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15. Abstract

Purpose and Need

Thermally segregated asphalt mix is difficult to compact because of reduced time window for adequate compaction. In some cases where the mix temperature drops too low to what is referred to as cessation temperature (Dickson and Corlew 1970), adequate compaction may not take place at all. Thus, thermal segregation can result in portions of the pavement not reaching the required density. Decreased density translates into increased air voids, increased permeability, and decreased shear strength, thereby leading to premature pavement distress and shortened service life. While a few studies have been conducted to determine the effects of thermal segregation on long-term pavement performance, several researchers suggested that thermal segregation would produce similar results to those of aggregate segregation. Since thermal segregation of HMA is generally considered difficult to identify by human visual inspection, previous research efforts have examined the potential of using a thermal camera in identifying portions of fresh laid HMA pavement that have substantial temperature differentials. Some of the past research efforts also showed how a thermal camera can be effectively used in identifying potential thermal segregation during asphalt pavement construction (Amirkhanian and Putman 2006).

Objective

The objective of the research reported here was to determine whether or not thermal segregation occurs in North Dakota asphalt pavement construction and if it does, identify probable causes of it and ways to reduce thermal segregation during asphalt pavement construction. This research was also intended to develop guidelines that will aid NDDOT inspectors in identifying potential thermal segregation using a thermal camera.

Scope

To achieve these objectives, thermal images of HMA were acquired from five active asphalt pavement construction projects in North Dakota, over a two-month period from September 2009 to October 2009. Analyses of these acquired images as well as the review of literature formed the basis for the findings reported here. Specifically, the following tasks were performed as part of this research.

Summary

Since a thermal camera can be an effective tool in identifying potential thermal segregation, it is recommended that NDDOT and asphalt paving contractors consider using one during asphalt pavement construction. Their potential use of a thermal camera may be in identifying cold mat areas for subsequent core density testing, which would complement current QC/QA density testing on random core samples. There are several state DOTs that are currently using thermal cameras for similar purposes.

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FINAL REPORT

Use of a Thermal Camera during Asphalt Pavement Construction

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FEDERAL HIGHWAY ADMINISTRATION

EXPERIMENTAL PROJECT REPORT

EXPERIMENTAL PROJECT	EXPERIMENTAL PROJECT NO. 1 STATE: NDSU YEAR: 2008 - NUMBER: 01 SURF: CONSTRUCTION PROJ NO: 8 LOCATION: 28 Cass
	EVALUATION FUNDING 48 1 X HP&R 2 CONSTRUCTION 3 DEMONSTRATION 4 IMPLEMENTATION NEEP NO.: 49 PROPRIETARY FEATURE?: 51 Yes X No
SHORT TITLE	TITLE 52 Use of a Thermal Camera during Asphalt Pavement Construction
THIS FORM	DATE 140 MO. October -- YR. 2009 REPORTING 1 INITIAL 2 ANNUAL 3 X FINAL
KEY WORDS	KEY WORD 1: 145 Thermal Camera KEY WORD 2: 167 Asphalt KEY WORD 3: 189 Pavement KEY WORD 4: 211 Segregation UNIQUE WORD: 233 PROPRIETARY FEATURE NAME: 255
CHRONOLOGY	Date Work Plan Approved: 277 May 2008 Date Feature Constructed: 281 Evaluation Scheduled Until: 285 Evaluation Extended Until: 289 Date Evaluation Terminated: 293 October 2009
QUANTITY AND COST	QUANTITY OF UNITS (ROUNDED TO WHOLE NUMBERS): 297 1 UNITS: 305 1 LIN. FT 2 SY 3 SY-IN 4 CY 5 TON 6 LBS 7 EACH 8 X LUMP SUM UNIT COST (*Dollars, Cents*): 306
AVAILABLE EVALUATION REPORTS	315 CONSTRUCTION PERFORMANCE FINAL X
EVALUATION	CONSTRUCTION PROBLEMS: 318 1 X NONE 2 SLIGHT 3 MODERATE 4 SIGNIFICANT 5 SEVERE PERFORMANCE: 319 1 EXCELLENT 2 GOOD 3 X SATISFACTORY 4 MARGINAL 5 UNSATISFACTORY
APPLICATION	320 1 ADOPTED AS PRIMARY STD. 2 PERMITTED ALTERNATIVE 3 ADOPTED CONDITIONALLY 4 X PENDING 5 REJECTED 6 NOT CONSTRUCTED *(Explain in remarks if 3, 4, 5, or 6 is checked)*
REMARKS	321 Since a thermal camera can be an effective tool in identifying potential thermal segregation, it is recommended that NDDOT and asphalt paving contractors consider using one during asphalt pavement construction. Their potential use of a thermal camera may be in identifying cold mat areas for subsequent core density testing, which would complement current QC/QA density testing on random core samples. There are several state DOTs that are currently using thermal cameras for similar purposes. 700

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Disclaimer

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Executive Summary

There is a growing concern that thermally segregated hot mix asphalt (HMA) pavements result in lower densities. A study reported herein was conducted to determine whether thermal segregation occurs during asphalt pavement construction in North Dakota. Thermal pictures were acquired from five ongoing asphalt pavement projects during the 2008 construction season, and from one of the projects, areas significantly colder than their surrounding pavement areas were found – observations from further analysis suggested paver operations as one possible cause of the cold areas. If thermal segregation is defined as the fresh HMA mat having an area 25°F colder than adjacent areas, thermal segregation does occur during asphalt pavement construction in North Dakota. However, densities of the observed "cold" areas are unknown although many previous research efforts found that densities of cold mat areas tended to be lower than their surrounding higher temperature areas. Furthermore, no well-defined relationship thus far exists between temperature differential and pavement density. Therefore, further research is needed to determine "threshold" mat temperatures below which pavement density is significantly affected and to identify other variables affecting density. A tool could also be developed that can predict pavement density given mat surface temperatures and other influencing variables.

Table of Contents

List of Tables

List of Figures

CHAPTER 1. INTRODUCTION

Since the mid 1980's thermal segregation has been considered a significant construction related problem that can adversely affect asphalt pavement quality. Thermal segregation could occur during the construction of hot mix asphalt (HMA) pavement if significantly cooler HMA is placed into the pavement mat. The cooler HMA placed into the mat originates from the cooler crust that forms on top of loose asphalt mix during transport from the plant to the jobsite. Although hot and cool HMA materials are remixed together in the paver hopper, significant time would be required to achieve a uniform temperature throughout the hopper load.

Thermally segregated asphalt mix is difficult to compact because of reduced time window for adequate compaction. In some cases where the mix temperature drops too low to what is referred to as cessation temperature (Dickson and Corlew 1970), adequate compaction may not take place at all. Thus, thermal segregation can result in portions of the pavement not reaching the required density. Decreased density translates into increased air voids, increased permeability, and decreased shear strength, thereby leading to premature pavement distress and shortened service life. While a few studies have been conducted to determine the effects of thermal segregation on long-term pavement performance, several researchers suggested that thermal segregation would produce similar results to those of aggregate segregation.

Since thermal segregation of HMA is generally considered difficult to identify by human visual inspection, previous research efforts have examined the potential of using a thermal camera in identifying portions of fresh laid HMA pavement that have substantial temperature differentials. Some of the past research efforts also showed how a thermal camera can be effectively used in identifying potential thermal segregation during asphalt pavement construction (Amirkhanian and Putman 2006).

RESEARCH OBJECTIVES

The objective of the research reported here was to determine whether or not thermal segregation occurs in North Dakota asphalt pavement construction and if it does, identify probable causes of it and ways to reduce thermal segregation during asphalt pavement construction. This research was also intended to develop guidelines that will aid NDDOT inspectors in identifying potential thermal segregation using a thermal camera. To achieve these objectives, thermal images of HMA were acquired from five active asphalt pavement construction projects in North Dakota, over a two-month period from September 2009 to October 2009. Analyses of these acquired images as well as the review of literature formed the basis for the findings reported here. Specifically, the following tasks were performed as part of this research.

SCOPE OF WORK

Task 1: Literature Review

Current asphalt pavement construction practices in the Midwest region, including those practices that could be used to reduce potential thermal segregation, were identified. Information was also gathered from other state transportation agencies that are currently using or considering the use of thermal cameras for inspection. The results of Task 1 are presented in Chapter 2.

Task 2: Field Data Collection

Initially, four asphalt pavement construction projects were selected for field data collection, considering asphalt mix types and equipment configurations that are typical in North Dakota. Table 1 lists the initial set of selected asphalt pavement projects. However, due to the construction schedule and site conditions, the Highway 1 project was not observed, and instead Highway 5 project that was carried out by the same construction contractor as Highway 1 project was chosen for field data collection. In addition, field data were collected during shoulder paving in the Interstate 29 project. Table 2 shows asphalt pavement projects from which field data were actually collected. The last two pavement projects observed had some construction activities going on in October so that any seasonal effects on thermal segregation could be studied.

For each of the pavement projects in Table 2, a job site and an asphalt plant were visited to acquire thermal images of HMA to track temperature variations within a single truck load of HMA over the entire construction process from loading to compaction. For some pavement projects, thermal images of HMA were acquired from more than one truck load as the field conditions permitted. During thermal image acquisition, a handheld GPS receiver was used to record the position of a thermal camera so that any potential cold spot or cold run could be located in relation to the camera position. Also during site visit to each pavement project, basic data such as construction equipment being used and ambient air temperatures were collected. Further details of field data collected are described in Chapter 3.

Table 1. Initially Selected Asphalt Pavement Projects

Road Name	Location	NDDOT District
Highway 23	From JCT 83 E to JCT 41	Minot
Highway 1	From NEKOMA SPUR N to JCT 5 LANGDON	Devils Lake
Highway 32	From CO LN N to 0.5 MI N JCT 17	Grand Forks
US 281	From JCT 200 CARRINGTON to S JCT 15	Devils Lake

Table 2. Actually Observed Asphalt Pavement Projects

Road Name	Observed Construction Activities	NDDOT District	Date of Site Visit and Data Collection
Highway 23	Mainline paving	Minot	September 12
Highway 5	Mainline paving	Devils Lake	September 23
Highway 32	Mainline paving	Grand Forks	September 17
US 281	Mainline paving	Devils Lake	October 3
Interstate 29	Shoulder paving	Grand Forks	October 24

Task 3: Data Analysis

Thermal images obtained from each pavement project were manually processed to separate asphalt from other regions captured on an image. This time-consuming manual processing was necessary to determine temperatures of only asphalt from a thermal image. Although the camera vendor's software calculates maximum, minimum and average temperatures of whatever region of interest on an image, it has no capability of automatically recognizing asphalt and thus the software user must indicate the region of interest for which temperatures to be calculated.

Asphalt temperatures measured during distinct construction steps were then compared to each other, in order to identify in what construction steps HMA experienced most significant temperature drops. When significant temperature loss of HMA was noted for one pavement project, potential factors contributing to the heat loss were related to those of other pavement projects to identify any systemic nature that may have affected thermal integrity of HMA. The results of data analysis are reported in Chapter 3.

Task 4: Recommendations for Minimizing Potential Thermal Segregation

Task 5: Guidelines for the Use of a Thermal Camera during Inspection

Based on the results of analysis in Task 3, recommendations were developed that would help to prevent significant temperature loss of HMA and minimize potential thermal segregation during asphalt pavement construction in North Dakota. Finally, guidelines were developed that would assist DOT inspectors in using a thermal camera to assess thermal adequacy of HMA during pavement construction. The results of Tasks 4 and 5 are presented in Chapter 4, along with suggestions regarding effective timing for thermal image acquisition and threshold asphalt temperatures that may merit further investigation through core sampling and density testing.

This report was written to document all activities performed as part of this research, methods used, and results, findings and outcomes of the research. It also contains recommendations for future research.

CHAPTER 2. LITERATURE REVIEW

BACKGROUND

Hot mix asphalt (HMA) segregation has been identified as a significant problem as early as in Bryant (1967). Stroup-Gardiner and Brown (2000) defined segregation as "lack of homogeneity in the hot mix asphalt constituents of the in-place mat of such a magnitude that there is a reasonable expectation of accelerated pavement distress(es)." Depending on what constituent of HMA is lacking "homogeneity," segregation is categorized into aggregate segregation and thermal segregation.

According to Williams et al. (1996), aggregate segregation is "non-uniform distribution of coarse and fine aggregate components." Aggregate segregation result from fine or coarse aggregates being concentrated in some area of asphalt mat and can be identified with significantly different gradation variations from one area of the asphalt mat to another (Adams et al. 2001). As the asphalt mat with aggregate segregation shows different surface textures, aggregate segregation is observable by human visual inspection. It is well known that aggregate segregation adversely affects pavement mat density and air voids, potentially leading to premature pavement distresses and shortened service life. For dense-graded hot mix, one percent increase in air voids (above a baseline value of seven percent) would result in a minimum 10 percent decrease in pavement life (Linden, et al. 1989).

