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Effects of Temperature Segregation on the Volumetric and Mechanistic Properties of Asphalt Mixtures

by

Louay N. Mohammad, Ph.D., P.E. (WY), Fellow-ASCE
Minkyum Kim, Ph.D.
Pranjal Phaltane

LTRC/LSU

4101 Gourrier Avenue | Baton Rouge, Louisiana 70808
(225) 767-9131 | (225) 767-9108 fax | www.ltrc.lsu.edu

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16. Abstract

Thermal segregation is a non-uniform temperature distribution across the mat of uncompacted asphalt mixtures during paving operation. The first investigation on temperature segregation was attempted in the late 1990s. The primary concern of temperature segregation phenomenon is the detrimental effect that may occur on the quality and performance of asphalt pavements. This is because some areas of the asphalt mat are cooler than the required compaction temperature resulting in lower field densities.

The objective of this research is to determine the impact of temperature segregation on the quality of asphalt mixtures as defined by measurements of density and mechanistic properties of asphalt mixtures. Seven asphalt rehabilitation projects across Louisiana were selected. A multi-sensor infrared bar (Pave-IR) system and a hand-held portable thermal camera were used to measure the temperature of asphalt mats. Field core samples were collected from areas with varying levels of temperature segregation.

Densities and mechanical properties from Loaded Wheel Tracking test, Semi Circular Bent test, and Indirect Tensile Dynamic Modulus test of roadway cores at uniform and non-uniform temperature zones were conducted.

Two distinctive patterns of non-uniform temperature distribution of asphalt mats were observed, namely, cyclic and irregular temperature segregations.

Cyclic temperature segregation occured as a fairly consistent cyclic fluctuation of temperature with a certain range of interval (typically 100 to 250 feet) due to continuous cooling of asphalt mixtures during the normal operation, while the irregular temperature segregation occurs at no specific intervals when the paving operation is stopped for an extended amount of time.

Results showed that the use of material transfer vehicle (MTV) and 12.5-mm nominal maximum aggregate size (NMAS) mixtures can improve the consistency of asphalt mat temperature. Laboratory test results showed that highly temperature segregated asphalt pavements (i.e., temperature differentials ≥ 75°F) can have significantly lower densities and the mechanistic properties than non-segregated area, especially when the temperature differentials are measured prior to the first breaking roller application.

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Louay N. Mohammad, Ph.D., P.E. (WY), Fellow-ASCE
Professor of Civil and Environmental Engineering
Department of Civil and Environmental Engineering
Louisiana Transportation Research Center
Louisiana State University

Minkyum Kim, Ph.D.
Research Associate
Louisiana Transportation Research Center
4101 Gourrier Ave., Baton Rouge, LA 70808

Pranjal Phaltane
Graduate Research Assistant
Department of Civil and Environmental Engineering
Louisiana State University

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IMPLEMENTATION STATEMENT

Specification recommendations were developed based on findings of this research in order to improve the performance of Louisiana asphalt pavements. It included the use of thermal scanning devices that can provide real-time thermal images. Thermal scanning is recommended to be performed prior to compaction to identify cooler mixture spots and adjust compaction efforts as needed to achieve adequate field densities. Further, preliminary range of temperature differentials (TD) and suggested actions by the project engineer were developed as shown below.

TD from Target Laydown Temp. (°F)	Actions
0 to 50	• No actions may be required.
50 to 75	• Require contractors to reduce TD below 50°F. • Require contractors to stop operation if TD is not reduced. • Measure field densities in the affected area. • QA cores may be taken from the area.
Above 75	• Require contractors to reduce TD below 50°F. • Require contractors to stop operation if TD is not reduced. • Obtain QA cores from the affected area. • Require contractors to remove the affected area if the density fails to meet the requirement.

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INTRODUCTION

Background

Segregation in asphalt mixtures can be described as a concentration of coarse materials in some area and fine materials in others, which results in non-uniform mixes that do not duplicate the original design, grading, or asphalt cement *[1]*. Once occur, the segregated area of a pavement is likely to develop localized premature distresses such as fatigue cracking, rutting, raveling, pothole, etc. Numerous researchers and engineers have investigated the topic for decades. The National Cooperative Highway Research Program (NCNRP) Report 441 is one of these efforts, in which segregation was further identified as (1) gradation segregation, (2) temperature segregation, and (3) aggregate-asphalt segregation (a.k.a., drain-down in stone matrix asphalt) *[2]*.

Gradation segregation would result in either coarse aggregate-rich or fine aggregate-rich spota and has been the most common problem encountered; therefore, many remedies have been introduced and resulted in significant reductions of the problem. Widely practiced remedies to reduce the chances of gradation segregation include multiple pile truck loading from the storage bin at the plant, use of material transfer vehicle (MTV) from truck bed to paver, and so on. The second type, temperature segregation (TS), is a recently found phenomenon thanks to the popular use of high-precision portable infrared thermal cameras in the paving sites. Several state agencies and researchers have investigated this latest phenomenon to find causes and possible effects on the performance of asphalt pavements *[2-28]*. While many studies reported similar causes of the TS such as differential cooling on the haul trucks, lack of remixing before laydown, inappropriate paver operation, etc., concerning the effects on the quality and performance of pavements, some studies found correlations, but others did not. The lack of agreement on the influence of TS to pavement quality and performance could have been resulted from inconsistent definition of temperature segregation and dissimilar ranges of asphalt mat temperatures investigated by different researchers.

Problem Statement

Louisiana standard specifications for roads and bridges require specific operational details such as the truck loading practice, discharge manner, use of MTV, paver requirements, etc., to prevent the gradation segregation *[29]*. Some of these practices such as the use of MTV have been commonly found to be effective in minimizing the temperature segregation by the researchers *[3-7]*. However, actual occurrence of the temperature segregation in Louisiana asphalt pavements has not been investigated until recently, and, under which circumstances, how often, how long, and how severe the temperature segregation occurs in the state have not been mostly known. Moreover, better understanding the ultimate link between temperature segregation and asphalt pavement performance via mechanical properties of asphalt mixtures will enable Louisiana pavement engineers to tailor the solutions to mitigate the problem.

Literature Review

Early Observations

Read observed that large temperature differentials of hot-mix asphalt mass on the haul truck and the subsequent asphalt mat, laid-down through end dump operations of the truck, occurred during the nighttime asphalt paving operations in Washington *[8]*. Continued investigation by Willoughby et al. concluded that "concentrated areas of significantly cooler hot-mix resulted in reduced compaction of these areas" with an average air voids increase of 3.9% *[3-4]*.

Temperature Differential Detection

Discovery of infrared radiation was the result of an experiment by F. W. Herschel who observed heat effects associated with various spectral ranges of Sun's radiation. Emissivity is a significant factor of a material surface that affects the amount of energy radiating from it at fixed temperature. The authors of this book have synthesized several methods, proposed in 1982, of evaluating surface emissivity. A recent addition in these methods is an infrared camera, which can be classified based on its infrared range and detector type. The atmosphere has two bands in infrared range. Infrared camera detectors can be long-wave and short-wave depending on their field applications. Also, the detectors can be cooled type and non-cooled type depending on the temperature range, in which the camera is needed. The mechanism of infrared temperature scanning starts with the thermal radiation of a surface, which arrives to the detector through the air. This radiation gets converted to electrical signals proportional to radiant emittance, which is amplified to display a thermal image *[9]*.

Stroup-Gardiner and Brown conducted research focused on developing procedures to define, detect, and measure segregation in aggregates and laydown temperature *[2]*. A total of 14 projects were selected for evaluation determining the ability of each method (nondestructive and destructive) to detect and quantify both types of segregation. Infrared thermography using infrared camera was conducted to measure level of temperature segregation at every 500-ft. section. Also, ROSANv laser surface texture measurement was conducted to determine surface texture changes with various levels of segregation. Other non-destructive testing equipment comprised of rolling nuclear density, moisture gauge, prototype of nuclear thin-lift asphalt content, and portable seismic pavement analyzer. Air voids, mix stiffness, tensile strength, gradation, and asphalt content were field tested. Infrared thermographic imaging was conducted during paving and also on recently constructed projects. The areas with temperature segregation were seen with same color (generally cooler) in the infrared images during paving. Infrared imaging on recently constructed pavements required solar gain (increase in surface temperature due to solar heat) to detect areas having higher air voids which were seen as warmer areas as they act as insulators (trap warm air near surface).

Infrared thermography was concluded as an excellent tool to detect temperature segregation during paving operations, however it was not found helpful to strongly distinguish areas with segregation in recently constructed projects. The study concluded that there was evidence of repetitive temperature differential, although this evidence did not explicitly mention any cyclic occurrences at equal intervals. Air voids were found to be 2-6% higher (medium level) and greater than 4 percent higher (high level) in segregated specimens than the non-segregated specimens. Although general trends were visible in air voids content measured using nuclear density gauge for different levels of segregation, it was stated that the difference in density was not statistically significant, and this method was not an accurate parameter (nuclear density) to identify this problem *[2]*.

Sebesta and Scullion conducted a research study to evaluate the "effectiveness" of Ground-Penetrating Radar (GPR) and Infrared (IR) imaging system in detecting segregations within pavement mats *[10]*. A 1000-ft. test section from each of three overlay projects was selected to collect infrared thermal data and GPR data. Infrared images were taken immediately after asphalt mixture laydown, and areas with temperature differentials of 20°F or greater were marked (along with uniform temperature areas) for further investigation. For each test section, data at 1-ft. interval was collected from GPR run in transverse direction at five locations after the pavement compaction. After reviewing data from the above nondestructive techniques, field cores were collected from selected areas that were tested for density (bulk and maximum theoretical), asphalt content, and gradation. Researchers further related observed nondestructive testing data to the mixture properties of cores, which led to the finding that changes in properties are significantly related to the yielded data from GPR and IR imaging. It was recommended to use IR imaging as a quality control tool during HMA placement to monitor temperature uniformity of paved mat. It could also be used to flag areas with potential segregation problems, of which follow-up testing could verify presence and magnitude of irregularities *[10]*.

Williams et al. also conducted a field evaluation of a thermal imaging device to determine its effectiveness in detecting aggregate segregation *[11]*. They found a non-destructive testing method that could quickly identify segregation. The concept behind the use of thermal imaging was that different-sized aggregates retain heat at different rates, and display different temperatures on thermal images. Thermal imaging equipment was field-tested at two locations: (1) existing pavement at HMA plant and (2) paving project. This equipment was used to determine its efficacy in detecting gradation segregation. However, the IR equipment (unspecified) was found to be ineffective in detecting material segregation *[11]*.

Stroup-Gardiner conducted an experimental research under Innovations Deserving Exploratory Analysis (IDEA) program in 2003 to develop a prototype infrared sensor bar *[12]*. The objectives of this research were to construct a paver-mounted sensor bar, develop an automated data collection and report-generation system, and conduct its preliminary evaluation. Stainless steel self-powered infrared sensors were searched online, and a sensor with field view of 5:1 with temperature measurement range between 260-310°F was selected. A vertically adjustable sensor bar mountable in two parts, each with 6 sensors, was designed as a prototype. An air purge system with one air-port per six sensors was provided to flush clean air before starting the equipment. A GPS antenna that connects directly to the portable computer was selected based on its low cost and acceptable accuracy of 10 to 30 feet. Data acquisition and signal conditioning hardware was connected to the sensor bar, and software programs to acquire data and generate reports were developed. A small tray carrying a battery, an inverter, signal conditioners, and a portable computer was clamped to the bar for monitoring and setting adjustments.

A trial run was conducted on an existing roadway of 200-ft. using half bar of six sensors attached to back of a truck. The sampling rate was set to collect data every three seconds, so the numbers of data points could facilitate in calculating the paver speed. Another trial run was conducted for a longer distance and retrieved data was used to generate reports. Results showed that the height of the sensors above the surface did not affect the temperature measurements, however the vehicle speed was found to affect the readings. High power requirements were observed to limit the data collection. Also, the setup of cables was cumbersome, which could pose a safety issue to the workers.

In continuation of 2003 research, Stroup-Gardiner et al. published a paper reporting further improvements on the prototype paver-mounted infrared sensor bar where a thermal-scanning of a test track at National Center for Asphalt Technology (NCAT) was conducted *[13]*. The sensor bar was designed to generate highly repeatable thermal data without continuous technician supervision. The specific objectives of this paper were to validate the sensor bar temperature measurements during hot mix asphalt pavement construction, and to estimate variability in the bar thermal data. A quick clamping modification, shorter sensor bar (6-ft.), and temperature shielded flexible wiring of sensors were the added features that eased the task of mounting the bar in addition to increasing safety near the walkway of the paver screed. During thermal scanning, the sensor bar operator held the infrared gun to monitor and compare the temperature readings against those from the sensor bar data. When compared, it was observed that with use of a reasonable offset temperature (~25°F), the sensor bar data can be correlated to the IR gun temperature readings.

Figure 1
A prototype Pave-IR system on NCAT test track (Stroup-Gardiner 2004)

The "PaveCool" software program that uses numerical solution method to estimate rate of cooling of HMA with input of specific parameters (temperatures, time of day, weather conditions, and lift thickness) was used to model anticipated HMA cooling. The calculated "anticipated pavement temperatures" from software were compared with the actual measured sensor data (at paver stop). A strong correlation was found between both temperature values, and the cooling curves from both sources nearly coinciding. A standard deviation of 37°F was observed across the bar width during paving with an MTV. The infrared sensor bar was concluded to deliver a reasonable approximation of temperature profile similar to other thermal imaging equipment, although the data acquisition was found to require a steady source of power from paver or battery *[13]*.

Texas DOT (TxDOT) reported the statewide implementation of infrared temperature scanning during paving in the TxDOT. The Pave-IR system is a modified paver-mounted infrared temperature scanning bar that provides real-time thermal profiling of paving operations to detect temperature segregation. More than 80 contractors and agency personnel attended a webinar that was conducted to introduce this new equipment along with brief information explaining temperature segregation and its effects on mixture properties. Following the webinar, the Pave-IR system demonstrations were conducted at eight construction projects across Texas, and their results were filed into this report.

Later, TxDOT implemented specifications stating use of the Pave-IR system as part of QC/QA for dense-graded asphalt mixtures through a test method Tex-244-F. Analyzing project specific data and collected thermal data, no strong evidence was found to suggest substantial impact of mix type, lift thickness, or haul distance on temperature non-uniformity. The projects using transfer devices were found to exhibit the least temperature differential occurrences. End dump operation of charging asphalt mixture in paver or MTD produced most severe cases of temperature segregation (75.1 to 100.0°F) among all scanned projects. Based on thermal profile summary generated by the Pave-IR software, a minimum temperature differential of 25°F was observed on all projects with an exception of one project *[14-15]*.

Development of Temperature Differential Detection Techniques

Mahoney et al. published a paper based on a previous study that examined construction-related temperature differentials in asphalt concrete pavements *[16]*. Four 1998 Washington DOT's paving projects were studied for existence and extent of mat temperature differentials. The mat laydown temperatures directly behind the screed of paver were measured using digital thermometers and a thermal camera. The difference in measurements from the thermometer and camera were found to be insignificantly low. Night-time paving operation of one project was observed to deliver asphalt mix at a temperature lower than desirable. Pavement density analysis showed that higher air voids were generated in areas where the compactors could not keep up with the laydown operations. Gradation and asphalt content analysis of obtained roadway cores did not show significant aggregate segregation in thermally segregated specimens. It was concluded that temperature differentials which resulted in low density areas that occurred at the beginning of every truckload of mix could cause cyclic segregation. Furthermore, it was advised to follow laydown practices such as "timely breakdown rolling and a proper rolling train" could adequately compact isolated thermally segregated areas *[16]*.

Stroup-Gardiner published a study part of NCHRP 9-11 research program to evaluate statistical changes in gradation, asphalt content, and air voids due to various levels of segregation. Although most of the study concentrates on gradation segregation and severity levels based on it, the study mentions temperature segregation as a cause for rutting. Furthermore, poor compaction leading to lower pavement density is concluded as effect of temperature segregation causing this permanent deformation *[2]*.

In 2003, an investigation was conducted to identify factors or conditions that contribute to temperature segregation in un-compacted mat using infrared thermographic imaging camera. It was hypothesized that temperature segregation and aggregate segregation have similar appearance in the finished pavement, although their causes may not be related. Projects with cold weather paving, night paving, seasonal paving (ambient temperature impact) were preferred for selection. Wearing course paving was closely monitored, and thermal images from 40 paving projects were collected over a period of 3 years (2000-2003). Out of all these projects, 4 projects were monitored for observing the effect that "heated bodies" had on the asphalt mixture during placement, and 11 projects were monitored to determine the effect of remixing using a material transfer vehicle (MTV) during paving. Occasionally, tasks such as conducting density profiles, obtaining material samples, recording time between truck loads, reporting spill locations, and collecting truck configurations were performed.

Based on the results, the density differentials increased with increase in temperature differential. Spillage of asphalt mix in front of paver before mixture laydown was observed to contribute to TD, depending on the quantity of material spilled, shape of spill, amount of time before mat laydown. The haul distance from the plant to the job site was observed to have negligible effect on the magnitude of the TD, although it did affect the size of a low severity thermally segregated area. The regression analysis of TD against haul distances indicated that the rate of heat loss became constant as time progressed (longer haul distance). The cooler weather conditions tended to remove heat faster from the edges, however the heat loss became nearly constant over time, thus reducing the magnitude of TD. Paving operations at night affected the rate of cooling, however the use of MTV significantly reduced the TD (reduction from 53°F to 12°F).

Remixing and non-remixing MTVs were both found to significantly reduce the magnitude of TD. As the infrared camera can measure and display temperature at the surface, it was not practical to measure the effect of base pavement temperature on that of the un-compacted mat. The authors suggested that all truck changes using end dump truck-bed produced distinct area of material at different temperature, because the material along the perimeter of the haul unit tended to cool faster than at the core *[17]*.

Amirkhanian and Putman conducted a study to detect variations in asphalt mix temperatures using an infrared camera, and determine their effect on segregation and physical properties *[6]*. Their research methodology also involved reviewing various models of infrared camera to identify one which could detect performance characteristics required for temperature variability studies. Depending on availability, the traditional paver with conveyor transfer, paver with auger transfer, and material transfer device (MTD) were evaluated for their effect on temperature differentials (TD). Infrared images of paved un-compacted asphalt mat, truck bed, pavement after compaction, paver, etc. were captured and project specific data (equipment, haul distance, surface temperature, and weather conditions) were recorded. A guide stating observations categorized as type of segregation and damage, probable causes, and possible solutions was drafted (Table 1) to aid in identification of a specific type and severity of TD.

Table 1
Segregation types, causes, and solutions (Amirkhanian and Putman 2006)

Segregation Type	Damage	Causes	Solutions
Cold Joint	Decrease in bonding Increase in transverse cracking	Time delay Work Stoppage TD between truckload	Ensure equipment functioning Maintain steady pace
Truck End	Decrease in density	Improper loading of HMA in truck Long haul distance Truck tarps not used	Use MTD Reduce haul distance – choose closer plant
Paver Wing Dump	Decrease in density	Material on wing is cooler	Use MTD Do not dump paver wings
Streak	Decrease in density	Problem with screed	Check operation and function of screed
Cold Spots	Decrease in density	Surface layer of truck mass is cooler	Use truck tarps

Thermal imaging technology was found to be an effective tool in identifying temperature segregation during paving. No evidence was found to indicate the proclivity of a particular asphalt mix or particular paver to form TD than other. At an ambient temperature of greater than 70°F, the time of day did not seem to affect the occurrences of TD. Aggregate segregation at the end of truck load or during paver wing dumping were identified as most probable causes of temperature segregation. Haul time greater than 70 minutes was observed to significantly affect the level of TD. The pavement density seemed to be less in areas with temperature differentials, although the relationship was statistically insignificant *[6]*.

Song et al. published a report on the use of thermal camera during asphalt pavement construction in North Dakota *[7]*. Research objective of this study was to identify occurrences of temperature segregation in North Dakota and determine their probable causes. Thermal images from five on-going asphalt pavement construction projects were captured. Also, a GPS receiver was used to record the position of a thermal image acquisition location to help relocate the cold areas for further follow-up testing. For each project, thermal images of at least one truck load process from loading (at asphalt mix plant) to compaction (on job site) were captured to understand the temperature loss. Typically, each project site had employed two types of hauling unit (live belly and bottom belly trucks) and three compactors (breakdown, intermediate, and finish). Scatter plots were generated showing gradual reduction of temperature against time. It was concluded that North Dakota does encounter temperature segregation (at least 25°F) at all paving projects. Paver adjustments to maintain constant head of material in auger and proper screed angle of attack were found to reduce potential segregated areas. Use of windrow elevators (or MTV) along with bottom belly trucks were observed to be effective in providing uniform paving temperatures *[7]*.

In Connecticut, 11 on-going paving project sites were selected, out of which 2 projects used a remixing transfer device during construction. Each monitored site was 500-ft. in length, and projects were selected based on safety considerations, traffic characteristics, and topography. Infrared video was recorded during paving on all sites. Six sites were monitored for a period of 5 years in order to observe their long-term pavement performance for occurrences of probable distress. Nuclear density tests were performed at each marked location, and cores were extracted to test for percent air voids (AASHTO T269), asphalt content (AASHTO T308), and gradation (AASHTO T30). When compared with target temperature specimens, temperature segregated specimens were observed to have lower densities. However, a plot of change in density against change in temperature did not show a strong correlation. Also, no significant difference was found to exist in grain size distribution and asphalt content of those between segregated and non-segregated areas. Furthermore, it was advised that the presence of temperature differential must not be overvalued as the pavement density could be the function of paving temperature alone (not TD). Conclusions showed that gradation segregation and temperature segregation were independent of each other, and the difference between them was non-discernible through use of thermal imaging. Also, conclusive statements regarding rates of deterioration between segregated and non-segregated areas could not be made because the condition of the underlying pavement seemed to affect the monitored pavement significantly *[18]*.

Gilbert published a study to detect temperature segregation and quantify its effect on finished pavement density *[19]*. The hypothesis (i.e., the material segregation may lead to temperature segregation in HMA as the coarse aggregates are expected to cool quicker than fine aggregates) was tested. A total of 20 projects were thermally monitored (infrared camera and gun), and project specific data was gathered along with thermal images. The temperature readings of same locations measured by an infrared camera and gun were reported. Statistical analysis of both temperature readings showed no evidence of significant difference in the measurements. Although it is not stated in the report what the abbreviations 'S' and 'SX' represent, it was implied that the S mixes are coarser than the SX mixes. The conclusions stated that the temperature segregation was three times more frequent in S mixes than that in SX mixes. End dump trucks without use of transfer or remixing vehicle were found to generate more evidences of temperature segregation than live bottom or belly dump trucks. Also, 77 percent of the locations having evidence of temperature segregation did not show aggregate (material) segregation *[19]*.

A South Carolina DOT's study outlined the efforts to gain specific insight on the long-term effects of temperature segregation on pavement performance. An infrared (IR) camera assisted with a handheld GPS unit was used to detect and record thermally segregated locations. Reports were filed with these thermal images, their GPS coordinates, probable causes of occurrence, project specific data, and tabulation of pavement temperatures (maximum, minimum, and average). Projects selection was based on the asphalt mix type used in the pavement construction (Superpave mix for various levels of traffic volume, Open Graded Friction Course, and Intermediate Type A, B, C varying in gradation). Distress survey was conducted every six months at pre-marked locations, and digital images of evident premature distress were captured along with report of relevant information. During the selection of an IR camera, features such as accuracy, live monitoring display, storage and access to storage, and report generation were preferred. The temperature segregation observed was differentiated into two types based on period of occurrence, namely: (1) Factors affecting the mix before placement (end of load, mix allowed to sit hopper, and paver wing dump) and (2) Factors affecting up-compacted mix after placement (wind cooling and work stoppages).

Factors affecting the mix before placement were observed to cause thermally segregated area formation extending up to entire depth of the mat which could further decrease the pavement density. The conclusions stated that the OGFC mix could alone be severely affected by temperature segregation (raveling) because this mix uses a "stiffer" asphalt cement which affects the level of compaction at high temperature, and it has an open, coarse texture which causes faster cooling. During the distress surveys, the pavement distress was classified into two types; (1) temperature differential damage (TDD) referring to damage due to temperature segregation only (no significant damage observed) and (2) simple deterioration referring to distress caused by factors such as age and subsurface conditions (deterioration due to age observed). Temperature differentials caused by end of load and paver wing dump were concluded to be the potential causes of temperature segregation *[20]*.

A research study by Cho et al. assessed the effects of temperature segregation in HMA paving construction *[21]*. Infrared thermal camera was used to identify areas with temperature differentials, and GPS was used to mark points of interest for future visits.

Secondary objective of this research was to reassess the data collected from construction sites' revisited for a series of freeze-thaw seasons. Thermographic imaging was performed after compaction of HMA laydown. Also, non-nuclear density gauge was used to obtain density data along with construction conditions. It was observed that use of a "pick-up machine" (instead of expensive MTV) between a belly dump truck and paver reduced frequency of temperature differentials significantly. The hypothesis that the temperature differentials cause premature distress from early stage of service life in regions with freeze-thaw cycles was tested, and it was found that distresses such as potholes and transverse cracking did begin to appear in the early stages. Furthermore, the study concluded that temperature segregation and pavement density showed a significant relationship. However, no correlation was found between temperature segregation and haul time or air temperature *[21]*.

Fernandez et al. conducted a study to primarily comprehend the causes of thermal segregation (TS) in asphalt pavements as part of an NCAT research *[22]*. The secondary objective of the study was to quantify effects of TS on in-place road density and fatigue performance of various asphalt mixtures. A total of 28 paving projects constructed in paving season 2010-2011 across Alabama were selected. In addition to 2500-ft. minimum paving length, projects were chosen based on mix type and mix layer. Paver-mounted infrared sensor bar, infrared camera, and temperature gun were used to collect temperature measurements through continuous scanning, truckload temperature, and uncompacted pavement temperatures respectively. During temperature scanning, field data such as job mix formula (JMF) details, hauling time/distance, hauling unit types, MTD/MRD type, paver type, weather conditions, and existing surface temperature were recorded to investigate factors affecting TS severity. Field cores were collected for mat in-place density test following AASHTO T-166 and fatigue performance measurements using Beam Fatigue test (AASHTO T 321) and Indirect Tensile Strength (AASHTO T 283) from thermally-segregated and non-segregated locations using GPS co-ordinates.

During data analysis, a General Linear Model (GLM) was executed to quantify significance of each factor causing TS. Results showed that MRD significantly reduced TS occurrences when compared with projects using MTD and using no transfer/remixing device. Also, warm mix asphalt (WMA) was suggested to help regulate mix temperature uniformity in comparison to hot mix (HMA), stone mix (SMA), and open-graded friction course (OGFC). In-place density results showed no significant difference between thermally-segregated and non-segregated specimens. Based on test results, except mix initial stiffness, no significant TS effect was observed on bending beam fatigue test parameter and fracture energy. In summary, none of the tests conducted showed statistically significant effect of TS on measured mixture properties *[22]*.

A recent study published by Elseifi and Dhakal determined whether temperature differentials measured using Infrared Thermography (IRT) appear in an overlay built on top of discontinuities (joints, cracks) *[23]*. Using a thermal camera with sensitivity of 0.1°C rate of cooling was monitored from asphalt mixture laydown to compaction at selective locations at three projects across Louisiana. For HMA overlays on top of rigid pavement, the locations of joints in the underlying layer were marked and scanned using IRT. Thermal images showed no signs of temperature segregation in case of overlays laid on top of un-milled asphalt surface and top of discontinuities in milled surface. In one project with heavy damage to underlying layer, however, temperature loss was observed to be occurring at joints which may later would have led to areas susceptible to cracking. It was concluded that cracks in underlying pavements did not necessarily influence temperature segregation level of the laid overlay. However, underlying wider joints caused inconsistency in temperature of laid asphalt mat *[23]*.

Temperature Differential, Temperature (Thermal) Segregation, and Temperature Differential Damage

It is noteworthy from the literature that similar terms such as temperature differential (TD), temperature (thermal) segregation (TS), and temperature differential damage (TDD) are used differently and/or interchangeably. Mostly, the definitions are not consistent. During the early investigation on the phenomenon , TD was determined as the difference in average mat temperatures between a concentrated “cooler area” and the surrounding “normal area” and related to the changes in the quality of asphalt pavements *[3-4, 8]*. Willoughby et al. later used the “difference in maximum and minimum mat temperatures in an area measured by a thermal camera” as the definition of TD *[4]*. The same definition was followed by Mahoney et al. and Sebesta and Scullion *[5], [10]*. Henault et al. separately defined the TD as “any localized temperature gradient at the plant, truck, paver, or mat” and the TS as “isolated areas of the mat that differ significantly from the main body of the mat in temperature” *[18]*. Amirkhanian and Putman used a similar definition of the thermal segregation given by Henault et al. to refer to the temperature differential damage (TDD) *[6]*. Song et al. argued that these existing definitions are all relative terms, which cannot provide a sound benchmark for the real issues associated with the “less-than-desirable” mat temperature problems *[7]*.

