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16. Abstract The objectives of this study were to assess whether temperature differentials measured using Infrared Thermography (IRT) occur in an overlay built on top of discontinuities such as joints and cracks and to study the horizontal and vertical thermal profiles in the asphalt overlay using a validated Finite Element (FE) modeling approach. To achieve this objective, an infrared camera was used to monitor the temperature profiles in the asphalt mat in a number of field projects from the time it was placed to after completion of the compaction process. The temperature profiles were monitored on top and away of severe discontinuities and joints in the existing pavement. Results showed that thermal measurements on top of the joints were consistently lower than away from it, which may indicate that temperature loss may occur at the joints. Further, a validated FE model predicted a slightly higher rate of thermal loss at the bottom of the overlay above the joint than away from it due to convection losses at the joint. While this difference may not be large enough to be identified as thermal segregation, it can influence the bulk properties of the overlay at the joints and promote early cracking. Thermal differences were also observed in the vertical direction as lower temperatures were predicted at the top and the bottom of the overlay during construction due to convection losses with the ambient atmosphere and conduction between the hot overlay and the existing pavement.		
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Use of Infrared Thermography to Detect Thermal Segregation in Asphalt Overlay and Reflective Cracking Potential

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EXCECUTIVE SUMMARY

The objectives of this study were to assess whether temperature differentials measured using Infrared Thermography (IRT) occur in an overlay built on top of discontinuities such as joints and cracks and to study the horizontal and vertical thermal profiles in the asphalt overlay using a validated Finite Element (FE) modeling approach. To achieve this objective, an infrared camera was used to monitor the temperature profiles in the asphalt mat in a number of field projects from the time it was placed to after completion of the compaction process. The temperature profiles were monitored on top and away of severe discontinuities and joints in the existing pavement. Based on the results of the study, it was concluded that cracks in the existing pavement do not influence the thermal profiles in a HMA overlay. This was expected given the small width of the crack in comparison to the mat surface area, which would not cause major convection losses through the crack. However, thermal measurements on top of a joint were consistently lower than away from it, which may indicate that temperature loss may occur at the joints.

A transient thermal FE model was successfully developed to simulate the temperature profile in the overlay during construction. The error in model prediction was less than 5% indicating an acceptable level of accuracy. The FE model predicted a slightly higher rate of thermal decrease at the bottom of the overlay above the joint than away from it due to convection losses at the joint. While this difference may not be large enough to be identified as thermal segregation, it can influence the bulk properties of the overlay at the joints and promote early cracking. Thermal segregation was observed in the vertical direction as well as in the horizontal direction. Lower temperature was predicted at the top and bottom of the overlay during construction due to convection losses and conduction between the hot overlay and the existing pavement. Further investigation of the findings of this study is recommended through laboratory testing of extracted cores.

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DISCLAIMER

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INTRODUCTION

Flexible pavements are initially constructed to minimize capital outlay while providing acceptable performance under pertinent environmental and traffic conditions. Yet, while design criteria can be met, a pavement may fail prematurely prior to the end of its service life. Non-uniform temperature, also known as thermal segregation, is the result of poor construction practices. The effects of thermal segregation on Hot-Mix Asphalt (HMA) performance have been debated by many studies. A number of studies have concluded that thermal segregation causes pavement to fail prematurely due to cracking, increased roughness, and change in mix stiffness *[1]*. Yet, other studies could not establish a clear correlation between mix performance and thermal segregation *[2]*. Generally, flexible pavements are designed to last for 15 years or more. However, thermal segregation could reduce the service life of pavements by as much as 50% by lowering density and increasing permeability of the installed mix *[3]*.

Thermal segregation is defined as a temperature differential exceeding 14°C in the paving mat and causes the appearance of weak spots with reduced field density *[2]*. The performance of asphalt pavements has been linked to the density achieved in the field as it provides an indication of the percentage of air voids in the mix *[3, 4, 5]*. While high air voids may lead to premature failure due to stripping, oxidation, raveling, and ultimately cracking, low air void may lead to rutting and shoving in the mix. One limitation of density measurements is that it is determined after construction is complete and that measurements are localized and do not provide a complete coverage of the installed mat. Therefore, immediate corrective actions may not be taken to improve the quality of the installed mix. The use of Non-Destructive Evaluation (NDE) tools such as Infrared Thermography (IRT) has the potential to address this limitation by offering real-time measurements of surface temperature of the installed asphalt mat and identifying weak spots caused by thermal segregation.

In the present study, the use of IRT is extended to a new application by monitoring the temperature profile of an HMA overlay placed on top of an existing pavement. Through the collected measurements and finite element (FE) modeling, this study compared the thermal profile of the asphalt mat on top of discontinuities such as joints and cracks to the thermal profile at a distance from the discontinuity. Based on the analysis, the study tested the hypothesis that the occurrence of thermal segregation in the paving mat on top of the discontinuities may result in weak spots at the bottom of the overlay and the premature appearance of reflection cracking at the surface.

BACKGROUND

Infrared thermography, also known as thermal imaging, has the potential to improve Quality Control (QC) activities because it can be used during paving operations. This approach measures the infrared energy emitted from the installed mat, converts it to temperature, and provides a color-coded image that identifies cooler areas in blue and warmer regions in red. Infrared cameras can be used to capture the thermal profiles of an asphalt mat at various stages of pavement construction (i.e., during transportation, prior to and after compaction). Thermal images can also be used to identify the areas of thermal segregation during construction at the locations with a significant temperature differential *[6]*.

Since its adaption to pavement applications in the late 1990s, infrared technology has advanced considerably in terms of accessibility, cost, and practicability, which has made it a useful tool for pavement engineers. While infrared cameras require a higher monetary investment, heat guns and thermometers can only measure the temperature of the asphalt mat at a single point whereas an infrared camera has the advantage to provide the temperature differential in the whole mat *[7]*. In 1999, a study evaluated 36 projects using IRT in Washington State *[8]*. The temperature differential in the mat was observed to vary from three to 38°C and a correlation was established between temperature differential and mix air voids. Based on this analysis, the authors estimated an increase in air voids by 2% or higher for a temperature differential of 14°C or higher. Under NCHRP Project 9-11 and using a combination of non-destructive and destructive tools, IRT and ROSAN laser surface texture measurements were recommended for detecting segregation *[9]*. Four levels of segregation were defined based on IRT:

- No segregation with a maximum temperature differential of 10°C or less;
- Low-level segregation with a temperature differential between 11 and 16°C;
- Medium-level segregation with a temperature differential between 17 and 21°C; and
- High-level segregation with a temperature differential of 21°C or greater

Mahoney et al. (2003) evaluated 40 different asphalt projects to analyze the effects of several variables including haul time/haul distance, material characteristics, spillage, and equipment issues on thermal segregation. Results showed that thermal and aggregate segregations could both result in a mix with high permeability, which would greatly affect the mix density and durability. The authors also emphasized the need to differentiate between aggregate and thermal segregations in order to select the best corrective actions for the problem. It was observed that thermal segregation tends to occur during truck change and rarely appears during the middle of a load. Furthermore, the pattern of failure in old pavements was observed to be similar with the pattern observed with the thermal camera on newly constructed projects *[10]*.

Henault et al. (2005) used an infrared camera to locate cold and hot spots on the mat surface of 11 asphalt projects. Infrared thermography was complemented with testing performed using nuclear density and volumetrics of extracted cores at various locations in the mat in order to compare differences in air voids and asphalt content between normal and segregated spots. Cold spots were observed to be less dense and had higher percentage of air voids than the surrounding areas. However, a sound relationship between change in density and temperature could not be established, as other factors (such as material type, lift thickness, and mix design) may have a substantial effect on the mix density. Both cold spots and the surrounding counterparts were observed to be similar in terms of asphalt content. Based on these results, the authors concluded that densities and air voids of HMA are more contingent on the temperature of HMA rather than temperature differential *[11]*.

Song et al. (2010) used infrared camera to acquire thermal images of HMA during loading, unloading, placement, and compaction of five field projects in North Dakota. In one project, thermal segregation was observed with a temperature differential of 14°C or higher. Thermal segregation was linked to the paver with a mat temperature colder than 121°C, which is the minimum mat temperature allowed in North Dakota. The authors concluded that the use of windrow elevators in combination with bottom belly dump trucks was effective in providing uniform mat temperature during laydown. The authors also recommend identifying cold mat areas based on the mat temperature rather than temperature differentials as the former directly related to the mat density *[12]*.