In contrast, thermal segregation is generally considered difficult to identify by the naked eye since it may or may not produce irregularities in the mat surface as aggregate segregation does (Adams et al. 2001). Thermal segregation results from concentrated placement of a cooler mass of HMA into the mat. This cooler mass is generally associated with the surface layer of HMA developed during transport from the asphalt plant to the job site (Read 1996). The cooler mass is usually deposited to the extreme left and right sides of a paver hopper in the wings and is the last to exit the hopper.

As thermal segregation often occurs at the end of each truckload, it used to be called “cyclic segregation” or “end-of-load segregation.” Read (1996) noted most of the “cyclic segregation” areas had less than desirable densities and that they were placed either during night paving operations or near the beginning or end of the normal paving season. These observations by Read (1996) suggested that not only aggregate segregation but also large temperature differentials can result in insufficient compaction, low mat density, and high air voids. Prior to Read (1996), there had been several studies that linked a decrease in achievable density directly to compaction temperatures (Parker 1959; Dickson et al. 1970; Hadley et al. 1971; Geller 1984; and Kennedy et al. 1984). Especially, the study by Parker (1959) indicated that the majority of compaction should be accomplished before the asphalt temperature goes down below 225°F. Willoughby et al. (2001) also suggested that the mat area having temperatures 25°F lower may not be compacted to the same level of density as other areas in the mat.

Since both aggregate and thermal segregation affect density, in-place density testing based on random sampling alone may not distinguish between two types of segregation. A study by Willoughby et al. (2001) reported that areas having large temperature differentials compared to the mat as a whole did not always show significantly different gradation variations. In other words, thermal segregation can occur when there are no signs of aggregate segregation. Thermal segregation could even manifest itself several months after construction is completed. However, once the newly paved road is open to the public, it would be difficult to control traffic and isolate any pavement distresses due to thermal segregation. Therefore, observing temperature differentials in the asphalt mat being laid is a more practical approach to identifying thermal segregation.

Stroup-Gardiner and Brown (2000) evaluated technology and methods used to detect and measure different types of segregation, including infrared technology. While they indicated infrared thermography could be used to specify levels of segregation and for inspecting mat uniformity during construction, Stroup-Gardiner and Brown (2000) pointed out that it cannot distinguish between thermal and aggregate segregation. They recommended that infrared cameras be used during laydown of the hot mix to determine any cooler areas prior to compaction and exclude these areas from the normal random sampling plan for acceptance testing. Given temperature differentials observed during laydown of asphalt mat, Stroup-Gardiner and Brown (2000) defined the levels of thermal segregation to be low (10°C to 16°C; 18°F to 28.8°F), medium (17°C to 21°C; 30.6°F to 37.8°F), and high (greater than 21°C or 37.8°F). They also suggested that payment for any lot with evidence of segregation should be made based on the level of segregation. Their rationale for this is that segregated areas control the life of the entire lot as pavements are typically overlaid or reconstructed rather than receiving localized maintenance. As such, if low levels of segregation are present within a lot, the pay factor may be 90%, consistent with a pay factor for a pavement with a 2% increase in air voids (Stroup-Gardiner and Brown 2000). For highly thermally segregated pavements that have temperature differentials greater than 21 °C (37.8 °F), Stroup-Gardiner and Brown (2000) recommended removal and replacement rather than pay adjustments.

As Brock and Jakob (1997) showed, concentrated cooler mat areas can be identified using an infrared camera. Although inexpensive thermometers and heat sensing guns can be used to measure temperature of points on the asphalt mat being laid, thermal cameras offer the advantage of showing temperature variations of the entire mat (Adams et al. 2001). This advantage allows the camera user to see temperature patterns of the asphalt mat in different colors and rapidly locate portions of the mat that have significantly lower temperatures than the surrounding area. These cool areas often show up on infrared images as small circular spots (“cold spots”), or long columns parallel to the length of the pavement (“cold runs”).

RESEARCH EFFORTS FOR CONNECTICUT DOT

There have been several research efforts that used a thermal camera to study thermal segregation of HMA during construction. One of the earliest studies following Read (1996) and Brock and Jakob (1997) was conducted by the Connecticut Department of Transportation (ConnDOT) and reported in Henault (1999). Eleven ongoing pavement projects were observed in September and October 1998, using an infrared camera to look at the asphalt mix being discharged from the truck to the paver and to the mat and to locate cold spots/areas in the mat. For six of the eleven projects, nuclear density tests were performed at cold spots/areas and adjacent higher temperature areas, and cores were also extracted at three locations from each project for density testing and asphalt content and gradation analyses. A general tendency was found that cold spots/areas were less dense and had higher air voids than their surrounding normal temperature areas. However, the linear association between temperature differentials and density differences was weak, and scatter plots of these variables showed no systematic pattern. This was also the case with a relationship between temperature differentials and increases in air voids. Henault (1999) also reported that asphalt content and gradation of cold spots/areas were similar to those of higher temperature areas. Cyclic occurrences of low temperature spots were observed when the paver's hopper wings were folded between truck loads, and a substantial reduction in temperature differentials on projects paved with some type of remixing equipment. Henault (1999) recommended that remixing equipment or an appropriate number of hauling units be employed to ensure smooth paving operations and hence minimal temperature differentials.

Following Henault (1999), Mahoney et al. (2003) observed forty (40) ConnDOT asphalt paving projects with a thermal camera. Infrared images were taken at the location where the paver stopped to change haul units when there was no material transfer vehicle (MTV) used. They calculated the temperature differential as the difference between the warmest and coolest spots on an individual thermal image. Nuclear density readings were taken at three foot intervals in a longitudinal line beginning fifteen feet before the coolest spot and ending fifteen feet after the cold spot, and the lowest density obtained within six feet of the cold spot was compared to the highest density of the longitudinal profile. Plotting density difference versus temperature differential, Mahoney et al. (2003) found a slight trend that as the temperature differential increases, the density difference increases.

From a plot of temperature differential against haul distance (with all projects using an MTV excluded), Mahoney et al. (2003) noted a weak trend that as the haul distance increased, the temperature differential increased. However, the rate of increase of temperature differential tended to diminish over long hauls. Cold spots observed from projects with varying haul distances were rather similar in terms of the magnitude of temperature differential but were appreciably different in their physical size. On the other hand, the magnitude of temperature differentials was smaller for one project with a haul distance of 56 miles that used an MTV than for another project with a shorter haul distance (43 miles) that was paved by the same crew and supplied by the same HMA plant but with no MTV. According to the study by Mahoney et al. (2003), the occurrence of cold spots has more to do with the interaction between haul units and the paver hopper, rather than with haul distance. Two other observations of theirs that supported this were:

- Most of the cold spots observed from projects using no MTV occurred 25 to 30 feet after the paver stopped for a truck change, and temperature differentials were much greater when the hopper wings were folded infrequently, which would expose the material from previous loads to the ambient air for an extended period of time.
- For projects where an MTV was used for a small portion of the project, the normally observed cold spots were virtually eliminated or greatly reduced. The only change to the equipment on the project when an MTV was employed was the remixing insert into the paver hopper.

Noting that the paver hopper can become a major source of the material that forms cold spots, Mahoney et al. (2003) recommended frequent, regular folding of hopper wings (or no folding at all during the day’s production) and the use of MTVs. They also indicated that the spillage of HMA in front of the paver should be removed since it can contribute to the formation of cold spots depending on several factors such as the length of time till the paver passes over the spill. For projects in which haul units dump HMA directly into the paver hopper, they suggested that the haul distance which can increase the size of the cold areas be kept to minimum.

Other variables that Mahoney et al. (2003) examined but had the difficulty finding a significant effect on temperature differentials include: mixture gradations, Marshall vs. Superpave mixes, compacted thickness, seasonal differences, and day vs. night time paving. While it is “next to impossible” to control these variables to isolate a single factor, the last two variables involved other issues. To examine seasonal differences, the temperature differentials were averaged for each month excluding data from projects using MTV; however, the temperature differentials did not grow larger as the weather became colder. Considering that average high and average low mat temperatures for November were significantly lower than for other months, temperature itself rather than temperature differential would have been more useful in identifying any seasonal effects on thermal segregation. For comparison of day and night time paving, the issue was lubricating water from steel wheel rollers that affects the mat surface temperature, and it was not possible with a thermal camera to correctly measure cooling rates of HMA as it is compacted, which would be different at night than they are during the day. As such, the temperatures of HMA were measured as it came out from behind the paver screed, and the temperature differentials for night paving projects were not much different from those of day paving projects (Mahoney et al. 2003).

Another important conclusion of Mahoney et al. (2003) is that thermal segregation can leave the pavement surface with an open texture as aggregate segregation does, making it difficult to differentiate the two types of segregation by both the naked eye and a thermal camera. They considered identifying the problem as either aggregate or thermal segregation to be a “stumbling block” to reducing segregation, and they emphasized the importance of this identification given that the methods to address each type of segregation may be very different.

Henault et al. (2005) monitored selected sites from the 1999 pavement projects (Henault 1999) for five years following construction, but the results of the five-year pavement condition survey showed little relationship between temperature differentials and pavement distress. Henault et al. (2005) hypothesized that “thermal segregation has a negligible effect [on pavement density] until cold area temperatures drop below certain threshold values,” and they suggested that “density achieved is more dependent on HMA temperatures than temperature differentials.” They also noted that other factors (mix design, base course, lift thickness, climate, and paving and compaction equipment) may have a more profound effect on pavement density than temperature differentials do. Their case in point was that one site paved over a cold-in-place recycled base course had the most severe temperature differentials but “held up the best” of all other monitored sites that were paved over existing pavements and in five years developed extensive reflective cracking. Therefore, Henault et al. (2005) recommended that incentive/disincentive payments and repairs/replacement not be specified solely by temperature differentials.

RESEARCH EFFORTS FOR WASHINGTON DOT

The Washington State DOT (WSDOT) performed an extensive study looking nearly 60 asphalt pavement projects over three years from 1998 through 2000 (Willoughby et al. 2001). During the 1998 paving season, four projects were chosen for study that were expected to have large temperature differentials – the projects were sampled either early or late in the paving season, or were night paving jobs. Using a thermal camera, mat surface temperatures were measured directly behind the paver screed before any compaction took place. Typical normal mat temperatures ranged from 222°F to over 300°F while cooler area temperatures ranged from 184°F to 262°F. Thus, the temperature differences between 13 pairs of cooler areas and the surrounding normal areas varied from 12°F to 70°F with an average of 38°F.

From nuclear densities and cores obtained following final compaction, it was found that the cooler mat areas always exhibited higher air voids by 1.6 to 7.8 percent with an average of 3.9 percent. Gradation and asphalt content analyses did not show significant differences between the normal and cooler areas, which leaves temperature differentials as the probable cause for an increase in air voids. However, Willoughby et al. (2001) noted that cooler portions in the mat may not always result in accelerated pavement distress if good paving and rolling practices are used that can offset the effects of temperature differentials. Specifically, they suggested that pneumatic rollers could be included in the compaction train as a breakdown or intermediate roller and consistently operate close to the paver to quickly compact isolated cooler areas.

The WSDOT’s 1999 study program was intended to determine possible effects of different factors (haul time, type of haul truck, and remixing) on temperature differentials. A total of 36 asphalt pavement projects were observed, and mat surface temperatures prior to compaction were measured directly behind a paver using a thermal camera. The typical (normal) mat temperatures varied from 225°F to 283°F, and the temperature difference between the normal and cooler portions of the mat varied from 8°F to 80°F. In general, the longer the haul time, the greater the temperature differential. Specifically, 70% of the projects with the haul time greater than 20 minutes had temperature differentials of 25°F or greater while only 35% of the projects with the haul time less than or equal to 20 minutes did so. However, the linear relationship of haul time and temperature differential was weak, and even when the haul time was less than 5 minutes, large temperature differentials were seen if the hot mix was not remixed in the paver or a material transfer vehicle/device.

On the other hand, remixing through some type of material transfer vehicles/devices seemed to have a more decisive effect on temperature differentials than did the haul time or the type of haul truck. Projects that used bottom belly dump trucks together with windrow elevators showed temperature differentials ranging from 8°F to 36°F, which is comparable to those (10°F to 40°F) of the end dump operations using a windrow elevator. Regardless of haul time, the end dump operations using a shuttle buggy showed temperature differentials less than 25°F (ranging from 10°F to 12°F) while the end dump operations with no material transfer vehicles or devices experienced temperature differentials ranging from 43°F to 80°F.

The 1999 study program also examined potential effects of other factors (air temperature, existing pavement surface temperature, and mix laydown and breakdown rolling temperatures) on in-place air voids. Although no strong correlation between any single factor of these and air voids was found, a laid mat area with temperature differential less than 25°F had the range of air voids under 2% more often times (87% as opposed to 35% when temperature differentials were greater than 25°F). This means that the asphalt mat with low temperature differentials can be compacted to more uniform densities (or air voids). In case of large temperature differentials that can result from end dumping with no remixing, there will be less time to adequately compact and thus aggressive breakdown rolling with pneumatic rollers can help to reduce variability of air voids in the mat.