Summary

According to the previous researches records, temperature differentials (TD) or temperature segregations (TS) occur in various patterns and at different extent during the asphalt paving process. A summary of potential factors causing TD and its likely consequences are presented below:

1. Factors causing temperature segregation:
    - Relatively cooler mass formed during hauling gets passed through paver
    - Lack of remixing before charging the asphalt mix in paver
    - Night time paving with air temperature lower than 70°F
    - Haul time greater than 70 minutes
    - Open Graded Friction Course (OGFC) mix found prone to segregation occurrences
    - End dump truck discharge
    - Equipment malfunction leading to work stoppage.
    - Lack of truck tarps
    - Material cooled on paver wing dumped with high temperature mix

2. Observed consequences of TS occurrences:
    - Density differentials
    - Decrease in bonding between two consecutive pavement parts due to cooling during work stoppage at joint
    - Transverse cracking caused by low bonding at such joint

In the literature, the TD of asphalt mixtures during the paving operations has been measured using a temperature probe, a temperature gun, a handheld infrared thermal camera, and a multi-sensor Infrared bar-type thermal scanning device such as the Pave-IR system. Among these various temperature detection techniques, the thermal camera and Pave-IR system provide more comprehensive area-wide thermal images of uncompacted asphalt mat unlike the temperature probe and the gun-type thermometers that can only measure one temperature of a point at a time. Thus, the thermal camera and Pave-IR system seemed to provide an excellent tool to detect temperature segregation during paving operations. Many previous researches recommend to use infrared imaging as a quality control measure during asphalt mixture placement and the TxDOT, in fact, requires the use of thermal imaging systems in almost all asphalt paving project for continuous monitoring and reduction of TD during paving.

To conduct the investigation on a consistent measure of temperature differentials, it was determined to use the target laydown temperature of a specific asphalt mixture as specified in the job-mix formula (JMF) at each project as the fixed benchmark to compute the TD at any locations of the uncompacted asphalt mat.

OBJECTIVE

The objective of this study was to determine the impact of temperature segregation on the quality and mechanical properties of asphalt mixtures as defined by density, fracture resistance, stiffness, and rutting performance of asphalt mixtures. Specific objectives of the study included were to:

- Ascertain and establish temperature segregation range during paving operation;
- Measure the density of roadway cores at uniform- and non-uniform temperature zones;
- Measure mechanical properties (Loaded Wheel Tracking test, Semi Circular Bend test, and Indirect Tensile Dynamic Modulus test) of roadway cores at uniform- and non-uniform temperature zones; and
- Establish an acceptable temperature segregation range during paving.

SCOPE

Seven asphalt paving projects across Louisiana were selected. The pavement surface area was thermally scanned using a multi-sensory infrared temperature scanning bar. Also, a hand-held portable thermal camera was used to measure the temperature of asphalt mats and evaluate the temperature differentials throughout the mats before compaction. Laboratory measurements of density and mechanical properties were performed on temperature-segregated and non-segregated field cores. These measurements included semicircular bending (SCB) test for fracture resistance, dynamic modulus in indirect tension (IDT|E*|) test for stiffness measurement, and Hamburg type loaded wheel tracking (LWT) test for permanent deformation performance. The following parameters were considered during project selection: asphalt mixture layer (i.e., wearing and binder course, incidental paving), asphalt binder grades (i.e., PG64-22, PG70-22, PG76-22, and PG82-22rm), two mixture types (i.e., hot-mix asphalt and warm-mix asphalt), and nominal maximum aggregate sizes (NMAS) (12.5- and 19-mm) were included in the investigation.

METHODOLOGY

Study Approach

To achieve the aforementioned objectives of the study, the following research tasks were planned and conducted:

- Task 1: Conduct Literature Review
- Task 2: Develop Experimental Design and Select Field Projects
- Task 3: Install and Calibrate of Temperature Measuring Device
- Task 4: Preform Thermal Profile Measurement
- Task 5: Identify Project Locations with Thermal Segregation
- Task 6: Perform Field Sampling and Laboratory Testing
- Task 7: Perform Data Analysis
- Task 8: Benefits of Implementation
- Task 9: Prepare Draft Final Report

Field Projects and Materials

Figure 2 shows approximate locations of the seven asphalt rehabilitation projects selected for this study across Louisiana. A total of seven field projects were selected through a consultation with the DOTD construction and research personnel. All relevant design and construction records were collected including project design proposals and mixture design job-mix formulas (JMFs). Table 2 presents project details of these seven field projects, which were divided into Phase I and Phase II, mainly accounting for the two consecutive construction seasons from December 2014 through June 2016. As shown in the table, during the Phase I, asphalt paving projects on LA30, LA1058, US165, and LA1053 binder course layers were investigated, while in Phase II, LA1053 wearing course layer, LA411, LA940, and LA1 paving projects were investigated. Out of the ten mixtures investigated, four were HMA and six were WMA mix types. Pavement density (Voids in Total Mix – VTM), Semi-Circular Bending (SCB), Loaded Wheel-Tracking (LWT), and Indirect Tensile Dynamic Modulus (IDT|E*|) were performed on field cores to measure the volumetric and mechanistic properties of compacted thermally-segregated asphalt mixtures.

Figure 2
Locations of projects selected for this research

Table 2
Description of field projects

	Route	Layer	Mix	MTV	Target Temperature	Laboratory Tests			
						VTM	SCB	LWT	IDT|E*|
Phase I	LA30	WC	HMA	✓	300°F	✓	✓		
	LA1058	WC	WMA	✓	275°F	✓			
	US 165	WC	HMA	✓	300°F	✓	✓		
	LA1053	BC	HMA	✓	300°F	✓	✓		
Phase II	LA1053	WC	HMA	✓	300°F	✓			✓
	LA411	WC	WMA	✓	290°F	✓			✓
	LA940	BC	WMA	✓	290°F	✓	✓	✓	
		WC	WMA	✓	290°F	✓			
	LA1	Shoulder	WMA		290°F	✓	✓	✓	✓
		BC	WMA	✓	290°F	✓	✓		

Table 3 presents details from the Job Mix Formula collected from each contractor of all investigated projects. The wearing course (WC) layer had 12.5 mm NMAS while binder course (BC) and Incidental Paving (IP) used 19.0 mm NMAS. Five asphalt binder grades, and target laydown temperatures of 300°F, 290°F, and 275°F were included among these projects. Table 3 shows compacted layer thickness and performed laboratory tests on field cores. In general, layer thickness of WC field cores ranged from 35 mm to 40 mm while that of BC and IP ranged from 50 mm to 70 mm. The asphalt content percentage typically was between 4 and 5 for all projects.

Table 3
Asphalt mixture properties

	Route	Layer	Mix	Binder PG	NMAS (mm)	Layer Thickness	Asphalt Content, %	RAP, % of mix	Anti-Strip, % of mix
Phase I	LA30	WC	HMA	PG76-22M	12.5	50mm	4.5	0.7	0.8
	LA1058	WC	WMA	PG70-22M	12.5	38mm	4.9	0.1	0.6
	US 165	WC	HMA	PG70-22M	12.5	50mm	4.5	1.1	0.6
	LA1053	BC	HMA	PG82-22RM	19	50mm	4.6	0.7	0.6
Phase II	LA1053	WC	HMA	PG82-22RM	12.5	38mm	5.2	0.7	0.6
	LA411	WC	WMA	PG64-22	12.5	38mm	4.1	0.7	0.6
	LA940	BC	WMA	PG70-22M	19	50mm	4.2		0.6
		WC	WMA	PG70-22M	12.5	38mm	4.2		0.6
	LA1	Shoulder	WMA	PG67-22	19	50mm	4.8	0.8	0.7
		BC	WMA	PG82-22RM	19	50mm	4.8	0.8	0.7

Field Thermal Scanning

Figure 3 shows the Pave-IR system used for continuous temperature monitoring during paving operation of all field projects investigated in this study. The Pave-IR has a 13 ft. long metallic body (aluminum), which has 12 infrared sensors at one-foot spacing from one another. Each sensor scans and generates a rectangular profile of dimensions 12 in. (transverse) by 4 in. (longitudinal).

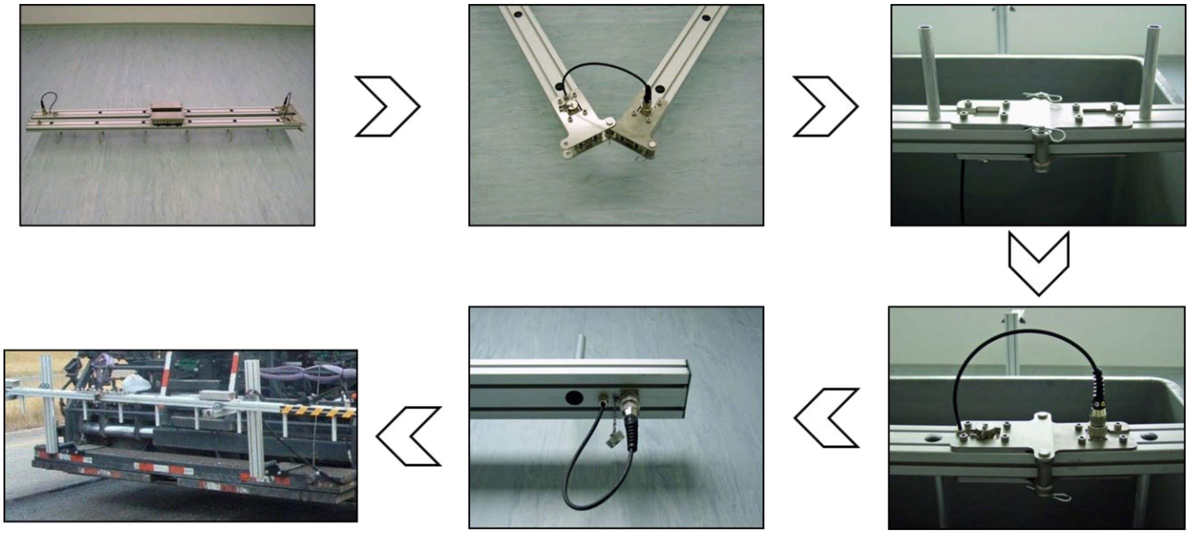


Figure 3
Process of unfolding and placing sensor bar ***(Pave-IR system installation manual)***

Before the scanning procedure starts, this sensor bar needs to be attached to the paver walkway, and its components need to be assembled and connected to parts of paver. Components of the Pave-IR system are listed below:

1. IR Sensor Basic Kit: Infrared sensor beam with an assembly of 12 sensors.
2. Operand board computer: Main board computer that helps a technician to calibrate, setup, and monitor thermal scanning.
3. Ram-mount: A moveable bracket to affix the operand on the sensor beam.
4. Odometer Sensor: A distance encoder that, once calibrated for paver wheel diameter, can provide live, constant, and accurate speed and distance output. A magnet clamp is used to mount this sensor on the paver wheel.
5. GPS receiver: A receiver component of Global Positioning System that provides data of location (latitude, longitude) of thermal-scanning along with the number satellites used and signal quality.
6. Storage drive: A storage device component to save the thermal data files to the computer. It can also be used to update software in the Operand.
7. Cables: There are four cables provided to connect components.
    a. Operand to Paver board power
    b. Odometer to Sensor bar
    c. Operand to Sensor bar
    d. Storage drive to PC for "saved data" extraction

The sensor bar and its components are provided with an instruction manual and an installation manual to help understand and install the system. To facilitate worker movement on the catwalk (a working platform above the screed of a paver), the Pave-IR is mounted on holders having two columns which have masts that securely hold the sensor beam using screws.

Operand screen displays following information to assist live monitoring during paving:

1. Status bar: It displays status of data collection, successful connections of odometer and sensor bar, and GPS quality.
2. Temperature Color Scale: It exhibits a vertical color scale (gradually changing) with assigned temperature value in °F for highest and lowest temperature.
3. Thermal profile: It shows current thermal-scan of 150-ft. colored respective to the temperature scale.
4. Bottom bar: This bar consists of current GPS position, driven distance, paver speed, and time of day.
5. Miscellaneous: Display of four icons to – Stop data acquisition, activate full-screen view, change temperature scale, display highest temperature differential (maximum temperature – minimum temperature every 150 ft.).

The calculations of paver speed and driven distance are primarily based on the radius of the paver wheel. To determine this parameter, it is essential to perform calibration before actual thermal scanning.

Calibration

When the paver reaches a starting position from where it will start paving in a one direction, the calibration program on the Operand could be activated. A point at distance of 200 ft. is marked on ground from the center of paver wheel diameter using a measuring wheel (4-ft circumference). The calibration module is programmed for 200 ft. Once the paving operation starts, the calibration is started. When the calibration is stopped at the marked position (200 ft.), it uses the number of rotations to calculate the radius of paver wheel.

This process of calibration is a requirement because the paver wheel radius may differ depending on model of paver. Also, it is recommended to manually measure the wheel radius using a tape to check whether the odometer is positioned exactly at the wheel's center. After the Pave-IR setup is calibrated, we could start the scanning by selecting a new scanning program. The program requests for a set of project specific information such as roadway ID, operator name, lift thickness, paving width, and height of sensor bar from mat. Once the information is entered, the sensor bar starts scanning, displaying, and recording. The operand displays distance and speed data from odometer, thermal data from infrared sensors, and GPS co-ordinates. During monitoring, the temperature scale can be adjusted to set the 'highest temperature' to be the target laydown temperature.

Figure 4
Paver stopped at 200-ft. calibration point

Tasks Performed during a Typical Thermal-scan Operation

The procedure started at each site by marking three to five points in the paving direction at an interval of 1000 ft. At these points, distances were checked on the Pave-IR system screen to validate that the calibration accuracy. Information such as maximum trucks waiting, truck waiting time, mix temperature in the truck, mix temperature in paver hopper, mix temperature in the auger during paver stop, reason of work stoppage, atypical crew operations, compactor number of passes, compactor wheel temperature, etc. was regularly recorded. A separate datasheet was maintained to note the station marks of paving start/end position including paver stops (location, paver stop/start time, temperatures before compaction). Paver stop locations were flagged using yellow-colored flags noted with station mark reading and lowest mat temperature. These thermally segregated locations were revisited during field coring. Contractor's asphalt mix plant was visited to obtain the Job Mix Formula (JMF) to get further insight on mixture properties.

The last station mark of every project was recorded, and thermal data was saved on the storage drive after the paving operations were completed for the day. The retrieved data was analyzed for potential segregated locations and patterns such as cyclic occurrences that may indicate probable specific causes.

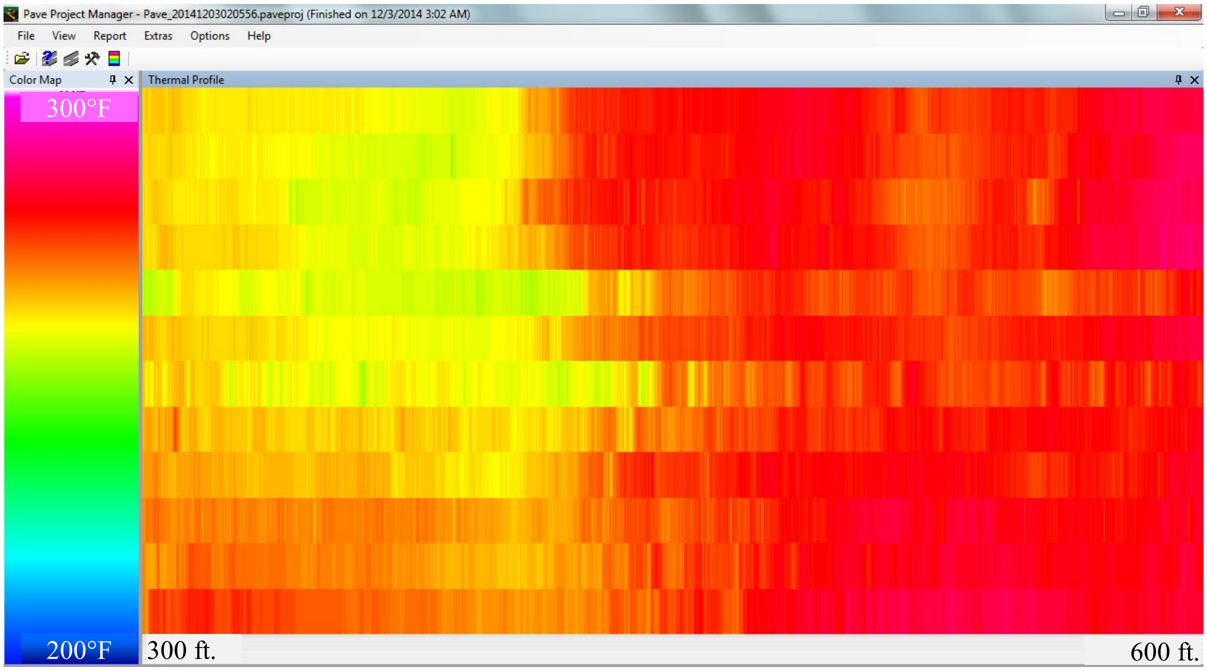


Figure 5
A typical thermal profile

Typical Thermal Profile

Thermal profiles can be viewed using the Pave Project Manager software provided by the manufacturer. Figure 5 shows a typical thermal profile displayed in the Project Manager. The software features a menu bar, toolbar, and working panel. The colored temperature scale is shown on the left side of the working panel. The color scale ranges from blue at the bottom to pink at the top. The color scale gradually shows the corresponding temperature ranges, which can be manually adjusted by users. For instance, if bottom and top limits are 200°F and 300°F, respectively, then blue at the bottom represents 200°F and pink at the top represents 300°F. In the middle, the green color represents 250°F. If the top limit is changed to 250°F and the bottom limit is changed to 150°F, then the corresponding temperature for the green color will change to 200°F. The length of the thermal profile displayed on the center of the working panel can be easily adjusted by the scroll of a mouse or by manual selection in a control panel. The example profile shown in Figure 5 was taken from 300 ft. to 600 ft. ranges of a 13,000 ft. long profile, which can be seen by completely zooming out the profile. The software also provides multiple functions that it can display individually or simultaneously in the working panel/space.

Some of the major required functions are as follows:

1. Thermal profile – A profile of scanned pavement displayed horizontally such that the left-most sensor reading is at top. A temperature color scale is provided to its left to

refer the colors from the profile for their temperature values. When clicked at any point on the profile, list of data such as temperature, distance from location scanning start point, and GPS co-ordinates can be seen.

2. Project Properties – This function displays the values entered before starting the scan. It also shows other properties of scanned length, units, zooming, etc. Furthermore, the highest and lowest temperature values of temperature color scale can be changed using this function.
3. Time Diagram – A diagram (time against distance) that shows time spent at each point every 4 in., which is useful to locate paver stop sites.
4. Speed Diagram – A diagram (speed against distance) that shows paver speed every 4-inches which can be found to be contrary to that of time diagram.
5. Temperature Class Diagram – This diagram shows a distribution of temperatures of current thermal profile. It is similar to a bar chart with each column representing 50°F class.

Thermal Scanning using Infrared Thermal Camera

One of the major advantages in scanning using a handheld infrared camera is that the rate of cooling of paved mat can be monitored until breakdown compaction by capturing images at time interval. Also, the temperature at laydown and temperature right before compaction can differ. Especially at paver stops, the temperature differential between these two can be significantly large. Thermal camera was primarily used to capture and record this temperature right before compaction. Thermal camera used in Phase II projects had a thermal sensitivity of 0.1°C and spectral range of 7.5 to 13 μm.

This battery-operated infrared camera is setup before the mat is laid by the paver. The camera is connected to a tripod using screws such that its movement along vertical axis is feasible. Once the camera is switched on, the operator uses the eyepiece at the back to face the pavement. During live monitoring, the camera enables the user to position four points on the image whose temperature is displayed in real-time. A focusing ring could be rotated to reach a sharper image. Switches are provided to adjust color temperature scale, and also to save thermal images in an in-built storage. In Phase II, thermal images were captured at start of paver stop and moments before compaction with additional images at an interval of about two minutes.

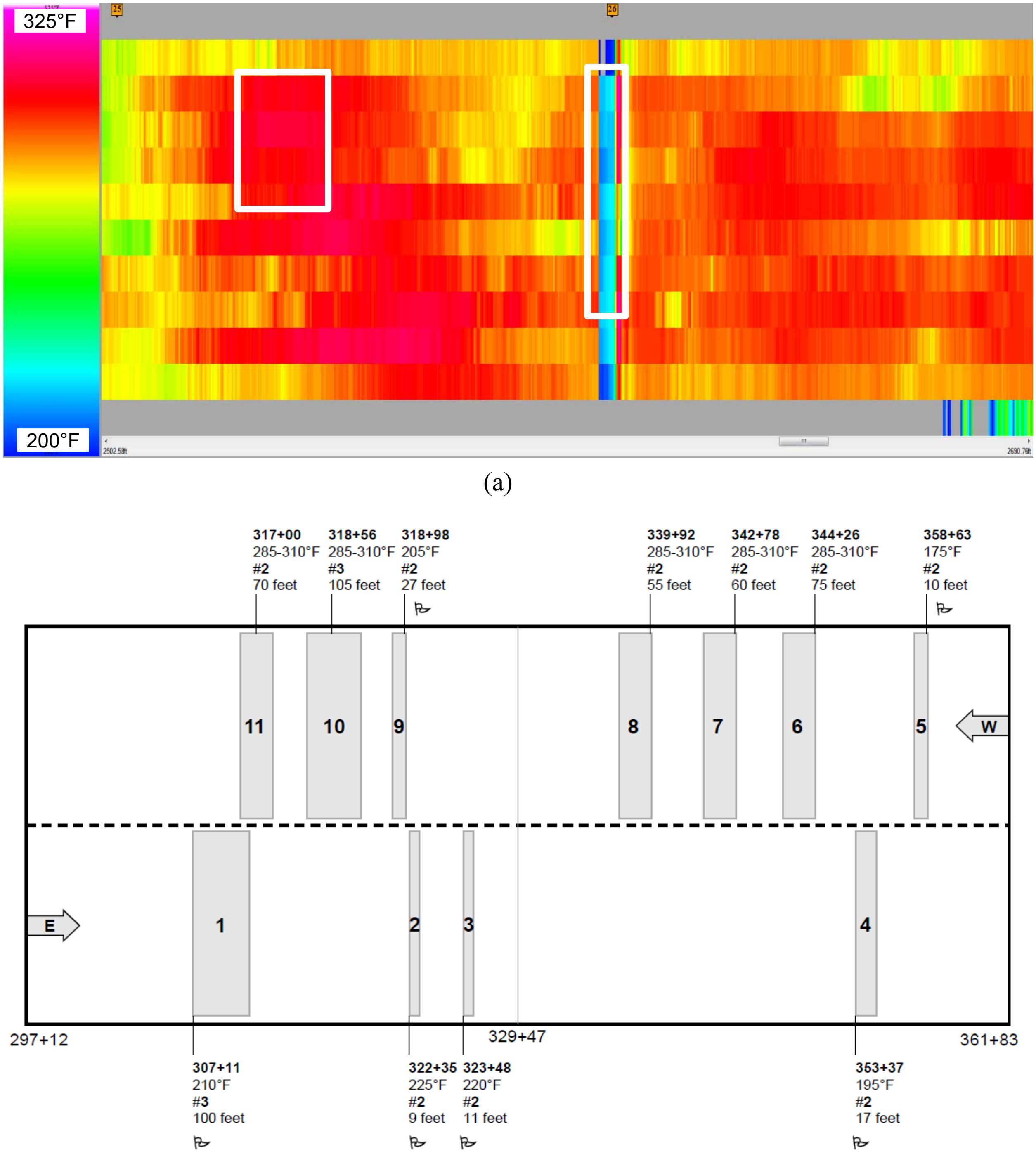
Field Sampling

As discussed earlier, the TD was computed as the difference in temperature between the target laydown and uncompacted mat. Table 4 shows the TD categories that were established to group asphalt mat areas with different levels of TD severity from None to very high. As seen in the first column of the table, each group has 25°F (i.e., ±12.5°F) temperature range. Thus, when the target temperature is 300°F, an asphalt mat with temperature between 312.5°F and 287.5°F has None severity level of TD and is designated by the group name "Target." Temperature ranges of the successive severity levels are defined by a successive 25°F drop at a time from the target temperature, and then, simultaneously apply ±12.5°F to that value. For example, when the target temperature is 300°F, the temperature range of the low severity group is defined as 275 ±12.5°F (i.e., from 287.5 to 262.5°F). In this way, the following groups of medium, high, and very high severity levels are found to have the temperature ranges of 250±12.5°F, 225±12.5°F, and 200±12.5°F, respectively, and their group names are given as combinations of the word "Target" and corresponding temperature differentials as shown in the last column of the table.

Table 4
Temperature differential (TD) severity levels

Temperature Range	Severity Level	Group Designation
Target ± 12.5°F	None	Target
(Target-25°F) ± 12.5°F	Low	Target-25
(Target-50° F) ± 12.5°F	Medium	Target-50
(Target-75° F) ± 12.5°F	High	Target-75
(Target-100° F) ± 12.5°F	Very High	Target-100

Field core locations were chosen by meticulously analyzing the thermal profile. Figure 6 (a) shows a partially zoomed-in thermal profile. The areas indicated with white rectangles are the selected coring locations for both non-segregated and thermally segregated field cores. Using distances from Pave Project Manager and on-site station marks, these coring areas were precisely located. The location information along with the number of cores to take on any given locations were drawn on a schematic map as shown in Figure 6 (b) to guide the field sampling operations. Six-inch diameter field cores were taken within a week or two after the completion of pavement sections using the coring rig shown in Figure 7.



(a)

(b)

Figure 6
(a) Selection of coring locations on thermal profile and (b) example coring plan map

Figure 7
Field coring operation

Laboratory Experiment

Thickness of field cores on wearing course (WC) lifts ranged from 35 mm to 40 mm, while that on binder course (BC) and shoulder ranged from 50 mm to 70 mm depending on their design layer thickness. The density of all core samples was measured in accordance with AASHTO T 166, “Bulk Specific Gravity of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens.” The measured core densities were further used to compute the density differential (DD), which is a difference between core densities of non-segregated specimens and segregated specimens.

Fracture resistance characterization of asphalt mixture was conducted using semicircular bending (SCB) test (ASTM D8044) based on a fracture mechanics concept where the critical strain energy release rate, also called the critical value of J-integral (J_c) is measured. To determine this critical value of J-integral, semi-circular specimens with two different notch depths at 25.4 mm and 38.1 mm, were tested using four or two replicates per notch depth depending on number of available field cores. The test was conducted at 25°C. The procedure follows a semi-circular specimen being loaded monotonically under a constant cross-head deformation rate of 0.5 mm/min in a three-point bend load configuration until fracture occurs. The load and deformation are continuously recorded and the critical value of J-Integral is determined by equation (1):

$$J_C = -\left(\frac{1}{b}\right)\frac{dU}{da} \tag{1}$$

where,
b = sample thickness (mm);
a = the notch depth (mm); and
U = the strain energy to failure (kJ)

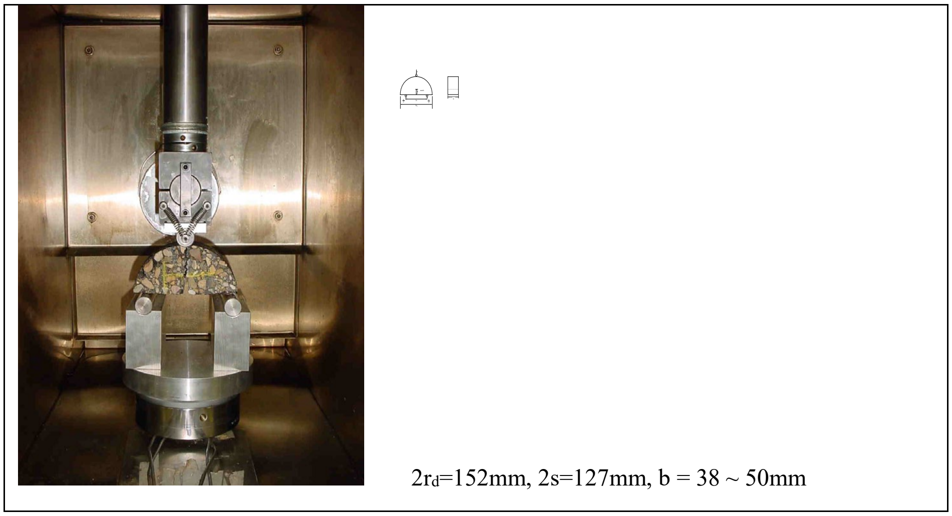


Figure 8
Setup of Semi-Circular Bending Test

Selected core samples from LA940 BC and LA1 shoulder were used to investigate whether the temperature segregation affects the rutting performance of compacted pavements using loaded wheel tracking (LWT) test. The rut depth at 20,000 wheel passes has been known to indicate long term rutting performance and moisture susceptibility at high service temperature. The LWT tests were performed in accordance with AASHTO T 324, "Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)." The rut depth versus number of passes plot from this test is analogous to the typical load-deformation behavior curve of asphalt mixture showing three phases of pre-consolidation, post-consolidation, and stripping. The increase in rate of rutting after stripping inflection point (SIP) may suggest number of passes with moisture damage to the field core sample. The test was conducted at 50°C. Two cylindrical specimens with sawed off edges placed tightly against each other in high density polyethylene molds are placed in steel tray submerged under water. A wheel weighing 158 ±

1.0 lb. passes 20,000 times at the rate of 52 ± 2 passes per minute over the specimens. Rut depth is measured and recorded at 11 locations along the wheel path.

