Application of Infrared Thermographic Imaging to Bituminous Concrete Pavements – Final Report

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16. Abstract

The application of infrared thermographic imaging to the analysis of asphalt concrete pavement provides an alternative method and means of evaluating the material with respect to segregation, future distress and overall lifespan. Several variables examined throughout this study were incorporated with the use of the thermographic camera to provide further insight as to the material properties as well as the practical application of asphalt pavement to Connecticut roads and highways. These variables include comparisons of temperature differential vs. compacted material density, remixing vs. non-remixing material transfer vehicles, day vs. night time paving, haul distances vs. temperature differentials, Superpave vs. Marshall mixes, as well as evaluations and close examinations of material gradations, transfer methods, paving equipment, crews, plants, haul units, weather and base conditions among other variables as they all apply to the thermal consistency as well as the overall quality of the finished road or highway. An evaluation of each variable examined throughout this study is found in the corresponding section of this report. Conclusions and recommendations as to the outcomes of this study are found following the completed analysis.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	mililitres	mL
gal	gallons	3.785	Litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C+32	Fahrenheit temperature	°F

°F 32 98.6 212 °F
-40 0 40 80 120 180 200
-40 -20 0 20 40 60 80 100
°C 37 °C

* SI is the symbol for the International System of Measurement

Application of Infrared Thermographic Imaging to Bituminous Concrete Pavements

Background

Most of the pavement in Connecticut is constructed of hot mix asphalt (HMA). For successful placing and compaction of HMA, each step in the placement procedure must be accomplished within the proper temperature range. Thus, when the mix temperature varies in material placed, the compaction and the performance of the in-place pavement can also be expected to vary. Infrared thermometers have long been used to check surface temperatures, but small areas of low temperature can easily be missed. Infrared thermographic imaging is an alternative to thermometers and has the ability to give a continuous plot of surface temperatures. The infrared camera displays and records temperatures as colored images with a reference scale.

Several studies have shown that the problem of temperature differentials in HMA construction is recognized throughout the United States. Observations over the years indicate that the open textured areas, sometimes referred to as segregated areas, often perform poorly, frequently raveling and breaking up at a much younger age than areas with tighter surface texture. Areas with lower temperatures may also exhibit an open texture from the asphalt binder being stiffer. The increased stiffness of the binder may cause the material to behave differently as it comes out from under the paver screed thus producing a surface texture that is very different from the surrounding material.

The infrared thermographic camera makes effective monitoring of temperature variations more possible than it was for earlier studies. If the causes of localized temperature differences can be determined, and techniques to reduce this differential developed, pavement life should increase.

Study Objectives

The purpose of the investigation was to use infrared thermographic imaging to identify factors or conditions that contribute to thermal segregation in fresh paver-placed asphalt pavement, which affect compaction and lead to premature distress of the pavement. Data obtained from the project was evaluated for its thermal characteristics. Thermal segregation and gradation segregation are factors that lead to pavement distresses such as raveling, potholes, and shortened service life. These two types of segregation have similar appearances in the finished pavement but their causes may or may not be related.

Temperature data was obtained using an infrared thermographic imaging camera, and related computer software, at paving sites in the field. Field conditions desirable for obtaining data on cold spots included:

- Cold weather paving
- Night paving
- Cold weather paving at night
- Seasonal paving – to rate severity/impact of temperature difference during summer and winter weather
- Paving equipment

Study Benefits

The Connecticut Department of Transportation would benefit through improved pavement performance. Better understanding of the relationship between placement conditions and mix temperatures would result in the development of improved placement procedures. Quantifying temperature differences based upon environmental conditions would assist DOT and industry personnel in the decision-making process related to paving operations under less-than-optimal conditions. Reduction in thermal segregation in the HMA during the placement operation should reduce the number of irregularities and consequently, decrease the penalties assessed to contractors. The result would be improved durability and rideability of the finished pavement which will ultimately benefit the motoring public by providing a smooth, longer lasting pavement. The benefits would be a reduction in maintenance costs and associated impacts to motorists during repairs.

Literature Review

In recent years, a number of studies have been conducted that attempt to explain field observations of segregation in bituminous concrete pavements. Types of segregation have been referred to as “end-of-load”, “cyclic”, “load to load”, “systematic” or “spot” segregation. An attempt was made to identify, define, and measure the types of segregation through laboratory testing, field observations, and visual inspection. As part of a comprehensive NCHRP 9-11 study, Stroup-Gardiner and Brown (2000) defined segregation as:

> “…a lack of homogeneity in the HMA constituents of the in-place mat of such a magnitude that there is a reasonable expectation of accelerated pavement distress(es). Constituents are interpreted to mean asphalt cement, aggregates, additives, and air voids.”

The primary focus of their study was to formulate procedures for identifying and measuring segregation (both gradation and temperature segregation) using various techniques. Each technique was evaluated for its usefulness in detecting and assessing segregation and included a wide-range of nondestructive and destructive testing approaches. Infrared thermography was one of the approaches analyzed along with nuclear density tests, cores, portable seismic pavement analyzer, and ROSAN$_v$ surface texture measurement system. Pavement condition surveys from six states (including Connecticut) were presented with respect to gradation and temperature segregation and showed a decrease in life ranging from 5 to 12 years for pavements exhibiting segregation. Infrared thermography was reported as a viable method for doing the following:

- Surveying each lot for temperature differentials which indicated the level of segregation, and then allot consequent pay adjustments;
- Estimating the level and percentage of segregation in a specified area of pavement mat;
- Developing percent uniformity measurement for each lot potentially through use of an infrared sensor bar mounted behind paver screeds, and displayed on a monitor posted next to the paver operator.

The researchers reported that infrared thermography was not useful in identifying the type of segregation (gradation versus temperature). Additionally, staff at NCAT developed a spreadsheet analysis program that normalized data from thermal photographs and then created a histogram of temperatures that was used to compute the percentage level of segregation.

Another study was conducted in Michigan to classify levels of segregation on nineteen field sites, comparing one-minute nuclear density measurements and gradation tests on cores. The study did not attempt to identify the causes of segregation, but observed statistical patterns between gradation values and nuclear-measured density values for "segregated" and "non-segregated" portions of the mat. A sampling technique along with statistical methods was developed; however, the infrared thermographic camera was not used in the study.

Researchers in the state of Washington examined four WashDOT paving projects in 1998 for evidence of end-of-load segregation. Mostly dense-graded asphalt concrete mixes were monitored using the thermal infrared camera to identify the existence and extent of mat temperature differentials and related material properties. The sampling and testing of hot-mix during placement and compaction was the focus for the study, in terms of evaluating segregation. Early and late season projects, along with night projects, were evaluated for temperature differentials in the mat. Equipment and construction practices were documented and in at least one project, a Material Transfer Vehicle (MTV) was used during paving operations. Samples were taken from the mat behind the paver screed and from the truck bed. Devices such as the nuclear gauge, non-nuclear gauge (PQI), and digital probe thermometer were used in addition to the thermal infrared camera and the extraction of cores. Density and percent air voids were determined and analyses using the Rice density test, gradation, and asphalt content were performed. Gradation and asphalt content analysis showed no significant aggregate segregation or difference in asphalt content within the cooler areas, although higher air voids were found in these areas. Temperature differentials for the four projects examined ranged between 7° and 39° C. It was reported that concentrated areas of significantly cooler material resulted in reduced compaction of these areas in the mat. The researchers also suggested that shorter haul times, insulated truck beds, warmer weather paving, improved rolling practices, and more frequent remixing of the HMA would help to greatly reduce or eliminate the occurrence of temperature differential damage.

John Henault (ConnDOT Research Division) completed a study on temperature differential damage for HMA projects in the fall of 1999. Thermal images were taken immediately after paver laydown and pairs of neighboring high and low temperature spots were selected. Nuclear measurements of the density after compaction were made on each spot. Comparisons of computed air voids for each pair (high and low temperature at time of compaction) revealed differences ranging up to 8%. For a limited number of pairs, cores were also taken and differences in actual air voids determined. Since the viscosity of asphalt binder is directly related to temperature, differences in the degree of compaction can be expected when the temperature varies. It was also reported that open-textured areas were frequently cooler at the time of rolling. Several other studies were found by Henault indicating that end-of-load segregation is recognized as an industry-wide problem. He confirmed that use of an infrared thermographic imager enabled more effective monitoring of localized temperature variations.

A similar study conducted by Washington State Department of Transportation was completed in Summer 2001. The study examined thermal segregation from many different angles. One factor identified by the report was the type of haul unit used to deliver the HMA to the job site. Of the different methods used to deliver HMA to the job-site, end dump haul units exhibited the greatest level of thermal segregation. In Connecticut, end dumps are the primary method used to convey HMA to the paving project. Additionally, the report proposed the concept of employing a density specification based upon the densities obtained in the mat where truck changes occurred. The rational behind density testing at the truck changes was that these areas are the most prone to fail and even though they represent a small percentage of the surface area, failure of these areas generally will require the entire pavement to be replaced. The Washington State Department of Transportation report also showed that there was some correlation between warmer ambient temperatures and the temperature differentials that were observed. Higher ambient temperatures reduced the temperature differentials observed.

Construction Data

For the CAP Lab study, construction data including thermal images was collected from 40 paving projects ongoing in Connecticut. The placement of the wearing surface was monitored. Leveling courses were not monitored due to the wide variability in the placement thickness. The monitored projects included Connecticut DOT Class 1 (nominal maximum aggregate size of 3/4 inch) and 12.5 mm Superpave mixes at traffic levels of 2, 3 and 4. Pavement for one site was placed in November 2000 and the remaining projects were in the 2001, 2002 and early 2003 construction seasons. The

HMA was produced at several different plants and limited sampling from truck beds was conducted at the plant for one project. There were 4 projects that were monitored exclusively for effect heated bodies had on the material at the time of final placement. On 11 projects, material transfer vehicles (MTV) were used for placement of at least a portion of the HMA. On 8 of the projects, the MTV used was a Roadtec 2500. This is significant because of the large amount of material the MTV stores within it and the remixing of the material being delivered prior to discharging it to the paver. The MTVs used on the other 3 projects did not provide direct remixing of the material. The paver hopper inserts were equipped with remixing paddles but the paddles were not operated during the periods of observation. There was some indirect remixing of the HMA during the discharge into the MTV and the dumping of the material into the hopper of the paver.

The procedure routinely consisted of gathering data and observations using the following:

- Visual observation,
- Infrared thermographic imaging camera and related computer software,
- Digital photographic imaging,
- Recording of image-specific site information (cold spot shape, etc.),
- Recording of exact location coordinates using GPS hand-held device for future monitoring,
- Entry of construction data into comprehensive Filemaker database.

Other tasks were performed occasionally in order to determine the impact of additional factors on the data presented. Examples of these tasks are as follows:

- Nuclear density testing of compacted material,
- Material samples taken immediately behind paver by DOT officials,
- Recording of time between truck load changes,
- Truck configurations
- Screed and spill locations

The ThermaCAM PM575 was used to capture thermal images of HMA mix while being discharged from the truck bed into the paver’s hopper and while being placed prior to compaction. Cool spots, or temperature differentials, in the uncompacted mat were marked for density tests to be made after compaction (when possible) for each monitored site. GPS coordinates were also recorded for referencing most of the cool spot locations. Thermal images were initially recorded during rolling operations from atop one of the rollers but safety concerns ended the use this vantage point. From then on, images were taken from the screed stop location. The screed stop location is taken as the point where the screed stops in between truck changes. Images were then processed and analyzed using the ThermaCAM Researcher 2000 software on a laboratory computer.

Variables Examined

A list of major variables considered by the CAP Lab personnel as influential to the generation of cold spots in freshly-placed asphalt concrete pavements are outlined below.

- **General temperature placement issues** – including cold weather and night paving, and cold weather paving at night, differences in base and air temperature.
- **Inclement weather conditions** – effect of precipitation, placement of asphalt on wet surfaces, and rapid cooling of pavement material during truck loading into paver and/or prior to rolling or between roller passes. No observations were made under these conditions due to the unpredictability of the weather combined with the uncertainty of whether or not paving will occur.
- **Equipment Issues** – e.g., frequency of folding hopper wings, auger movement and depth of material in augers, paver shadow, use of material transfer device (MTV), removal of spilled loose material.
- **Thickness Variation** – including thickness of lift (1.5” versus 2.0”) and leveling prior to overlays.
- **Truck Changes** – e.g., length of time between trucks, amount of material retained on pavement after truck pull out, amount of material in hopper, and loading delay incurred when paving under overpasses.
- **Haul Distance/Haul Time –** distance from HMA plant to the project and travel time of haul from HMA plant to the project.
- **Segregation** – due to temperature or gradation.
- **Paving Material Characteristics** – such as virgin binder versus presence of RAP.

Many other lesser variables also enter into the generation of the cold spots. These variables are much harder to track and even harder to quantify. Examples of these lesser variables would be the head of material on the screed augers, continuous rotation of the screed auger, rate at which material is loaded into the paver hopper, the amount of material over the hopper conveyors and flowgates, how tightly or loosely the material was tarped in haul unit, the screed angle, moisture in the aggregates, paver speed and having to perform multiple drops into the paver hopper when going uphill. There are many more lesser variables that will affect the temperature differentials observed in a paving project.

Methodology

Every attempt was made to collect data as similarly as possible between projects. All images unless otherwise noted were taken at the location where the screed stopped at truck changes for end dump transfer of material from the haul unit to the paver hopper. For MTVs, this location was approximated as it was not readily apparent where the material changed from truckload to truckload. Also, using the thermal camera, the mat was observed throughout the entire discharge of material. Any anomalies were noted and imaged. The temperature differentials noted throughout the report include only the data gathered off of the thermal images taken at the truck changes unless otherwise noted. Haul distances and haul times represent one-way travel from the HMA plant to the project.

During the 2002-2003 construction season, attempts were made to take thermal images of all truck exchanges made while CAP Lab personnel were present at the project. This was done to reduce bias caused by selectively imaging only colder loads. Some of the previously collected images were selectively taken only at cold spots therefore the data was not necessarily representative of the material being placed. The location of each thermal image weas determined, whenever possible, using a handheld Trimble GeoExplorer 3 GPS unit. On selected projects, nuclear densities were also determined on a longitudinal profile through cold spots. Obtaining nuclear densities was a large challenge. Safety was a primary concern as traffic control on some projects was not adequate to accommodate testing. It was therefore not always possible to collect as many readings as desired. Also, the collection of data required 15-20 minutes after finish rolling. Having sufficient time at the completion of rolling was not always possible because traffic had to be shifted onto the new HMA mat. Any differences observed were noted for later analysis.

After collecting the thermal images, they were processed through ThermaCAM Researcher 2000 – March edition software that was provided with the thermal camera. Using this software, all of the temperature scales on all of the images were adjusted to between 190°F and 300°F, therefore the temperatures represented by each color were similar from image to image. On several occasions the high end scale for the images had to be increased above 300°F to accommodate the observed temperatures. These images can be found in the Filemaker database described in the following section. Also, the software allowed for the warmest and coolest surface temperatures on the mat to be determined. The difference between the warmest and coolest spot on an individual thermal image will be referred to as the temperature differential. These observed temperatures were chosen to be relatively close to each other to avoid problems associated with temperature differences created by normal cooling. The coolest spots were marked on the mat and density readings were recorded at 3 foot intervals along a straight longitudinal line to obtain information pertaining to a possible drop in density due to the corresponding cold spot. The zero distance on the density plots represent the cold spot with the negative distances representing material placed before the cold spot and positive distances after the cold spot.

Database

A database was developed to handle the large amount of data. The original database was developed using Microsoft Access. As the project continued, modifications were required to be performed to the database. Implementing these changes to the Access database was presenting many problems due to the limited experience manipulating Access databases. Therefore it was decided to convert the database to Filemaker. The CAP Lab has a good deal of experience using Filemaker which allowed for more efficient modifications and data analysis. Without the use of a database, it would have been nearly impossible to conduct this study as there are approximately 1,250 images with all of their corresponding information.

The database was designed to store all of the pertinent information gathered in the field as well as to perform necessary computations. This pertinent information included GPS coordinates, density information and a copy of the thermal image for display on every screen for the appropriate record. This allowed for a better analysis of the images as all of the information was available with the image. The database also allowed for images to be excluded from the mat temperature computations if they were deemed to be irrelevant. Examples of images excluded from the computations would be paver hoppers, haul units, duplicate images etc.

Monitored Sites

Table 1 contains a listing of the paving projects monitored for this project. A detailed narrative for each of the sites monitored during this study can be found in Appendix A.

Table 1 - Monitored Sites

Route	Date	Town	Project	Weather[1]	Ambient Temp.°F	Base Temp.	HMA Type	Compacted Thickness, in.	Plant Location	Haul Time 1 way (min)	Haul Distance 1-way (miles)	MTV	Avg. Temp. Differential,°F	Avg. Density Differential (pcf)
I-395	11/8/00	Lisbon	72-76	***	***	***	Class 1	1.5	Montville			No	48.8	4.40
I-395	11/9/00	Lisbon	72-76	***	***	***	Class 1	1.5	Montville			No	55.7	6.85
I-395	11/13/00	Lisbon	72-76	***	***	***	Class 1	1.5	Montville			No	46.3	7.18
I-395	11/15/00	Lisbon	72-76	sunny windy	35-45	52	Class 1	1.5	Montville			Roadtec	17.32	6.20
I-395	11/16/00	Lisbon	72-76	sprinkles	30-40	45-50	Class 1	1.5	Montville			Roadtec	20.92	***
I-395	11/18/00	Lisbon	72-76	sunny	35-40	***	Class 1	1.5	Montville			No	45	4.14.
I-395	11/20/00	Lisbon	72-76	***	40	36	Class 1	1.5	Montville			No	49.4	3.00
I-395	11/21/00	Lisbon	72-76	sunny	35	45	Class 1	2.0	Montville			No	51.9	***
178	5/1/01	Bloomfield	171-293C	sunny	85-90	124	Class 1	2.0	Granby	15	10	No	51.4	***
178	5/2/01	Bloomfield	171-293C	sunny	85-90	***	Class 1	2.0	Granby	15	10	No	46.9	***
2	6/14/01	Norwich	172-327A	cloudy	75	***	SP 12.5	2.0	Montville	10-May	5	Roadtec	14.9	***
66	6/19/01	Windham	172-327G	sunny	80-85	120	Class 1	1.5	Manchester	30	18	No	54.9	***
2	6/29/01	Stonington	137-137	partly sunny	70	100	SP 12.5	2.0	Groton	15	10	Roadtec	14.38	***
8	7/5/01	Torrington	174-295A	cloudy night	70	85	SP 12.5	2.0	Torrington	10	3	Blaw-Knox	25.5	***
195	7/10/01	Mansfield	172-327K	sunny	85	110	Class 1	1.5	Palmer Mass.	45	25	Blaw-Knox	26.9	3.93
195	7/11/01	Mansfield	172-327K	sunny	85	120	Class 1	1.5	Palmer Mass.	45	25	No	58	6.83
I-91	7/12/01	Enfield	46-118	cloudy night	***	75	SP 12.5	2.0	Westfield Mass.	20	16	No	56.1	6.78
140	8/7/01	Ellington	171-293J	sunny	85-100	90-110	SP 12.5	1.5	Granby	35	22	No	66.4	5.57
140	8/9/01	Ellington	171-293J	sunny	85-100	90-110	SP 12.5	1.5	Granby	35	22	No	61.4	8.85
189	8/21/01	Bloomfield	171-293K	sunny	85	108	Class1	1.5	Granby	10	5	No	59.6	***
44	8/27/01	Norfolk	174-295J	cloudy	75-80	***	Class 1	***	Westfield Mass.	85	43	No	62.5	7.47
44	8/28/01	Norfolk	174-295J	sunny	75-85	78	Class 1	***	Westfield Mass.	85	43	No	51	6.19
1A	6/12/02	Stonington	172-338C	cloudy	75	***	Class 1	1.5	Montville	30	23	No	75	***
Tolland TPK.	6/13/02	Manchester	76-190	cloudy	65	***	Class1	2.0	Newington	12	20	No	47.4	5.9
607	6/14/01	Killingly	172-337N	cloudy	65	***	Class1	1.5	Wauregan	12	5	No	47.7	6.45
16	6/19/01	Colchester	172-337C	sunny	68	91	Class1	2.0	Franklin	25	16	No	42	1.8
16	6/21/01	Colchester	172-337C	sunny	80	***	Class1	2.0	Franklin	25	16	No	52.5	5.9
101	6/26/02	Killingly	172-337H	sunny	80-90	95-100	Class1	2	Wauregan	20	15	No	54.5	***
89	6/27/02	Lebanon	172-337F	sunny	80-90	110	Class 1	2	Franklin	15	10	No	33.8	4.23
7	7/2/02	Falls Village	174-305H	sunny	95	100	SP 12.5	2	Westfield Mass.	100	56	Blaw-Knox	37.1	4.63
7	7/8/02	Falls Village	174-305H	sunny	93	110	SP 12.5	2	Westfield Mass.	100	56	Blaw-Knox	31.4	3.7
6	7/10/02	Farmington	171-303H	sunny	80	100	Class 1	1.5	New Britain	15	7	No	38.2	***
196	7/15/02	East Hampton	172-337K	sunny	78-90	100	Class 1	2	Killingly	60	56	No	53.6	3.9
196	7/16/02	East Hampton	172-337K	sunny	72	75-80	Class 1	2	Killingly	60	56	No	53.7	6.4
I-91	7/17/02	Wallingford	173-348	sunny	80-90	100	SP 12.5	2	Wallingford	10	5	Roadtec	9.1	1.75
31	7/19/02	Coventry	171-302I	sunny	85	100-125	Class 1	2	Manchester	25	14	No	54.8	***
31	7/22/02	Coventry	171-302I	sunny	76	100-125	Class 1	2	Manchester	25	14	No	52.9	4.9
31	7/31/02	Coventry	171-302I	sunny	90	100-125	Class 1	2	Manchester	25	14	No	59.5	5.1
195	7/25/02	Storrs	172-337J	sunny	70-75	155**	Class 1	2	Killingly	35	21	No	65.6	8.88
195	7/26/02	Storrs	172-337J	sunny	70-75	85	Class 1	2	Killingly	35	21	No	70	***
6	8/2/02	Manchester	171-302H	sunny	90	110	SP 12.5	2	Newington	20	15	No	36.9	8.75
6	8/5/02	Manchester	171-302H	cloudy	78	90	SP 12.5	2	Newington	20	15	No	45.9	6.77
I-91	8/8/02	Windsor	164-224	clear night	73	80	SP 12.5	1.5	East Granby	15	9	Roadtec	11.9	***
74	8/28/02	Vernon	171-302J	cloudy	70-75	75	Class 1	2	East Granby	40	28	No	50.26	***
94	9/3/02	Glastonbury	171-303C	day	80	***	SP 12.5	2	Newington	20	16	No	66.5	***
94	9/4/02	Glastonbury	171-303C	sprinkling	85	***	SP 12.5	2	Newington	20	16	No	51	12
94	9/5/02	Glastonbury	171-303C	day	75	***	SP 12.5	2	Newington	20	16	No	61.7	13.7
94	9/10/02	Glastonbury	171-303C	day	90	110	SP 12.5	2	Newington	20	16	Roadtec	16	***
94	9/17/02	Glastonbury	171-303C	drizzling	65	75	SP 12.5	2	Newington	20	16	Roadtec	20.4	5.35
5&15	9/12/02	Newington	171-303F	night windy	55	***	SP 12.5	2	New Britain	20	12	Roadtec	14	***
I-95	10/3/02	New London	94-202	night	57	67	SP 12.5	2	Groton	10	5	Roadtec	10.5	***

Table 1 - Monitored Sites – Continued

Route	Date	Town	Project	Weather[1]	Ambient Temp.°F	Base Temp.	HMA Type	Compacted Thickness, in.	Plant Location	Haul Time 1 way (min)	Haul Distance 1-way (miles)	MTV	Avg. Temp. Differential,°F	Avg. Density Differential (pcf)
4	10/15/02	Farmington	51-249	sunny	42	45	Class 1	1.5	Farmington	10	5	No	46.3	***
4	10/22/02	Farmington	51-249	sunny	40	45	Class 1	1.5	Farmington	10	5	No	47.9	***
10	10/15/02	Southington	131-162	drizzle night	48	49	Class 1	2	New Britain	20	10	No	52.9	***
22	10/28/02	North Haven	173-348H	cloudy	53	70	Class 1	1.5	North Branford	18	10	No	37.4	***
22	10/29/02	North Haven	173-348H	day	45	50	Class 1	1.5	North Branford	18	10	No	43.6	***
8	11/1/02	Winchester	162-131	cloudy	40-45	50	SP 37.5	4	Torrington	20	11	No	***	***
10	11/2/02	Farmington	174-305E	sunny	28	29	Class 1	1.5	Farmington	8	4	No	49.7	8
10	11/2/02	Farmington	174-305E	sunny	28	29	Class 1	1.5	New Britain	15	10	No	42.1	3
Farmington Ave.	11/5/02	West Hartford	155-149	day	45	45	Class 1	2	New Britain	20	10	No	53.3	7.5
320*	6/6/03	Willington	171-306C	sunny	65	80	Class 1	2	Killingly	45	***	No	N/A	N/A
176*	6/9/03	Newington	171-307H	sunny	65-70	82	Class 1	2	Newington	8	5	No	N/A	N/A
186*	6/11/03	Somers	129-107	sprinkling	75	87	Class 1	1.5	Springfield	20	15	No	N/A	N/A
201*	6/16/03	Griswold	57-106	day	60	80	Class 1	2	Killingly	25	***	No	N/A	N/A
201*	6/17/03	Griswold	57-106	day	65	85	Class 1	2	Killingly	25	***	No	N/A	N/A

(1) Night paving denoted with night in weather description
* - Site was monitored exclusively for the study of heated truck bodies
** - Base temperature reflects that of a recently placed leveling course
*** - Data was not collected

It should be noted that of these 40 monitored sites, there were several sites that were paved by the same crew. Table 2 shows 8 crews that were observed on at least two different projects as well as the monitored site numbers where they were present.

Observed Crew	1	2	3	4	5	6	7	8
Monitored Sites	13, 14, 20, 23	15, 17, 28	16, 27, 29	19, 21, 30, 35(north)	25, 35(south)	24, 33	9, 10, 26	8,11,18

Table 2 – Crews observed on multiple sites

Nuclear Density Testing

Whenever possible, Nuclear Density Testing was performed through cold spots. The quantity of tests performed were limited by the amount of time available after rolling was completed before traffic was to be placed on the new mat as well as problems associated with the vehicle used to transport the nuclear density gauge. The nuclear density gauge used for the study was the Troxler 3450 for the vast majority of the sites. The thin lift mode was used throughout the project with no bias.

A single test for a cold spot location consisted of performing a series of readings through the cold spot in a longitudinal direction. Typically, readings were taken at three foot intervals beginning fifteen feet before the cold spot and ending fifteen feet after the cold spot. The density value used for each longitudinal point was the average of two readings. These two readings were taken by placing the nuclear density gauge parallel with the direction of paving and then rotating the gauge 180 degrees and obtaining a second value.

The density computations used throughout this study examined the relative differences between the highest density obtained at each series of cold spot tests with the lowest density value obtained within 6 feet of the cold spot. Occasionally, the lowest density was not obtained at the exact cold spot as it was marked. On several occasions the lowest density was obtained 3-6 feet from that spot. The relative densities were used to eliminate potential problems associated with applying a bias for the gauge as well as on several occasions density series were performed before finish rolling had occurred. Density series performed before finish rolling were deemed to be acceptable provided no additional rolling of the test area occurred while testing was ongoing. Density testing was sometimes performed before finish rolling had occurred. This was generally during the hottest days as it took a long while for the pavement to cool sufficiently for finish rolling. For this study, taking density measurements before finish rolling occurred was assumed to have little impact on the data as the focus was placed on the relative difference in the density. Table 3 contains information regarding density differentials broken down by month.

Table 3
Breakdown of Relative Density Differences

Month		Relative Density Difference End Dump, pcf	Relative Density Difference with MTV, pcf
May*		N/A	N/A
June		4.97	N/A
July		6.38	3.58
August		7.07	N/A
September*		12.6*	5.35
October		4.95	N/A
November		5.36	6.2*

* One Project

The relative density differences for MTV must be viewed cautiously as the amount of data for September and November is very small. In this study, the total quantity of data for the MTVs is quite small as they significantly and consistently reduced the temperature differentials. It was therefore determined that the main focus of the study should exclude projects using a MTV.

Figure 1 shows a plot of relative density vs. temperature differential. While there is a slight trend indicating that as the temperature differential increases, the relative density difference increases, this trend is not very strong.

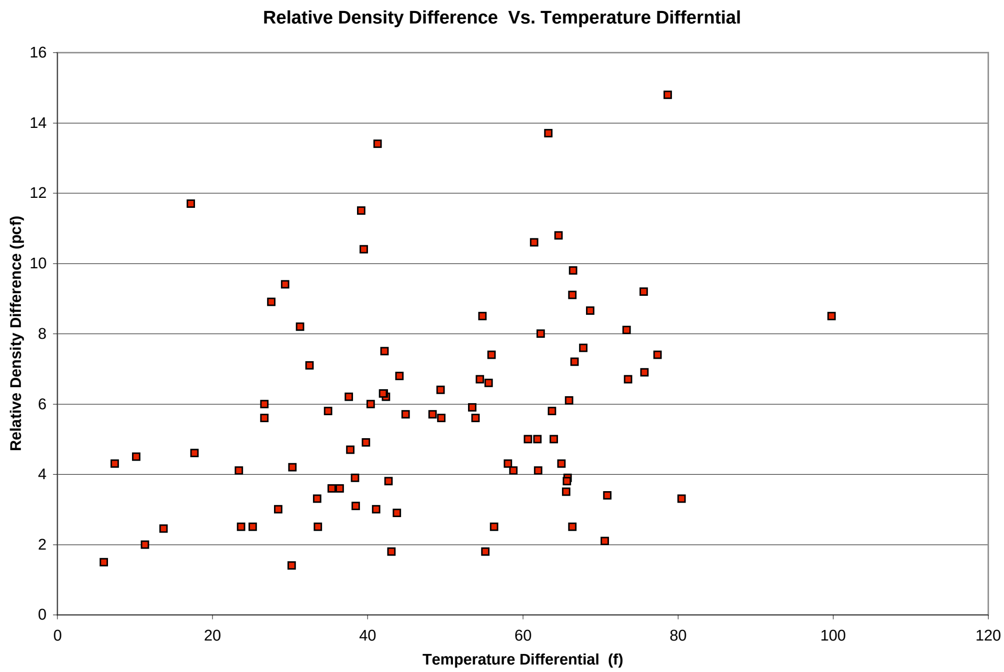


Figure 1 - Relative Density vs. Temperature Differential

Tracking Material through the Paver

The origin of the cooler material exiting the paver screed is unknown. The idea was to track material passing through the paver by placing small metallic pieces into the paver hopper and then locate the point in the mat where it was deposited using a metal detector. If, after repeatedly placing the pieces in the same location of the hopper, the pieces consistently were located in cool spots, it could be assumed that was the location of origin for the cool material. Knowing the origin of the cooler material would then help in the formulation of methods to reduce the problem.

To ensure the pieces could be located with a metal detector, small metallic pieces, approximately the size of the nominal maximum aggregate size, were placed in front of the paver and their positions marked. Attempts were then made to find these pieces after the pavement was compacted. Unfortunately, the success rate of locating the pieces from a known position was less than 25%. This poor rate of relocating the pieces lead to the conclusion that it would be nearly impossible to locate an object that could be almost anywhere in the mat from that truckload of material, assuming it came out of the hopper in the first place.

Paver Hopper Wings

The frequency of folding of the paver hopper wings was very dependent upon the paver operator. Some paver operators tended to fold their wings after every load or two while others tended to fold their wings very infrequently. The temperature differentials observed without folding the paver hopper wings was 48.5°F while the temperature differential for when the paver hopper wings were folded was 51.2°F. The difference between these numbers is skewed by data from infrequent paver hopper wing folding. The magnitude of the temperature differentials observed for the infrequent hopper wing folding was much greater than for the frequent hopper wing folding. Figures 2 and 3 show the effects of a hopper wing fold after placing four loads and then a hopper wing fold after the next successive load was placed.

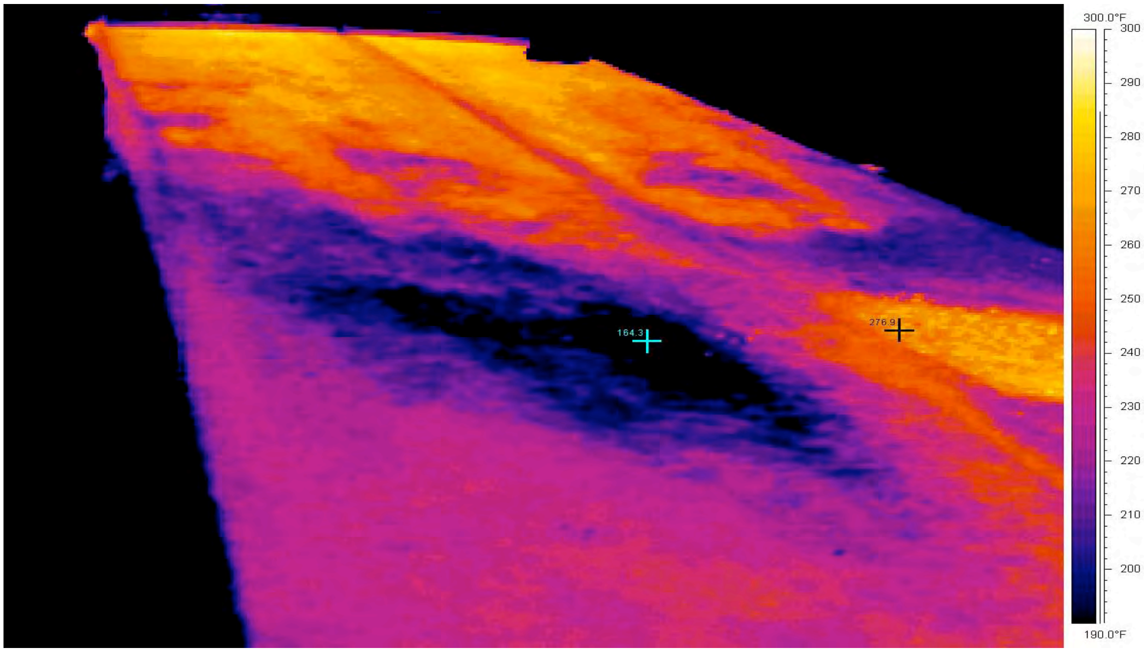


Figure 2 Thermal Image after 4 loads between hopper wing folds.

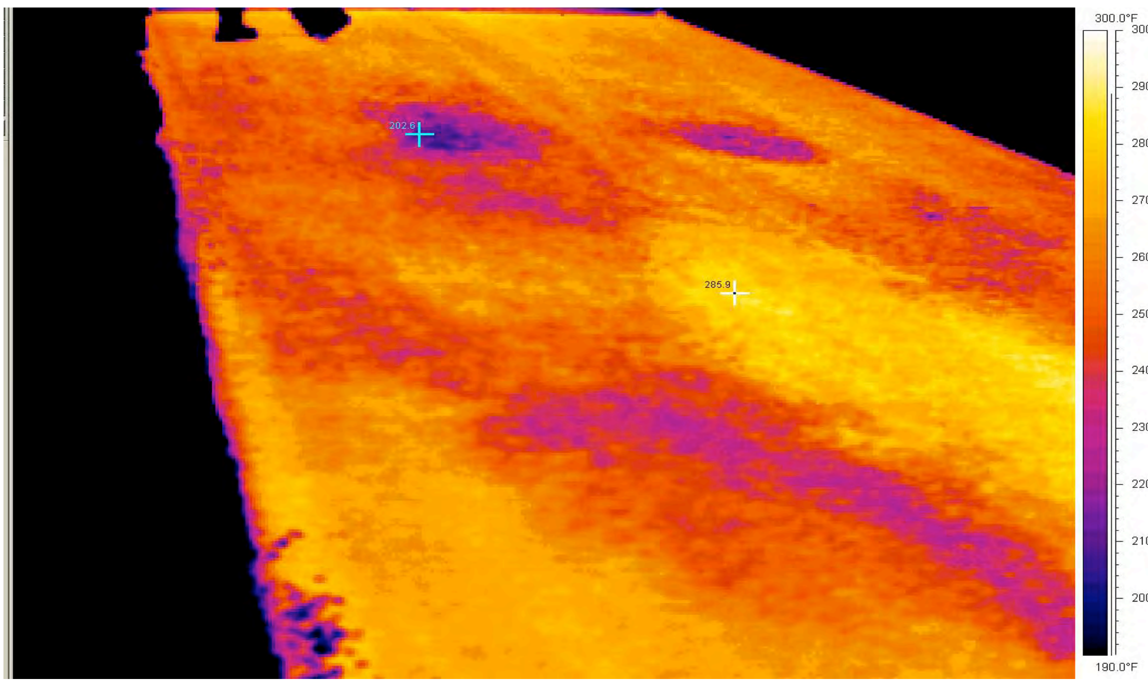


Figure 3 Thermal Image after hopper wing fold, 1 load after Image in Figure 2 was taken.