While the 1999 study found a general relationship between increasing temperature differentials and increasing air voids, the 2000 study program focused on evaluating a “density profile” method with 17 pavement projects. In this method, the location of a 50 feet long profile on the compacted mat is determined based on temperature differentials and if the temperature differential is over 25°F, that profile is tested for nuclear density at every five feet. A density profile passes if the density range (maximum – minimum) is within 6 pcf and the density drop (average – minimum) within 3 pcf. From the 17 projected visited during 2000, a total of 69 density profiles were taken. 33 (over 80%) of the 41 profiles taken in areas with temperature differentials of less than 25°F passed, but only 3 of the 28 profiles from areas with temperature differentials of 25°F or greater passed. This suggests that pavements that experience large temperature differentials can produce substantial density differentials. As random quality assurance tests do not capture cooler temperature areas, those QA tests for the 17 study projects typically showed passing densities. Conversely, when density readings from each profile were expressed as a percent of maximum theoretical density as for QA, 27 of the 33 profiles that failed profile tests would have also failed QA tests.

From the 2000 study, it was also observed that when the temperature differential was 25°F or greater, 20% of the density profiles related to pneumatic rollers met the test criteria while none of the profiles compacted by only steel wheel rollers passed the test. This suggests that the impact of *large* temperature differentials on density can be mitigated by including in the compaction train pneumatic rollers as the breakdown or intermediate roller. In case the temperature differential was lower than 25°F, it made little difference whether the compaction train consisted of only steel wheel rollers or included a pneumatic roller.

Summarizing all the data collected over the three construction seasons in Washington, Willoughby et al. (2001) made the following conclusions:

- End dump operations without remixing can often cause cyclic patterns of cold spots, which usually lead to lower density.
- Temperature differentials tend to decrease when remixing occurs, and material transfer devices and vehicles, when properly operated, can reduce temperature differentials.
- Timely compaction and the use of pneumatic rollers may be able to mitigate some of the impact of temperature differentials on density.

At the same time, they noted that these equipment and techniques can be used to offset the occurrence and effects of temperature differentials but no one single piece of equipment or operation would guarantee that temperature differentials will not occur. Finally, Willoughby et al. (2001) added that even if temperature differentials exist, the finished pavement can serve its purpose for its intended length of time if it has a uniform density of 93 percent or greater (for dense-graded mixes).

RESEARCH EFFORTS FOR MINNESOTA DOT

In a Minnesota DOT (Mn/DOT) research, Adams et al. (2001) analyzed infrared temperature data collected on 16 asphalt pavement projects during September to November 2000. A total of 64 density profiles were obtained through the similar procedure to that used in the WSDOT study program and were examined according to the same criteria (density range within 6 pcf and density drop within 3 pcf). While 27 (over 90%) of the 29 profiles taken in areas with temperature differentials of less than 25°F passed, only 17 of the 35 profiles from areas with temperature differentials of 25°F or greater passed. Consistent with Willoughby et al. (2001), Adams et al. (2001) also found a general relationship between increasing temperature differentials and increasing density differences and suggested that if the asphalt mat laid has temperature differentials within 25°F, it would likely have little or no reduction in density.

In view of some outlining data, they however noted that a large temperature differential in a profile does not necessarily mean a large density difference. While the Mn/DOT research did not show if the temperature differentials and density drops observed were significantly influenced by asphalt mix type, haul time or use of remixing equipment, Adams et al. (2001) underscored the importance of using good paving practices in achieving uniform mat densities, particularly under large temperature differentials. They enumerated specific construction events to be avoided to minimize the occurrence and effects of temperature differentials, which include: (1) allowing the paver to stop; and (2) emptying the paver hopper.

RESEARCH EFFORTS FOR COLORADO DOT

Similar to Adams et al. (2001), Gilbert (2005) adopted 25°F of temperature differential that Willoughby et al. (2001) had determined may lead to inadequate compaction. Twenty Colorado DOT paving projects were visited, and areas of the asphalt mat that were at least 25°F colder than adjacent areas were identified using a thermal camera. “Cold” areas identified were tested for percent relative compaction and compared to adjacent “hot” areas, in order to determine if cold areas would have lower densities. In fact, most of the “cold” areas had lower percent relative compactions than their adjacent “hot” areas; however, almost 60% of the “cold” areas still achieved the minimum 92% relative compaction.

Gilbert (2005) also collected and examined data such as use of MTVs and windrow elevators, truck type, and mixture gradations, in order to identify practices or factors that could help to reduce thermal segregation. The data showed that when a windrow elevator that does not remix material was used, the frequency of “cold” areas was comparable to that with a material transfer vehicle that does remix. In contrast, where no windrow elevator or MTV was used, “cold” areas were found far more often times, nearly 80% of which is accounted for by direct end dumps – the remaining 20% corresponds to the projects in which HMA was unloaded directly into the paver through the sole use of live bottom trucks or mixed use of live bottom and end dump trucks.

Coincidentally, all of the direct end dumps without an MTV took place in projects that specified coarse gradation mixes, which experienced three times more frequent occurrence of “cold” areas than for finer gradation mixes (one “cold” area per every 68 tons of coarse gradation mixes, opposed to one per every 214 tons for finer gradation mixes). Thus, it appeared that “a great deal of Colorado’s temperature segregation problems could be solved simply by using [finer] SX gradation mixes instead of [coarse] S gradation mixes.”

As “cold” spots occurred in end dumps discharging into the paver ten times as often as in end dumps feeding into an MTV, Gilbert (2005) suggested that “end dump trucks should not be used without an MTV if temperature segregation is a concern.” Besides the type of equipment used in paving, the use of industry best practices was considered to play an important role in reducing thermal segregation; for example, keep a constant flow of material going to the paver, and keep the rollers close to the paver.

SUMMARY

Through the tremendous research efforts and numerous field observations made since the late 1990’s, it has become clear that thermal segregation adversely affects asphalt pavement density. However, attempts to identify factors that significantly contribute to temperature differentials have had limited success. While a general trend was found between increasing haul distance and increasing temperature differential, none of the factors previously examined has been found to have a strong correlation with observed temperature differentials. Even seasonal effects expected of paving jobs in lower ambient temperatures contradicted the perception that temperature differentials would grow larger. Nevertheless, the prior research efforts identified several factors that appeared to be effective in reducing the magnitude of temperature differentials, including the use of MTVs/MTDs and aggressive breakdown rolling. These operational factors had formed the basis of best practices that the asphalt paving industry has been using to reduce thermal segregation.

CHAPTER 3. DATA ANALYSIS

DATA COLLECTED

For each of the five pavement projects shown in Table 2 (page 3), a one-day site visit was made to collect project specific data such as haul distance, equipment being used and ambient air temperatures. As shown in Table 3 below, the five projects visited were paved by four different contractors and varied in haul distance ranging from 4 miles to 27 miles. Typically, the paving projects employed two different types of haul trucks on a single job, live belly trucks and bottom belly trucks, to have HMA delivered to the job site, and used a windrow elevator to pick up the material discharged onto the existing pavement and feed it into the paver hopper. All the paving projects were using three compactors as breakdown, intermediate, and finish rollers, except for the I-29 shoulder paving where only two rollers were operating at the time of site visit. All the compactors in use except one were of tandem steel wheeled, vibratory types. Ambient air temperature was higher than 70ºF for the first two paving projects that were visited in September, and it came down to 56ºF on the day in October when the last site visit was made.

Also during site visits, thermal images were acquired using an infrared camera Fluke Ti40FT (Figure 1) at the times of HMA being loaded, unloaded, laid down, and compacted. Attempts were made to take thermal images of a single truck load of HMA over the entire construction process if the field conditions permitted. During thermal image acquisition, a handheld GPS receiver was used to record the position of the camera so that the scenes captured on images could be located in relation to the camera position.

Figure 1. The thermal camera used

Table 3. Project Specific Data Collected

1 Route	2 District	3 Site visit date	4 Contractor	5 Mix type	6 Compacted thickness	7 Haul distance (mi)	8 Haul truck	9 Pick-up machine	10 Paver
Hwy 23	Minot	9/12/08	A	Superpave FAA[1] 45	1st lift 2" + 2nd lift 2"	16	live belly, bottom belly	In use, make and model not recorded	CAT AP 1055D (track-mounted)
Hwy 32	Grand Forks	9/17/08	B	Superpave FAA[1] 40	1st lift 1.5" + 2nd lift 1.5"	18	live belly (cap. 30 ton), bottom belly (cap. 28~29 ton)	CAT WE 851B	Blaw Knox PF 3200 (wheel mounted)
Hwy 5	Devils Lake	9/23/08	C	Superpave FAA[1] 45	1st lift 2" + 2nd lift 1.5"	27	Bottom belly (no live belly trucks seen during visit)	In use, make and model not recorded	CAT AP 1055B (track-mounted, self-propelled), Blaw Knox PF 3180 (wheel mounted)
US 281	Devils Lake	10/3/08	B	Superpave FAA[1] 43	1st lift 2" + 2nd lift 2"	4	live belly (10 ea), bottom belly (8~9)	CAT WE 851B	Blaw Knox PF 3200 (wheel mounted)
I-29	Grand Forks	10/24/08	D	Marshall (PG58-28)	1st lift 2" + 2nd lift 2"	24	live belly, bottom belly	Cedarapids MS-1	Blaw Knox PF 5510 (track-mounted)

Note: [1] fine aggregate angularity

Table 3. Project Specific Data Collected (Cont'd)

1 Route	11 Breakdown roller	12 Intermediate roller	13 Finish roller	14 Weather	15 Air temperature	16 Remarks
Hwy 23	CAT CB-634C (tandem, vibratory)	HD-120 HAMM (tandem vibratory)	BOMAG BW 202ADH (tandem vibratory)	sunny, wind 15 mph	High 78 ºF	4 haul trucks in queue for dumping
Hwy 32	Dynapac CC 722 (tandem vibratory)	Dynapac CC 622 VHF (tandem vibratory)	CAT CB 634C (tandem vibratory)		High 73 ºF	No delay between trucks
Hwy 5	CAT CB 534D (tandem vibratory)	Dynapac CP 271 (pneumatic, self-propelled)	CAT CB 634C (tandem vibratory)	cloudy, T-storm morning and afternoon, wind 16 mph, had 1.5" rain the night before	High 68.0 ºF, Low 51.0 ºF	No thermal images were taken of HMA loaded at asphalt plant because of weather.
US 281	Dynapac CC501 (tandem vibratory)	Dynapac CC 622 HF (tandem vibratory)	CAT CB 634C (tandem vibratory)	clear sky, breezy	High 65.8ºF, Low 37.2ºF	Cold-in-place RAP base
I-29	IR DD 130 (tandem vibratory)	IR DD 130 (tandem vibratory)		clear sky, breezy 5 mph	High 56.8ºF, Low 32.4°F	25% RAP, trucks covered with a tarp

APPROACH TO DATA ANALYSIS

To determine the occurrence of thermal segregation, one needs sound, quantitative definition of thermal segregation. From the literature review presented in the previous chapter, it is observed that there is no such definition and that temperature differential has been used as a primary criterion to identify thermal segregation in the fresh laid asphalt mat. However, it is argued that temperature differential is an inadequate term to define thermal segregation and that cold spots determined on the basis of temperature differential should not be taken as thermal segregation. Unlike the percent passing on standard sieves (the "fixed" benchmark) used to determine aggregate segregation, the magnitude of temperature differential (the "floating" benchmark) changes depending on temperatures of the surrounding mat area and so does the occurrence of cold spots.

For example, consider two different mat areas: one whose minimum and maximum temperatures are 230ºF and 260ºF, and the other with 200ºF and 230ºF. If a certain value of temperature differential, say 25ºF, is taken to indicate "cold" spots, cold spots in the former mat are 230ºF to 235ºF high, and those in the latter are 200ºF to 205ºF. Thus, a 230ºF spot is a cold spot in one mat and is not in the other mat. With the same value of temperature differential, these two mats may or may not be compacted to the same density, and the resulting densities may or may not meet the specified density requirements. Even though areas 25ºF colder than adjacent areas would have lower densities as many previous research found, some of the "cold" areas may still be able to achieve the specified density through the use of material transfer vehicles, aggressive breakdown rolling, etc. Furthermore, if the in-place density of a "cold" spot does not achieve the specified density, it may be due to either thermal segregation, or aggregate segregation, or both. Thus, determination of thermal segregation requires not only testing "cold" spots for nuclear density and/or core density but also gradation analysis.

In analyzing thermal images acquired as part of this research, focus was placed on temperature changes of HMA as it was unloaded, laid down, and compacted. Observations were made in reference to the NDDOT Standard Specifications for Road and Bridge Construction (2002), without attempting to identify “cold” spots according to the magnitude of temperature differential. The NDDOT Specifications state in Section 408.04 F (p.194) that: “The temperature of the [hot bituminous] mix at laydown shall be a minimum of 230°F when the ambient temperature is above 60°F, and 250°F when the ambient temperature is below 60°F.” For the sake of clarity, the “laydown” temperature is interpreted in this report to mean the temperature of HMA at the time it comes out from behind the paver screed.