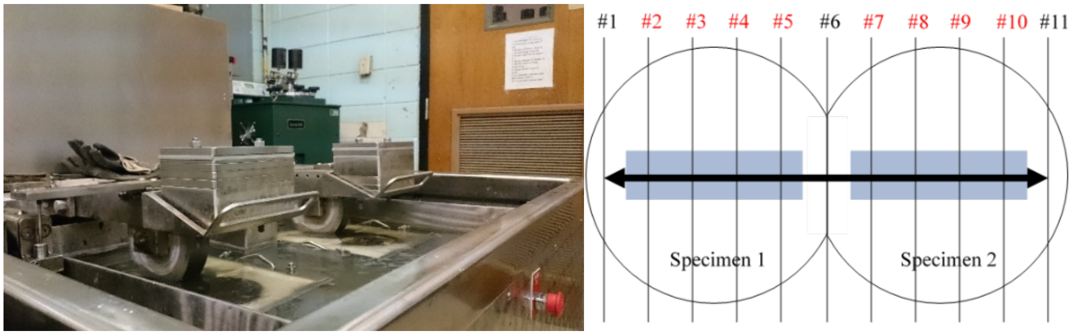


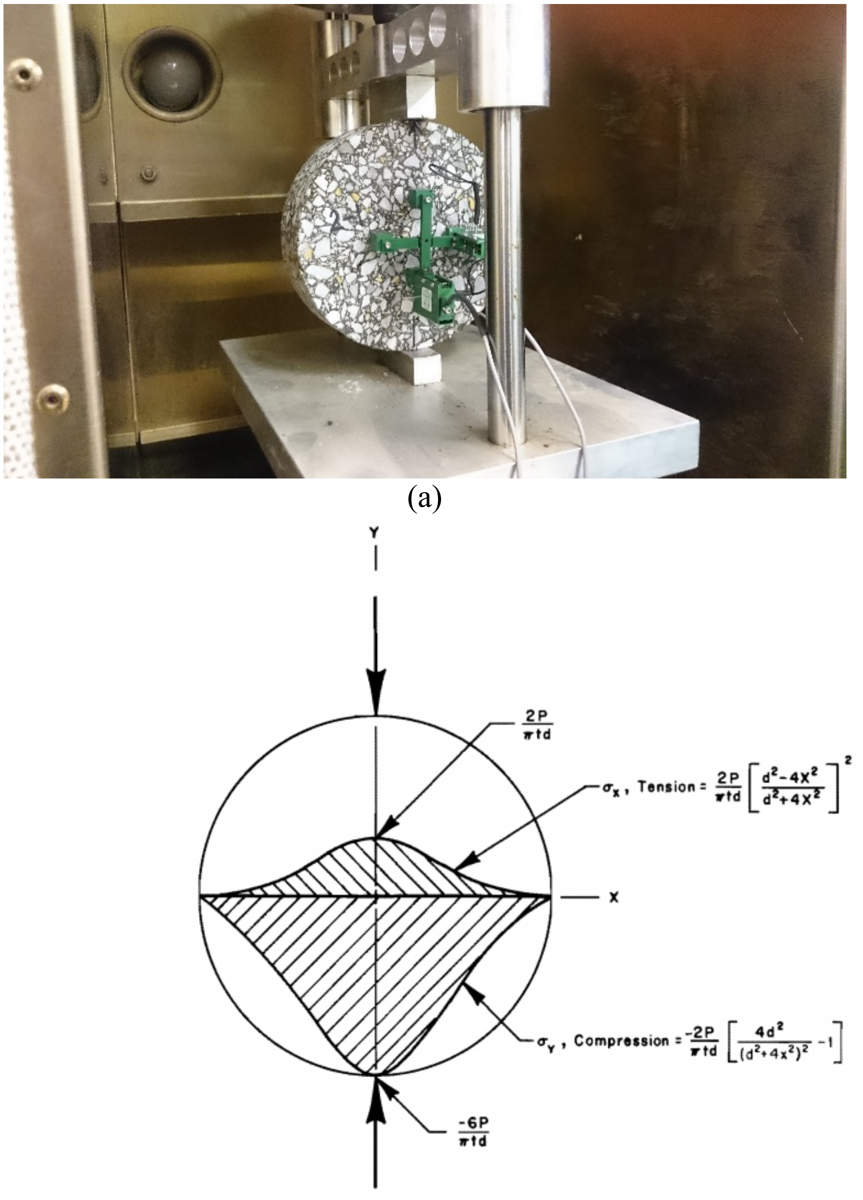
Figure 9
Setup of Loaded Wheel Tracking test

Selected samples from LA1053 WC and LA411 WC were tested for the dynamic modulus characterization under indirect tension mode (IDT |E*|) in accordance with a proposed standard test procedure by Kim et al., "Determining the Dynamic Modulus for Hot Mix Asphalt (HMA) Using the Indirect Tension Testing Method *[30]*."

The IDT|E*| test applies a sinusoidal compressive stress to the diametric axis of an unconfined cylindrical field core specimen. This test was conducted at three temperatures of -10, 10, and 30°C (14, 50, and 86°F) and at five loading frequencies of 10, 5, 1, 0.5, and 0.1 Hz at each of the three temperatures. The compressive stress applied on the test specimen results in tensile stress-strain along the horizontal axis of the specimen. A target tensile strain level of 40 to 60 microstrain is maintained to keep the specimens in the linear viscoelastic region. The dynamic modulus is computed using the following equation:

$$|E^*| = \frac{2P_0}{\pi a d}\frac{\beta_1\gamma_2-\beta_2\gamma_1}{\gamma_2 V_0-\beta_2 U_0} \tag{2}$$

where,
P_0 = Peak-to-peak load, N;
a = loading strip width, m;
d = thickness of specimen, m;
V_0 = peak-to-peak vertical deformation, m;
U_0 = peak-to-peak horizontal deformation, m; and
γ_1, γ_2, β_1, and β_2 = geometric constants.



(a)

(b)

Figure 10
(a) IDT|E*| test setup and (b) stress distribution along X-axis

Experimental Data Analysis

Temperature Uniformity Analysis

Temperature uniformity of all pavement sections was evaluated using two different calculation techniques. Similar to Pave Project Manager software, the entire length thermal profile is divided into multiple 150-ft. long segments. Within a single 150-ft. long segment, there are 5,400 temperature readings. After filtering outliers from the temperature data, a standard deviation from the mean temperature in the segment was calculated. All such standard deviations from all segments were then plotted on a line chart to show how much the asphalt mat temperature changes within a segment and throughout the entire paving of a project.

The second temperature uniformity measure was to use TD severity levels. Let's assume a typical profile length is 12000 ft., which has approximately 500,000 temperature readings. Now, each temperature reading belongs to one of the five TD severity levels (Table 4). Each temperature reading was converted to TD severity level. Finally, percentage of each severity level out of the 500,000 total readings was calculated.

In LA1 shoulder and BC, three scenarios of MTV use were investigated, i.e., no-MTV, light-MTV, and full-MTV. The major difference between light and full-MTV is the 30-ton storage of Full MTV that helps it to carry about one truckload of asphalt mixture thus maintaining steady speed of construction in case of delay in supply. Temperature uniformity of each section was compared to evaluate the effect of MTV use. Also, the effects of other construction factors such as ambient temperature, target laydown temperature, nominal maximum aggregate size (NMAS), etc. were evaluated using these two parameters (i.e., standard deviation and %severity levels).

Statistical Analysis

Laboratory test data were statistically analyzed using the t-test procedure provided in Microsoft Excel program from Microsoft Corp. A paired comparison with a risk level or 'p-value bound' of five percent was performed on the means of different parameters obtained from laboratory tests (critical J_c-integrals, dynamic modulus, air voids content). Each t-test was performed to compare obtained parameter of a segregated group of specimens against target or non-segregated group of specimens; i.e., TD severity level None was paired with Low, Medium, etc. separately to calculate individual t-test p-value. The interpretation of these values was based on normal distribution probability curve. P-values greater than or equal to five percent indicated insignificant difference in paired parameter, while values lower than five percent indicated 'statistically significant' difference.

Another statistical test used in analysis was the Tukey test to compare several projects together in terms of common construction factor such as nominal maximum aggregate size (NMAS). This test runs analysis of variance (ANOVA) procedure followed by grouping between different projects. Tukey test assigns a letter to each category or project considered. Categories or projects that do not share the same letter have significantly different values in terms of factors considered for comparison.

Pavement Performance Prediction

Rutting performance using loaded wheel tracking test was performed on selected projects. This test result showed that specimens of all temperature segregation severity levels performed within DOTD specification limits. Therefore, mechanistic-empirical pavement design software was opted to perform pavement rutting prediction on two projects to gain further insight on rutting performance of thermally segregated specimens.

Pavement ME is a software that calculates pavement responses such as stress, strain, deflection under traffic and environmental loading, and accumulates the total damage over design analysis period. This software is based on AASHTO Pavement Mechanistic Empirical Design procedure. Pavement ME was used to evaluate the effects of the measured indirect tensile dynamic modulus (|E*|) for various segregation severity levels on the predicted rutting performance for two pavement projects. The HMA wearing course layer stiffness values from IDT|E*| test were used for input. Catalog values of |E*| for binder course layer and of G* for asphalt binder properties, and actual traffic data were used for calculation.

Additionally, rut factor (|E*|/sinδ) was calculated at slow loading – high temperature testing configuration (0.1Hz, 30°C) at various segregation severity levels.

DISCUSSION OF RESULTS

Temperature Segregation

Two distinctive patterns of temperature segregation were constantly observed in all of the seven field projects, namely, a cyclic temperature segregation and irregular temperature segregation.

Cyclic Temperature Segregation (CTS)

Figure 11 presents a typical thermal profile measured from a 13,000-ft. long asphalt paving. The color scale is set from 200 to 325°F. Throughout the entire paving, repetitive temperature fluctuations as represented by the alternating colored strips of green, yellow, and red are clearly visible with fairly consistent spacings between adjacent strips. In consultation to the color scale on the left, these colored strips represent temperature ranges around 260, 280, and 300°F, respectively, which is a gradual increase pattern in temperature. The reverse order (i.e., red-yellow-green) is a gradual decrease pattern in temperature. Thus, combined together, it is clear that the temperature of asphalt mixture continuously rose and dropped throughout the entire paving process. Therefore, this pattern of TS was defined as the cyclic temperature segregation (CTS). To better quantify the magnitude of temperature fluctuations, the temperature reading data associated with the thermal profile shown in Figure 11 were extracted into a numerical format and plotted as a line charts shown in Figure 12.

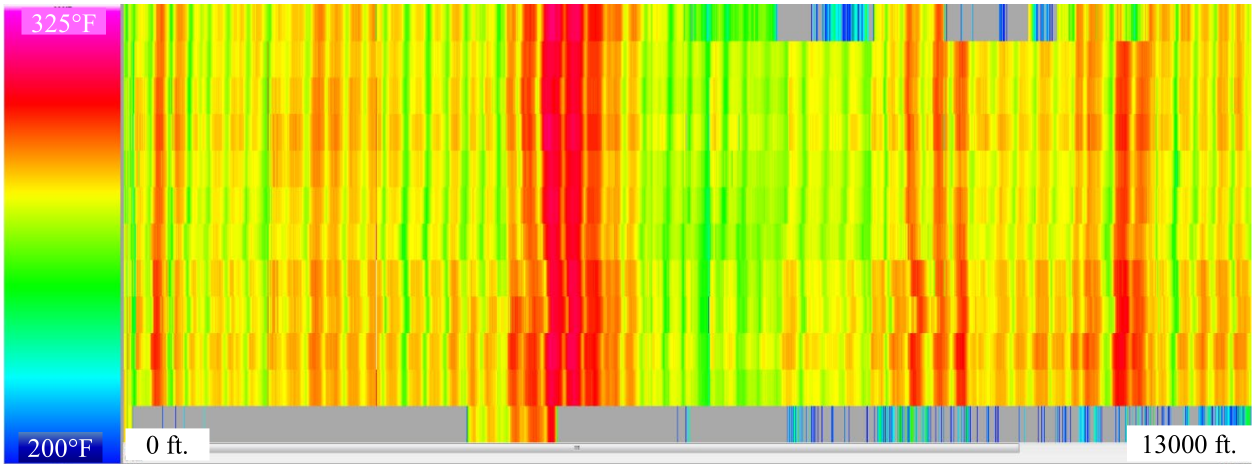


Figure 11
Typical cyclic pattern in thermal profile

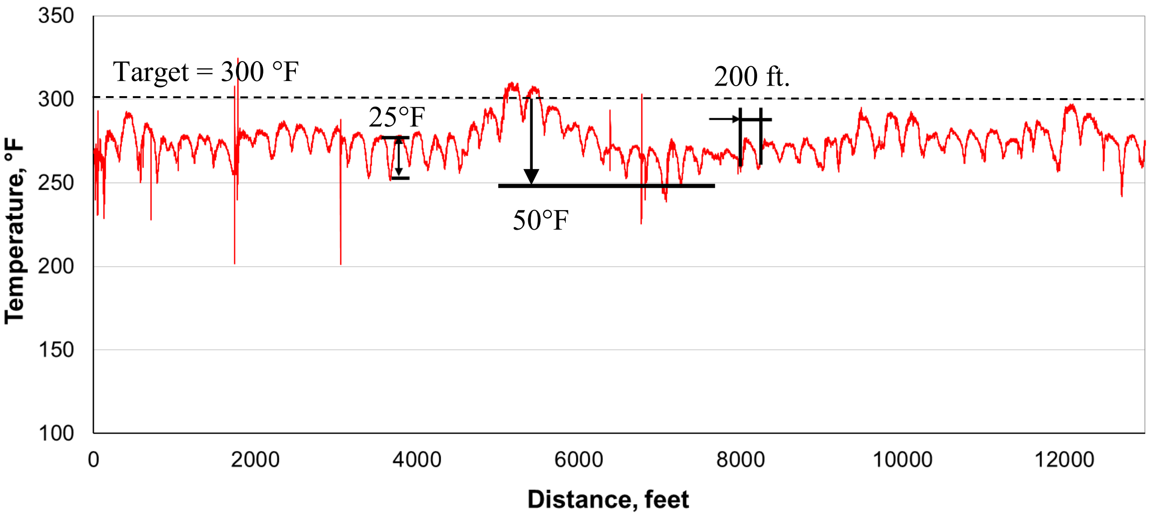


Figure 12
Typical magnitudes and periods in cyclic temperature patterns

In Figure 12, the cyclic temperature fluctuation pattern is clearly shown with a typical magnitude of a cycle about 25°F. When measured from the target laydown temperature, the cyclic temperature fluctuation resulted in about 50°F of TD at around 7,000 ft. distance mark. The magnitude appeared to be dependent on the discharge temperature at plant, haul distance, truck waiting time, etc.

The period of each cyclic fluctuation, also, seemed to be fairly constant typically varying between 100 and 250 ft. range. Interestingly, this range in period is comparable to the length of paving that one truckload of asphalt mixture (i.e., 17 to 25 metric tons depending on the size of a haul truck) can cover for a 1.5 to 2 in. thick pavement layer. With a typical average paver speed of 25 ft./min, it takes up to 10 minutes to place a truckload of asphalt mix on the road. And it seems reasonable to conclude that approximately 25°F of temperature drop in 10 minutes had occurred due to unavoidable natural cooling of asphalt mixtures under a moderate weather condition.

Regardless of MTV use, CTS occurred at all seven field projects with the severity level ranging from low to medium during the normal paving operations. Since the main cause of CTS is the invariable natural cooling of asphalt mixtures that takes place during the normal operation of laydown, it would not be possible to completely eliminate it. However, since the maximum temperature drop observed from all seven field projects did not exceed the medium severity level, the occurrence of CTS can be excused unless there are sufficient reasons to suspect the quality of finished pavement sections.

Irregular Temperature Segregation (ITS)

In Figure 12, in addition to the cyclic patterns of temperature fluctuations, instantaneous drops of temperature at irregular intervals are shown by relatively longer vertical lines at multiple locations. These sudden drops in temperature were identified as the irregular temperature segregation (ITS), which only occurred when the paving process was stopped for any reasons. Such work stoppages are generally caused by equipment failure, mixture spillage during transfer, and the shortage of asphalt mix supply to jobsites. Stroup-Gardiner and Brown and Sebesta and Scullion also reported similar patterns of temperature segregations *[2, 14-15]*. Figure 13 shows a zoomed-in thermal profile of a work stoppage area. Unlike the CTS, boundaries of ITS is very well defined as shown in the figure. The straight boundary between the orange (285°F) area and blue (187°F) colored areas is where the Pave-IR sensor bar stopped. The extent of the blue colored cold spot is typically about 5 ft., which corresponds to the distance from the sensor bar to the end of the paver screed. During the work stoppage, the mixture discharged from the paver screed, but remained un-scanned by the Pave-IR sensors within this 5 ft. wide area was simply allowed to cool down until the work resumed and so the Pave-IR. In about a little longer than 10 minutes of work stoppage, the mix cooled down nearly 100°F.

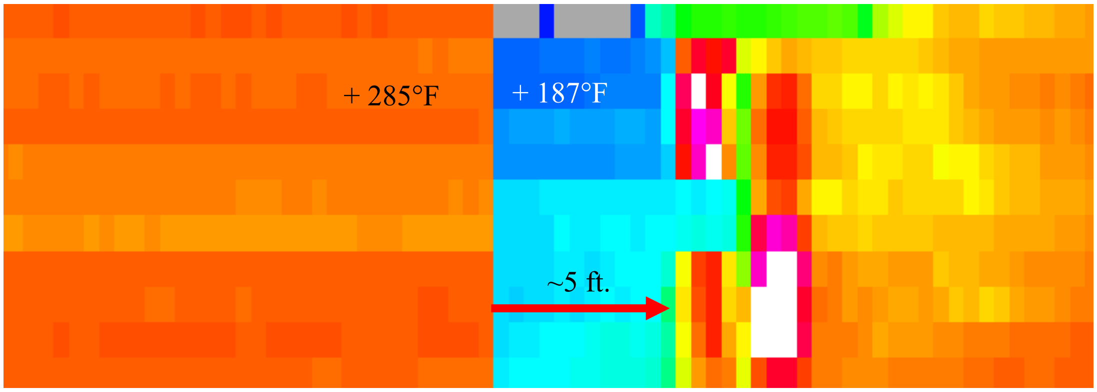


Figure 13

Zoomed-in thermal profile of irregular temperature segregation (ITS)

However, it was found that the actual affected areas were typically much wider than 5 ft., since the wider areas of the asphalt mat behind the paver up to where the breakdown roller stopped left uncompacted until the operation resumed. The length of the actual uncompacted mat behind the paver was observed as little as 12 ft. and as much as 165 ft. depending on how close the roller followed the paver. Thus, the Pave-IR measured mat temperature of 285°F shown on the orange colored area of Figure 13 may not be very close to the actual compaction temperature of the mat. During the Phase I projects, segregated cores were collected from the smaller areas shown in the thermal profile by the Pave-IR system. During the Phase II projects, a handheld thermal camera was used to capture and record mat temperatures in the wider affected area until the first breakdown rolling was applied.

Unlike the CTS, the severity of ITS can be significantly worse as shown in the example case of Figure 13 depending on many factors such as the duration of work stoppage, ambient temperature, initial mix temperature, etc. Following two preventive measures can be recommended to the contractors to minimize excessive cooling of such uncompacted mats behind the paver.

1. It is necessary that the breakdown roller compacts the mat behind the paver as closely as possible at all work stoppages.
2. Insulating blankets or tarps may be used in an area where the breakdown roller cannot reach to keep the area warm until the work resumes.

Table 5
Effect of construction factors on average standard deviation in temperature

Construction Factor	Category	Number of Mixtures	Number of segments	Average Std. Deviation, °F	Tukey test Grouping
MTV	No	1	47	18	A
	Light	1	30	10	B
	Full	1	36	6	C
Contractors	A	1	51	6	A
	B	1	69	5	A
	C	1	84	6	A
	D	1	90	7	A
NMAS	12.5-mm	6	>300	12	A
	19-mm	3	230	14	B
Target Temp.	275°F	1	92	11	A
	290°F	4	266	13	A
	300°F	4	>300	12	A
Ambient Temp.	50-65°F	2	219	12	A
	65-80°F	4	>300	12	A
	80-95°F	3	257	14	A

Temperature Uniformity Analysis

Table 5 presents the average standard deviation in temperature and its relationship to varying levels (category) of construction factors, i.e., the MTV type, contractors, nominal maximum aggregate size (NMAS), targeted mixture laydown temperature, and the average air temperature during the construction. Also, the sample size associated with the categories in each of the five factors are shown.

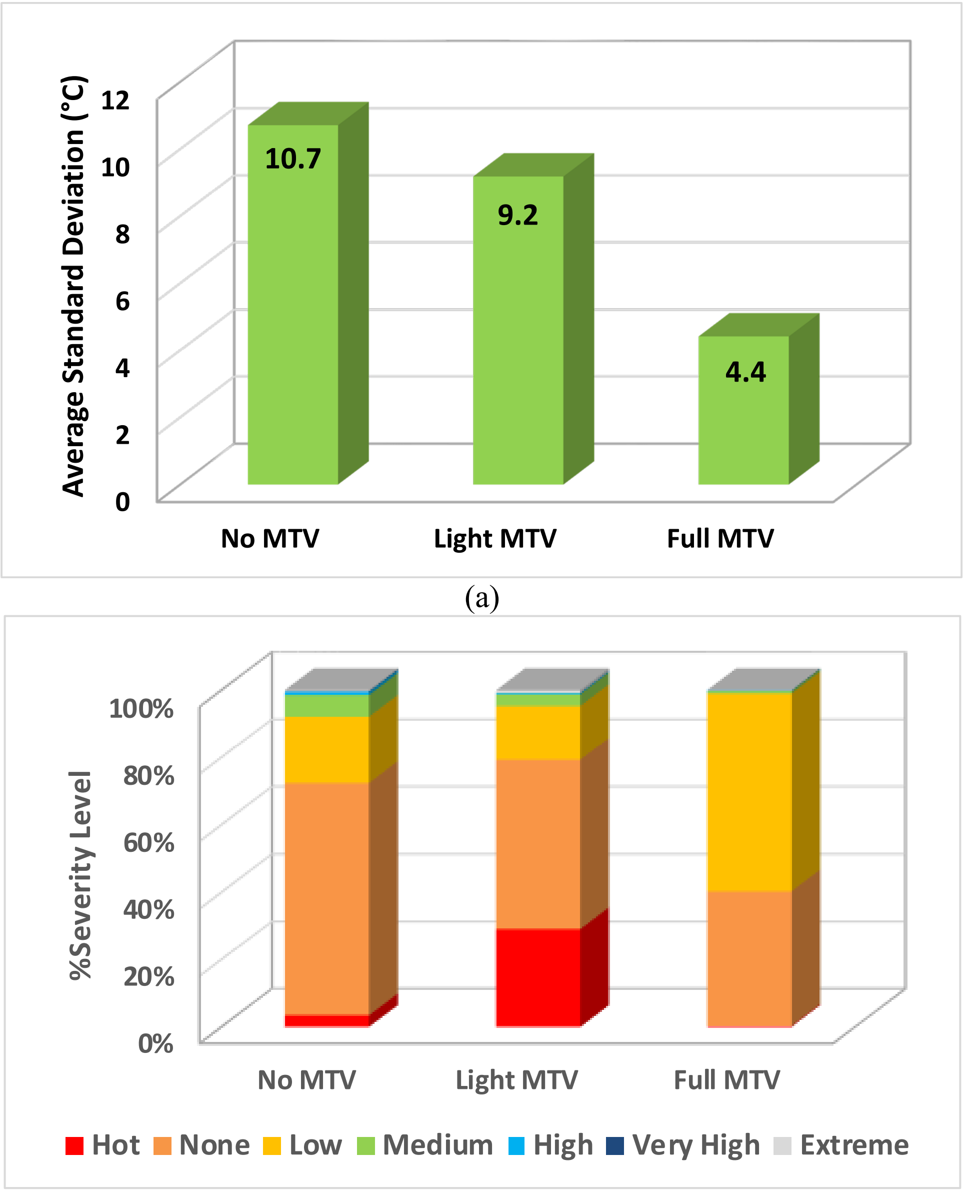
Before calculation of average standard deviation, the complete thermal profile of each project was divided into 150-ft. segments to observe overall changes in deviation from average temperature. These deviation values were found to be fairly uniform and not exceeding 20°F in most segments. Refer to the Appendix for further details. The number of 150-ft. segments shown in Table 5 gives an estimate of profile length and sample size used to conduct Tukey analysis for finding differences and similarities among different categories in a factor. From this statistical analysis it was observed that the use of Light or Full MTV improves temperature uniformity compared to No MTV. Also, Full MTV delivered significantly better temperature uniformity than Light MTV as its grouping, C, differs clearly from that of Light MTV, B. For the temperature uniformity in four different contractors, no significant differences were observed in their grouping, i.e., all four were grouped as A. All projects used nominal maximum aggregate size as 12.5 mm for WC and 19 mm for BC. The 19-mm aggregate is known to have more surface area open to environment which could increase temperature differential. In Table 5, it is evident that the temperature uniformity of 19-mm NMAS mixtures was worse than that of 12.5-mm NMAS mixtures. It can be noted, however, the difference in the average standard deviations of the two NMAS is merely 2°F, although the Tukey test grouping shows two different letters, A and B. For the target temperature and ambient temperature, no significant differences were found among different levels.

Table 6
Effect of construction factors on severe temperature differential

Construction Factor	Category	Number of Mixtures	%Severe*	Tukey test Grouping
NMAS	12.5-mm	6	0.7	A
	19-mm	3	1.8	A
Target Temp.	275°F	1	0.4	A
	290°F	4	0.6	A
	300°F	4	1.9	A
Ambient Temp.	50-65°F	2	1.3	A
	65-80°F	4	0.9	A
	80-95°F	3	1.1	A

*%Severe = %Medium + %High + %Very High

Table 6 presents the combined percentage of severe temperature differentials, which includes medium, high, and very high severity levels as defined in Table 4. Due to limitations in sample size, only three construction factors including NMAS, Target, and Ambient temperatures were considered in the Tukey analysis for their effects on the occurrence of temperature differentials. As shown in the table, it was found that none of the three construction factors have statistically significant effects on the occurrence of severe temperature differentials.



(a)

(b)

Figure 14

(a) Average standard deviation in temperature (b) %severity levels of TD

Figure 14 further presents the results of two different temperature uniformity analyses, i.e., standard deviation and %severity levels of TD concerning the MTV use. It should be noted that the additional severity levels such as “Hot” and “Extreme” are presented in Figure 14 (b). These two additional levels were introduced to adequately fragmentize the entire temperature data into equally spaced groups, which were not experienced in the Phase I study. The Hot severity level includes the temperature differentials that are at least 25°F hotter than the target range, i.e., (Target+25) ± 12.5°F. For example, if the Target temperature is 290°F, the temperature range of Hot severity level is from 302.5 to 327.5°F.

Figure 14 (a) shows a decreasing trend in average standard deviation with the lowest value of 4.4ºC for “Full MTV” section. In Figure 14 (b), Full MTV section shows 60% of low severity level temperature differential. It must be understood that in Figure 14 (a), the deviations are calculated from average temperature of the complete thermal profile, as a relative measure of the quality of paving. When the deviation is low, the asphalt mixture could have been paved uniformly at high severity level or uniformly at low severity level. On the other hand, Figure 14 (b) shows the entire distribution of the temperature differentials into separate severity levels. Therefore, the two measures shown in Figure 14 (a) and (b) together tell more precise story about the effects of MTV use in temperature uniformity and about the paving work in general.

For the No MTV section paving, it was observed that the entire section has the highest average standard deviation at 18°F, while Light MTV and Full MTV sections have significantly lower values at 10 and 6°F, respectively. Also, the No MTV section shows the most number of severity levels all the way from Hot to extreme, which says that the mixture temperature during the paving indeed varied a lot, suggesting the overall quality of the paving in question. While the Full MTV section showed the lowest standard deviation among the three, it also showed that a significant portion (nearly 60%) of the entire TD falls in the low severity level and more (i.e., medium, high, very high, and extreme). On the other hand, the Light MTV section shows less percentage of the TD (slightly over 20%) falls in the same severity levels. This observation alone can mislead to a conclusion that the light MTV provides better paving quality. In fact, however, Figure 14 (b) shows what could have happened to result in this observation. In the Light MTV bar, considerably large percentage of TD (about 28%) is marked as Hot, which means that the asphalt mixtures left the asphalt plant significantly “over heated” than the mixtures used in Full MTV section. Hence, during the paving operation, the mixtures in Light MTV section mostly stayed in the Hot and None severe TD levels until it eventually cooled down to Low and more severe TD levels. Moreover, the number of severity levels present in the Light MTV bar of Figure 14 (b) is larger than that of the Full MTV bar, which only shows three levels at None, Low, and Medium.

