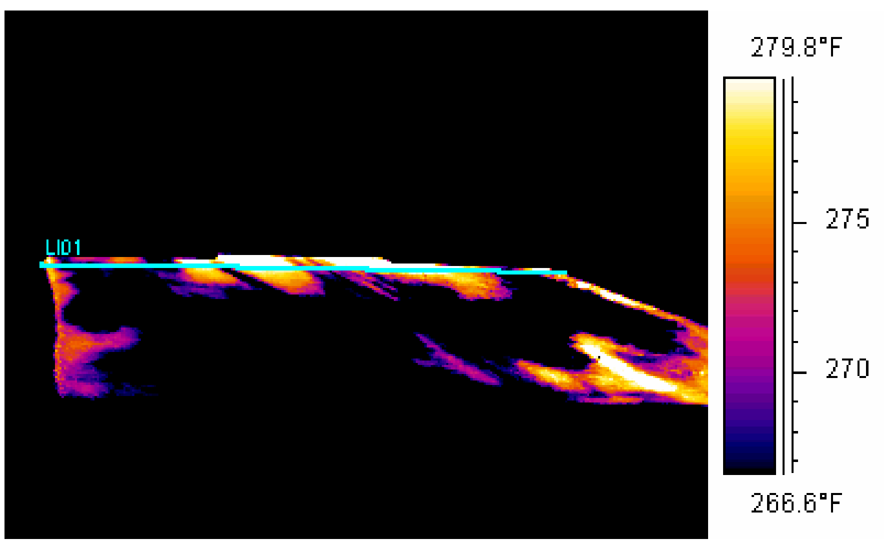
Effects of Various Variables on TDD

Another method of measurement that was used to evaluate different variables was to take a thermal picture of a pavement's cross section (5 feet along the length of the pavement by the width of the pavement). Five feet was an adequate size of the pavement that could be reasonably photographed. The location of the cross section was determined by stratified random sampling. Each cross section was marked off, and a thermal picture was taken. Figure 7 shows a typical thermal picture of a cross section of a pavement.

To satisfy Objective 3 of this study, each thermal picture was analyzed using the software package to determine the average and standard deviation of the temperature of the cross section. This information was then used to determine the distribution of the temperature across the pavement. These distributions were then compared to each other to determine the effects of different variables (e.g., mix type, equipment type, daytime vs. nighttime paving, etc.) on TDD.



(a)



(b)

Figure 6: Thermal image of (a) an asphalt mix behind a paver divided into five sections for analysis and (b) the same image with the temperature scale adjusted to the mean pavement temperature ± one standard deviation.

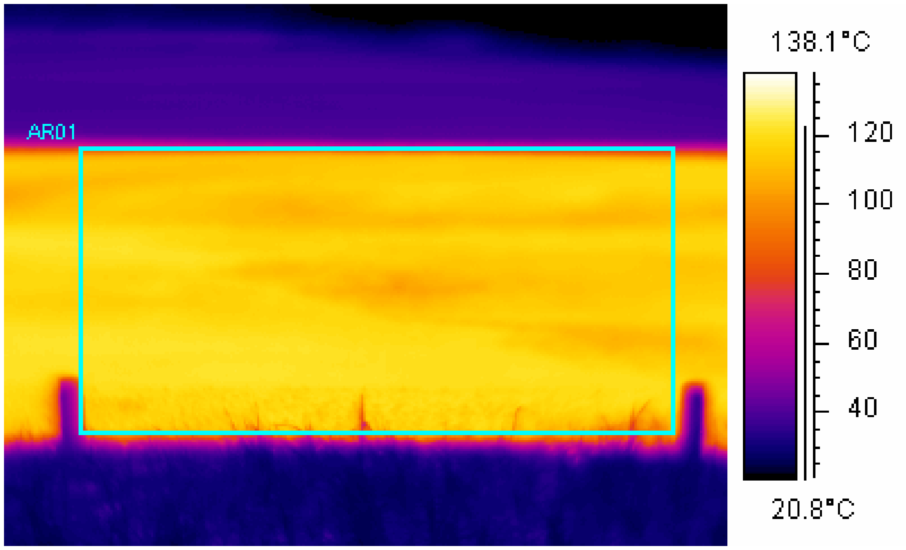


Figure 7: Thermal image of an asphalt pavement cross-section.

<u>Effects of TDD on Compaction</u>

Before the paving began, the random core locations were marked off and a thermal picture was taken immediately after the paver passed over each location. The average pavement temperature was then calculated by obtaining the average of temperatures of all core locations (e.g., 5 per day) for the cross section of that particular pavement. The coldest point of each thermal picture was determined. Then, the average pavement temperature was subtracted from this number to obtain the temperature differential. This value was then used to determine the effects of TDD on compaction by comparing it to the density of the pavement determined using a nuclear density gauge.

<u>Other Observations</u>

Based on the SCDOT's request, for each project, cold spots were actively sought out and thermal pictures of these locations were taken. These pictures were analyzed separately from the random core images. These pictures were taken at least one foot from the edge of the pavement. The nuclear density gauge was used to obtain the density of the mat at the location of the cold spot after compaction was completed. These values (temperature differentials and density) were then evaluated as previously explained.

Data Evaluation

Once the data was collected, it was sorted to avoid overlapping. The problem with this approach was that there was not enough data in each category (e.g., mix type) to ensure that each variable was completely isolated and could be statistically analyzed.

After the data was sorted, it was evaluated using both graphical and statistical methods. The graphical means was the simplest and more productive method to evaluate the different variables. The statistical method (SAS) was not as productive at evaluating some of the gathered information due to lack of data (e.g., mix type). The findings are listed in the following chapters.

CHAPTER V: DATA COLLECTION PROBLEMS AND RESULTS

Data Collection Problems

Contractor's Cores

Initially, the locations of cores obtained by the contractor were selected as the locations to measure TDD. However, this data collection method was not very successful. This problem was due to the change in mix production throughout the day. Efforts were made to keep up with production changes, but this could not always be accommodated.

Temperature Segregation Observations

Actively seeking temperature differentials was a much more effective means of collecting data. The problem with this type of data collection is its reliance upon the data obtained from the nuclear density gauge. The difficulty associated with using the nuclear gauge instead of the contractor's random core locations is that the core is still the basis of acceptance testing.

Mix Types

The research team actively tried to collect data from various projects with different mix types, but due to the availability of some projects on a given day and poor weather conditions, this task was difficult to accomplish.

Findings for Objective 3

Relationship between TDD and Density

One of the objectives of this study was to determine the effects of TDD on compaction. Therefore, the research team obtained thermal pictures from observed cold spots of pavement cross-sections. The data showed that there was a direct relationship between TDD and the ability to achieve compaction (Figure 8). In almost every instance, a loss in compaction was observed with an increase in temperature differential. It is important to note that this finding was expected because the observations were from the areas with cold spots, indicating the possibility of a lack of adequate compaction.

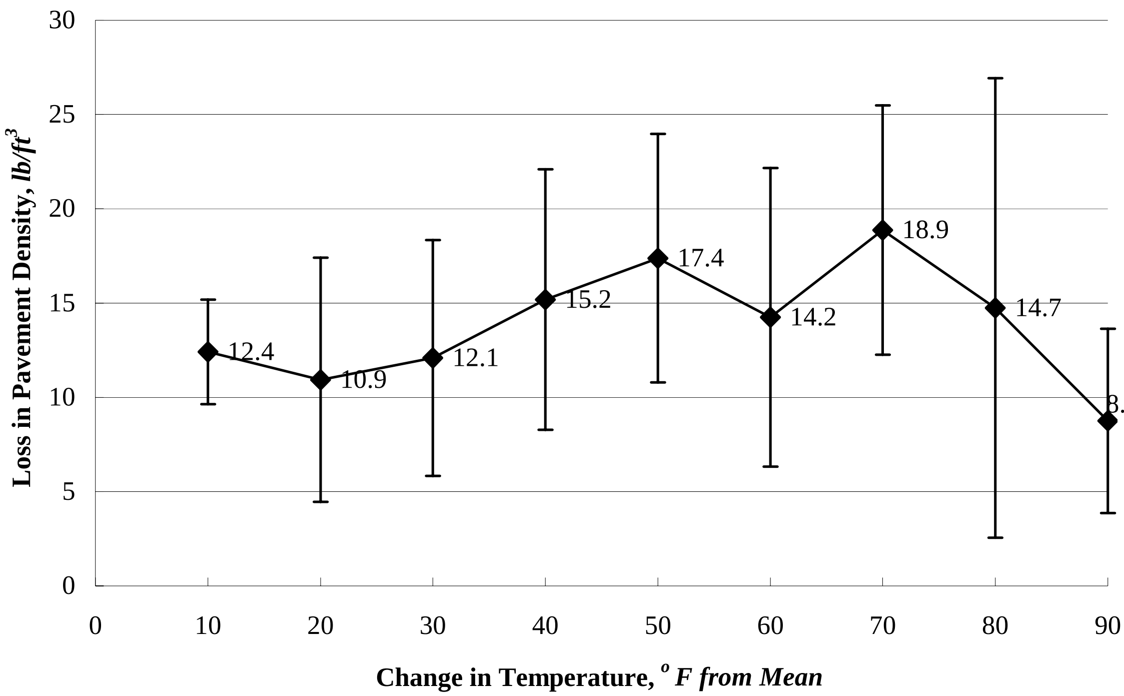


Figure 8: Effect of TDD on pavement density.

However, when the data gathered from the contractor's random core locations was used, the results were different. The findings from the contractor's core data show that there is no relationship between TDD and the ability to achieve compaction. The difference in findings could be attributed to the fact that all of the density measurements, conducted by the contractor, were within SCDOT's acceptable specification range indicating a proper technique was used to compact the mat.

Asphalt Paving Equipment

During the course of this study, three different asphalt paver brands were evaluated for their ability to reduce the occurrence of TDD. To determine the effectiveness of the different asphalt pavers, thermal images of asphalt pavement cross-sections were evaluated. The average and standard deviation of the temperature of each thermal image was obtained using the Flir software. The research team decided to use 5^{o}F increments to analyze the data. The percent pavement affected by the TDD was obtained by calculating the area under the curve for a particular temperature differential (e.g., below 15 ^{o}F). This curve was assumed to be a normal distribution. For instance, in Figure 9, the value of 17.3% was obtained by calculating the shaded area under the curve.

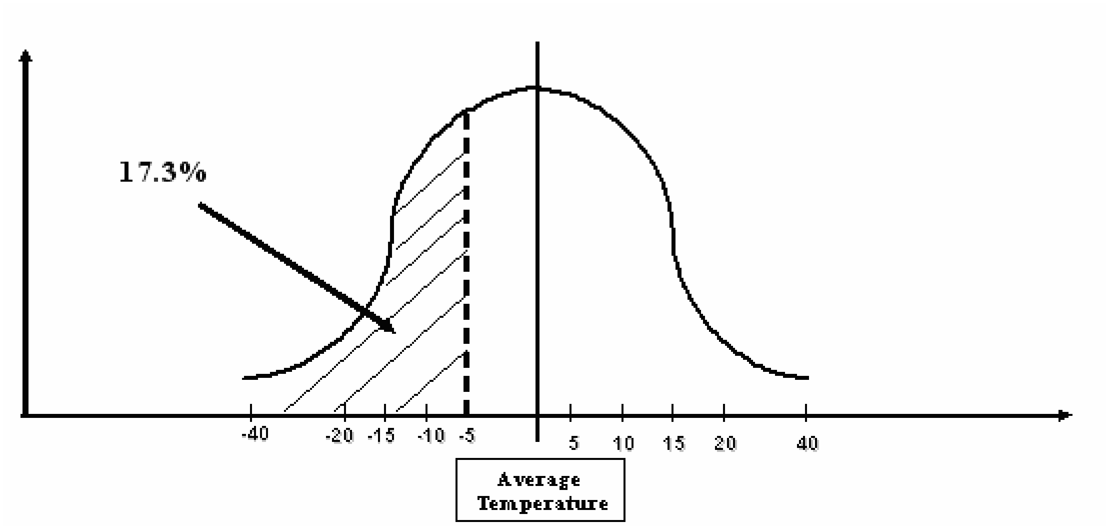


Figure 9: Typical curve used to calculate the percent of pavement affected by TDD.

Figures 10, 11, and B-1 through B-3 (Appendix B) indicate that Paver B, in most cases, when compared to Pavers A and C had lower percentages (6 to 8%) of pavement affected by TDD. In most cases, there was not a difference between Pavers A and C.

For the thermal pictures taken from the pavement cross-sections, the amount of TDD present in the asphalt pavements was determined. Then, the trend for the distribution of temperature differentials across the width of the pavement was determined. After reviewing the graphs in Appendix B (Figures B-4 through B-11), it appears that the data is inconclusive regarding paver manufacturer and TDD.

Material Transfer Vehicle

One piece of equipment that had been proven in previous field studies to be effective in reducing the amount of TDD was the material transfer vehicle (MTV). During the course of this field study, data was collected in an effort to determine the effects of the MTV on TDD.

Figure 12 indicates that the MTV did have an effect on the amount of temperature differentials that were present in the asphalt pavement for this particular project. The

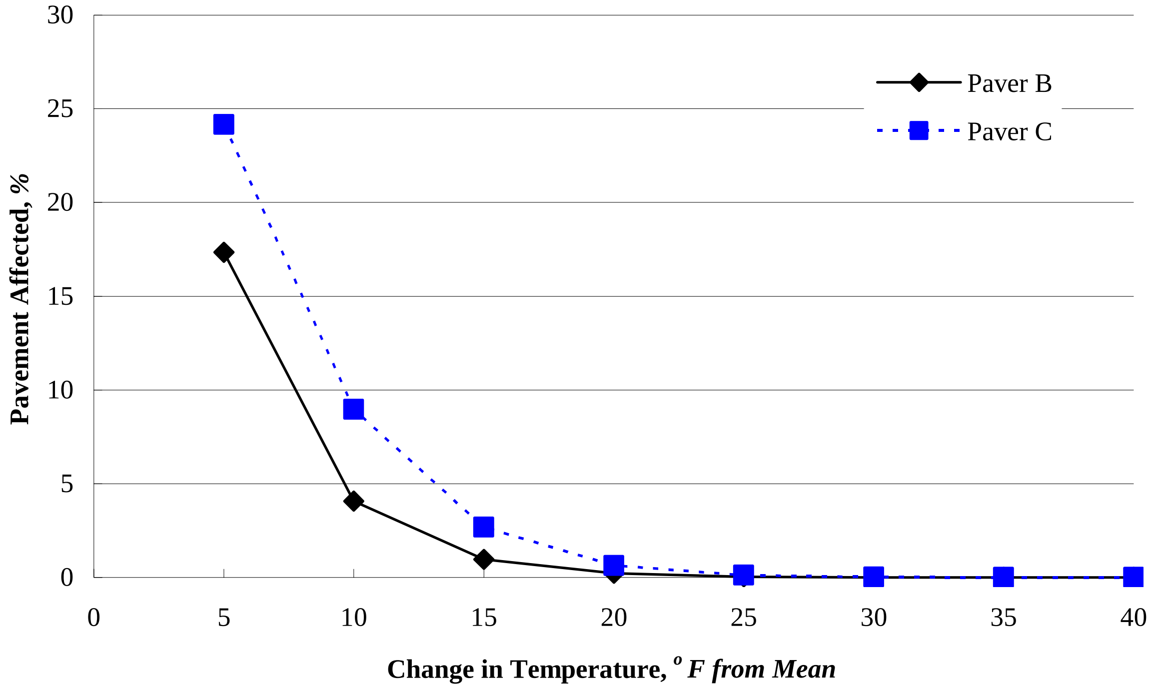


Figure 10: Comparison of TDD from different asphalt pavers from different manufacturers (20–30 min. haul time).