The Texas Department of Transportation (TXDOT) has used thermal imaging of HMA during construction since 2000 and has implemented the use of thermal imaging in its specifications, Test Method Tex-244-F. Since then, an automated method of thermal profiling, known as Pave-IR, was developed and consists of attaching a series of infrared sensors to the paver and transfer the captured images to a computer. Sebasta and Scullion (2012) used Pave-IR to monitor 14 projects and to relate thermal segregation to field performance after three to seven years in service *[13]*. Mixed results were observed for the projects with thermal segregation; though most of the projects did not show any distress in the zones of segregation, few showed evidence of cracking. It was also found that thermal segregation did not affect the mix performance against rutting as predicted from the loaded-wheel track (LWT) results. Overall, the researchers could not establish a clear correlation between thermal segregation and mix performance.

However, it was recommended to continue monitor thermal segregation during construction, which could provide cost saving in the long-term.

From the review of past studies, research results conducted on the use of ITR identified the adverse effect of thermal segregation on asphalt density and pavement performance; however, further research is needed to understand the clear mechanism leading to thermal segregation. Since the introduction of ITR, pavement engineers have successfully used this technology to detect thermal differential in the asphalt mat during laydown such that thermal segregation can be minimized. The advancement of new generation of infrared cameras with wider precision, greater storage, lightweight and crisp thermal imaging has facilitated the implementation of this technology to detect thermal segregation.

Thermal Modeling

As detailed in the previous section, thermal segregation is a complex phenomenon and its effect on asphalt mixture density and performance is difficult to examine in the field and requires years of monitoring. Further, temperature variation with time and within the pavement layers cannot be monitored during construction. The Finite Element Method (FEM) is one of the few techniques that can be used to study these effects. When heat transfer mechanisms within the pavement layers are accurately simulated, thermal profiles within the pavement layers and the influence of material properties on the temperature gradient can be studied through computer simulation. However, limited studies have been conducted to study the change in asphalt paving temperature during construction using FEM.

Al-Qadi et al. (2005) developed a FE model to study heat transfer mechanisms between pavement layers in flexible pavements. Convection, conduction, and radiation mechanisms were simulated in the developed FE model. The authors correlated heat transfer mechanisms between the layers to the gap distance between the two layers and the contact pressure. Within 24-hr temperature variation, the temperature of the pavement surface varied between 22 and 48°C and between 23 and 46°C at the bottom of the layer *[14]*. Pais et al. (2004) developed a three-dimensional (3D) FE transient model to predict the temperature profile in flexible pavement. A good agreement was obtained between calculated and measured temperature values obtained at various depths within every hour for a period of one year. The average error between measured and calculated temperature values was estimated to be approximately 2°C during the winter months while it reached up to 4°C in the summer months *[15]*.

Li and Harvey (2010) postulated that the temperatures at the surface and near the surface had higher values and fluctuations over the day while the temperature at some distance from the pavement surface varied little with time *[16]*. Based on the results of an integrated local model, Li and Harvey (2010) predicted that the temperature at the pavement surface and near the surface would be significantly higher than the ambient air temperature (20 and 10°C higher, respectively). In contrast, the temperature at some distance from the surface (e.g., middle of aggregate base) varied little over time. Rahman et al. (2013) performed a 3D finite element analysis to estimate the heat loss at the interface when a hot mixture is laid on an existing pavement *[17]*. They observed non-uniform temperature distribution at the pavement layer interface. As expected, the cessation temperature at which compaction of the mat would no longer be effective was achieved faster for cold pavement (defined at a temperature of 5°C). They concluded that compaction during cold weather should be performed within 4 minutes of HMA placement to avoid thermal segregation.

In the present study, field monitoring results were used to validate a 3D heat transfer FE model. Upon validation, the FE model was used to conduct a parametric study to evaluate the effects of joints and discontinuities on thermal profile in an asphalt overlay with time and depth during construction.

OBJECTIVE

The objectives of this study were to assess whether temperature differentials measured using IRT occur in an overlay built on top of discontinuities such as joints and cracks and to study the horizontal and vertical thermal profiles in the asphalt overlay using a validated FE modeling approach. Field experiments were used to assess the benefits of this technology and its potential implementation as a quality control NDE tool.

APPROACH

The research approach consisted of monitoring surface temperature during asphalt paving operations in a number of field projects. An infrared camera was used to monitor the thermal profile of the asphalt mat from the time it was placed to after completion of the compaction process. The thermal profiles were monitored on top and away of severe discontinuities and joints in the existing pavement. Field monitoring results were then used to validate a three-dimensional heat transfer finite element (FE) model. Upon validation, the FE model was used to conduct a parametric study to evaluate the effects of discontinuities on the thermal profile in an HMA overlay placed on top of an existing pavement and on the vertical thermal profile in the overlay.

METHODOLOGY

The research approach adopted in this study consisted of identifying a number of construction projects in Louisiana, conducting field-testing, analyzing the collected data to determine the feasibility of the technology, and developing correlations for assessing construction quality using Infrared Thermography (IT).

The research team also conducted a finite element analysis to simulate heat transfer mechanisms during paving and compaction in order to expand the scope of the experimental measurements and to study the variation of temperature within the depth of an asphalt overlay. The developed FE model was calibrated and validated based on the results of the experimental program. The three-dimensional model provided insight into the temperature gradient with time that develops in the pavement layers in the horizontal and vertical directions.

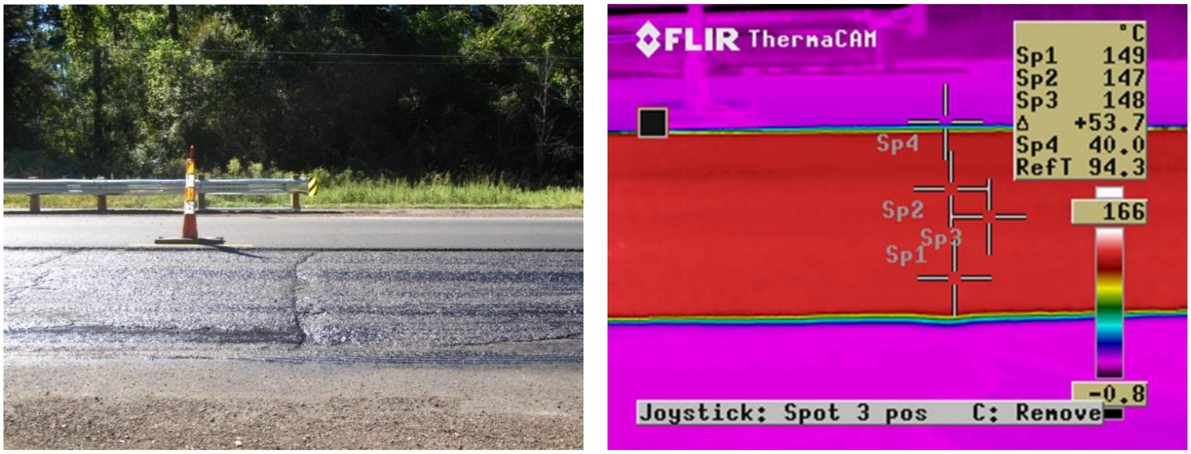
DISCUSSION OF RESULTS

Field Monitoring

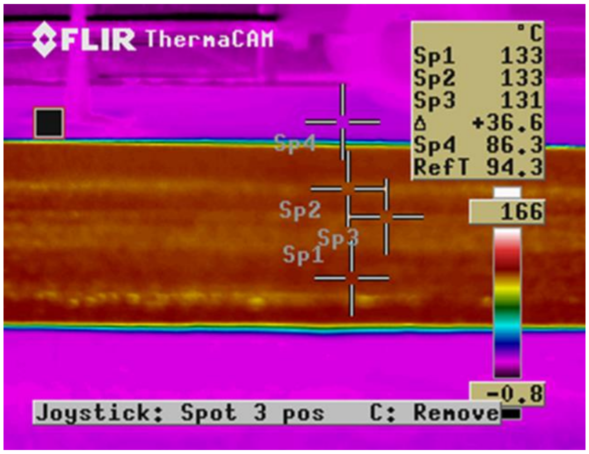
Field measurements were collected continuously during paving and until the end of the compaction operations with particular emphasis on the locations near the joints and discontinuities. However, areas away from the joints were also scanned using IRT for comparison purposes. The variation of thermal measurements during construction operations was also monitored. For HMA overlays on top of a rigid pavement, the locations of the joints in the underlying layer were marked prior to asphalt paving and were then scanned using IRT. An Infrared FLIR THERMACAM PM 675, which is a handheld thermal imaging camera, was used to collect field measurements. The camera has a thermal sensitivity of 0.1°C and a spectral range of 7.5 to 13 μm. Three field projects were evaluated in this study. A description of these projects and the results of the measurements are presented.