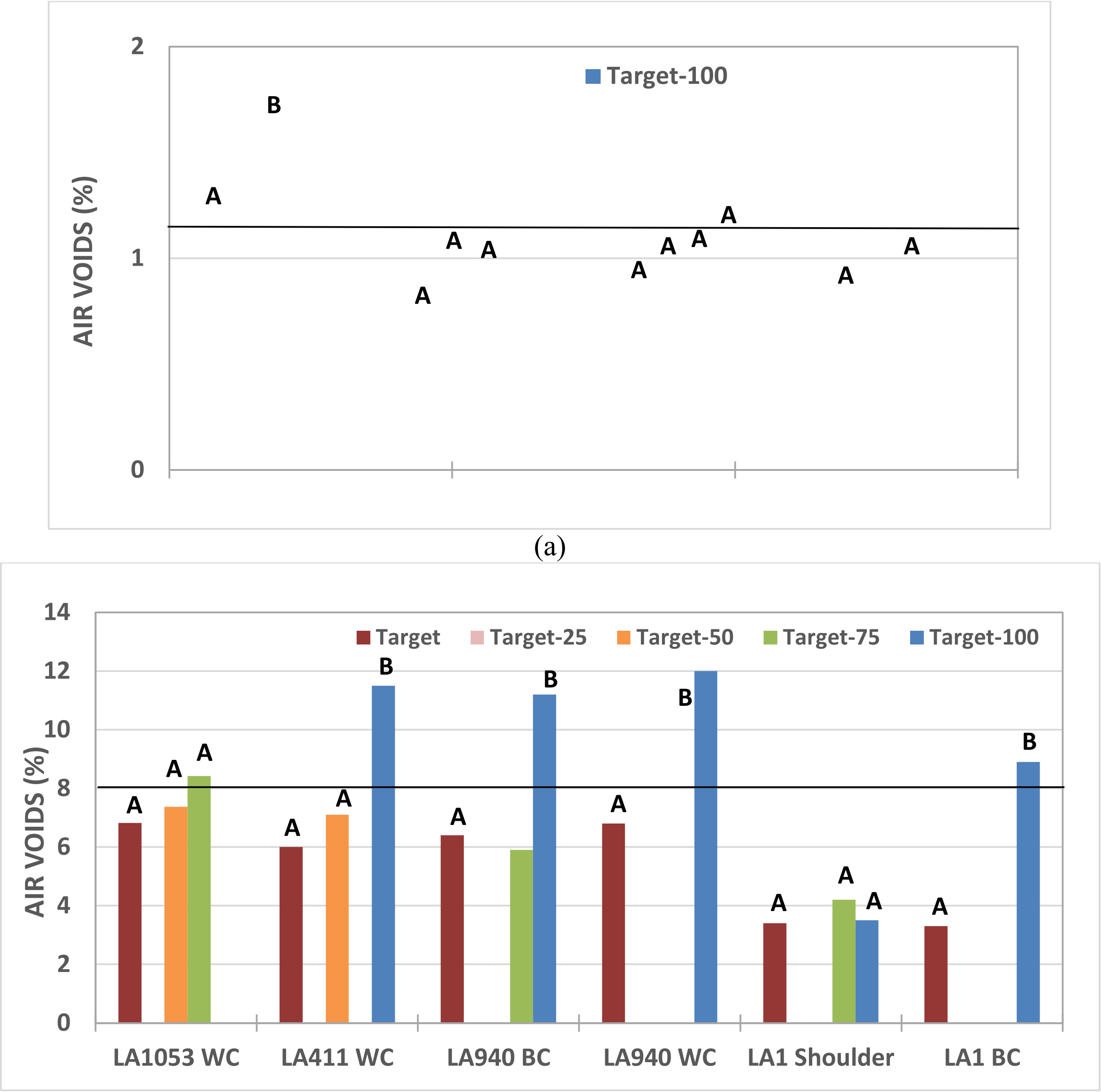
Thus, one can conclude that the Full MTV section has the most uniform temperatures throughout the entire section. It is also noteworthy that this better temperature uniformity and quality was achieved without having to overheat the asphalt mixtures in the plant, which is beneficial for the producer in reducing the fuel cost and potential issues in the environmental protection.

Density Differentials

Figure 15 shows density measurements of ten mixtures at various TD severity levels. The averaged air voids content shown in these charts have sample sizes ranging from two to eleven with less than 20 percent of coefficient of variation. Overall, the bar charts show an increase in air voids with increase in severity level. The maximum allowable specification limit is 8 percent.

Among the Phase I projects in Figure 15 (a), LA30 WC is the only project that shows significant increases in air voids of segregated specimens. The Tukey comparison analysis of the mean air voids of different TD severity levels shows that the LA30 WC samples were the only mixtures that showed clearly different letter groupings among different TD severity levels. Increasing trends of air voids are graphically visible in other projects, too, but the differences between and among different TD severity levels are not statistically significant, as their letter groupings resulted all in a single group, A. Note that the TD severity levels of Phase I projects were determined at laydown using the Pave-IR system immediately behind the paver.

Unlike the Phase I projects, the TD severity levels were determined at the time of the first breaking roller compaction using the IR camera. Among the Phase II projects in Figure 15 (b), LA411 WC, LA940 BC, LA940 WC, and LA1 BC showed clear distinctions in air voids between the Target and segregated samples, especially when the TD severity level is worse than Target-75. According to the Tukey comparisons, no difference was detected between the Target and segregated samples up to the Target-75 severity level in five of the six projects (LA1 Shoulder is the only exception). Then, as the severity worsened, four of the six projects started to show clear distinctions between their Target and Target-100 samples. In fact, among the five projects that include Target-100 samples, LA1 Shoulder was the only project that did not show increased air void in Target-100 samples. This could have resulted in due to the temperature gradient of asphalt layer in depth. The layer thickness of LA1 Shoulder is 100 mm, while the layer thicknesses of other projects were either 38 mm or 50 mm. The IR thermal sensors and cameras measure the temperature of asphalt mats on the surface, but the temperature in a certain depth of the mat is normally higher and rises as the depth goes deeper. Thus, it may be possible that the actual in-depth layer temperature of the 100 mm thick LA1 Shoulder at the time of compaction was closer to the target temperature than was measured on the surface.



(a)

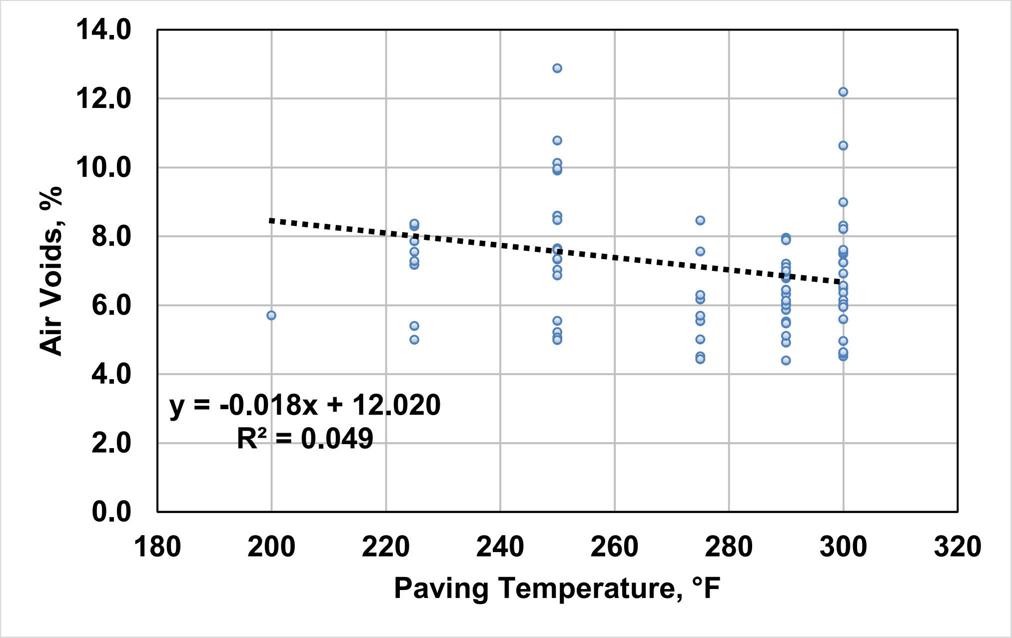
(b)

Figure 15
Density test results: (a) Phase I (b) Phase II projects

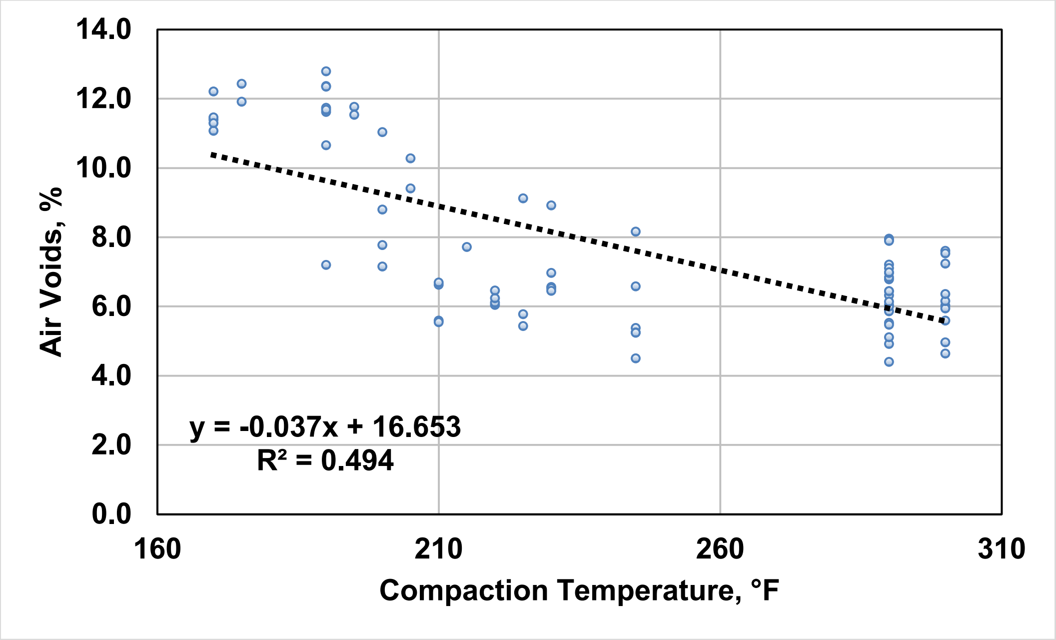
The clear contrasting observations between the Phase I and Phase II projects in Figures 15 (a) and (b) suggest that the TD must be evaluated at compaction rather than laydown operation. Also, the layer thickness of asphalt mats should be taken into account for the evaluation.

Correlation between Temperature and Air Voids

Figure 16 presents the relationship between the air voids and mat temperature as measured by (a) Pave-IR at laydown during Phase I and (b) portable IR camera at compaction during Phase II.



(a)



(b)

Figure 16
Air voids vs. mat temperature: (a) Phase I (b) Phase II projects

No correlation is observed in Phase I, which suggests no significant change in air voids with decreasing laydown temperature. On the other hand, the Phase II plot showed better correlation than Phase I. The correlation proved significant change in air voids with decrease in uncompacted asphalt layer temperature affected by cooling for considerable amount of time before compaction due to work stoppage. Thus, mat temperature segregation defined at laydown can be misleading in evaluating the impact on the pavement quality while temperature immediately prior to compaction would show the real impact of TD on the quality of pavement.

Random Sampling vs. Targeted Sampling

Figure 17 presents deviations of the field core densities from the minimum specification limit of 92%. Positive deviations show over achievement in field compaction, while negative deviations show under achievement.

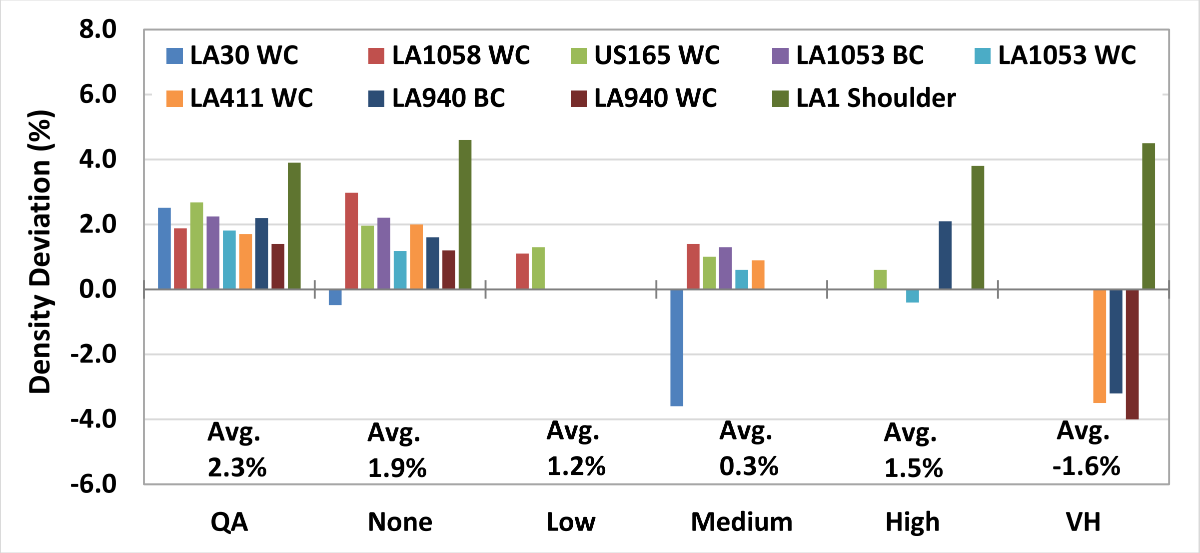


Figure 17
Density deviations of nine mixtures from 92% minimum requirement

Among the ten asphalt mixtures investigated, quality acceptance (QA) core density data of nine mixtures were available except the LA1 BC. The deviations of QA cores were compared with the deviations of field cores at different TD levels. Note that the former represents the random sampling process used in the current QA protocol and the latter represents the targeted sampling process followed throughout this study. An average deviation of the nine QA samples is 2.3%, which is an excellent achievement, while an average deviation of None severity level TD samples is 2.2%, which is very similar to that of QA samples. However, the deviations of TD samples tend to decrease as the TD level gets worse. For instances, deviation values of 1.2, 0.3, 1.5, and -1.6% were recorded for Low, Medium, High, and Very

High (VH) TD levels, respectively. The observation suggests that the pavement qualities assessed by the current QA sampling protocol can be deviated from the real quality due to the inherent risk associated with the random sampling process. In fact, the thermal imaging techniques used in this study can be used not only to help effective quality control activities during the construction, but also to guide the project inspectors to determined targeted sampling locations for the quality acceptance tests.

Effect of Construction Factors on Density Differentials

As discussed in the Methodology section, the density differential (DD) is the difference in non-segregated and segregated specimen densities.

Table 7
Effect of construction factors on average density differential

Construction Factor	Category	Number of Mixtures	Average Density Differential, %	Tukey test Grouping
NMAS	12.5-mm	6	2.6	A
	19-mm	3	3.8	A
Target Temp.	275°F	1	1.5	A
	290°F	4	4.7	B
	300°F	4	1.6	A
Ambient Temp.	50-65°F	2	3.2	A
	65-80°F	4	3.2	A
	80-95°F	3	2.5	A

Table 8
Effect of construction factors on maximum density differential

Construction Factor	Category	Number of Mixtures	Maximum Density Differential, %	Tukey test Grouping
NMAS	12.5-mm	6	3.1	A
	19-mm	3	3.8	A
Target Temp.	275°F	1	1.5	A
	290°F	4	5.3	B
	300°F	4	1.8	A
Ambient Temp.	50-65°F	2	4.3	A
	65-80°F	4	3.2	A
	80-95°F	3	2.7	A

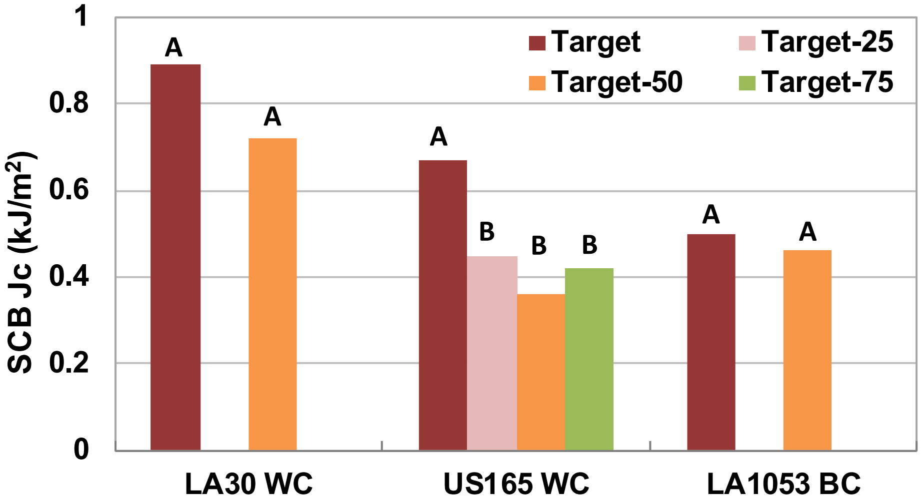
Table 7 and Table 8 present average DD and maximum DD, respectively, expressed in percentages under two or three categories of three construction related factors. The average DD is the difference between the two average densities, while the maximum DD is the largest difference from the average non-segregated density to individual segregated samples' densities.

According to the Tukey test Grouping, the NMAS showed statistically insignificant effects on both average and maximum DD. The observation implies that using either 12.5- or 19-mm NMAS mixtures in paving would not make differences in pavement density differentials even though some moderate levels of temperature differentials exist in the laid down mat. Similarly, the ambient temperature was observed not to affect both the average and maximum DD as all three categories share the same letter. On the other hand, the Target laydown temperatures appeared to affect the average and maximum DD among the three categories. The mixtures with laydown temperature 275°F were Foamed WMA, 290°F were Latex-modified WMA, and 300°F were HMA. Although the number of observations are small, it would suggest that the foamed WMA and HMA make no difference in DD, while the latex modified asphalt mixtures can cause higher DD when TD occurs.

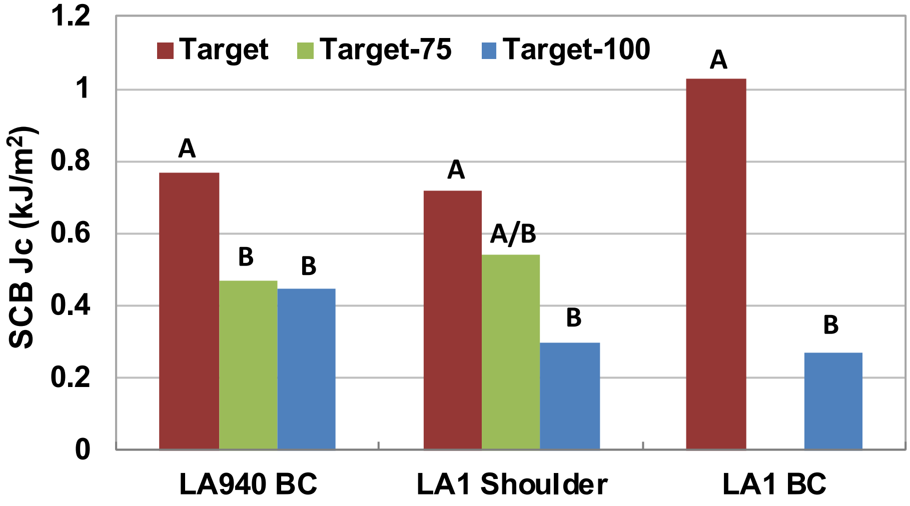
Fracture Resistance Variations

Limited core samples from Phase I projects (i.e., LA30 WC, US165 WC, and LA1053 BC) and Phase II projects (i.e., LA940 BC, LA1 BC, and LA1 SHOULDER) were tested for fracture resistance evaluation using the SCB test. DOTD 2013 specification requires a minimum J_c value of 0.5 kJ/m^2 for asphalt mixtures designed for low volume roads. Figures 18 (a) and (b) present the SCB J_c values of all six mixtures and their Tukey analysis results.

For all Phase I projects, a decreasing trend in J_c values was observed as the TD severity level worsened: LA30 WC showed a decrease of 0.17 kJ/m^2 in J_c value from Target to Target-50 samples; US165 WC showed 0.22, 0.31, 0.25 kJ/m^2 reductions in J_c for Target-25, Target-50, and Target-75, respectively; and LA1053 BC showed a slight decrease of 0.04 kJ/m^2 in J_c value from Target to Target-50 samples. A similar trend was observed for Phase II projects with more profound decreases in J_c values: for LA940 BC, J_c values decreased by 0.30 and 0.32 kJ/m^2 for Target-75 and Target-100, respectively; for LA1 Shoulder, J_c values decreased by 0.18 and 0.42 kJ/m^2 for Target-75 and Target-100, respectively; and for LA1 BC, a huge decrease of 0.76 kJ/m^2 from Target to Target-100 specimens was observed. The differences in the magnitude of J_c value reduction between Phase I and Phase II projects are caused by the different ranges of the TD severity levels included; i.e., up to Target-75 TD samples were included in Phase I and up to Target-100 TD samples were included in Phase II. When combined together, on an average, 0.22, 0.17, 0.24, and 0.50 kJ/m^2 of J_c reductions were observed for Target-25, Target-50, Target-75, and Target-100 TD samples, respectively.



(a)



(b)

Figure 18
SCB test results: (a) Phase I and (b) Phase II projects

On the other hand, the Tukey comparisons of SCB J_c values shown with the letter groupings in Figures 18 (a) and (b) indicated that these reductions are not always significant. The Target-25 sample showed statistically significant reduction in J_c value, but with only one observation (i.e., pink bar). Two of three Target-50 samples (i.e., orange bars) in Phase I showed that the reductions are not statistically significant. Two of three Target-75 samples (i.e., green bars) showed the reductions are significant, while the remaining one appeared to be on the border line with the double-letter grouping of A/B. All three Target-100 samples (i.e., blue bars) showed the reductions are statistically significant.

Overall, it can be concluded that the effects of TD up to Target-50 (i.e., Medium severity) level on the SCB J_c values may not be significant; however, the effects become clearer and more significant when the TD level becomes as bad as Target-75 and worse (i.e., High and Very High).

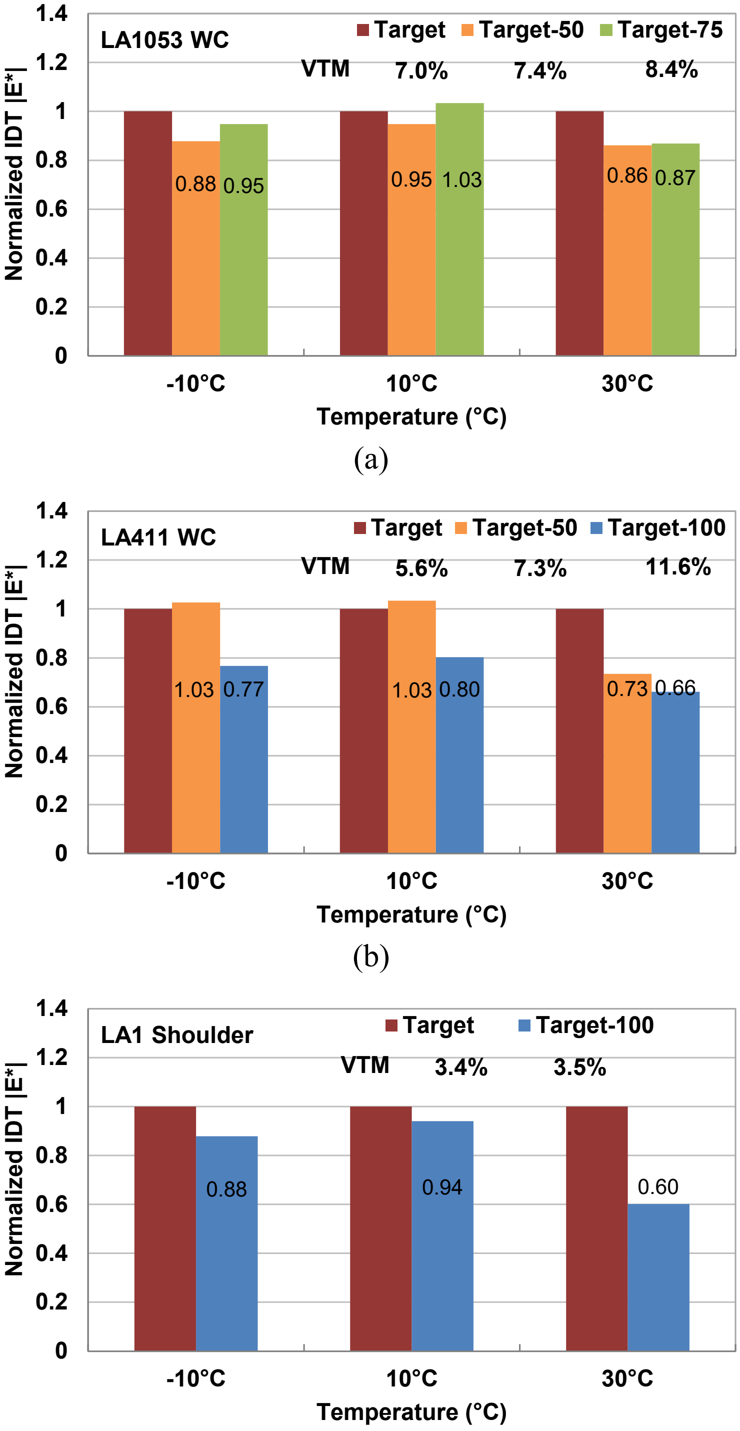
Stiffness Variations

Selected core samples from LA1053 WC, LA411 WC, and LA1 Shoulder were tested for the IDT |E*| to determine the effects of TD on the stiffness of compacted asphalt pavements. For comparisons, the |E*| values of TD samples were normalized by the |E*| value of the Target sample at three temperatures (i.e., -10°C, 10°C, and 30°C) and at 0.1 Hz.

Figure 19 presents the normalized IDT |E*| values of LA1053 WC, LA411 WC, and LA1 Shoulder samples, respectively.

Figure 19 (a) shows that the stiffness of Target-50 sample was decreased by 12, 5, and 14 percent at -10°C, 10°C, and 30°C, respectively; while that of Target-75 sample gained mixed results except at 30°C where 13 percent reduction in stiffness was recorded. With up to 20 percent of typical experimental variability of IDT |E*| tests, the observed stiffness reductions did not seem significant. Statistical comparisons using the t-tests also showed that the differences were not significant by returning the two-tailed p-values much higher than 0.05. It is noteworthy that the density differentials of both Target-50 and Target-75 samples were not substantially large, i.e., 0.4 and 1.4 percent higher than that of Target samples, respectively.

In Figure 19 (b), similar mixed observations were made with Target-50 samples of LA411 WC where stiffness at -10°C and 10°C increased slightly and suddenly decreased by 27 percent at 30°C. The t-test results returned *p*-values of 0.78, 0.46, and 0.01 for -10°C, 10°C, and 30°C, respectively. The density differential of the Target-50 sample was 1.7 percent. On the other hand, the Target-100 sample showed consistently higher stiffness reductions across all three temperatures with a density differential of 6 percent. The t-test results indicated that these reductions are statistically significant with all *p*-values much lower than 0.05.



(a)

(b)

(c)

Figure 19
IDT|E*| test results: (a) LA1053 WC, (b) LA411 WC, and (c) LA1 Shoulder

In Figure 19 (c) of LA1 Shoulder, the Target-100 sample showed consistently lower stiffness than the Target sample did at all three temperatures. Specifically, the stiffness was significantly reduced by about 40 percent at 30°C, t-test of which returned a p-value of 0.00.

However, the other two t-tests between means of Target and Target-100 at -10°C and at 10°C showed statistically insignificant difference with respective *p*-values of 0.67 and 0.21. It should be noted that the density differential between the two samples was merely 0.1 percent.

Overall, the observations clearly suggest that, as long as the final density (or air voids) of the finished pavements is within the acceptable specification limit, the stiffness of Medium to High level temperature segregated pavements may not be adversely impacted. However, when the temperature drops to Very High TD severity level (Target-100) and gets compacted, the stiffness of that area would be definitely lower than that of normal pavements, and be more prone to premature distresses.