<u>Gradation Analysis</u>

HMA samples were collected from behind the paver for two projects to evaluate the level of gradation segregation that was occurring. On one project production day, five samples were taken for gradation analysis. Two samples were taken from cold spots and three from normal temperature locations. Table 4 contains the results of these gradation analyses. The average of the 3 gradations taken from normal temperature locations was considered to be the target gradation for the day's production. There was very little variation in gradation between the three normal temperature samples. Figure 4 is the thermographic image of the location where Cold Spot Sample number 1 from Table 4 is obtained. In the image, the sample location is denoted by the shovel. The maximum temperature differential observed in Figure 4 is 54.6°F. Figure 5 is the thermographic image of the location where Cold Spot Sample number 2 from Table 4 is obtained. The maximum temperature differential observed in Figure 5 is 60.3°F.

Table 4, Observed Gradation of Cooler and Warmer Areas.

Sieve Size, mm	Average Gradation of 3 Normal Temps. % Passing	Cold Spot number 1 % Passing	Cold Spot number 2 % Passing	ConnDOT Tolerances (+/-)
19.0	100	100	100	6
12.5	96.9	94.7	96.5	6
9.5	74.4	69.2	66.9**	6
4.75	54.7	49.6	45.3**	6
2.36	46.3	41.9	38.1**	6
1.18	38.8	35.0	31.6**	4
0.60	28.2	25.4	23.5**	4
0.30	14.6	13.4	13.2	3
0.075	3.2	2.8	3.6	2
% AC *	5.68	5.25**	5.99	0.4%

* Determined using the ignition oven, no correction factor applied.
** Outside ConnDOT Tolerances

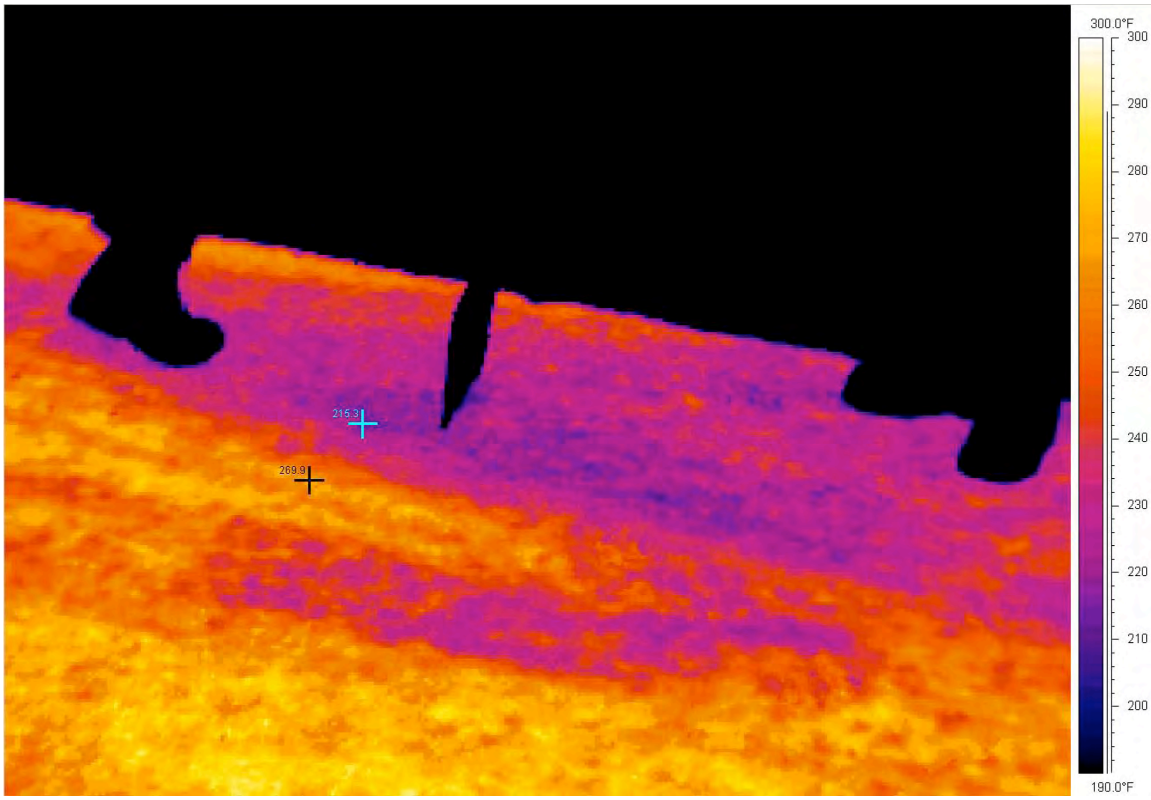


Figure 4 - Location where Cold Spot sample number 1 from Table 4 was obtained

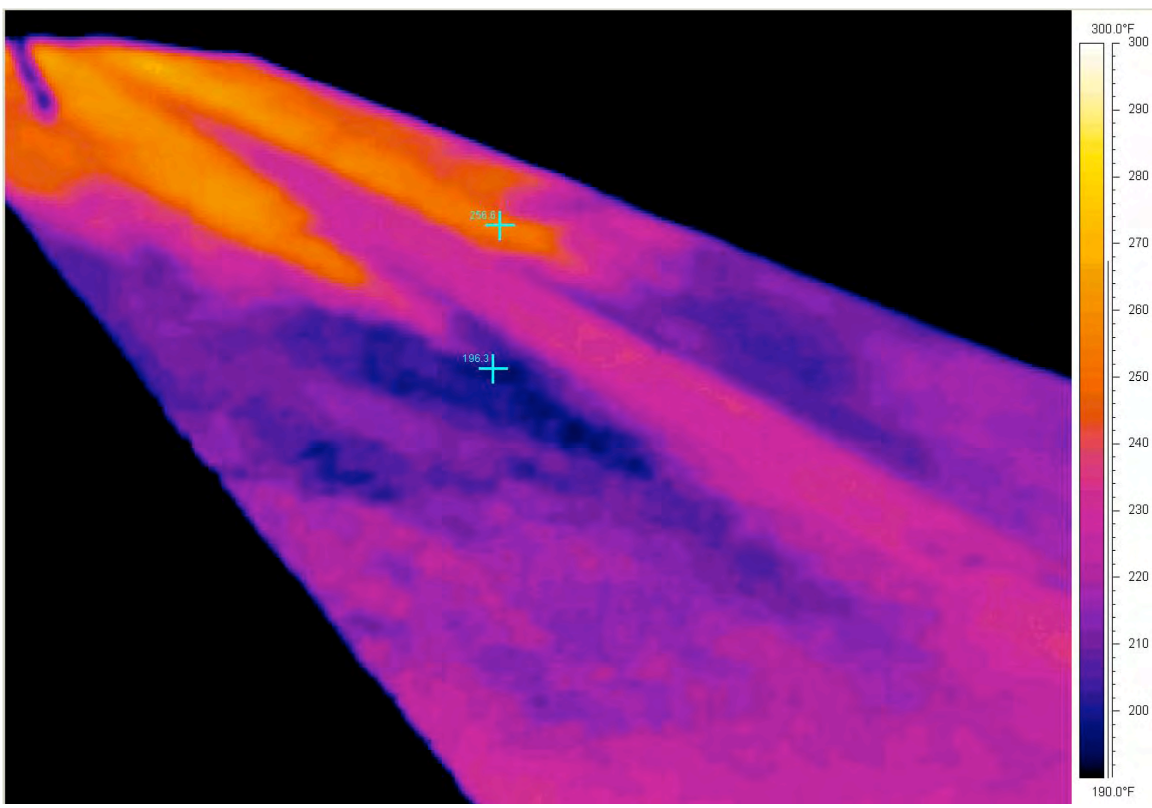


Figure 5 - Location where Cold Spot Sample number 2 from Table 4 was obtained

Cold Spot sample number 2 would be outside of the Connecticut Department of Transportation gradation tolerances for Job Mix Formula (JMF). Cold Spot Sample number 1 would be outside of the acceptable limits for asphalt content.

Samples from cold spots were also collected from a different project for comparison with the JMF. Table 5 contains the results of the gradation analyses. Both samples' gradations were outside of ConnDOT requirements on several sieves, indicating some level of aggregate segregation.

Table 5, Observed Gradation of Cooler and Warmer Areas.

Sieve Size, mm	JMF	Cold Spot number 1	Cold Spot number 2	ConnDOT Tolerances (+/-)
19.0	100	100	100	6
12.5	93	93.5	93.8	6
9.5	72	63.1*	63.0*	6
4.75	44	34.4*	33.0*	6
2.36	33	25.7*	24.1*	6
1.18	24	20.5	19.6*	4
0.60	18	16.6	16.1	4
0.30	10	11.3	11.0	3
0.15	5	5.8	5.8	3
0.075	3.6	2.8	2.8	2

* Outside of ConnDOT Tolerances

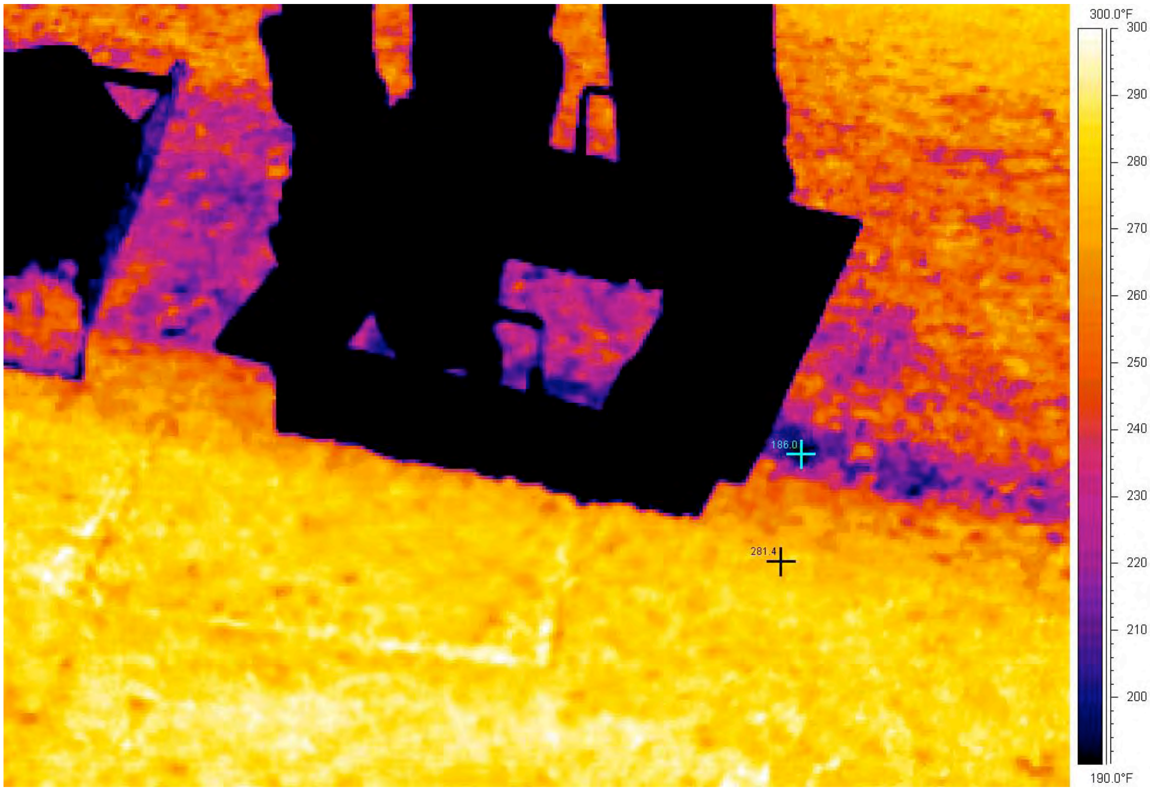


Figure 6 - Location where Cold Spot Sample number 1 from Table 5 Obtained

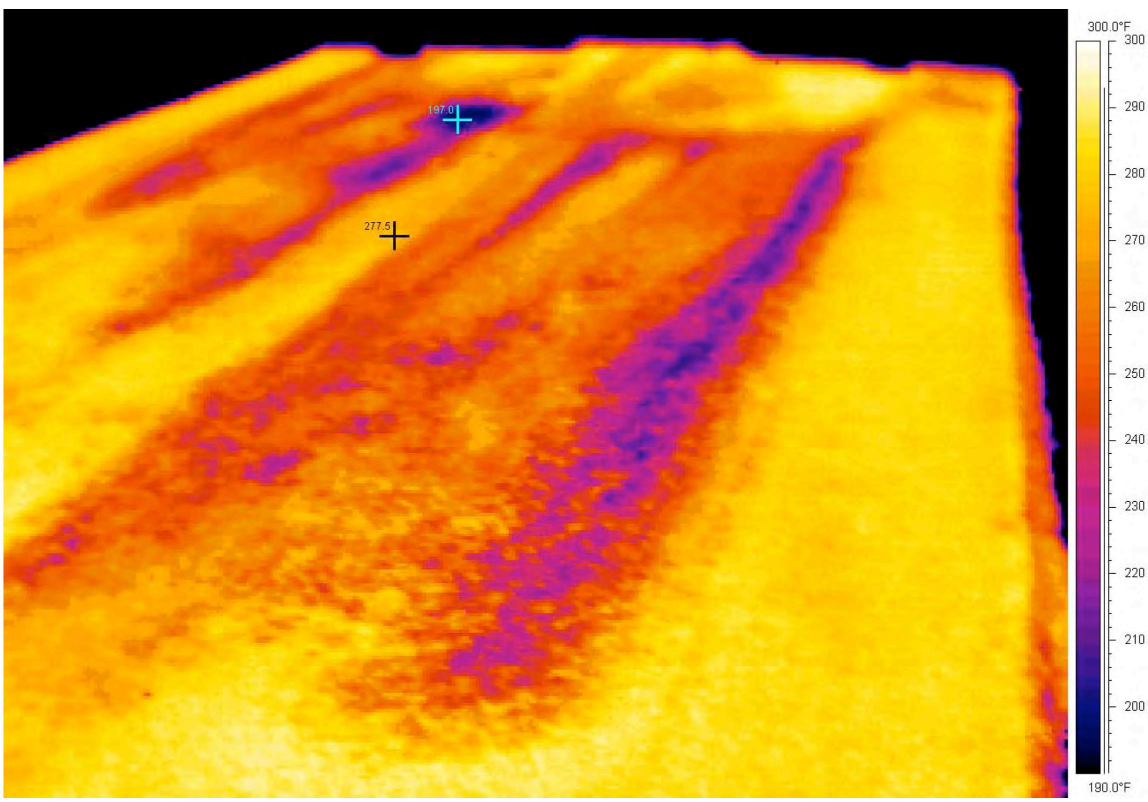


Figure 7 - Location where Cold Spot Sample number 2 from Table 5 Obtained

Figure 6 shows the thermal image of the location where Cold Spot Sample number1 was being obtained. The maximum temperature differential for that location was 95.4°F. Figure 7 shows the thermal image for the location where Cold Spot Sample number 2 was taken. The maximum temperature differential for that location was 75.5°F. The sample was obtained in the darkest portion of the image. Both of these sampling locations exhibited visual segregation. Figure 8 shows the segregation observed in the pavement at the location seen in the Figure 7 approximately one year later.

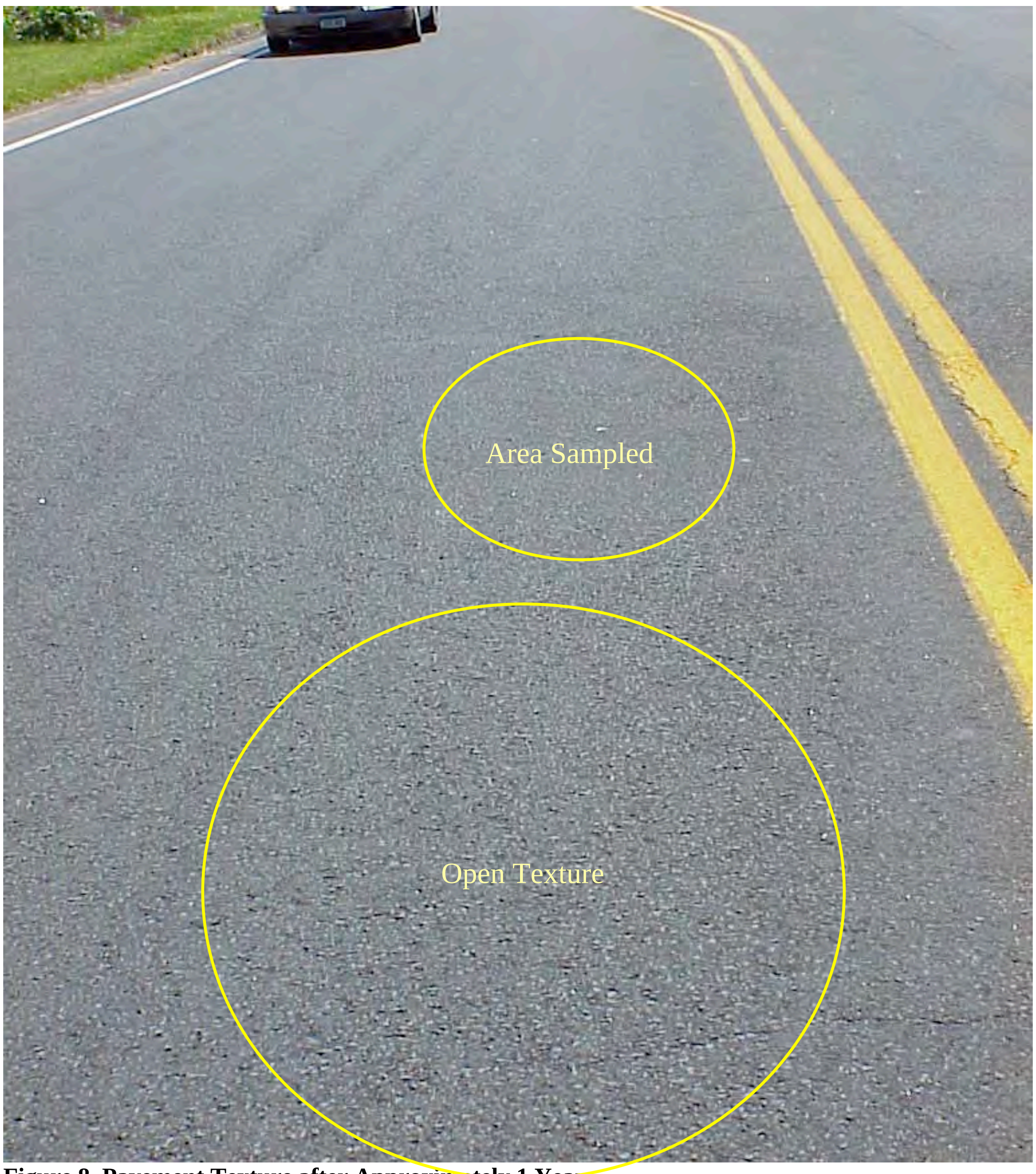


Figure 8, Pavement Texture after Approximately 1 Year.

Figure 9 shows the job mix formula gradation of two Superpave mixes made at the same HMA plant. One of the mixes was designed for traffic level 2 and the other was designed for traffic level 3. The mixes were placed approximately 1 month apart. One of the mixes did not show any significant visible segregation while the other mix did. The haul distance for both projects was essentially the same. The mix not exhibiting any significant visual segregation had an average temperature differential of 40.9°F. The mix exhibiting visual segregation had an average temperature differential of 62.7°F.

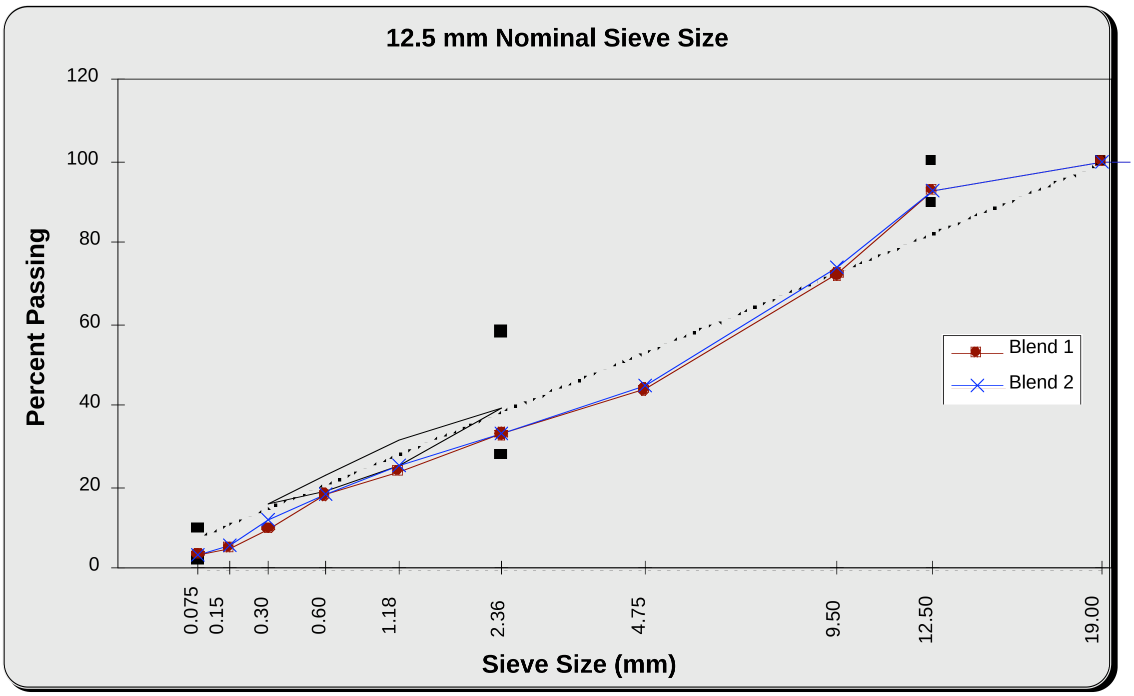


Figure 9 Gradation of two mixes from same plant

Figure 10 shows the job mix formula gradations of the three mixes that had the most visible segregation observed during this project. As can be seen in Figure 10, the three gradations are appreciably different. The observed temperature differentials for the three projects were: Blend 1 – 48.6°F, Blend 2 – 50.3°F and Blend 3 – 62.7°F. Based upon the wide variation of gradations it does not appear the gradation of the mixture significantly contributes to the temperature differentials observed in the field.

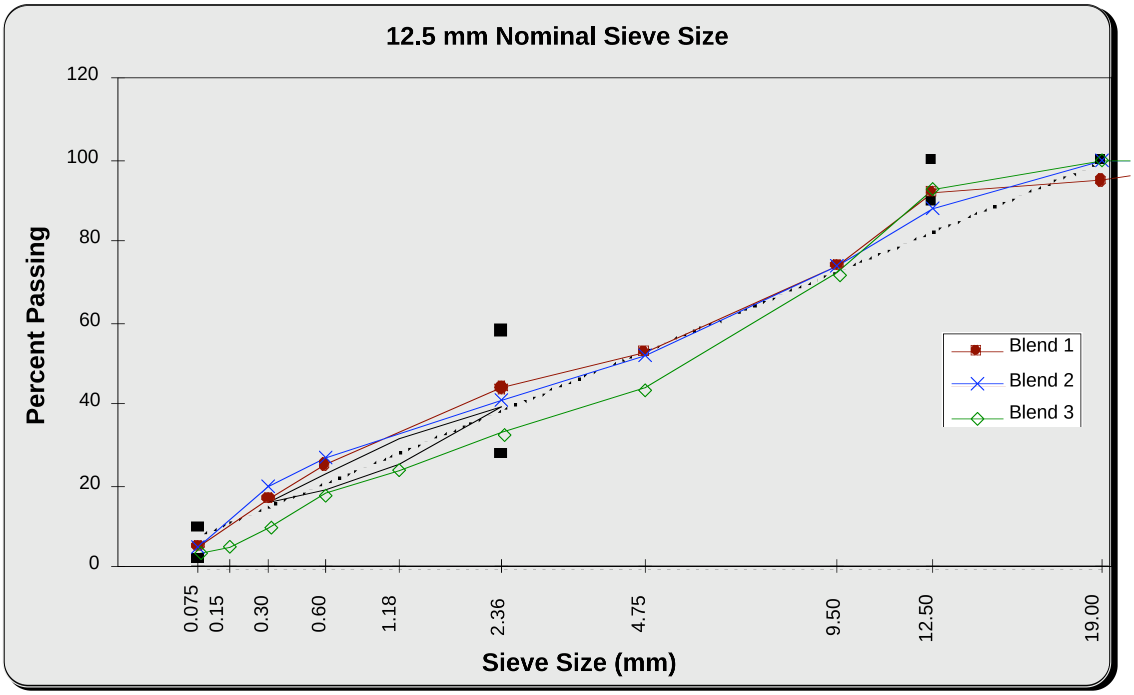


Figure 10 – JMF for most visibly segregated mixes observed

Spillage

The spillage of material in front of the paver was observed to contribute to the formation of cold spots under some conditions. Factors that influenced the formation of the cold spots included the quantity of material spilled, the shape of the spill, length of time before paver passed over it and both the ambient and pavement temperatures. The length of time required for the paver to pass over the spilled material had the greatest influence on the severity of the cold spot. If the paver passed over the spill immediately after it occurred, the temperature differential observed was minimal but the longer before the paver passed over the spill the greater the temperature differential. The ambient air temperature and pavement temperatures also affect the rate at which the spilled material cools. Therefore the temperature differentials induced from spills is dependent on the air temperature, pavement temperature and time lapse before the paver passes over the spill.

The quantity of material and the shape of the spill also work together to influence the severity of the cold spot. Larger piles tended to be more conical and thus the tops of the cones could cool off quicker because of less mass for the surface area and therefore when the paver screed ran into the pile it would pick up the cool material and create a cold spot. Larger spills then tend to form larger cold spots provided they have time to cool. Figures 11 and 12 show a visual image of a spill along with the corresponding thermal image. The thermal image clearly shows the effect of the large mounds of loose material that were present. The temperature differential in the thermal image was 81.6°F. Figure 13 shows a thermal image of material spilled in front of the paver hopper. Figure 14 is a thermal image of exactly the same location after the paver has passed over the spilled material and prior to compaction.

Figure 11 - Visual image of a spill

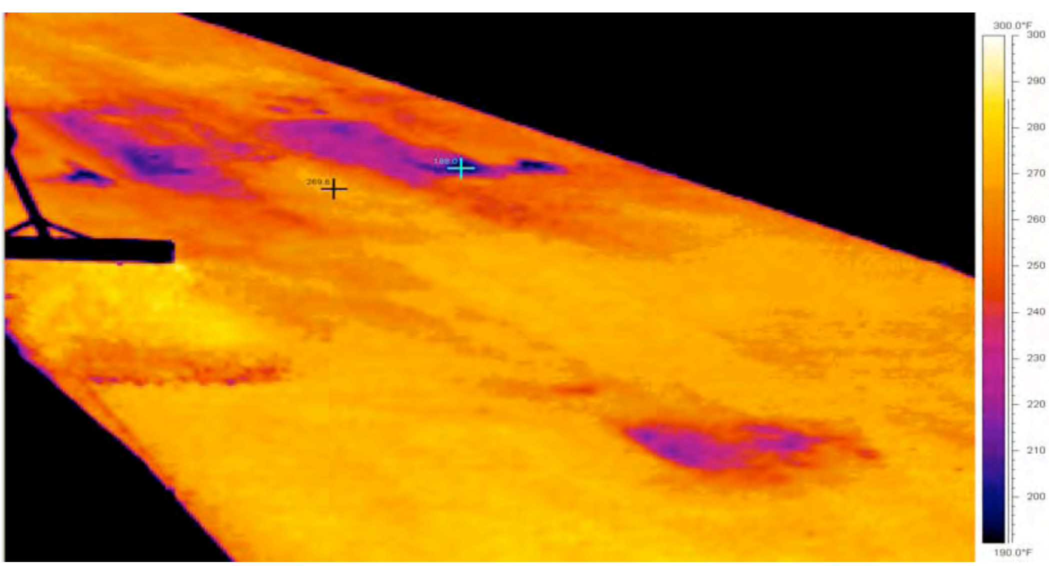


Figure 12, Spilled Material and Corresponding Thermal Imaging

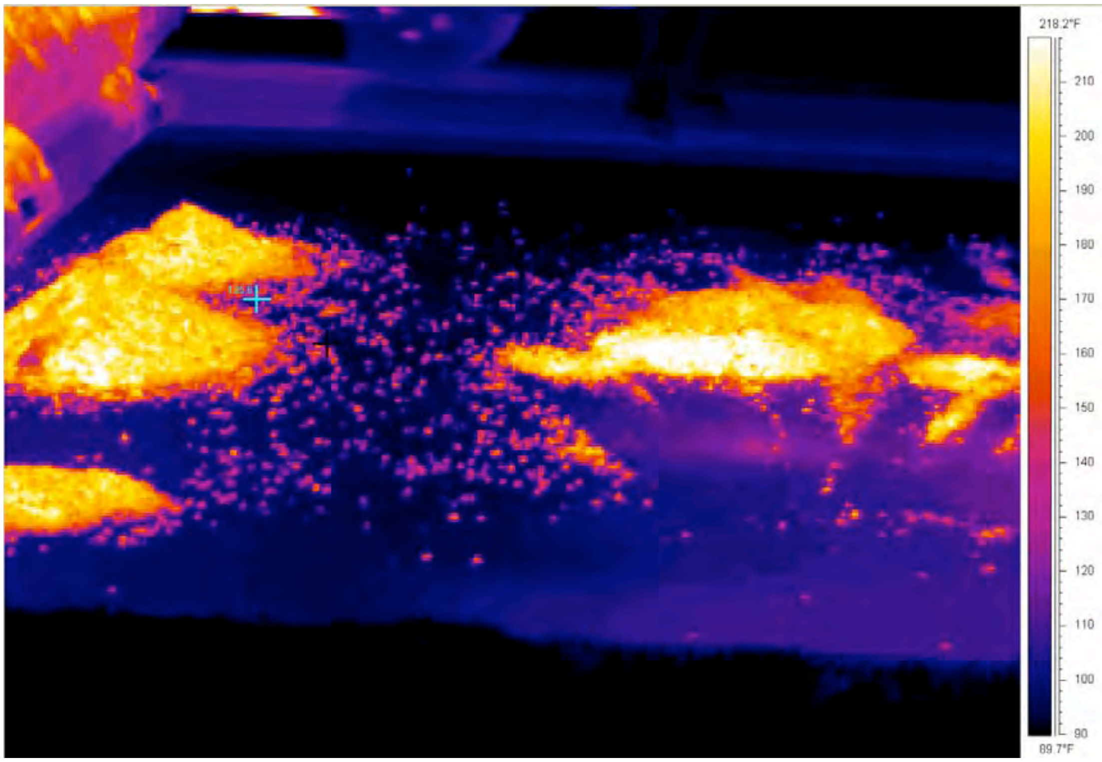


Figure 13 - Thermal Image before Paver has Passed over spilled material in Figure 14.

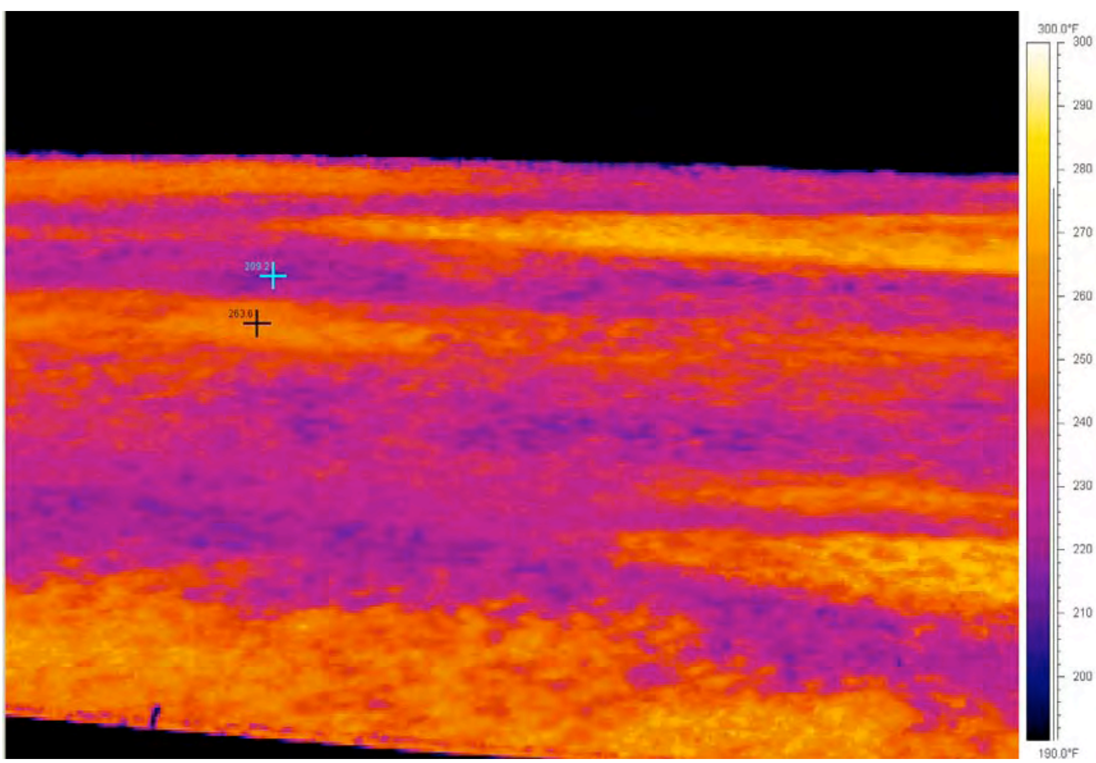


Figure 14 - Thermal Image after Paver has Passed over spilled material in Figure 13.

Haul Distance

The distance the HMA was hauled had very little effect on the magnitude of the temperature differentials observed using the thermal imaging camera. It did have a great effect on the physical size of the cold spots observed. Figure 15 shows a typical thermal image from a project with an approximate haul distance of 8 miles, one-way. The images from projects with shorter haul distances tended to have smaller areas with cool material. The magnitude of the temperature differential in Figure 15 is 51.7°F.