US 190 Field Project

The first field project consisted of a 50.8-mm asphalt overlay that was placed over a milled asphalt concrete pavement, located on US 190 between LA 63 and LA 441. The project details are presented in Table 1. The haul distance and haul time for the project was 8.0 km and 7.0 minutes, respectively. End dump trucks were used to transport the mix. The existing milled asphalt surface was in relatively good conditions with the exception of some areas, which showed significant damage in the existing pavement. The digital and thermal images for a heavily cracked location are presented in Fig. 1. The average mat temperature was relatively uniform so generally no temperature differential was observed during paving and 30, 60, 90, 120, and 150 seconds after paving and during compaction, Fig. 1(b and c). It is noted that four locations (Sp1 to Sp4) were monitored at each point of interest (i.e., above the discontinuity and away from it). At time zero, the average temperature of the mat was 148°C with a maximum thermal differential of 2°C. After compaction, the average temperature of the mat was 132.3°C with a maximum thermal differential of 2°C. There was a reduction in HMA temperature by approximately 15°C during the period between production and placement. Based on these results, it is concluded that no thermal segregation was detected in this project. Fig. 2 presents the measured temperature profiles above and away from the discontinuity from time zero to after completion of the compaction process. As shown in this figure, the effect of the discontinuity on the mat temperature was negligible.



(a) Digital Image of a Discontinuity **(b) Infrared Image on Top of the Discontinuity (t=0)**



(c) Infrared Image after compaction

Figure 1

Digital and Infrared Images of the Pavement Section (US 190 Field Project)

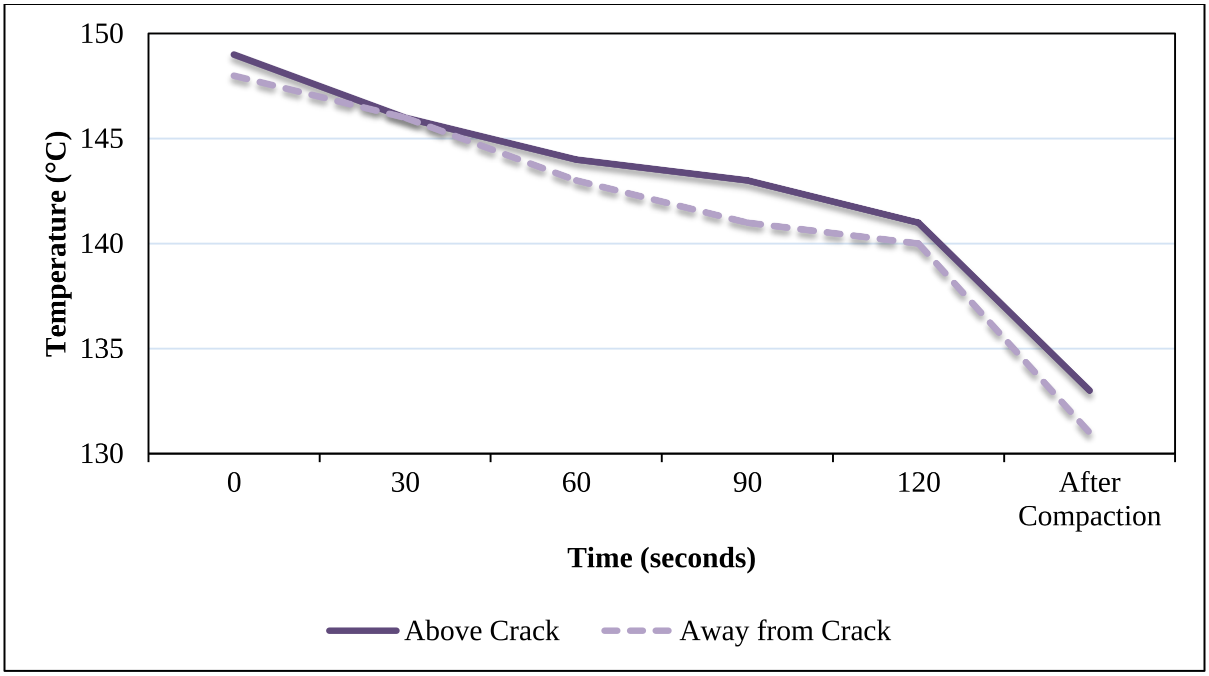
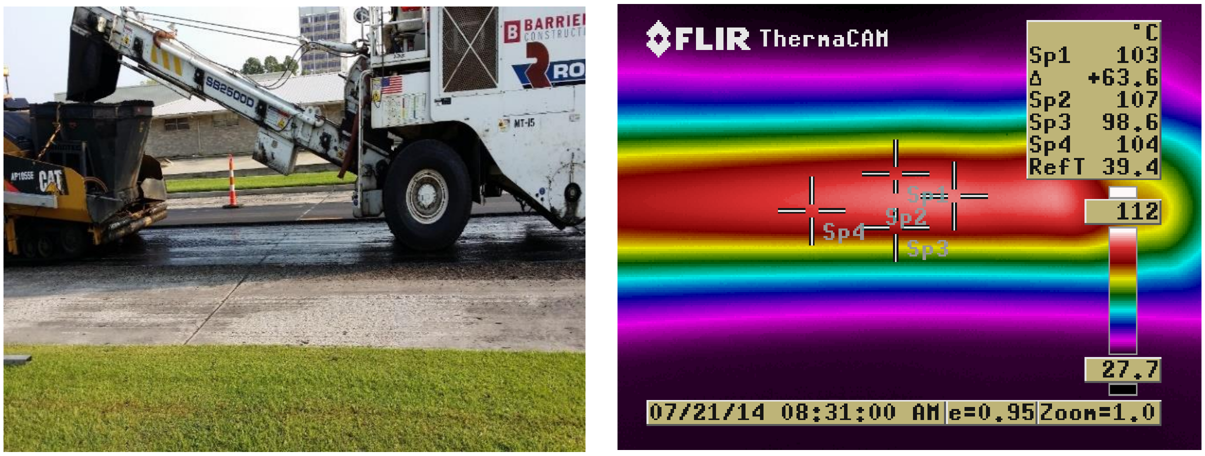


Figure 2

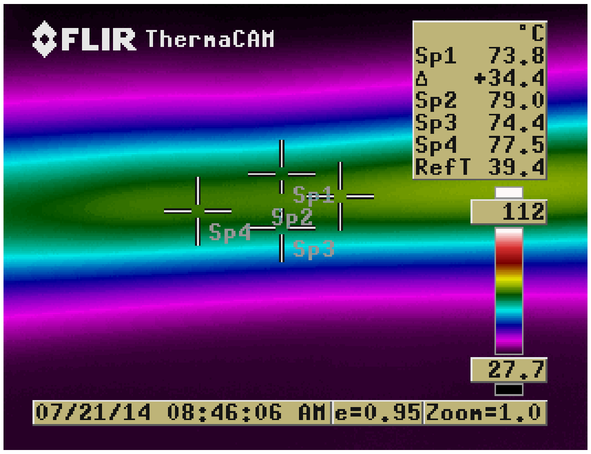
Variation of Temperature on the Overlay Surface with Time (US 190 Field Project)

Tom Drive Field Project

The second field project consisted of the resurfacing of an existing concrete pavement with a HMA overlay, located on Tom Drive in Baton Rouge (LA), Table 1. The existing concrete pavement was patched and the joints were sealed before placing the HMA overlay. The haul distance and haul time of the project were 124 kilometers and 90 minutes, respectively. On this project, a material Transfer Device (MTD) was used and the contractor used a CAT paver, a CAT steel wheel compactor, and a pneumatic tire roller for compaction. Temperature measurements were obtained from the time of paving to after completion of the compaction process, emphasizing the locations on top and away from the underlying joints. The joints were marked and located by means of GPS coordinates for future reference. For this project, the average mat temperature was 137.8°C with a maximum thermal differential of 4.1°C at time zero. After compaction, the average mat temperature dropped to 106°C with a maximum thermal differential of 2°C. Results were similar for most surveyed locations in the pavement section. However, in one area, the average mat temperatures at time zero and after compaction were 103.2°C and 76.4°C with a maximum thermal differential of 8.4°C and 5.3°C as presented in Figure 3(a and b). Based on these results and according to the recommendations of NCHRP 9-11, it is concluded that no thermal segregation was detected in this project. Digital and thermal images on top of the underlying joints are presented in Fig. 3. Fig. 4 presents the variation of the temperature profiles above and away from an underlying joint from time zero to after completion of the compaction process. As shown in this figure, the temperature on top of the joint was consistently lower than away from it, which may indicate that temperature loss may occur at the joints. This trend was further investigated using finite element modeling.