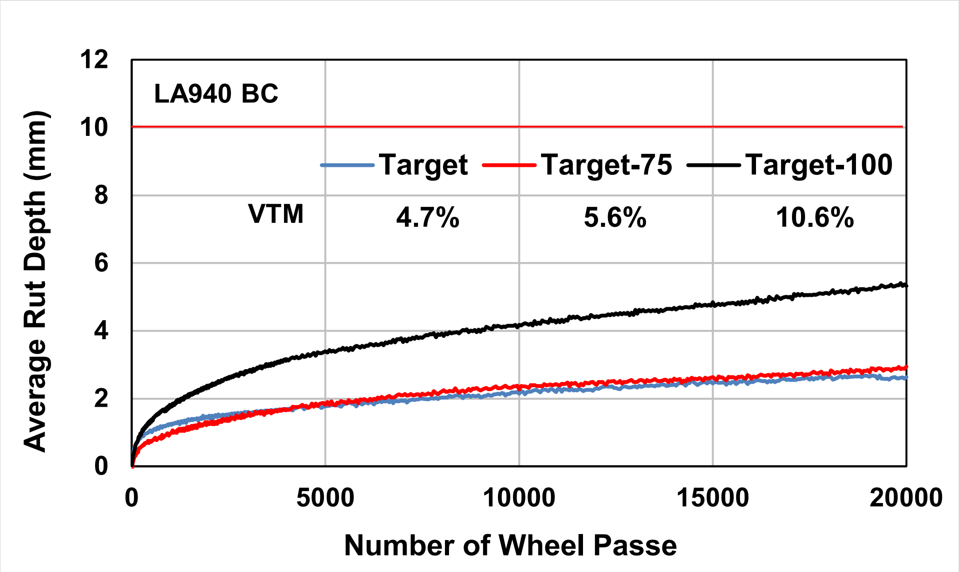
Permanent Deformation Variations

LWT Test Analysis

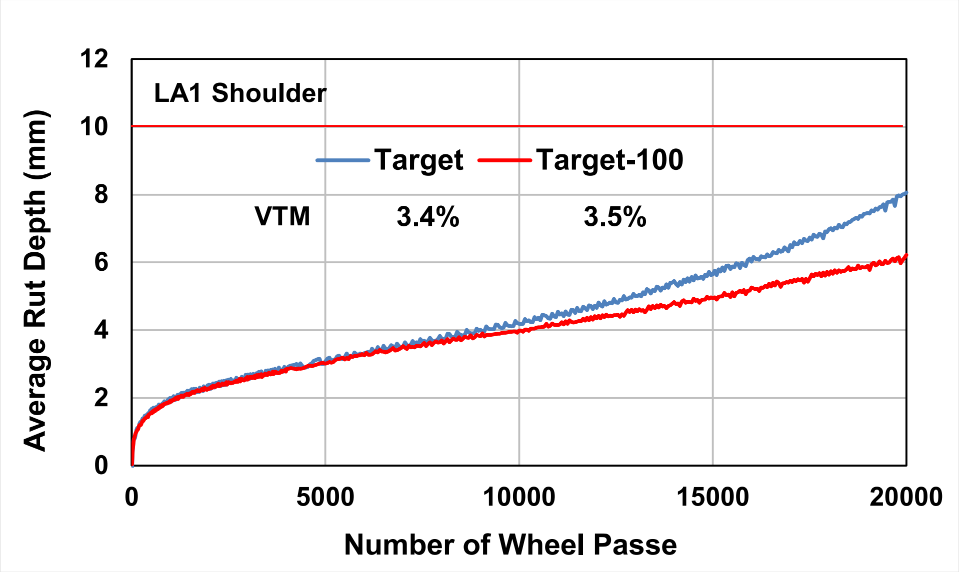
The rutting resistance of a selected field core samples from LA940 BC and LA1 Shoulder layers was evaluated using the loaded wheel tracking (LWT) device. Figures 20 (a) and (b) present the average rut depth measurements of the two pavement samples for 20000 passes of wheel loading. Also shown are the maximum allowable rut depth of 10 mm at 20000 passes specified in the Standard Specifications and average air voids (VTM) of tested samples *[29]*.

In LA940 BC, a distinctively higher rut depth of the Target-100 sample was observed compared to the rut depth of Target and Target-75 samples. The difference started from the early stage of the test and kept increasing until the terminal stage. Terminal rut depth values were 2.6, 2.9, and 5.4 mm for Target, Target-75, and Target-100, respectively. It is noteworthy that the higher rut depth of 5.4 mm for the Target-100 sample is still significantly below the specification limit. It is also interesting to note that the trend in terminal rut depth values of the three TD level samples roughly matches the trend of their corresponding air voids content.

In LA1 Shoulder, a slightly reversed trend in rut depth measurements was observed: the terminal rut depth value of 8.1 mm for the Target sample is higher than 6.1 mm rut depth for the Target-100 sample. Nonetheless, these rut depth values are still lower than the specification requirement, and the pavements are expected to perform well in service resisting the rutting. Interestingly, the rut depth increase patterns of the two samples were almost the same up to 10,000 wheel passes and only diverted from each other beyond that point, with the Target sample showing clearer signs of stripping around 15,000 wheel passes. VTMs of these two samples were almost the same. Overall, with the limited observations on the LWT rut depth evaluations of the TD samples, it is not clear whether the rutting resistance of asphalt pavements is affected by the measured temperature segregation, but the air voids (or density) of compacted asphalt pavements may be more responsible for the rutting.



(a)



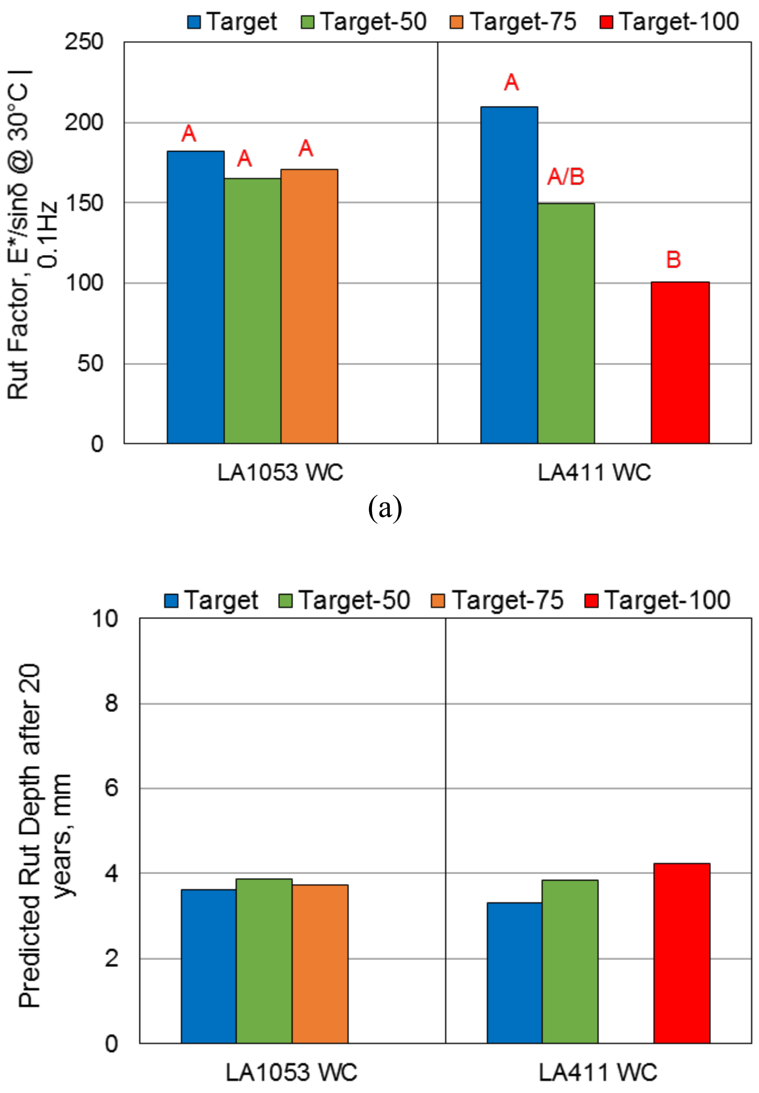
(b)

Figure 20
LWT test results: (a) LA940 BC and (b) LA1 Shoulde

Rutting Performance Prediction Using Rut Factor and Pavement ME

Mohammad et al. presented permanent deformation prediction based on the rut factor to quantify rutting performance using stiffness parameter *[31]*. A sub-factorial was drafted to use stiffness parameter of selective projects for rutting prediction to gain further insight on difference in rutting performance. Rut factors were calculated for LA1053 WC and LA411

WC mixtures, while Pavement ME was used for rutting prediction of LA1053 WC and LA411 WC projects.



(a)

(b)

Figure 21

Rutting analysis results: (a) rut factor and (b) Pavement ME rutting prediction

Figure 21 (a) presents rut factors for permanent deformation analysis, |E*|/sinδ|0.1Hz, 30°C at various segregation severity levels. Dynamic modulus (|E*|) values and Phase angle (δ) difference between applied load and resultant horizontal strain at high temperature and slow loading frequency were used to calculate the rut factor. In both LA1053 WC and LA411 WC mixtures, the rut factor of Target specimens was relatively greater than that of the segregated specimens. A higher rut factor suggests more resistance against rutting. An overall decreasing trend was observed in LA411 WC, which clearly shows the effect of temperature segregation on rutting performance. Tukey comparison analysis returned same letters for all severity levels in LA1053 WC. In LA411 WC, Target-100 presented a different letter showing significant reduction in rut factor compared to target severity level.

Figure 21 (b) presents the Pavement ME predicted rut depths of segregated and non-segregated cores of the two projects. Measured dynamic modulus data of wearing course layer, catalog dynamic modulus values of binder course layer, surveyed traffic data from project proposal document, and typical binder properties were entered as the input data of the simulations. The overall results showed that the predicted rut depths of both pavements are less than the specification requirements of 10 mm regardless of the TD severity levels. In LA411, 1 mm increase in rut depth from None to Very High severity case scenario is evident. Comparison for LA1053 rut depths at different segregation severity levels showed stiffness decrease of 14% caused rut depth increase of 13% for medium severity. Similarly, in LA411, a stiffness decrease of 34% caused a rut depth increase of 29% from None to Very High severity.

Comparing the trends separately observed in Figures 21 (a) and (b) together, it can be easily noticed that the pattern of rut factor plot is similarly duplicated in the Pavement ME predicted rut depth plot, but only in opposite manner. This observation conforms well with the expected rutting performance of asphalt pavements; i.e., when an asphalt mixture possesses higher rut factor, a reduced rutting problem is expected and vice versa.

SUMMARY AND CONCLUSIONS

The objectives of the study were to evaluate the effects of temperature differential (TD) on the initial quality and the performance of asphalt pavements, as measured by the core density and laboratory measured mechanical properties such as fracture and rutting resistance, to ascertain and establish the TD ranges and recommendations.

Seven asphalt rehabilitation projects, which include ten different asphalt mixtures across Louisiana, were selected for this research. Varying levels of construction related factors such as contractors, use of material transfer vehicle (MTV), ambient temperature, target laydown temperature, and nominal maximum aggregate size (NMAS) were considered during the study. The study was carried out through two paving seasons. Two infrared (IR) thermal imaging techniques were used for temperature measurements: the Pave-IR system was used for continuous temperature monitoring on all seven projects under Phase I and Phase II, while a handheld portable IR camera was used on Phase II projects, in addition. The Pave-IR system measured temperature of asphalt mixture near the screed behind the paver, while the IR camera measured temperature at a stationary work stoppage location until the first breaking roller compacts the area.

Field cores from varying levels of TD locations were obtained and tested for the density and mechanical properties in the laboratory. Bulk specific gravity testing was conducted to measure pavement density in accordance with AASHTO T 166. Semi-circular bending test (ASTM D8044) was performed to measure the fracture resistance at intermediate temperature, while loaded-wheel tracking test (AASHTO T324) was conducted for rutting resistance measurements. In addition, Indirect Tensile Dynamic Modulus (IDT|E*|) test was performed to measure the mixture stiffness, which was used in additional rutting performance analyses by the rut factor ($|E^*|/\sin\delta$) and the Pavement-ME predicted ruttings.

Observations and findings of the study are summarized below:

- Analyses on the thermal profiles obtained from all seven field projects showed two distinctive temperature patterns, i.e., a cyclic temperature segregation (CTS) and an irregular temperature segregation (ITS). While the CTS occurs due to the natural cooling of asphalt mixtures during the normal operation and may be at low risk severity levels of TD, the ITS occurs at work stoppages with the severity ranging widely from low to extremely high depending on the work stoppage time and ambient temperatures.
- According to the temperature uniformity analysis, use of MTV significantly improved the uniformity of asphalt mixture temperature across the uncompacted mat. Pavement

sections where full-size MTV with 20-ton storage capacity was utilized showed significantly better consistency than the sections where no MTV and light MTV were utilized. Lager aggregate mixtures with 19-mm nominal maximum aggregate size (NMAS) appeared to have higher temperature variability across the mat than the 12.5-mm NMAS mixtures. Other factors, i.e., ambient temperature, contractors, and target laydown temperature did not appear to influence the temperature uniformity significantly.

- Laboratory test results showed mixed trends in relationships to the temperature differentials:
    a. For the density, a fair correlation ($R^2 = 0.49$) between the density and temperature differential was found in Phase II projects where the temperature differential was measured right before compaction at work stoppage locations. Density differential comparisons between random samples and targeted samples showed that the thermal imaging technique would be helpful to guide decisions on QA sampling locations for better quality assessments.
    b. In Phase I, only one project showed the effect of TD on the fracture resistance measured by the SCB J_c values, while in Phase II, the effects were clearly observed in all three field projects with High and more TD severity levels.
    c. IDT |E*| values of high severity TD samples at 30°C showed significant stiffness reductions around 35 to 40%, while the reductions were not significant at lower temperatures (e.g., -10 and 10°C)
    d. Rut depths measured by LWT and the Pavement-ME predicted rutting values both showed significantly higher ruttings in the high severity TD areas, although the values still satisfy DOTD’s specification limit.

Based upon the analysis and findings presented, the following conclusions can be drawn:

- Temperature differential, as measured at the time of compaction, affects mixture properties depending on its level of severity.

a. TD of 25°F or 50°F does not cause severe effect on mixture properties
b. TD of 75°F shows inconclusive effect, i.e., it affects severely in a few cases.
c. TD of 100°F or higher causes severe effect on mixture properties

- TD measured right before compaction in Phase II projects correlated well with decrease in density, fracture resistance, dynamic modulus, and increase in rut depth.

The Pave-IR system used for the study appeared to be a helpful device in monitoring the temperature uniformity across the asphalt mat immediately behind the paver, providing a vital quality control information in real-time during the paving process. However, the ultimate relationship between the temperature differentials measured at laydown to the quality and performance of the pavements could not be confidently established throughout the study, since many other uncertainties are still involved in the process between the laydown and the actual compaction of the asphalt mat. As observed, on the other hand, much better correlations were established between the temperature differentials measured right at compaction and the quality and performance of the pavements. Therefore, temperature segregation must be redefined as the non-uniform temperature distribution in the uncompacted asphalt mat, measured just before the first breakdown compaction, which causes significant reductions in pavement quality and performance.

RECOMMENDATIONS

The use of thermal scanning devices such as the Pave-IR system or handheld portable thermal camera in Louisiana asphalt paving projects is recommended as the technology provides real-time thermal images of the uncompacted asphalt mats that can help making guided decisions by both contractors and DOTD project engineers for the quality control (QC) and quality acceptance (QA). It is strongly recommended that the thermal scanning is to be performed just prior to the compaction.

- When using the Pave-IR system, the full length thermal profile of a day work can be obtained and submitted to the project engineer for review.
- When using the portable thermal camera, a minimum of one thermal image per each 150-ft. long segment may be obtained and submitted to the project engineer for review.

The thermal profile information can be used by the contractors to identify significantly colder than desirable spots on the mat, and adjust the compaction efforts as needed to achieve adequate field densities for a better guided QC. Also, the information collected and submitted by the contractors can be used by the project engineers or inspectors to determine targeted QA sampling spots for the better assessment of the construction quality. Table 9 suggests the range of temperature differentials and corresponding actions that can be required by the project engineers (inspectors).

Table 9
Range of temperature differentials and suggested actions by the project engineer

TD from Target Laydown Temp. (°F)	Actions
0 to 50	• No actions may be required.
50 to 75	• Require contractors to reduce TD below 50°F. • Require contractors to stop operation if TD is not reduced. • Measure field densities in the affected area. • QA cores may be taken from the area.
Above 75	• Require contractors to reduce TD below 50°F. • Require contractors to stop operation if TD is not reduced. • Obtain QA cores from the affected area. • Require contractors to remove the affected area if the density fails to meet the requirement.

When paving process is interrupted by the shortage of mix supply or field troubleshooting of any equipment in the paving train, both contractors and project engineers need to monitor the temperature of uncompacted mat closely until the process resumes. Contractors should practice preventive actions to avoid an excessive cooling, 100°F or more below the target laydown temperature, in the area. Project engineers may require contractors to remove the area, if the temperature differential of 100°F or more is detected.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
ANOVA	analysis of variance
BC	Binder Course
CTS	Cyclic Temperature Segregation
DD	Density Differential
DOTD	Louisiana Department of Transportation and Development
ft.	Foot/feet
GLM	General Linear Model
GPR	Ground Penetrating Radar
GPS	Global Positioning System
HMA	Hot Mix Asphalt
IDEA	Innovations Deserving Exploratory Analysis
IDT	Indirect Tensile
IDT|E*|	Indirect Tensile Dynamic Modulus
in.	Inch(es)
IP	Incidental Paving
IR	Infra-Red
IRT	Infra-red Thermography
ITS	Irregular Temperature Segregation
J_c	Critical Strain Energy Release Rate
JMF	Job Mix Formula
kJ-m	Kilojoule-meter
lb.	Pound(s)
LTRC	Louisiana Transportation Research Center
LWT	Hamburg Loaded-Wheel Tracking
m	Meter
ME	Mechanistic-Empirical
MRD	Material Remixing Device
MTD	Material Transfer Device
MTV	Material Transfer Vehicle
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NMAS	Nominal Maximum Aggregate Size
OGFC	Open-Graded Friction Course
PC	Post-consolidation

AASHTO	American Association of State Highway and Transportation Officials
QA	Quality Acceptance
QC	Quality Control
RD	Rut depth
ROSAN	Road Surface Analyzer
SCB	Semi-Circular Bending
SCDOT	South Carolina Department of Transportation
SIP	Stripping Inflection Point
SMA	Stone Matrix Asphalt
TD	Temperature Differential
TDD	Temperature Differential Damage
TS	Temperature Segregation
TxDOT	Texas Department of Transportation
VTM	Voids in Total Mix
WC	Wearing Course
WMA	Warm Mix Asphalt
WSDOT	Washington Department of Transportation

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APPENDIX

A: Job Mix Formula

Table A 1

JMF of Phase I projects

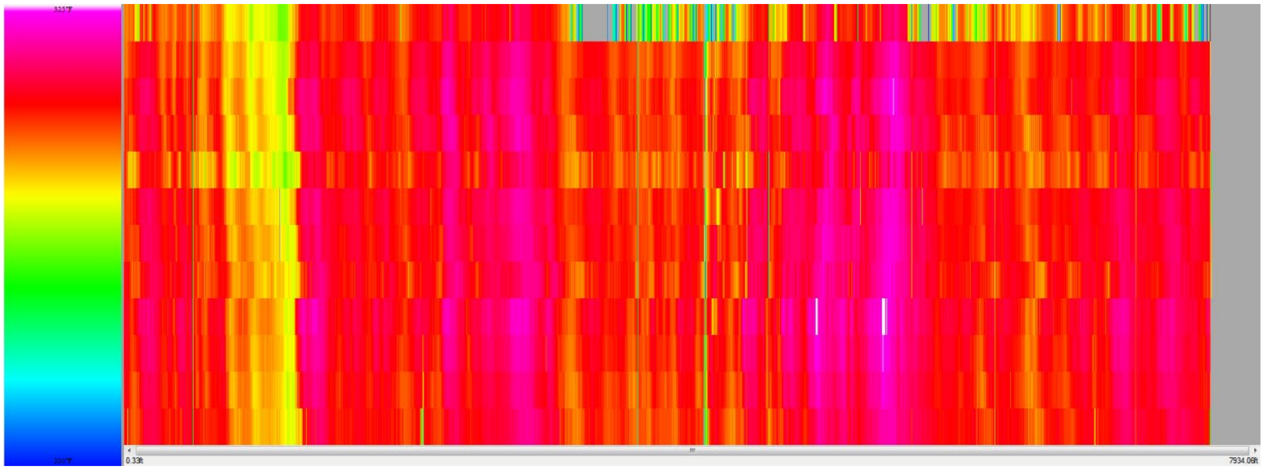
Parameter	LA30 WC	LA1058 WC	US165 WC	LA1053 BC
Gmm	2.499	2.383	2.497	2.413
VMA	13.4	13	13.6	13
VFA	75	73	74	74
%Voids	3.4	3.5	3.5	3.4
%Design AC	4.5	4.9	4.5	4.6
Comp Temp	300	275	300	300
%DF Crushed	100	94	100	97
1 ½ (37.5mm)	100	100	100	100
1 in (25mm)	100	100	100	100
¾ (19mm)	100	100	100	97
½ in (12.5mm)	98	93	97	77
3/8 in (9.5mm)	89	81	84	66
No. 4 (4.75mm)	55	60	59	51
No. 8 (2.38mm)	34	41	42	38
No. 16 (1.18mm)	26	31	32	29
No. 30 (600µm)	21	24	24	23
No. 50 (300µm)	11	14	15	14
No.100 (150µm)	6	8	8	8
No. 200 (75µm)	5.0	5.7	5.5	6.6
%AC Extracted	4.5	4.9	4.5	4.6
Dust/Pbeff	1.16	1.36	1.28	1.57
Gse	2.678	2.556	2.677	2.58
Pba	0.25	0.71	0.21	0.37
Pbe	4.3	4.2	4.3	4.2

Table A 2

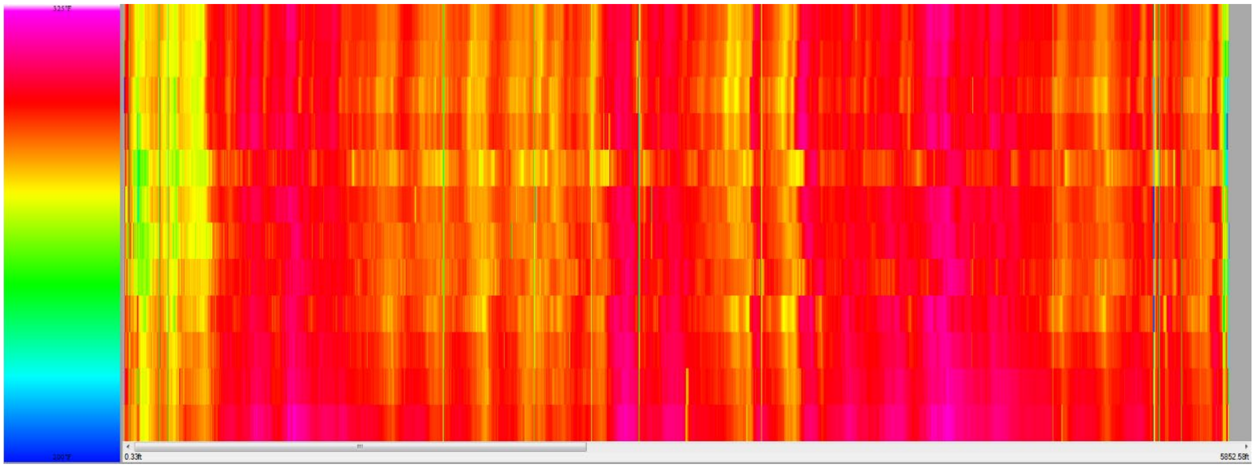
JMF – Phase II projects

Parameter	LA1053 WC	LA411 WC	LA940 BC	LA940 WC	LA1 Shoulder	LA1 BC
Gmm	2.385	2.502	2.522	2.508	2.470	2.474
VMA	14	13	12.6	13	13.9	13.8
VFA	76	73	70.2	74	75	75
%Voids	3.4	3.5	3.76	3.38	3.5	3.5
%Design AC	5.2	4.1	3.7	4.2	4.8	4.8
Comp Temp	300	290	290	290	290	290
%DF Crushed	98	NA	100	100	99	99
1 ½ (37.5mm)	100	100	100	100	100	100
1 in (25mm)	100	100	100	100	100	100
¾ (19mm)	100	100	96	100	99	99
½ in (12.5mm)	96	95	84	98	93	87
3/8 in (9.5mm)	84	75	67	81	82	75
No. 4 (4.75mm)	58	46	39	47	44	42
No. 8 (2.38mm)	39	35	31	33	31	30
No. 16 (1.18mm)	28	28	24	25	25	25
No. 30 (600µm)	22	23	19	20	21	21
No. 50 (300µm)	14	13	11	11	11	10
No.100 (150µm)	8	7	7	8	6	6
No. 200 (75µm)	5.0	5.2	4	4	4.1	4.1
%AC Extracted	5.2	4.1	3.76	4.16	4.8	4.8
Dust/Pbeff	1.05	1.30	1.12	1.03	0.91	0.93
Gse	2.570	2.664	2.671	2.671	2.657	2.662
Pba	0.43	0.11	0.012	0.048	0.31	0.36
Pbe	4.8	4.0	3.68	4.06	4.5	4.4

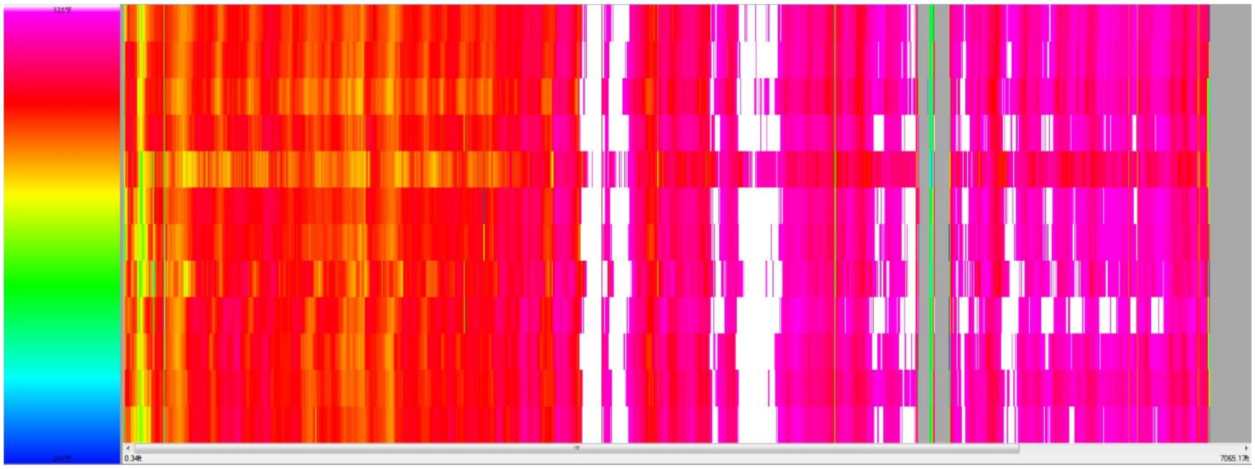
B: Thermal Profiles from Pave-IR system



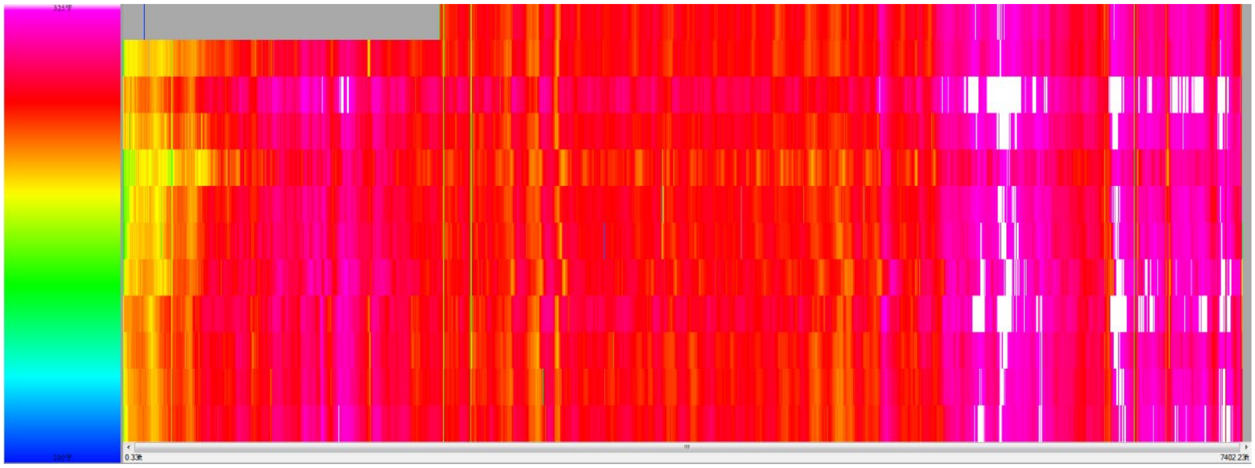
LA30 WC (profile 1)