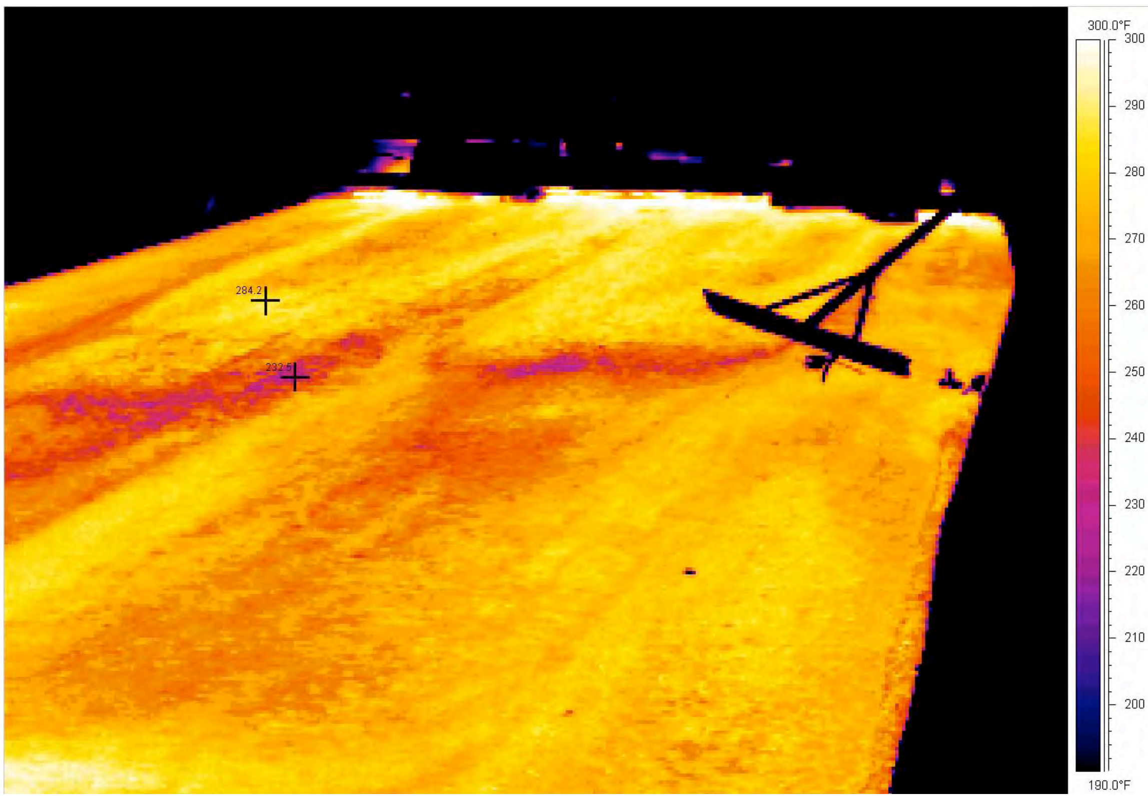


Figure 15 – Typical Thermal Image for Short Haul Distances

Figure 16 shows a typical thermal image from a project with an approximate haul distance of 56 miles, one-way. The magnitude of the temperature differential is 49.5°F. The magnitude of the temperature differential is similar but the colder areas are much larger for longer hauls.

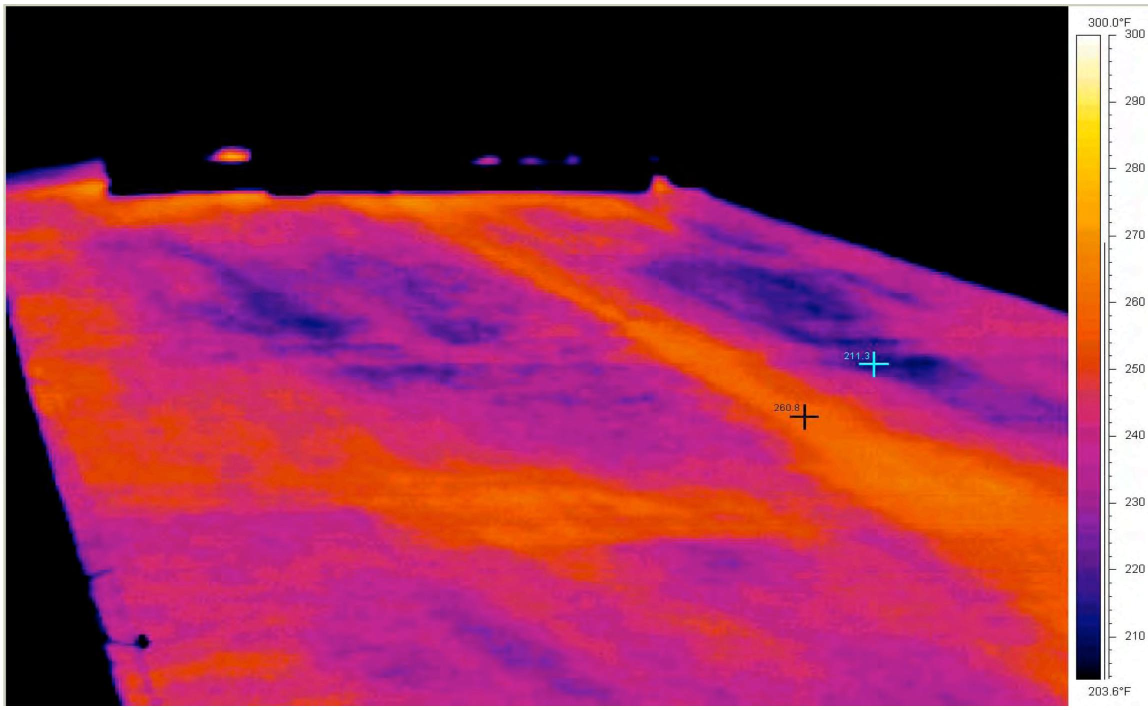


Figure 16, Typical Thermal Image for Project with Approximate Haul Distance of 56 miles.

The use of a material transfer vehicle will help to reduce the effects of long haul distances. Figure 17 is a typical thermal image taken on a different project with an approximate haul distance of 56 miles. The major difference for this project was the use of a non-remixing MTV. The magnitude of the temperature differential in the thermal image was 23.9°F.

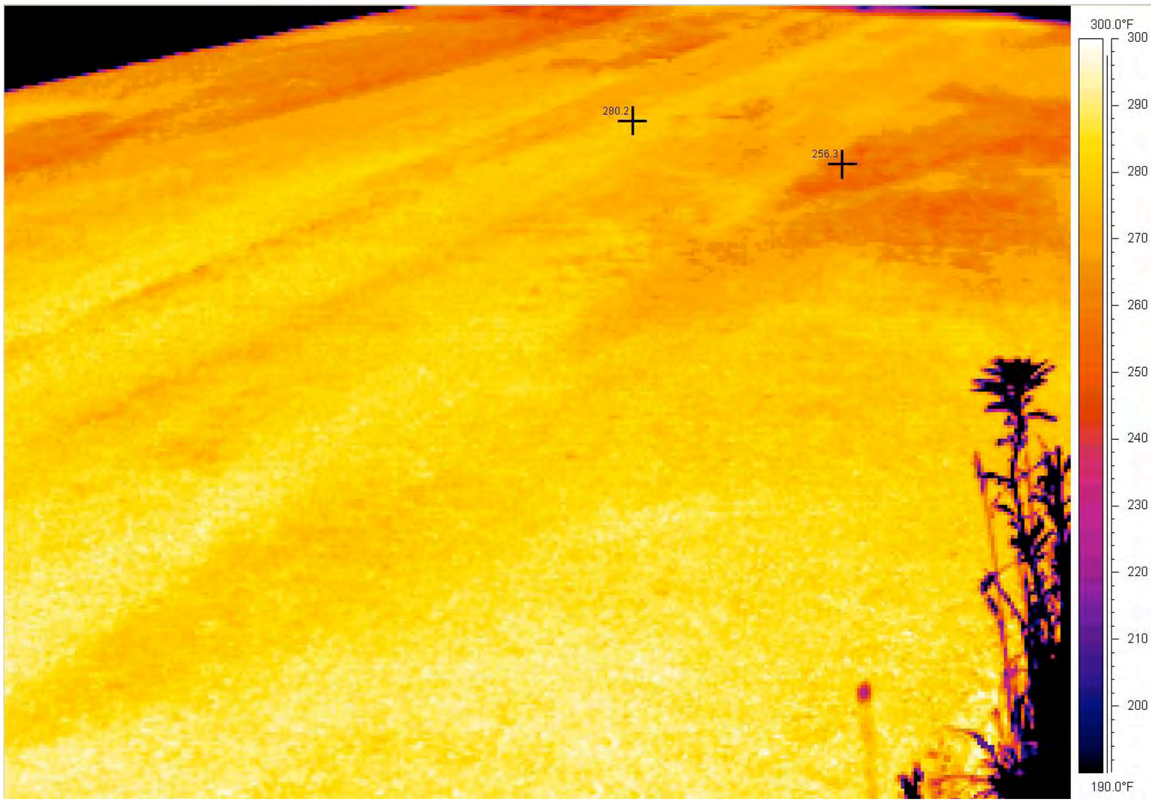
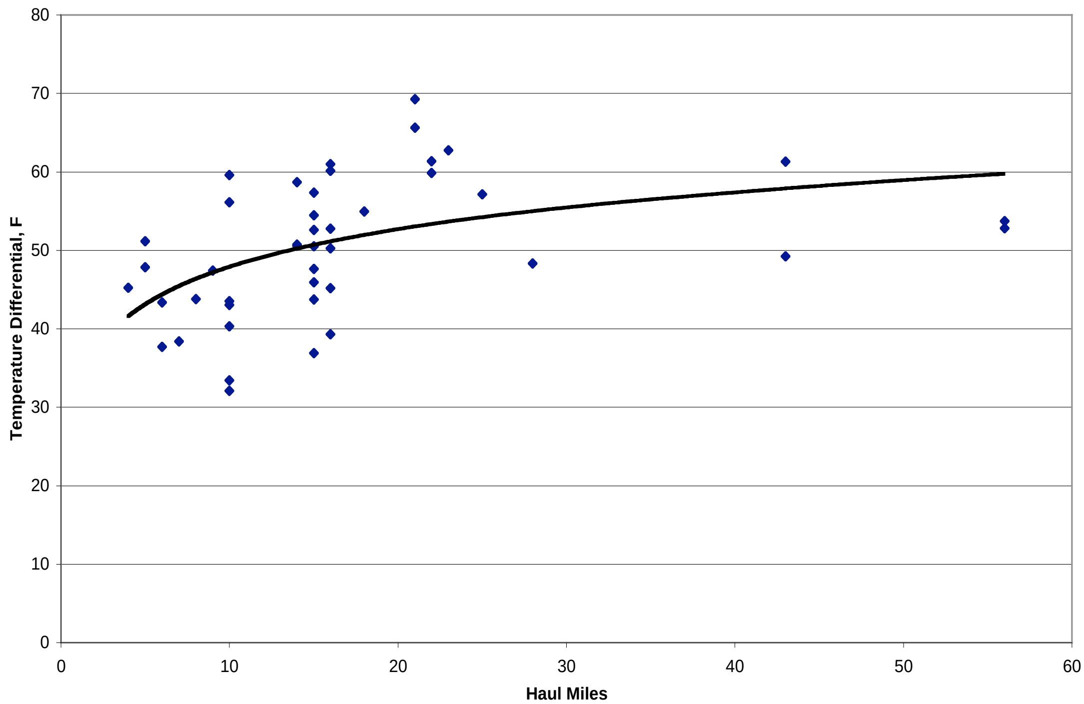


Figure 17, Typical Thermal Image for Project with Approximate Haul Distance of 56 miles using a non-remixing MTV.

Figure 18 shows a plot of temperature differential against haul distance. All projects utilizing a MTV were removed from the plot. There is a weak trend showing that as the haul distance increases, the temperature differential increases. The magnitude of the temperature differentials tends to level out over further haul distances. This is not to say that this does not have a negative impact on the pavement. What it does indicate is that the rate of heat loss begins to become constant throughout the mass in the haul unit as time progresses, thus reducing the temperature differentials observed.

Figure 18, Temperature Differential vs Haul Distance



<u>Material Transfer Vehicles (MTV)</u>

There are two different types of MTVs, remixing and non-remixing. Both types of MTVs place the material into a paver hopper insert. The paver hopper insert significantly increases the storage capacity of the paver hopper. The remixing MTV stores a large quantity of material (approximately 25 tons) within the unit. As additional HMA is introduced it is combined and mixed with the material stored within the remixing MTV. The remixed material is conveyed out of the MTV and then deposited in the paver hopper insert. The non-remixing MTV acts as a large conveyor between the haul unit and the paver. The material from a non-remixing MTV is then deposited in the paver hopper insert. Some of these non-remixing MTVs have the option of powering remixers in the paver hopper insert. Throughout this study, none of these paver hopper remixers were connected and powered. Both types of MTVs increase the potential output by reducing or eliminating the amount of time the paving train has to stop during truck changes.

Both types of Material Transfer Vehicles (MTV) are an effective method for reducing temperature differentials at the time of placement for HMA. The remixing MTVs virtually eliminate the observed temperature differentials and the non-remixing MTVs greatly reduce the magnitude of the temperature differentials. As MTVs produced relatively uniform temperature profiles throughout projects, less emphasis was placed on them during the study.

Table 6 shows the observed average temperature differentials for the various methods of conveying the material to the paver. The data contained in Table 6 shows that large differences in the magnitude of the temperature differential are related to the method used to deliver the mix to the paver hopper. In the table, End Dump Exchange refers to an image of the lay down taken shortly after a truck change. Middle of Load refers to images when approximately 50% of the load has been placed using the end dump exchange method.

Table 6
Various Methods of Conveying Material to Paver Hopper

		Average Temperature, °F		
	Number of Images	Difference	High	Low
End Dump Exchange	690	50.2	273.5	223.4
Middle of Load	65	36.0	279.9	243.9
Non-Remixing MTV	72	32.1	273.3	241.2
Remixing MTV	137	13.5	267.9	254.3

The difference between the end dump into the paver hopper and the non-remixing MTV for the temperature differential is 18.1°F and the temperature differential between the end dump and the remixing MTV is 36.7°F. The average temperature differential for the middle of load and non-remixing MTV are very similar. The conveying of material into the large paver hopper insert by the non-remixing MTV does cause some indirect remixing of the material in the paver hopper much the same way that the middle of the load for an end dump has some indirect remixing occurring. Figures 19 and 20 show typical thermal images taken on the same project one day apart Figure 19 was taken when a non-remixing MTV was used and had a temperature differential of 20.4°F.

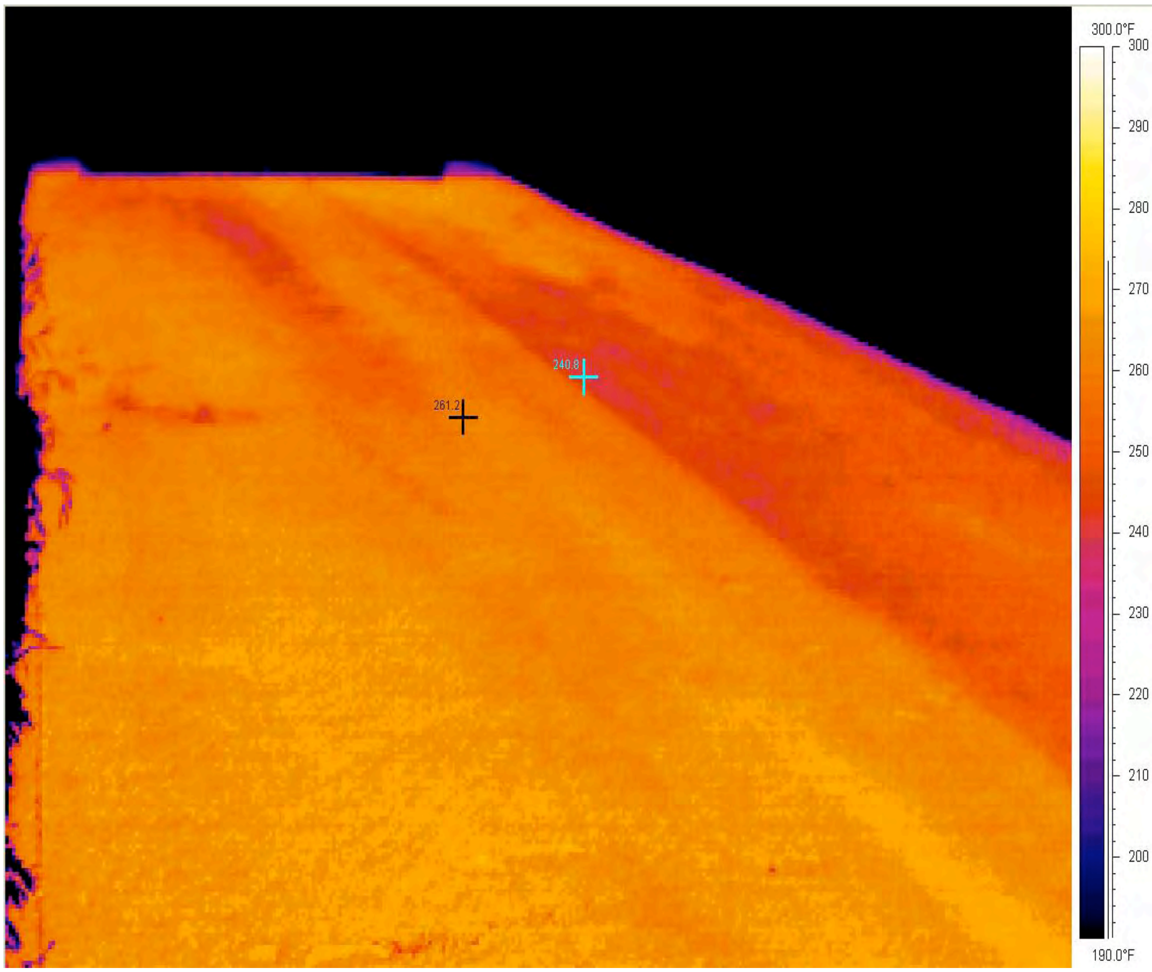


Figure 19 – With non-remixing MTV

Figure 20 was taken when using the end dump method of conveying material to the paver hopper and had a temperature differential of 51.0°F.

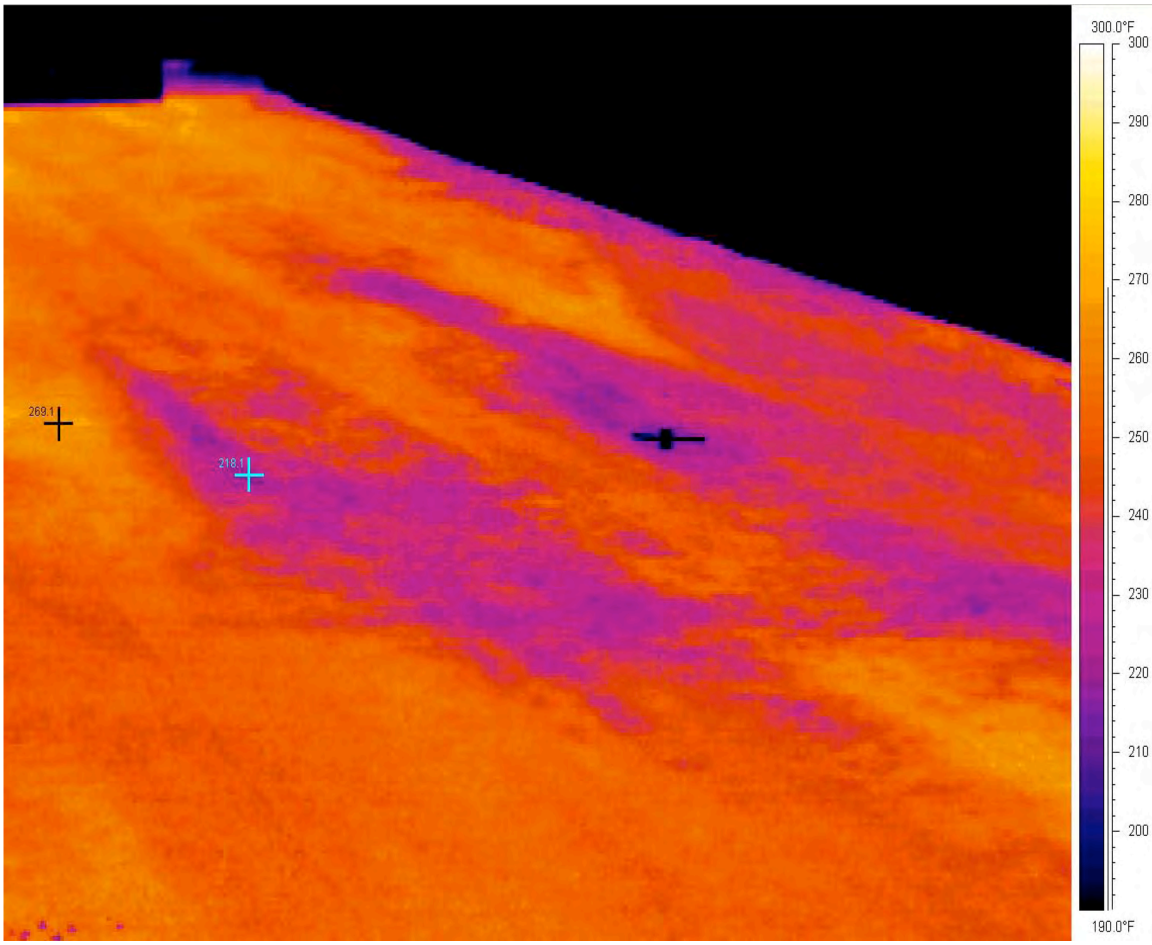


Figure 20 - Using end dump method

Figures 21 and 22 show typical thermal images taken on a project where in Figure 21 a remixing MTV was used and in Figure 22 the end dump method MTV was used. The temperature differential in Figure 21 was 16.9°F and was 51.9°F in Figure 22.

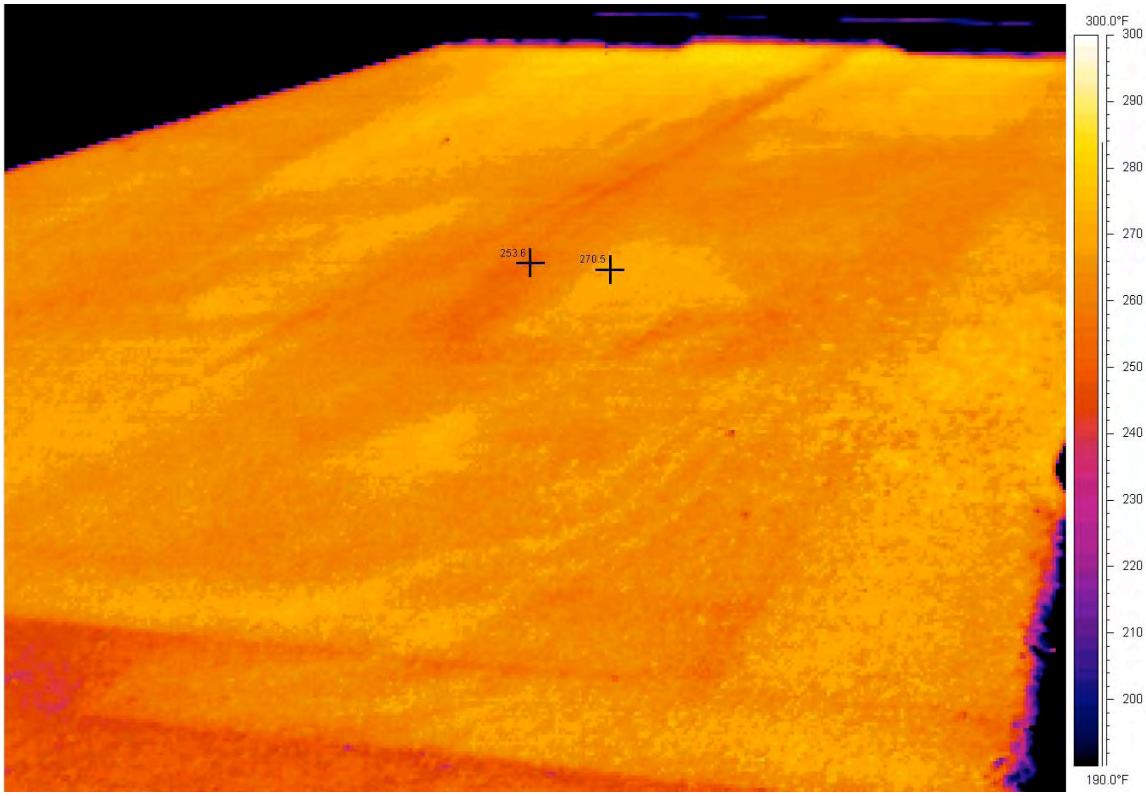


Figure 21 - With Remixing MTV

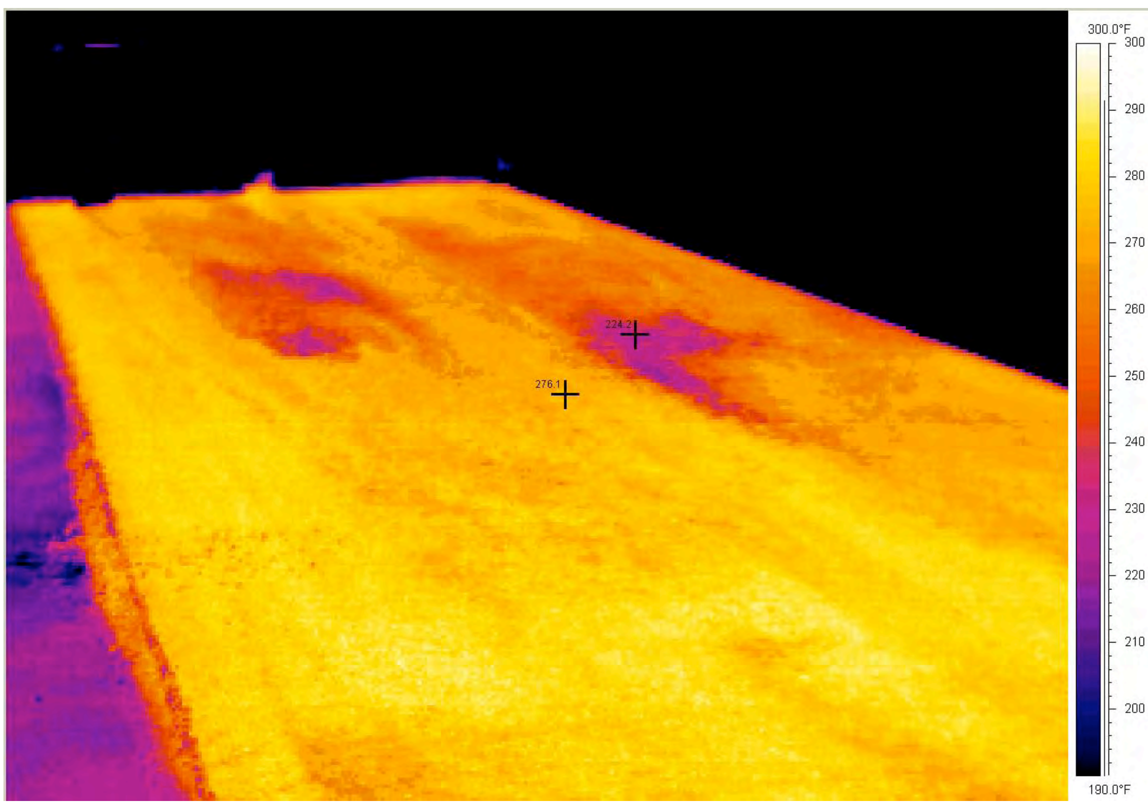


Figure 22 - Same Project as Figure 21 using end-dump technique

Figure 23 is a thermal image taken after the paving train stopped for approximately 30 minutes to service the MTV. The weather at the time of the photo was very windy, approximately 40°F and light sleet was falling. The temperature differentials observed here are no different than any other taken on that day. The maximum temperature differential for this image is 15.7°F.

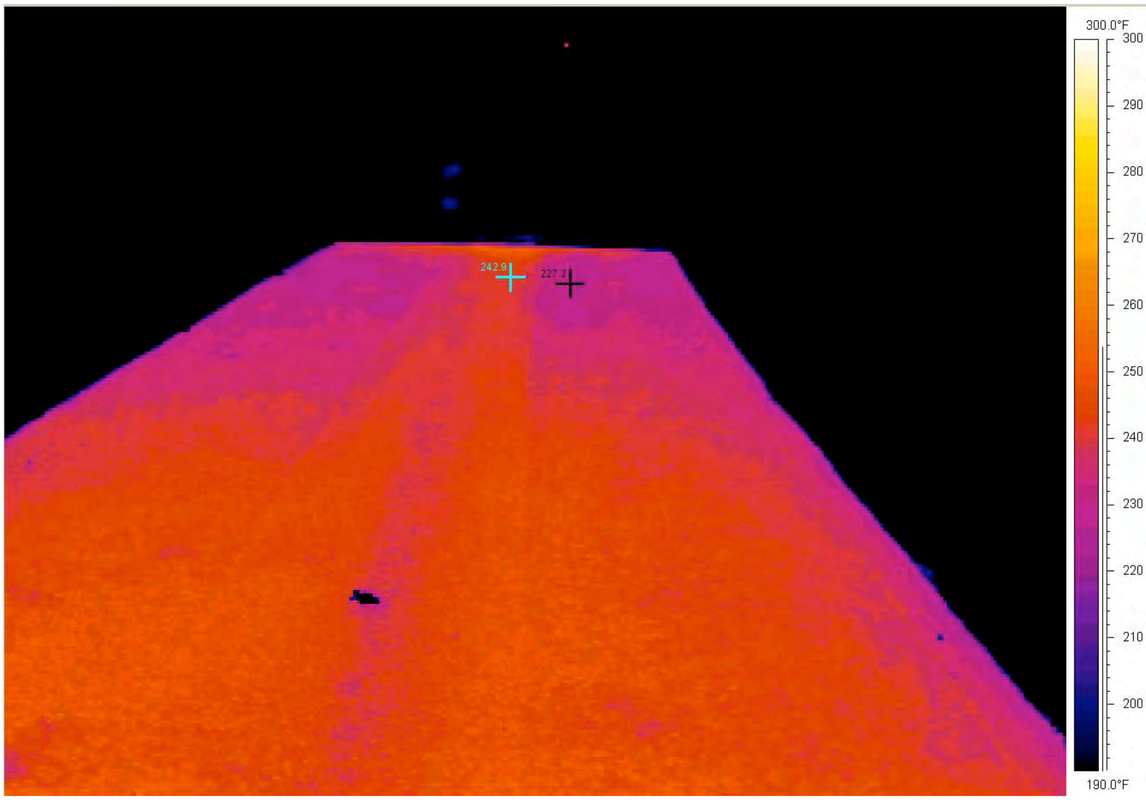


Figure 23, Thermal image taken after 30 minute stoppage for servicing remixing MTV During cold and windy weather. (Dark spot is a leaf that has blown onto mat)

Figure 24 shows a thermal image taken on a project using a non-remixing MTV on a very hot day in July. This picture was taken after a 50 minute wait for material to arrive. The observed temperature differential for the image was 72.4°F.

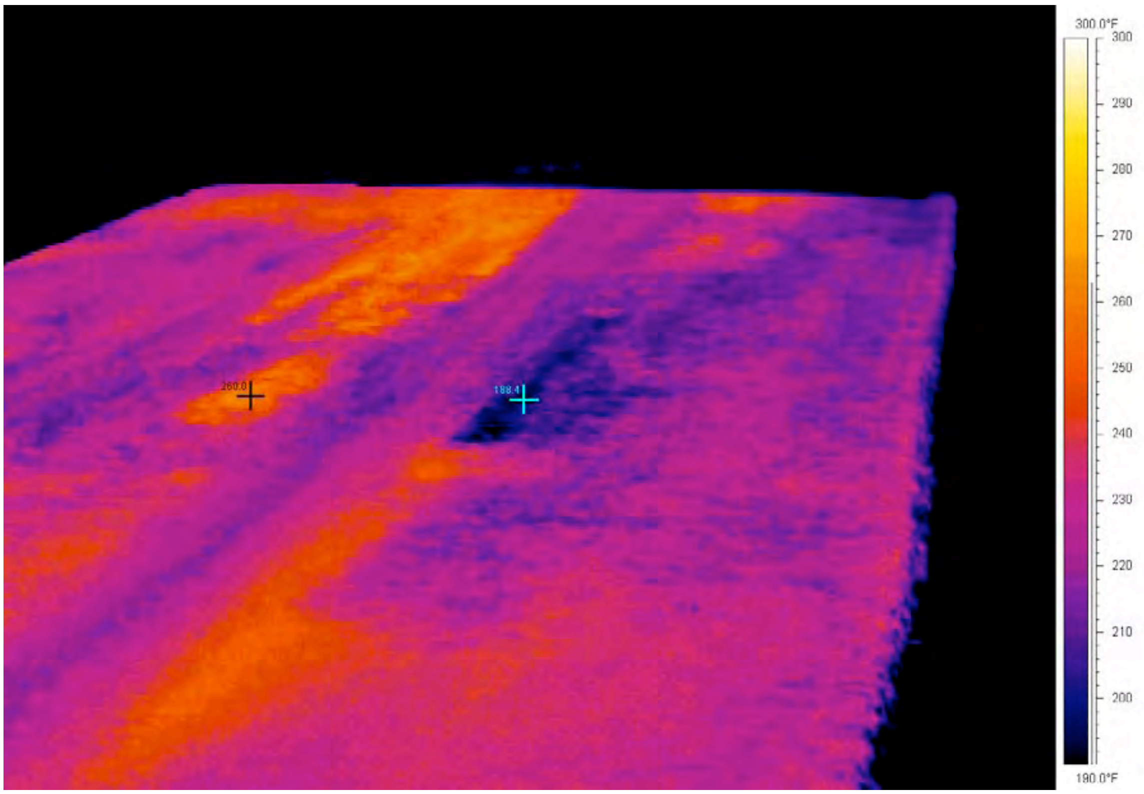


Figure 24, Thermal image taken on project using non-remixing MTV after 50 minute wait.

Same Plant, Same Paving Crew, Long Haul - MTV on One Project

There were two projects supplied by the same HMA plant with approximate haul distances of 43 and 56 miles. The project with the 56 mile haul distance employed a MTV the 43 mile haul distance did not. Table 7 summarizes the results.

Table 7, Same HMA Plant and Paving Crew, Long Hauls One Project with MTV and One Without

	Number of Photos	Approximate Haul Distance, mi	Temperature Differential, F
No MTV	27	43	53.6
With non-remixing MTV	58	56	37.1

The use of the non-remixing MTV did significantly reduce the observed temperature differentials even though the haul distance was considerably larger. Figure 25 shows the streakiness of the cold material for the project with a haul distance of 43 miles not employing a MTV. The observed temperature differential in Figure 25 is 62.5°F. Figure 26 shows the improvement of the homogeneity of the temperature from the non-remixing MTV. The observed temperature differential in Figure 26 is 27.6°F.