(a) Digital Image of a Joint Section **(b) Infrared Image above Joint (t=0)**



(c) Infrared Image above Joint (t=15minutes)

Figure 3

Digital and Infrared Images of the Pavement Section (Tom Drive Field Project)

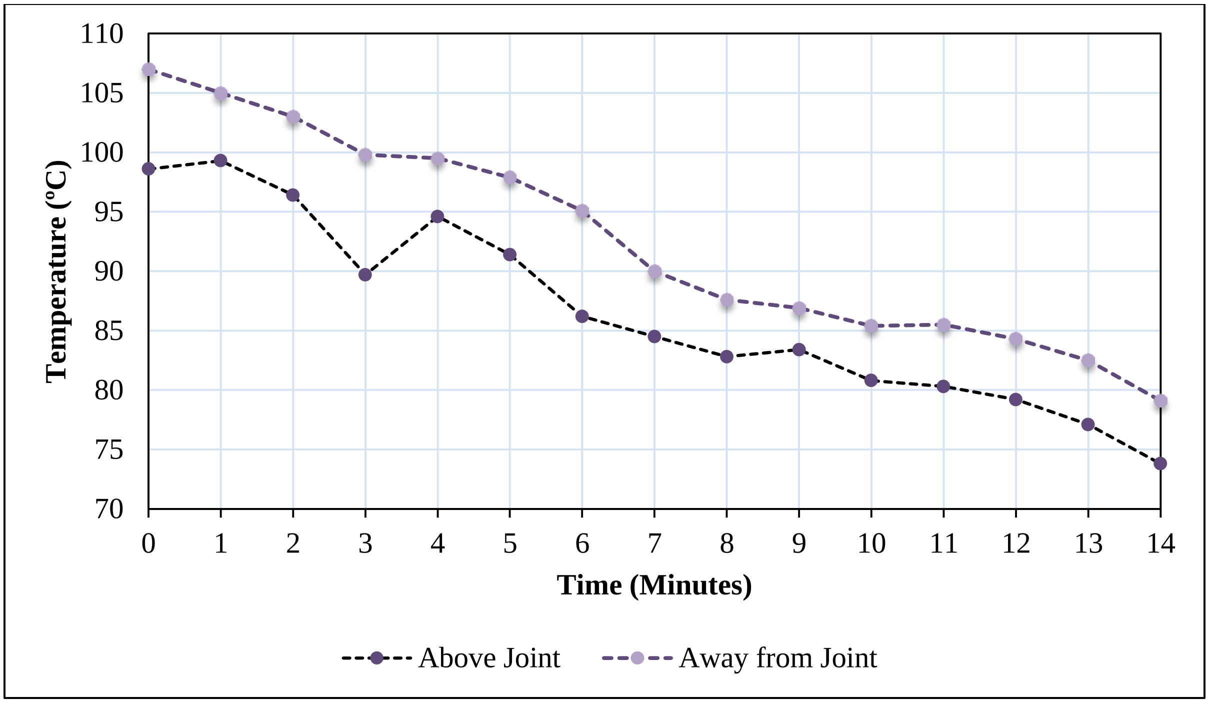
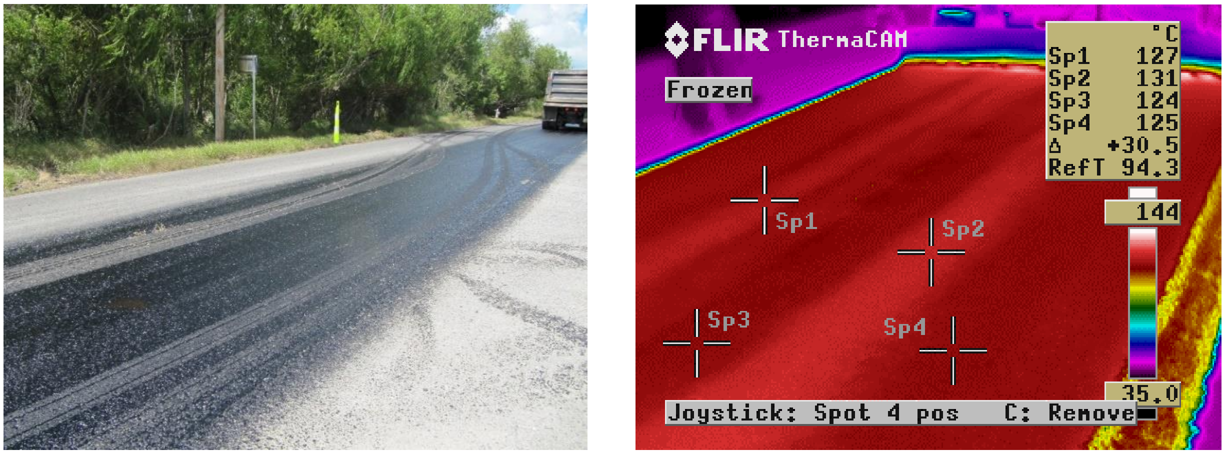


Figure 4

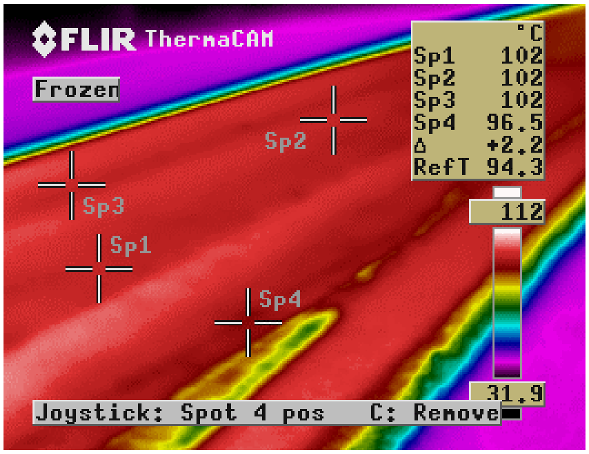
Variation of Temperature on the Overlay Surface with Time (Tom Drive Field Project)

LA 3257 Field Project

The project consisted of a 50.8mm HMA overlay that was placed over an unmilled asphalt pavement, located on LA 3257. The existing surface was in relatively good conditions with polished aggregates and minor cracking. The average mat temperature was relatively uniform so generally no temperature differential was observed during paving and 30, 60, 90, and 120 seconds after paving and during compaction. End dump trucks were used to transport the mix. The project details are presented in Table 1. For this project, the average mat temperature was 126.8°C with a maximum thermal differential of 7°C at time zero. After compaction, the average mat temperature dropped to 100.6°C with a maximum thermal differential of 5.5°C. Based on these results, it is concluded that there was no thermal segregation detected in this project. Thermal and digital images of the pavement section are presented in Fig. 5.



(a) Digital Image the Roadway **(b) Infrared Image at Overlay Surface (t=0)**



(c) Infrared Image after Compaction

Figure 5

Digital and Infrared Images of the Pavement Section (LA 3257 Field Project)

Table 1

Field Project Details

Project / **Description**	**US 190**	**Tom Drive**	**LA 3257**
HMA Thickness (mm)	50.8	50.8	50.8
Mix Type	Superpave	Superpave	Superpave
HMA Production Temperature (°C)	162	157	135
Contractor	Gilchrist	Barriere	Barriere
Haul Distance (km)	8	124	64
Haul Time (minutes)	7 minutes	90 minutes	60 minutes
Asphalt Paver	CAT	CAT	CAT
NMAS (mm)	12.5	12.5	12.5
Air Temperature (°C)	36	31	30.5

Summary of Field Measurements

Thermal measurements obtained on top of an unmilled asphalt surface and on top of discontinuities in a milled surface did not show signs of thermal segregation. Based on these results, one may postulate that heavily damaged surface would not influence the thermal profiles in a HMA overlay. This was expected given the small width of the crack in comparison to the mat surface area, which would not cause major convection losses through the crack. Based on the results in Tom Drive field project, the temperature data on top of a joint were consistently lower than away from it, which may indicate that temperature loss may occur at the joints. However, observed differences were not large enough to conclude that thermal segregation was detected according to the recommendations of NCHRP 9-11. Nevertheless, the presence of cooler areas around the joints may result in weak spots more susceptible to cracking including reflective cracking. These trends were further evaluated using theoretical FE modeling.