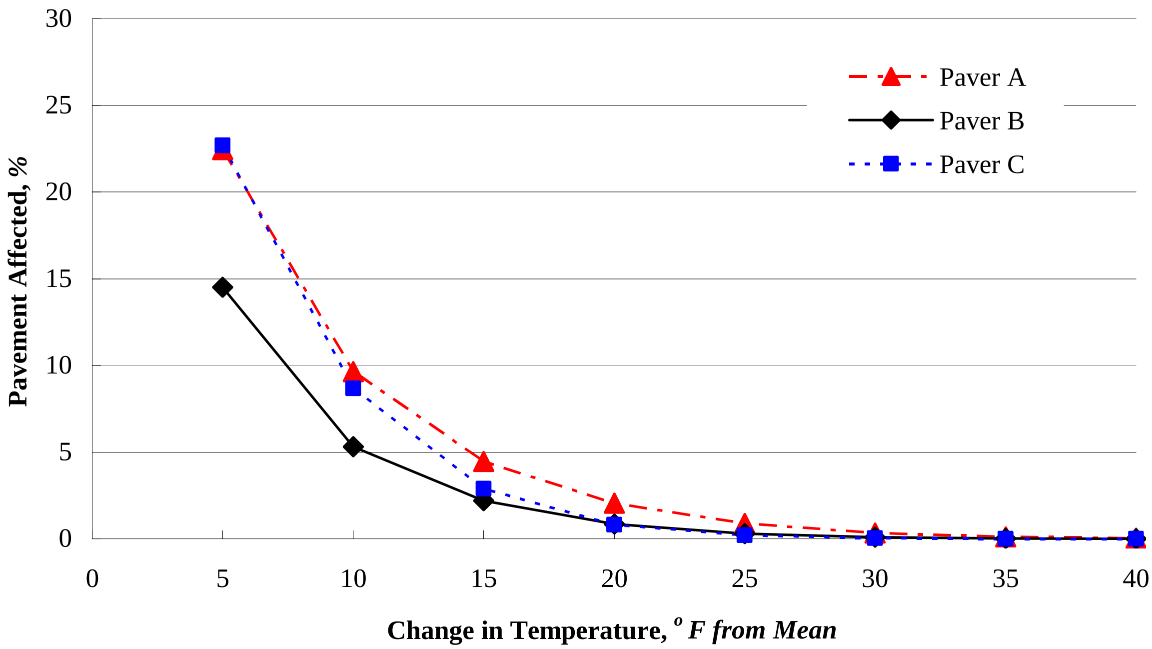


Figure 11: Comparison of TDD from different asphalt pavers from different manufacturers (40–50 min. haul time, all projects).

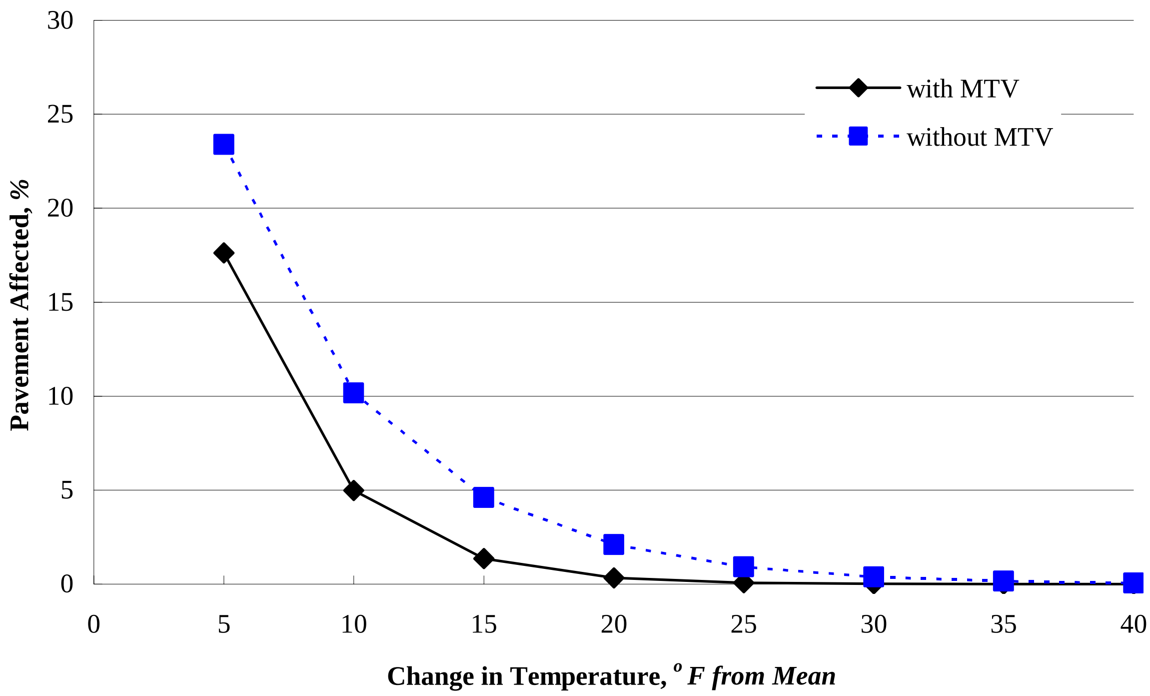
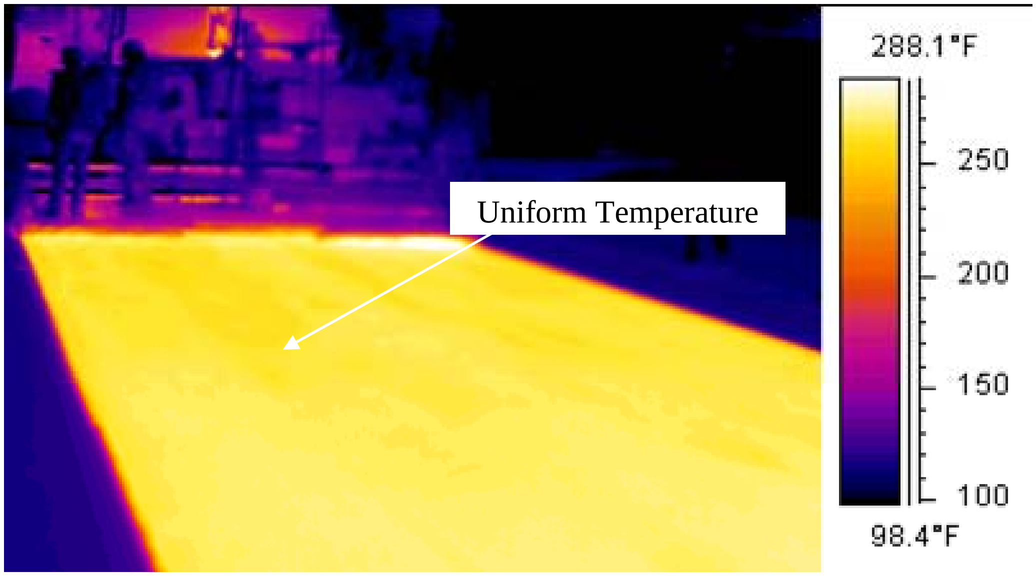


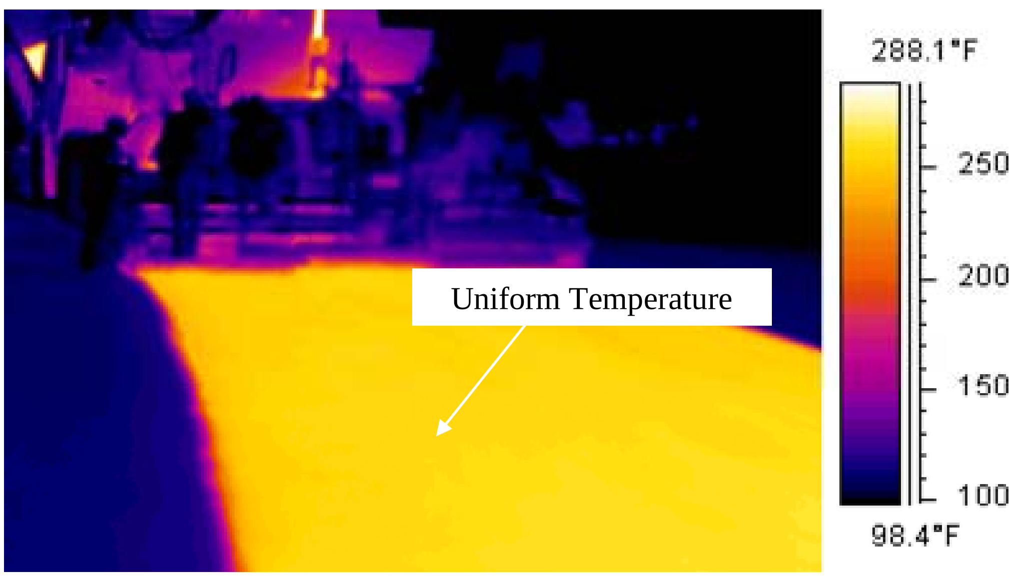
Figure 12: Effectiveness of material transfer vehicle (MTV) in reducing TDD (20–30 min. haul time).

amounts of temperature differentials were less for projects that properly used a MTV when compared to projects that did not utilize this device. It was also determined that the utilization of a MTV was more effective in reducing the amount of temperature differentials for the projects with longer haul times. There was an occasion when a contractor utilized a MTV without a box in the paver hopper. This project showed signs of TDD due to the build-up of HMA in the paver wings. When a MTV was used in conjunction with a box in the paver hopper, as is recommended practice, the result was a pavement mat of uniform temperature.

Figures 13 through 16 show the differences between construction projects that utilized a MTV and those that did not. Figure 13 illustrates the uniform temperature of the fresh asphalt throughout the width of the asphalt pavement. In this case, it can be seen that there is no cold joint in the pavement. This is because when a MTV is used in the paving operation, the paver rarely has to come to a stop which results in no cold joints in the mat. Figure 14 shows a typical section of freshly laid pavement when a MTV was not used.

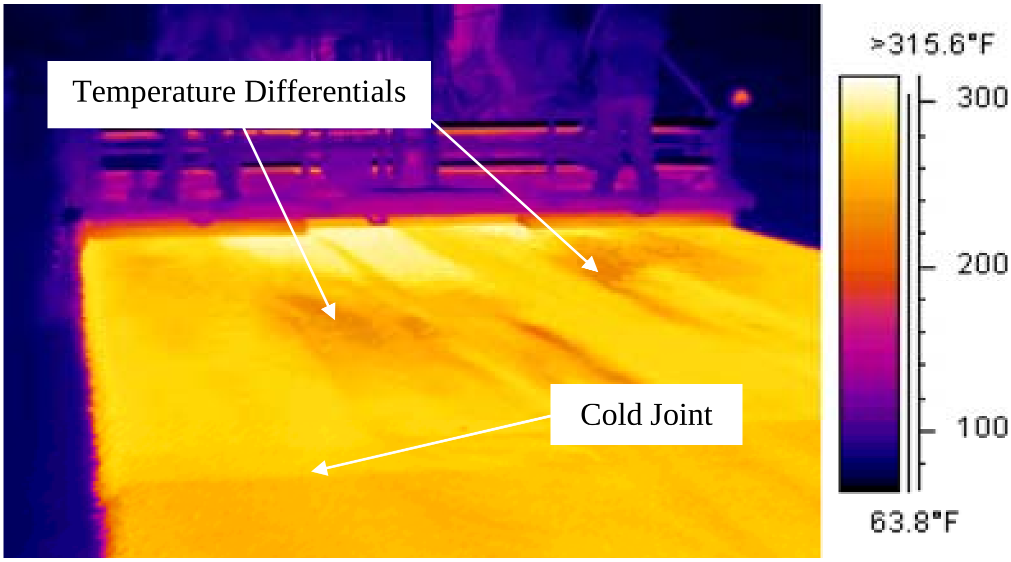


(a)

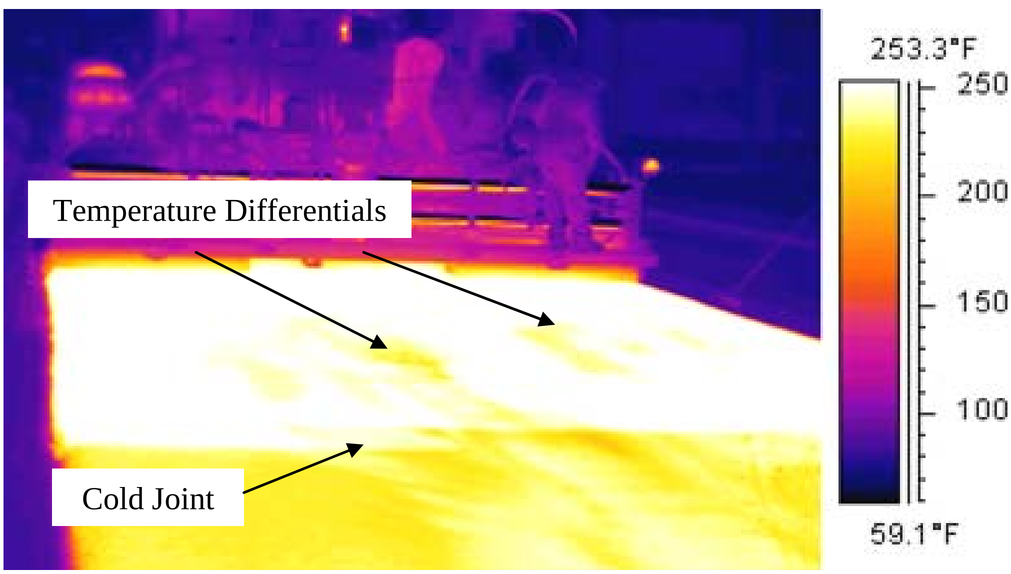


(b)

Figure 13: Thermal images from two paving projects: (a) daytime paving and (b) nighttime paving. Both projects were paved by the same contractor using a MTV.



(a)



(b)

Figure 14: Thermal images from two projects paved during the day. The projects were paved by different contractors, both using a MTV.