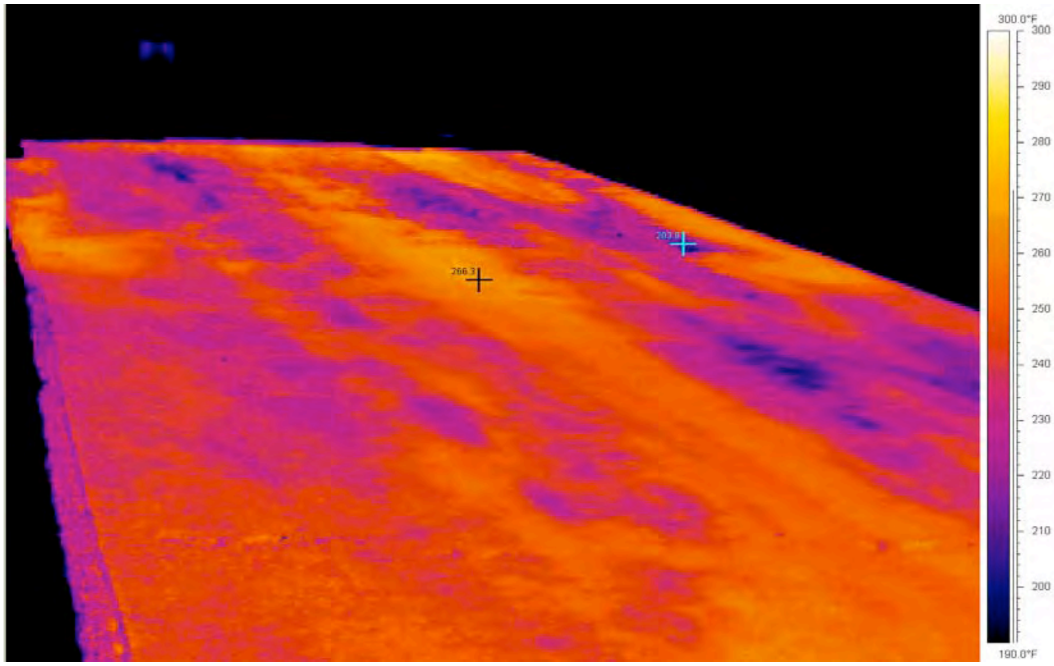


Figure 25, Thermal Image taken on project with 43 mile haul distance and no MTV

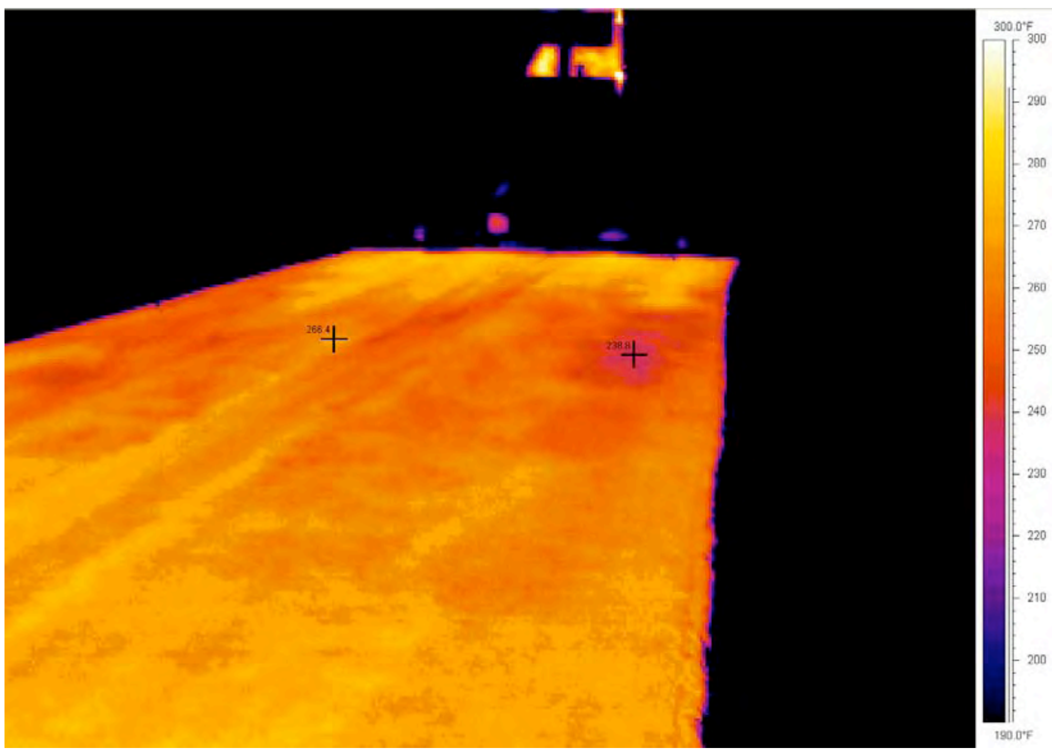


Figure 26, Thermal Image taken on project with 56 mile haul distance and non-remixing MTV

Delays Between Trucks

For this study, the amount of time between trucks unloading into the paver hopper was recorded if there was an unusual amount of time between trucks unloading into the paver hopper. Figure 27 show a plot of the delay between trucks and the corresponding temperature differential once paving did resume.

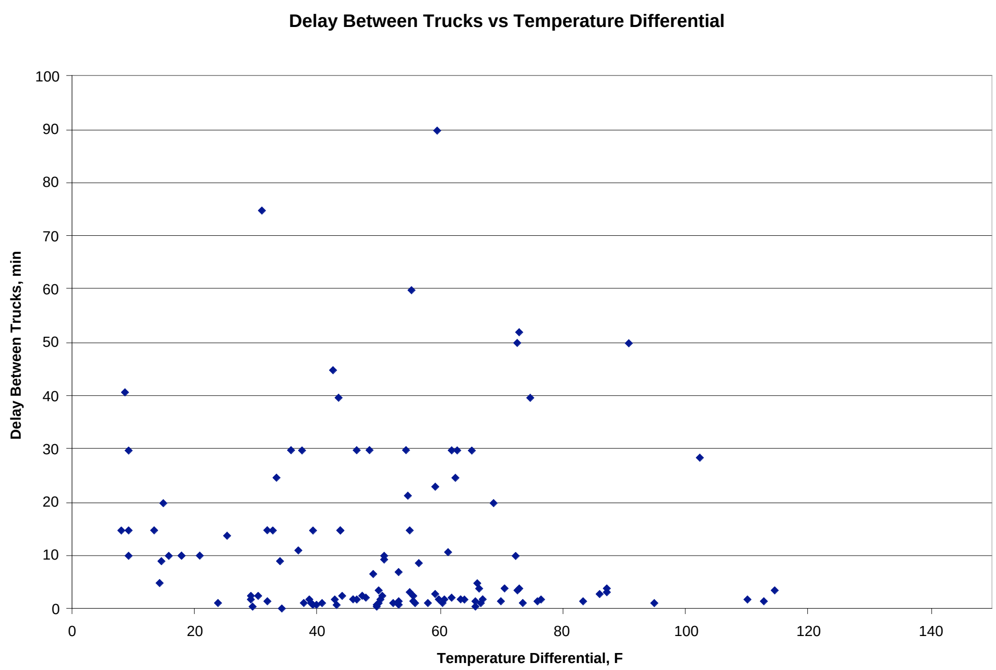


Figure 27 – Delay between trucks vs. difference in temperature.

The scatter in this chart indicates there is no strong tie between delay time and temperature differential

Seasonal Differences

Monthly differences in the magnitude of the temperature differentials observed as the material comes out from behind the paver screed can be seen in Table 8. Table 8 excludes data from projects utilizing either type of MTV. The data in this table tends to contradict the logic that as the weather turns colder the magnitude of the temperature differentials would be expected to grow larger. The possible explanation of this could be similar to what appears to occur during long hauls. The cooler weather tends to remove heat faster from the edges and then the heat loss begins to become close to constant thus reducing the magnitude of the temperature differentials. The fact that the average high and average low temperature for November is significantly lower than for other months, tends to support that the overall temperature of the material is decreasing.

Table 8, Breakdown of Data by Month at End Dump Exchanges Excluding Data from Projects with MTV

Month	Number of Images	Average Temperature, F			Relative Density
		Difference	High	Low	Difference, pcf
May*	28	50.0	279.8	229.8	N/A
June	113	47.7	276.3	228.6	4.97
July	176	55.3	274.2	218.9	6.38
August	109	49.7	281.4	231.7	7.07
September*	56	60.4	285.1	224.7	12.6
October	115	43.4	274.7	231.3	4.95
November	193	48.2	261.9	213.7	5.36

* One Project

Day vs Night Paving

Most night paving projects occur on divided highways. As paving projects on divided highways tend to use large quantities of HMA, contractors tend to use MTVs on these projects to increase output. During this study we observed six night paving projects. MTVs were employed on 4 of those projects. Table 9 shows the results of the projects. The data in Table 9 is very comparable to the overall data obtained for the study (Table 6). Therefore it can be concluded that night paving has little to no effect on the temperature of the material coming out from behind the paver. This is not to imply that additional care is not needed to pave successfully at night. Cooling rates for the pavement after it leaves the paver are much different at night than they are during the day. Attempts to record these differences were unsuccessful as the thermal camera only measures the surface temperature of the pavement. Water from the steel wheel rollers tended to cool the surface which made it impossible to measure the cooling rate differences between night and day with the thermal imaging camera.

Table 9, Average Temperature Differentials for Night Paving Projects

	Number of Projects	Number of Photos	Average Temperature Differential, °F
No MTV	2	29	52.5
Non - Remixing MTV	1	10	25.5
Remixing MTV	3	42	11.9

Ambient Air Temperature

Attempts to correlate ambient air temperature to cold spot formation were unsuccessful. Ambient air temperature did not have an effect on the magnitude of the observed cold spots. Ambient air temperature does control the rate at which the HMA cools after leaving the paver and thus does control the amount of available time for compaction. Using the thermal camera it was not possible to measure the rate of cooling experienced by the pavement as it was compacted. Water from the rollers tended to cool the surface and since surface temperature was what the thermal imaging camera measures, it was not indicative of the internal mat temperature. Figure 28 shows a plot of the average high and low temperature recorded at Bradley International Airport against the average temperature differentials recorded for that date on the study.

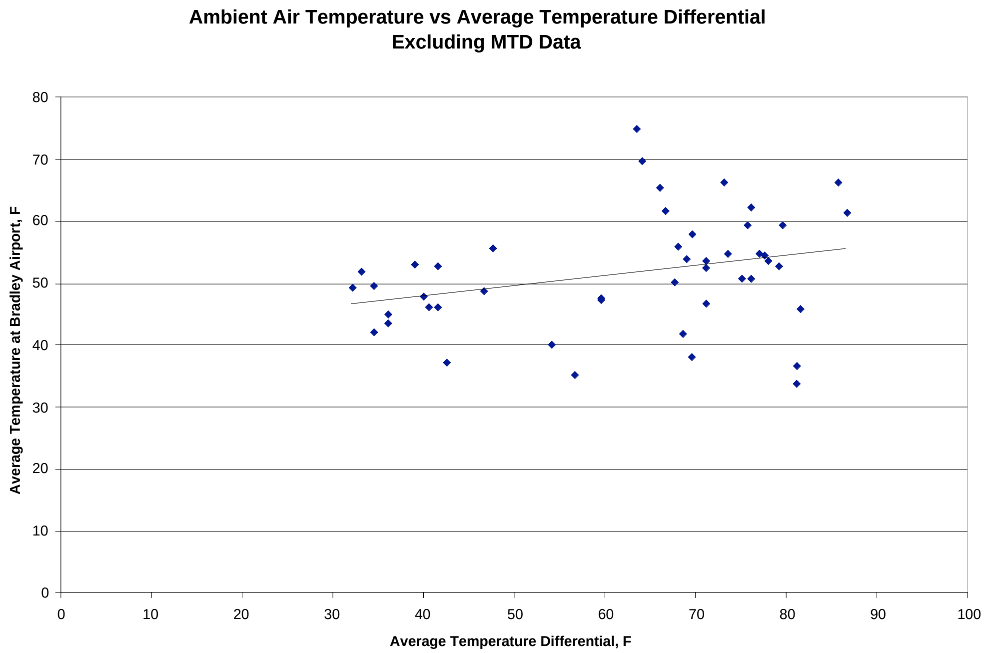


Figure 28 – Average air temperatures at Bradley Airport vs. Average temperature differential

As seen in Figure 28, there appears to be a slight trend indicating that as the ambient air temperature is increasing, the magnitude of the temperature differentials is also increasing. This may be the result of accumulating the effects of the many temperature control factors rather than just air temperature.

Base Temperatures

Base temperatures play an important role in the construction of a HMA pavement. For this study, the effect of base temperature on the pavement could not be determined. With the thermal imaging camera, only the surface temperatures could be determined. This window of accurately measuring the surface temperature would end as soon as compactive rolling begins. The water from the rollers rapidly reduces the surface temperature of the mat as it evaporates. Figure 29 shows a thermal image of a pavement after the breakdown rolling. It is apparent that after breakdown rolling the surface temperature measured with the thermal camera is greatly affected by the quantity of water being applied during compaction. The base material will absorb heat but in the short observation window present before breakdown rolling occurs, the heat transfer to the base would not have a chance to reflect through the 1.5 to 2.0 inches of material to be captured by the thermal imaging camera. Typically the breakdown roller would begin compaction 30-60 seconds after the truck change occurred.

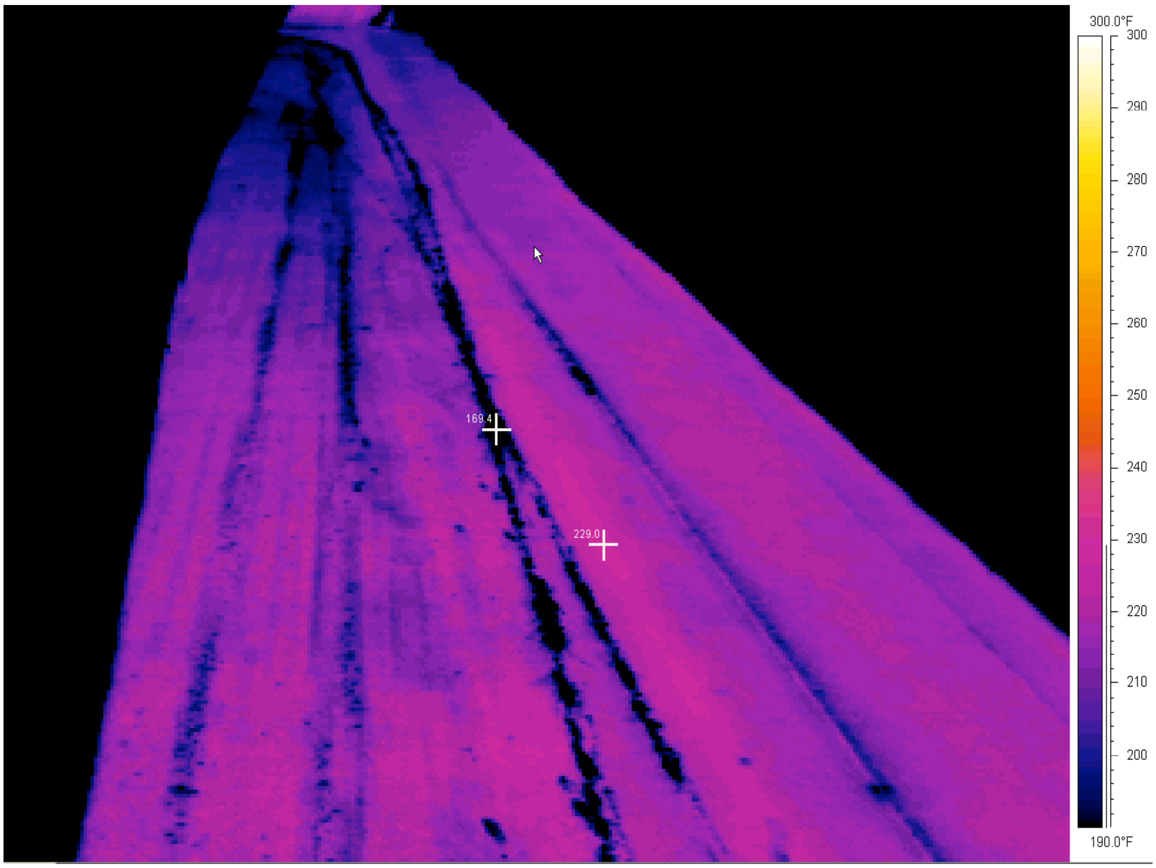


Figure 29, Thermal Image of Pavement after Breakdown Rolling

<u>Base Mix and Leveling Courses</u>

Thermal Imaging of base courses did show temperature differentials in the pavement. Evaluating these mixes later in their services lives would be difficult as failure could occur in the surface or in the base. Therefore, no emphasis was placed on imaging base mixes.

Attempts to use the thermal imaging camera on leveling courses did not work. Material placed over the high spots tended to cool off very quickly. Because the camera tended to reveal the thin spots in leveling course and not actual cold spots, no imaging was performed on leveling courses.

<u>Recycled Asphalt Pavement (RAP)</u>

During this study, 10 days were observed using Superpave 12.5 mm mixes containing RAP without a MTV in use. The average observed temperature differential for mixes containing 10% RAP was 51.4°F. The average observed temperature differential for 12.5 mm Superpave mixes with no RAP was 48.8°F. Given the limited data for Superpave mixes containing RAP versus Superpave mixes containing no RAP, it would appear that the RAP had very little influence on the magnitude of the temperature differentials.

<u>Lift Thickness 1.5 vs 2.0 Inches</u>

The target compacted thickness of the HMA mat varied by project from 1.5 inches to 2.0 inches. Only one project varied the target compacted thickness from 1.5 to 2.0 inches. It is difficult to truly establish the effect of increasing the compacted thickness with only one project varying the thickness within the project. The effect on that particular project was to decrease the area of the cold spots.

The comparison of projects where the targeted thickness remained the same requires some caution as the conditions between projects are not the same. The variation of these conditions may have a larger influence on the magnitude of the observed temperature differentials than the compacted thickness of the mat. For a compacted target thickness of 1.5 inches 301 thermal images were taken and the average temperature differential for all of these images was 48.6°F. For a target compacted thickness of 2.0 inches 400 thermal images were taken and the average temperature differential was 51.5°F. Data collected on days were a MTV was used was excluded from both averages.

Heated Bodies vs Non-Heated Bodies

The CAP Lab monitored 4 different sites to study the effects of heated bodies on temperature differentials. The results of this data are not included in the overall averages reported throughout the rest of the study. The magnitude of the temperature differences were recorded for both heated and non heated bodies. The determination of whether or not a haul unit was heated was not a trivial task. Ultimately, the only definitive method for determining if the haul unit had a heated body (and if it was in use) was to ask the driver. This assumes the information from the driver was correct. It also became clear that there were different methods of running the truck's exhaust through the body. The efficiency of the various heating methods was unclear and beyond the scope of this study.

Observations were made of 73 loads of HMA being delivered. Of the 73 loads, it was determined that 30 had heated bodies and 43 did not. The average temperature differential for loads with heated bodies was 39.2°F and for non-heated bodies was 44.53°F. There were no apparent differences observed in the size of shape of the cold spots between loads placed from heated and non-heated haul unit bodies. This data was collected in June so that these differences may or may not be different during the cold weather months.

Measurements of the temperature of the skin of the trucks also showed some differences between heated and non-heated bodies. The average of the highest temperatures observed on the outside of the trucks for 4 loads was 187.0°F for heated bodies and 161.3°F for 11 loads with non-heated bodies. This would indicate that the heating of the haul unit body with the truck's exhaust does increase the body temperature somewhat.

Superpave versus Marshall Mixes

During this study, the Connecticut Department of Transportation was transitioning from HMA mixes designed using the Marshall method to HMA mixes designed using the Superpave method. Temperature differentials were calculated for these mixes. Table 10 shows the temperature differentials between Marshall and Superpave mixes with no MTV. There are many more images available for the Marshall mixes than there are for the Superpave mixes because the Superpave mixes tended to be specified for highways where MTVs were more likely to be used. The temperature differential for the types of mixes were nearly identical.

Table 10, Temperature Differentials Between Marshall and Superpave Mixes Excluding MTV Data

	Number of Photos	Temperature Differential, F
Marshall	427	50
Superpave	162	51

Same Paving Crew and Equipment, Different Mix Plant

Throughout this study, two different crews were observed on 4 different projects each. Crew 1 used a MTV on one project, that data was excluded. By observing the same paving crew and equipment, the goal was to learn whether maintaining essentially the same paving crew and equipment had any influence on the magnitude of the cold spots. Tables 11 and 12 show the temperature differentials for the various projects for both paving crew 1 and paving crew 2.

Table 11, Same Paving Crew and Equipment Different HMA Plant - Crew 1

	Number of Photos	Approximate Haul Distance, mi	Temperature Differential,°F
Project 1	23	7	38.2
Project 2	26	10	37.4
Project 3	21	4	48.8

Table 12, Same Paving Crew and Equipment
Different HMA Plant - Crew 2

	Number of Photos	Approximate Haul Distance, mi	Temperature Differential,°F
Project 1	8	13	47.4
Project 2	22	5	47.7
Project 3	36	56	53.7
Project 4	26	21	68.8

This data does show some consistency on a couple of projects for each paving crew. The limited quantity of data makes it difficult to conclude whether or not the paving crew influences the magnitude of the temperature differentials.

Same HMA Plant – Different Paving Crews

During this study it was observed that 5 HMA plants supplied material to at least two different paving crews not using a MTV. Table 13 shows the average temperature differentials for the 5 different mix plants and their associated projects. While the data in Table 13 has no discernable pattern, it does provide some indication that the observed temperature differentials are not caused by the mix plant.

Table 13, Same Mix Plant Different Paving Crew Excluding MTV Data

Plant 1	Number of Photos	Approximate Haul Distance, mi	Temperature Differential, °F
Project 1	56	16	60.4
Project 2	48	15	40.9
Project 3	8	12	47.4
Plant 2			
Project 1	22	5	47.7
Project 2	13	15	54.5
Plant 3			
Project 1	12	16	56.1
Project 2	27	43	53.6
Plant 4			
Project 1	15	10	52.9
Project 2	24	10	42.1
Project 3	23	7	38.2
Plant 5			
Project 1	21	4	48.3
Project 2	31	5	47.3

Same Project – Two Paving Crews – Two HMA Plants – Same Day

One monitored project used material from two different mix plants, two different paving crews placing all of the material in a single day. This project occurred in the beginning of November on an extremely cold day for the time of year. Table 14 summarizes the data for that project. These observed temperature differentials are below the average end dump temperature differentials of 50.2°F for the entire study. The data in the table shows that the southern paving crew using the mix hauled slightly farther than the northern crew had an average temperature differential difference that was six degrees lower than the northern crew under essentially the same environmental conditions.

Table 14, Same Project, 2 HMA Plants
2 Paving Crews – Same Day - No MTV

	Number of Photos	Approximate Haul Distance, mi	Temperature Differential, °F
North Crew	21	4	48.3
South Crew	24	10	42.1

Same Project, Same Equipment – Different Paver Operators

One paving project changed paver operators. Everything else remained the same. The magnitude of the temperature differentials for the original paver operator was 53.5°F with a relative density difference of 4.9 pcf. The new paver operator had temperature differentials of 59.5°F and a relative density difference of 5.1 pcf. This very limited information may indicate that the paver operator may have an influence on the formation of cold spots. This may be due to the level of material remaining in the paver hopper at the time of truck changes. As the research team was not permitted on the equipment, it was difficult to estimate the amount of material remaining in the paver hopper during truck changes without interfering with the standard truck change procedure.

Pavement Distress – Same HMA Plant, Same Paving Crew, 2 Different Projects

Figure 30 shows a thermal image taken on a roadway that exhibited highly visible segregation at the time of placement. Figure 31 is a visible image of that same spot approximately one year later. Figure 31 is showing some signs of early distress.

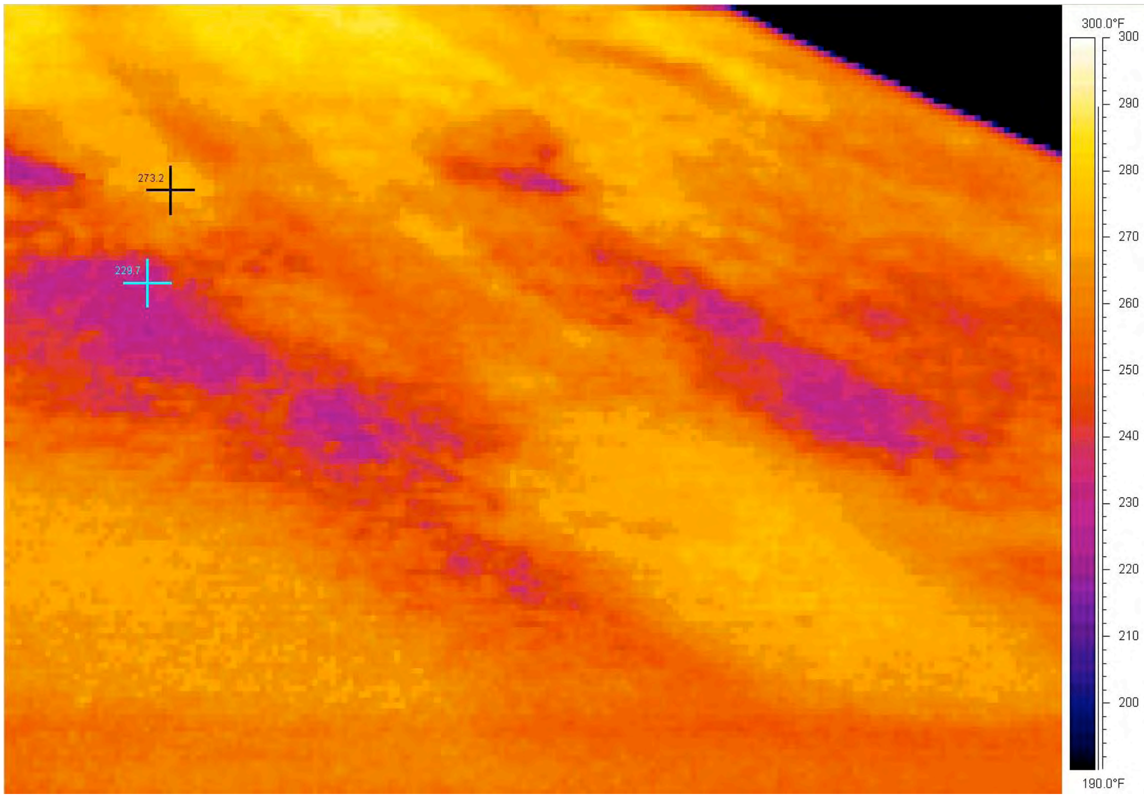


Figure 30 - Thermal Image of spot visible in Figure 31 (Image taken from centerline)


Figure 31 – Visible image of Figure 30 taken one year after placement (Image taken from shoulder)

Figures 32 and 33 show a thermal image taken at the time of placement and a visible image taken 22 months after construction. The observed temperature differential was 64.0°F. In Figure 33, there is no visible distress. Both sets of Figures 30 and 31 as well as 32 and 33 are of material placed by the same paving crew, with material from the same HMA plant and only five miles separating the two projects. The only difference between the two projects was the project that yielded Figures 30 and 31 was ConnDOT Class 1 while Figures 32 and 33 came from a project using 12.5 mm Superpave.

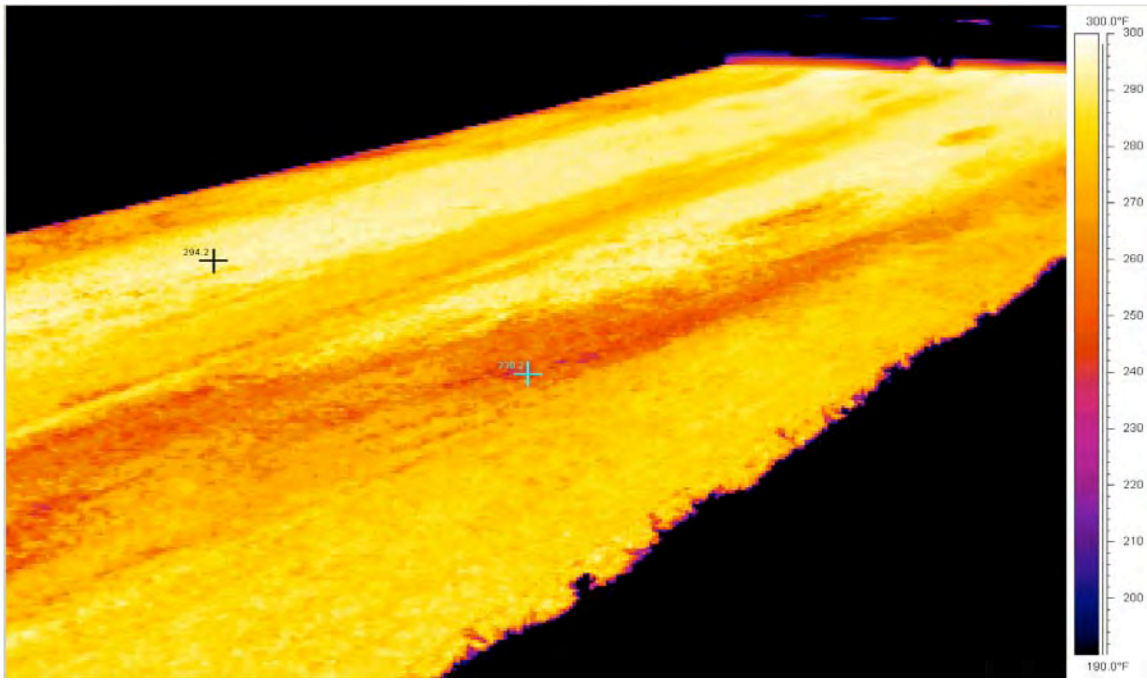


Figure 32 - Thermal image taken at time of construction 2 years ago.

Figure 33 - Visible Image of Figure 32, 2 Years Later– no visible distress.

Conclusions

The formation of cold spots in the freshly placed HMA is a very complex process. As segregation can take on two different forms, gradation and thermal, identifying the direct cause is most difficult as they present themselves similarly. They look similar to both the naked eye and the thermal camera and are therefore difficult to differentiate. Gradation segregation tends to leave the surface of the pavement with a very open texture as there typically are not enough fines to fill in the voids in visually detected segregated areas. Thermal segregation tends to leave the surface with an open texture as well. This is caused by the colder material not "flowing" under the paver screed as easily as the warmer material, therefore the material is stretched as compared to the warmer material and has more air voids in it. In either case, the density of the material is greatly reduced in these segregated areas and the durability of the pavement suffers. One of the larger stumbling blocks to reducing segregation may very well be correctly identifying it as either gradation or thermal segregation as the corrective actions may be very different for each case. This may explain why some methods sometimes do not work to eliminate the problem. The segregation problem may be thermal segregation where the method employed was to improve gradation segregation.

Having examined many different pavements for this project it has become clear that identifying visually segregated areas was very much dependent upon the direction of sunlight hitting the area as well as the presence of cloud cover. What was seen in the morning may not be visible in the afternoon. Openness is most visible when the sun is in front of the observer as shadows of the coarse aggregate then stand out.

The occurrence of cool spots in the mat immediately after placement tends to create areas with lower densities. These areas of lower density will tend to show distress first due to accelerated aging of the asphalt binder due to increased air voids as well as increased water permeability. Depending upon the temperature differential and surface area of the cold spot, these spots may even be visible to the naked eye after compaction has been completed. Observing older pavements, the pattern in which many of them fail is similar to the common patterns observed with the thermal imaging camera. The common patterns observed in failing pavements indicates that anything that reduces the thermal gradients observed at the time of construction would tend to increase the life of the pavement.

Most of the observed cold spots occurred 25 to 30 feet after the position where the paver screed stopped for a truck change when there was no remixing MTV. Rarely were cold spots observed during the middle of the load. This would indicate that truck changes are a major contributor to the formation of the cold spots. There appeared to be two ways in which the trucks pulling away from the paver may cause cold spots to appear.

The largest contributor to the formation of the cold spots appears to be the interaction between the haul unit and the paver hopper. The origin of cold material for this type of cold spot would be the paver hopper. When a truck pulls away from the paver hopper without disturbing the material on the edge of the hopper, the next truck backing into the paver hopper will more than likely knock a portion of this material down onto the paver's conveyor. Since the material on the edge of the paver hopper has been exposed to the ambient air temperature for an extended period of time, its temperature will be significantly lower than desired. Occasionally, the angled cold spot occurs on one side of the mat. This may be explained by the new truck backing into the paver, off center, knocking cooler material onto only one of the paver's conveyors, thus sending material to only one of the screed augers and the cold spot occurs only on one side.

Virtually all truck changes using end dump produce a distinct area of cooler material. This is caused by the fact that the material around the perimeter of the haul unit tends to cool faster than the core of the material in the haul unit. The formation of the cold spots is easily explained by the fact that the last HMA out of a haul unit will tend to be cooler than the material coming out of the middle of the haul unit. The first HMA being dumped into the paver hopper coming from the next haul unit will also tend to be cooler. This combined with the last HMA out of the previous haul unit will tend to create a large mass of cooler material which is then spread by the paver. Occasionally, folding the wings of the hopper also puts colder material into the conveyor and augers.

Spillage onto the pavement under certain conditions will cause a cold spot to form. Spillage tends to become more problematic based upon the size of the spill, ambient air temperatures and the length of time before the paver passes over. Figure 34 shows a spill of loose HMA onto the existing pavement caused by the haul unit cleaning the loose material from its bed by raising the dump body after pulling away from the paver. Hopper wing folding may also cause material to be spilled ahead of the paver. If there is a delay between trucks and this material is allowed to stay on the existing surface, this material is already cooler than desired and will continue to cool before the paver spreads fresh hot material over it. Cooler weather conditions exacerbate this problem as well as having extended waiting periods for materials to arrive at the paving site. Figures 11 and 12 show a cold spot that corresponds to the location of spilled material on the existing surface from the raising of the truck bed to remove loose material. Figure 35 is an example of a V-shaped cold spot. The V-shape of the cold spots indicates that cold material came from the hopper as it was being moved out laterally by the auger as the paver moved forward.

Figure 34. Material Spilled By Truck Pull-Out After Discharge into Paver.

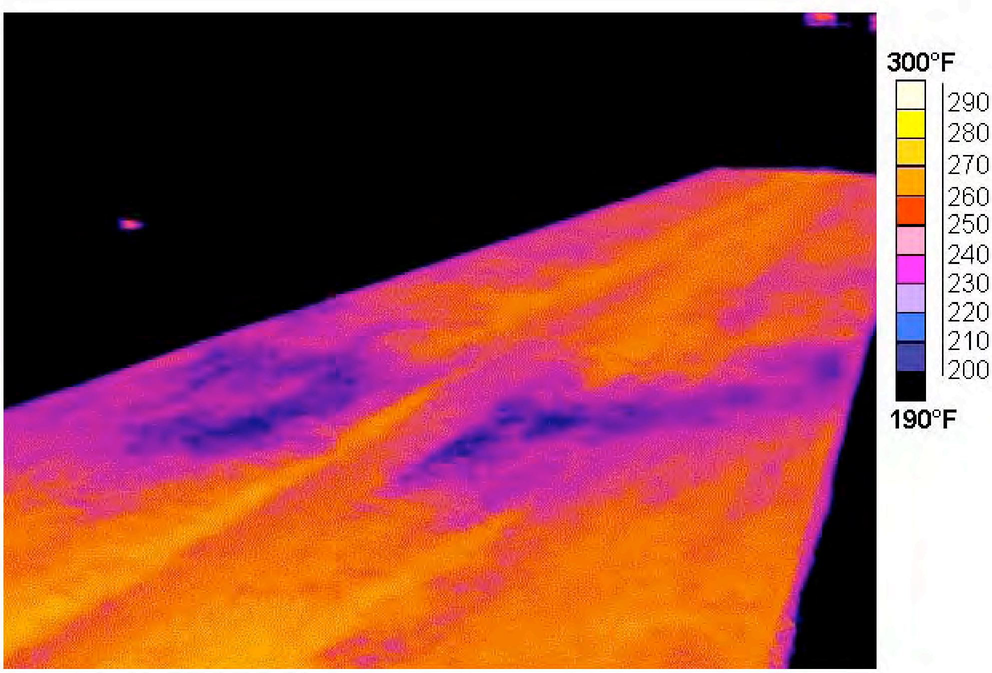


Figure 35, V-Shaped Cold Spot

The exact location of the cold spot in relation to the point where the paver stopped for a truck change varied depending how far the paver traveled without material being dumped into the hopper. The further the paver traveled without material being dumped into the hopper, the closer to the stop point the cold spot would occur. The location of the cold spot did not effect the magnitude of the temperature differences observed.

The use of a MTV greatly reduces the size and magnitude of the cold spots. This became very evident on monitored projects where a MTV was only used for a small portion of the project with no other changes to the equipment on the project. The only difference in the paver when a MTV is employed is the paver hopper insert. The rest of the paver is unchanged so therefore the material that forms the cold spots must originate from the standard paver hopper without the insert or the haul unit itself. It can also be concluded that the operation of the slat conveyors and screed augers do not significantly contribute to the formation of cold spots as these did not change when a MTV was used.

The remixing MTVs virtually eliminated all of the cold spots normally observed. The remixing action produced a virtually homogeneous temperature profile in the placed mat. The remixing MTVs also eliminated the visual segregation on two projects where visual segregation was distinct before a remixing MTV was employed. Over the course of this study, no projects were monitored where visual segregation was occurring and a non-remixing MTV was used for a portion of the project. Therefore, it is not possible to draw conclusions as to their effectiveness at reducing visually segregated areas. It was demonstrated that non-remixing MTVs do reduce thermal segregation.

Observations of pavement being placed on bridge decks were not made. Most of the paving projects observed did not have any bridge decks or if they did, they were not being resurfaced during the mainline paving operations.

The use of RAP in the pavement did not contribute to the temperature differentials observed in our projects. The temperature differentials observed for mixes that did or did not contain RAP was virtually identical. The use of RAP did not appear to have any influence on areas with visually segregated areas.

The paving crew may have a slight influence on the magnitude of the temperature differentials. But as was consistently demonstrated throughout the study, no paving crew can greatly reduce the magnitude of the cold spots without the use of a MTV.

The collection of data from night paving projects that did not use a MTV was very limited. From this limited data, it appears that night paving without a MTV does not influence the magnitude of the temperature differentials coming out from the paver. Night paving still requires added vigilance as the material will cool off quicker after it has been placed. Extra care must also be used to identify segregation during night paving operations as it is harder to identify them under reduced lighting.