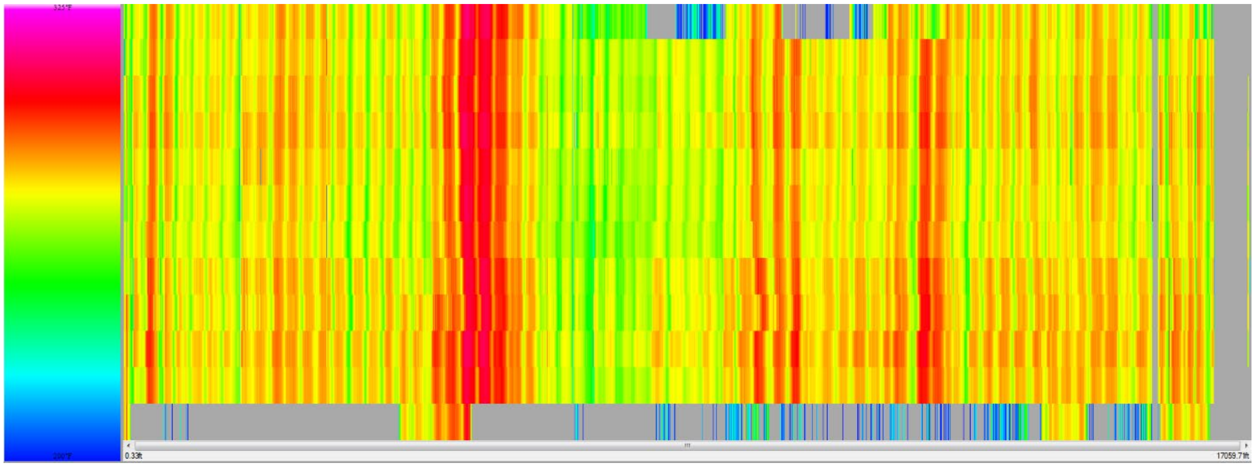
LA30 WC (profile 2)



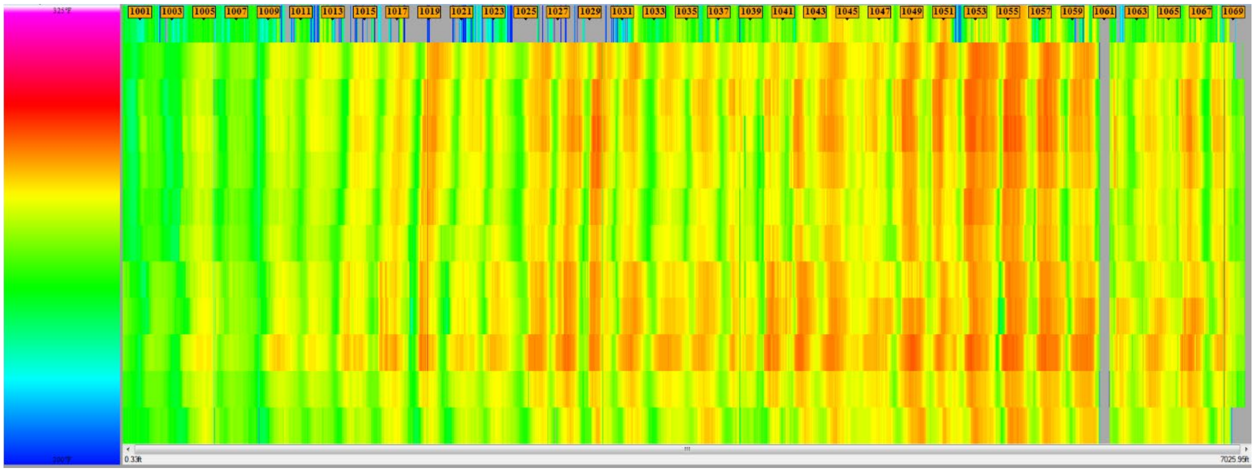
LA30 WC (profile 3)



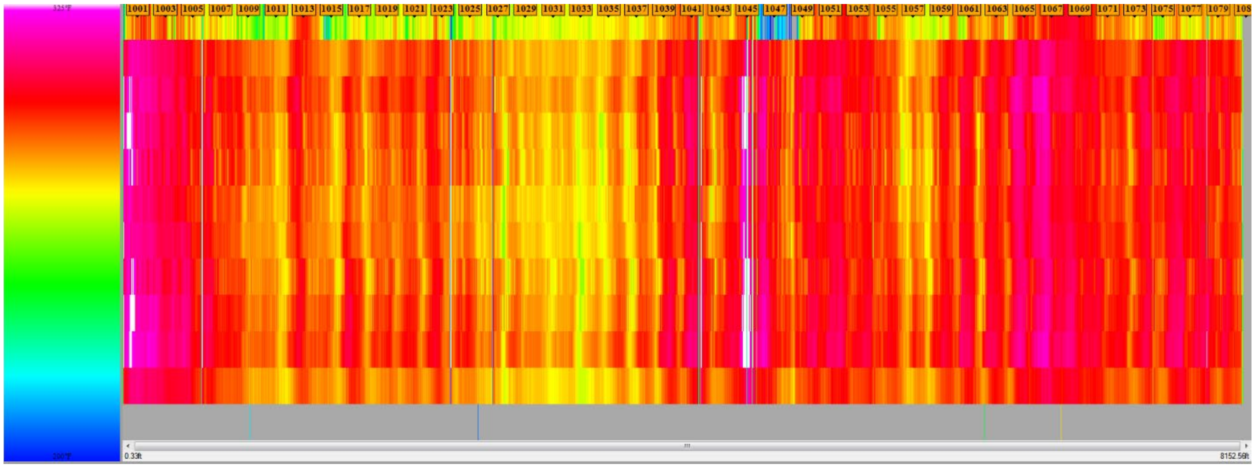
LA30 WC (profile 4)



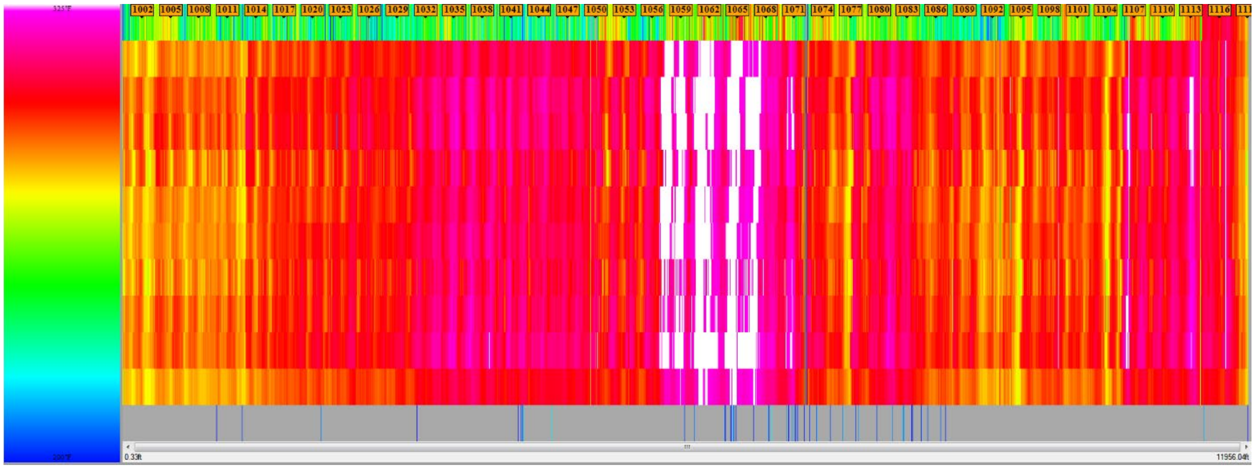
LA1058 WC (profile 1)



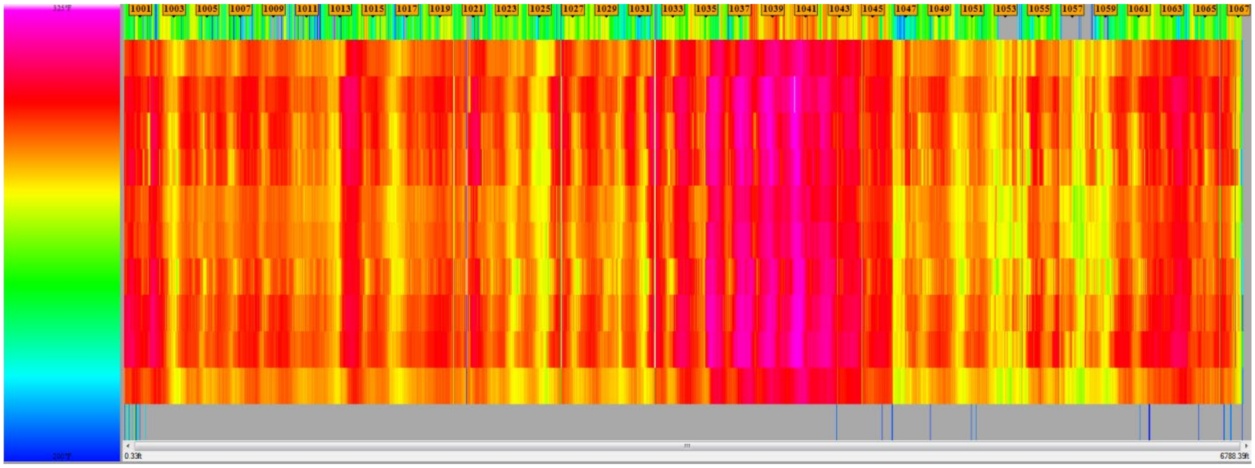
LA1058 WC (profile 2)



US165 WC (profile 1)



US165 WC (profile 2)



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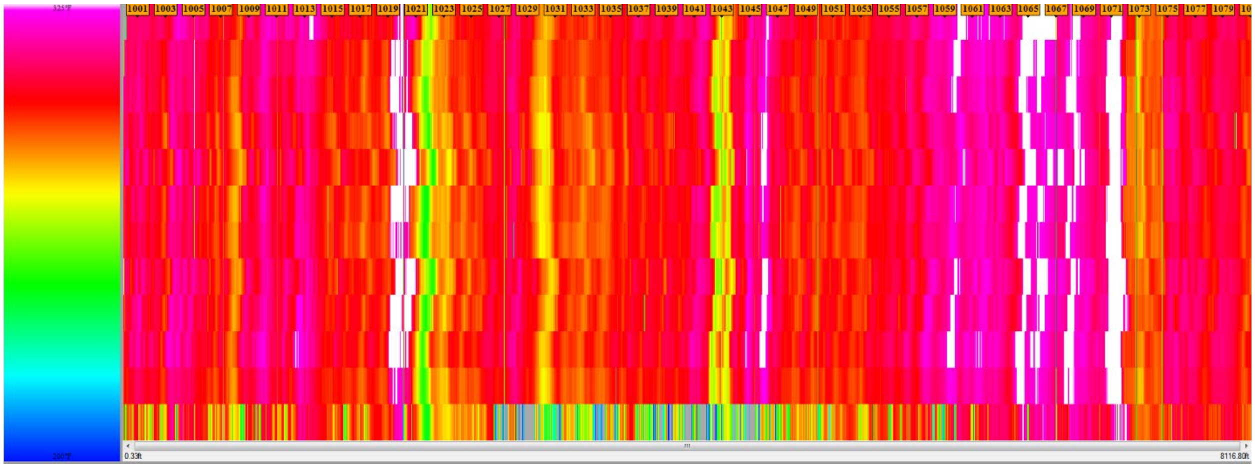
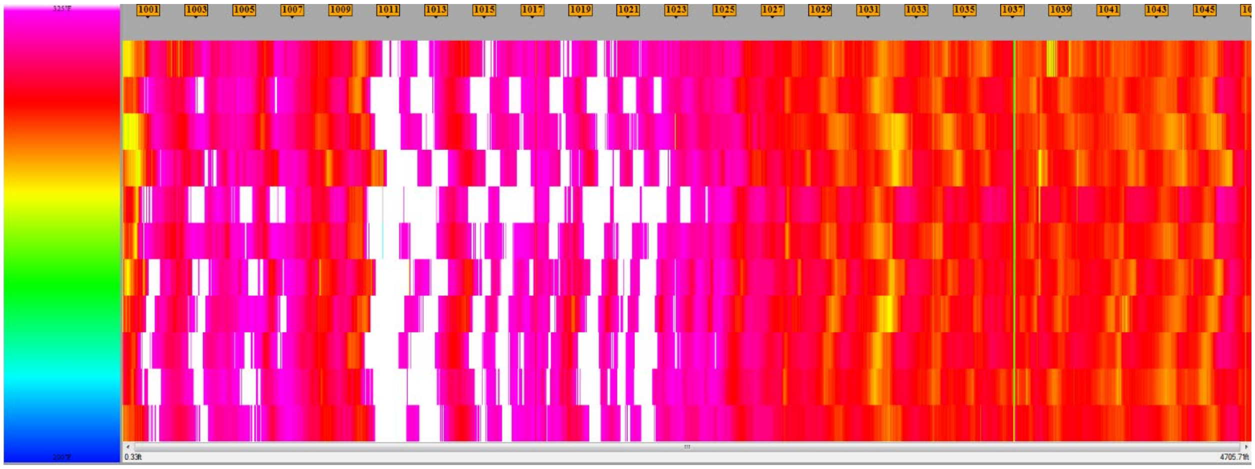
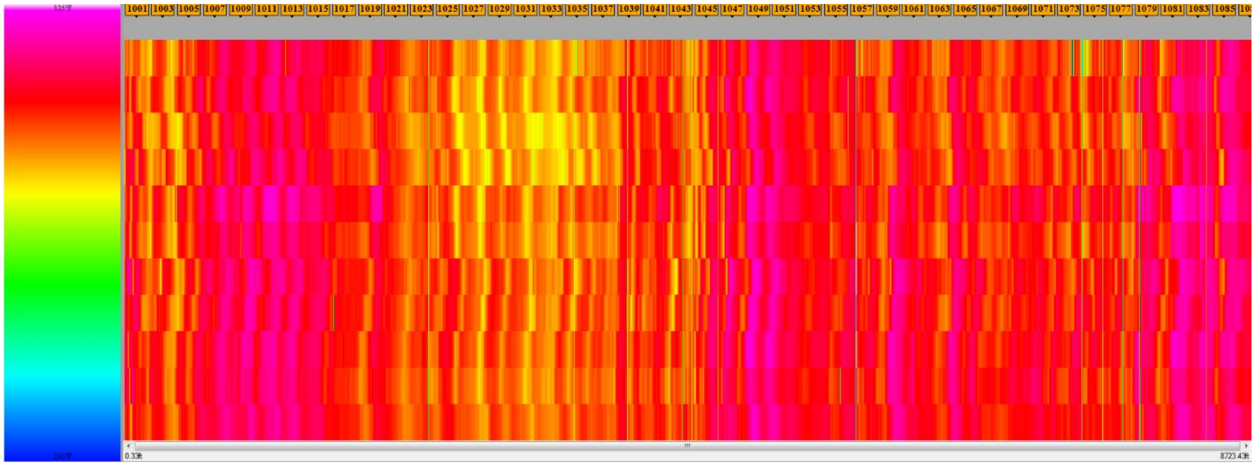


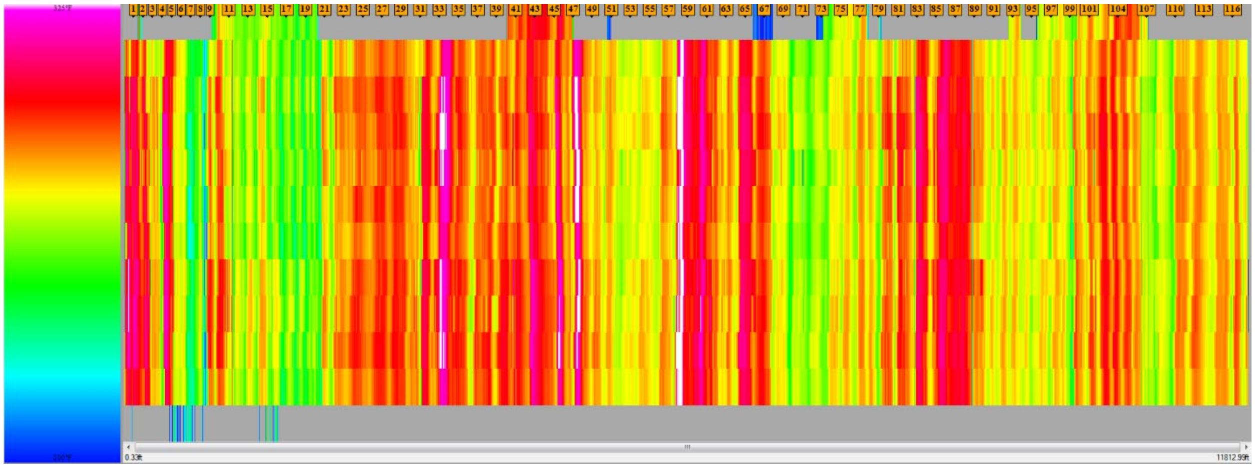
LA1053 BC



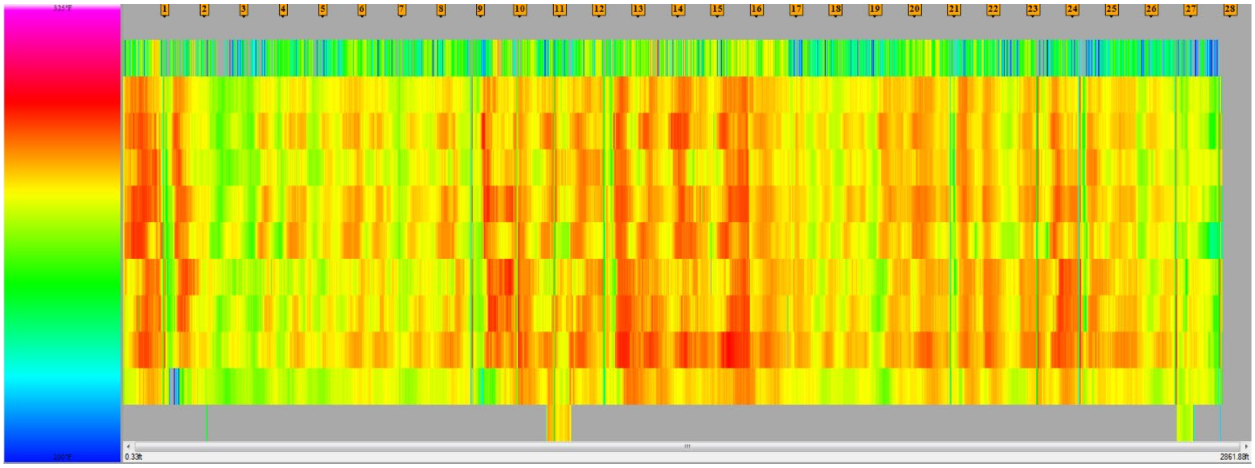
LA1053 WC (profile 1)



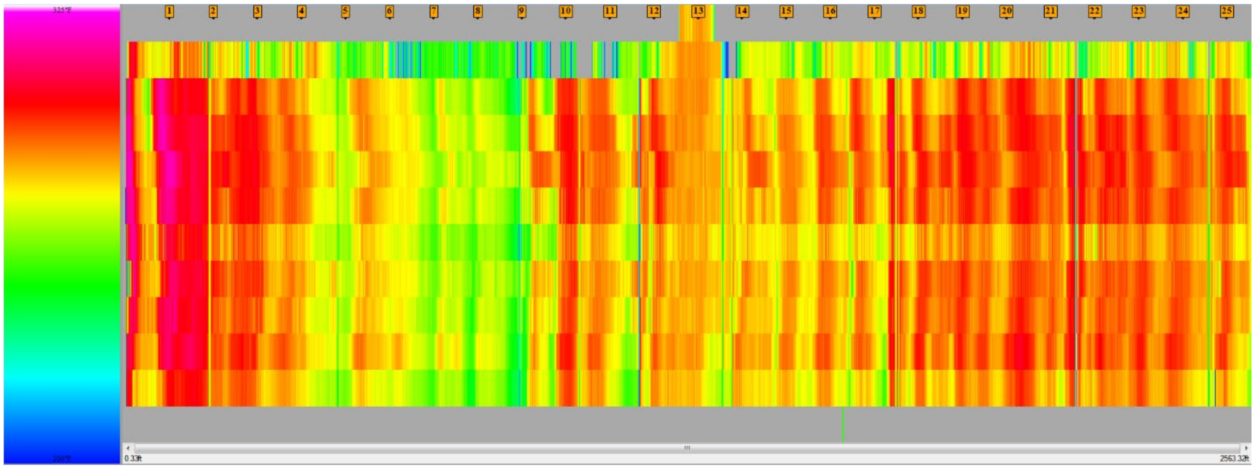
LA1053 WC (profile 2)



LA411 WC



LA940 BC (profile 1)



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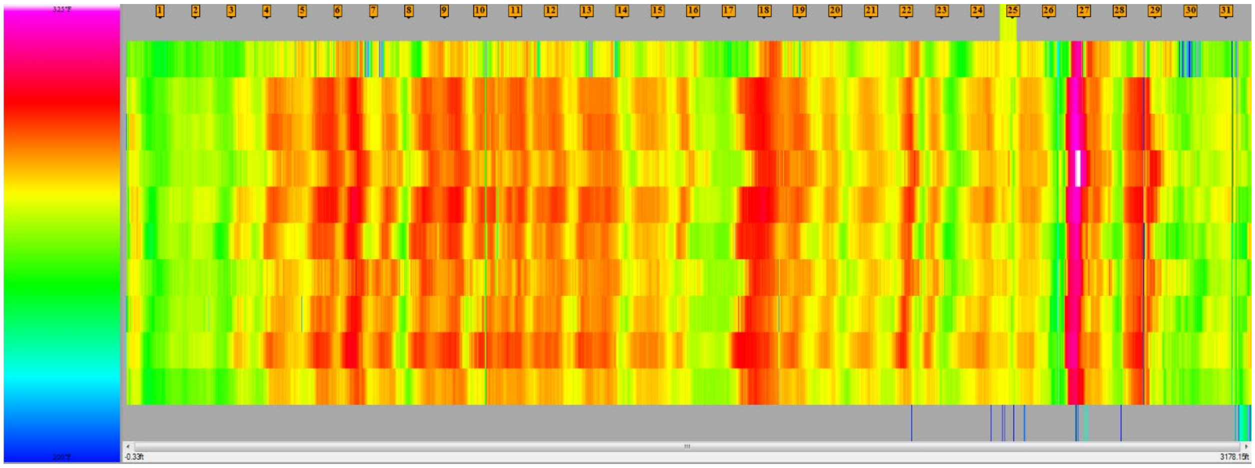

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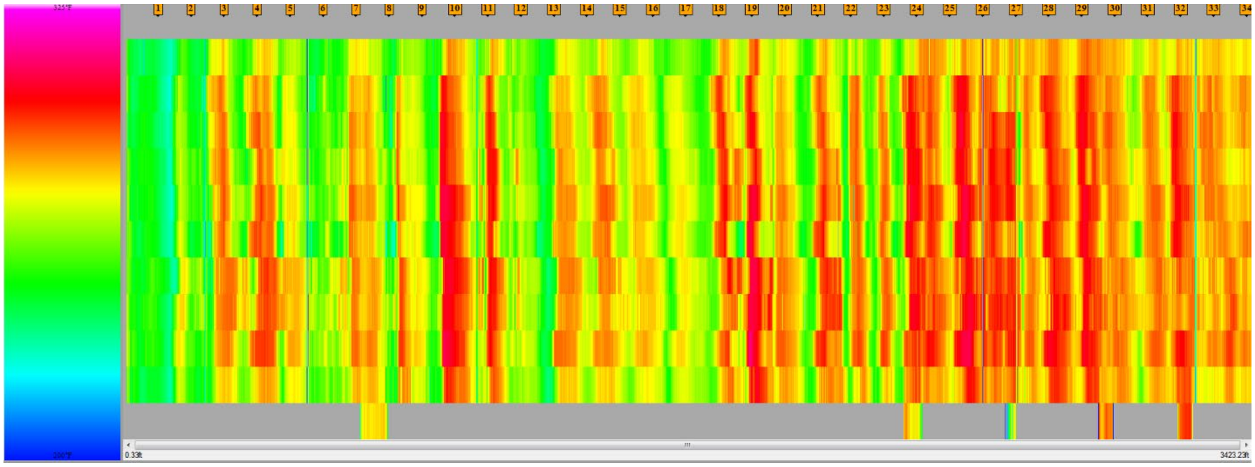

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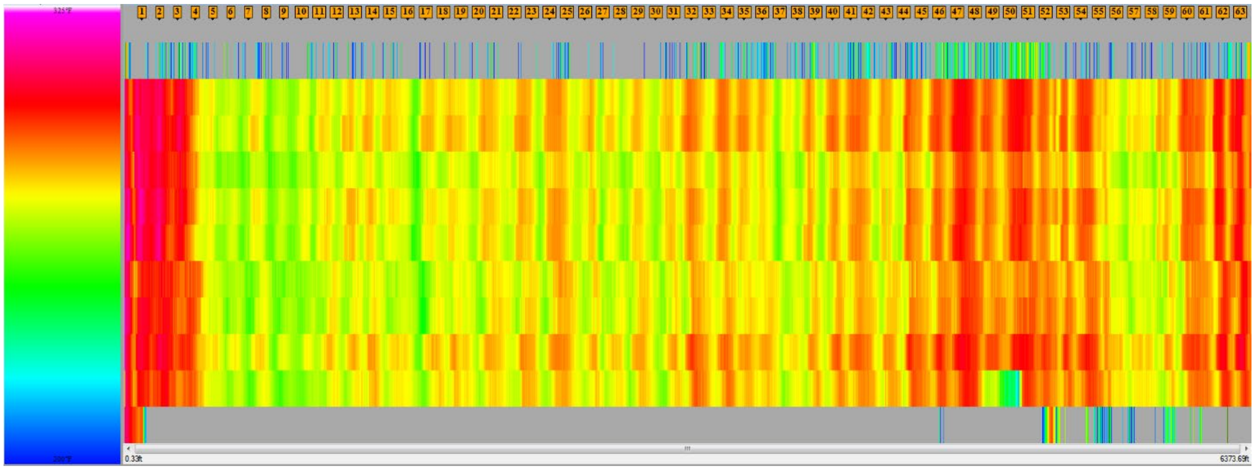

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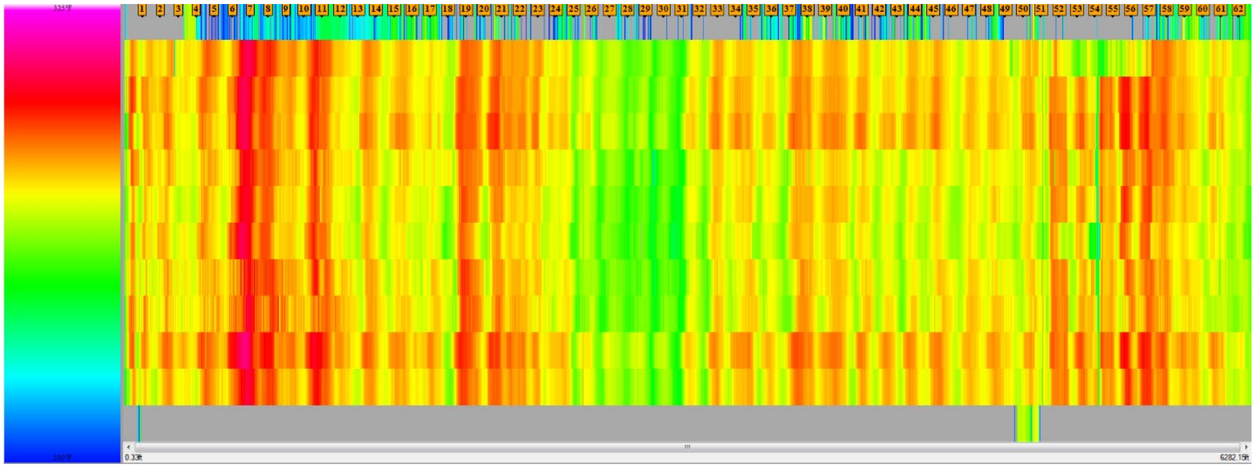