Theoretical Analysis of the Test Section

The field investigation provided some insight into the surface temperature variation in a HMA overlay placed on top of heavily cracked pavement, jointed concrete pavement, and unmilled asphalt pavement. However, to expand the scope of the experimental measurements and to study the variation of temperature within the depth of the overlay, a 3D FE model was developed to simulate heat transfer mechanisms during paving and compaction. The developed FE model was calibrated and validated based on the results of the experimental program. An overview of the model formulation is presented followed by the results and discussion of the analysis

Model formulation

The commercial software ABAQUS 6.11 was used in FE modeling of an asphalt overlay construction over an existing concrete pavement, similar to the Tom Drive field project. Fig. 6 presents the general layout of the FE model. The dimensions of the developed model were 1900mm x 1122mm. The adopted mechanical and thermal properties of the pavement layers are presented in Table 2. The concrete layer and HMA overlay were simulated as a set of horizontal elements of constant thickness. Heat transfer analysis was conducted using a transient thermal analysis model for a period of 15 minutes with a time increment of 60 seconds. Three-dimensional continuum elements were selected to simulate pavement field conditions. A sensitivity analysis was performed to evaluate the effect of element dimensions on the model results. The models with element dimensions of 20mmx20mm, 30mmx30mm, and 35mmx35mm yielded similar results. Based on these results, a uniform and fine mesh with element dimensions of 30mmx30mm was utilized in the analysis.

Heat transfer analysis was conducted in order to study the temperature variation at various depths in the HMA overlay from the time of paving until after completion of the compaction process. The temperature profile was predicted from the model results, which was dependent on the temperature of the asphalt overlay, the concrete layer, and the air trapped in the joint between the concrete slabs. The ambient air temperature had also an important impact on the mat temperature over time due to convection losses. The heat transfer mechanisms taking place and simulated in the model were conduction between the layers and convective heat losses between the HMA overlay and ambient air. The ambient air surrounding the asphalt mat was assigned a film coefficient of 15W/m2K based on the results of previous studies (Al-Qadi et al. 2005). Four different node sets were created to study thermal segregation; each set was assigned an initial temperature field that corresponded to what was measured in the field. The model was simulated for two different construction conditions: one with uniform temperature and the other exhibiting a temperature differential of 8.4°C at time 0.

Table 2

Pavement Layer Properties

Layer	c_p^ (J/kg.C)	K^+ (W/m.K)	α^- (1/ °C)	ν^o
Asphalt	920	0.75	1.4E-05	0.20
PCC	800	0.3	7.4E-06	0.15
Air	1003	0.025593	0.00343	----

^ Specific heat, $^+$ Thermal conductivity, $^-$ Thermal expansion, ^{o} Poisson's Ratio

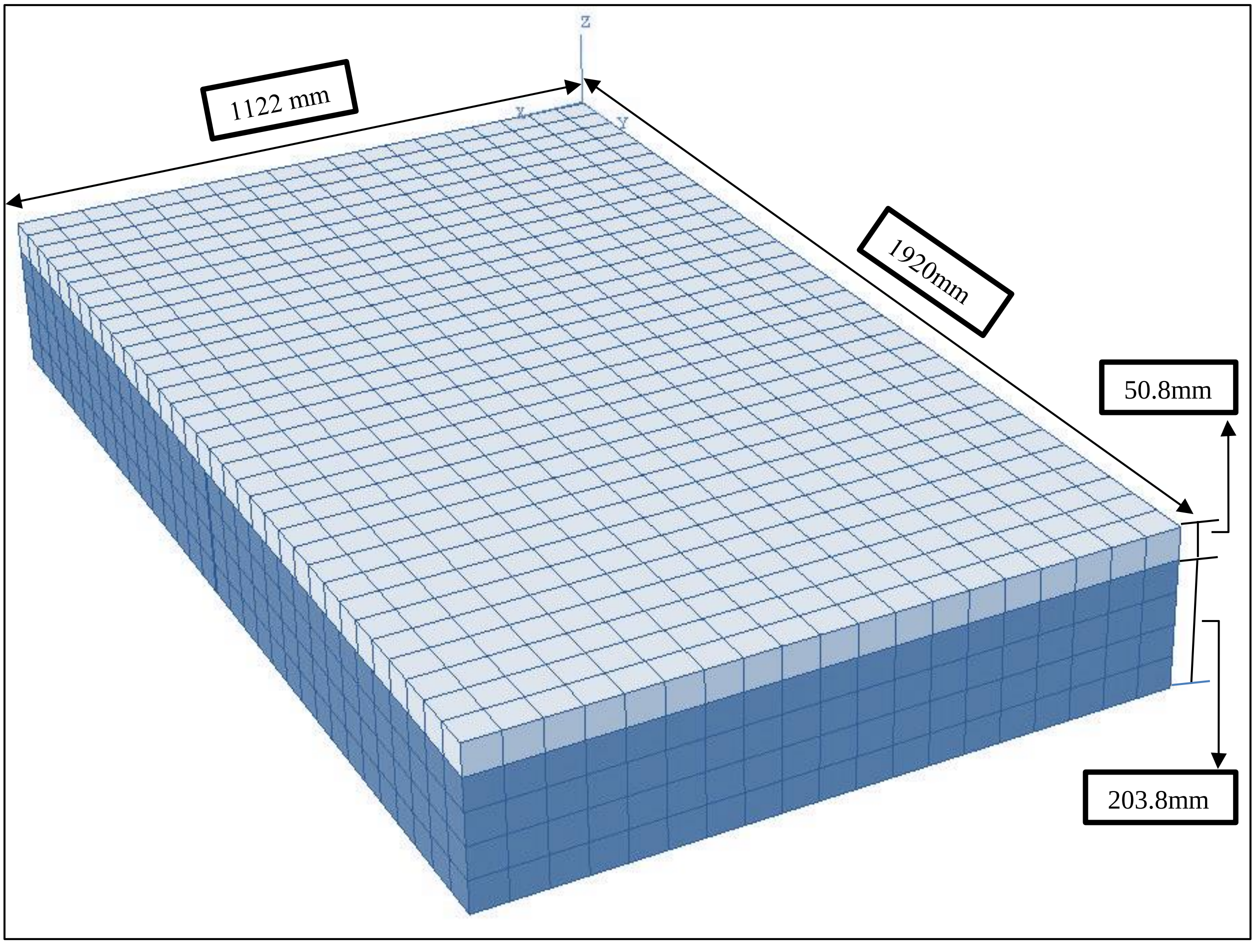
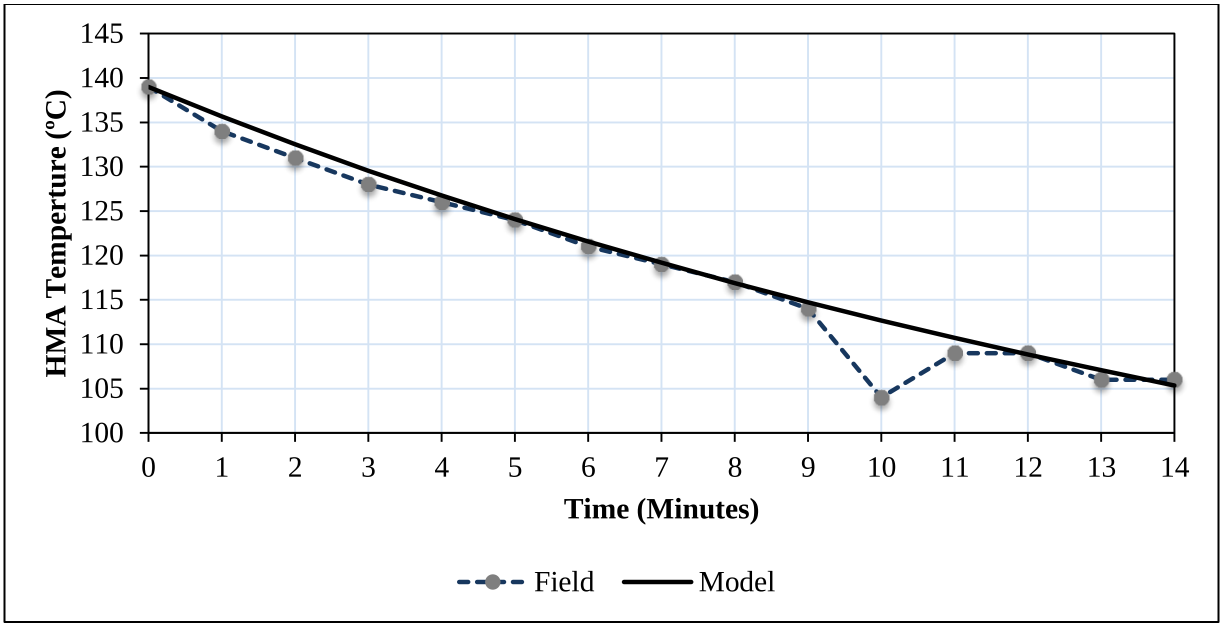