There is no correlation between ambient air temperatures and temperature differentials observed as the material leaves the paver. Like night paving, additional care must be used when paving during less desirable conditions as the material in general will tend to cool off quicker.

The folding of paver hopper wings at frequent, regular intervals after each load does not contribute to the formation of cold spots in the pavement. When the paver hopper wings are folded infrequently, colder material from the wings is then incorporated into the mat forming a large cold spot and decreasing the density in that specific area. See Figures 2 and 3.

Segregation both thermal and gradation has many factors that can influence it. Throughout this study, it became clear that controlling these factors to isolate a single variable would be next to impossible. As much as possible, every attempt was made to isolate as many variables as possible.

Recommendations

Segregation, both gradation and thermal, greatly reduces the lifespan of the pavement. There are several things that can reduce the impact of thermal and gradation segregation. Remixing MTVs greatly reduce if not eliminate both types of segregation. The remixing that occurs in the machine homogenizes both the gradation and temperature of the material. This remixing tends to produce a mat with a uniform temperature profile along with a uniform surface texture. Some of the non-remixing MTVs have an option that allows for remixing in the paver hopper. While this option was never observed in use during this study, its use would be highly recommended based upon the results observed with the remixing MTVs. Even without the remixing paver hopper insert, non-remixing MTVs do greatly reduce thermal segregation. The use of MTVs should be encouraged.

Removing spilled HMA from the roadway prior to passing over the spillage with the paver will also help to reduce thermal segregation. This becomes especially important for spills of material containing more than one or two shovelfuls that will be on the roadway for an extended period of time prior to being covered with fresh material. The ambient air temperature and wind speed will also tend to cool any spilled material much quicker making removing the spillage more important on cool and windy days. Also, the cleaning of haul units should be performed in a designated area not in the area to be paved. Material cleaned out of the haul units in front of the paver acts like spillage and can create cold spots.

When using haul units that will be required to dump directly into the paver hopper the haul distance should be kept as short as possible. The results of this study indicate that while the haul distance does increase the size of the cold areas compared to those projects with a shorter haul distance. The monitored project with the greatest haul distance utilized a non-remixing MTV. The use of a non-remixing MTV did mitigate the effects of the long haul and produced a temperature profile similar to projects with much shorter haul distances.

Folding of the paver hopper wings should either be performed frequently such as after each load or not at all during the day's production. If the hopper wings are folded frequently, the flaps on the front of the paver hopper should be in good condition to reduce spillage out the front of the hopper when the wings are folded. When folding the hopper wings, attention should be paid to the quantity of material present in the hopper. If there is too little material in the hopper, the cooler material from the hopper wings will strongly influence the thermal profile of the pavement. If the paver hopper is too full, then the material from the hopper wings will over flow out the front of the paver hopper. It is important to also maintain the level of material in the paver hopper to cover the conveyors and permit a uniform flow of material to enter the paver tunnel at the flow gates.

While night paving and cold weather did not produce large temperature differentials, additional care must still be used when paving in these conditions. The effects of night paving and cold weather paving could not be observed in this study as the infra-red camera only measures the surface temperature of the pavement. The surface temperature of the pavement is only indicative of the pavement's temperature before rolling commences as water from the rollers will produce a false temperature reading for the surface of the pavement.

The use of heated bodies on the haul units did reduce the magnitude of the observed temperature differentials by approximately 5°F. While this use of heated bodies does not resolve the problem of thermal segregation, it does help to reduce the problem. Additional study of the different types of heating systems for the haul units should be undertaken using the thermal camera to determine their effectiveness.

The thermal imaging camera is an excellent tool for identifying areas of freshly placed HMA pavements that may have segregation problems. The camera readily identifies areas with temperature differentials. Density testing should be performed in these low temperature areas with a nuclear density gauge to identify the reduction in the density in these areas. Additional research work should be performed to identify a procedure for testing areas with low temperatures during construction as some state Departments of Transportation have instituted maximum allowable temperature differentials in an attempt to minimize thermal segregation problems. Other states are attempting to implement a procedure to perform density testing profiles through cold spot areas.

Two monitored sites for this study had serious visible segregation when the end dump method for material transfer was used. In the middle of paving these projects, a remixing MTV was used for several days of placement thereby eliminating the visible segregation when the MTV was in use. Studying these projects further as they age would help to establish how much additional life span, if any, could be expected with the use of a remixing MTV. One monitored project for this study did use a non-remixing MTV for one day of production. This project could also be monitored for the life expectancy differences between portions constructed with the non-remixing MTV and the portions constructed with the haul units dumping directly into the paver hopper.

Throughout this study GPS coordinates were obtained at the location where each thermal image was taken. The GPS coordinates provide location references in order to allow further study of these pavements as they age. It is recommended that an additional study be conducted in approximately 5 years to document the condition of the pavements 5-7 years after they were constructed. This additional study would help to document how the recorded temperature differentials at the time of construction have impacted the service life of the pavement. This may be practical only where pavements can be assessed without the need for traffic protection.

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Appendix A

This appendix contains detailed information about the 40 sites monitored during the study. All thermographic images unless otherwise noted were taken in the direction of paving. The thermographic images were taken at the approximate location where the paver screed was stopped at the time of the truck change. On the graphs of density vs distance, 0 distance represents the center of the cold spot, negative distances represent HMA placed before the cold spot and positive distances represent HMA placed after the cold spot.

Table A1 - Monitored Sites

Site Number	Project Number	Route Number	Town	Date
1	72-76	I-395	Lisbon	11/8/2000
1	72-76	I-395	Lisbon	11/9/2000
1	72-76	I-395	Lisbon	11/13/2000
1	72-76	I-395	Lisbon	11/15/2000
1	72-76	I-395	Lisbon	11/16/2000
1	72-76	I-395	Lisbon	11/18/2000
1	72-76	I-395	Lisbon	11/20/2000
1	72-76	I-395	Lisbon	11/21/2000
2	171-293C	178	Bloomfield	5/2/2001
2	171-293C	178	Bloomfield	5/1/2001
3	172-327A	2	Norwich	6/14/2001
4	172-327G	66	Windham	6/19/2001
5	137-137	2	Stonington	6/29/2001
6	174-295A	8	Torrington	7/5/2001
7	172-327K	195	Storrs	7/10/2001
7	172-327K	195	Storrs	7/11/2001
8	46-118	I -91	Enfield	7/12/2001
9	171-293J	140	Ellington	8/7/2001
9	171-293J	140	Ellington	8/9/2001
10	171-293K	189	Bloomfield	8/21/2001
11	174-295J	44	Norfolk	8/27/2001
11	174-295J	44	Norfolk	8/28/2001
12	172-338C	1A	Stonington	6/12/2002
13	76-190	Tolland Turnpike	Manchester	6/13/2002
14	172-337N	SR. 607	Killingly / Danielson	6/14/2002
15	172-337C	16	Colchester	6/19/2002
15	172-337C	16	Colchester	6/21/2002
16	172-337H	101	Killingly	6/26/2002

Table A1 – Continued

Site Number	Project Number	Route Number	Town	Date
17	172-337F	87	Lebanon	6/27/2002
18	174-305H	7	Falls Village	7/2/2002
18	174-305H	7	Falls Village	7/8/2002
19	171-303H	6	Farmington	7/10/2002
20	172-337K	196	East Hampton	7/15/2002
20	172-337K	196	East Hampton	7/16/2002
21	173-348	I-91	Wallingford	7/17/2002
22	171-302I	31	Coventry	7/19/2002
22	171-302I	31	Coventry	7/22/2002
22	171-302I	31	Coventry	7/31/2002
23	172-337J	195	Storrs	7/25/2002
23	172-337J	195	Storrs	7/26/2002
24	171-302H	6	Manchester	8/2/2002
24	171-302H	6	Manchester	8/5/2002
25	164-224	I-91	Windsor	8/7/2002
26	171-302J	74	Vernon	8/28/2002
27	171-303C	94	Glastonbury	9/3/2002
27	171-303C	94	Glastonbury	9/4/2002
27	171-303C	94	Glastonbury	9/5/2002
27	171-303C	94	Glastonbury	9/10/2002
27	171-303C	94	Glastonbury	9/17/2002
28	171-303F	5 & 15	Newington	9/12/2002
29	94-202	I-95	New London	10/3/2002
30	172-338L	184	Groton	10/10/2002
30	172-338L	184	Groton	10/17/2002
31	51-249	4	Farmington	10/15/2002
31	51-249	4	Farmington	10/22/2002
32	131-162	10	Southington	10/15/2002
33	173-348H	22	North Haven	10/28/2002
33	173-348H	22	North Haven	10/29/2002
34	162-131	8	Winchester	11/1/2002
35	174-305E North Crew	10	Farmington	11/2/2002
35	174-305E South Crew	10	Farmington	11/2/2002
36	155-149	Farmington Avenue	West Hartford	11/5/2002
37	171-306C	320	Willington*	6/6/2003
38	171-307H	176	Newington*	6/9/2003
39	129-107	186	Somers*	6/11/2003
40	57-106	201	Griswold*	6/16/2003

* Monitored for heated body study only

Monitored Site 1

Research was conducted at the first paving site for the study on I-395 Southbound one mile north of exit 86 from November 8 through November 21, 2000. Conditions for the segments paved were as listed in Table A2 on the days of observation:

Table A2 - Placement Variables Observed on I-395 in Lisbon

Date	% RAP	Silo Used	Compacted Thickness	MTV Used
11-8-2000	0	No	1.5 Inches	No
11-9-2000	0	Yes	1.5 Inches	No
11-13-2000	10%	Yes	1.5 Inches	No
11-15-2000	20%	Yes	1.5 Inches	Yes
11-16-2000	20%	Yes	1.5 Inches	Yes
11-18-2000	0	No	1.5 Inches	No
11-20-2000	0	No	1.5 Inches	No
11-21-2000	0	No	2.0 Inches	No

The materials used appeared to have little effect on the presence of cold spots. Since all sections, with or without the presence of RAP and with or without silo storage, showed some cold spots, it appears that the major cause of such spots may be in handling. Figure A1 shows the thermal images of cold spots in a Virgin, Silo placement and in the 10% RAP, Silo placement. Most cold spots were observed nearly across the entire width of the mat in a V-shaped pattern. This indicates cool material conveyed to the screed augers such that the augers continued to push the cool material outward from the center of the screed as the paver moved forward, thus creating the V-shaped cool spots. The cold spot elongated longitudinally probably due to material spilled during truck changes being pushed or pulled by the paver.

Days that included paving from silo storage showed little difference from the days when no silo storage was employed. However, the use of silos may reduce loading delays between trucks Figure A2 shows images of cold spots in a Virgin, No Silo placement and in Virgin, Silo placement.

The thickness of the asphalt lift was altered on the last day of paving. The lift thickness was increased from 1.5 inches to 2.0 inches, and the mix was kept constant as Virgin, No Silo. The major difference in the two cases was the significantly decreased visibility of cold spots (visibly segregated patches) on the surface when the 2-inch lift was paved. In the 1.5-inch section, cold spots were easily identified since they were visible to the human eye on the surface of the freshly placed pavement where the front of the paver had been stopped during truck changes. These cold spots were either barely or no longer visible to the human eye on the 2-inch lift; however, significant cold spots were visible in the thermal infrared images. Figure 3 illustrates the images of cold spots in both a 1.5-inch and 2.0-inch lift section. Cold spots observed in the 2.0-inch lift also were found to cover a smaller area than those observed in the 1.5-inch section. This was the only site monitored where the target compacted thickness was intentionally changed for a day's paving.

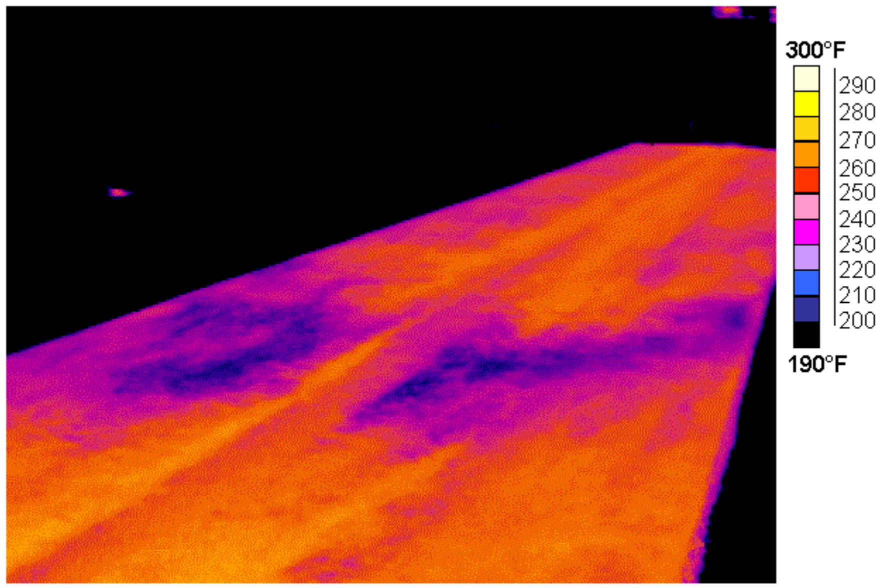
There were approximately 16 to 18 trucks hauling every day and the same amount of material in every truck, regardless of the capacity of the truck. The material in the semi trailers flared out to zero depth at one end, possibly leading to more cooling. Frequently, trucks pulling away from the paver spilled material on the pavement in front of the paver, as shown in two digital photographs presented in Figure A4. The spilled material was shoveled onto the shoulder, into the hopper, or on several occasions, it was left lying on the pavement in front of the paver. Cold spots were then recorded in the spillage area after the paver had passed over the area (see Figure A5). When unloading a truck, the main flow of material is to the rear, but a lateral flow can occur through the triangular opening between the tailgate and the end of the truck bed sidewall. The corner of the bed of a new truck backing in can also knock some of the side pile into the conveyor and a cold spot tends to occur on that side.

For two days, a Roadtec 2500 MTV was used and as a result, the paver moved as much as 3,000 feet without stopping. Occasionally some material was spilled on the pavement as a truck pulled away from the MTV front hopper; however, as the paving train did not stop, it was impossible to shovel this material out of the paver path. Surprisingly, thermal inspection revealed no cold spots as shown in Figure 6. The hopper that the trucks dumped into on the Roadtec MTV tended to spread any spilled material on the existing surface to a thickness of approximately the largest aggregate present in the HMA. The spreading out of the material by the Roadtec MTV combined with the speed of the paving train minimized uneven cooling of the HMA mat. These two factors, combined with the remixing of the HMA occurring within the Roadtec MTV greatly reduced or eliminated the appearance of cold spots altogether. Likewise, cold spots were not visible even when the operations were stopped for refueling of the paver or when waiting for additional material. Table A2 shows average temperature differentials and average density differences for each of the eight days of monitoring.

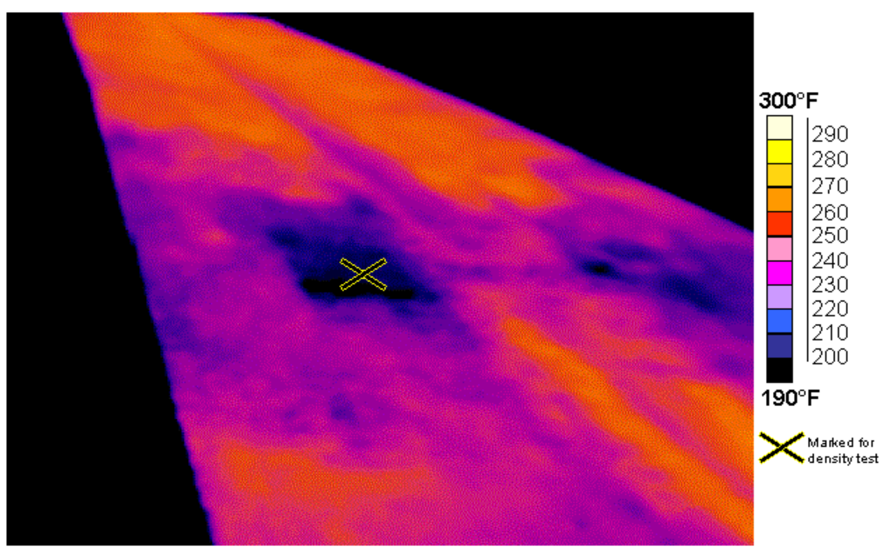
Table A3– Average Temperature Differentials and Corresponding Average Density Differences

Date	Average Temperature Differential, (°F)	Average Density Difference, (pcf)
11-08-00	48.8	4.4
11-09-00	55.7	6.85
11-13-00	46.3	7.18
11-15-00	17.32*	6.2
11-16-00	20.92*	No densities taken
11-18-00	45	4.14
11-20-00	49.4	3.0
11-21-00	51.9	No densities taken

* A re-mixing MTV was utilized

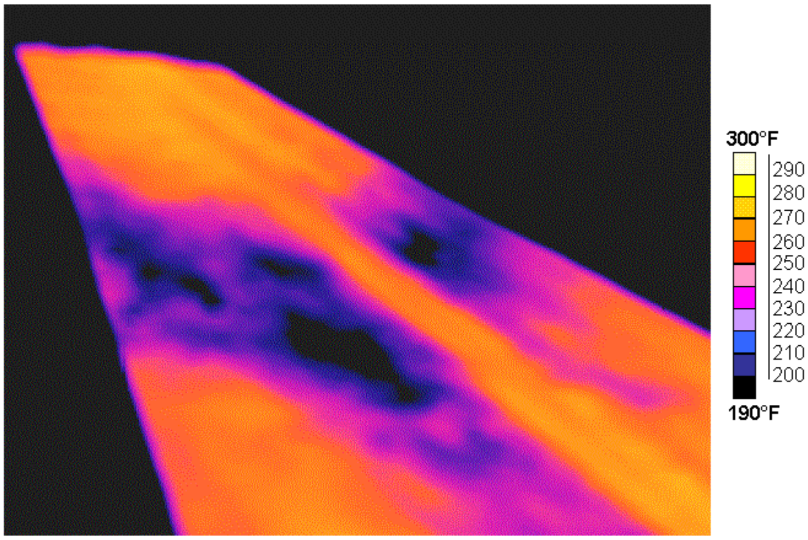


Virgin, Silo – V-shaped Cold Spots

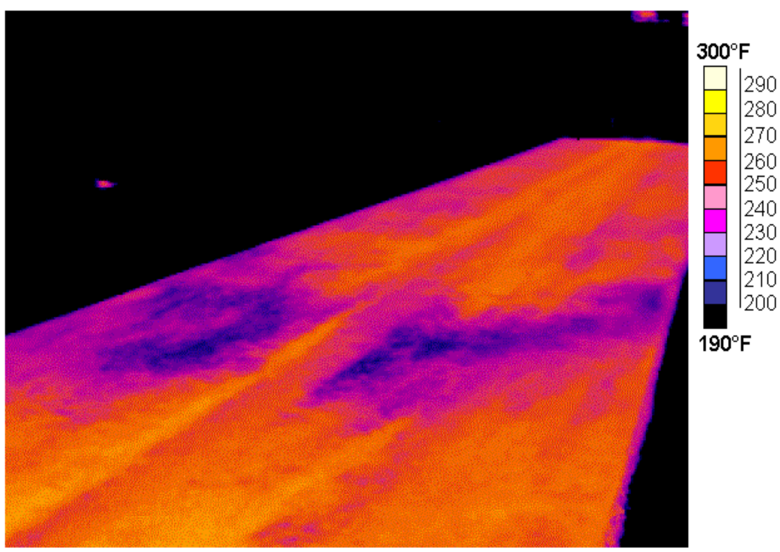


10% RAP, Silo – V-shaped Cold Spots

Figure A1: Effect of Mixture Type, Virgin versus RAP, Shown in Thermal Images of Cold Spots in Paved Section I-395.

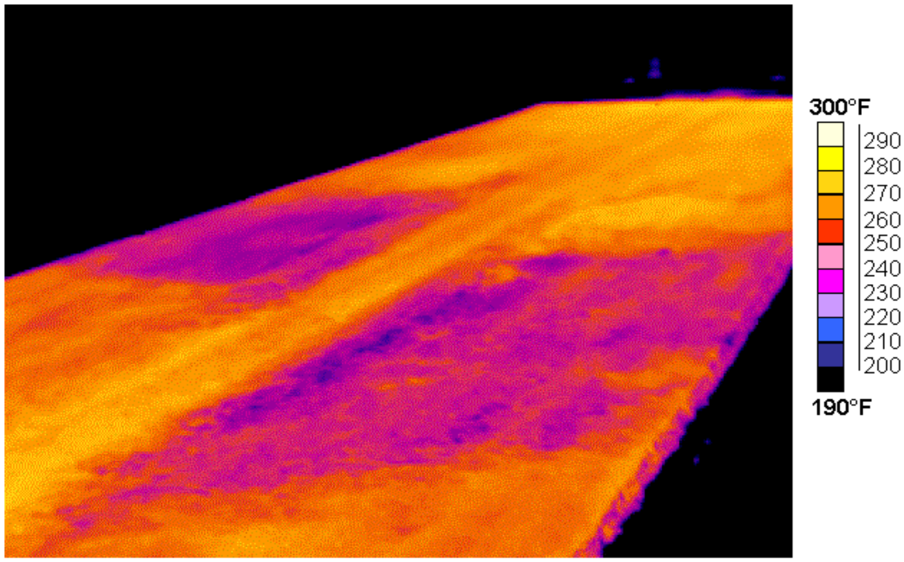


Virgin, Non-Silo – V-shaped Cold Spots

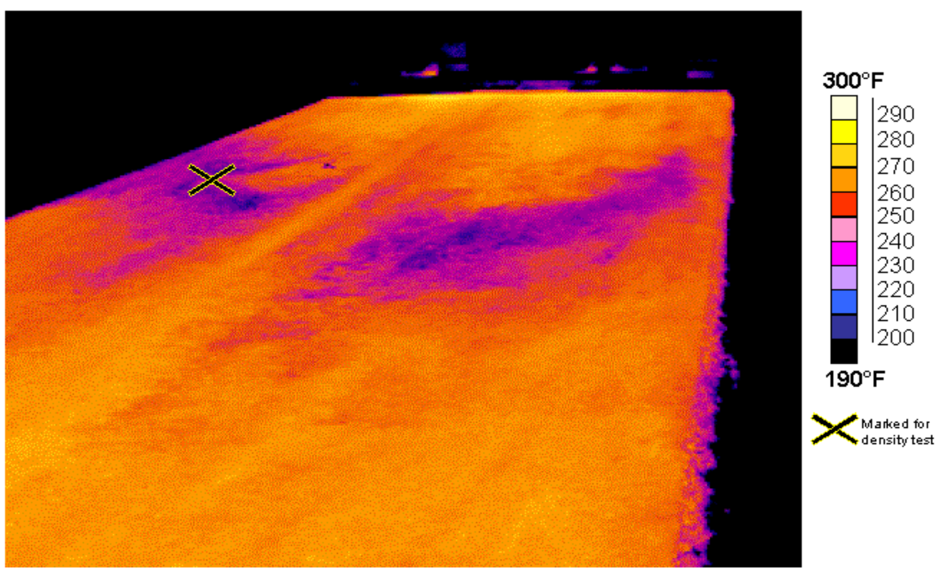


Virgin, Silo – V-shaped Cold Spots

Figure A2: Effect of Material Storage, Silo versus No Silo, Shown in Thermal Images of Cold Spots in Paved Section I-395.



1.5-inch Virgin, Non-Silo – Cold Spots Both Sides of Lane



2.0-inch Virgin, Non-Silo – Smaller V-shaped Cold Spots

Figure A3: Effect of Mat Thickness, 1.5 versus 2.0 inch, Shown in Thermal Images of Cold Spots in Paved Section I-395.

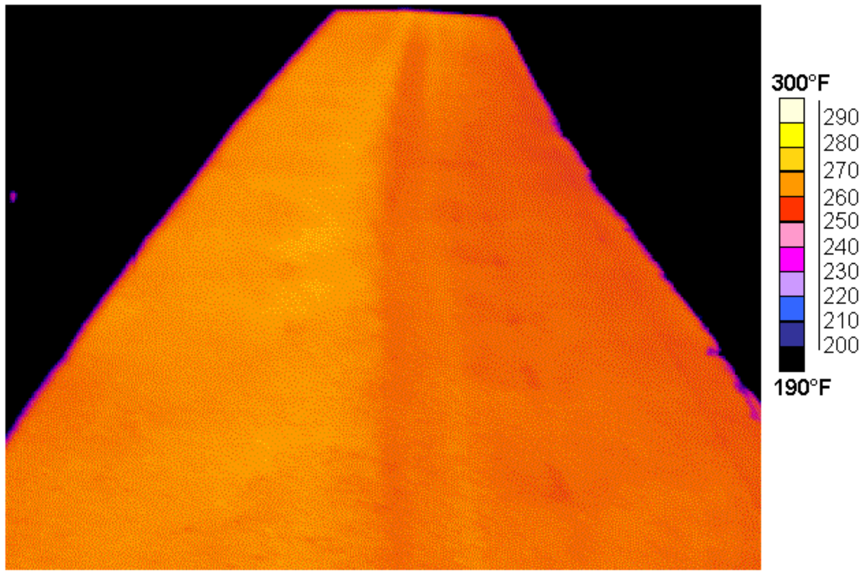
Spillage of Material in Front of Paver and Out of Hopper Bed

Figure A4: Two Examples of Material Spillage in Front of Paver on I-395.

Virgin, Silo, 1.5" Lift Thickness – Open Texture in Compacted Mat Corresponding to Cold Spot

10% RAP, Silo, 1.5" Lift Thickness – Open Texture in Compacted Mat Corresponding to Cold Spot

Figure A5: Two Examples Where Cold Spots, Found with Infrared Thermal Camera, Are Visible on Surface of Pavement on I-395.



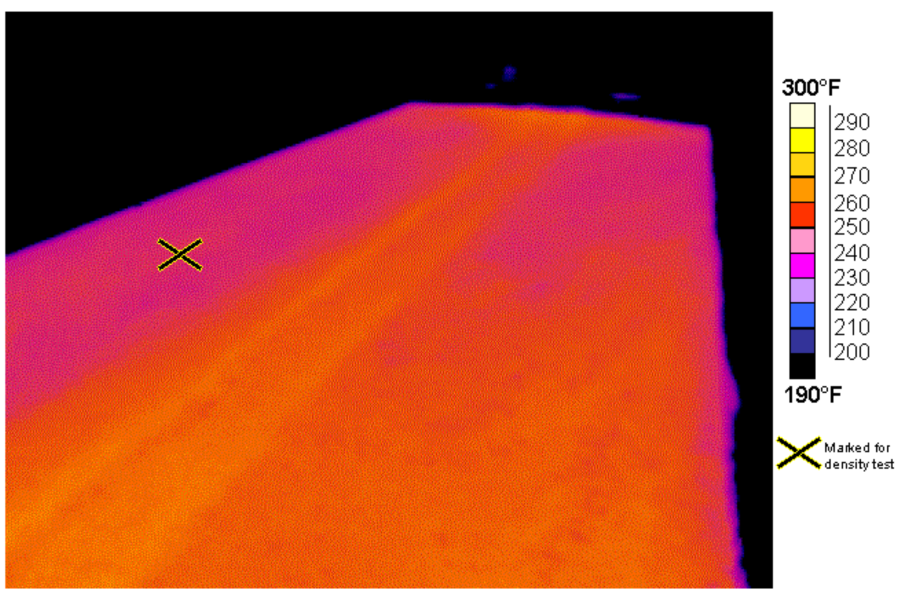


Figure A6: Effect of Material Transfer Device - Mat Shows No Evidence of Cold Spots in Thermal Images for Paved Section I-395 (20% RAP, Silo, 1.5" Lift Thickness).

In cold weather paving, the time available for compaction is limited by rapid cooling of the mat. It may be suggested that roller operators should be alert to the formation of cold rolling cracks. Cold rolling cracks were formed when roller spacing was not tight enough and the surface of the mat cooled too much before the rolling process had been completed. These cracks were sometimes observed even on the day when the material transfer device was in operation and when the 2.0-inch mat was paved (see Figure A7). It appears that rolling these cracks out completely is not possible, and they may later become the initiators of active surface cracks. The number of rollers needed may increase when paving in cold weather. For example, if three rollers are adequate on a 50°F day, it may require four rollers on a 40°F day because faster cooling decreases time for compaction.

Nuclear density tests were taken through a few cold spots at some locations. The typical mat temperature was approximately 265°F and the maximum temperature differential was typically around 70°F. The distribution of temperature differential with change in density is shown in Figure A8. The figure indicates that as the temperature differential increases, there is an increased density differential. This drop in density can be explained by the cooler HMA's resistance to compaction. Cold spots observed on this project typically started 1.5 feet to either side of the paver pass centerline and extended forward and towards the edges of the paver pass. These tend to be cyclic, occur when the haul units dumped directly into the paver hopper.

1.5-inch 20% RAP, Silo, Material Transfer Device Used – Cold Rolling Cracks

2.0-inch Virgin, No Silo – Cold Rolling Cracks

Figure A7: Effect of Roller Spacing – Cold Rolling Cracks When Rollers Were Not Spaced Tightly.

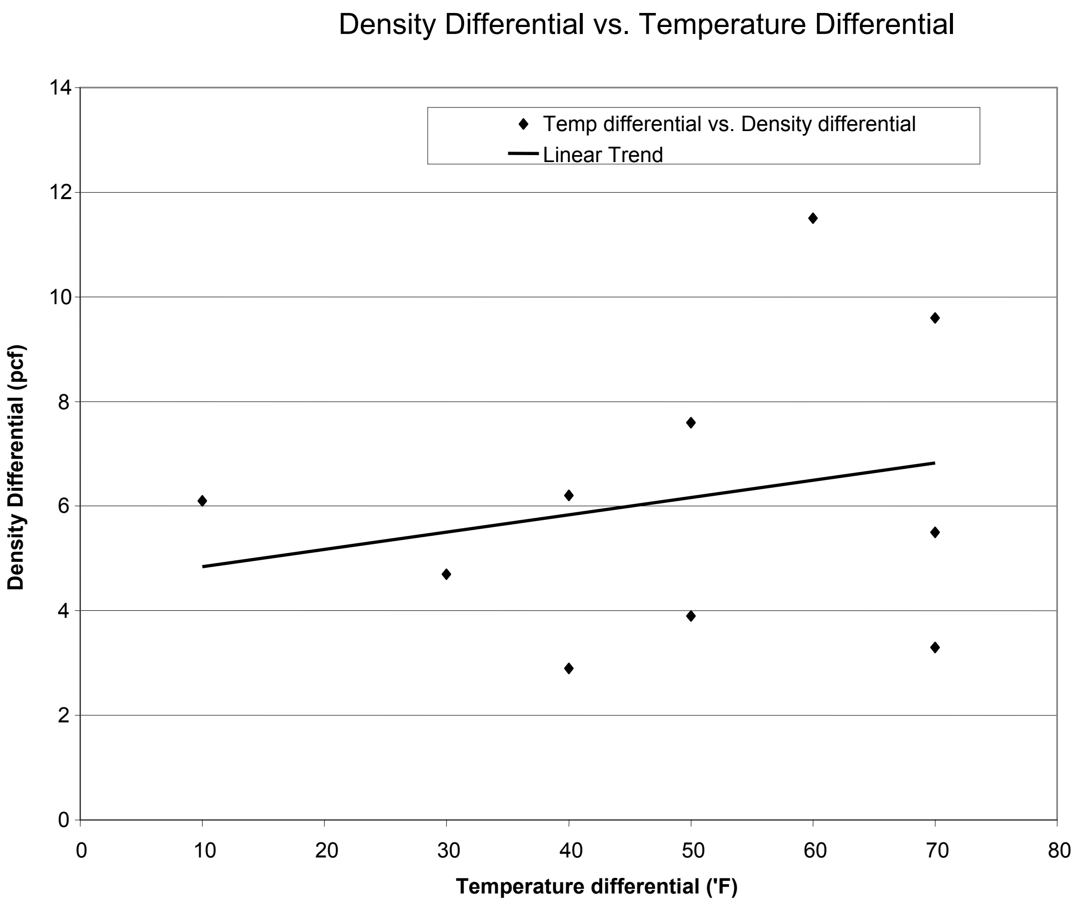


Figure A8. Distribution of Temperature Differential with Maximum Change in Density.

Monitored Site 2

The second site selected for monitoring was a resurfacing project located on Route 178 between Routes 185 and 189. Route 178 was completed under project number 171-293C. The pavement was placed on May 1st and May 2nd, 2001 and the haul time was approximately 15 minutes for a distance of 10 miles. The weather conditions were sunny with an ambient air temperature of 88°F. A batch plant was used to produce 2000 tons of Connecticut DOT Class 1 mix (PG 64-28 binder) wearing course placed at 50-mm (2.0-inch) compacted depth. Typical mix temperatures were recorded in the truck beds at approximately 280°F and typically three drops of material were loaded per truck.

The paving contractor used a Cedar Rapids Greyhound CR551 paving machine and loosely-tarped tri-axle dump trucks carried the material from the mix plant. There was no remixing of any kind implemented. An Ingersoll-Rand DD110 breakdown vibratory roller was used along with an 18-ton Hypac 50 C340CW finishing roller. A simple truck configuration study was conducted both days on site to determine pivot height, pivot-to-lip distance, pull-out height of lip, and pull-out spillage. There was a considerable amount of material spilled in front of the paver after each load was discharged into the hopper, as seen in Figure A9. Additional material was spilled on the existing surface when the haul units shook the beds and cleaned out the tailgates after discharging their loads into the paver.

Figure A9. Material Spilled By Truck Pull-Out After Discharge into Paver.

The existing mat surface temperature, prior to placement of wearing course, was recorded to be 124°F. Temperature differentials in the freshly placed pavement were observed with the thermographic camera as being typically in the outer portions of the lane. The typical mat temperature behind the screed and prior to rolling was recorded as 270°F. The maximum temperature differential within the mat was observed to be as high as 80°F and the average temperature differential on this site was 54.1°F on the first monitoring day and 46.9°F on the second day. Figure A10 shows a temperature differential of approximately 60°F in the uncompacted mat.

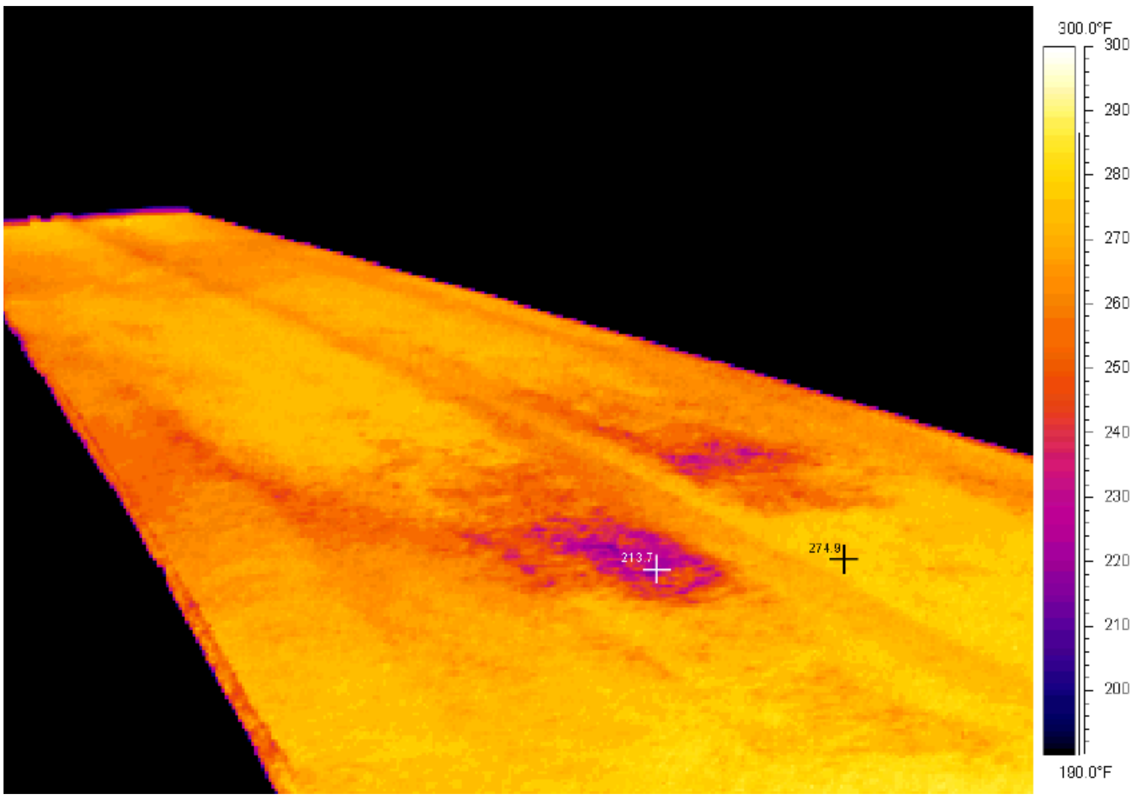


Figure A10. Temperature Differential in Mat Prior to Compaction on Route 178.