RESULTS OF DATA ANALYSIS

Figures 2 through 4 show thermal images of HMA coming out from behind the paver, corresponding to three paving projects, Highway 5, US 281, and I-29, respectively – see Appendix for all thermal pictures acquired from these three projects. The images acquired from the other two projects were excluded from further analysis because of inadequate image quality. Numbers shown on the images in Figures 2 to 4 indicate temperature in °F of a single point (e.g., “P1”); for lines such as one annotated by “L0”, maximum, average and minimum temperatures of all the points on a line are given. Comparing these temperatures of HMA from thermal images to the relevant specifications of NDDOT, it can be seen that on the production day the site was visited, two of the three paving projects met the specified mix temperature at laydown. Figures 2 and 3 show asphalt mix being laid down on Highway 5 and US 281, and at the time the thermal images were obtained, the ambient temperature was above 60°F, for which the NDDOT specifies the required minimum temperature of HMA is 230°F.

For the I-29 shoulder paving shown in Figure 4, the ambient temperature was below 60°F. While the asphalt mix immediately behind the paver screed was 260°F or higher, there were some areas in the laid mat that were colder than the specified minimum temperature 250°F. Compared to the Highway 5 paving, the I-29 paving had a similar haul distance (24 miles vs. 27 miles) and used similar types of haul trucks and paving equipment. Also, despite the lower ambient temperature, a windrow of HMA placed on the I-29 shoulder had as high temperature as for the Highway 5 mainline paving. This may be that haul trucks for I-29 paving were covered with a tarp, offsetting potential effects of the low ambient temperature during transport. A more likely cause of the cold areas observed during the I-29 paving is the paver that may have been unable to make adjustments, such as auger speed and screed attack angle, to keep material flow constant given the varied thickness of the shoulder tapering towards the outer edge.

Figure 2. Mainline paving on Highway 5 (ambient temperature 64°F)

Figure 3. Mainline paving on US 281 (ambient temperature 61°F)

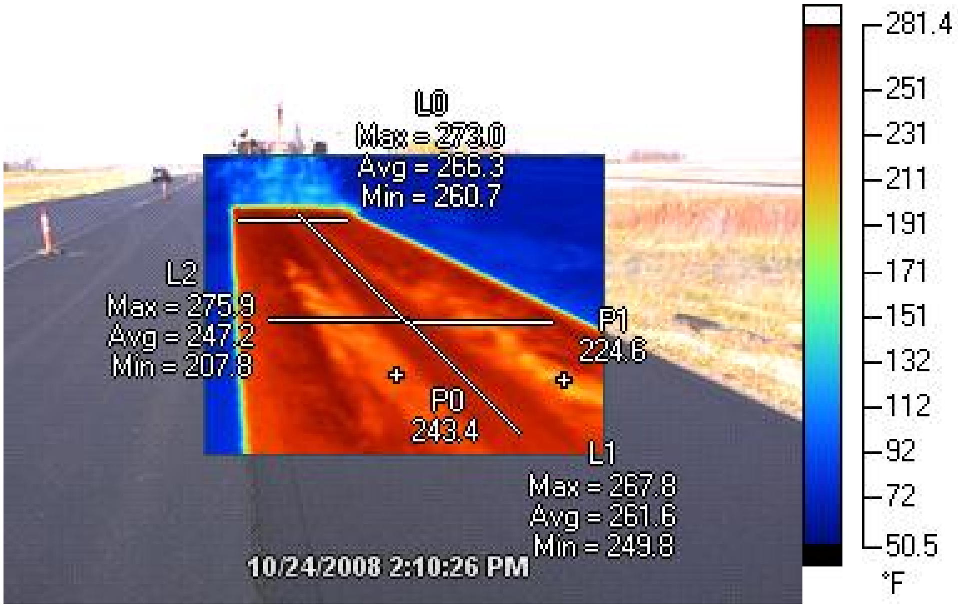
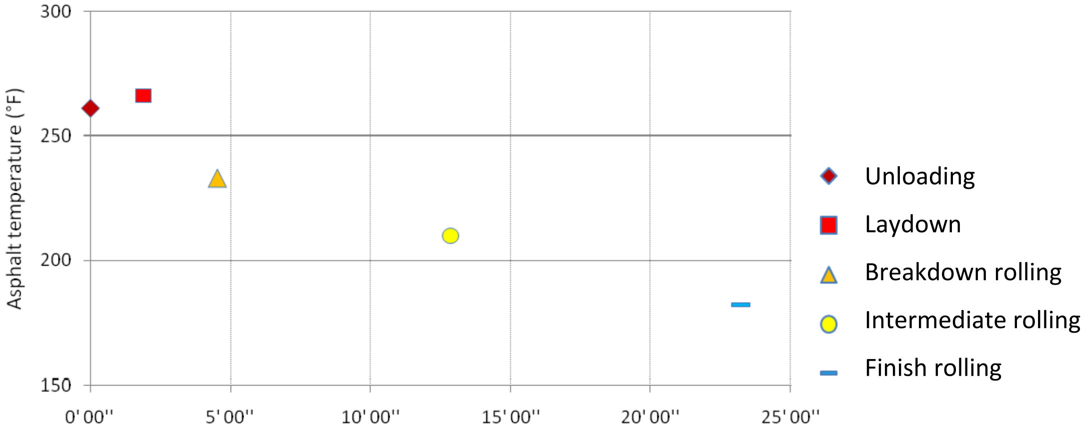
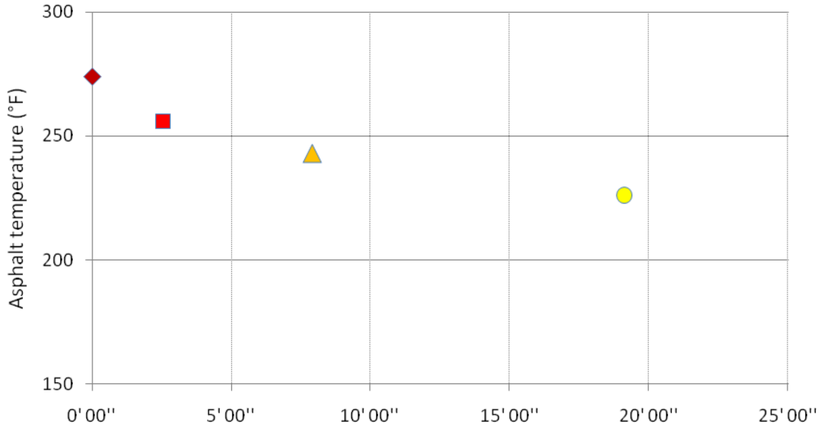


Figure 4. Shoulder paving on I-29 (ambient temperature 54°F)

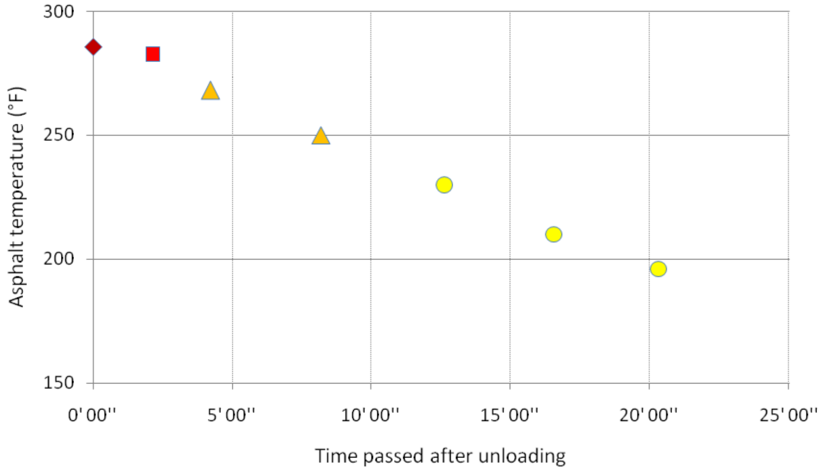
Although some areas in the asphalt mat laid on the I-29 shoulder were observed to be colder than 250°F, subsequent rolling operations were carried out within a time frame similar to the Highway 5 and US 281 paving projects. Figure 5 shows how in these three paving projects HMA temperature changed over the construction process, starting from dumping (unloading). As shown in Figure 5(c), intermediate rolling for the I-29 project was completed about 20 minutes after a bottom belly truck unloaded a windrow of HMA on the existing pavement. This was when the mat temperature was down at 196°F and accords to the NDDOT specifications that apply to shoulder compaction: Section 408.04 I.2 (p.196) states that "Intermediate rolling shall be completed before the mat temperature falls below 185°F." However, it is unknown whether each placed mat shown in Figures 2 to 4 has achieved the specified density requirements or not. Considering that the I-29 paving project was one of the last jobs in 2008 construction season for North Dakota, asphalt pavement construction earlier in the season would have experienced no serious temperature issues as far as the NDDOT specifications are concerned. In reference to the research findings over the past decade, it is however noted that even with the high ambient temperature, achieved in-place densities could be relatively low without the use of industry best practices including timely rolling.



(a) Highway 5, 9/23/08, ambient temperature 64°F



(b) US 281, 10/3/08, ambient temperature 61°F



(c) I-29, 10/24/08, ambient temperature 54°F

Figure 5. HMA temperature changes over time

Another industry practice observed during this research was the use of windrow elevators that pick up asphalt mix discharged on the existing pavement and feed it into the paver. As asphalt mix goes through a windrow elevator, it is remixed, and compared to end dumping directly into the paver hopper, the mix will come out from the paver screed in relatively uniform temperatures. Figures 6 to 8 illustrate how one truck load of asphalt mix changed in temperature over the time from loading through dumping to laydown. Note that all thermal images in Figures 6 through 8 have identical temperature scales, thus the same color representing the same temperature from image to image. As shown in Figure 6, asphalt mix out of the plant mixer underwent considerable temperature loss in two minutes, starting to form a cool crust. This cool crust on top of the haul unit will become cooler in transit to the job site since temperature loss is a natural process that can only be delayed, for example, through tarping the haul unit.

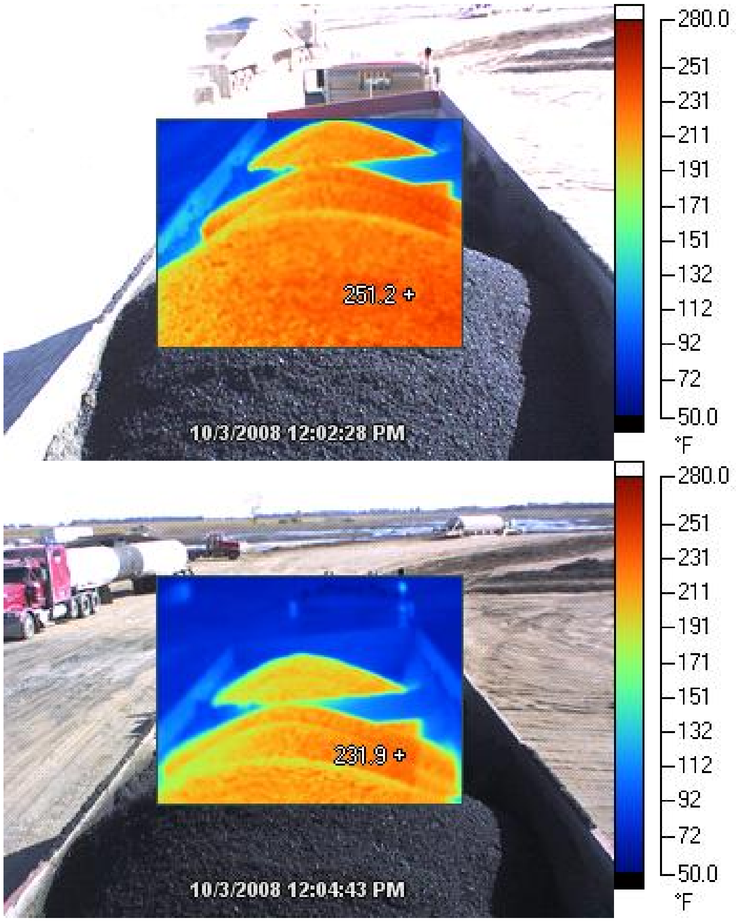


Figure 6. Temperature loss of HMA loaded in a haul unit

By the time the truck load of asphalt mix was discharged onto the existing pavement, it exhibited significant temperature variations, as can be seen from Figure 7. In contrast, only minimal temperature variations can be observed from the mat placed out of this particular load (Figure 8), which is attributable to the working of windrow elevator. All five paving projects visited in this research were using a windrow elevator along with live belly trucks and bottom belly trucks. However, it should be noted that the observations reported here are all based on a very limited set of data and do not represent each visited project as a whole.