Figure 6

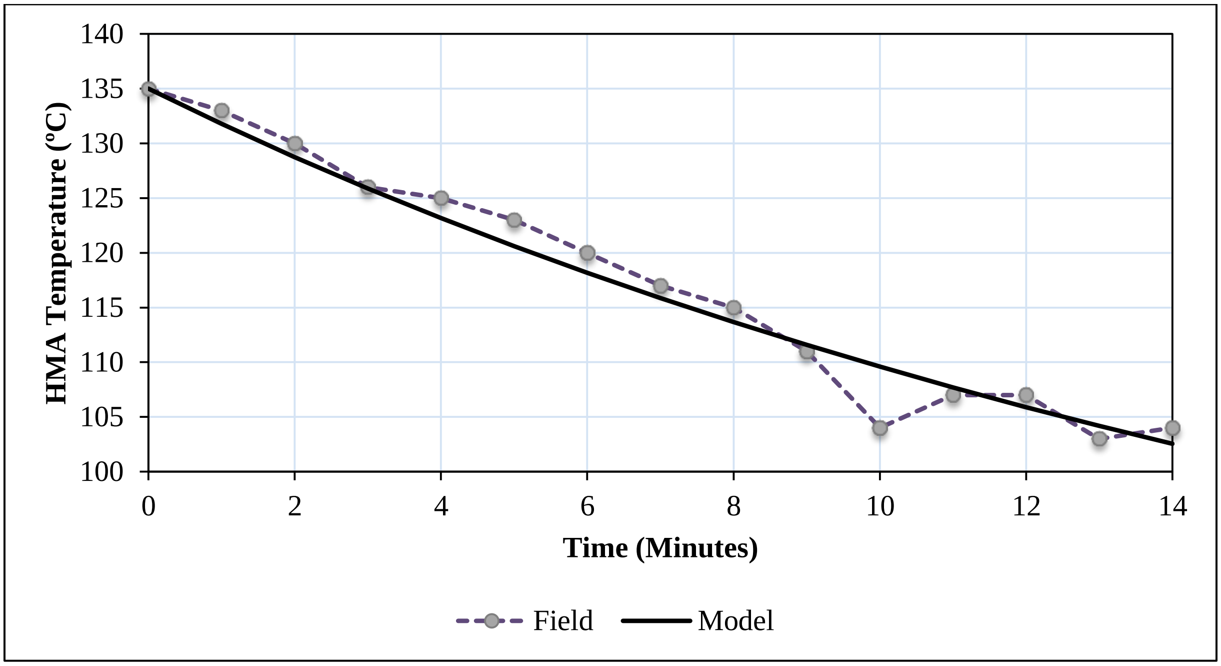
General Layout of the FE Model

FE Simulation Results

Results from the heat transfer analysis provided insight into the temperature gradient that develops in the pavement layers in the horizontal and vertical directions. Fig. 7 and Fig. 8 compare model prediction to field measurements for a 15-minutes time interval above and away from the joint for the pavement sections with uniform and non-uniform mat temperature. As shown in these figures, the model predicted a linear decrease in temperature after mat placement, which is in general agreement with field conditions with slight variability in the measurements. As shown in Fig. 7 and Fig. 8, the model prediction was reasonably accurate. As compared to field measurements, the error in model prediction was less 5% with the exception of when abrupt variability in the measurements occurred indicating an acceptable level of accuracy. Upon validation, results from the FE model were used to extend the scope of the experimental measurements and to provide further insight into the thermal behavior of asphalt pavement during construction as presented in the following section.



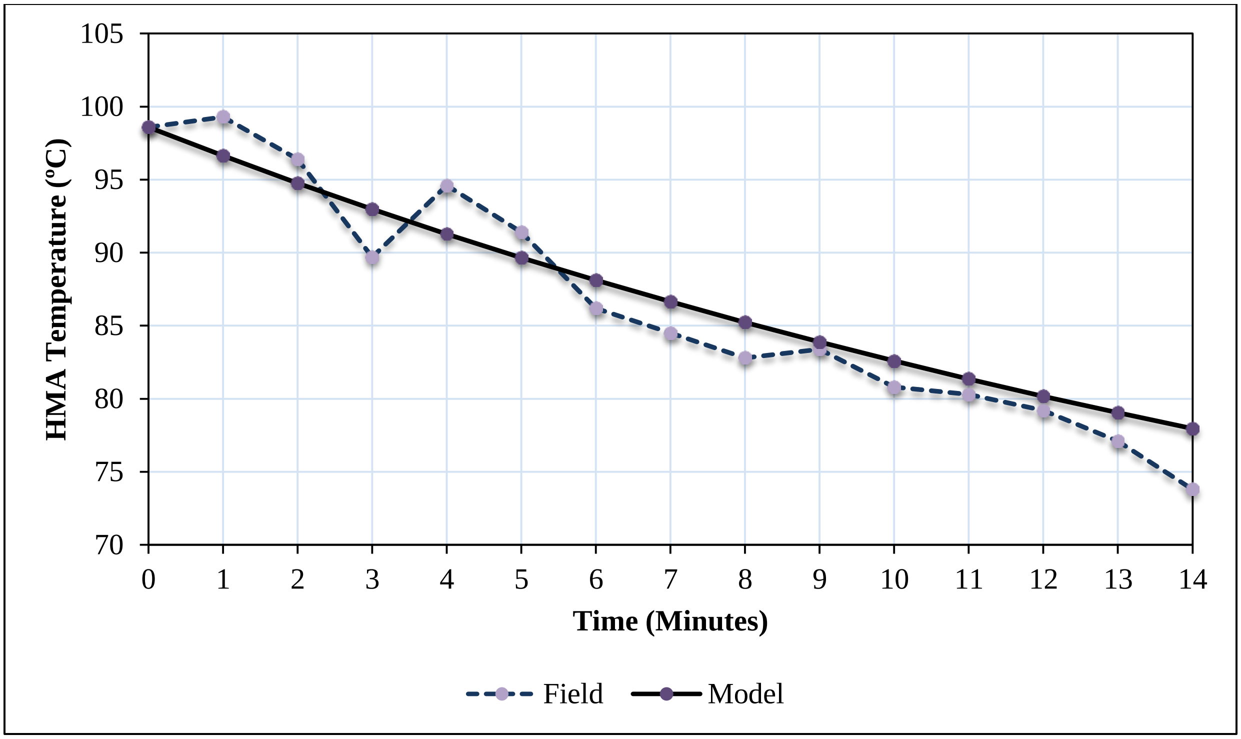
(a) Temperature Profile at a Point above the Joint