The cool spots observed in mats on Route 178 were typically not cyclic; however, they appeared to occur in conjunction with spilled material in front of the paver. The image shown in Figure A11 illustrates a temperature differential of approximately 55°F with a weak v-shaped cool spot.

A nuclear gauge was not available; therefore, no compaction data for determining the change in air voids or range of air voids was gathered, however, visual inspection showed areas of open-textured mat, such as that seen in Figure A12, that were observed as cool spots in the same location using the infrared thermographic camera.

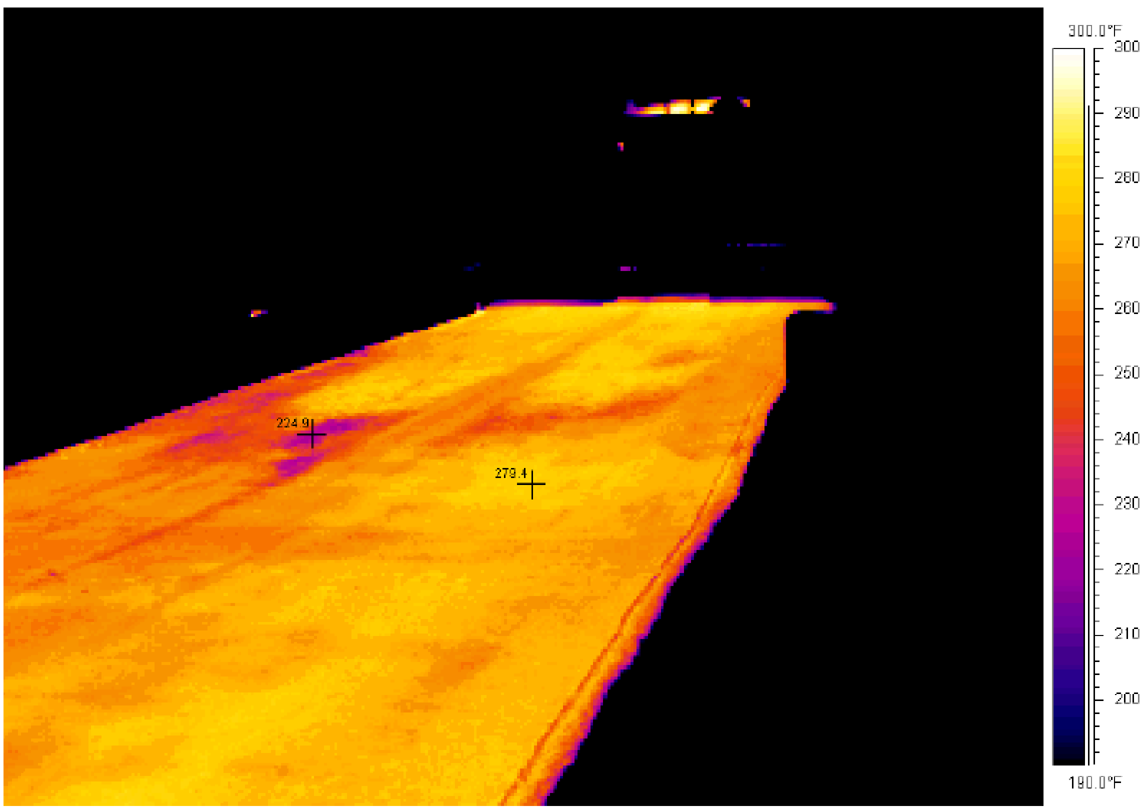


Figure A11. Temperature Differential in Mat Prior to Compaction on Route 178

Figure A12. Open-textured Mat Observed Prior to Compaction.

Monitored Site 3

This site was the resurfacing of Route 2 in Norwich, project number 172-327A. The project was monitored on June 14th, 2001. The day was cloudy and ambient temperatures were around 75°F. The material being placed was Superpave 12.5 mm and it had a compacted thickness of 2.0 inches. This project placed HMA with a RAP content of 10%. The material was hauled 5 miles from a plant in Montville. The hauling time for the trucks was about 10 minutes. The contractor paved with a CAT model AP1055B paver and two Ingersoll-Rand model DD110 rollers for breakdown and finish rolling. The contractor also used a RoadTec model SB-2500 material transfer vehicle. At the time, only images of cold spots were taken rather than every truck change therefore only 3 images were taken. The relatively small temperature differentials are indicative of a remixing MTV. The average temperature differential observed on this project was 14.9°F. There were no densities observed or recorded for this project.

Monitored Site 4

The next site selected for monitoring was a resurfacing project (172-327G) on June 19, 2001, located on Route 66 in Windham. The sunny day had an ambient air temperature of 83°F and the existing pavement surface temperature during the daytime hours was recorded at 120°F. Loosely-tarped tri-axle dump trucks were unloading HMA into a CAT AP-1055B paving machine. A 10-ton Hyster 350 breakdown roller was used for initial compaction, followed by a Hyster 766 15-ton vibratory finish roller.

A compacted thickness of 1.5 inches of Connecticut DOT Class 1 (PG 64-28) mix was placed as a wearing course. There was no remixing device used on this project. The 1000 tons of material was produced at a batch plant approximately 25 miles away and had a 30-minute haul time. The typical temperature of the HMA recorded while unloading from the haul units was 310°F. The average temperature difference that was observed on this site was 54.9°F.

The typical mat temperature prior to compaction was 290°F. Cyclic cool spots were observed typically in the middle of the pass and a maximum temperature differential of approximately 60°F was documented. Spilled material was often left on the existing pavement in front of the paver. Delays between haul units arriving at the site permitted excessive cooling of this spilled-loose material. It was more difficult to compact once the spilled material was covered by fresh HMA since effective heat transfer between the two materials was not attained. Figures A13 and A14 show typical cold spot configurations observed at this location. The cool spots were not nearly as large as were observed at other projects. This was most likely the result of the ambient air temperature being warmer than on the other projects that had much more expansive cold spots and the 2.0 inches thickness.

Figure A15 shows an image taken after a long delay between truckloads of material being delivered to the site. The image has the paver moving away in the image and the black region at the bottom of the image shows that the pavement placed before the delay was cooler than 190°F. The delay was approximately 50 minutes and the resulting temperature difference in Figure A15 was almost 90°F.

There was some difficulty acquiring data at this project due to its location in downtown Willimantic and the urban nature of the traffic patterns. Nuclear density readings were not obtained at this site.

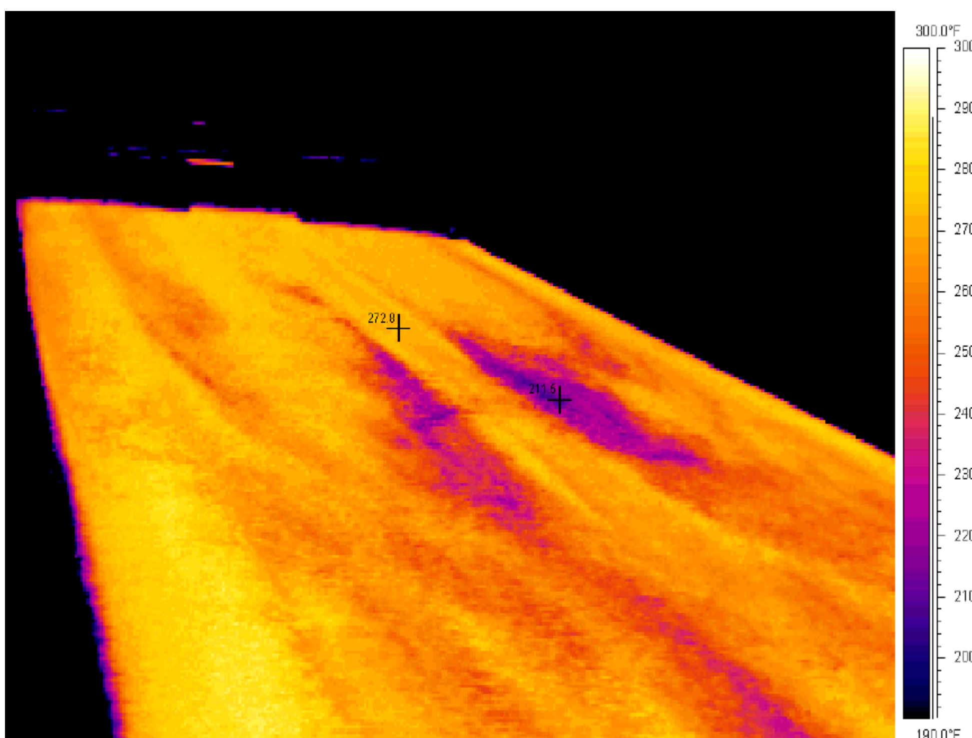


Figure A13 – Typical Cold Spot configuration observed on Route 66 in Windham

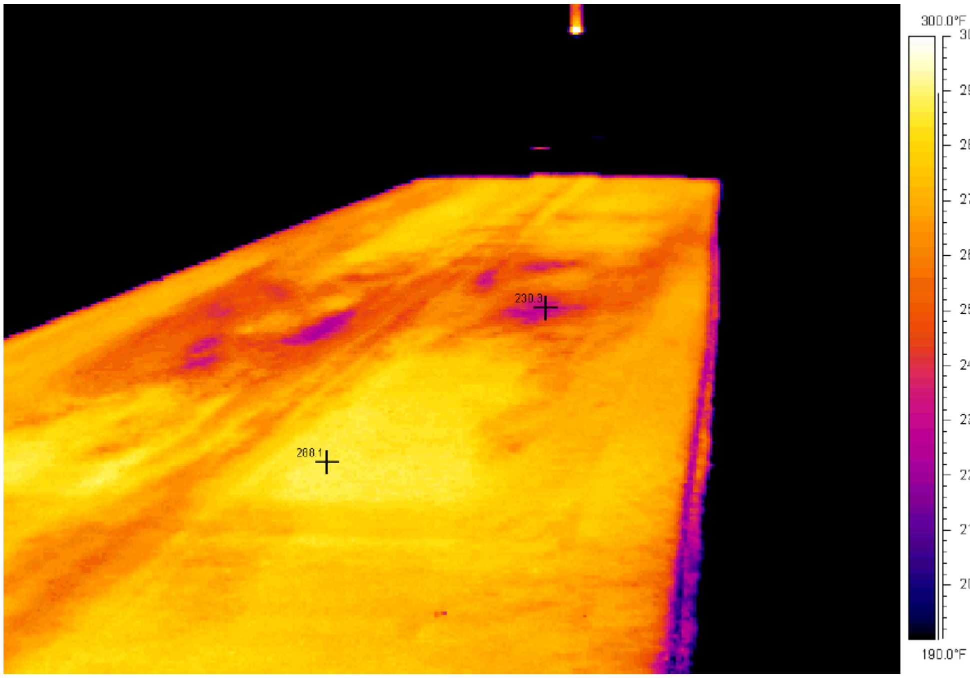


Figure A14 – Typical Cold Spot configuration observed on Route 66 in Windham

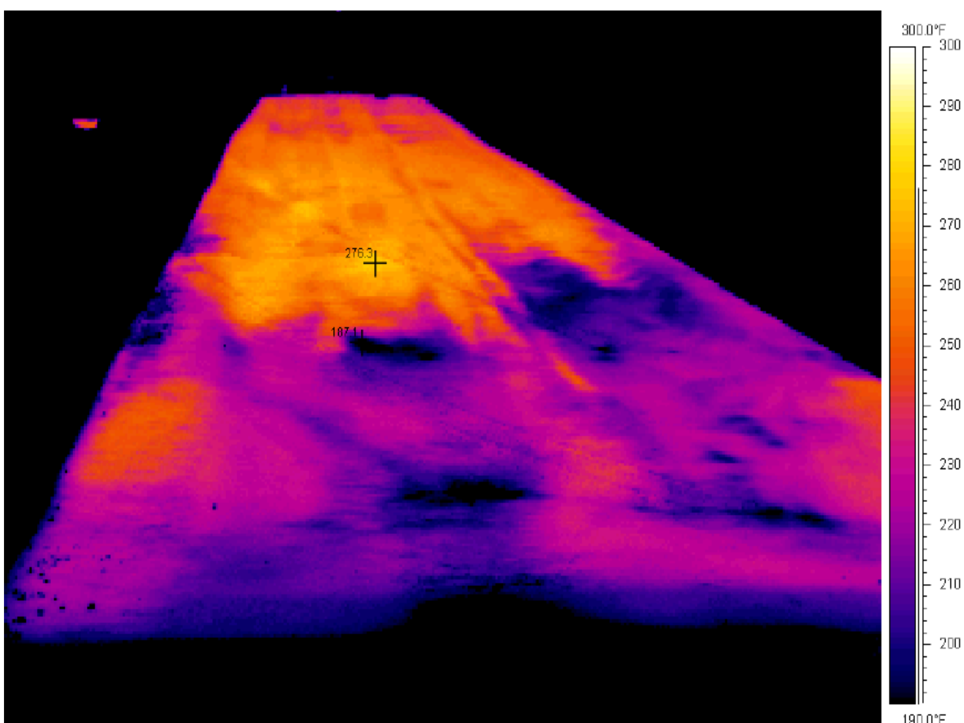


Figure A15 – Image showing effect of approximately 50 minute delay between truck loads of material being delivered to the site – Route 66 in Windham.
(The paver is moving away in this image)

Monitored Site 5

The fifth site monitored was a resurfacing project (137-137) of Route 2 in Stonington. The pavement operation was observed during daytime hours on June 29, 2001 and the haul time was approximately 15 minutes for a distance of 10 miles. The weather conditions were partly sunny with an ambient air temperature of 70°F. A drum plant was used to produce a virgin Superpave 12.5 mm mix (PG 64-28 binder), placed at 50-mm (2.0-inch) depth. Mix temperature was recorded in the truck beds at 310°F and typically three drops of material were placed in each truck.

The Paving Contractor used a Blaw-Knox PF-200B paving machine and loosely-tarped tri-axle dump trucks carried the material from the mix plant to the site. Remixing of material was accomplished by the utilization of a Roadtec 2500 material transfer vehicle (MTV). An Ingersoll-Rand DD-110HF vibratory roller was used for breakdown compaction along with a vibratory Hyster finishing roller.

Infrared images indicated that the existing mat surface temperature, prior to placement of wearing course, was recorded to be 100°F. Temperature differentials in the freshly placed pavement were observed to be minimal with the thermographic camera. It appeared that the lack of material spillage and the advantage of remixing provided by using the material transfer vehicle virtually eliminated the presence of temperature differentials. The average temperature differential observed on this site was 14.4°F. Figure A16 shows the typical thermographic profile observed at this project.

Compaction data was not obtained for this particular site.

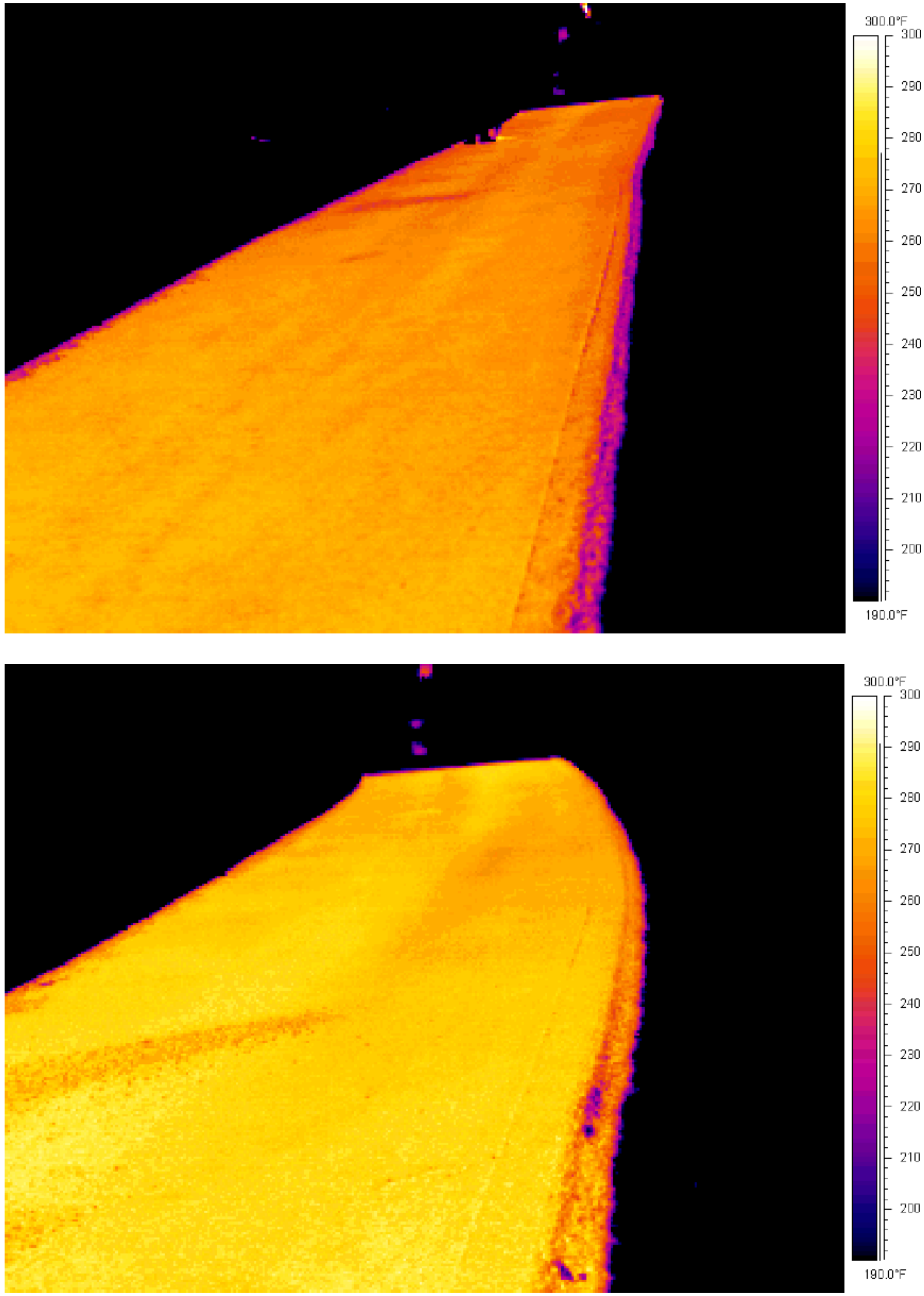


Figure A16 – Typical Thermographic Images from Route 2 in Stonington where a remixing MTV was used.

Monitored Site 6

The resurfacing project of Route 8 in Torrington (project number 174-295) was the next site monitored for the study. This pavement was placed at night on July 5, 2001 which gave the opportunity to record temperature differentials and observe nighttime construction operations. The average differential for this site was 25.5°F. The haul time was approximately 15 minutes for a distance of 10 miles. The weather conditions were cloudy with an ambient air temperature of 70°F. A batch plant was used to produce Superpave 12.5 mm mix (PG 64-28 binder) placed at compacted thickness of 2 inches (50 mm). Typical mix temperatures recorded in the truck beds were approximately 310°F.

The paving contractor used a Blaw-Knox PF 3200 paving machine with a Blaw-Knox MC330 MTV and loosely-tarped tri-axle dump trucks, loaded with three drops, brought material from the mix plant to the site. The MTV did not remix the material prior to dumping it into the paver hopper insert. The remixers on the hopper insert were not utilized. One 12-ton Ingersoll-Rand DD-90HF vibratory roller was used for breakdown compaction and another for intermediate rolling and finishing.

Infrared images indicated that the existing base surface temperature, prior to placement of the wearing course, was approximately 85°F. Temperature differentials in the freshly placed pavement were not observed to be as severe as in the paving sites where a material transfer vehicle was not used. Trucks dumping into a MTV tend to spill less material since there is no concern for maintaining some material in that hopper unlike when trucks dump directly into the paver hopper. By allowing the MTV hopper to empty completely, all of the material in the haul unit can be easily delivered to the MTV hopper. The speed of the paving train did not allow any material that did spill to cool substantially before it was incorporated into the mat. This type of MTV does not directly remix the material but the transfer of the material into the paver hopper insert does cause some remixing which helped to reduce the presence of temperature differentials as well as decreasing the severity; however, it did not eliminate them entirely. Figure A17 shows a typical image containing temperature differentials observed during the placement of the material.   As can be seen in Figure A17, the presence of cool spots was greatly reduced, but unlike the remixing MTVs the cool spots were still visible.

Compaction data was obtained for this particular site using a Campball nuclear density gauge. The theoretical maximum density for this project was cited as 165.1 pcf.

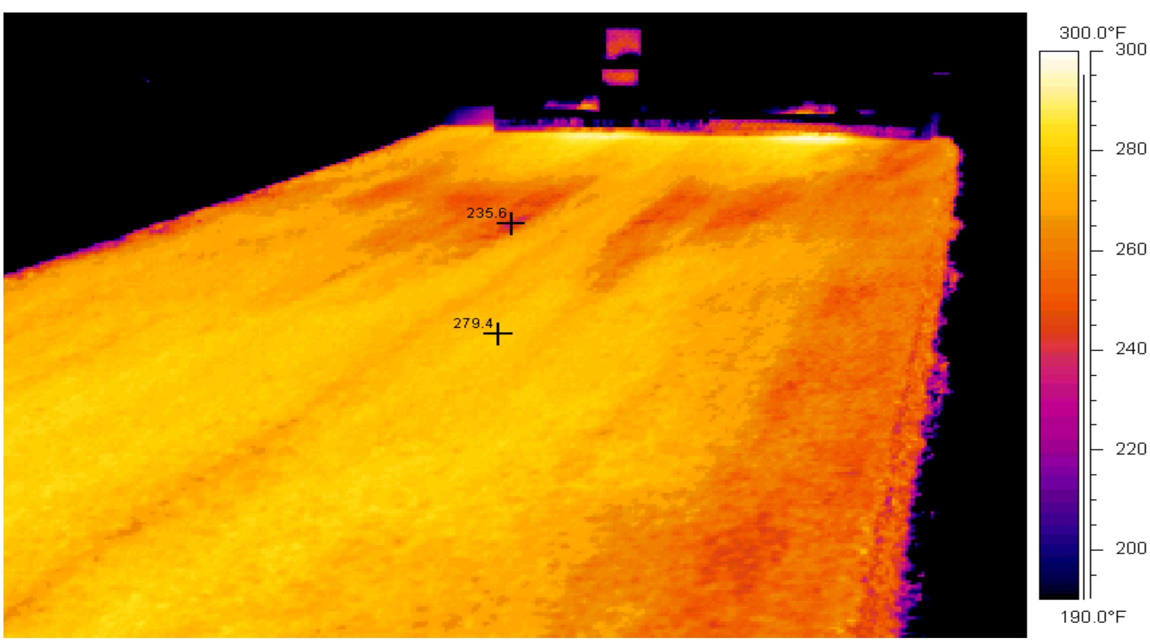


Figure A17, Area of Cooler Material Behind the Paver using a MTV that does not remix Material.

Monitored Site 7

The seventh site monitored was the resurfacing of Route 195 in Mansfield, Connecticut. These observations were made on July 10 and 11, 2001. The wearing surface for this project was to have a compacted thickness of 1.5 inches. The paver both days was a Blaw-Knox PF200B. On July 10^{th} a Blaw-Knox model MC30 MTV was used while on July 11^{th} the MTV was not used. The haul time was approximately 30 minutes for a distance of about 25 miles. The breakdown roller was an Ingersol Rand DD90. Information on the intermediate/finish roller was not recorded.

On July 10^{th} the weather was sunny with an ambient air temperature of 85°F and a base temperature of 110°F. The MTV, a Blaw-Knox model MC30, was the same make and model as was observed at Site 6. The size and magnitude of the cold spots observed did not appear as large as the projects not using a MTV. On this day, the largest temperature differential observed was 40°F.

On July 11^{th} the weather was again sunny with an ambient air temperature of 85°F and a base temperature of 120°F. The Blaw-Knox MTV was not in use for this day of paving. Without the MTV, the cold spots were considerably larger and the temperature differentials were greater. This project demonstrated the advantages of MTVs for reducing cold spots. The average temperature differential on the first day was 26.9°F and the average density difference was 3.93 pcf. On the second day when there was no transfer vehicle used, the average temperature differential was 58°F and the average difference in density was 6.83 pcf. Figures A18 a & b show typical thermographic images of the mat observed on the day the MTV was in use as well as when the MTV was not in use.

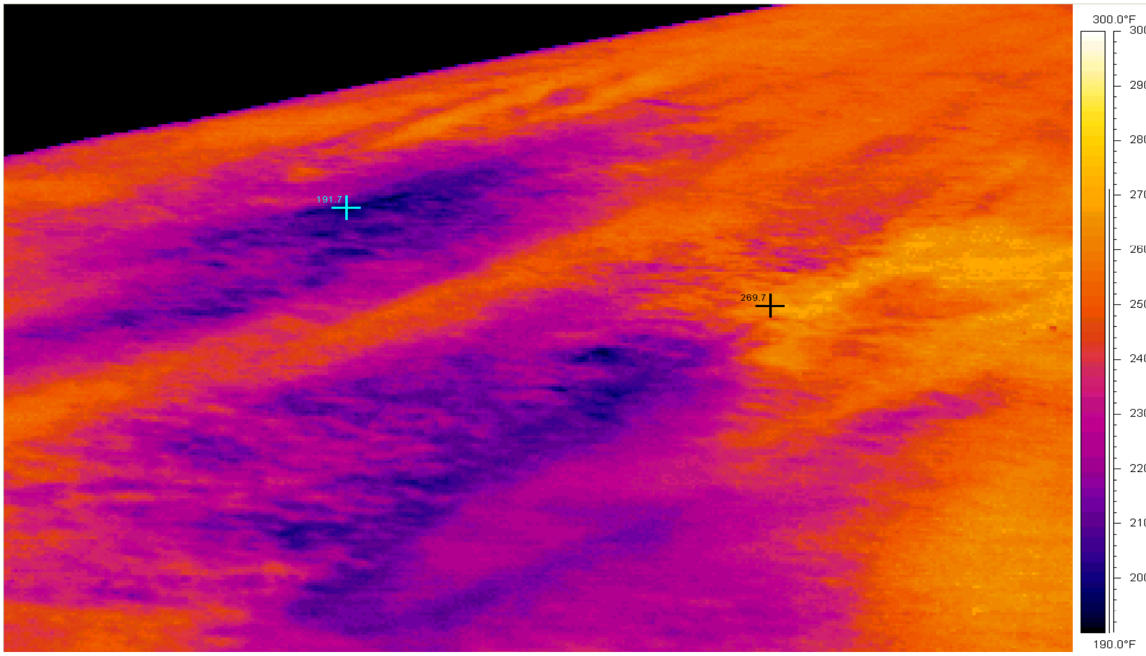


Figure A18a - Image of cold spots on 7-11-01 Storrs with no MTV.

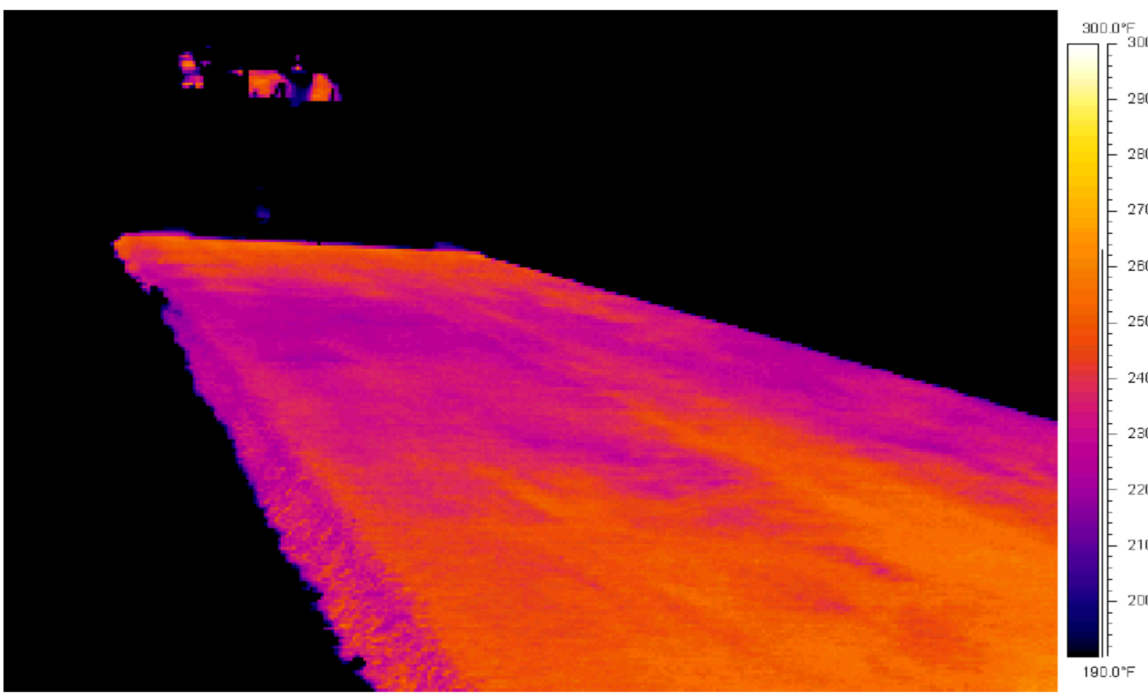


Figure A18b – Typical Thermographic Image of Paving on Route 195 with a non-remixing MTV

Monitored Site 8

This paving site was Interstate 91 in Enfield (Project 46 – 118) which took place during night time hours on July 12, 2001. The haul distance was approximately 16 miles, accounting for an average 20 minutes of haul time. The weather was cloudy with no precipitation and the base pavement temperature was 75°F.

The paving equipment consisted of a Blaw-Knox Model PF3200 paver, an Ingersoll Rand model DD90HF vibratory breakdown roller, a 28 ton CAT model PS360B rubber tired intermediate roller, and an Ingersoll Rand model DD90HF finish roller. No material transfer vehicle was used.

The thermographic images from this project indicate periodic cold spots with corresponding drops in density at those relative locations as seen in Figures A19 and A20. The average difference in temperature in the thermal images was observed to be 56.1°F and the average difference in density between warmer and cooler areas was 6.78 pcf for this site.

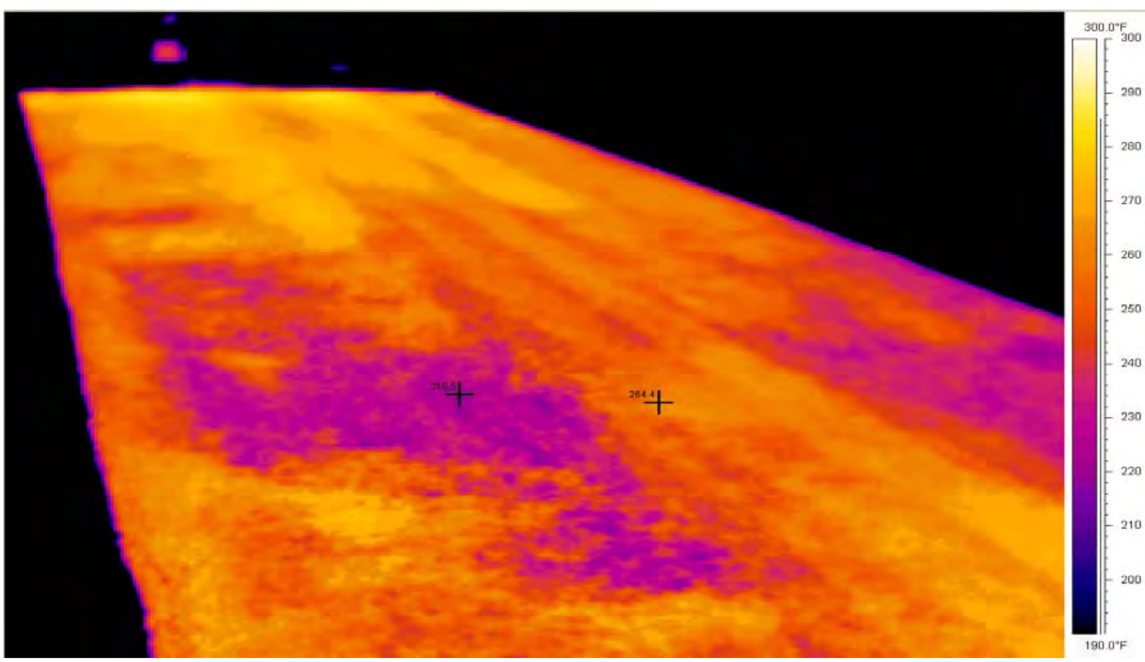


Figure A19 - Image of cold spot from shoulder of I-91

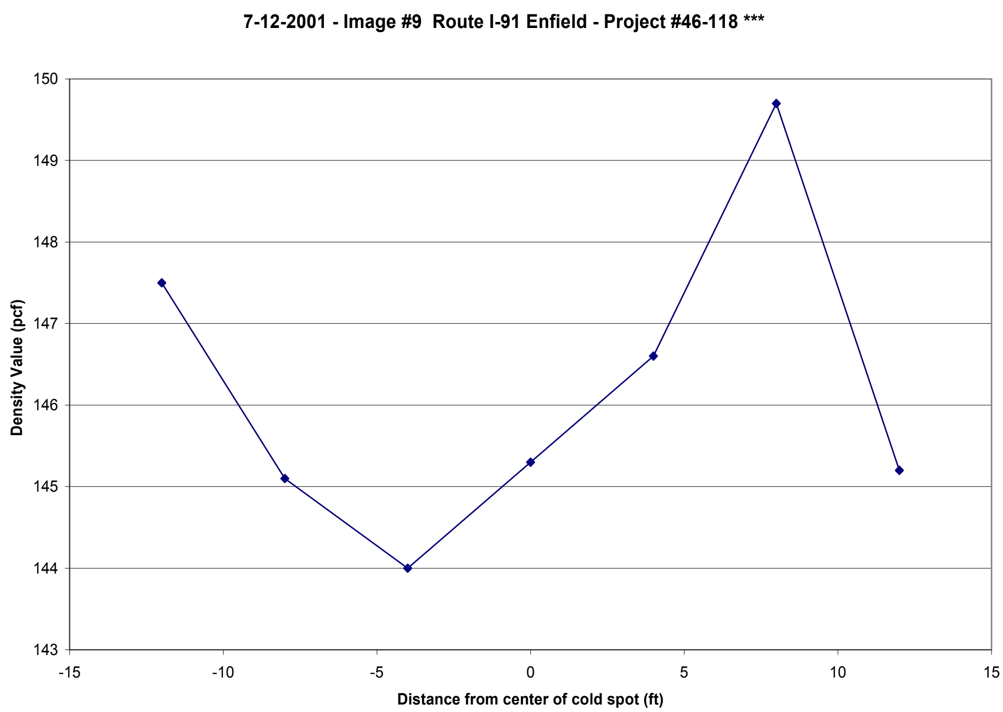


Figure A20 - Density vs Distance from cold spot

<u>*Note Image # at the top of each density plot refers to the image # for that corresponding thermal image in the Filemaker database</u>**

<u>Monitored Site 9</u>

Images were taken at this site in Ellington on two days, 8-7-01 and 8-9-01 on Route 140. The number for this paving project was 171-293J. The weather was sunny and ambient air temperatures ranged from 85°F - 100°F on both days. The material used was Superpave 12.5 mm with a compacted thickness of 1.5 inches. The HMA was hauled 22 miles from Granby which yielded approximately a 35 minute haul time. The base pavement temperature ranged from 105°F - 110°F in the sun and from 90°F - 95°F in the shade on both days.