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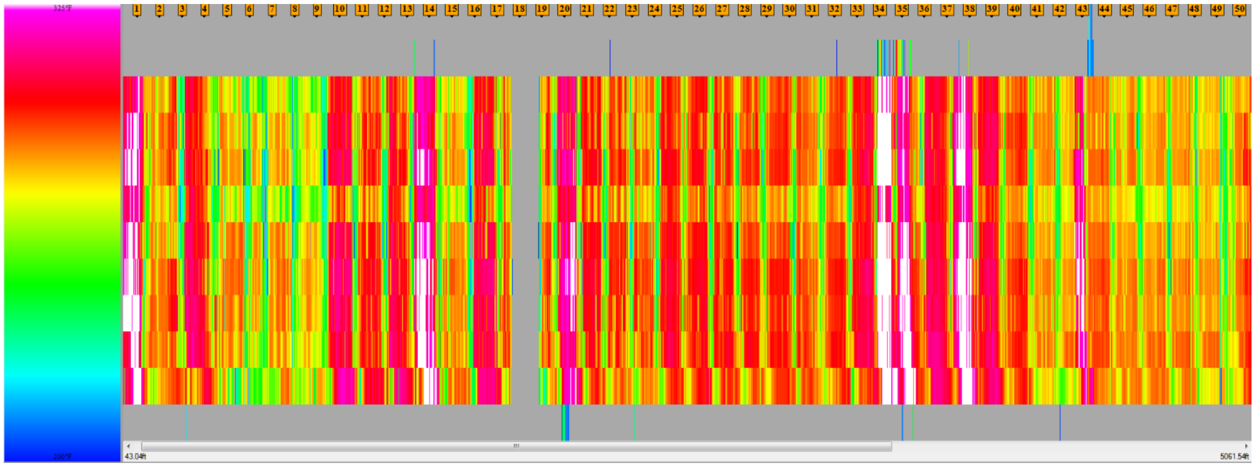
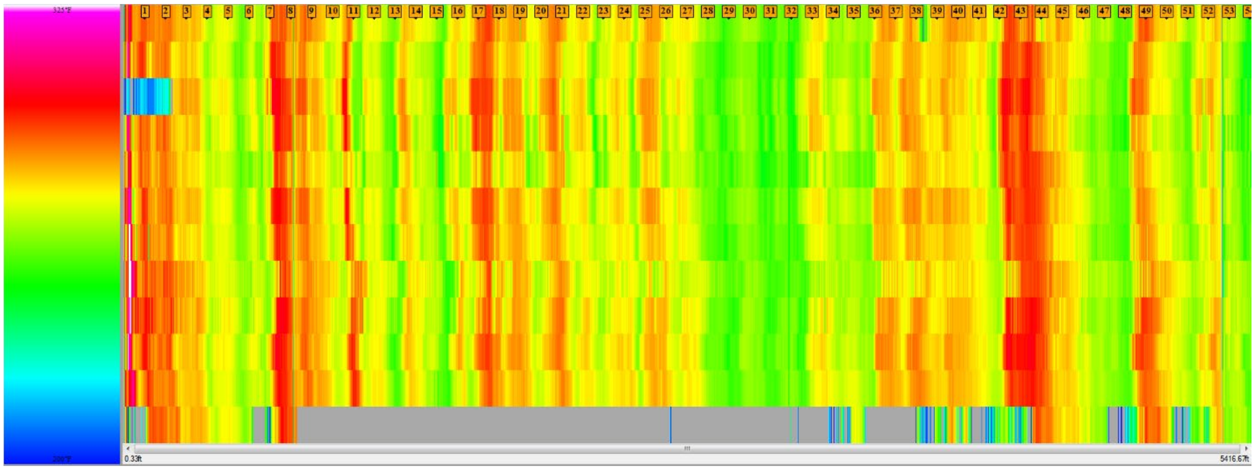


LA1 Shoulder



LA1 BC

C: Density Test Results

Table C 1

Density test results – Phase I projects

Project	TD Severity Level	Number of Cores	Average Air Voids, %	Tukey test Grouping
LA30 WC	None	8	8.5	A
	Medium	8	11.6	B
LA1058 WC	None	4	5.0	A
	Low	4	6.9	A
	Medium	3	6.6	A
US165 WC	None	5	6.0	A
	Low	5	6.7	A
	Medium	5	7.0	A
	High	5	7.4	A
LA1053 BC	None	6	5.8	A
	Medium	4	6.7	A

Table C 2

Density test results – Phase II projects

Project	TD Severity Level	Number of Cores	Average Air Voids, %	Tukey test Grouping
LA1053 WC	None	4	6.8	A
	Medium	2	7.4	A
	High	2	8.4	A
LA411 WC	None	5	6.0	A
	Medium	5	7.1	A
	Very High	5	11.5	B
LA940 BC	None	11	6.4	A
	High	7	5.9	A
	Very High	6	11.2	B
LA940 WC	None	5	6.8	A
	Very High	4	12.0	B
LA1 Shoulder	None	4	3.4	A
	High	2	4.2	A
	Very High	4	3.5	A
LA1 BC	None	2	3.3	A
	Extreme	2	8.9	B

D: SCB Test Results

Table D 1

SCB test results – Phase I projects

Project	TD Severity Level	Number of Cores	SCB J_c, kJ/m^2	Tukey test Grouping
LA30 WC	None	4	0.89	A
	Medium	4	0.72	A
US165 WC	None	4	0.67	A
	Low	4	0.45	B
	Medium	4	0.36	B
	High	4	0.42	B
LA1053 BC	None	4	0.50	A
	Medium	4	0.46	A

Table D 2

SCB test results – Phase II projects

Project	TD Severity Level	Number of Cores	SCB J_c, kJ/m^2	Tukey test Grouping
LA940 BC	None	2	0.77	A
	High	2	0.47	B
	Very High	2	0.45	B
LA1 Shoulder	None	2	0.72	A
	High	2	0.54	A/B
	Very High	2	0.30	B
LA1 BC	None	2	1.03	A
	Very High	2	0.27	B

E: IDT |E*| Test Results

Table E 1

IDT |E*| test results

Project	TD Severity Level	Number of Cores	|E*| at 30°C, 0.1Hz (ksi)	Normalized |E*|
LA1053 WC	None	3	102.5	1.00
	Medium	3	88.2	0.86
	High	3	89.0	0.87
LA411 WC	None	3	118.1	1.00
	Medium	3	86.8	0.73
	Very High	3	78.1	0.66
LA1 Shoulder	None	2	116.8	1.00
	Very High	2	70.2	0.60

F: Rut Factor Results

Table F 1

Rut factor results

Project	TD Severity Level	Number of Cores	|E*| at 30°C, 0.1Hz (ksi)	δ Phase Angle, °	Rut Factor
LA1053 WC	None	3	102.51	34.2	182.3
	Medium	3	88.24	32.3	165.3
	High	3	89.03	31.4	171.0
LA411 WC	None	3	118.13	34.2	210.1
	Medium	3	86.76	35.4	149.7
	Very High	3	78.07	50.8	100.7

G: Weather Data

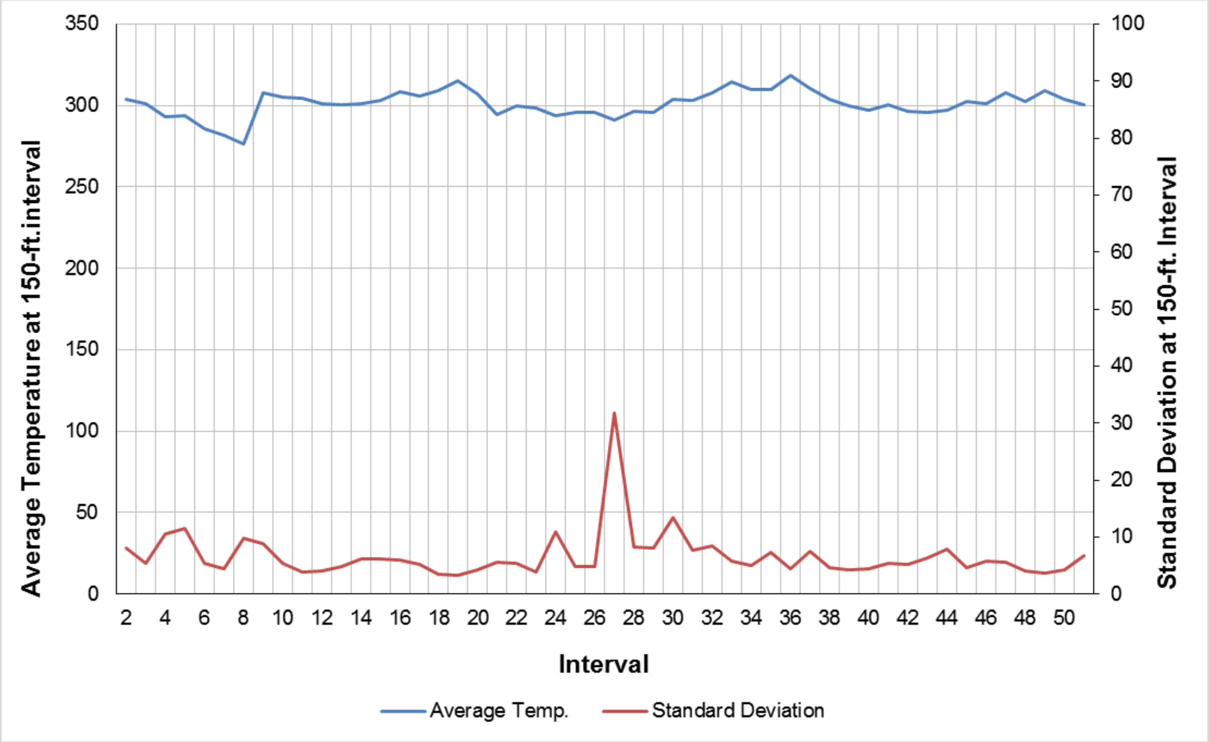
Table G 1

Project weather data

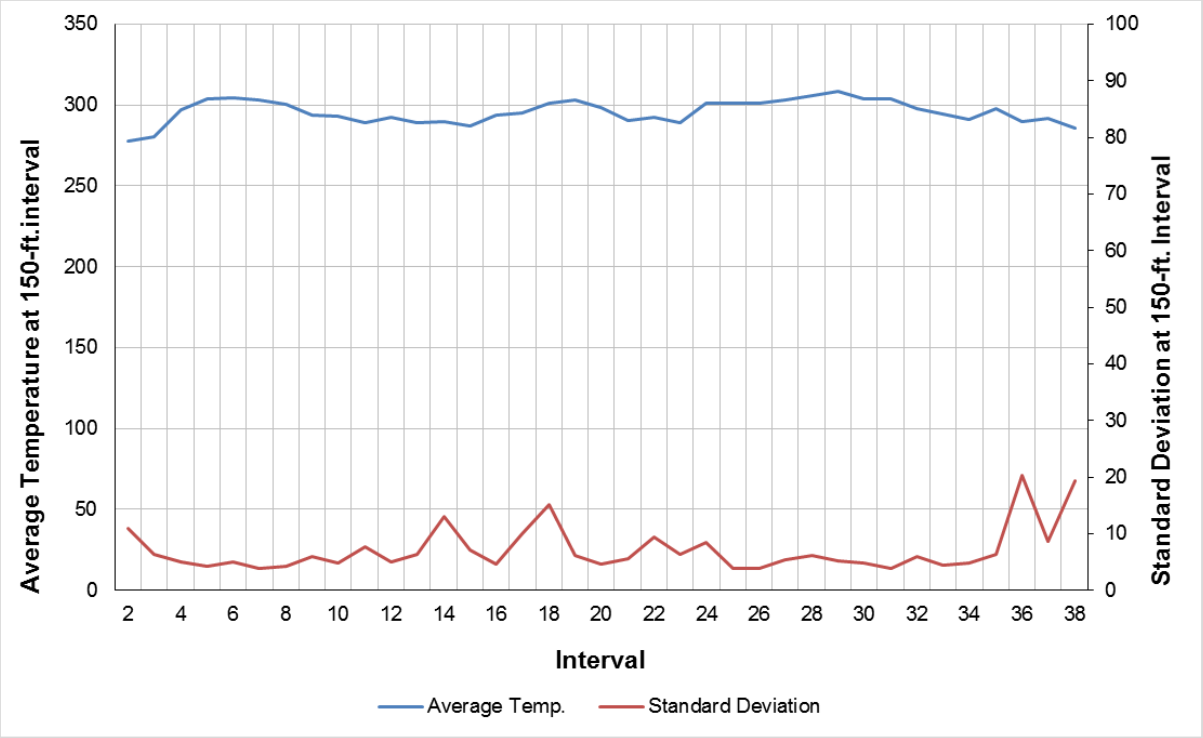
Project	Mix layer	Temperature, °F			Humidity, %	Wind Speed, mph
		Avg.	Max.	Min.		
LA30	WC	54	65	42	97	4
LA1058	WC	73	83	60	71	7
US165	WC	75	82	65	70	11
LA1053	BC	84	88	72	70	6
	WC	89	93	79	63	6
LA411	WC	64	70	53	55	6
LA940	BC	71	73	67	82	9
	WC	76	80	63	45	7
LA1	Shoulder	89	93	81	52	5
	BC	90	97	81	60	5

H: Temperature Uniformity

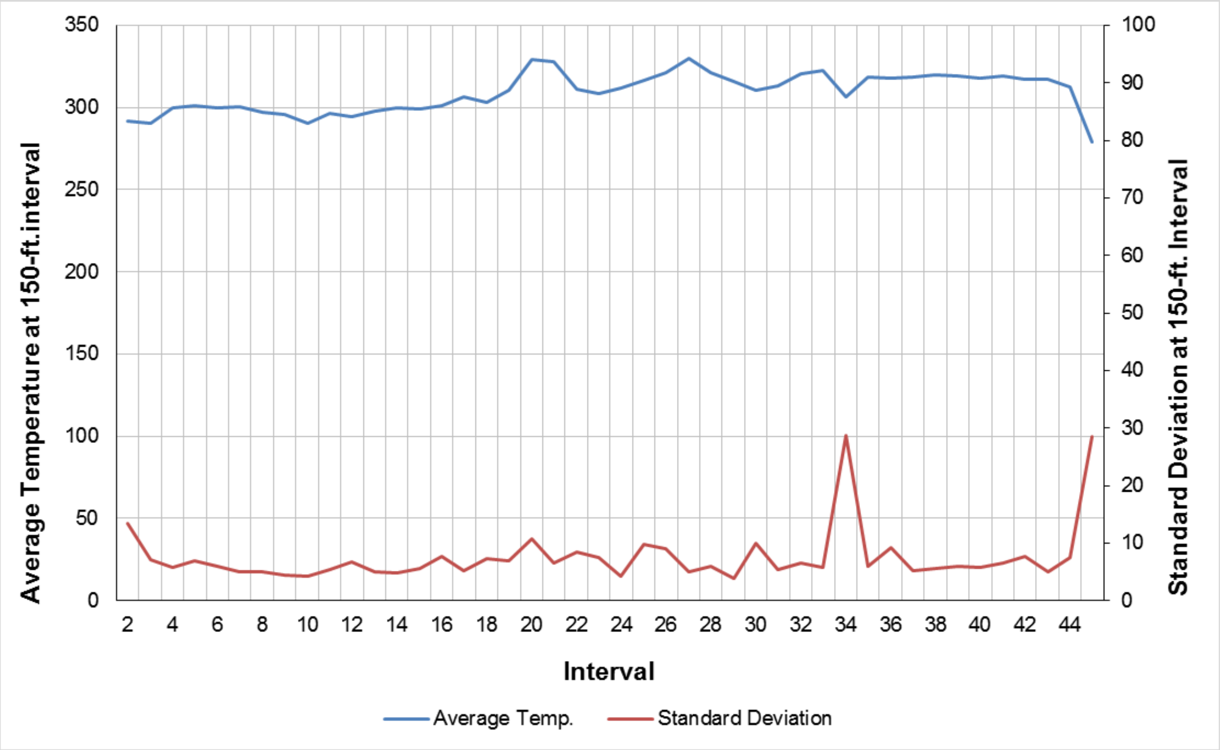
Average Temperature and Standard Deviation Plots



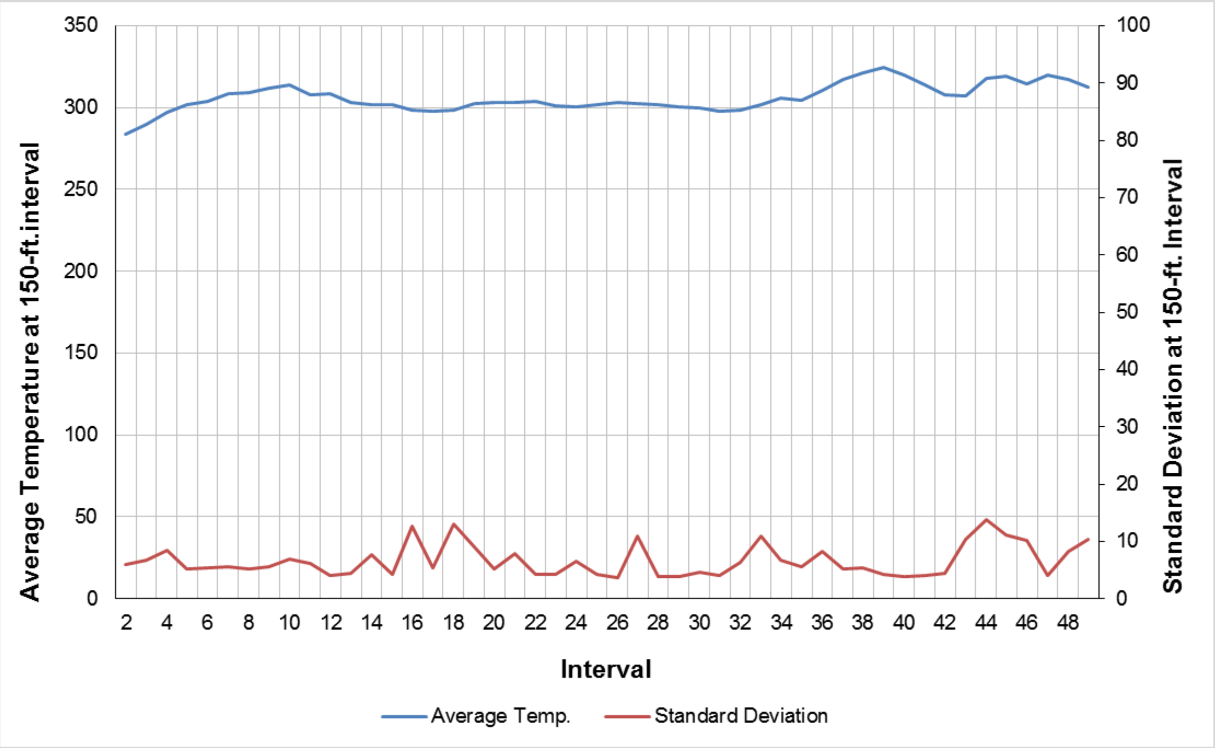
LA30 WC (profile 1)



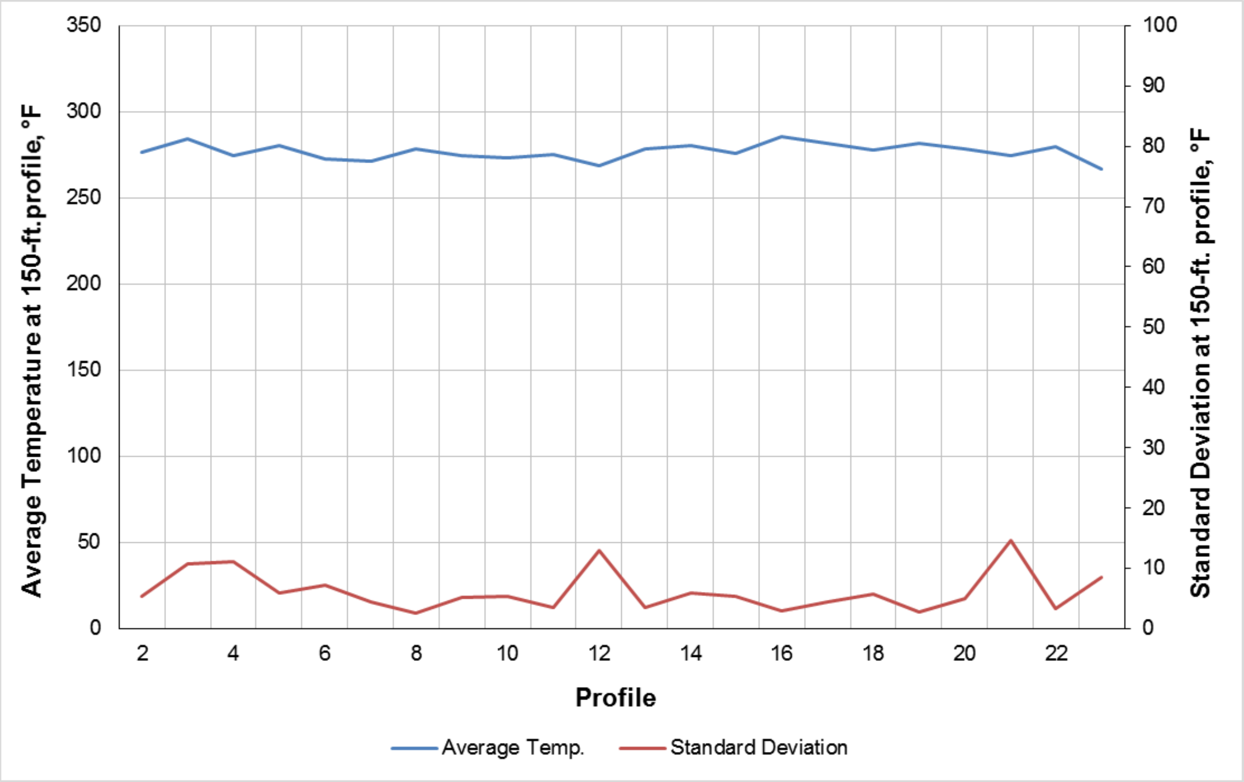
LA30 WC (profile 2)



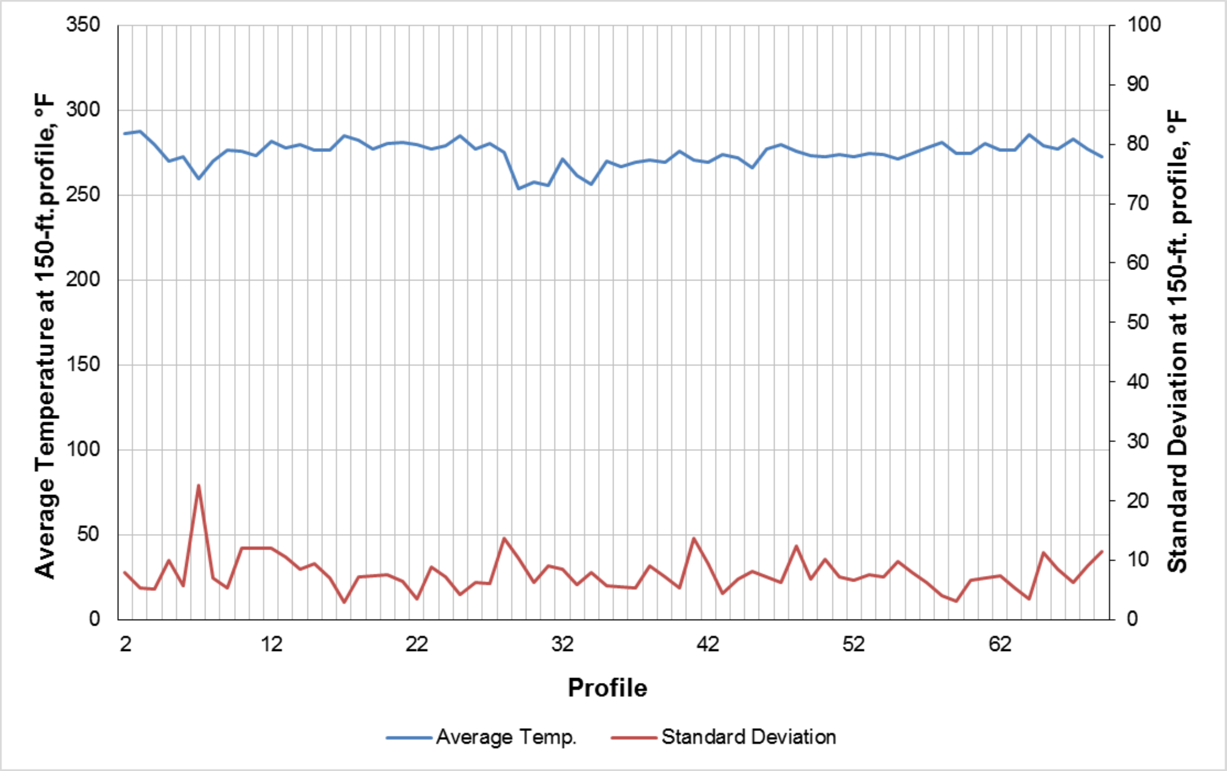
LA30 WC (profile 3)



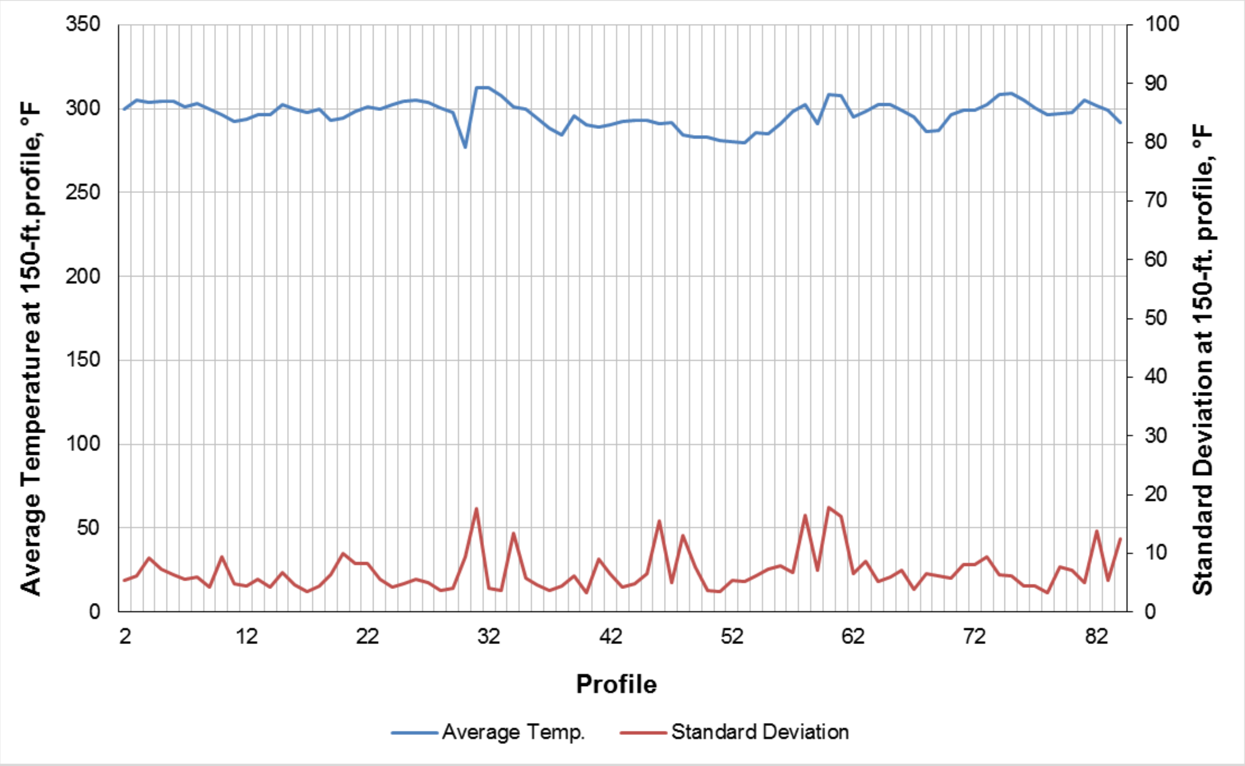
LA30 WC (profile 4)



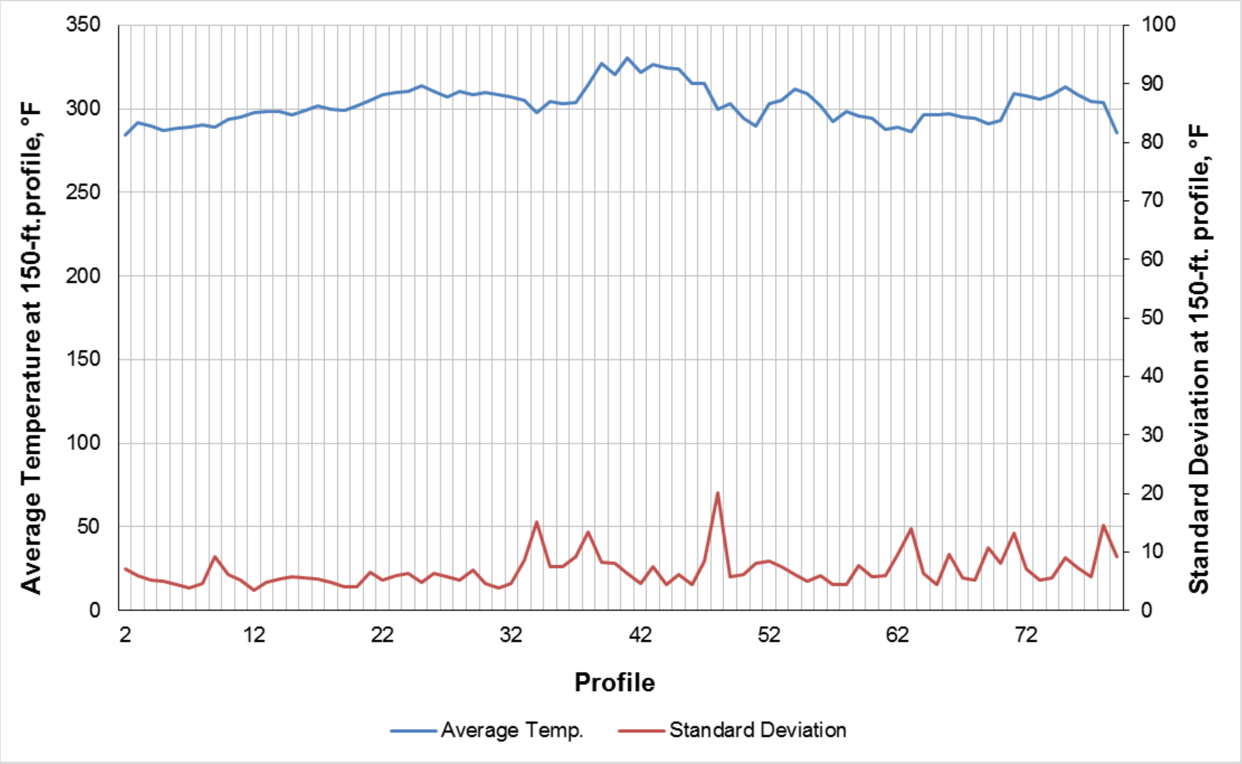
LA1058 WC (profile 1)