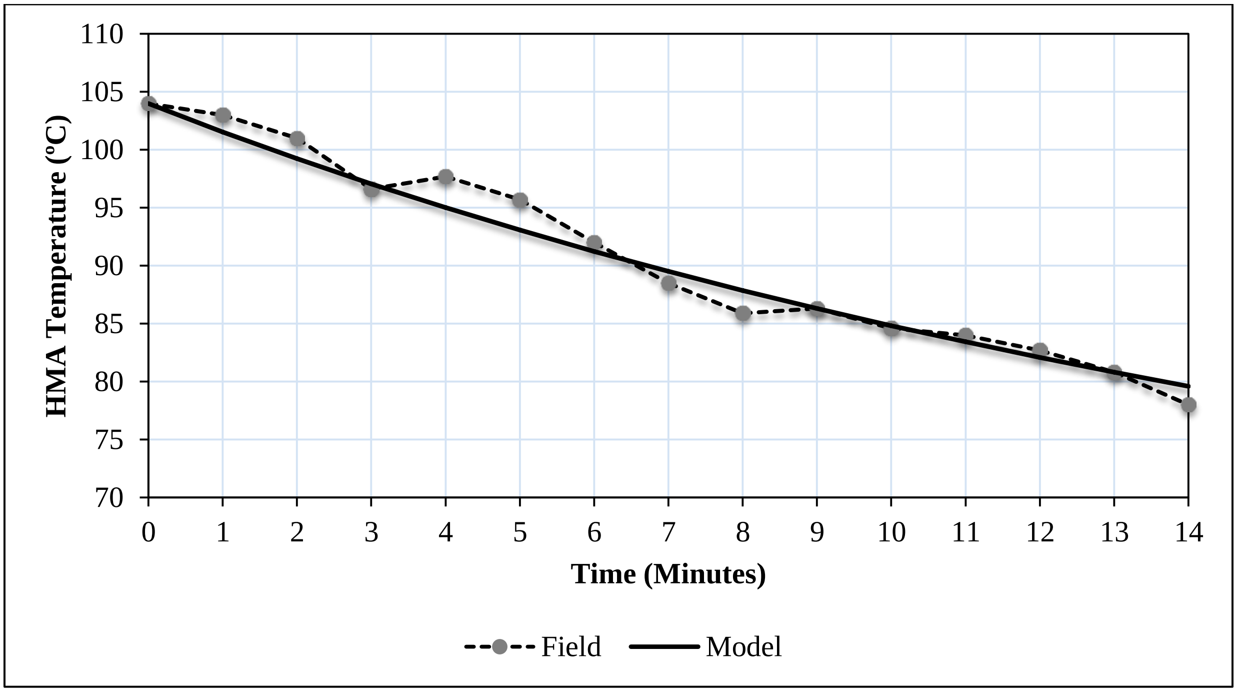
(b) Temperature Profile at a Point away from the Joint

Figure 7

Temperature Profiles for Pavement without Thermal Segregation



(a) Temperature Profile at a Point above the Joint



(b) Temperature Profile at a Point Away from the Joint

Figure 8

Temperature Profiles for Pavement with Noticeable Temperature Difference

Parametric Study

Results of the FE model allowed to extend the scope of the experimental measurements and to provide further insight into the thermal behavior of asphalt overlays during construction. Fig. 9 illustrates the predicted temperature variation at the bottom of the overlay on top and away of the joint considering an initial temperature differential of 8.4°C at the surface. As shown in this figure, the temperature above the joint was consistently lower than away from the joint. Further, the FE model predicted a slightly higher rate of thermal decrease at the bottom of the overlay above the joint than away from it due to convection losses at the joint. After 15 minutes, the differences in final temperature at the bottom of the overlay at and away from the joint was approximately 7°C. While this difference may not be large enough to be identified as thermal segregation, it can influence the bulk properties of the overlay at the joints and promote early cracking.

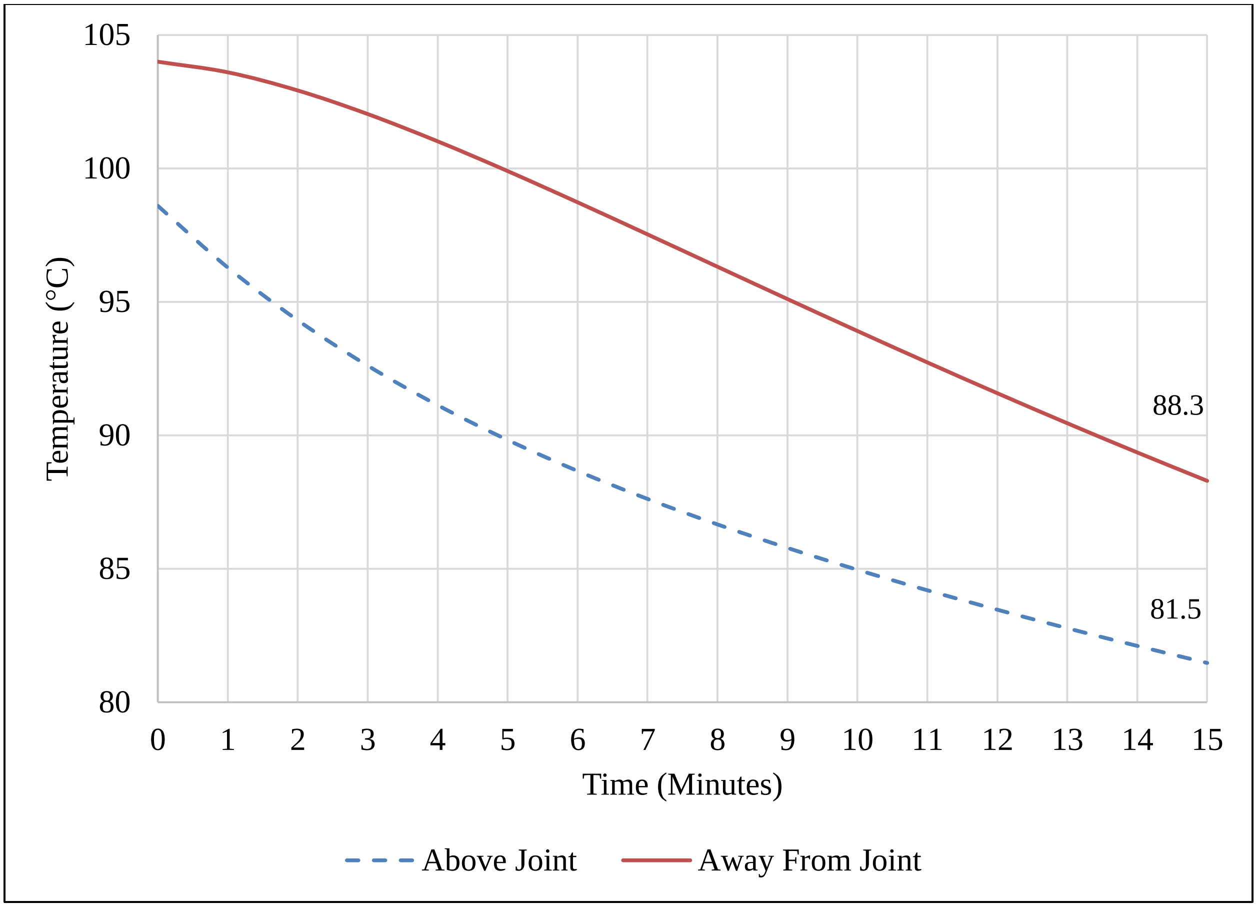


Figure 9

Temperature Distribution at the bottom of the HMA Overlay

The FE model was also used to study the vertical temperature profile at various depths in the asphalt overlay. The initial mat temperature of 139°C as recorded by infrared camera in one of the sections of Tom Drive Field Project was used to calibrate the thermal model. Fig. 10 presents the variation of the temperature gradient with time through the depth of the HMA overlay. The instantaneous drop in temperature at the mat surface as compared to the temperature at mid-depth of the overlay is the consequence of convective heat transfer loss with the ambient atmosphere. At the bottom of the overlay, the effect of conductive heat transfer is maximized because of the substantial difference in temperature between the HMA layer and the top of the concrete surface. These results show that thermal differences occur in the vertical direction as well as in the horizontal direction. While vertical thermal differences have not been investigated to date, it can influence the bulk properties in the vertical direction resulting in a stiffer mix at mid-depth as compared to the top and bottom of the overlay. It can also lead to non-homogeneous properties of the mix in the field. Further investigation of vertical thermal difference is recommended through laboratory testing and by examining the internal air voids structure of extracted cores.