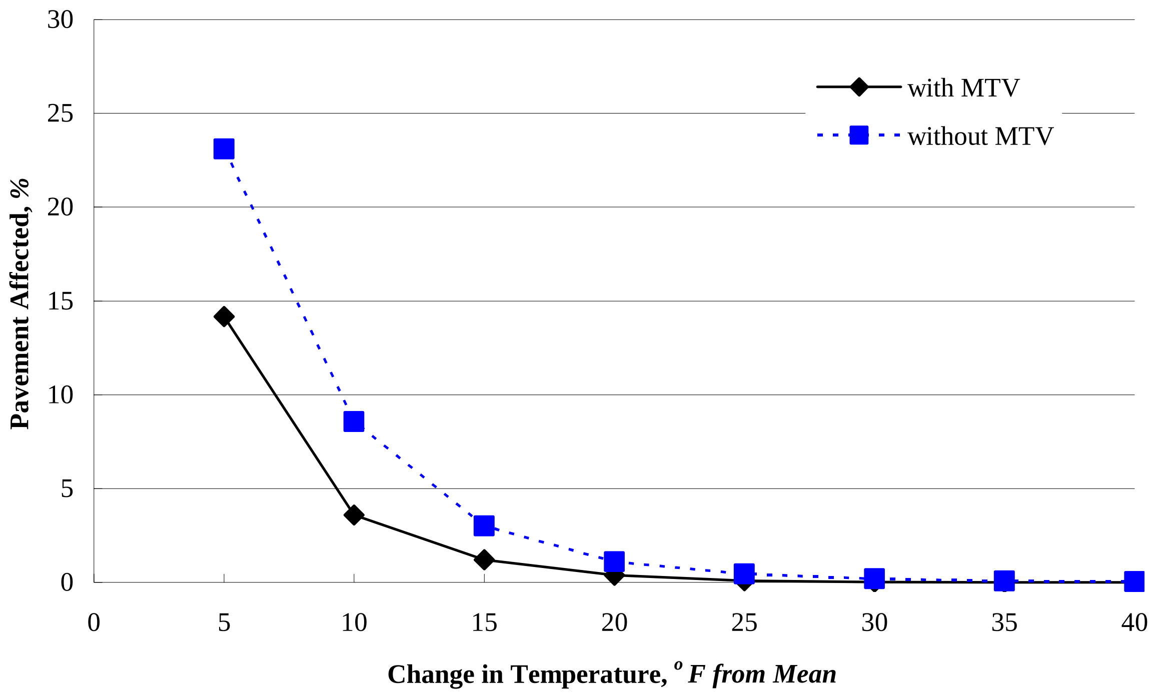


Figure 15: Effectiveness of material transfer vehicle (MTV) in reducing TDD (30–40 min. haul time).

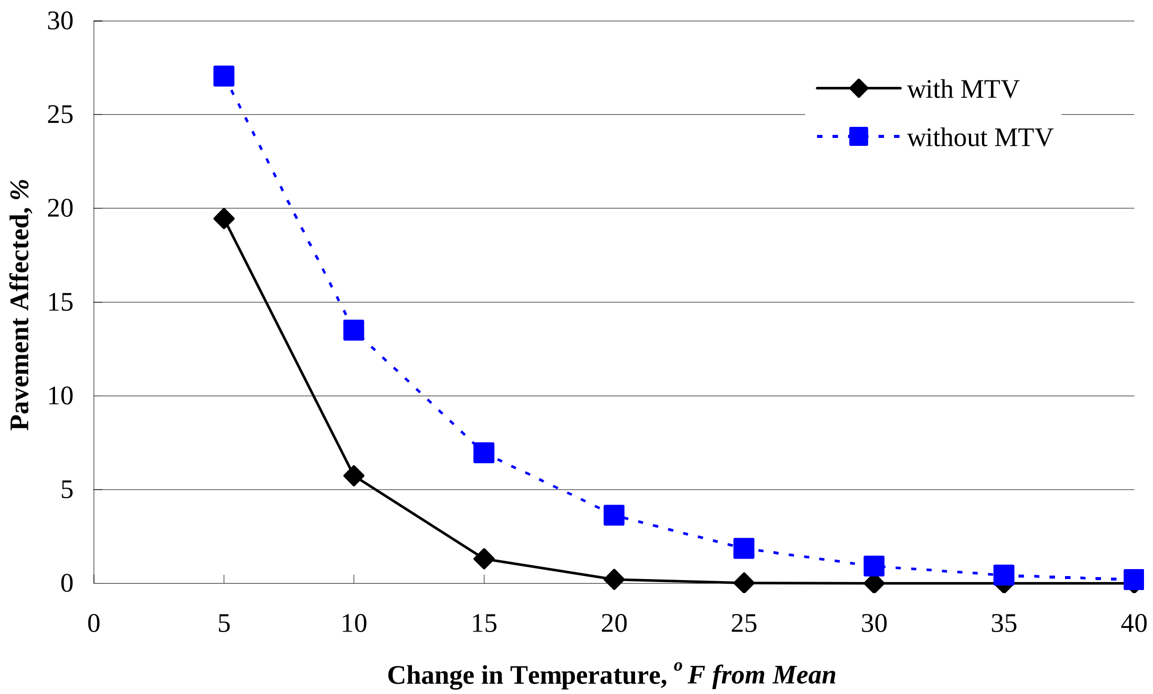


Figure 16: Effectiveness of material transfer vehicle (MTV) in reducing TDD (50–60 min. haul time).

Time of Day

Another variable that was considered during this field study was the effects of nighttime versus the daytime paving. The hypothesis was that nighttime paving will be more susceptible to TDD than daytime paving. This was based on the fact that nighttime paving typically has a lower ambient temperature than that of daytime paving. This cooler temperature results in the HMA losing more heat during transport from the plant to the jobsite and during the construction process.

In general, the data (Figures 17 and B-12) did not reveal any significant relationship between time of paving (day vs. night) and TDD. The temperature range in the haul truck, however, was typically higher during nighttime paving. This trend was also expected. It is important to note that the data for night paving was collected during the middle of summer. During this time frame, the temperature during nighttime paving was typically over 70°F. At this temperature, it is acceptable to assume that the data does not represent all of the temperature ranges that might have been encountered throughout the paving season. Capturing data from both the early spring (March) and late fall (November), when there are lower ambient temperatures, might have produced results that show that TDD is affected by nighttime paving more than daytime paving.

Effects of Haul Time on TDD

The time that it takes for the fresh HMA to get to the job site from the plant was another variable that was studied during the course of this research. It was hypothesized that this variable had an effect on TDD. The results indicate that haul time has a definite effect on TDD, as shown in Figure 18. The relationship was relatively proportional—TDD increased as haul time increased. In most cases, if the haul time was less than 70 minutes, there was no major difference in the percentage of the pavement affected by TDD. This observation was based on all projects, excluding the projects that utilized a MTV. However, there were noticeable differences between the percentages of the pavement affected by TDD when the haul duration was greater than 70 minutes. It should be noted that there was a limited number of projects that had haul times greater than 60 minutes, as indicated in Figure 18.

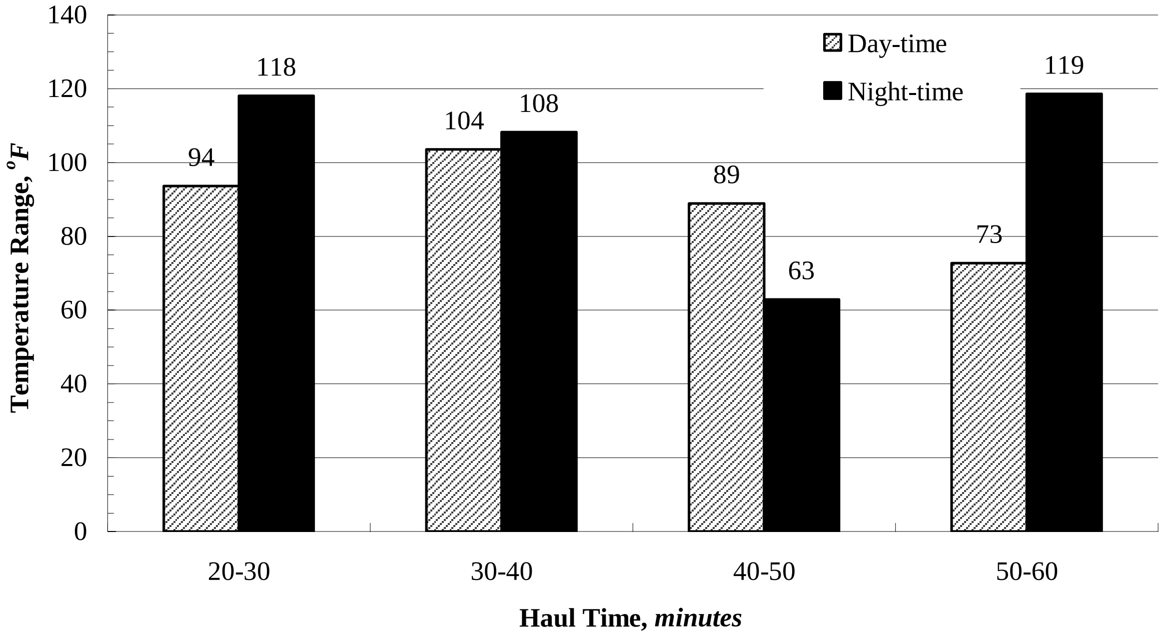


Figure 17: Temperature range of HMA in the truck bed.

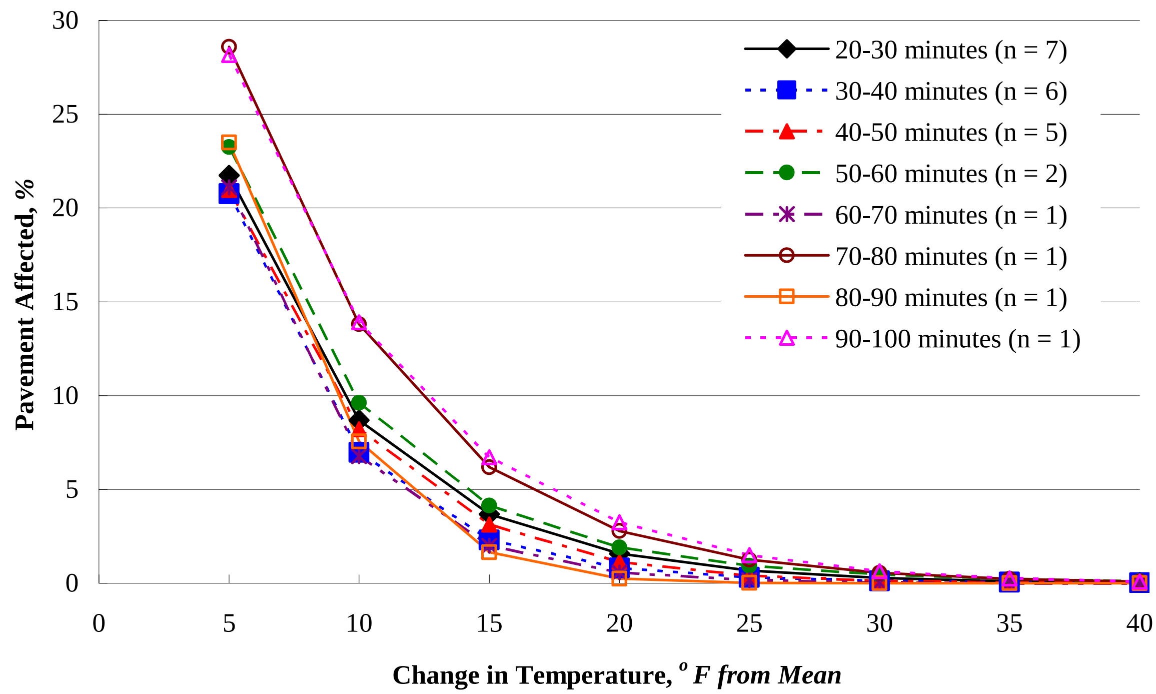


Figure 18: Effect of haul time on TDD.

Another method that was used to study the effect of this variable was to document the temperature differential in the haul truck prior to loading the asphalt paver. Figure 19 demonstrates the temperature differential that was identified in the bed of the haul truck. This method showed that as the haul time increased, so did the temperature range of the HMA in the truck. For projects with longer haul times (50 minutes or more in duration) there was a more noticeable temperature difference (Figure B-13).

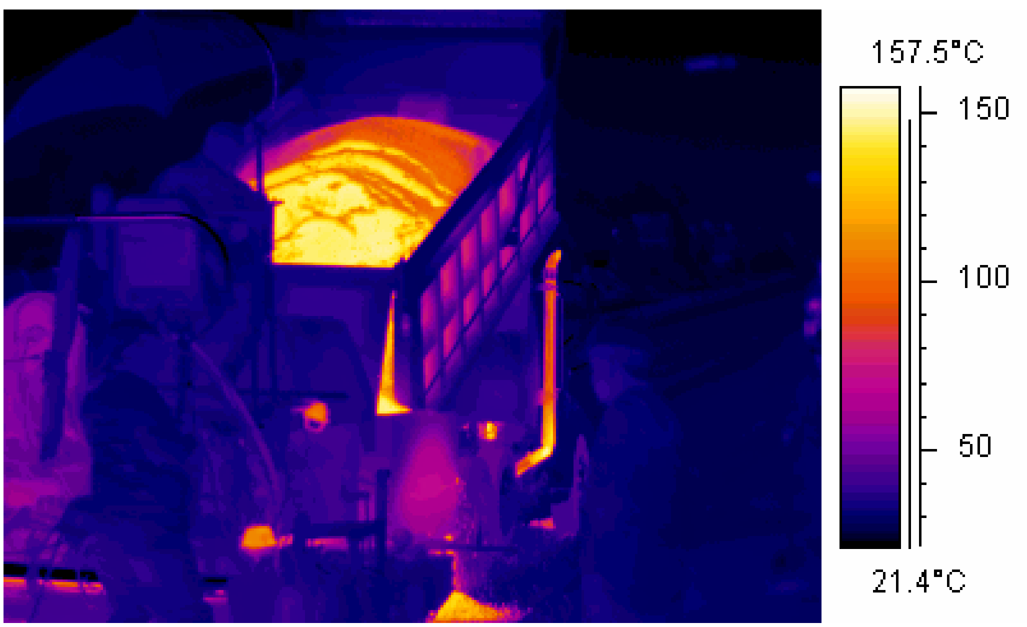
Mix Type

Mix type was another variable that was studied during the course of this investigation to determine its effects on TDD. The mix types that were studied included Surface Types 1C, 3, and Superpave 12.5 mm. However, the bulk of the projects that were studied during the course of the research project were Surface Type 1C because more of this type paving was available at the time of data collection process. The results indicated that the Surface Type 1C was not affected by TDD as much as the other two mix types (Figures 20 and 21). For both Surface Type 3 and Superpave 12.5 mm, there did not appear to be a significant difference to indicate that one was more susceptible to TDD than the other.

Contractor Influence

The influence that the contractor had on paving projects, along with haul time, was arguably one of the most important variables in controlling the TDD. It was the contractor's practices, with respect to the production, transportation, placing, and compaction of the HMA, which could have made a difference if TDD occurred in a paving project. The results indicated that for projects that had a short haul time, Contractor B had the least amount of temperature differentials followed by Contractors C and F, respectively (Figure 22). In the longer hauls, the previous trend does not take place (Figures 23 and 24). The data indicated that Contractor C experienced a lesser amount of TDD as the haul time increased.

(a)



(b)

Figure 19: Temperature range in a haul truck: (a) truck bed not elevated and (b) truck bed elevated 5 seconds after (a).