LA1058 WC (profile 2)



US165 WC (profile 1)



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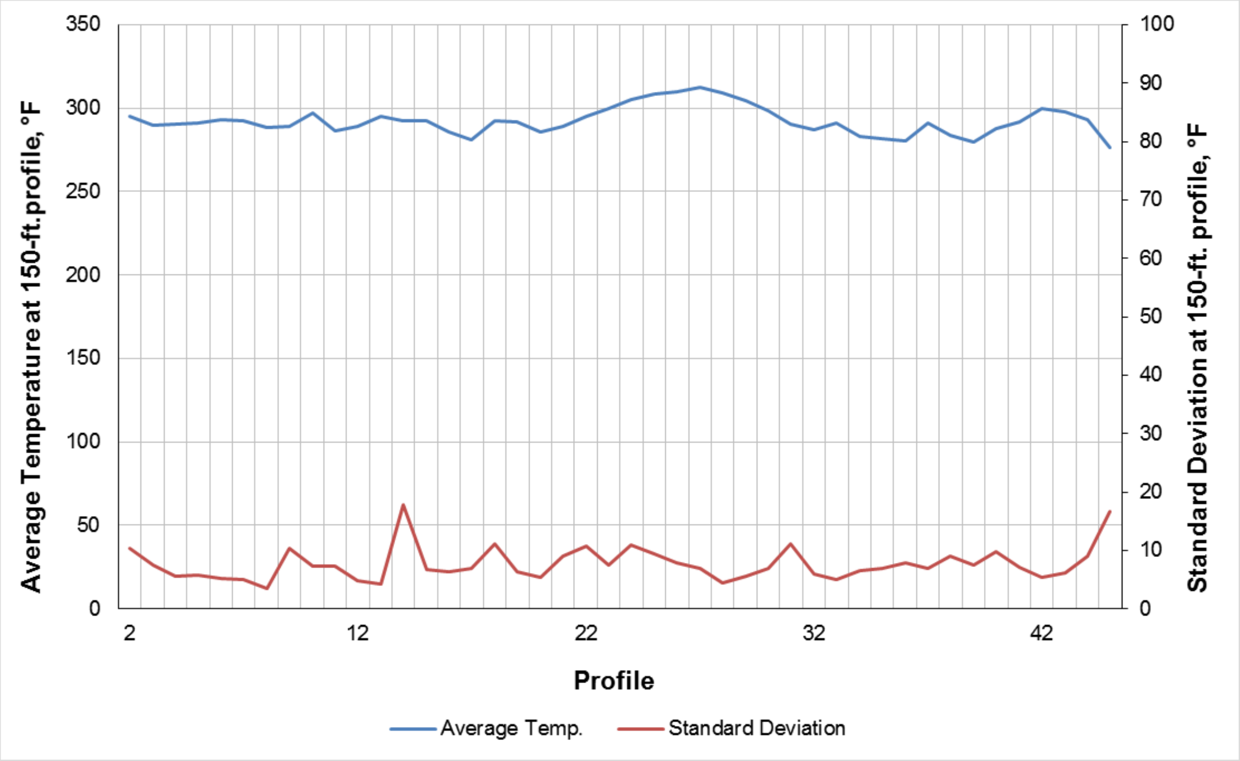

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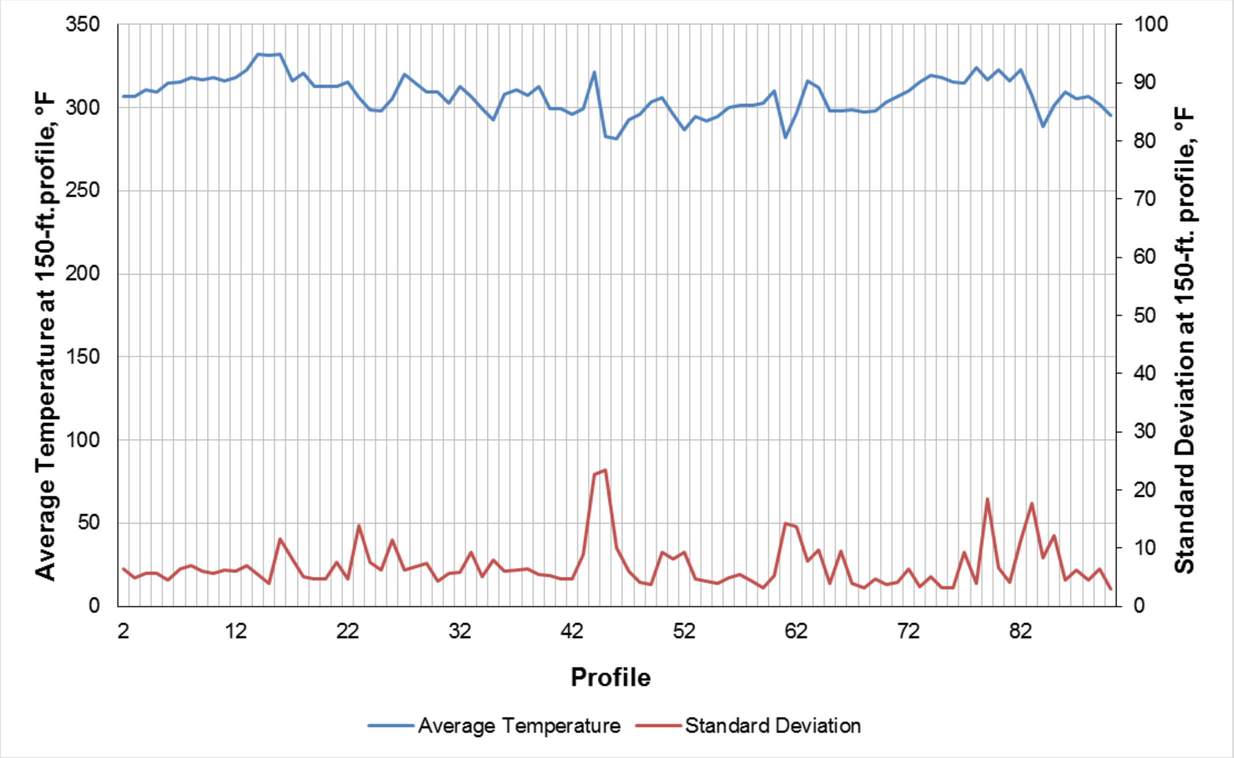

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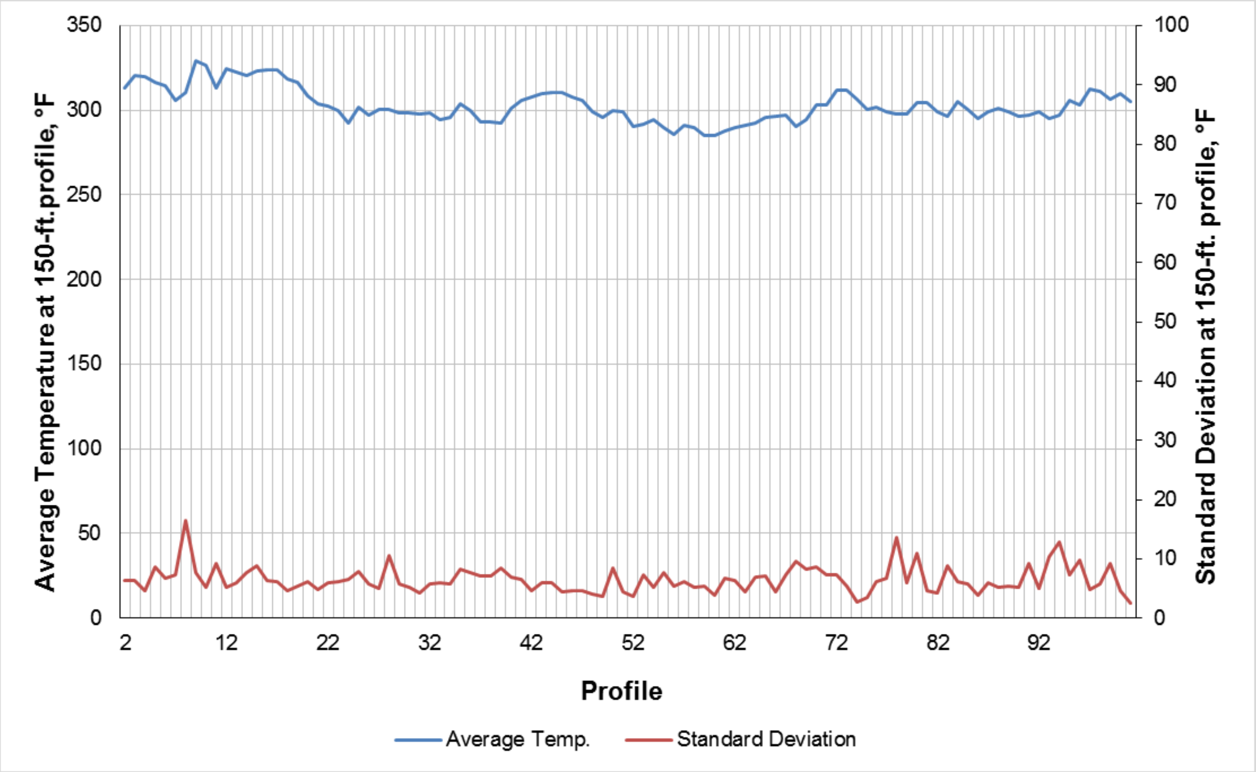
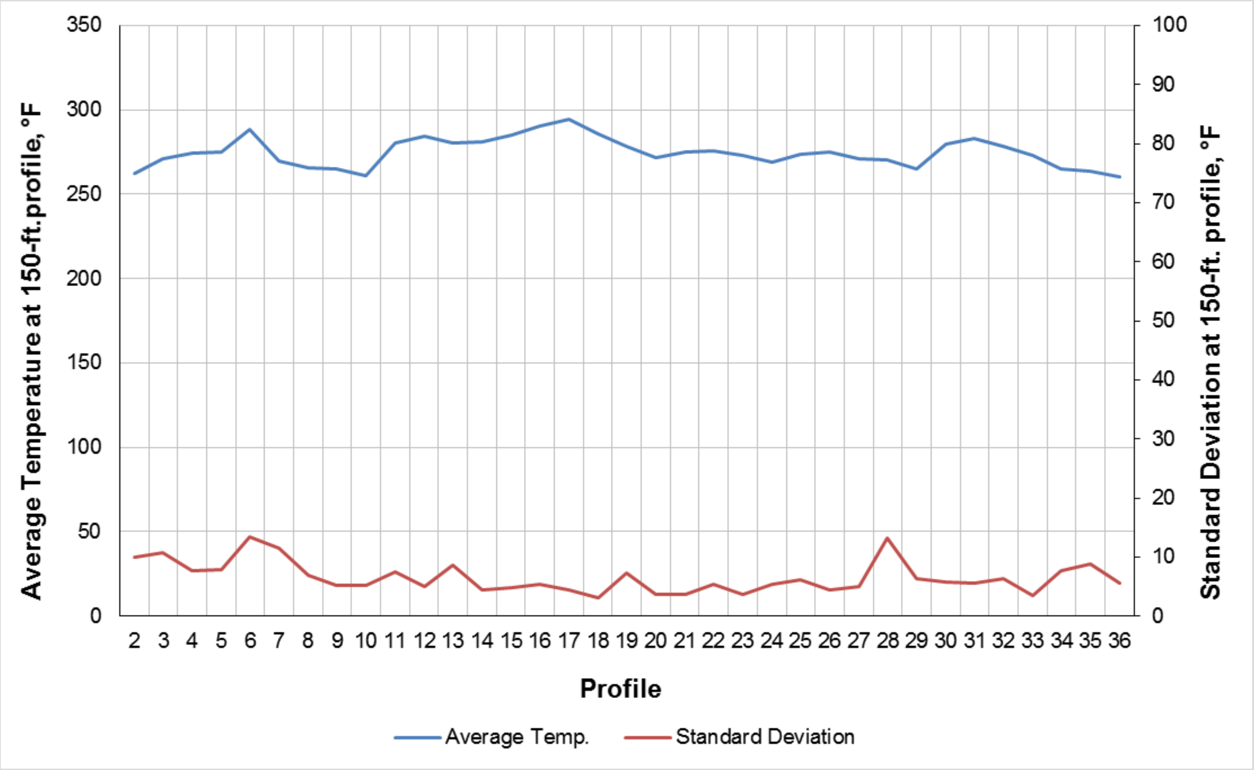
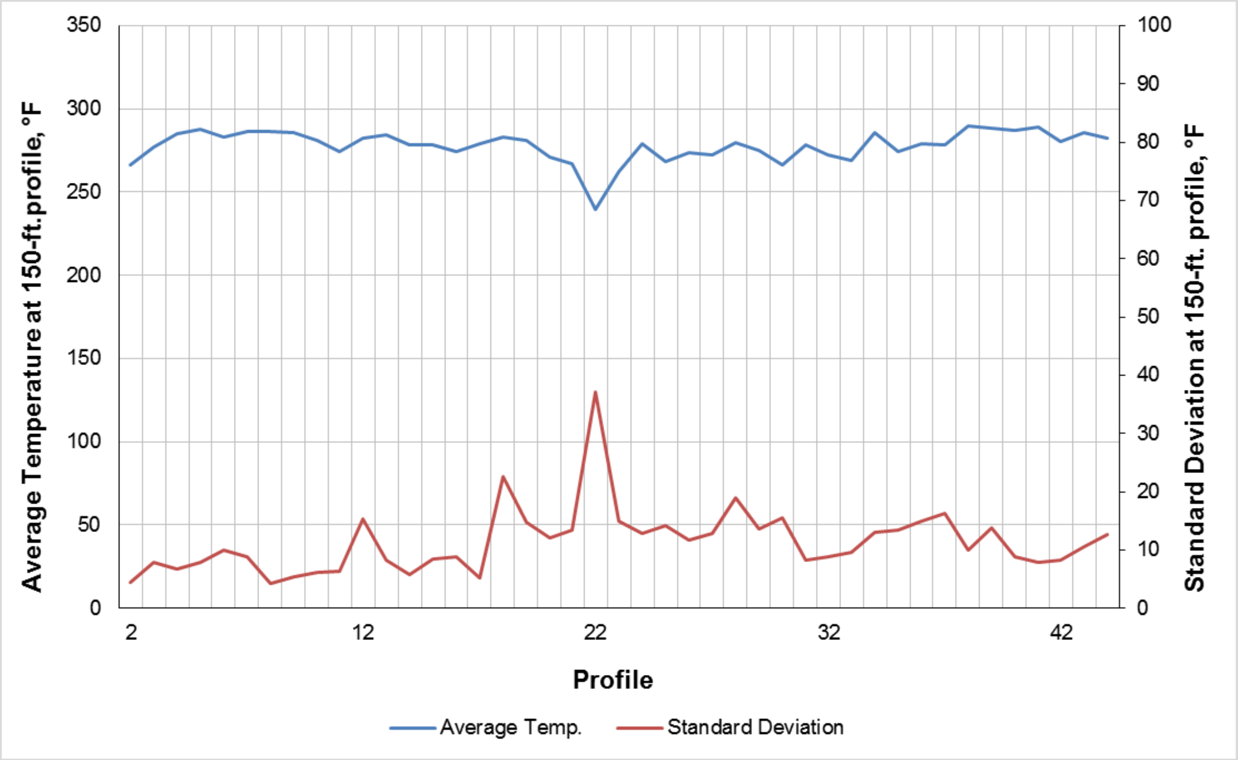


LA1053 WC

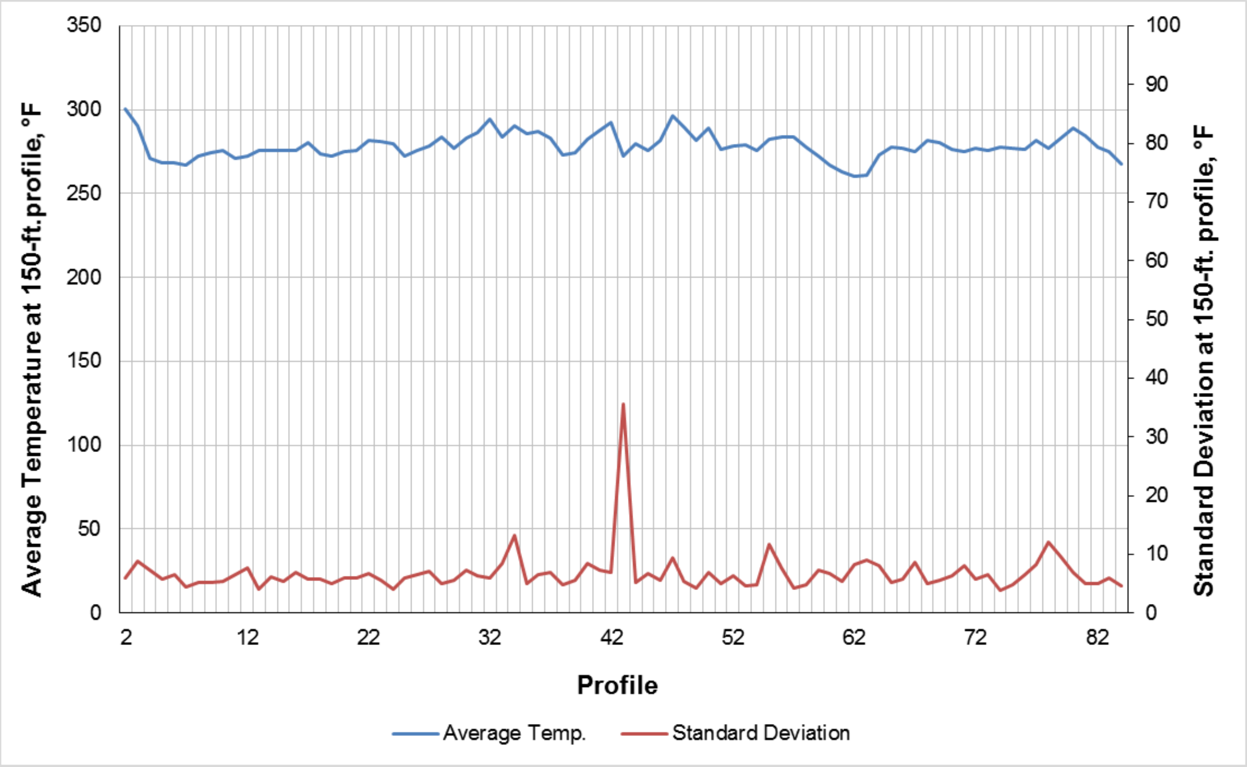


LA411 WC

LA940 BC (profile 1, 2)



LA940 BC (profile 3, 4)



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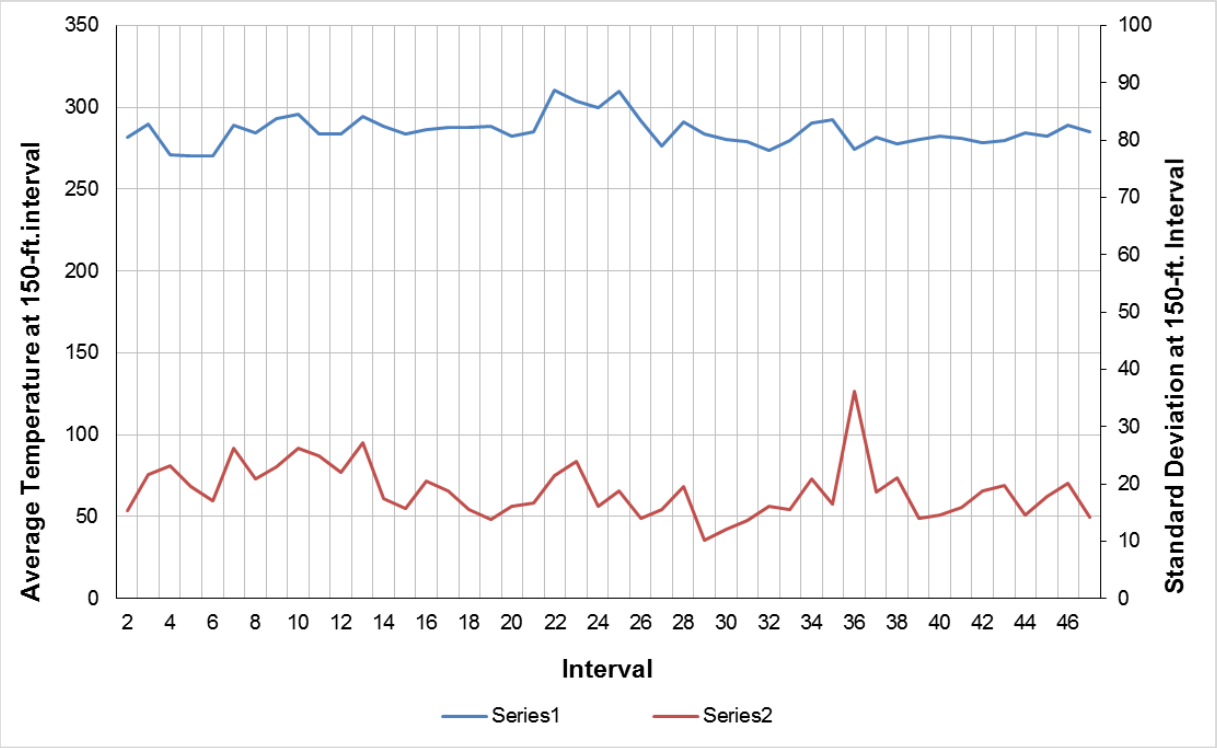
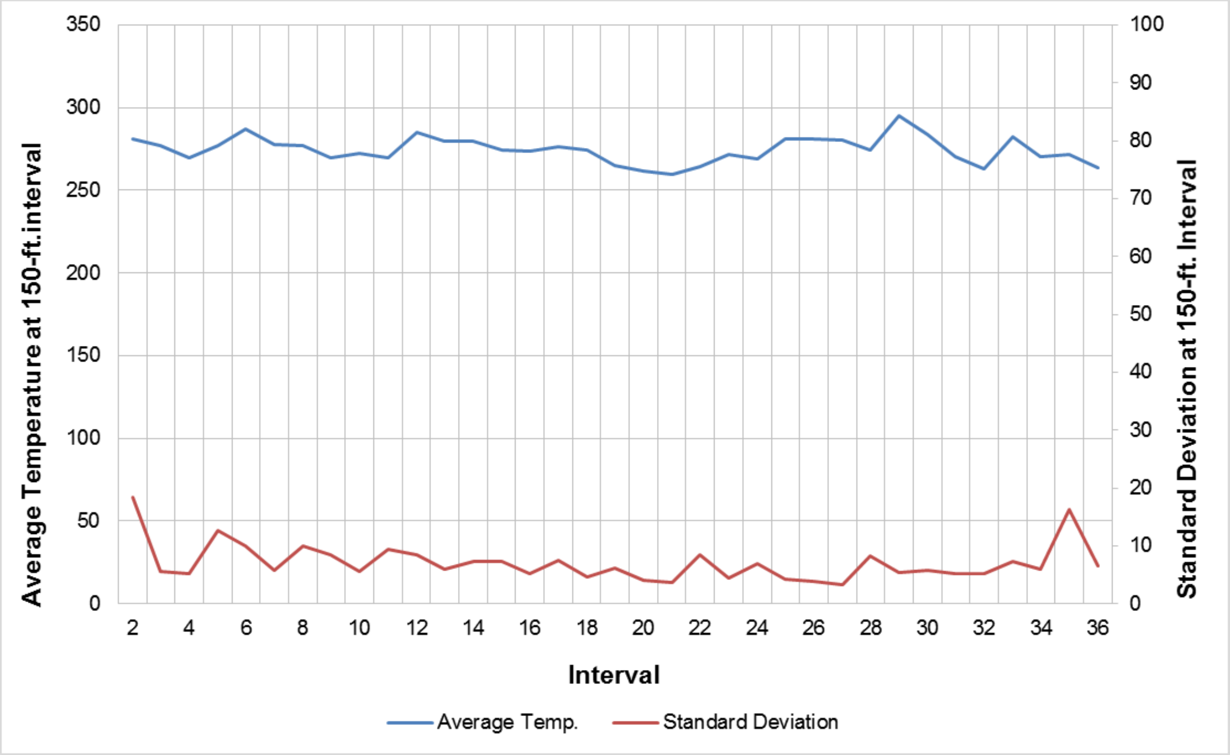
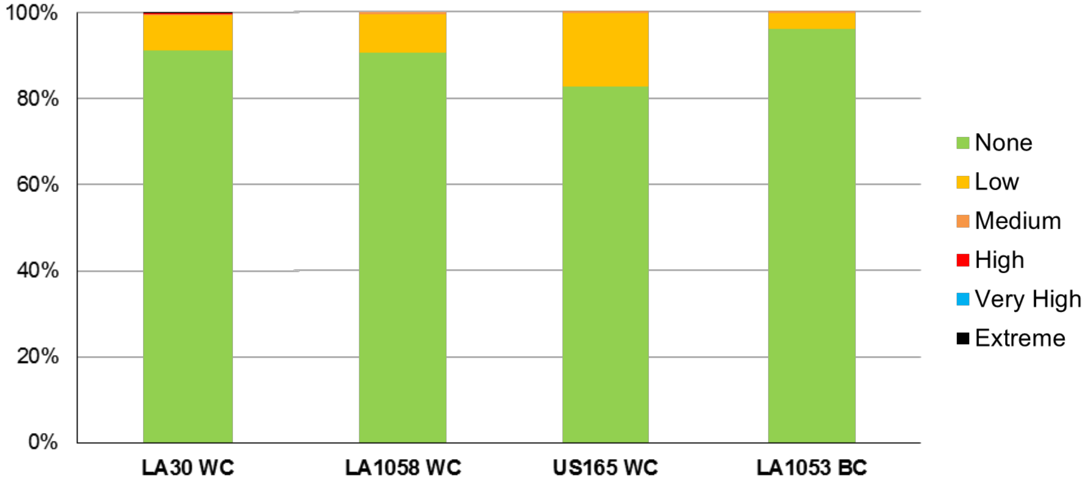


LA1 Shoulder

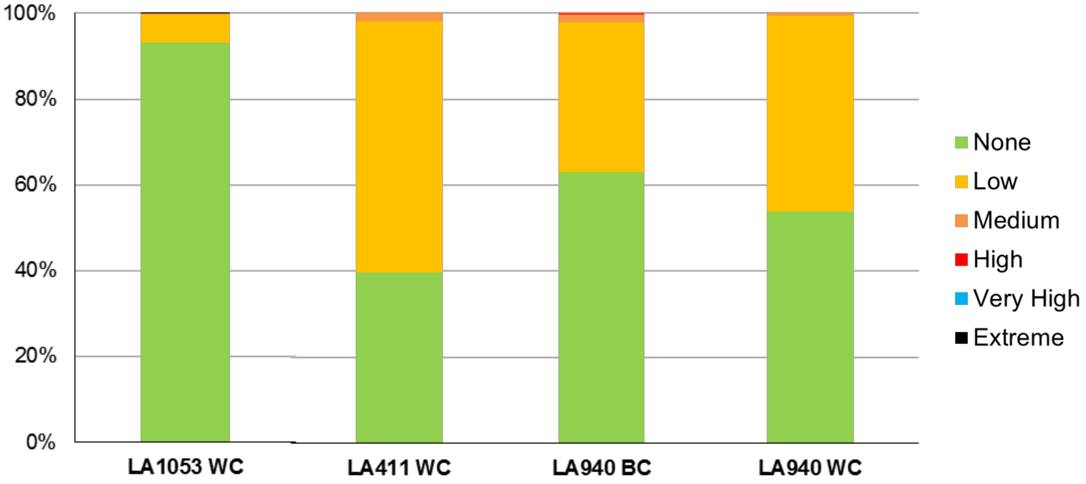


LA1 BC

%Severity Level Charts



Phase I Projects



Phase II Projects

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