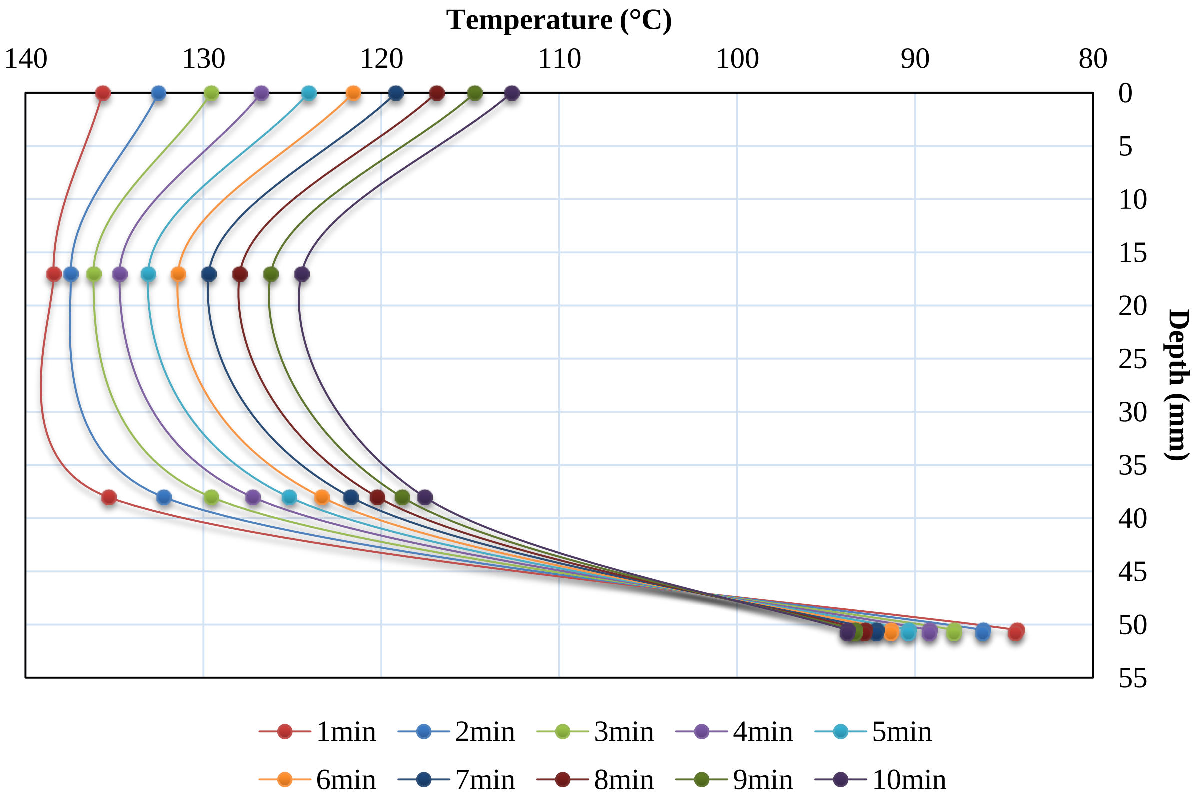


Figure 10

Vertical Temperature Profile at Various Depths in the HMA Overlay with Time

CONCLUSIONS AND RECOMMENDATIONS

The objectives of this study were to assess whether temperature differentials measured using IRT occur in an overlay built on top of discontinuities such as joints and cracks and to study the horizontal and vertical thermal profiles in the asphalt overlay using a validated FE modeling approach. Based on the results of the study, the following conclusions may be drawn:

- **Based on IRT measurements:**
  - Cracks in the existing pavement do not influence the thermal profiles in a HMA overlay. This was expected given the small width of the crack in comparison to the mat surface area, which would not cause major convection losses through the crack.
  - Thermal measurements on top of a joint were consistently lower than away from it, which may indicate that temperature loss may occur at the joints.
- **Based on FE simulations**:
  - A transient thermal FE model was successfully developed to simulate the temperature profile in the overlay during construction. The error in model prediction was less than 5% indicating an acceptable level of accuracy.
  - The FE model predicted a slightly higher rate of thermal decrease at the bottom of the overlay above the joint than away from it due to convection losses at the joint. While this difference may not be large enough to be identified as thermal segregation, it can influence the bulk properties of the overlay at the joints and promote early cracking.
  - Thermal segregation was observed in the vertical direction as well as in the horizontal direction. Lower temperature was predicted at the top and bottom of the overlay during construction due to convection losses and conduction between the hot overlay and the existing pavement.

The present study investigated the temperature differential in an asphalt overlay caused by the discontinuities or joints in an existing pavement. Further investigation of the findings of this study is recommended through laboratory testing of extracted cores and through evaluation of additional field projects.

REFERENCES

1. Brock, J. D.; and Jakob, H. “Temperature Segregation/Temperature Differential Damage.” Roadtec, 1997.

2. Sebesta, S.; and Scullion, T. “Performance Monitoring Pavements with Thermal Segregation in Texas.” Report No. FHWA/TX-12/0-6080-1, 2012.

3. Phillips, L. “Infrared Thermography Revolutionizes Asphalt Paving-Significant Cost Saving for States and Municipalities.” FLIR in Focus, Cost Justification Series, 2008.Santucci, L.E.; Allen, D.D.; and Coats, R.L. “The Effect of Moisture and Compaction on the Quality of Asphalt Pavements.” Proceedings of the AAPT, Vol. 54, pp. 168-208, 1985.

4. Huber, G.A.; and Hernam, G.H. “Effect of Asphalt Concrete Parameters on Rutting Performance – A Field Investigation.” Proceedings of the AAPT, Vol. 56, pp. 33-61, 1987.

5. Brown, E.R. “Density of Asphalt Concrete – How Much Is Needed?” Transportation Research Record, No. 1282, pp. 27-32, 1990.

6. Amirkhanian, S.; and Hartman, E. “Applications of Infrared Cameras in the Paving Industry.” InfraMation 2004 Proceedings, 2004.

7. Adams, J.; Mulvaney, R.; Reprovich, B.; and Worel, B. “Investigation of Construction-Related Asphalt Concrete Pavement Temperature Differentials.” Commercially Unpublished Report to the Office of Materials and Road Research. Minnesota Department of Transportation, 2001.

8. Willoughby, K.A.; Mahoney, J.P.; Pierce, L.M.; Uhlmeyer, J.S.; Anderson, K.W.; Read, S.A.; and Moore, R. “Construction-Related Asphalt Concrete Pavement Temperature Differentials and the Corresponding Density Differentials.” Report No. WA-RD 476.1, Washington State Department of Transportation, 2001.

9. Stroup-Gardiner, M.; and Brown, E.R. “Segregation in Hot-Mix Asphalt Pavements.” Report No. 441. Transportation Research Board, 2000.

10. Mahoney, J.; Zinke, S.A.; Stephens, J.E.; Myers, L.A.; and DaDalt, J.A. “Application of Infrared Thermographic Imaging to Bituminous Concrete Pavements.” Final Report No. 2229-F, pp. 3-7, 2003.

11. Henault, J.W.; Larsen, D.A.; and Scully, J.J. "Development of Guidelines for Reduction of Temperature Differential Damage (TDD) for Hot Mix Asphalt Pavement Projects in Connecticut." Report No. FHWA-CT-RD-2222-1-99-5, Connecticut Department of Transportation, Bureau of Engineering and Highway Operations, Division of Research, 2005.

12. Song, J.; Abdelrahman, M.; and Asa, E. "Use of a Thermal Camera during Asphalt Pavement Construction." North Dakota Department of Transportation, 2009.

13. Sebesta, S.; and Scullion, T. "Statewide Implementation of PAVE-IR in the Texas Department of Transportation." Report No. FHWA/TX-12/5-4577-05-1, Texas Transportation Institute, 2012.

14. Al-Qadi, I.L.; Hassan, M.M.; and Elseifi, M.A. "Field and Theoretical Evaluation of Thermal Fatigue Cracking in Flexible Pavements." Transportation Research Record: Journal of the Transportation Research Board, 1919(1), pp. 87-95, 2005.

15. Minhoto, M.J.; Pais, J.C.; Pereira, P.A.; and Picado-Santos, L.G. "Predicting Asphalt Pavement Temperature with a Three-Dimensional Finite Element Method." Transportation Research Record: Journal of the Transportation Research Board, 1919(1), pp. 96-110, 2005.

16. Li, H.; and Harvey, J. "Numerical Simulation and Sensitivity Analysis of Asphalt Pavement Temperature and Near-Surface Air Temperature Using Integrated Local Modeling." 90th Annual Meeting of the Transportation Research Board. Washington, pp. 11-3125, 2010.

17. Rahman, M.M.; Grenfell, J.R.; Arulanandam, S.J.; and Ianakiev, A. "Influence of Thermal Segregation on Asphalt Pavement Compaction." Transportation Research Record: Journal of the Transportation Research Board, 2347(1), pp. 71-78, 2013.