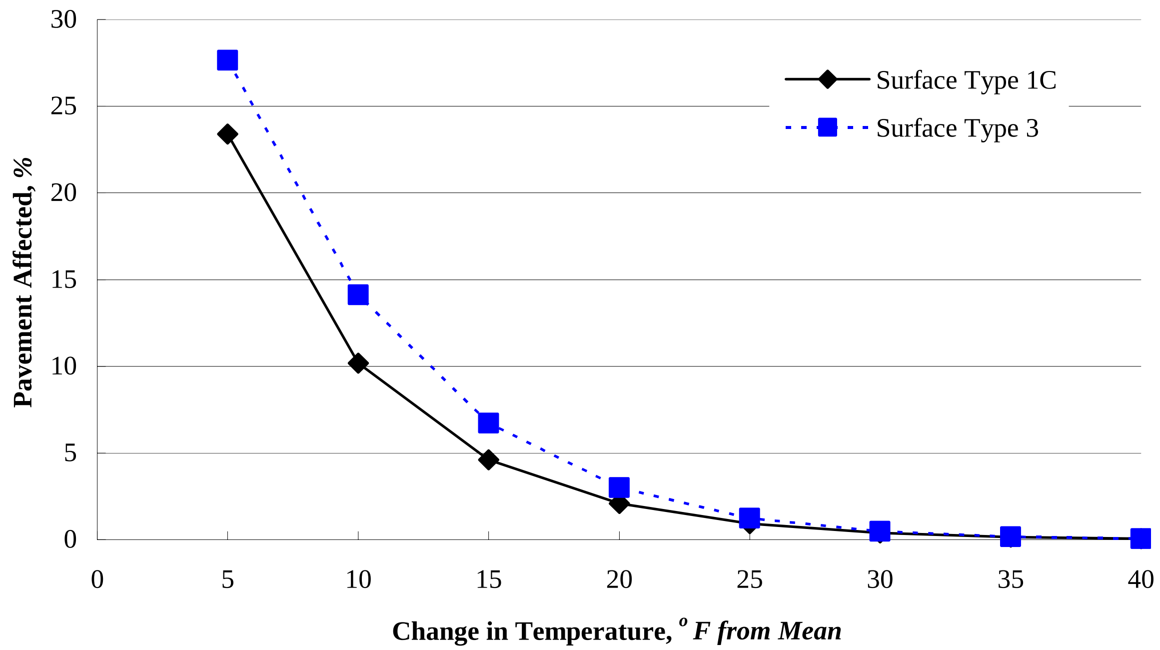


Figure 20: Effect of mix type on TDD (20–30 min. haul time).

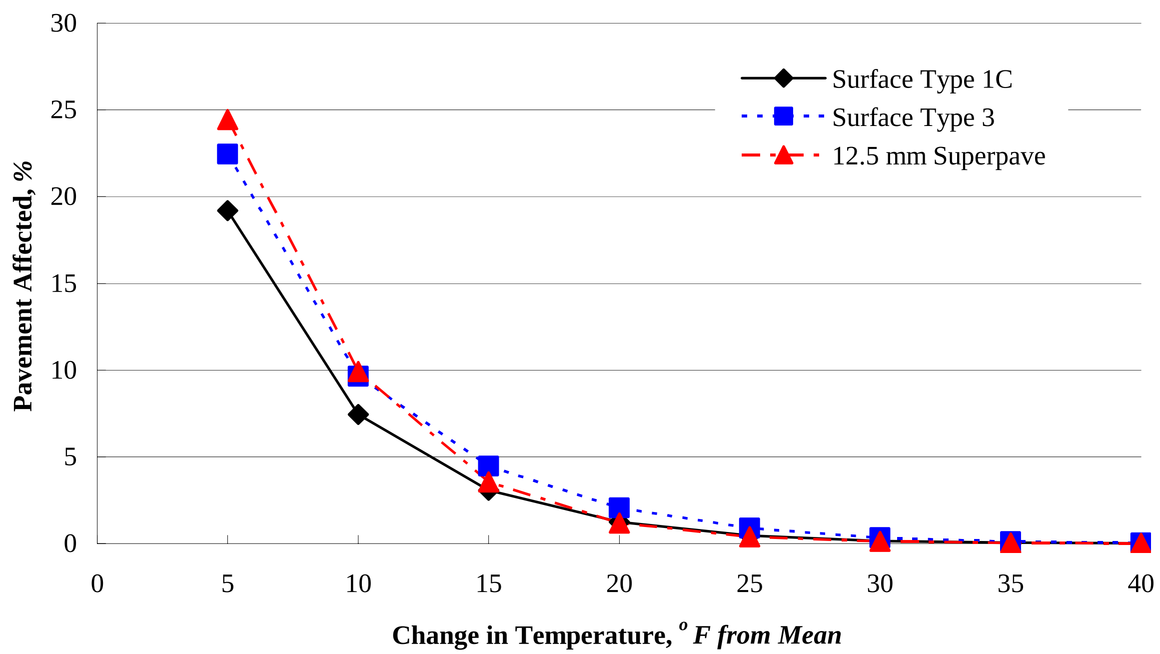


Figure 21: Effect of mix type on TDD (40–50 min. haul time).

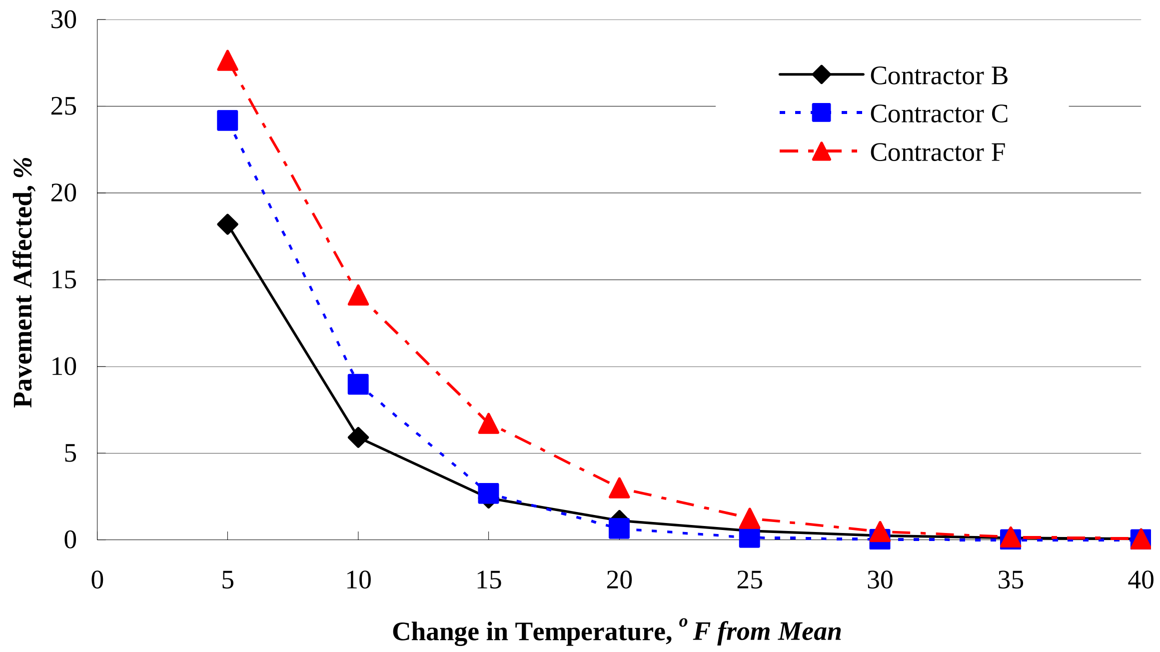


Figure 22: Effect of contractor on TDD (20–30 min. haul time).

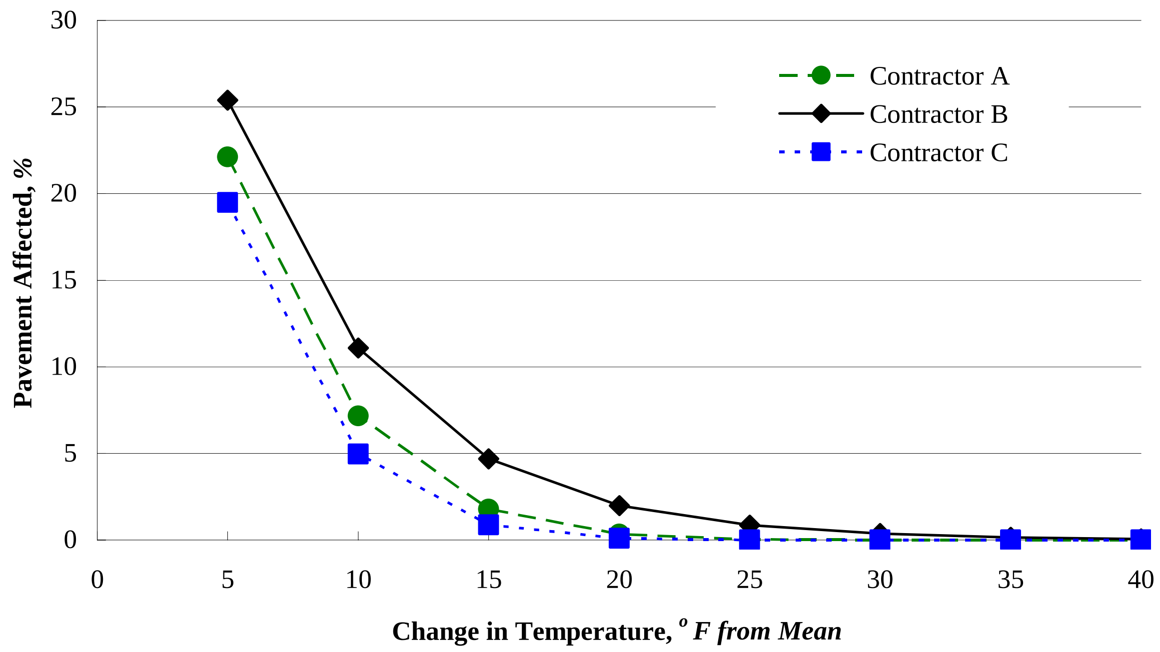


Figure 23: Effect of contractor on TDD (30–40 min. haul time).

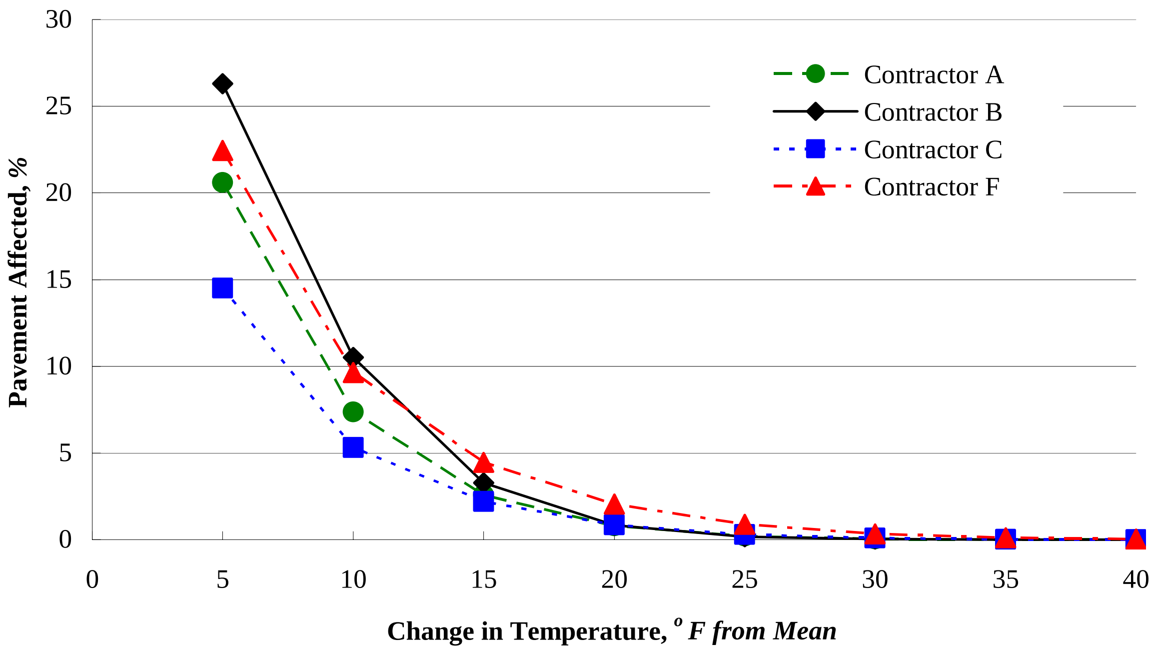


Figure 24: Effect of contractor on TDD (40–50 min. haul time).

Findings for Objective 7

The following are results from the evaluation of the 21 projects evaluated in this phase of the research to seek out cold spots to satisfy Objective 7.

Mix Type

Six different asphalt mix types were included in these projects: Open-graded friction course (OGFC) (3 projects), Surface Type 1C (6 projects), 12.5 mm Superpave (4 projects), 19.0 mm Superpave (2 projects), Binder Type 1 (2 projects), and Base Type 1 (4 projects). The SCDOT gradation specification for each of these mixes is included in Table 1 (11). The following observations were made by the research team regarding the effect of mix type on the occurrence of temperature segregation.

OGFC

It was difficult to obtain a uniform temperature when viewing OGFC mixtures with the thermal camera. This could be due to several factors such as the relatively thin lift thicknesses, high void content, and presence of clumps of fiber and binder. Additionally,

Table 1: SCDOT gradation specifications for mixture types evaluated (11).

Sieve	Percent Passing				
	OGFC	**Type 1C**	**12.5 mm**	**19.0 mm**	**Binder Type 1**
1 in.	--	--	100	100	100
3/4 in.	100	100	98 - 100	90 - 100	90 - 100
1/2 in.	85 - 100	90 - 100	90 - 100	75 - 90	72 - 90
3/8 in.	55 - 75	70 - 92	74 - 90	64 - 80	--
No. 4	15 - 25	42 - 60	46 - 62	38 - 54	42 - 60
No. 8	5 - 10	22 - 42	25 - 41	22 - 36	30 - 48
No. 30	--	10 - 25	9 - 21	8 - 18	12 - 29
No. 100	--	4 - 14	4 - 12	3 - 9	6 - 16
No. 200	2 - 4	2 - 8	2 - 8	2 - 8	2 - 8

since a MTV was utilized on each of the OGFC projects, TDD was most likely not an issue, even though the images may have suggested otherwise.

Surface Type 1C

Temperature segregation resulting from either truck-end segregation or wing dumps was commonly observed for this mix type. However, it was difficult to determine which was the cause, since the wings were always dumped at the end of each truck load. In general, the pavement mat showed uniform temperature, with the exception of the end of each truck load.

12.5 mm Superpave

Each of the four projects that paved 12.5 mm Superpave surface courses utilized a MTV. However, even though the MTV was used, the mat still showed temperature differentials due to wing dumps when a box was not used in the paver hopper. Aside from issues related to proper utilization of the MTV and paving delays, there were no observations that could be attributed to this specific mixture type.

19.0 mm Superpave

Typically, for this mixture, temperature differentials were only witnessed at the end of a truck load. This is most likely not the result of the mixture itself, but the operation of the paver, which will be discussed later. One of the projects did, however, have several cold spots resulting from the mix accumulating on the treads of the paver and from the asphalt plant. This problem was identified by the crew and the problem was rectified.

Binder Type 1

Again, the temperature differentials observed for this type of mix can be attributed to factors other than the mix type. For example, frequently, there was temperature segregation at the end of each load.

Base Type 1

Again, temperature differentials were most likely not a result of mix type as most differentials were noticed at the end of a truck load or due to delays between truck loads. Mix from one project did have tuck loads that were emitting smoke due to excessively high mix temperatures.

Material Transfer Vehicle

Of the 21 projects evaluated in this phase of the research, eight employed a MTV in the paving operation. When used correctly, the MTV allowed for a pavement mat having uniform temperature to be placed. Problems that were encountered when using a MTV stemmed from not discharging the mix from the MTV into a box placed in the hopper of the asphalt paver. When a box was not used, the paver hopper was typically overfilled, which created the need for the contractor to dump the wings of the paver. When the wings were dumped, temperature segregation was noticed in the mat. One contractor that did not use a box, however, did not have any issues with temperature segregation. This was due to proper monitoring of the quantity of mix in the paver hopper at any given time, which did not require the operator to dump the wings.

Another issue that was encountered on one of the projects, was that the MTV was allowed to run empty as the result of truck delays. This allowed materials waiting in the paver to lose a significant amount of heat resulting in cold spots in the mat.

For each project where a MTV was not employed, temperature differentials were frequently observed at the end of truck loads. Again, this could occur for two main reasons: segregation of material at the end of the truck load or colder material entering the material stream as the result of dumping the paver wings.