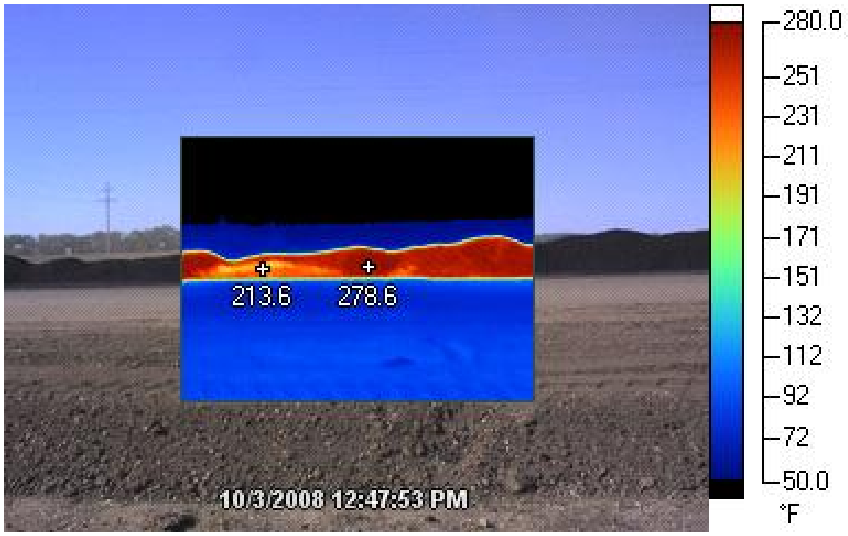


Figure 7. Temperature variations within a windrow of HMA

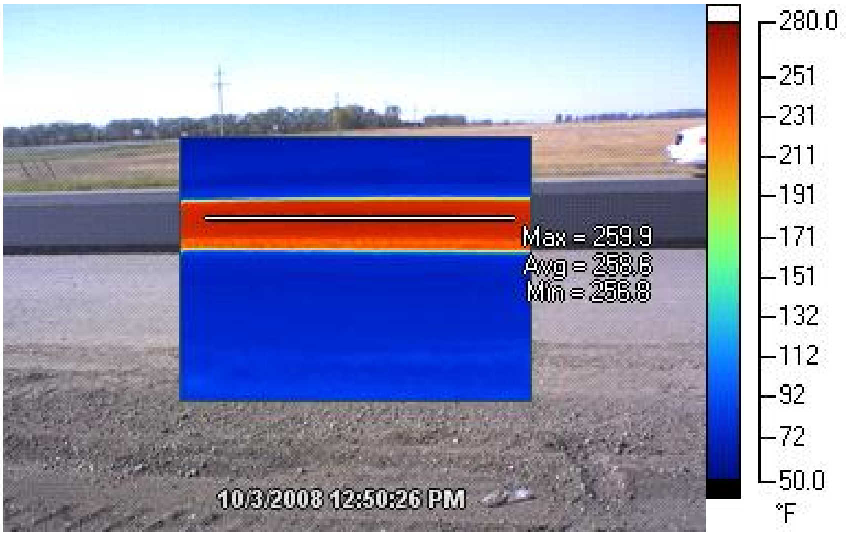


Figure 8. Temperature variations within the asphalt mat placed

CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

The research reported here was intended to determine whether thermal segregation occurs during asphalt pavement construction in North Dakota. In support of the research objective, a one-day site visit was made to each of the five ongoing pavement projects in the state, over a two-month period from September to October 2008. Project specific data including types of equipment in use were collected, and thermal images of hot mix asphalt in distinct but interrelated paving operations were acquired using an infrared camera.

Observations from this limited set of data suggested that thermal segregation, if defined as the freshly laid mat having an area 25°F colder than adjacent areas, does occur in North Dakota asphalt pavement. During the site visit to I-29 shoulder paving, areas more than 25°F colder than surrounding mat areas were observed. These areas were colder than 250°F, which is the minimum mat temperature NDDOT specifies for laydown under the ambient temperature below 60°F. To identify causes of these cold areas, data collected were analyzed, and observations from this analysis suggested paver operations over the shoulder as one possible cause. Paver adjustments, such as those made to maintain a constant head of material in the auger and the proper angle of attack of the screed unit, may help to reduce potential cold areas during shoulder paving. Also, windrow elevators working with bottom belly dump trucks were observed to be effective in providing uniform HMA temperatures at laydown. Thus, continued use of windrow elevators is recommended, especially when the ambient temperature is below 70°F and the haul distance is longer than 20 miles.

It should be noted that the occurrence of thermal segregation in North Dakota asphalt paving is a preliminary finding supported by anecdotal evidence and based on the existing, questionable definition of thermal segregation. Currently in the literature, thermal segregation is defined in relative terms of temperature differential, which invariably changes depending on the temperature of adjacent “hot” areas. Furthermore, core densities of the observed “cold” spots were not determined and are unknown even though prior research suggested that these “cold” mat areas would generally have lower densities.

Therefore, to conclusively determine the occurrence of thermal segregation and its effects on density, asphalt mat temperatures rather than temperature differentials should be related to resulting densities. To track mat surface temperatures from laydown to finish rolling, a thermal camera could be set up on a tripod at fixed locations ahead of the paver and alongside the roadway, and aimed down on an area to be paved. This set-up would minimize potential safety hazards and obstruction to ongoing paving operations. The strength of correlation between temperatures and densities should be compared to that of correlation between temperature differentials and densities. Through this comparison, the hypothesis of Henault et al. (2005) can be tested that density achieved is more dependent on temperatures than temperature differentials. It may also be possible to determine threshold mat temperatures below which pavement density would be significantly affected. The threshold temperatures determined could then be used as minimum temperatures to be met at the times of laydown and rolling. Ideally, a tool could also be developed that can predict pavement density given asphalt mat surface temperatures and other influencing variables.

Since a thermal camera can be an effective tool in identifying potential thermal segregation, it is recommended that NDDOT and asphalt paving contractors consider using one during asphalt pavement construction. Their potential use of a thermal camera may be in identifying cold mat areas for subsequent core density testing, which would complement current QC/QA density testing on random core samples. There are several state DOTs that are currently using thermal cameras for similar purposes. However, they take density readings not only from a cold spot but also at three foot intervals in a longitudinal line beginning fifteen feet before the cold spot and ending fifteen feet after the cold spot. Then they compare the lowest density to the highest density of the longitudinal profile and accept or reject the profile depending on the density difference. Thus, this longitudinal profile method being used by other state DOTs is still based on the relative terms of temperature differences and density differences.

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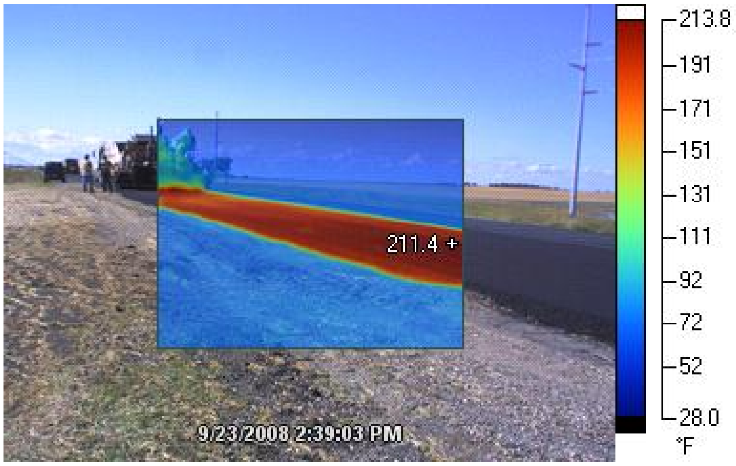
APPENDIX

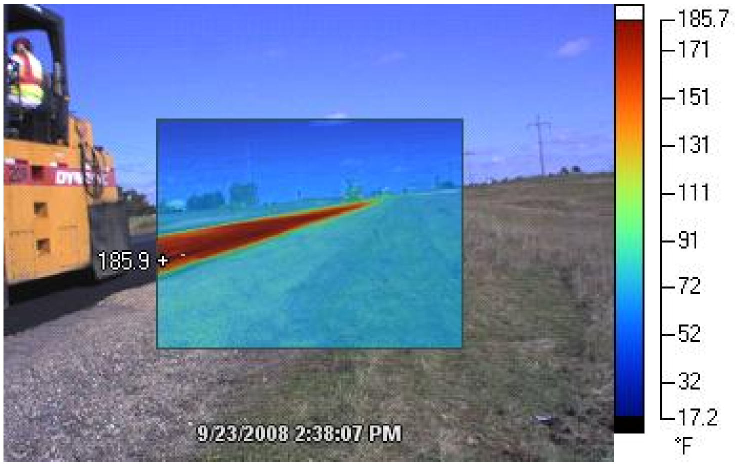
Thermal pictures shown below were taken from Highway 5, US 281, and I-29 paving projects, and they are ordered according to related construction sequence. As these pictures were taken over more than one cycle of paving construction (from loading at plant to compaction) for each project, they are sorted by each cycle which is associated with paving on a particular section of road.

THERMAL PICTURES FROM HIGHWAY 5 PAVING

Cycle No. 1



Compaction



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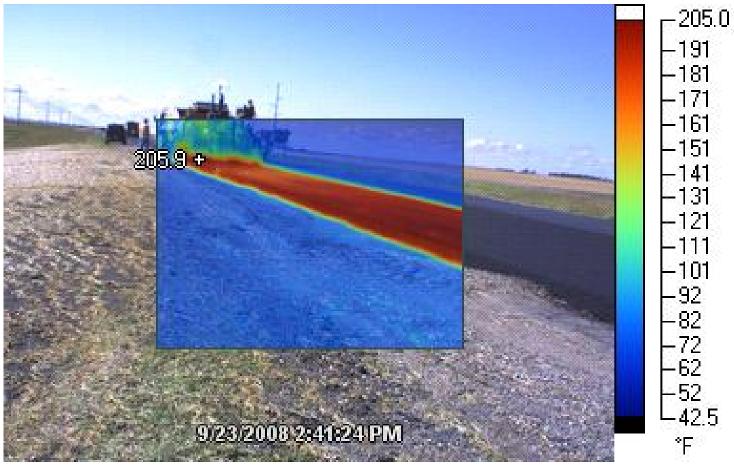

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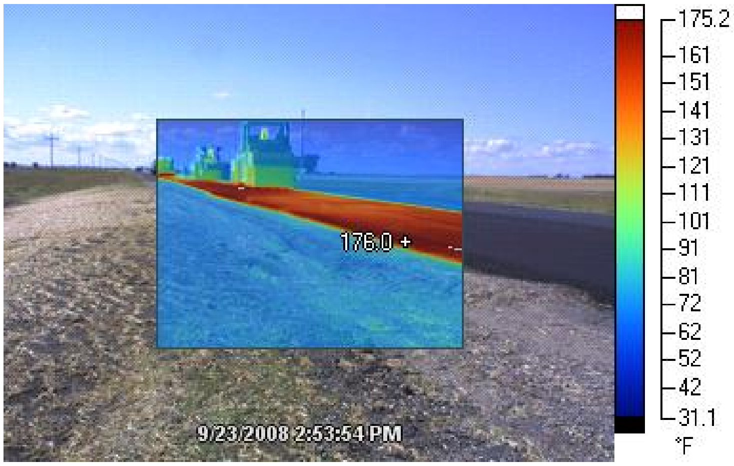

Compaction

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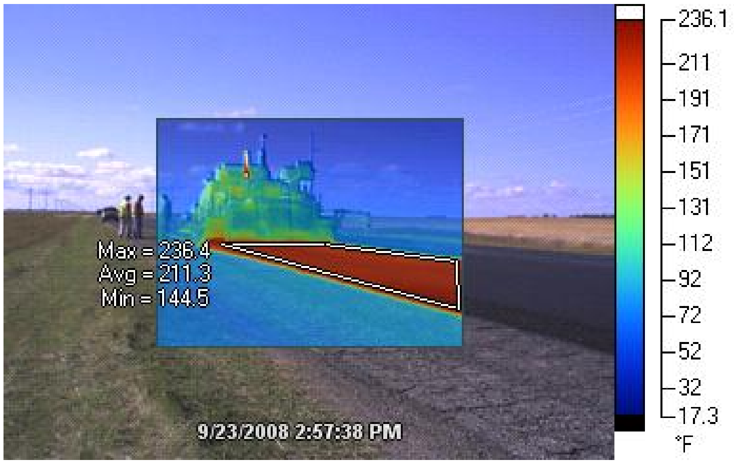
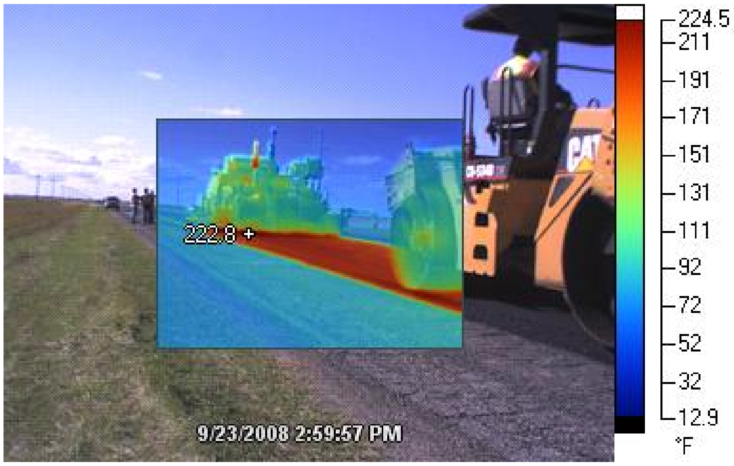