The contractor paved with a Cedar Rapids paver and a Hypac model C788B vibratory breakdown roller. The intermediate roller was an Ingersoll Rand model DD-110 vibratory followed by a Hypac model C340CW finish roller. There was no transfer vehicle used on either of the two days and the equipment was the same for both days.

The cold spots in these images correspond to areas where there was either spill caused by trucks pulling away from the paver hopper or where material that was cleaned out of the truck was allowed to cool on the pavement. Again, there is an apparent drop in density at these locations as can be seen by the density plot. The average temperature differential was 66.4°F and 61.4°F for the first and second day respectively. The average difference in density was observed at 5.57 pcf on the first monitoring day and at 8.85 pcf on the second day of monitoring. Three densities were taken on August 8th and only two taken on August 9th due to poor traffic control. The images of typical cold spots for each day can be seen in Figures A21 and A23 and their corresponding plots of density variation vs. distance from cold spot center are shown in Figures A22 and A24 respectively.

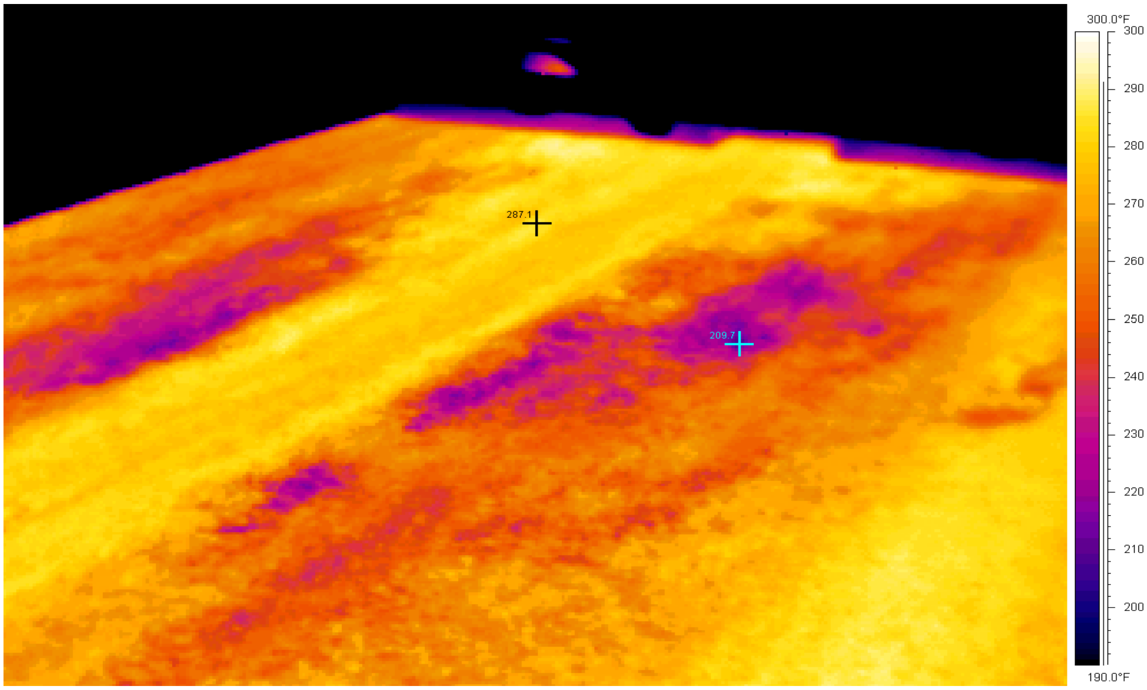


Figure A21 – Image of cold spot generated by spilled material on Route 140 on 8-7-01

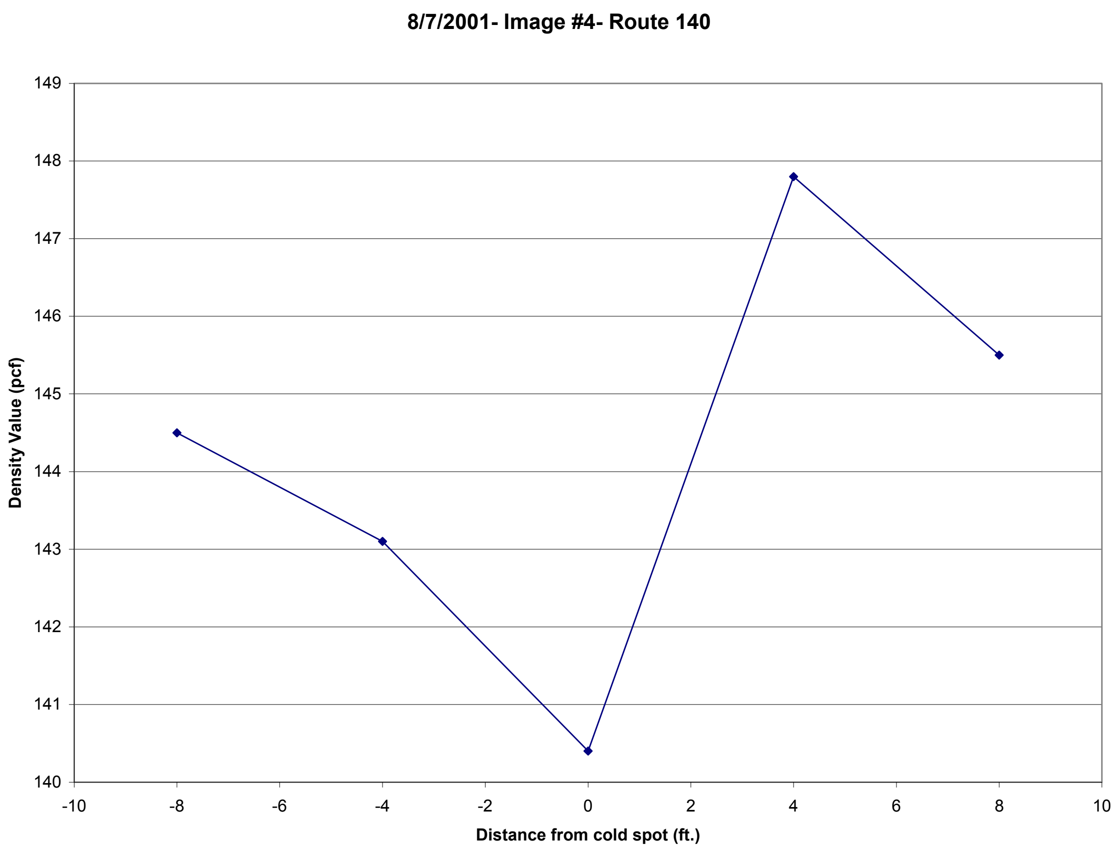


Figure A22 - Density vs Distance from cold spot

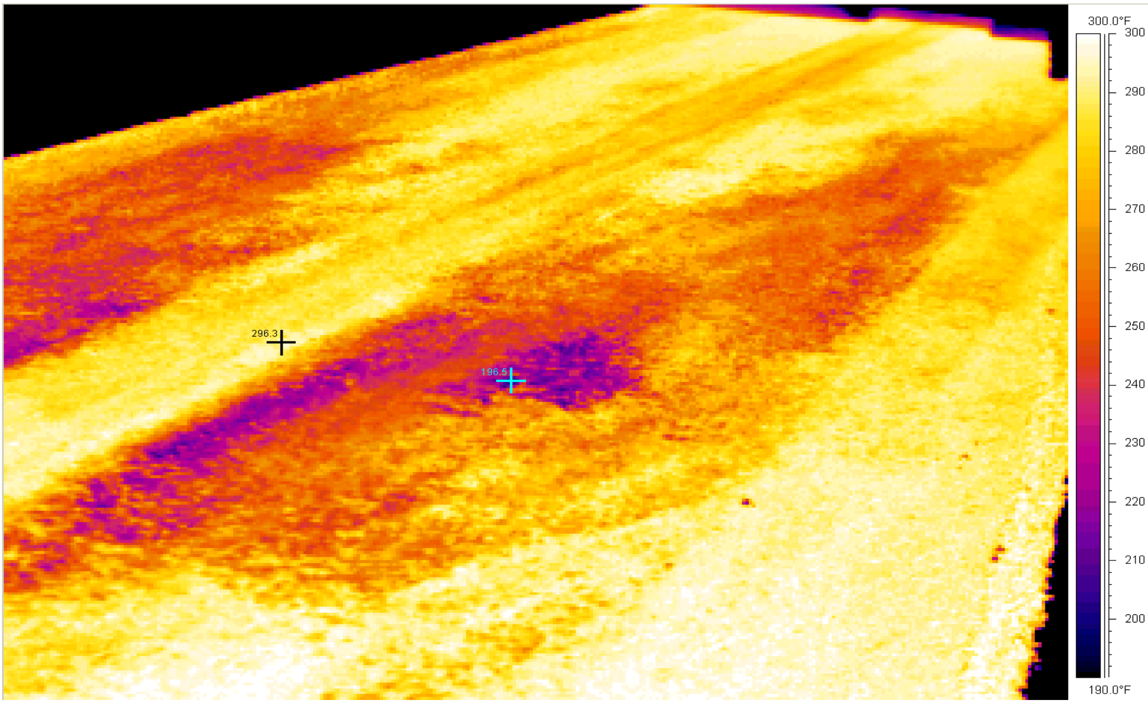


Figure A23 – Image of cold spot generated by spilled material on Route 140 on 8-9-01

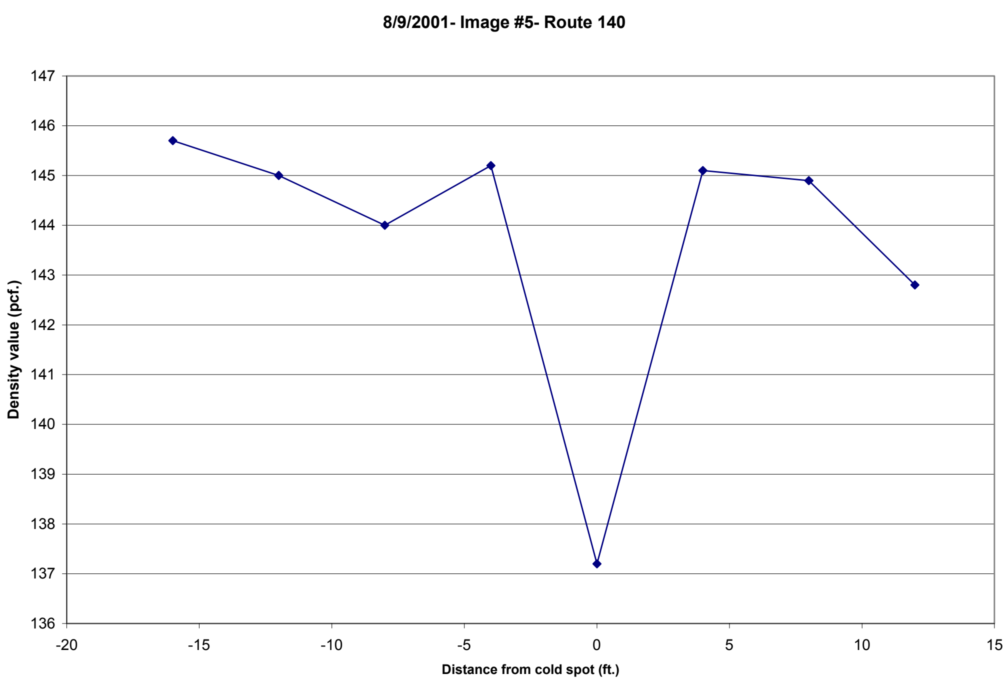


Figure A24 - Density vs Distance from cold spot

Monitored Site 10

This site was Route 189 in Bloomfield, Project number 171-293K, on August 21st, 2001. Only four thermal images were taken. The weather was sunny with a temperature of 85ºF. There were 4 passes of Class 1 material at a 1.5 inch compacted thickness. The images taken were of the third pass which was a travel lane. There was a constant supply of material and the project took place very close to the plant which is in Granby. The haul time was about five minutes. The contractor paved with a Cedar Rapids paver and a Hypac model C788B vibratory breakdown roller. The intermediate roller was an Ingersoll Rand model D-110 vibratory and the finish roller was a Hypac model C340CW. There was no transfer vehicle used. This equipment was the same equipment that was used on August 7th and August 9th on project 171-293J in Ellington, (Monitored Site 9). The average temperature differential observed on this project was 59.6°F. No compaction tests were performed at this project.

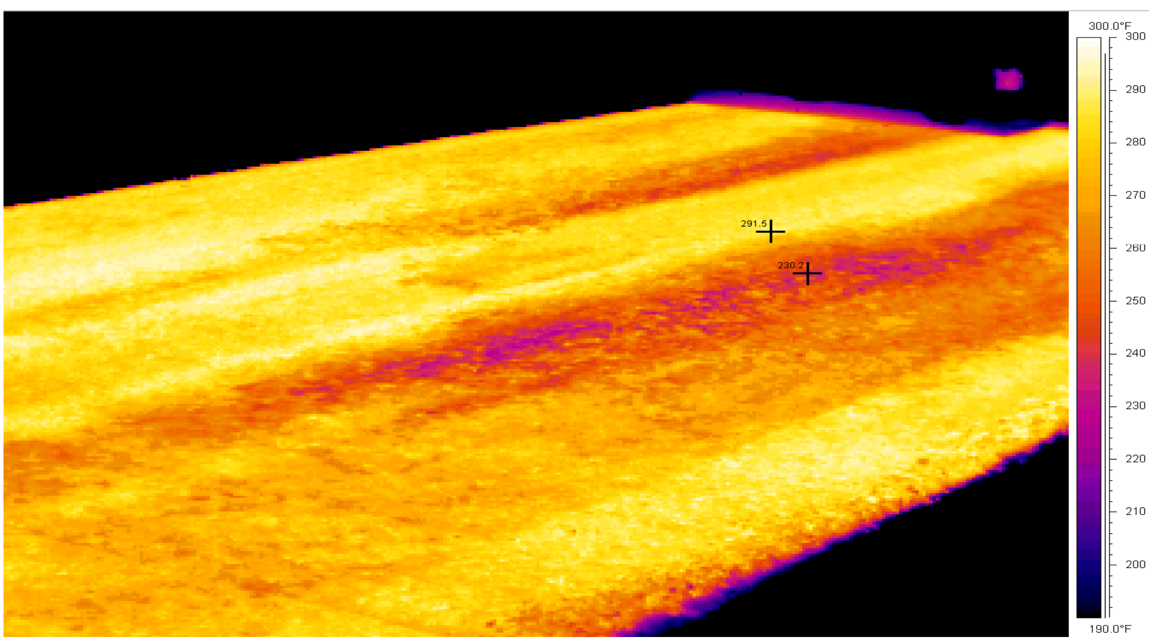


Figure A25 - Typical thermographic image of Route 189 in Bloomfield 8-21-01.

Monitored Site 11

The project number for this site in Norfolk on Route 44 was 174-295J. This project was monitored for two consecutive days on August 27th and August 28th, 2001. On August 27th the weather was cloudy with temperatures ranging from 75ºF to 80ºF . On August 28th, the weather was sunny with temperatures ranging from 75ºF to 85ºF. The material was hauled from Westfield Massachusetts, which is between 40 and 45 miles from Norfolk and the haul time was approximately 85 – 90 minutes. The contractor paved with a Cedar Rapids paver on August 27th but experienced problems with that unit and switched to a Blaw Knox model PF180H for August 28th. There was no transfer vehicle used on either day. Temperature differentials did not change significantly from the first day to the second Figure A26 demonstrates how the temperature differentials were very noticeable when viewed through the thermal camera. The average differential was 62.5ºF on August 27th and 51ºF on August 28th. The average difference in density was observed at 7.47 pcf on the first day and 6.19 pcf on the second day. Figures A26-A29 illustrate the two days of monitoring with typical thermal images for both days as well as their corresponding density plots.

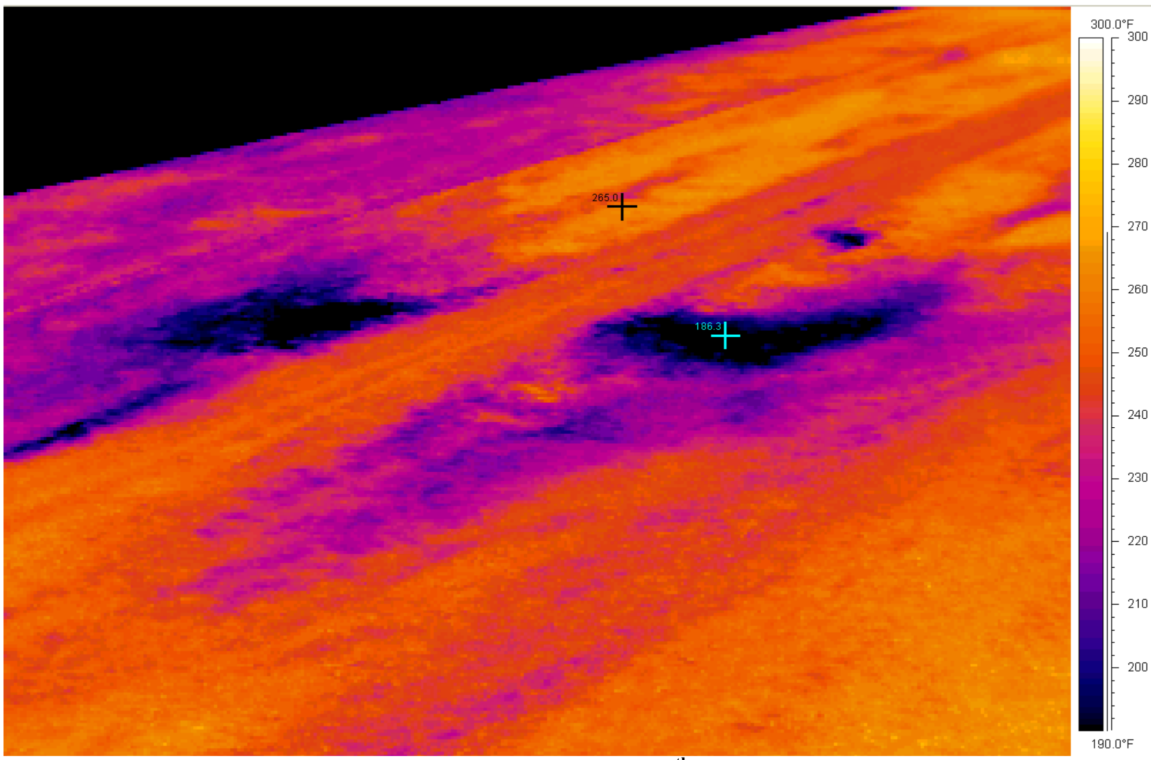


Figure A26 – Image of cold spot on August 27th, 2001 on Route 44, Norfolk

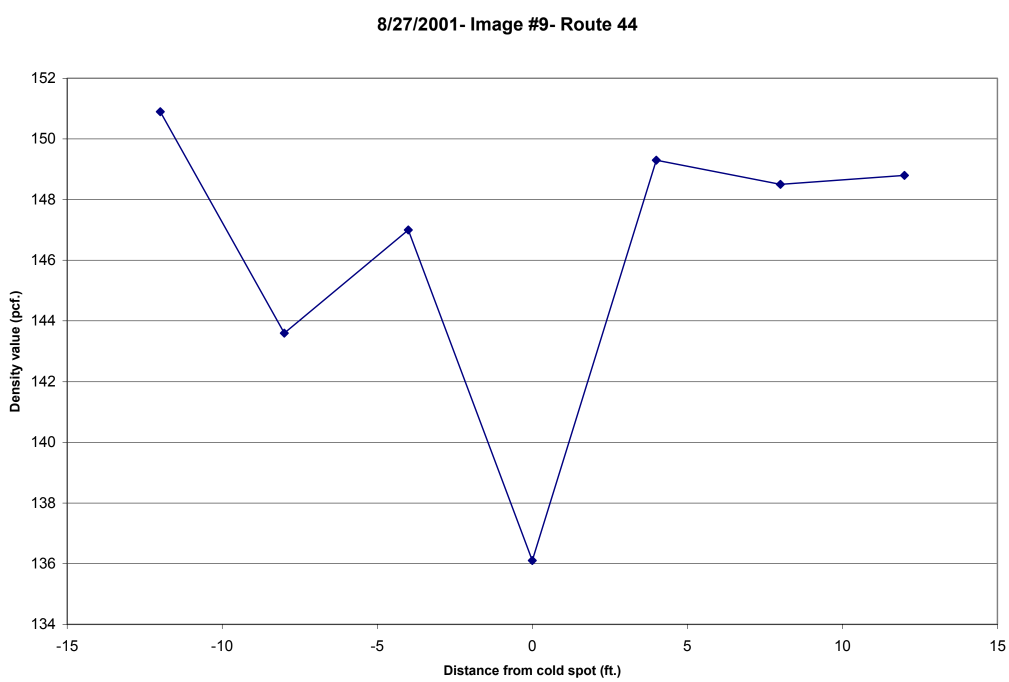


Figure A27 - Density vs Distance from cold spot

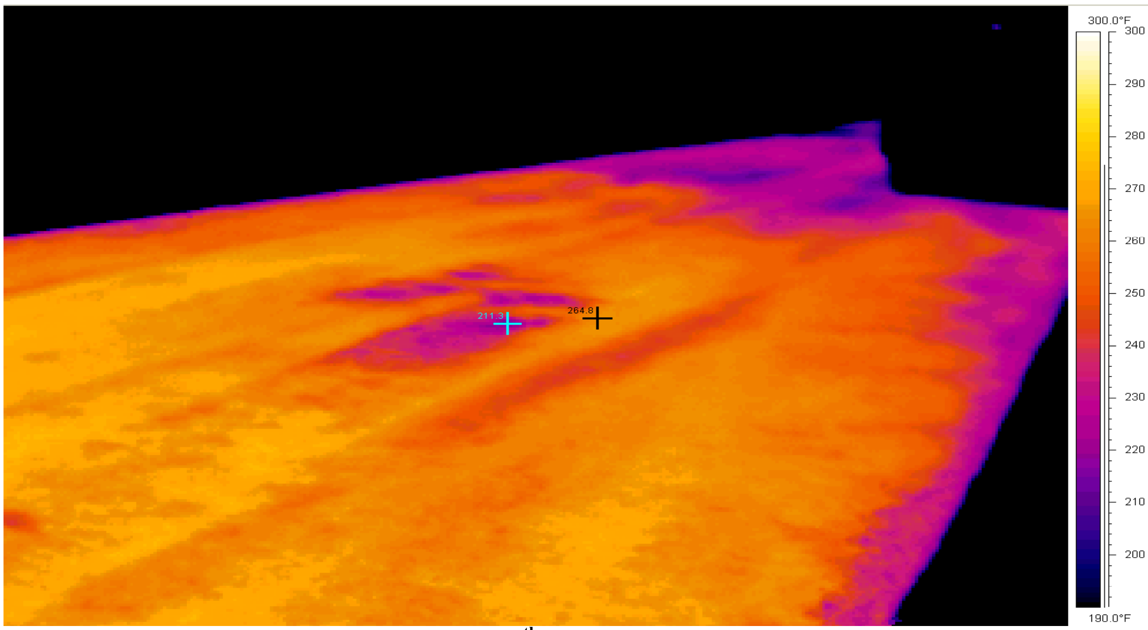


Figure A28 – Image of cold spot on August 28th, 2001 on Route 44, Norfolk

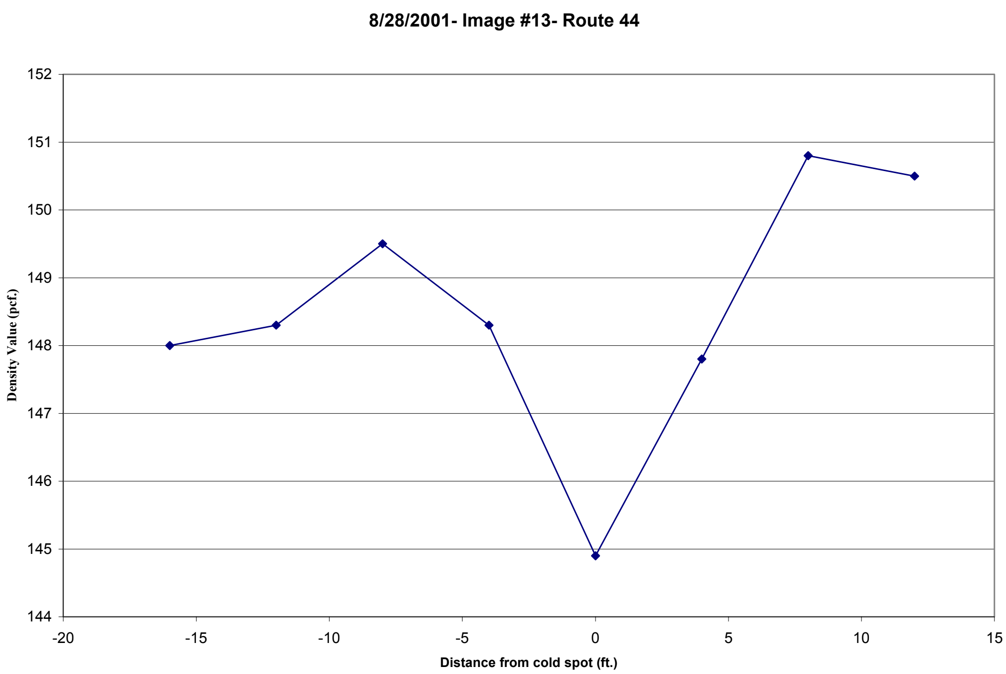


Figure A29 - Density vs Distance from cold spot

Monitored Site 12

Monitoring of sites resumed in 2002 on June 12th in Stonington on Route 1A, project number 172-338C. The weather was cloudy and the temperature was approximately 75ºF. The material was Class 1 and the compacted thickness was 1.5 inches. It was hauled from Montville which was approximately 20 – 25 miles from the project. The haul time was approximately 30 minutes. The contractor paved with a CAT model AP-1055B paver. There were two Hypac rollers and no transfer device. 10 images were taken with the thermal camera as well as GPS coordinates corresponding to each of the images except one location where the signal was poor. The average temperature differential on this site was 75ºF. There were no densities taken in Stonington.

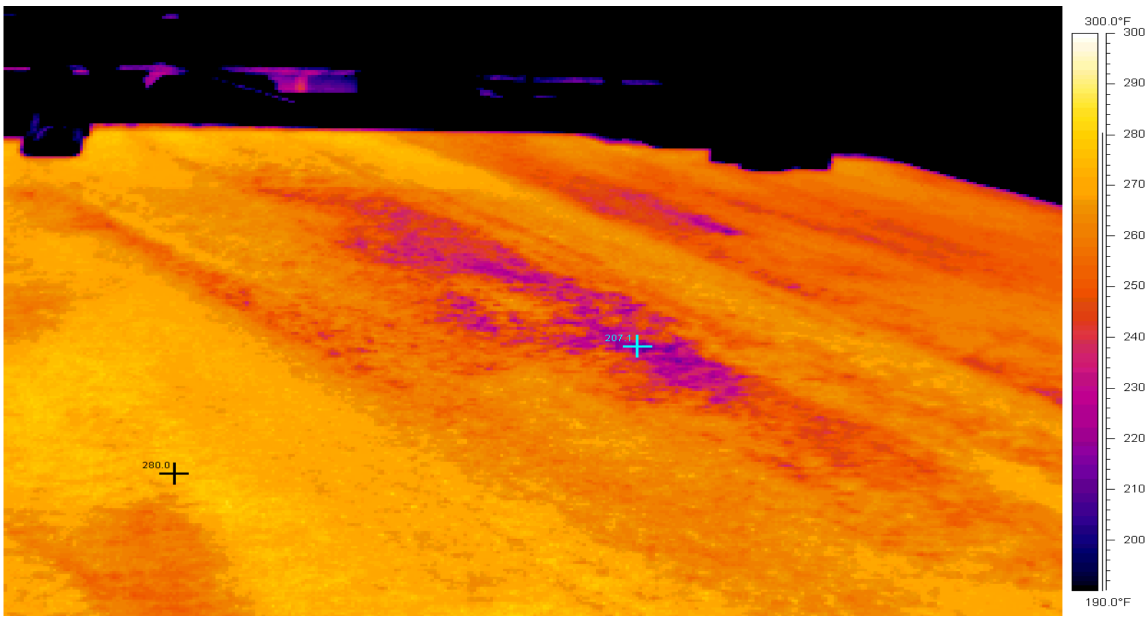


Figure A30 - Typical thermographic image of Route 1A in Stonington.

Monitored Site 13

This site was project number 76-190, on Tolland Turnpike in Manchester in the vicinity of Route I-291 on June 13th, 2002. The weather was cloudy and the temperature was about 65°F. The contractor was placing Class 1 material at a compacted thickness of 2 inches. The plant was located in Newington, about 12-13 miles from the project. The haul time was approximately 20-25 minutes. The paver being used was a Blaw Knox

PF3200. A CAT model CB634C vibratory roller was used for breakdown and a CAT model CB534 was used for intermediate rolling as well as finish rolling. There was no transfer vehicle used on this job. There were only 8 images taken on this particular day because the plant broke down and the contractor was slowed considerably. The cold spots seen in the images of this project correspond to truck change locations and there were significant drops in density levels at these cold spots as seen in Figures A31 and A32. The average temperature differential on this site was 47.4ºF and the average density difference between warm and cool areas was 5.9 pcf.

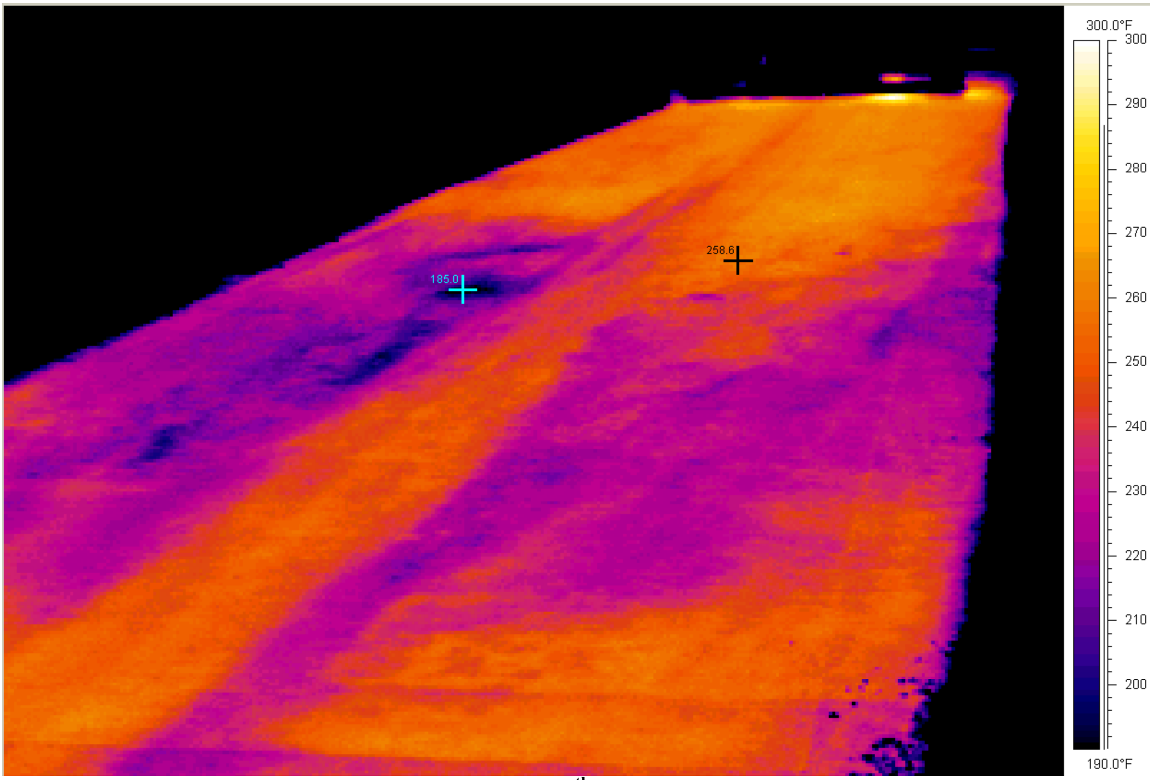


Figure A31 – Image of cold spot on June 13th, 2002 on Tolland Turnpike in Manchester

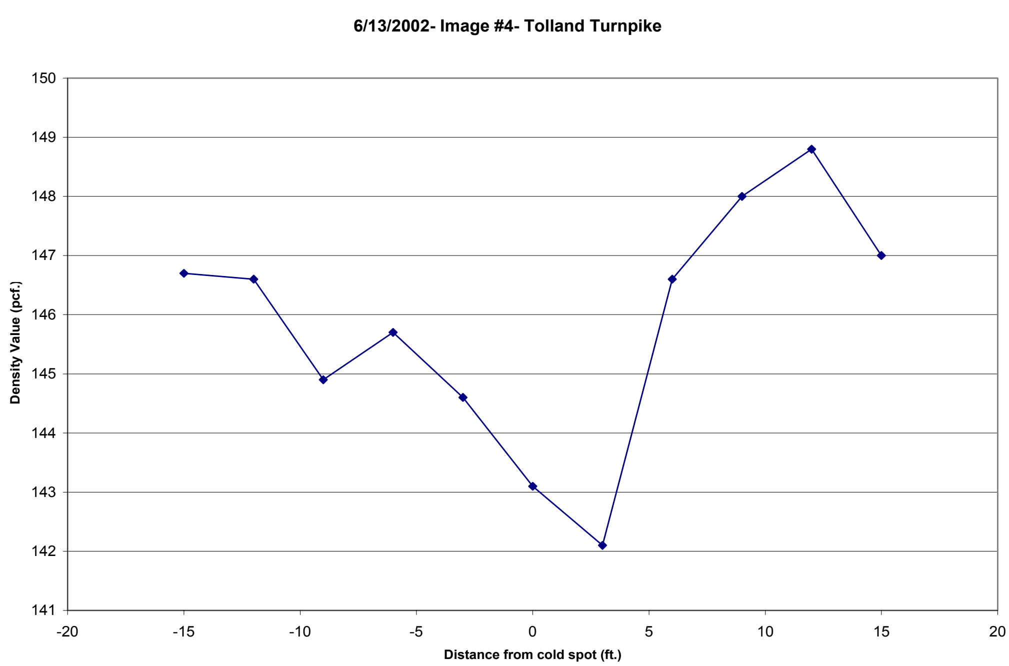


Figure A32 – Density vs Distance from cold spot

Monitored Site 14

The 14th monitored site was project number172-337N on Route 607 (Westcott Rd.) in Killingly/Danielson on June 14th, 2002. The weather was cloudy giving way to light rain in the afternoon and the temperature was approximately 65°F. The material placed was Class 1 at a compacted thickness of 1.5 inches. The plant was located 5-8 miles away in Wauregan, giving a haul time of about 12 minutes. Equipment used by the contractor consisted of a Blaw-Knox PF3200 paver, a CAT model CB634C vibratory breakdown roller and a CAT model CB534 intermediate roller, which was also used as the finish roller. The crew and equipment on this project were the same as project number 76-190 in Manchester (Monitored Site 13). There was no transfer vehicle used on this project.

There were a significant number of cold spots observed their locations were consistently located at the truck changes both with and without spilled material. The average temperature differential on this project was 47.7ºF. Two density readings were taken and they show a drop in density for both cold spot locations. The average density difference between the warm and cold material on this site was 6.45 pcf. It was sprinkling while the images were taken as well as while the densities were being determined. Figures A33 and A34 show a typical image and corresponding density values.