Paver Type

Pavers having two different configurations for transporting mix from the hopper to the screed were observed: auger-fed and slat-fed. An auger-fed paver was only used on three of the projects, while the remainder utilized slat-fed pavers. There was no discernable differences noticed about the occurrence of temperature differentials between the two types of pavers. When not using a MTV, both had temperature segregation at the end of truck loads.

Paver Manufacturer

While pavers from three different manufacturers were observed during this study, there was no difference between them, with respect to temperature segregation within the pavement mat.

Contractor

While eight different contractors were included in this phase of the study, there is not much information about temperature segregation that can be attributed to an individual contractor. Although multiple projects were evaluated for several contractors, the geographical location of the projects prohibited any comparison because multiple crews were observed. Also, the type of paving has an effect on the equipment used and, therefore, the operation of the crew. For example, it is not valid to compare a crew paving an interstate surface course, which would likely employ a MTV, to a crew paving a binder course in another part of the state, even if they were working for the same contractor.

Haul Trucks

Based on the information collected from the 21 projects, the haul trucks did not seem to have a significant effect on temperature segregation. All of the trucks utilized tarps, although some were strapped while others were not. The number of dumps per load or charging the tailgate did not appear to have an impact on temperature differentials at the end of a truck load.

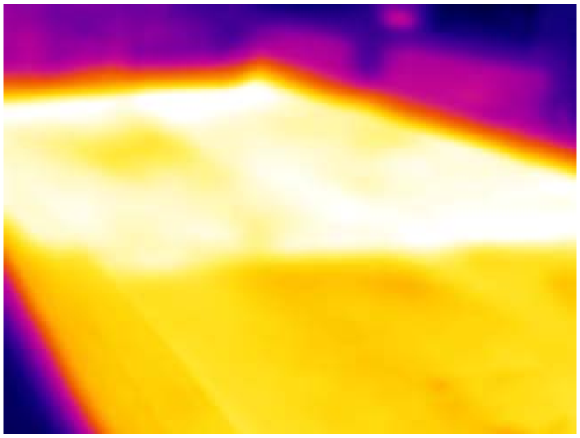
CHAPTER VI: FIELD GUIDE FOR COMMON TEMPERATURE SEGREGATION

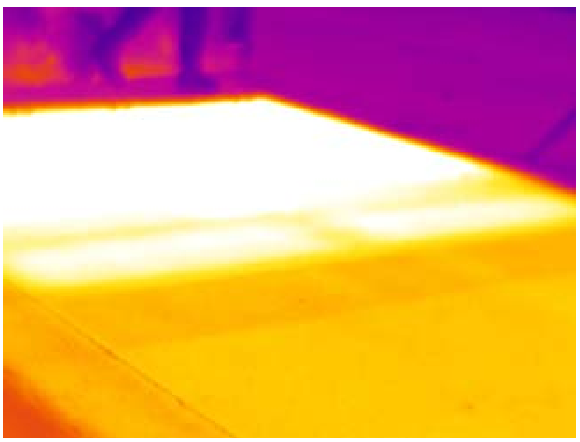
For Objective 7, research included documentation of cold spots on several paving projects. Paving projects were selected by availability with the intention of including as many different mix types and paver combinations as possible. For each project, the mix type, paver type, approximate haul time, and location of the cold spots were recorded. In addition to this, where possible, the GPS location of each cold spot was documented to aid continuing research and follow up efforts by SCDOT.

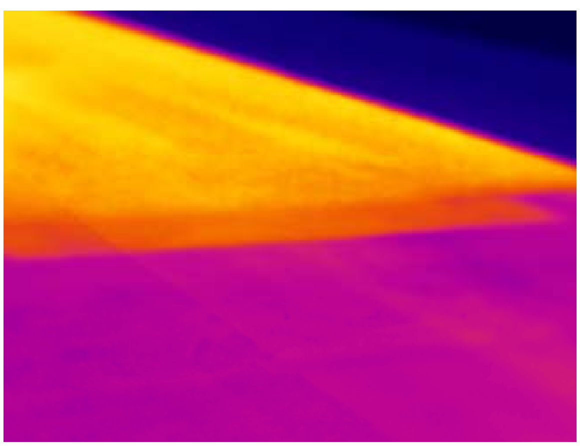
While every effort was made to meet these parameters, circumstances beyond control of the research team kept some from being fulfilled. Unfortunately, auger-fed pavers are not prevalent in South Carolina, so it was only possible to record data for this type of paver from two contractors. Also, even though several mix types were recorded, the paving season in which the research was done seemed to have an abundance of Surface Type 1C projects. All data and findings, however, have been reported in this paper. The SCDOT will be provided with the images and GPS data for their own use.

The guide that follows was compiled from data collected during several paving seasons. Its purpose is to aid in the identification of a specific type and severity of TDD. There are sections relating to cold joints, truck end, wing dumps, streaks, and cold spots. Severity was judged based on the actual temperature differential and the area of coverage. It is recommended that SCDOT use this as a guide in identifying the level of severity of TDD in future projects. In addition, it is recommended that the guide be modified, if necessary, after obtaining more data in the future by SCDOT.

Cold Joint Segregation


Low Severity Cold Joint


Moderate Severity Cold Joint


High Severity Cold Joint

Type of Damage

- Localized decrease in bonding.
- Possible increase in transverse cracking.

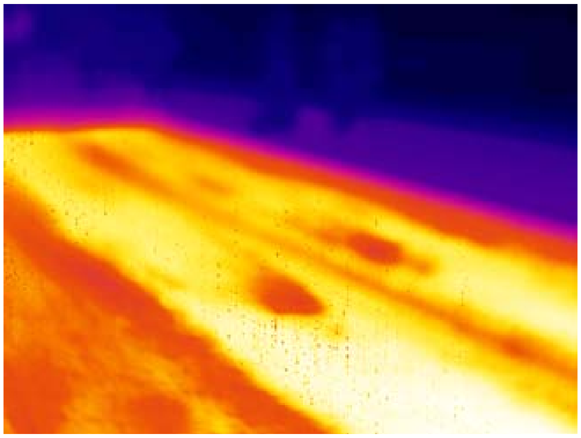
Possible Causes

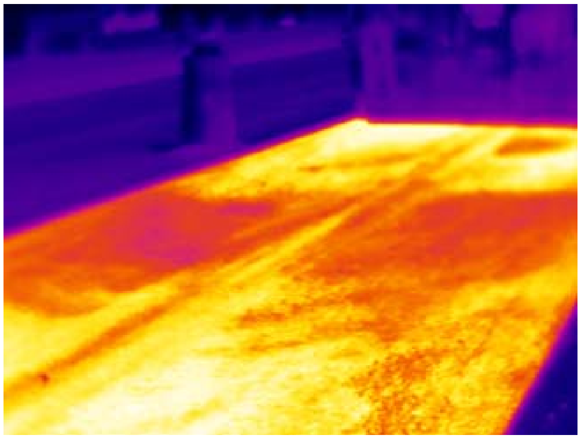
- Time in between truck delivery too great.
- Work stop caused by equipment malfunction or other problem.
- Temperature differential between consecutive truck loads .

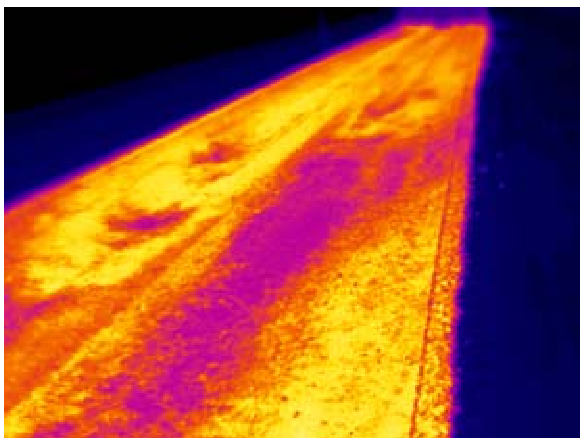
Possible Solutions

- Ensure equipment is functioning properly.
- Check to see if the asphalt plant is experiencing problems or any other changes in production.
- Maintain a steady pace and make provisions for steady delivery of HMA.

Truck End Segregation


Low Severity Truck End Segregation


Moderate Severity Truck End Segregation


High Severity Truck End Segregation

Type of Damage

- Localized decrease in density, which can lead to future distress.

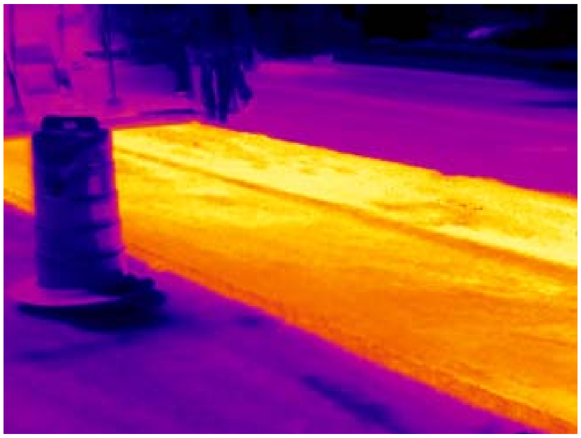
Possible Causes

- Improper loading of HMA into transport truck.
- Transport time too great.
- Truck tarps not used or used incorrectly.

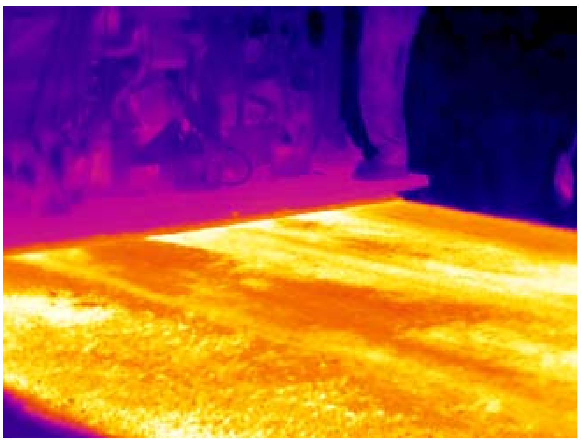
Possible Solutions

- Investigate truck loading procedure.
- Decrease the duration between truck loading and unloading.
- Use MTD to remix material.

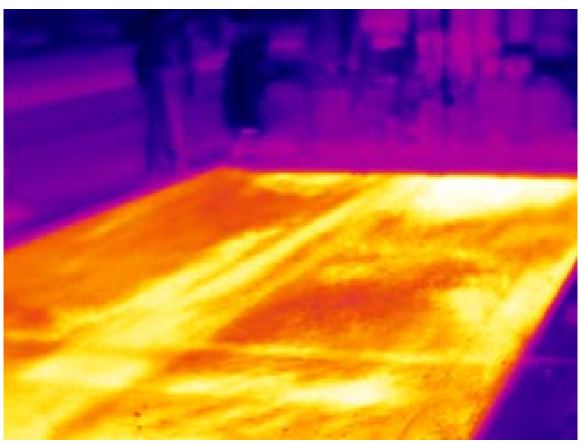
Temperature Segregation Due to Paver Wing Dump



Low Severity Wing Dump



Moderate Severity Wing Dump



High Severity Wing Dump

Type of Damage

- Localized decrease in pavement density, which can lead to future distress.

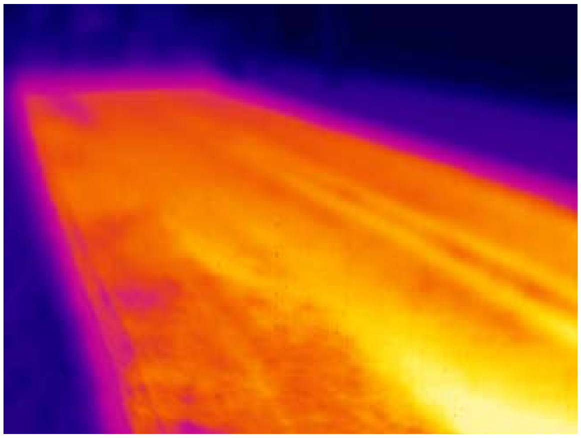
Possible Causes

- Material in paver wings is substantially cooler than surrounding HMA.

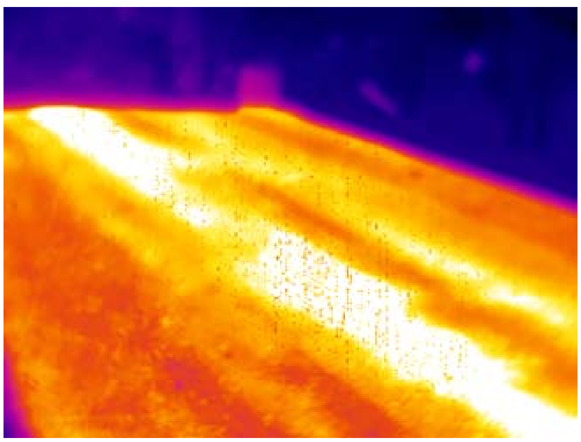
Possible Solutions

- Do not dump the paver wings and waste the material in the wings.
- Use a MTD with a box to keep material mixed.

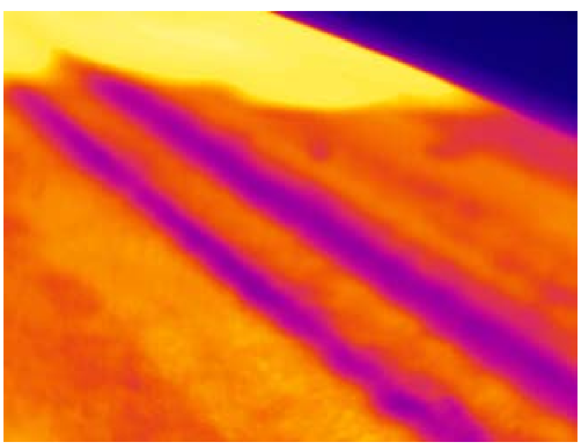
Temperature Segregation: Streaks



Low Severity Streak



Moderate Severity Streak



High Severity Streak

Type of Damage

- Localized decrease in pavement density, which can lead to future distress.

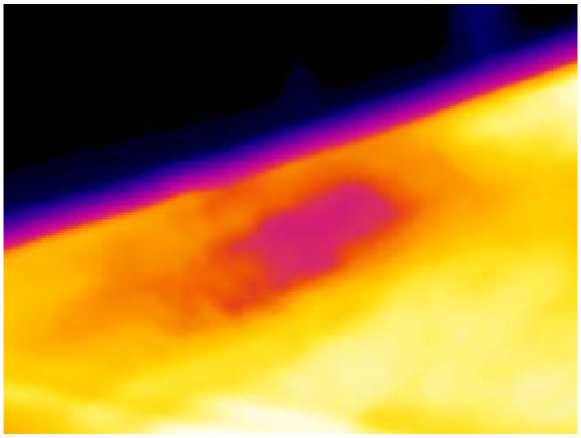
Possible Causes

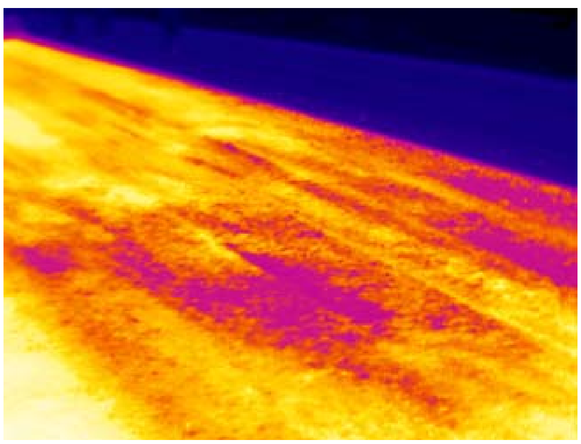
- Problem with screed maintaining a uniform temperature.