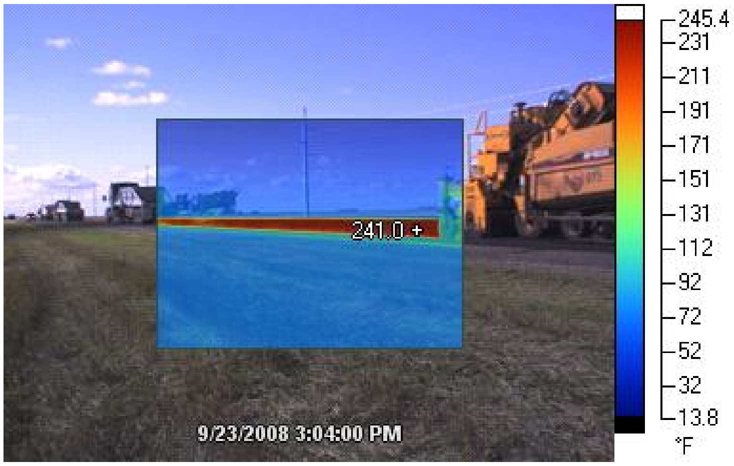
Laydown



Laydown

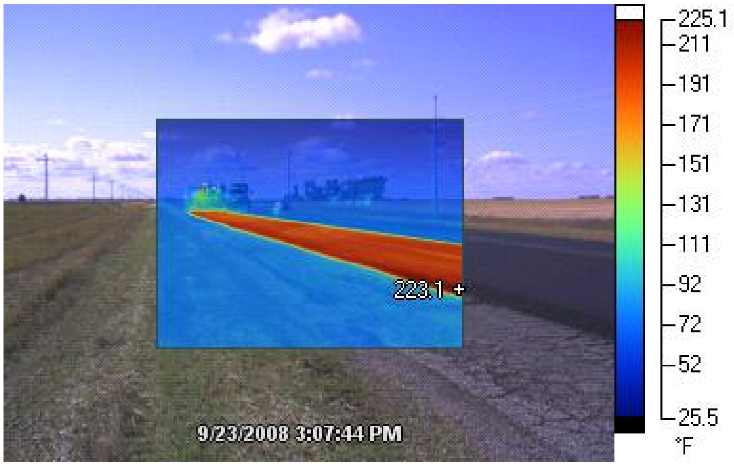
Compaction

<u>Cycle No. 3</u>



Dumping

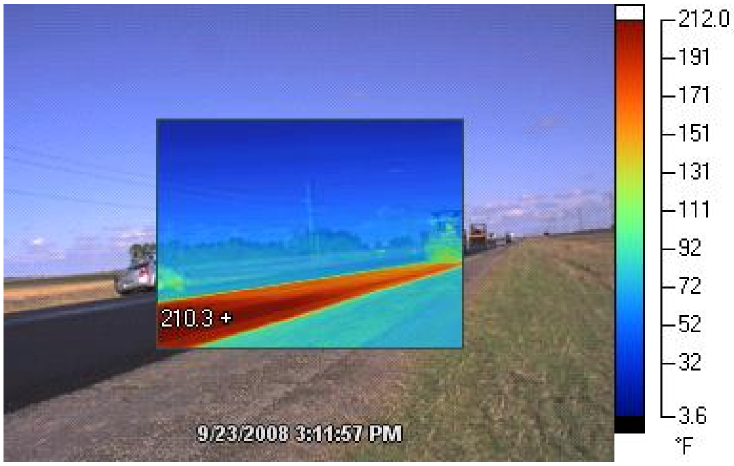
Laydown



Breakdown rolling

<u>Cycle No. 4</u>

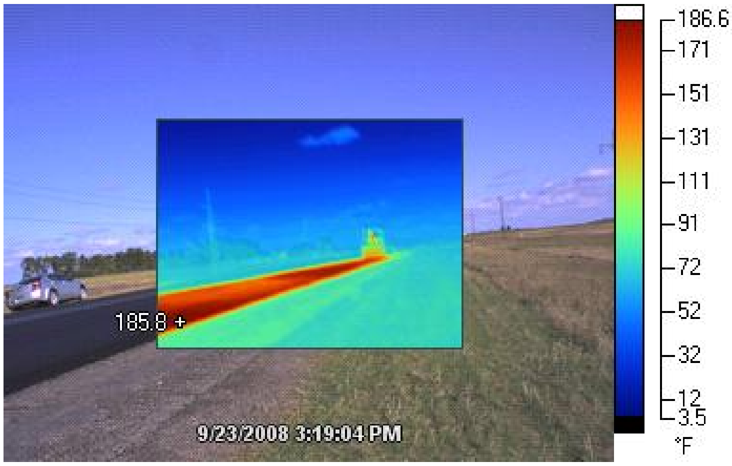
Laydown



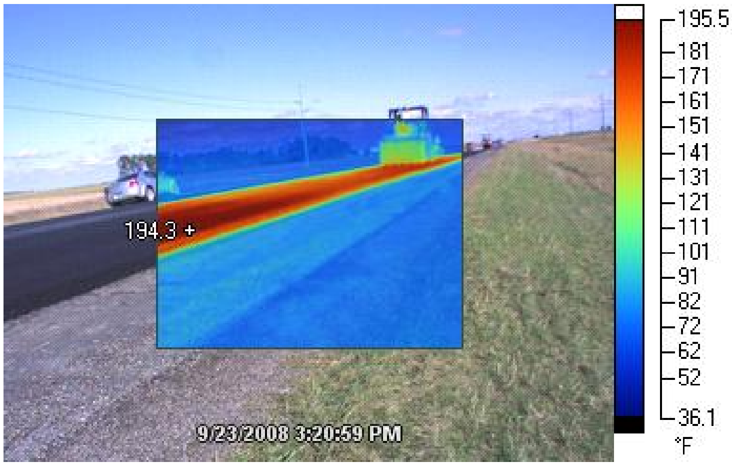
Breakdown rolling

Breakdown rolling

Breakdown rolling

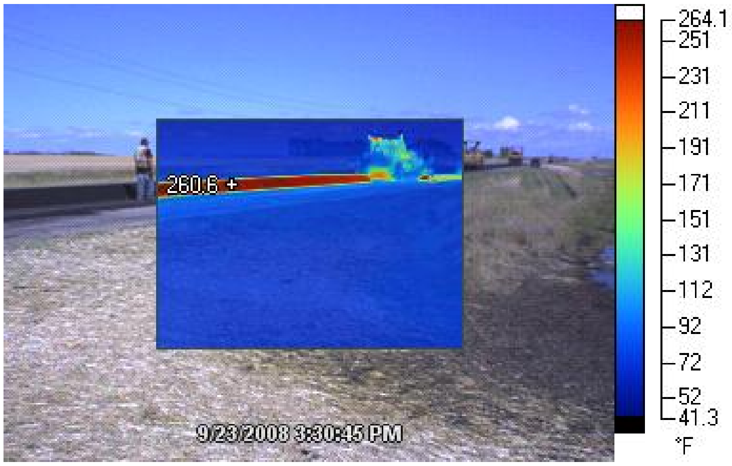


Intermediate rolling



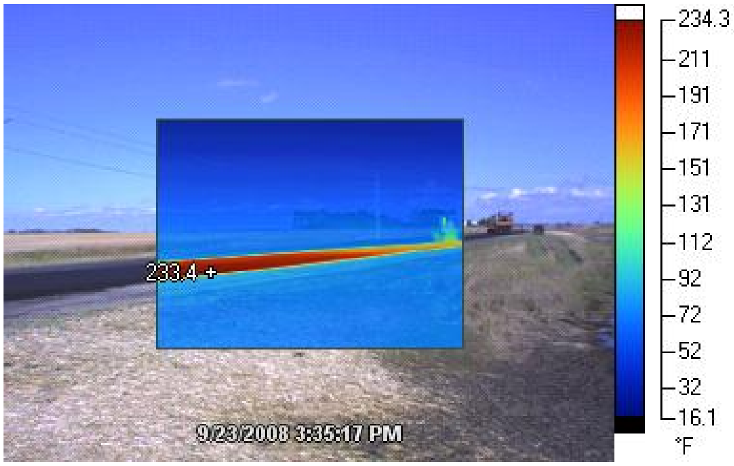
Intermediate rolling

Cycle No. 5



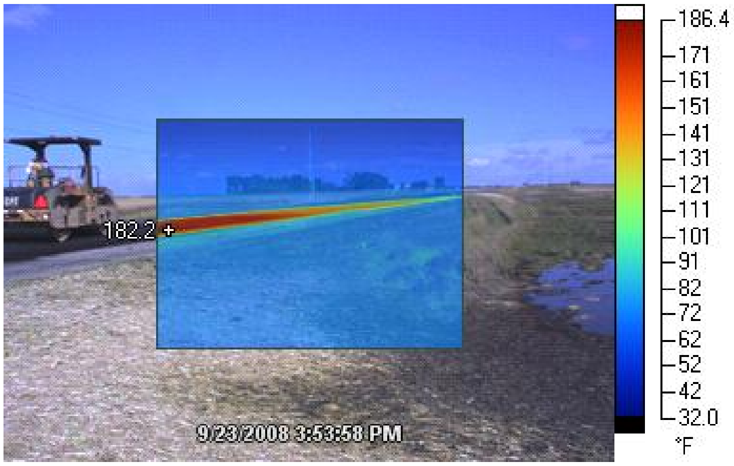
Dumping

Laydown

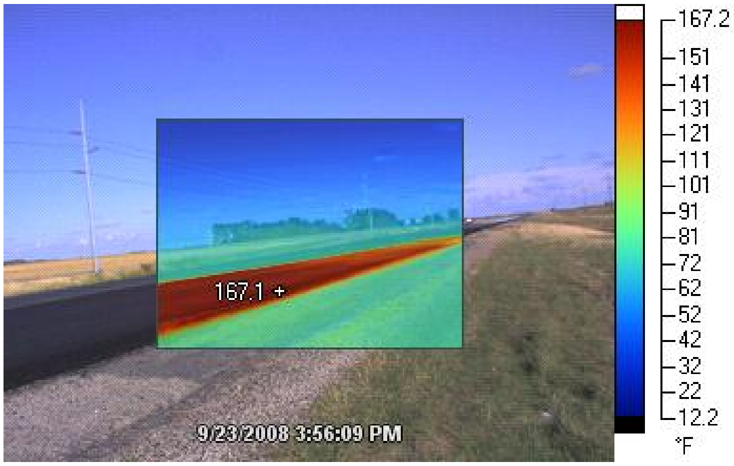


Breakdown rolling

Intermediate rolling



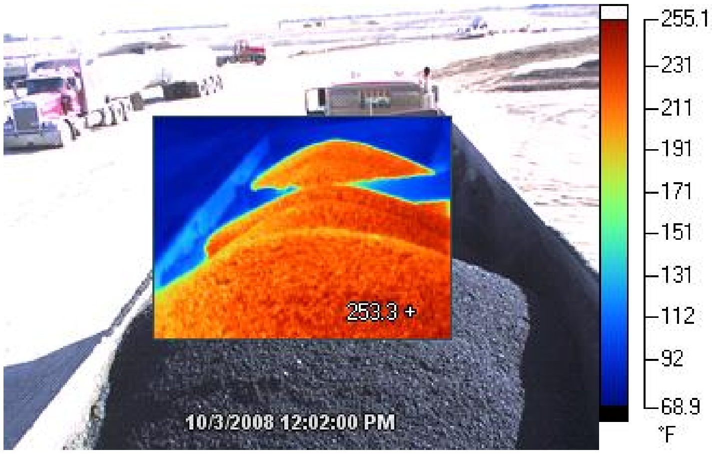
Finish rolling



Finish rolling

THERMAL PICTURES FROM US 281 PAVING

Cycle No. 1



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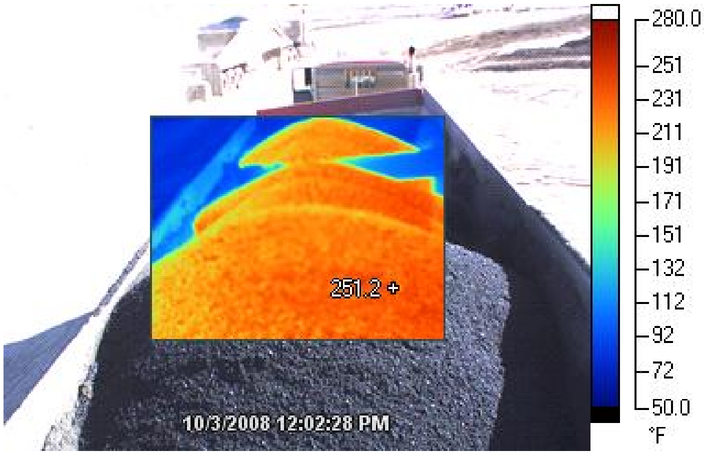