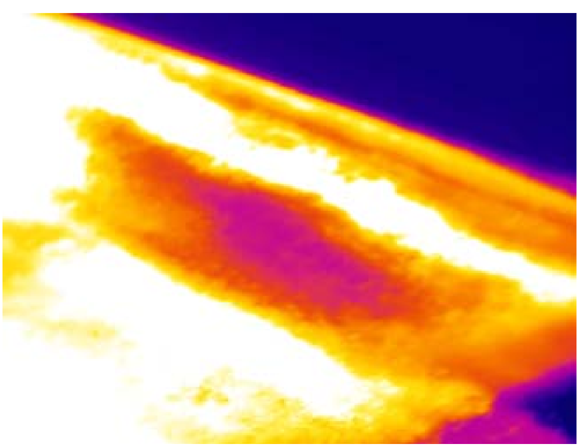
Possible Solutions

- Check operation and function of the screed.

Temperature Segregation: Cold Spots


Low Severity Cold Spot


Moderate Severity Cold Spot


High Severity Cold Spot

Type of Damage

- Localized decrease in pavement density, which can lead to future distress.

Possible Causes

- Material from top layer of HMA in the truck that has cooled during transport.
- Material that was caught in the paver, due to an obstruction, that is cooled before being loosened.

Possible Solutions

- Make sure tarps are being used properly on trucks.
- Monitor paver to see if material is being caught up by an obstruction.

CHAPTER VII: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

One of the most common and costly problems in the paving industry has been segregation of hot mix asphalt (HMA). This problem can occur for many reasons (e.g., improper truck loading) and at many locations during the construction process (e.g., hopper of the paver, etc.). In recent years, temperature segregation has been identified as one of the most important concepts concerning segregation. Therefore, it was necessary to find a tool that will identify temperature segregation immediately during the construction process so that the problem can be rectified. An infrared camera is one of the tools that has been recognized to be effective in identifying temperature segregation. By using an infrared camera, pictures of HMA can be taken throughout the construction process, including the HMA at load out, in the truck during transport, in the truck prior to dumping, in the paver hopper, behind the screed prior to the compaction, and after compaction.

One of the objectives of this study was to investigate variation in HMA mix temperatures during daytime and nighttime paving using an infrared camera. Various steps in the paving operation (e.g., haul, field operations, etc.) were also investigated. Several projects, utilizing several different types of SCDOT mixtures, constructed by different contractors around the state were selected for collection of data. Seven different mix types (Type 1C, Type 3, 12.5 mm Superpave, 19.0 mm Superpave, OGFC, Binder Type 1, and Base Type 1) were evaluated. In addition, the effects of equipment on TDD were studied. Three pieces of equipment that were observed included: traditional paver with conveyor transfer from hopper, paver with auger feed from the hopper, and material transfer vehicle (MTV).

For each project, the contractor and/or the SCDOT inspector for that job were notified. The photos were taken at various stages of each project (e.g., truck bed, behind paver, after compaction, etc.). For each project, several pieces of information were recorded and noted including: equipment types and models used; mixture type; haul distance; ambient temperature; surface temperature; and weather conditions.

In addition to these objectives, the scope was revised to include the filming of paving projects as they were being constructed to find any areas of temperature segregation. Upon finding an area that showed signs of TDD, a thermal image was captured and the location was documented using GPS coordinates. A wide variety of mix types and contractors were studied to get a basic understanding of the occurrence of TDD and the long term effects on pavements. This data has been passed on to the SCDOT for the purpose of continuing research in the area of temperature segregation by SCDOT officials.

Conclusions

Based on the results of this limited study, the following conclusions can be made:

- The thermal camera is an effective tool in identifying temperature segregation in the field during the paving operation. Additionally, the capabilities of the software enable the user to quantitatively determine the severity of such differentials.
- Based on the information collected during this study, there is no evidence indicating that one particular type of asphalt mix is more susceptible to TDD than another.
- The thermal camera was not able to accurately detect temperature differentials in open-graded friction course (OGFC) mixtures. This was likely due to either the thin lift thickness, high void content, or clumps of fiber and binder.
- Based on the asphalt pavers evaluated in this study, there was no discernable difference in the occurrence of temperature segregation between either different paver manufacturers or paver types (i.e., auger-fed or slat-fed).
- The most identifiable cause of temperature segregation within a pavement appeared to be due to either material segregation at the end of a truck load, or the introduction of cooler material as the result of dumping the paver wings. Because the wings were typically dumped at the end of a truck load, it was difficult to identify which was the primary cause.
- The proper utilization of a material transfer vehicle (MTV) (e.g., with a hopper box) appears to be the most effective means to minimize temperature differentials in the pavement mat for many mixtures.
- Based on the projects evaluated, there is no evidence that suggests that the time of day in which paving takes place has an effect on TDD. It is, however, important to mention that the ambient temperature of most of the observed nighttime projects was greater than 70^{o}F. Even though the findings indicate that there is no evidence that TDD increases with nighttime paving, it is believed that this variable does have an effect on the finished asphalt pavement.

- Haul time appeared to be one of the largest factors contributing to TDD. With haul times greater than 70 minutes, the occurrence of temperature segregation increased. For durations less than 70 minutes, there was no major difference observed.

- The analysis of the data did not indicate that one contractor was more effective than another in preventing temperature segregation. It was determined that some practices of a paving crew do lend themselves to either causing, or minimizing the occurrence of temperature differentials (e.g., paver speed, haul truck spacing, wing dumping, and MTV utilization methods).

- There is a correlation with the mat temperature and the ability to achieve pavement compaction. The pavement density in the locations of cold spots was typically less than the areas of the pavement not affected by temperature differentials. Such a reduction in pavement density can lead to future pavement distress such as raveling, rutting, moisture susceptibility, potholes, etc.

Recommendations

Based on the findings of this study, the following recommendations have been made to minimize the occurrence of TDD in South Carolina's asphalt pavements:

- The SCDOT should continue to monitor the construction of future pavements with the thermal camera to identify TDD. This will continue to expand the pool of data necessary to develop contractor's best practices to minimize TDD. It is recommended that the following information be focused on:

    - Observing, repeatedly, the practices of individual paving crews on similar projects. This will provide valuable information regarding the practices that contribute to, or minimize TDD. In particular, the crews should be asked, by SCDOT, to vary the operation of the paver with regard to wing dumping. For example, pave several truck loads with wing dumps after each truck load, then pave several truck loads with more frequent wing dumps, and finally, pave several truck loads without dumping the paver wings.
    - Observing more projects using OGFC mixtures. More data will determine whether a thermal camera could be utilized to detect TDD in such mixes.
    - Observing the effect of nighttime paving in the late fall and early spring on the occurrence of TDD.
    - Observing the effectiveness of auger-fed pavers in reducing TDD.

- Contractors should implement the following techniques to minimize temperature segregation in HMA pavements:

    - Be sure that the asphalt plant is functioning properly and producing mix that is the proper temperature satisfying the SCDOT's specification requirements.

- Be sure to schedule the loading and release of haul trucks so as to reduce the number of trucks in queue at the job site or to prevent paving delays.
- Be sure to properly use the tarps to cover the mix in the haul trucks. This will reduce the amount of wind exposure that can cool the mix during transport.
- Be sure to check that the paver is working properly before paving (e.g., screed function, no obstructions, etc.).
- Be sure to maintain a constant paver speed with no delays. Paving stoppages result in cold joints.
- Be sure to not dump the paver wings between truck loads. In most cases wing dumps tend to lead to TDD.
- Be sure to maintain a continuous supply of mix through the paver. Do not let the paver be overloaded or run low.
- Be sure to use a hopper box when using a MTV. If a hopper box is not available, be sure not to dump the paver wings.

- The locations of temperature differentials identified in this study should be regularly monitored to determine the long-term effects of TDD on pavement performance. This will enable the SCDOT to establish correlations between temperature segregation severity and its effect on long-term pavement performance, which could prove to be valuable information when monitoring the construction of future pavements using a thermal camera.

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APPENDIX A: THERMAL CAMERA AND SOFTWARE OPERATION

Thermal Camera Instructions

One of the activities during this project was to learn how to use the Flir ThermaCam PM695 so that the maximum amount of data could be collected in the field during the study. The following paragraphs are meant to be a brief instruction guide for future users of the thermal camera.

Battery Power

This particular Flir thermal camera has four, two-hour batteries that are used to power the thermal camera. It is recommended that a power converter be assigned to the camera so that the batteries can be recharged at the project site (i.e., in the vehicle).

There are instructions with pictures on both the camera and the battery that will instruct the user on how to insert the batteries in the camera. One of the features of the power supply is that it communicates to the user when the battery power is low by flashing a message on the view screen and flashing the diode light on the rear of the camera. If, for some reason, the battery cannot be switched out immediately, there is still about 10 minutes of power left in the battery. The camera directly stores the information to a memory card, so if the power does run out, and the camera is not shut down properly the information is not lost.

Memory Card

The card only fits in the camera one way, but it has a tendency during transport to become disconnected. When the card is disconnected, pictures cannot be stored. It is a good practice to always check that the memory card is connected when the batteries are being switched out. The memory card is also able to hold an extensive amount of information (approximately 200+ pictures). In general, this is more than enough memory to collect data at a project for 1-2 days. If the project is going to require more than two days of information gathering, either the information must be transferred to a computer or another memory card must be purchased.

Calibration Cycle

Once the thermal camera has been turned on, a calibration cycle begins. This takes about 20 seconds, and once this has taken place the camera will be thermally adjusted to the surrounding environment. The user can then look through the view finder and see the surrounding environment thermally.

Focusing the Camera

To adjust the thermal image, the user must use both the toggle switch and “A” button that are on the camera. The toggle switch is used to zoom and focus the thermal camera. Using the “A” button can also focus the thermal camera. By simply pressing the “A” button, the camera will reset itself so that a range of the different thermal ranges can be seen.

Taking a Thermal Picture

Once the camera has been adjusted, the user can take a picture by simply holding down the “S” button for at least one second. The camera will then take the picture and save the information to the memory card. At this time, the camera will display the message “saving” in the view screen. When this message is no longer seen in the view screen, the camera is ready to take the next picture.

The camera also has a feature where a picture can be taken and frozen in the view screen. The user can then view the picture and determine whether to keep or discard the picture. This feature can be utilized by pressing the “S” button briefly. The image will then become frozen. After deciding to save the picture, the “S” button must be held down for at least a second and the camera will save the picture. If the decision is to discard the picture, the user simply has to press the “S” button briefly and the camera will display what is seen by the lens in the view screen.

Special Features

To activate some of the special features and settings that the thermal camera has, the ENTER button must be used. This button brings up the file window that is present in the top portion of the view screen. At this point, the toggle switch can be used to toggle though the different features that the camera has to offer.

Thermal Camera Software Package

After the thermal pictures have been taken, they must be analyzed using the Flir thermal camera software package. This package has a number of features that can be used to get as much information from a picture as possible. A few of the features include being able to dissect a thermal picture by taking information from a single point, or a cross-section of information along a straight line, or a grouping of information inside a closed shape. The information derived from this process could determine the average temperature, the standard deviation, and maximum and minimum temperatures for that section of the pavement. The data that is taken from the picture can also be used to plot a histogram which will help show the distribution of the data.

Program Startup

To load the pictures in the computer, the button with the file that has the “IMG” associated with it must be pressed. This will bring up another screen that will give the user the ability to select the location where the desired pictures are located. Once this has been accomplished, the user can highlight the desired pictures that need to be studied and the “add” button must be pressed.

Special Features

To highlight certain portions of a picture, simply select the method of data collection by either selecting a single point, a line of data points, or an area of data points. This can be accomplished by pressing the desired button that is located to the left of the thermal picture. Once the button has been pressed, simply use the mouse to place the single point, or the beginning of the line or the corner of the shape, and then move the curser to the desired end point that will encompass the desired data points. The data can then be viewed. This includes either a profile, a histogram, or both. To view these pieces of information simply press the correct tab at the bottom of the screen.

The temperature range of a typical picture could vary, thus, changing the colors of the thermal picture. Selecting the high or low temperature range tabs that are located above the thermal picture in the default window can do this. As the tab is being moved, the thermal picture will instantly rescale itself to incorporate the increased or decreased temperature range.

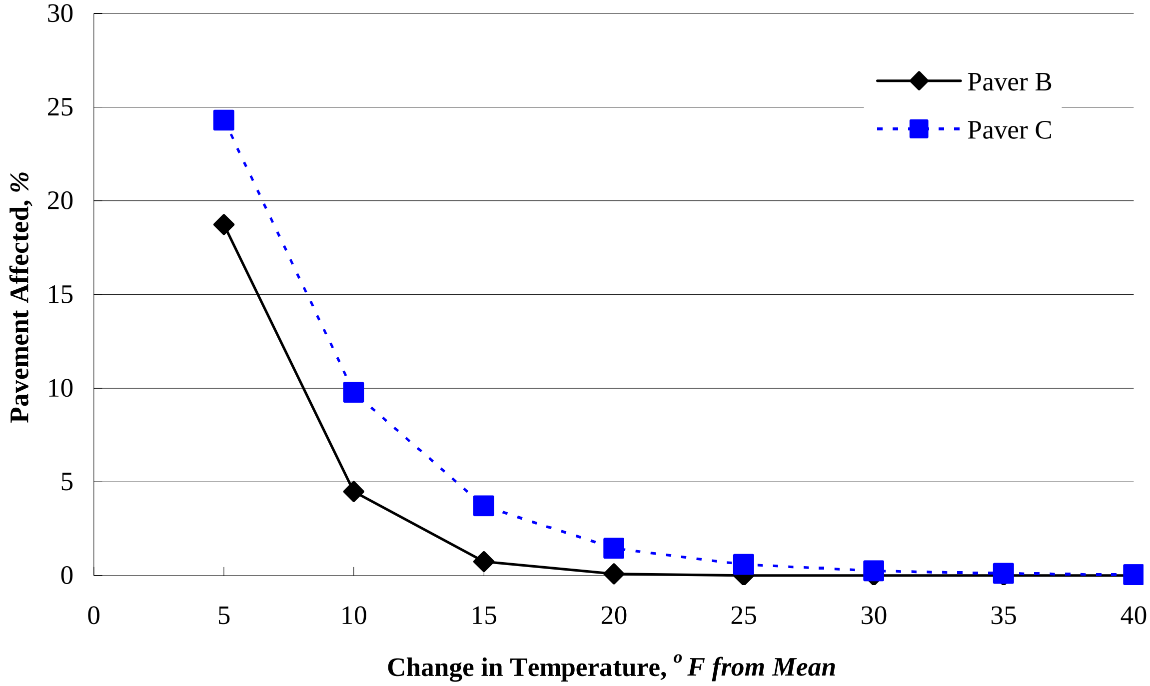

Figure B-1: Comparison of TDD from different asphalt pavers from different manufacturers (30–40 min. haul time).

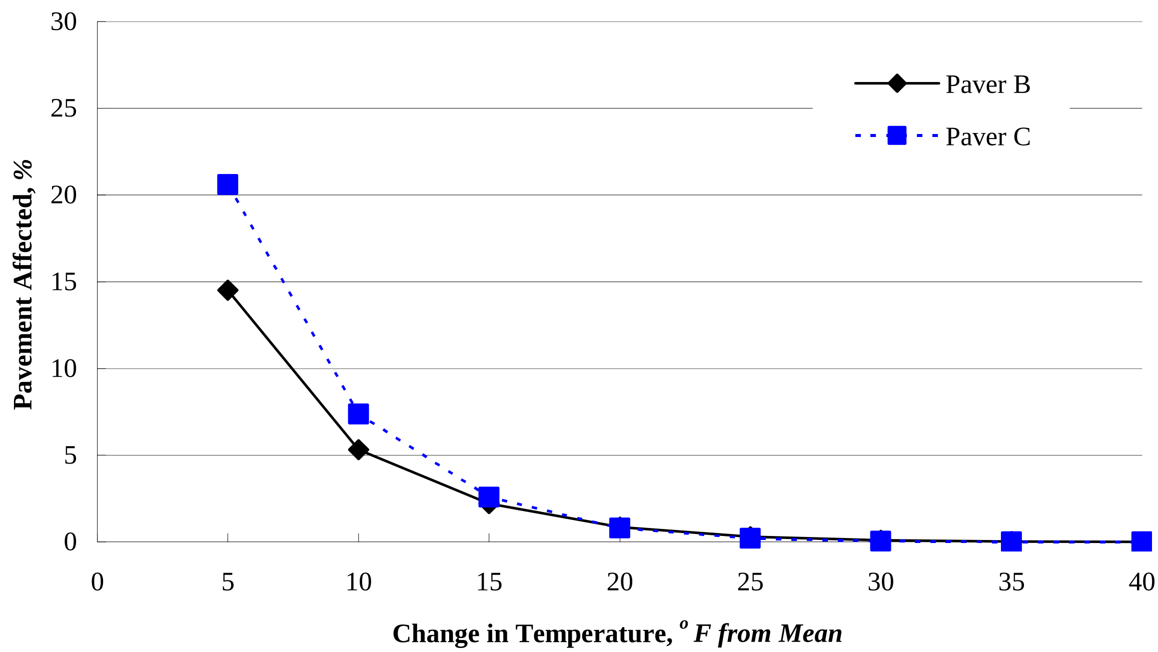

Figure B-2: Comparison of TDD from different asphalt pavers from different manufacturers (40–50 min. haul time, daytime paving).

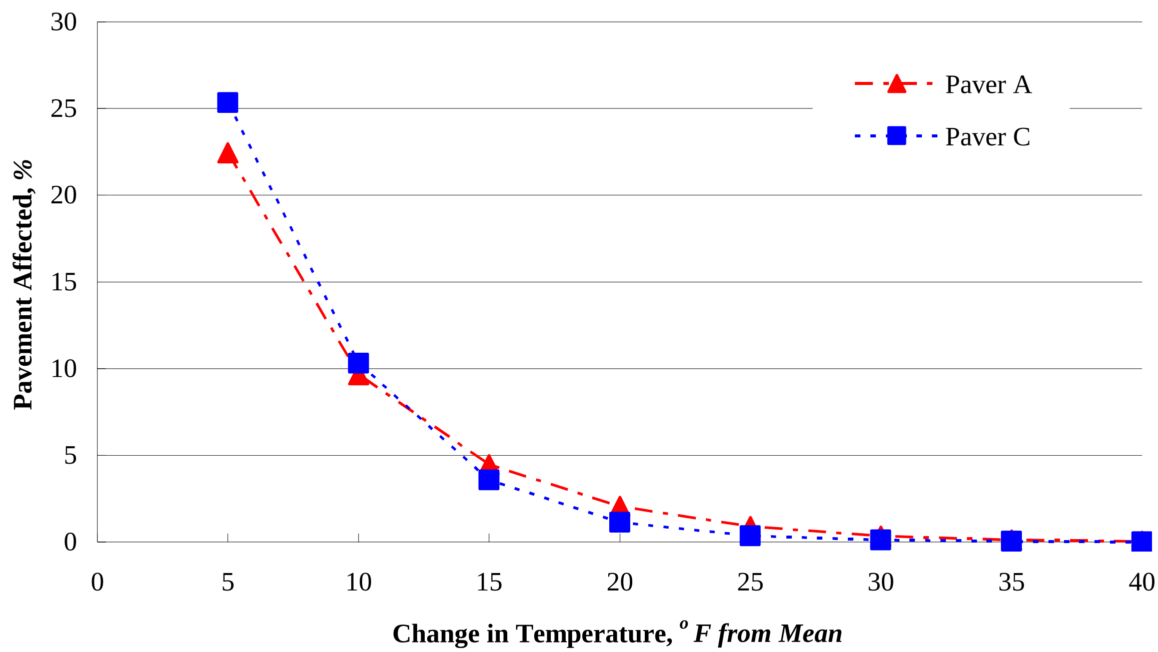

Figure B-3: Comparison of TDD from different asphalt pavers from different manufacturers (40–50 min. haul time, nighttime paving).

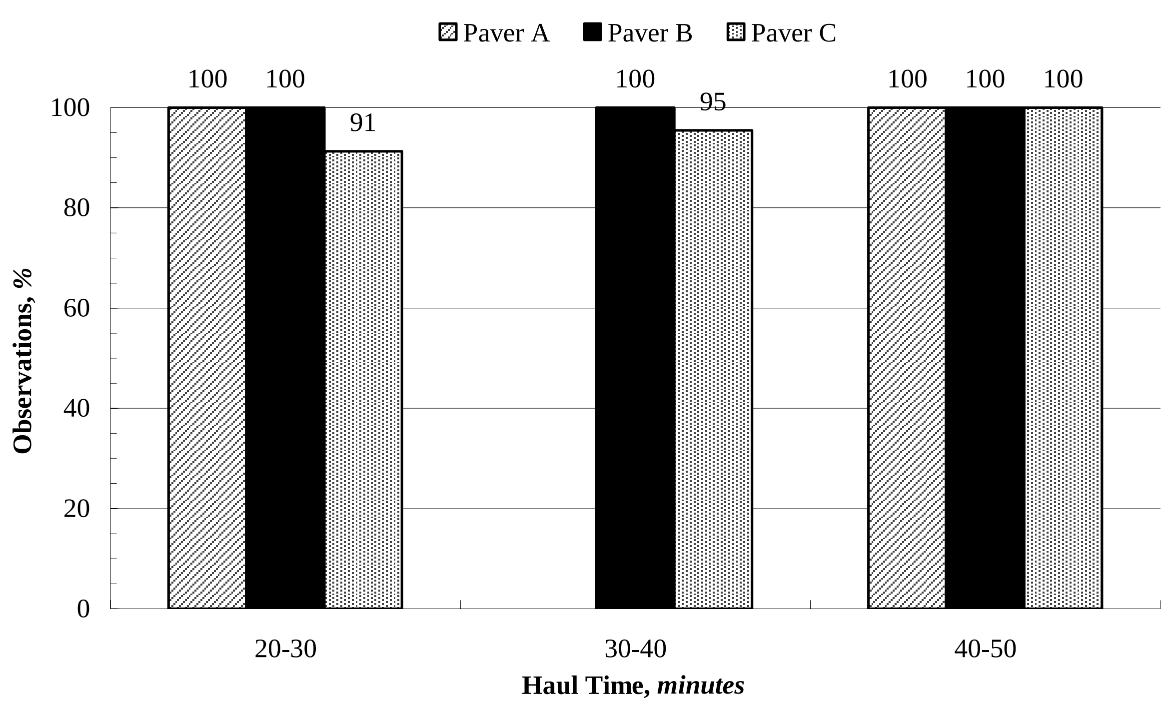

Figure B-4: TDD observations greater than one standard deviation from the mean located behind a paver.

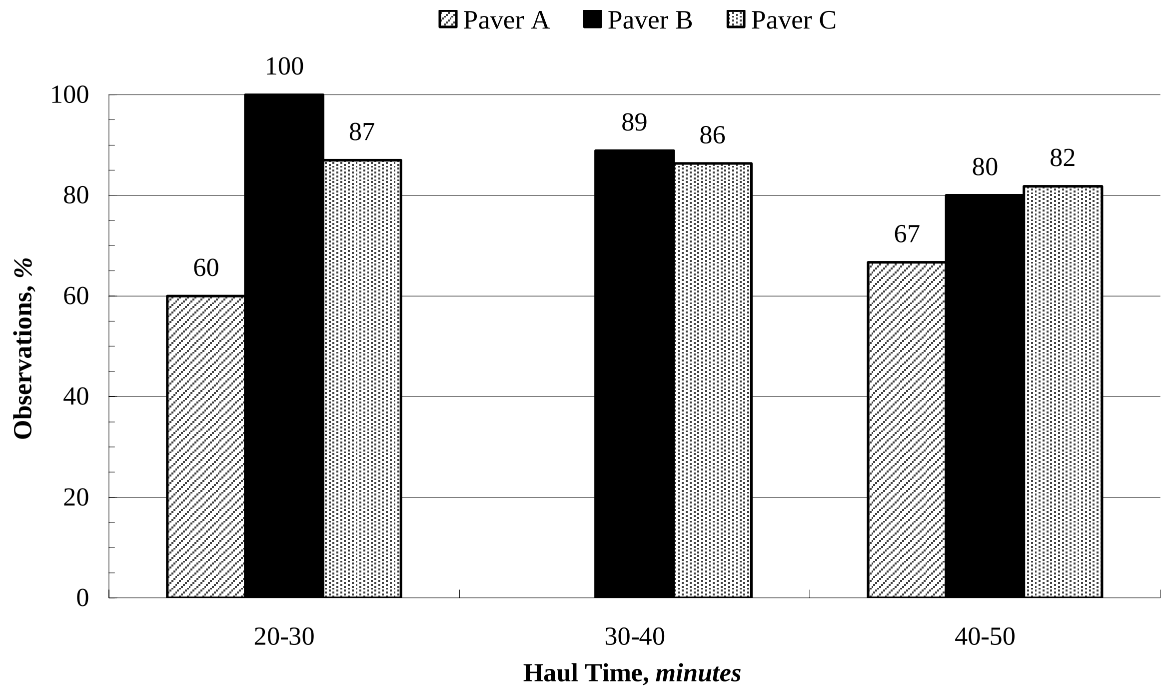

Figure B-5: TDD observations greater than two standard deviations from the mean located behind a paver.

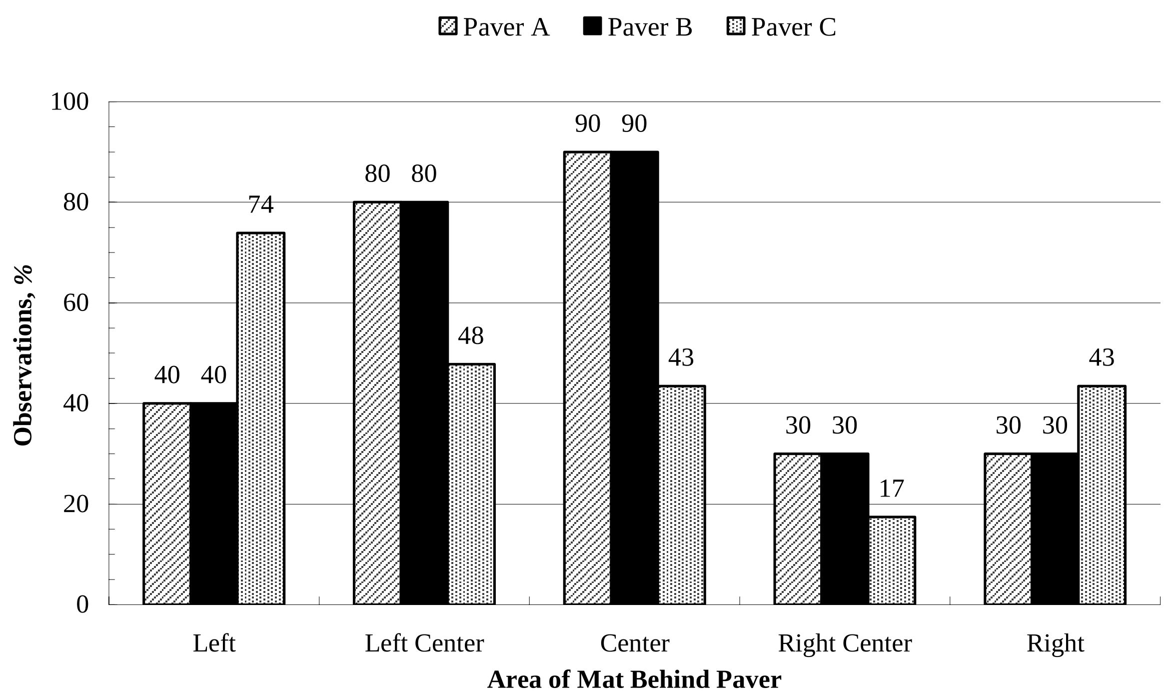

Figure B-6: TDD observations greater than one standard deviation from the mean in different locations behind the paver (20–30 min. haul time).

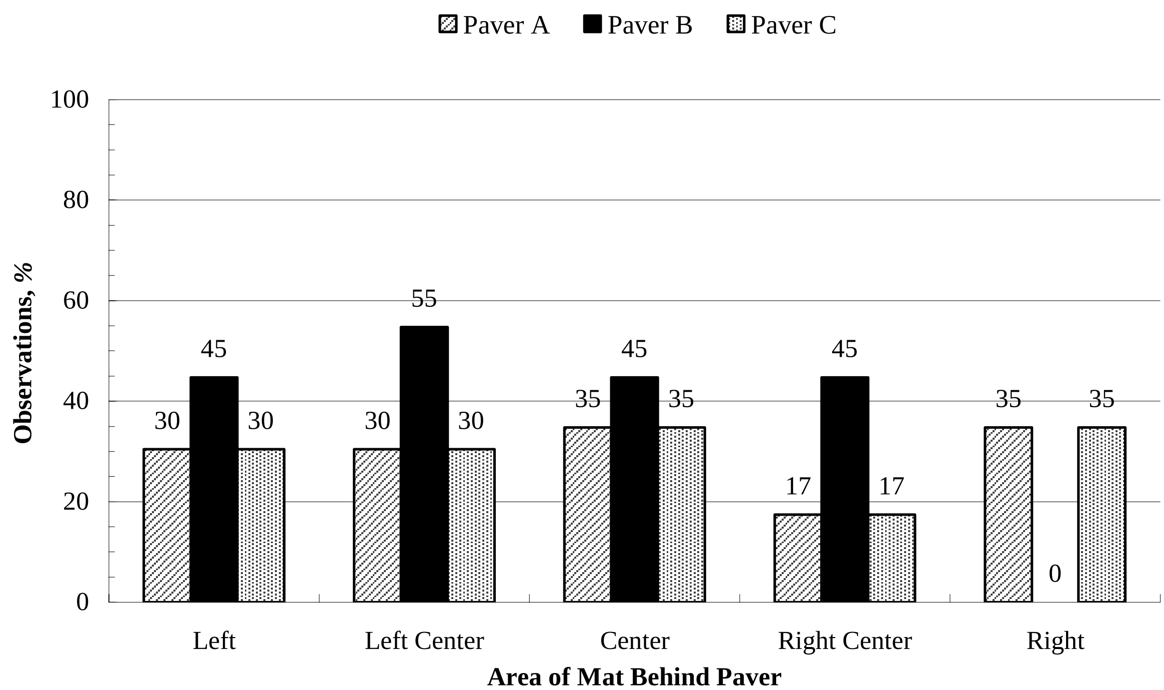

Figure B-7: TDD observations greater than two standard deviations from the mean in different locations behind the paver (20–30 min. haul time).