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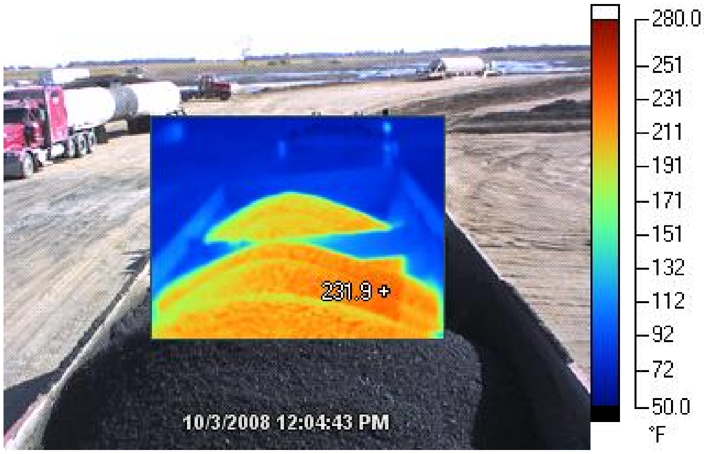
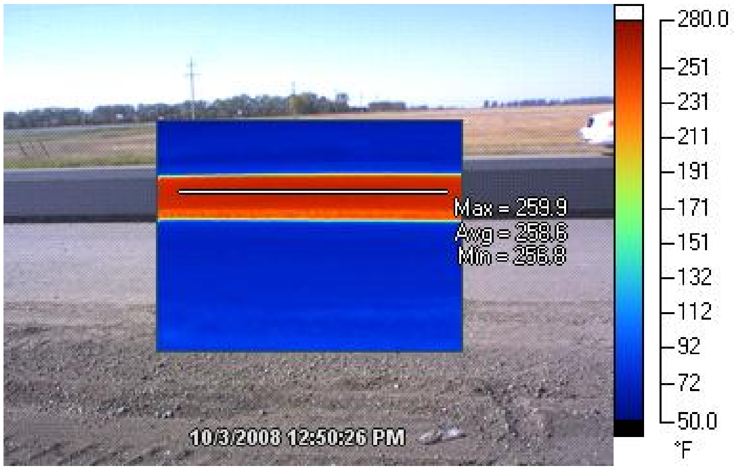


Loading

Dumping

Dumping

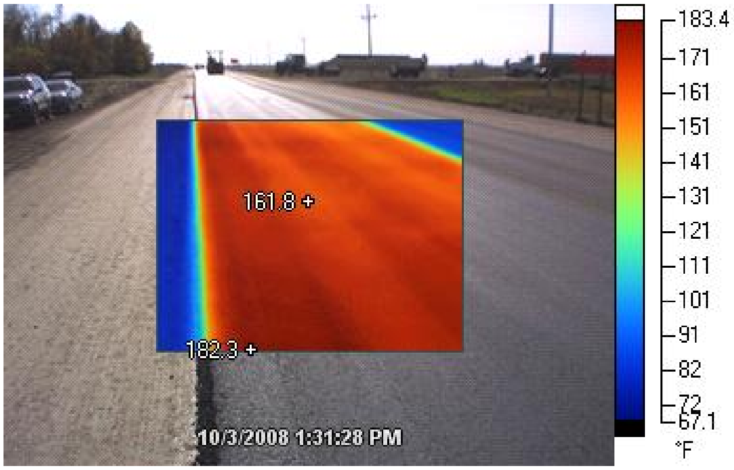


Laydown

Laydown

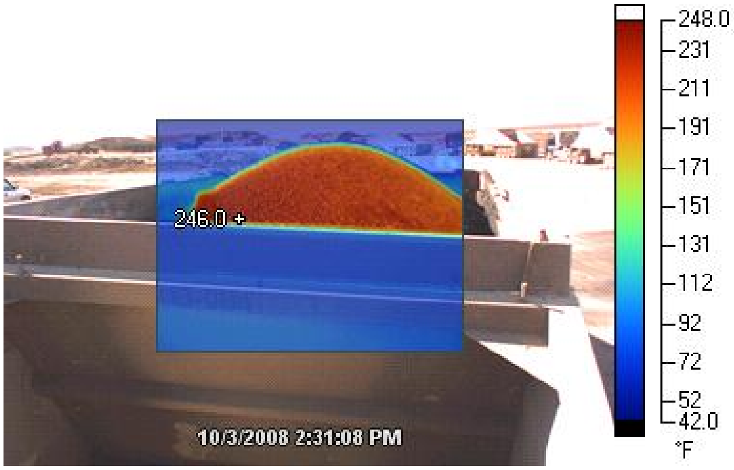
Breakdown rolling

Intermediate rolling



Finish rolling

Cycle No. 2



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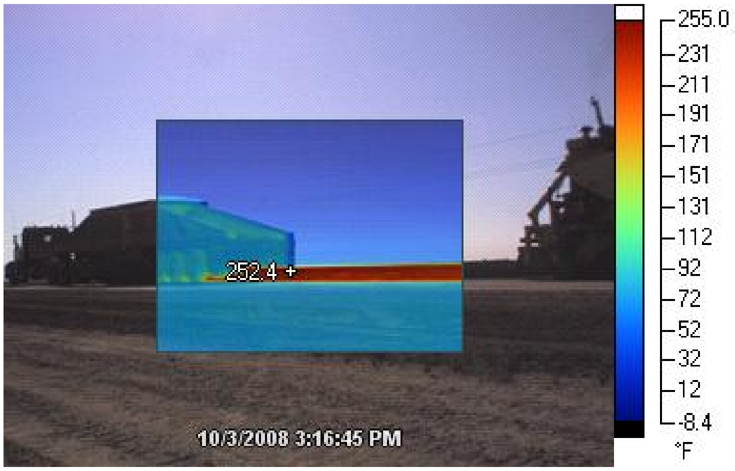

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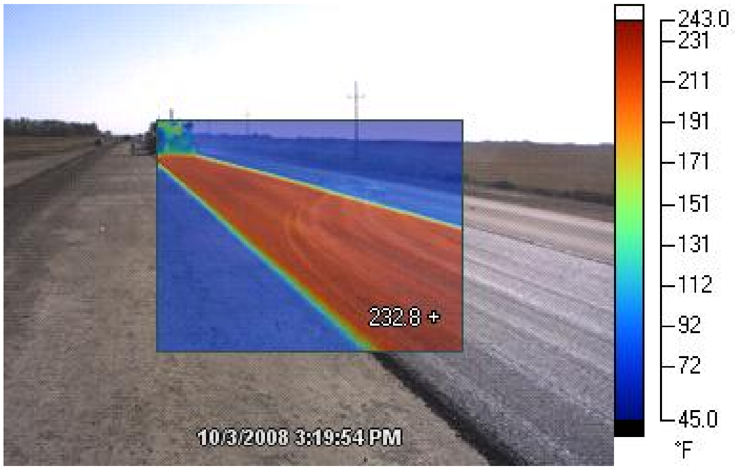
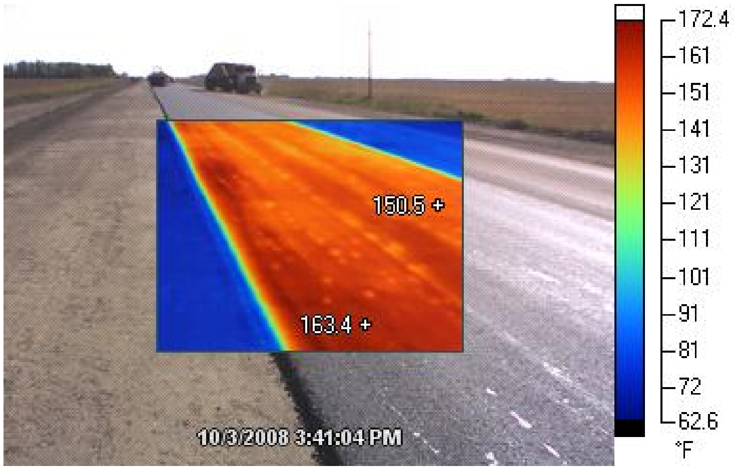


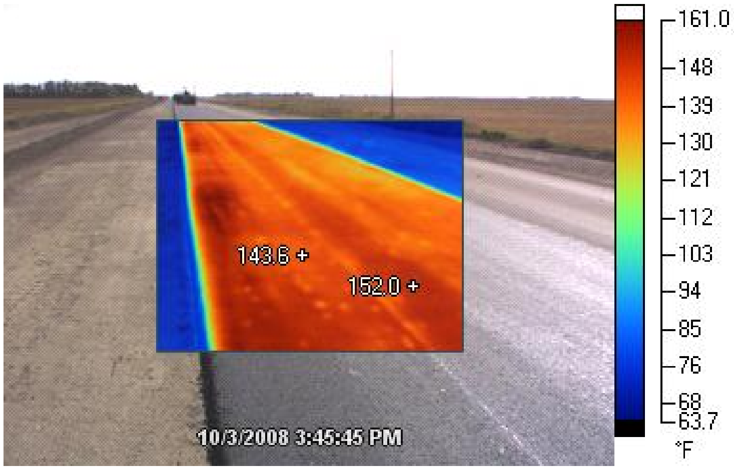
Breakdown rolling

Breakdown rolling

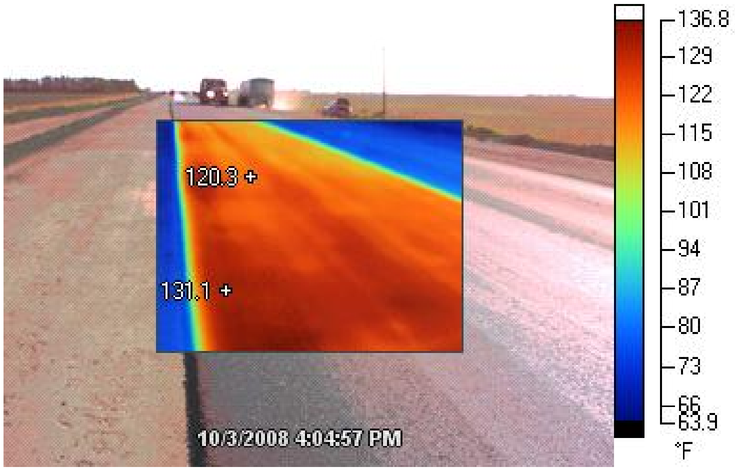
Intermediate rolling



Intermediate rolling



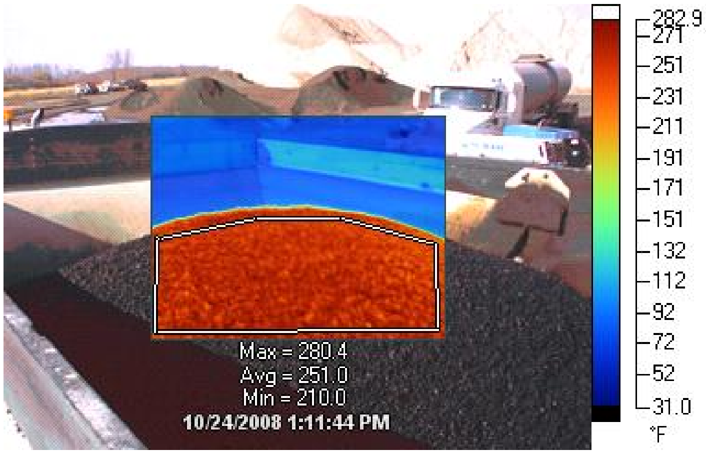
Finish rolling



After finish rolling was completed

THERMAL PICTURES FROM I-29 SHOULDER PAVING

Cycle No. 1



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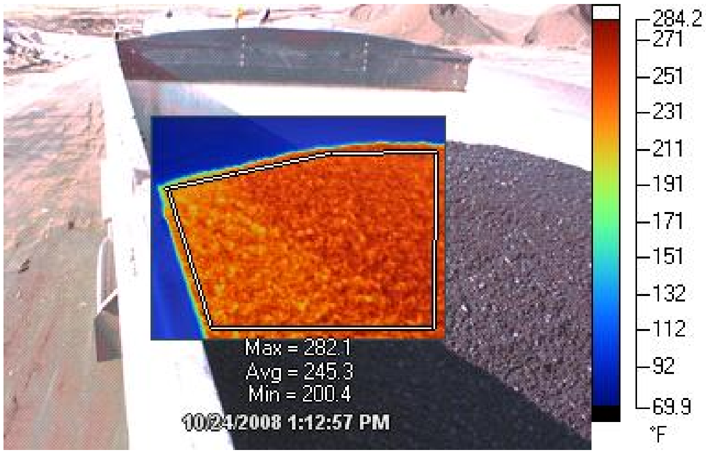