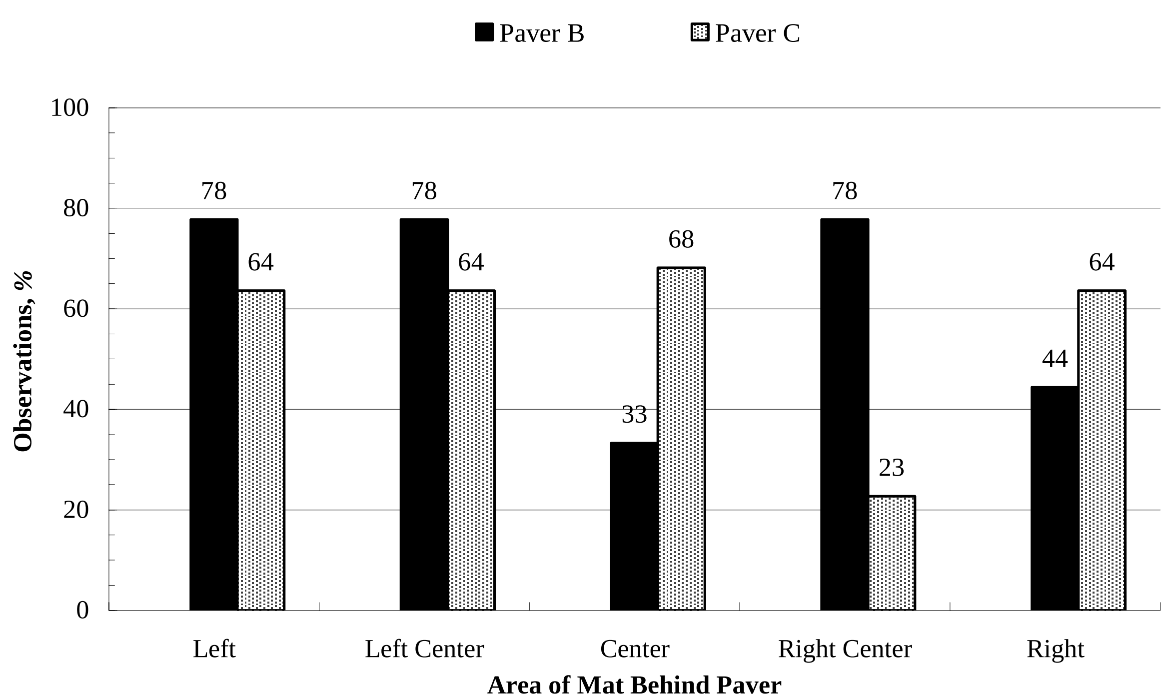

Figure B-8: TDD observations greater than one standard deviation from the mean in different locations behind the paver (30–40 min. haul time).

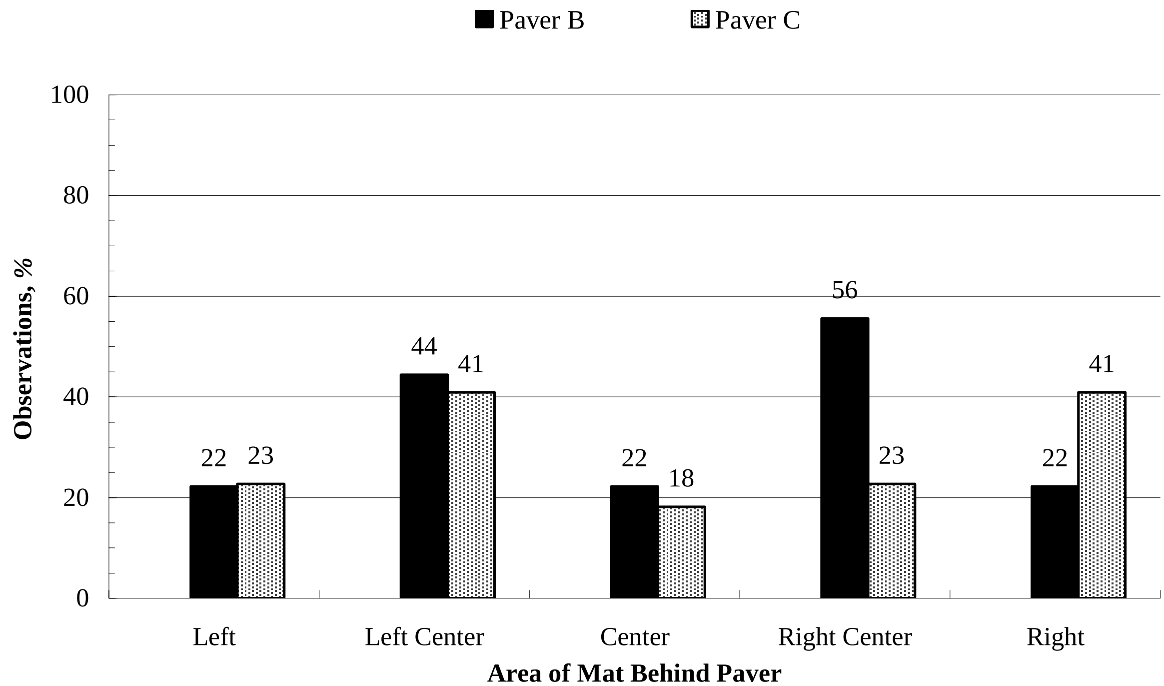

Figure B-9: TDD observations greater than two standard deviations from the mean in different locations behind the paver (30–40 min. haul time).

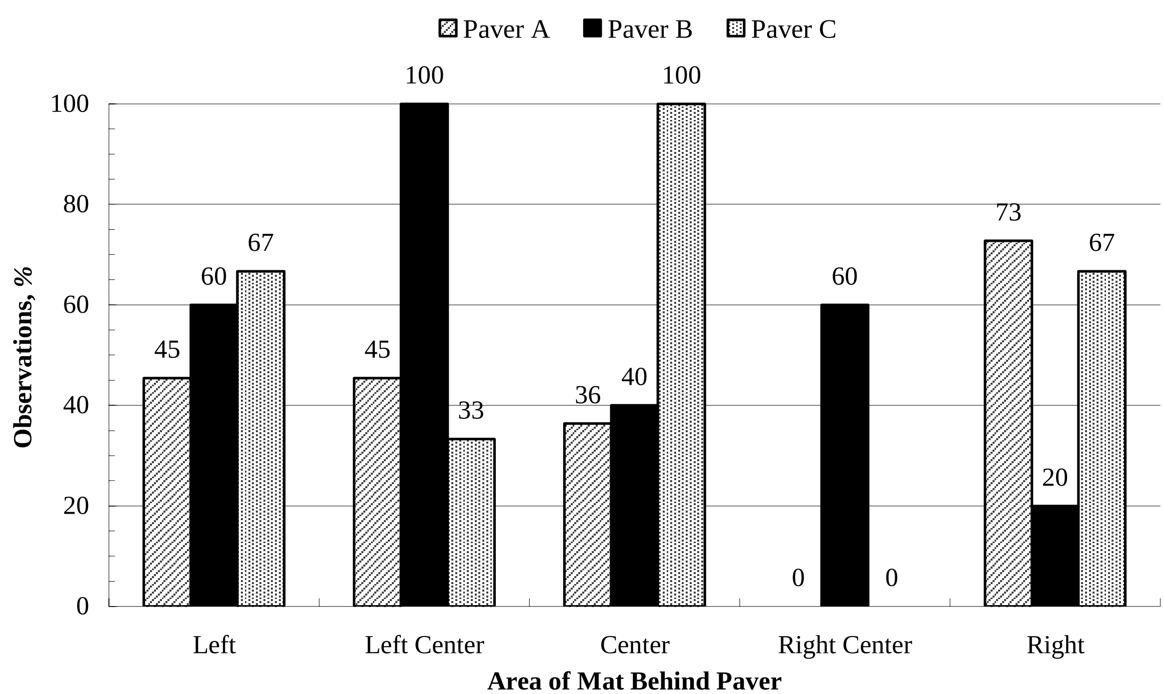

Figure B-10: TDD observations greater than one standard deviation from the mean in different locations behind the paver (40–50 min. haul time).

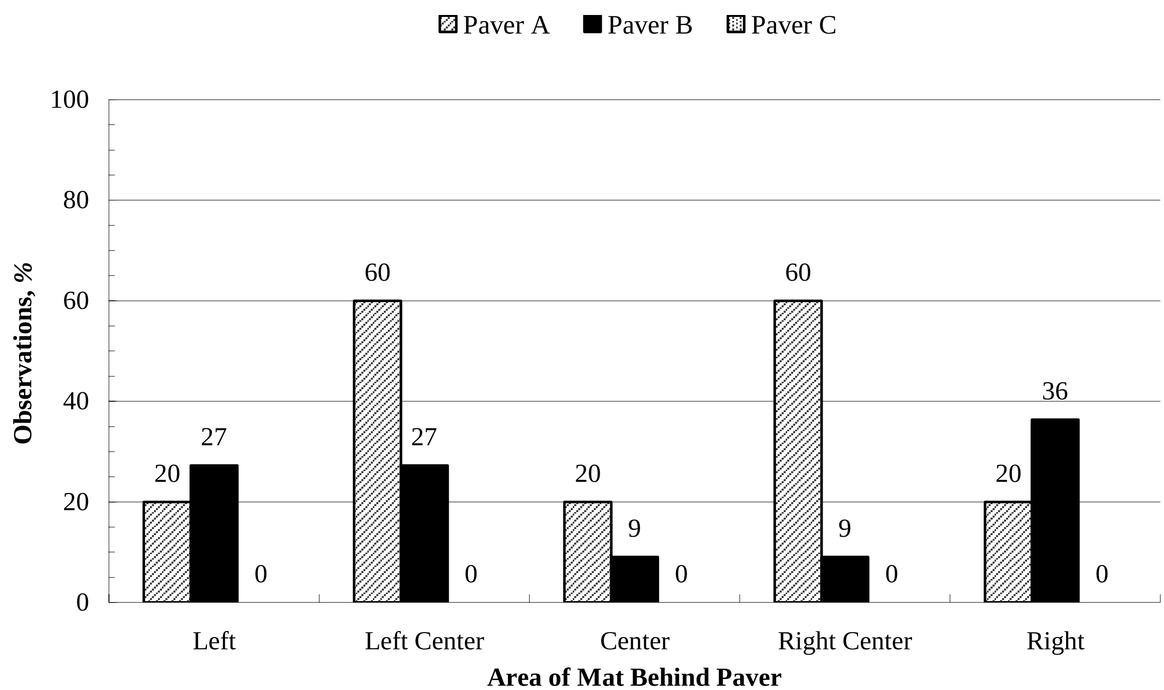

Figure B-11: TDD observations greater than two standard deviations from the mean in different locations behind the paver (40–50 min. haul time).

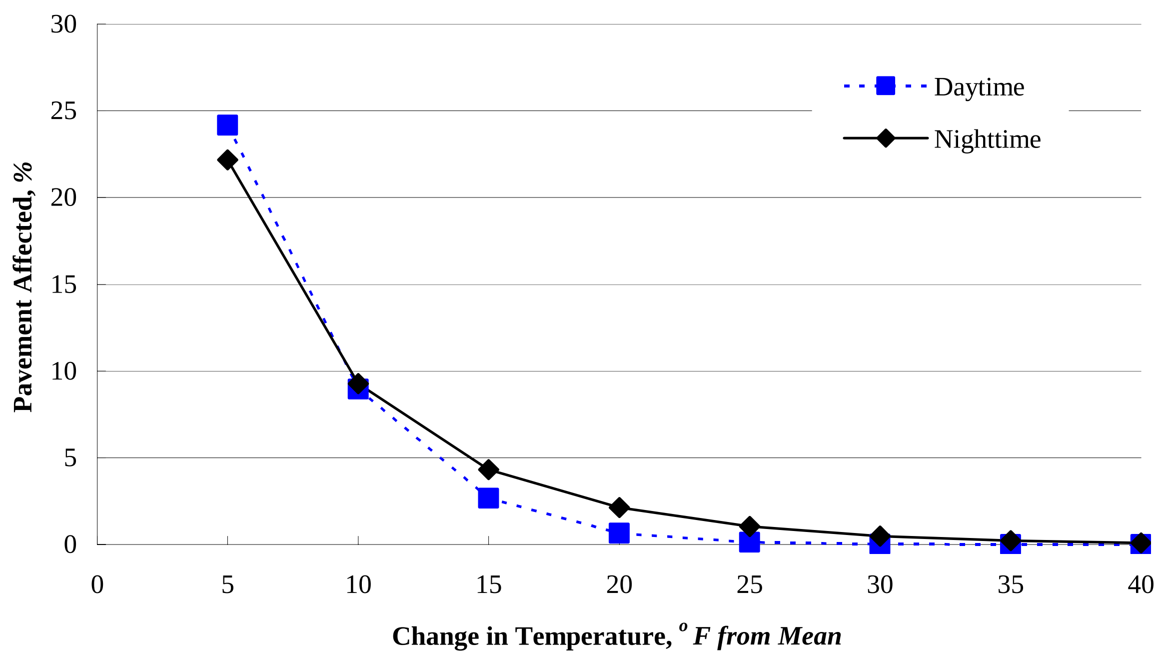

Figure B-12: Comparison of daytime vs. nighttime paving (20-30 min. haul time).

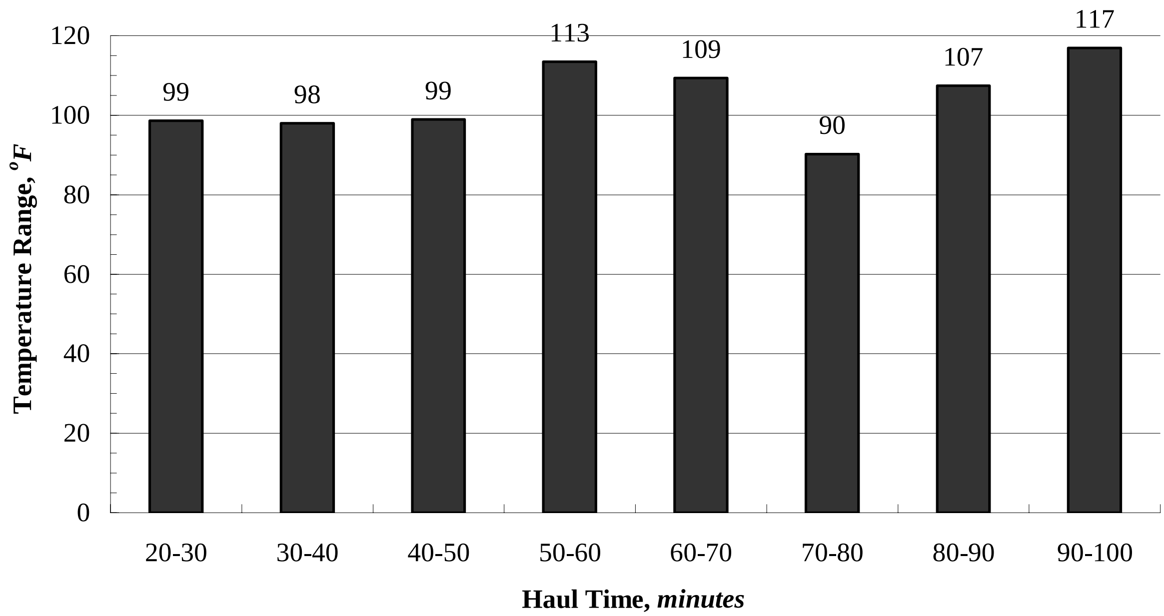

Figure B-13: Temperature range of HMA in trucks with respect to haul time.