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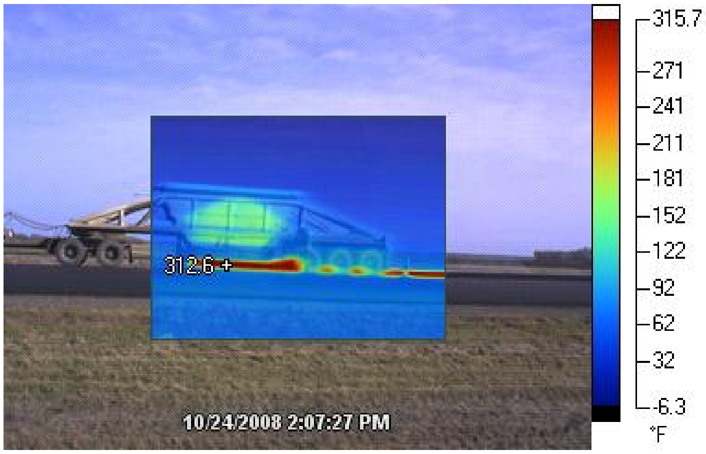

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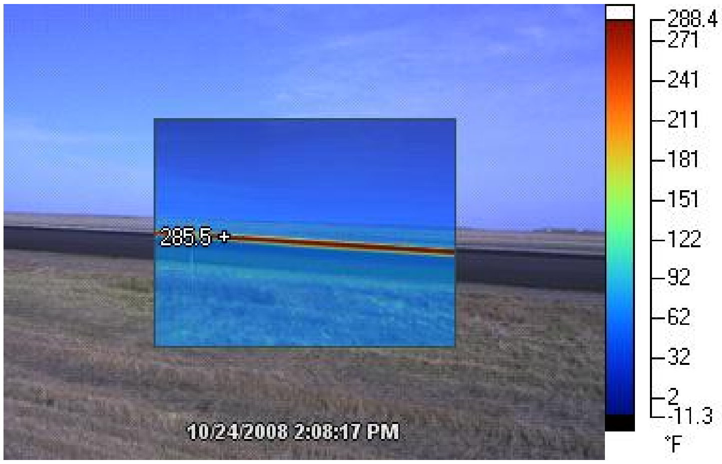

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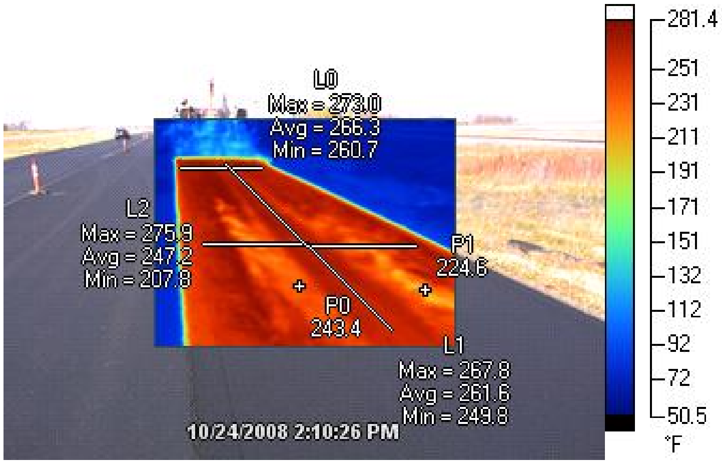
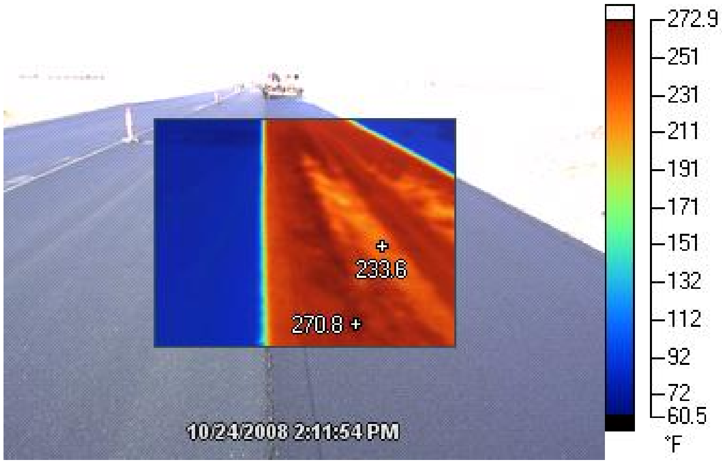
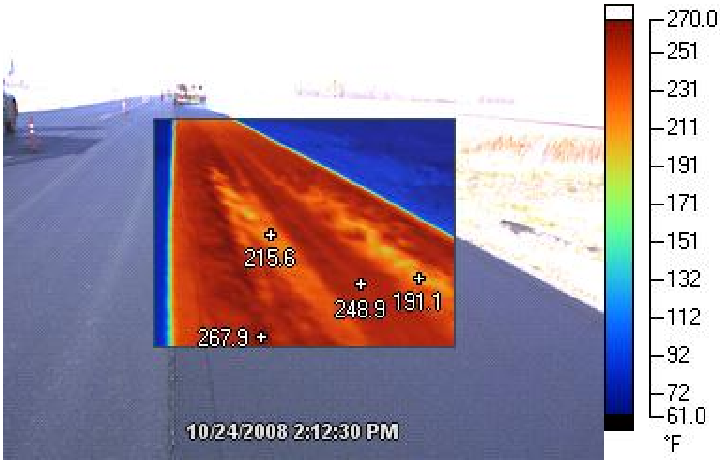


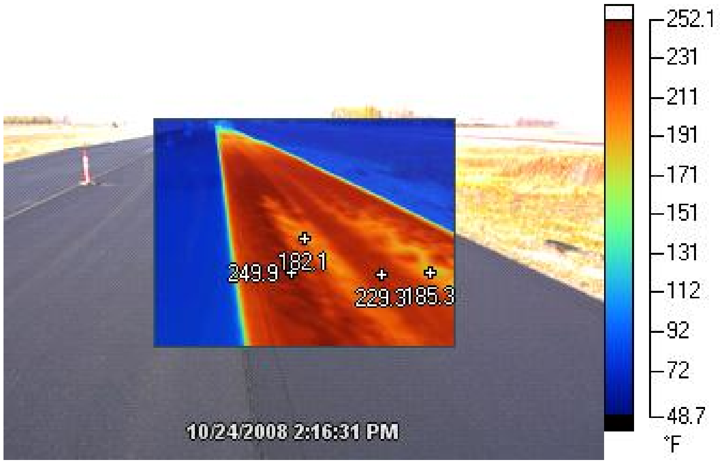
Laydown



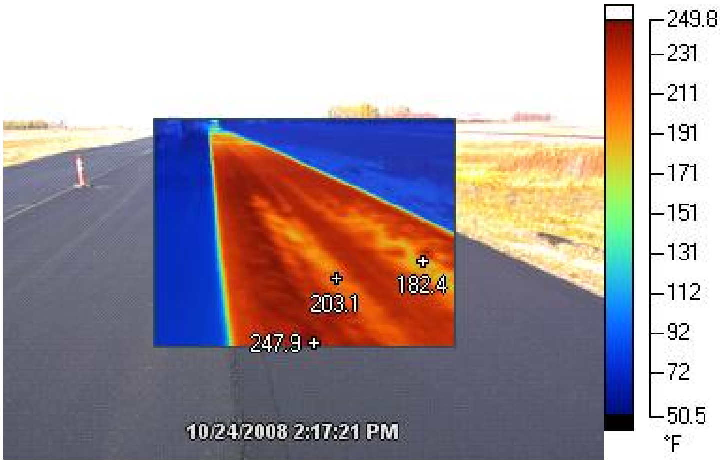
Laydown



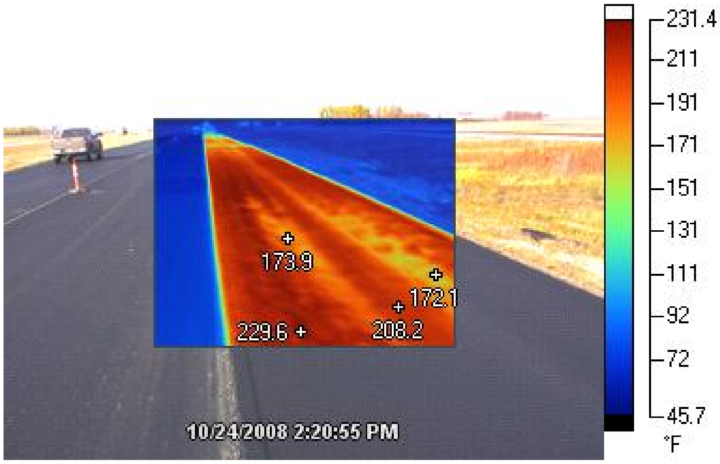
Breakdown rolling



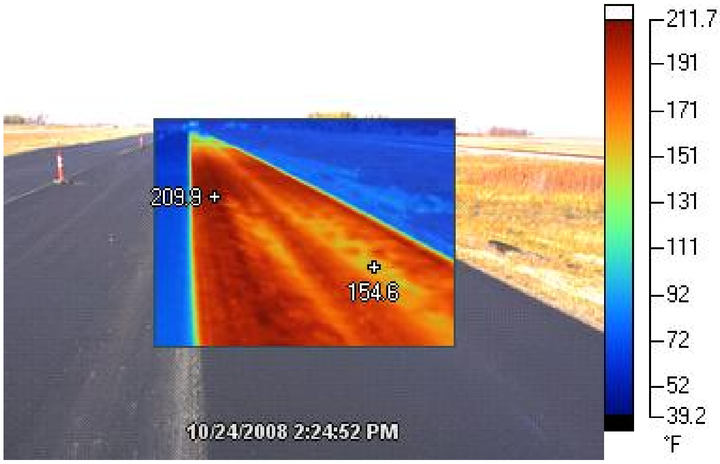
Breakdown rolling



Breakdown rolling

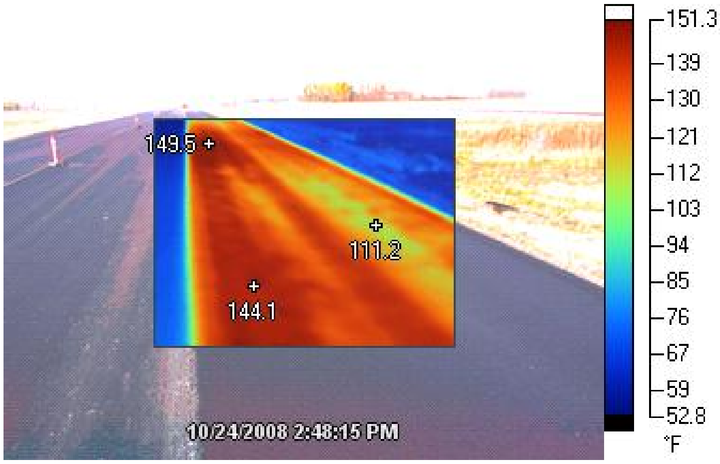


Intermediate rolling



Intermediate rolling

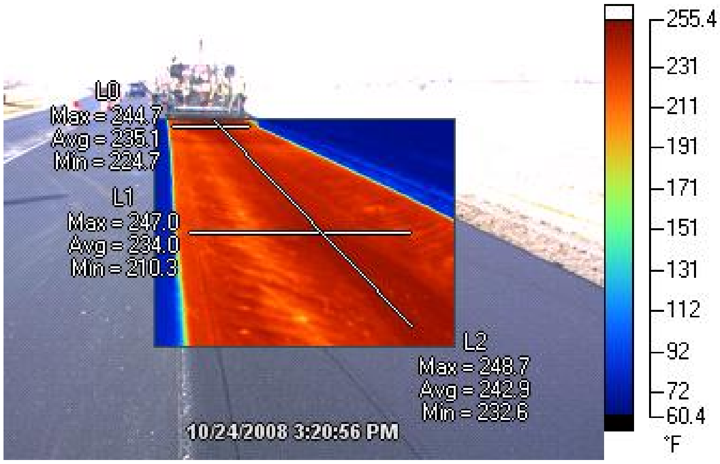
Intermediate rolling



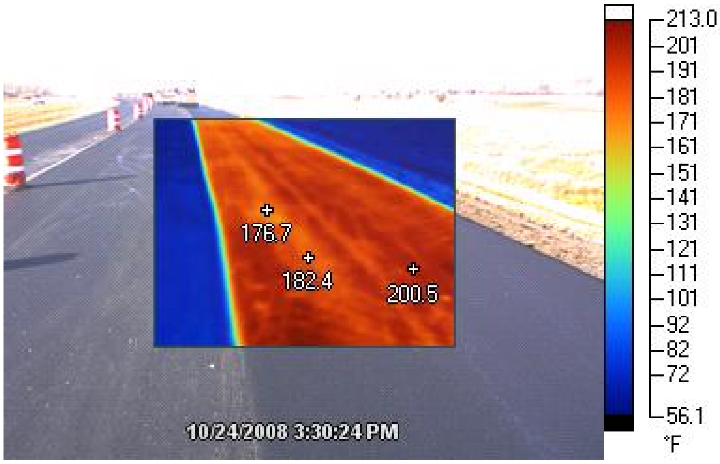
After finish rolling was completed

Cycle No. 2

Dumping



Laydown



Breakdown rolling

Intermediate rolling