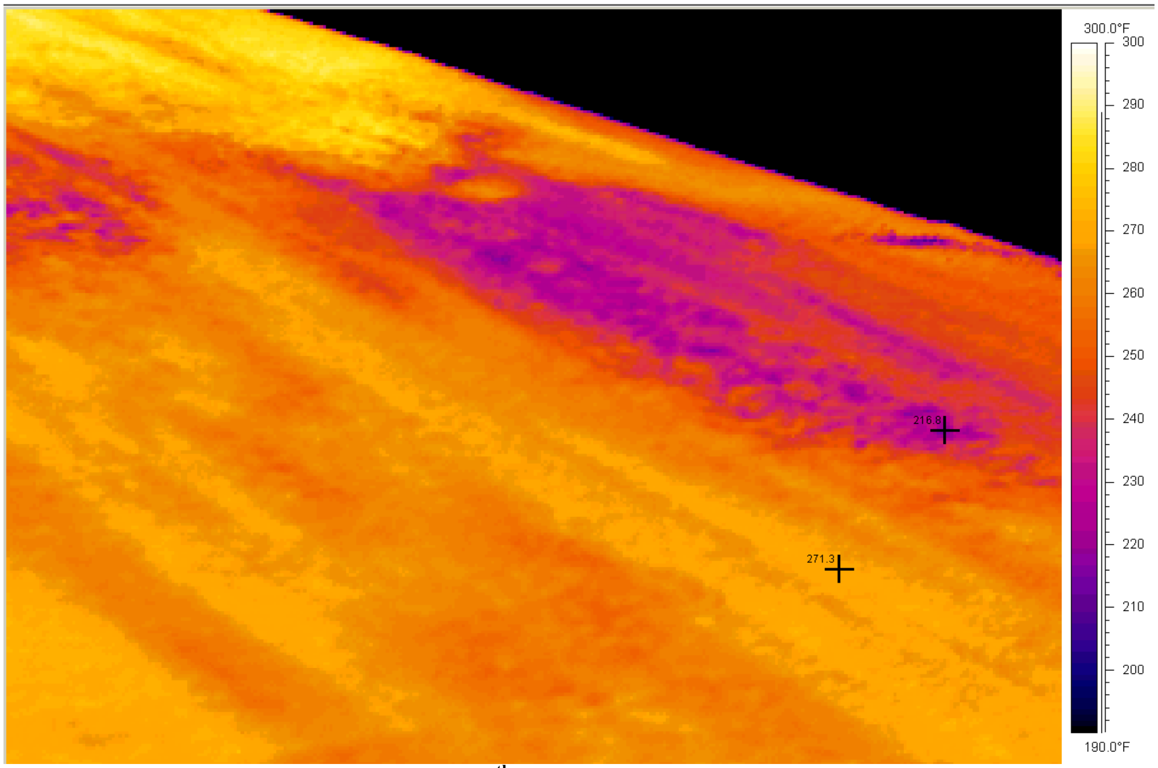


Figure A33 – Image of cold spot on June 14th, 2002 on Route 607 in Killingly/Danielson

Figure A34 - Density vs Distance from cold spot

Monitored Site 15

This site was monitored on June 19th, as well as June 21st, 2002 on Route 16 in Colchester/Lebanon. The project number was 172-337C. The weather was sunny with temperatures approximately 65°F-70°F on June 19th. The base pavement temperature was about 90°F. On June 21st, the weather was also sunny with temperatures ranging from 75°F -85°F. The material being placed was Class 1 and the compacted thickness was 2 inches. The plant was 15 miles away in Franklin, which yielded a 25 minute haul time for the trucks. The contractor used a Blaw-Knox model PF-200B paver, a Hyster breakdown roller and an Ingersoll-Rand model DD-110 for intermediate rolling as well as finish rolling. The equipment did not change from June 19th to June 21st and there was no material transfer vehicle involved. The trucks appeared to be loaded with a single drop at the plant on both monitoring days. The frequency of cold spots did not appear to change between the two days either. The average temperature differential on day one of monitoring was 42°F and 52.5°F on the second day of monitoring. The densities measurements taken show data resembling that of typical cold spots with density values dropping at the cold spot location as shown in Figure A36. Figure A36 shows density measured first at the cold spot center and then from increasing distances from the cold spot center. The density values increase as the distance from the cold spot increases which corresponds to increasing temperatures of the mat. The average difference in density between warm and cool areas seen on this day was 1.8 pcf. The densities taken of the cold spots on the second day, June 21, contain more complete data as there was more time available for densities to be read. The average difference in density between warm and cool areas seen on this day was 5.9 pcf. Figures A35 and A37 show typical thermal images of the first and second day of monitoring respectively. Figures A36 and A38 show typical densities taken on both days of monitoring.

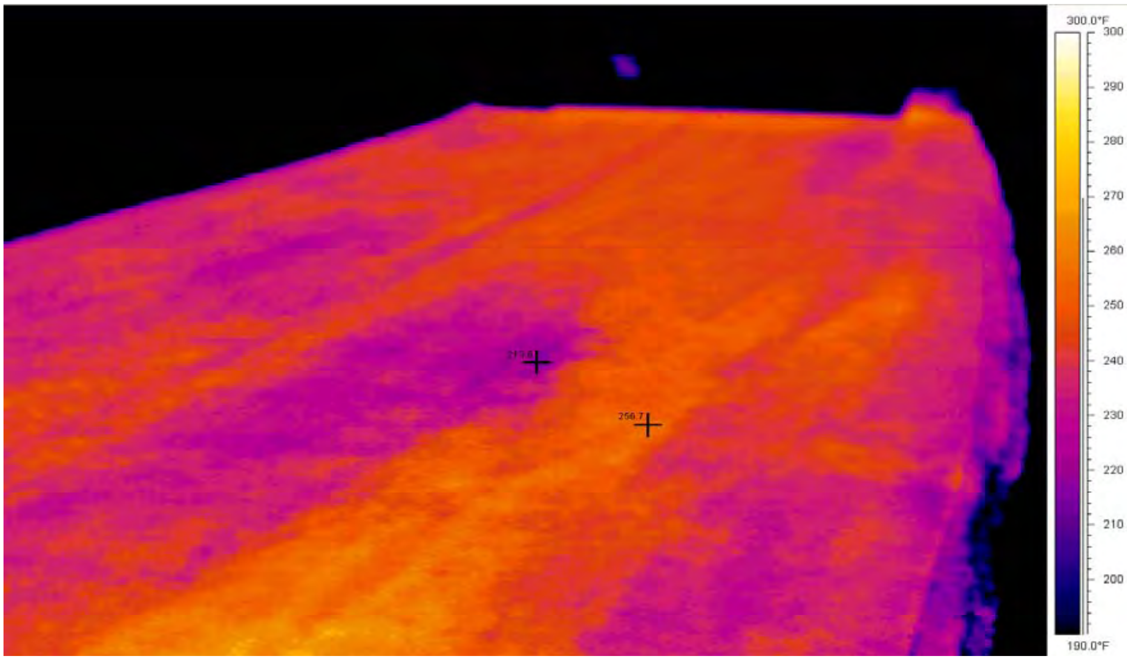


Figure A35 – Image of cold spot on June 19th, 2002 on Route. 16 in Colchester.

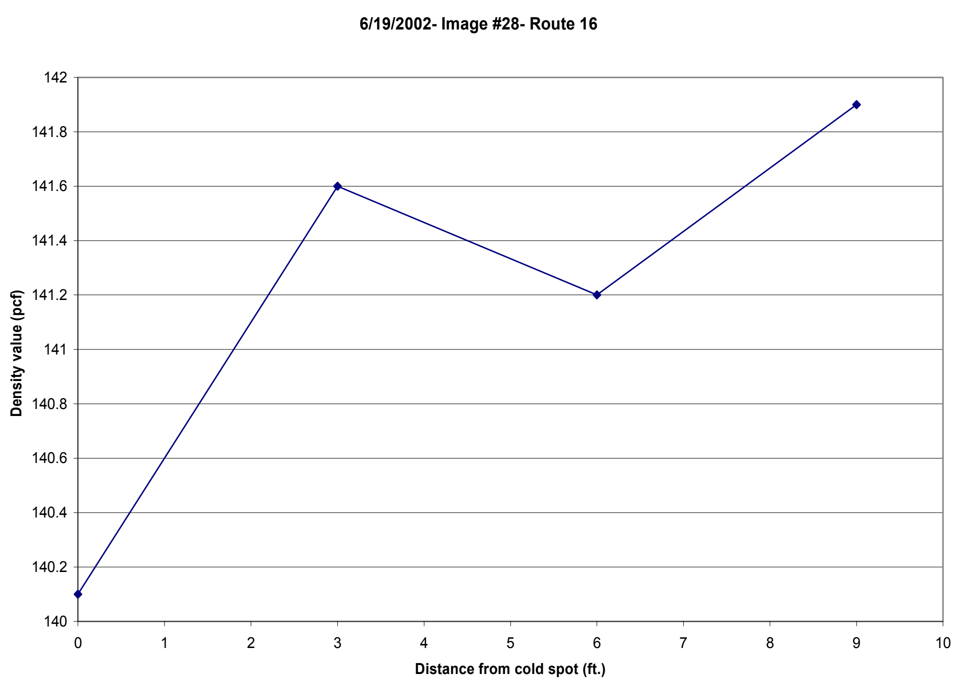


Figure A36 - Density vs. Distance from cold spot

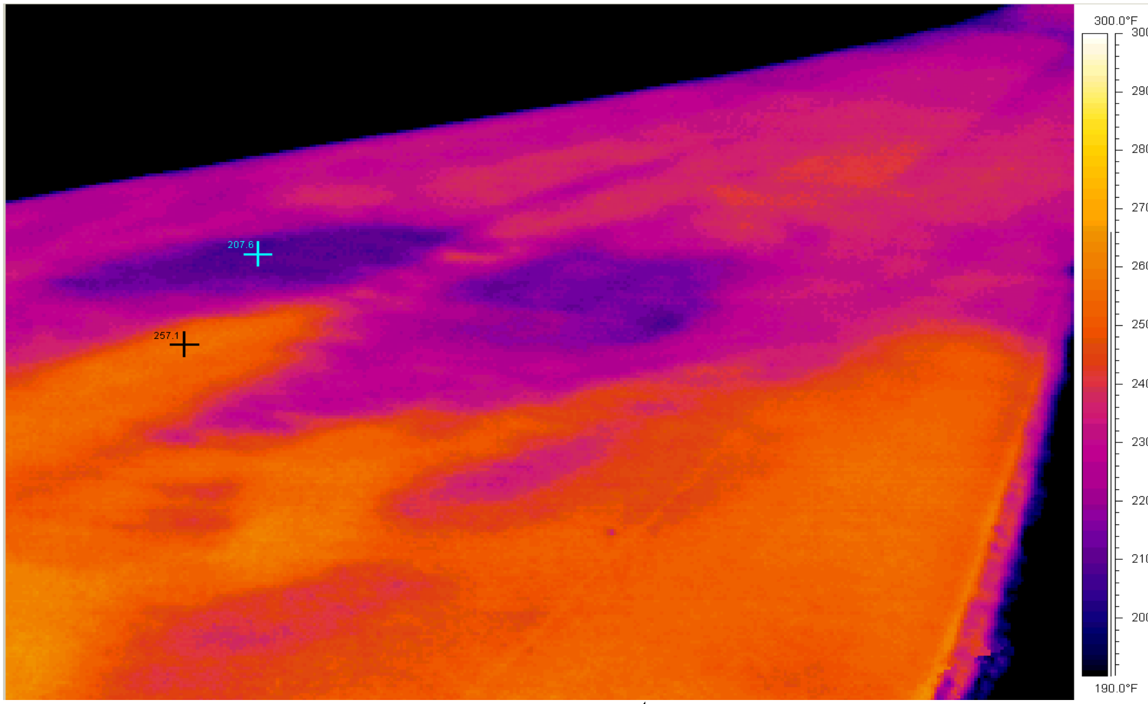


Figure A37 – Image of cold spot on June 21st, 2002 on Route 16 in Colchester

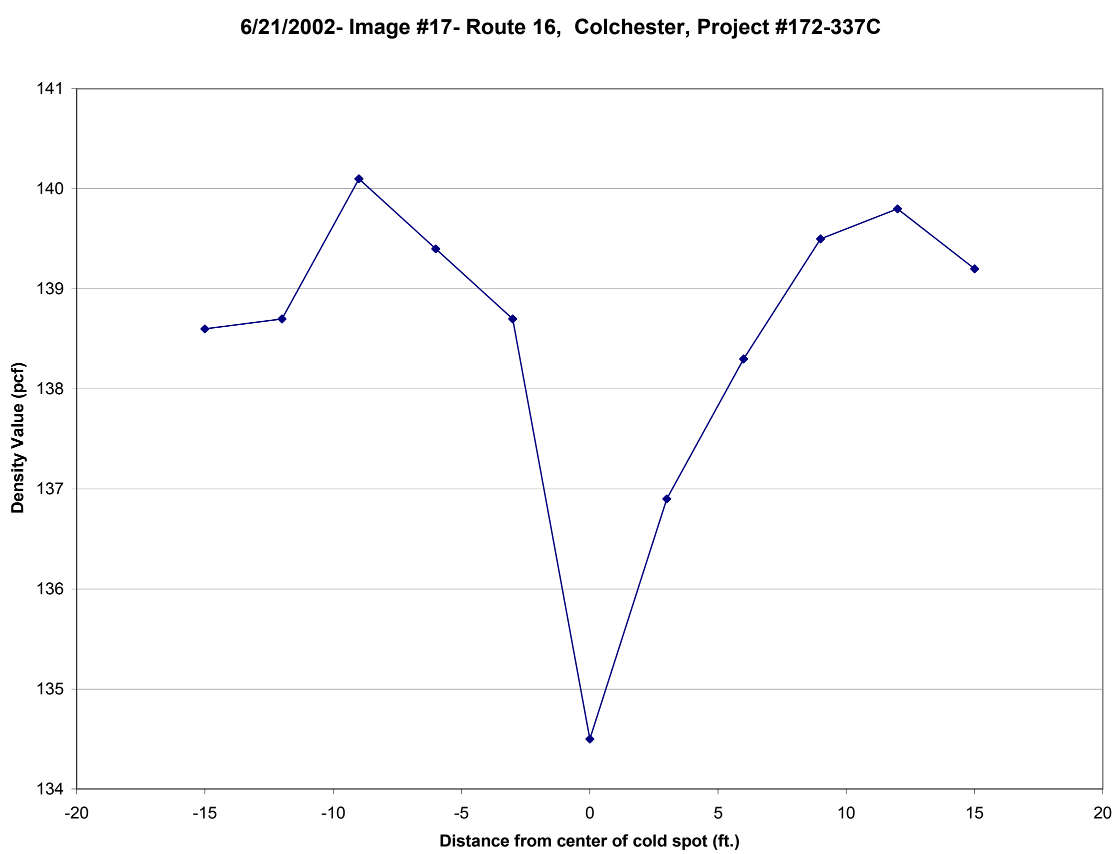


Figure A38 – Density vs Distance from cold spot

Monitored Site 16

The 16th monitored site was project number 172-337H, Route 101 in Killingly on June 26th, 2002. The weather was sunny with temperatures ranging from 80°F-90°F. The material was Class 1 placed at a compacted thickness of 2 inches. The base pavement temperature was 95°F-100°F. The plant was located 15 miles from the project in Wauregan which accounted for a 20 minute haul time for the trucks. The trucks were loaded with one silo drop at the plant. The equipment used by the contractor consisted of a CAT model AP-1055B paver, a Hypac breakdown roller and an Ingersoll Rand model DD-110 Intermediate roller which was also used for the finish rolling. There was no material transfer vehicle used on the project.

The cold spots seen at this site coincided with material spilled from trucks pulling away from the paver hopper as well as from cleaning truck bodies. The average temperature differential for this project was 54.5°F. There was no nuclear density testing performed on this project by the CAP Lab.

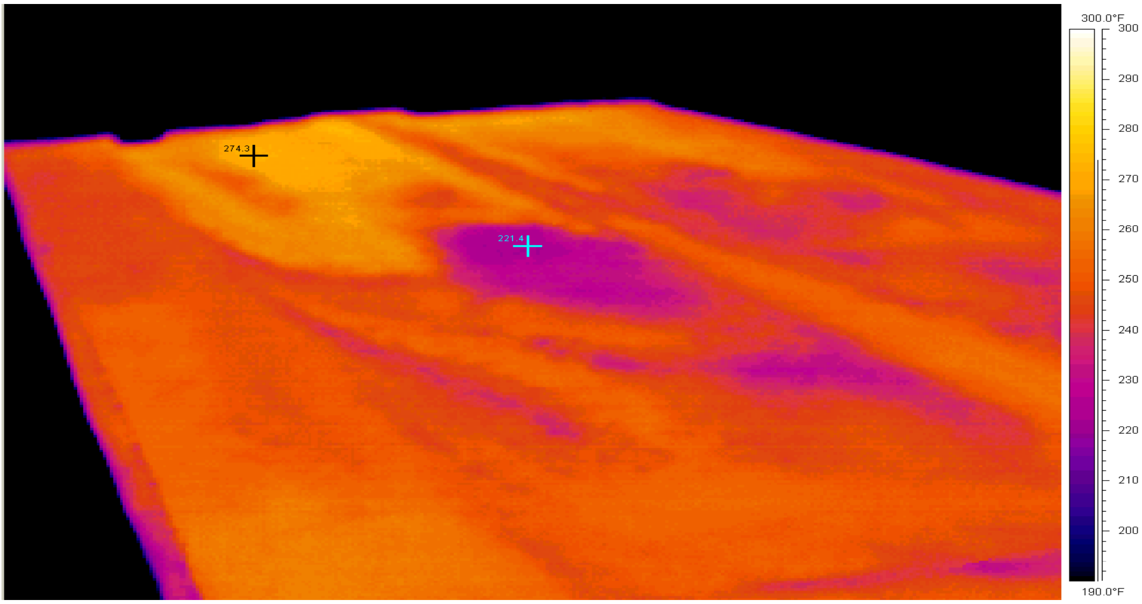


Figure A39 - Typical Image of mat on 6-26-02 in Killingly

Monitored Site 17

Project number 172-337F took place on Route 89 in Lebanon on June 27th, 2002. The weather was sunny with temperatures ranging from 80°F-90°F. The material was Class 1 and placed at a 2 inch compacted thickness. The material was hauled from Franklin which was 10 miles away and the haul time was 15 minutes. The contractor used a Blaw-Knox model PT-200B paver, a Hyster breakdown roller and an Ingersoll-Rand model DD-110 for intermediate rolling as well as finish rolling. The crew and equipment were the same as those from June 19th and June 21st on Route 16 and there was no transfer vehicle used on this project.

The cold spots seen on this project again coincide with spilled material at the corresponding location and do not have the characteristic V-shape seen on other projects. The average temperature differential for this day of monitoring was 33.8°F. Figure A40 is a typical thermal image from this project and its corresponding density plot can be seen in Figure A41. The average difference in density between the warm and cool areas for this day was 4.23 pcf.

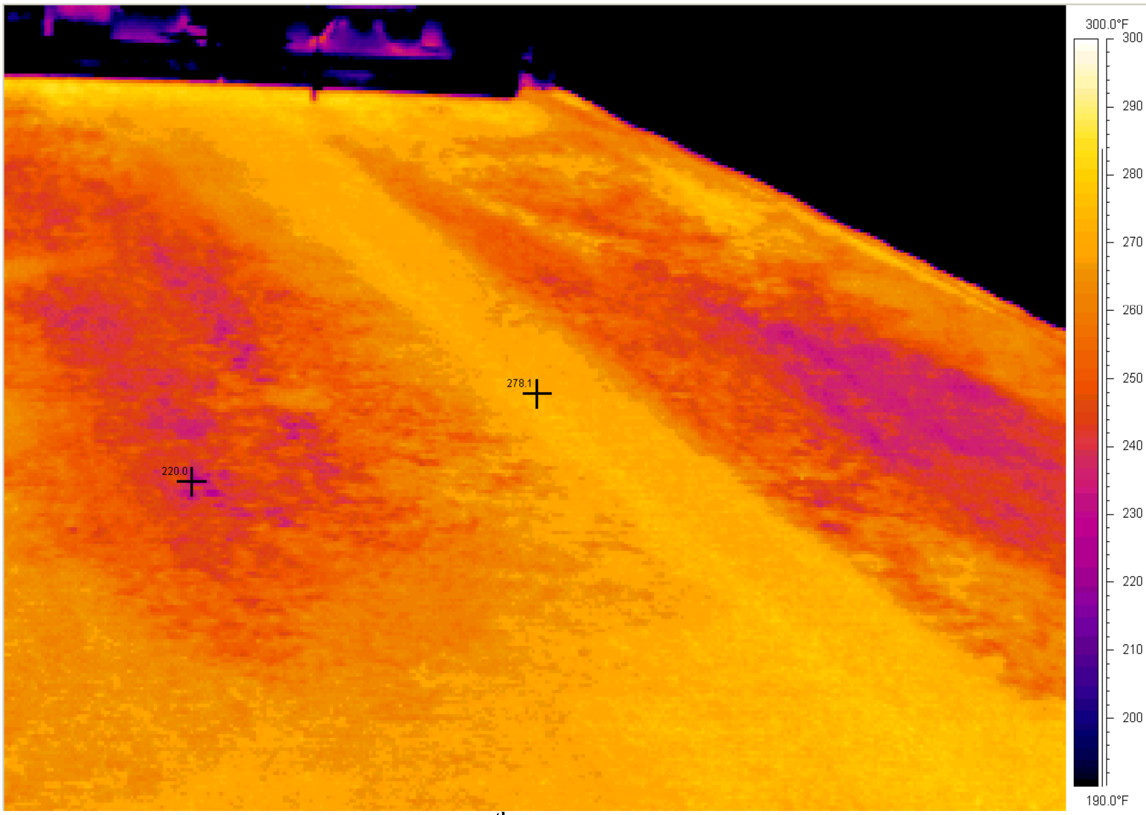


Figure A40 – Image of cold spot on June 27th, Route 89 in Lebanon

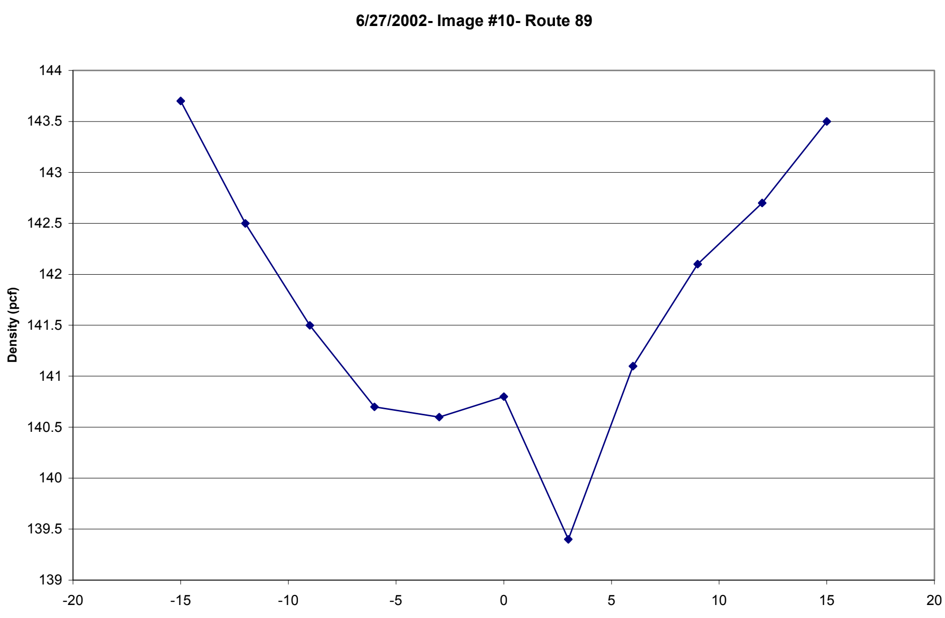


Figure A41 – Density vs Distance from cold spot

Monitored Site 18

The eighteenth monitored project was number174-305H on Route 7 in Falls Village on July 2nd and July 8th, 2002. The weather was sunny and hot with temperatures approximately 95°F on both days. The material was Superpave 12.5 mm and the thickness was 2 inches. Trucks were loaded with three drops at the plant. The base pavement temperature was about 100°F on July 2nd and about 110°F on July 8th. The plant was located in Westfield Massachusetts, which was 55-60 miles from the project and hauling took about 100 minutes. The contractor paved with a Blaw-Knox model PF3200 paver, an Ingersoll Rand model DD90 HF breakdown roller, a Hypac intermediate roller and an Ingersoll Rand model DD-110HF finish roller. The contractor also used a Blaw-Knox model MC-30 material transfer vehicle both days. Due to use of the MTV, judgment of the location of material change was difficult resulting in approximated truck change locations and several images taken on rare occasions when the MTV stopped at the actual screed stop locations. Cold spots on this project were sporadic and the average temperature differentials were 37.1°F and 31.4°F for the first and second monitoring days respectively. Figures A42-A45 show typical thermal images from Route 7 with their corresponding density readings. The average difference in density for the first monitoring day was 4.63 pcf. The second day's average difference in density between the warm and cool material was 3.7 pcf.

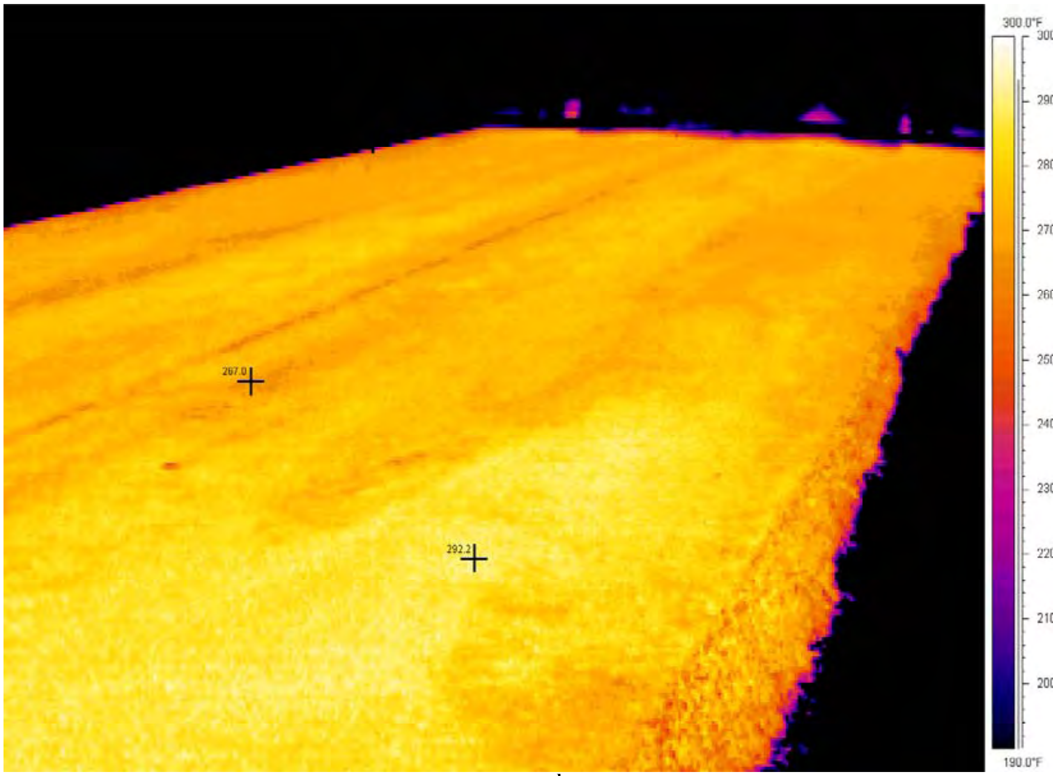


Figure A42 – Mat on July 2nd, Route 7 in Falls Village

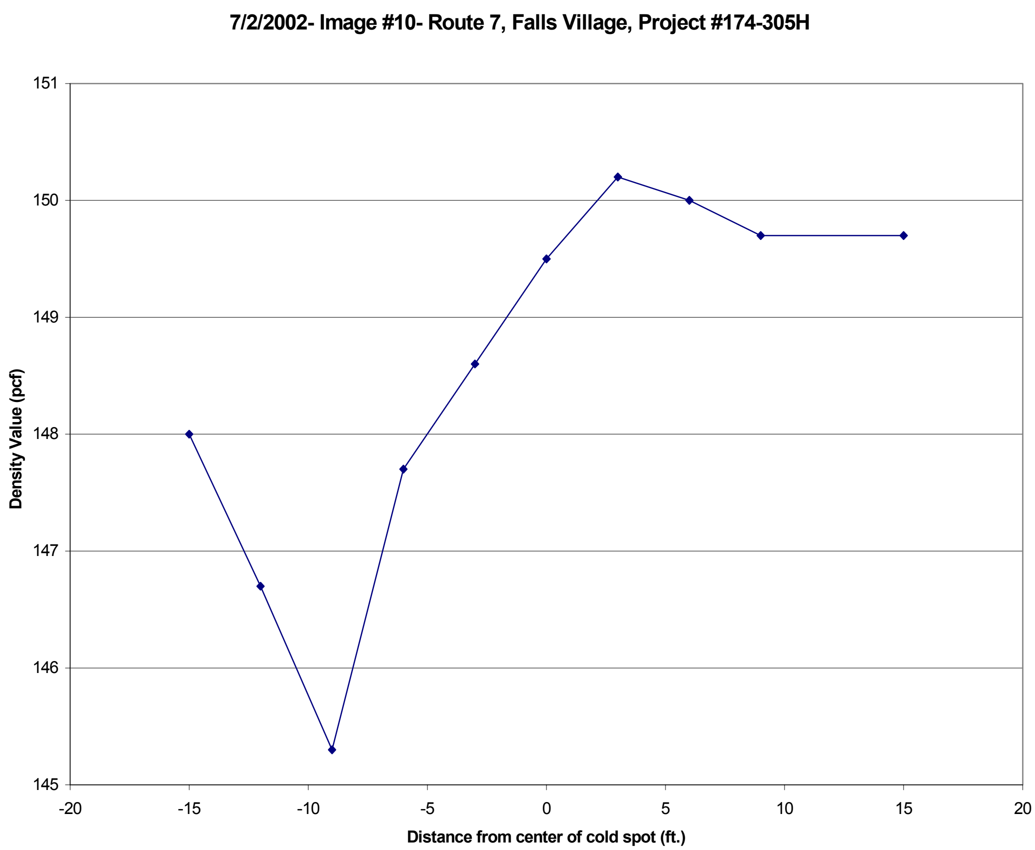


Figure A43 – Density vs Distance from cold spot

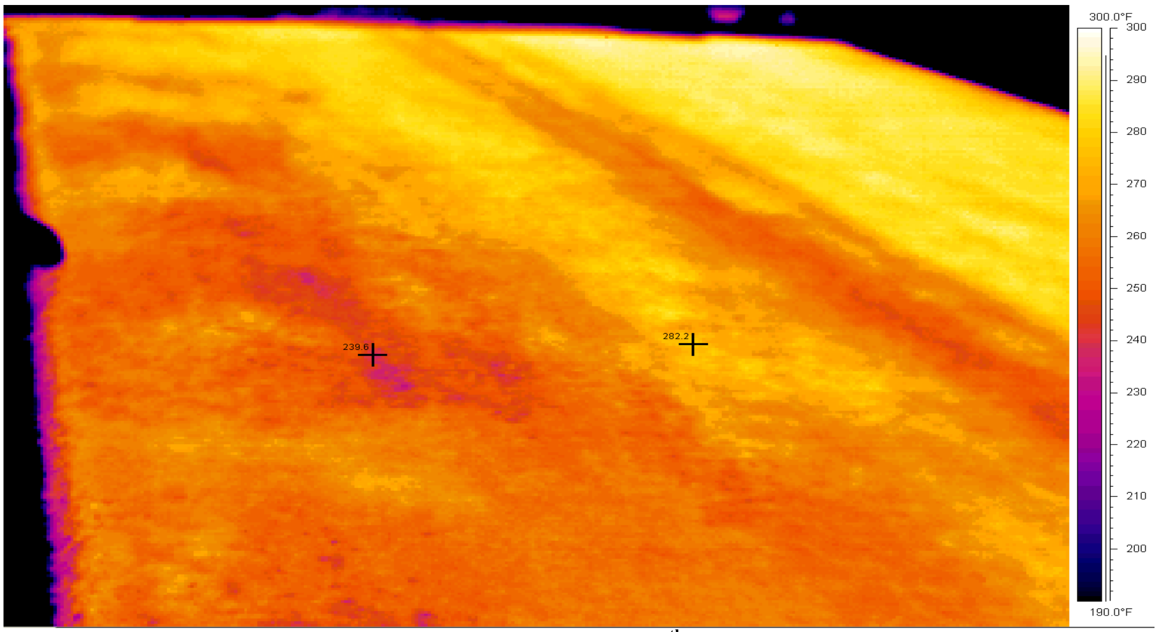


Figure A44 – Image of cold spot on July 8th, Route 7 in Falls Village

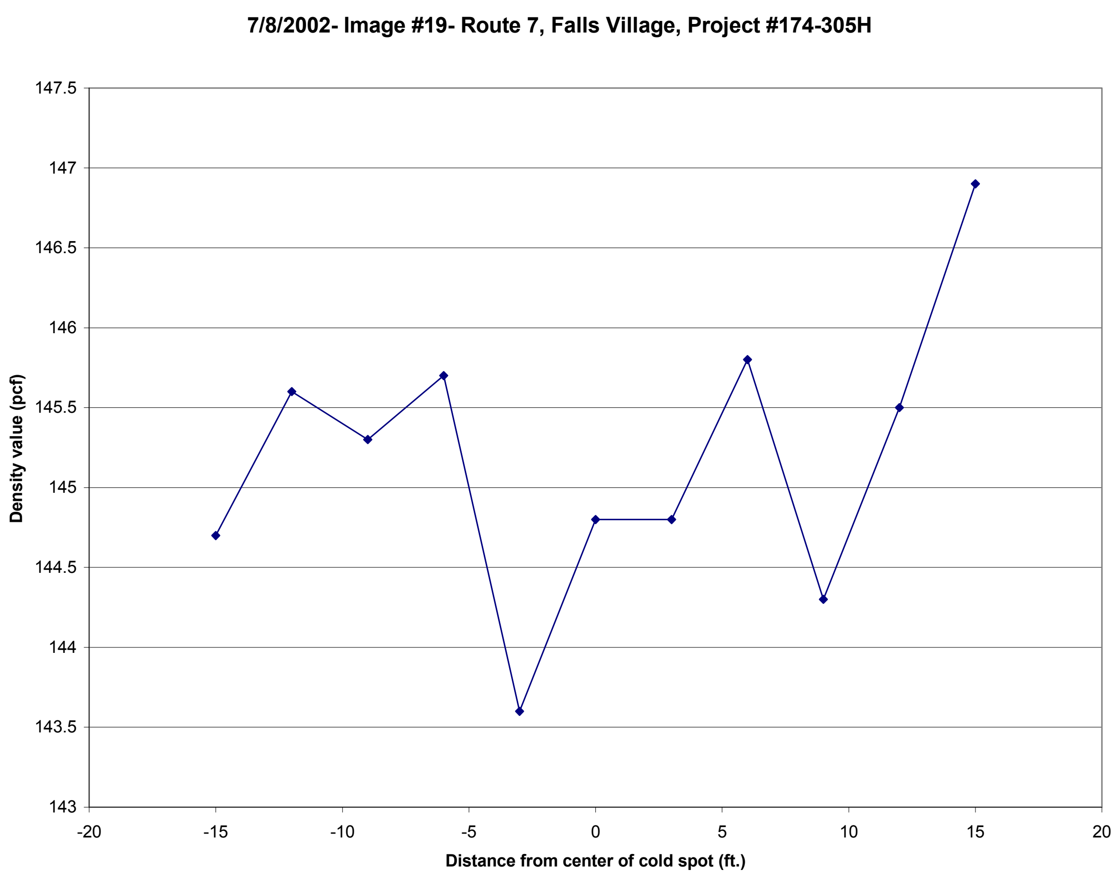


Figure A45 – Density vs Distance from cold spot

Monitored Site 19

The next site was project number 171-303H on Route 6 in Farmington on July 10, 2002. It was approximately 80°F and sunny. The Class 1 material was being hauled from a plant in New Britain and placed to a compacted thickness of 1.5 inches. The trucks were loaded with 2 drops at the plant, which was about 7 miles away from the project and the trucks had about a 15 minute haul time from the plant to the project. The contractor paved with a CAT model AP1000B paver. The breakdown roller was a Hyster model C340 and a CAT model CB634D was used for finish rolling. There was no material transfer vehicle used on this project. The project consisted of paving several different spots such as intersections and small stretches of Route 6 in Farmington. The average base temperature was about 100 °F and the average temperature differential was 38.2°F. No density readings were taken on this day by the CAP Lab due to the lack of mainline paving on the project. Figure A46 is a typical thermal image from this monitored site.

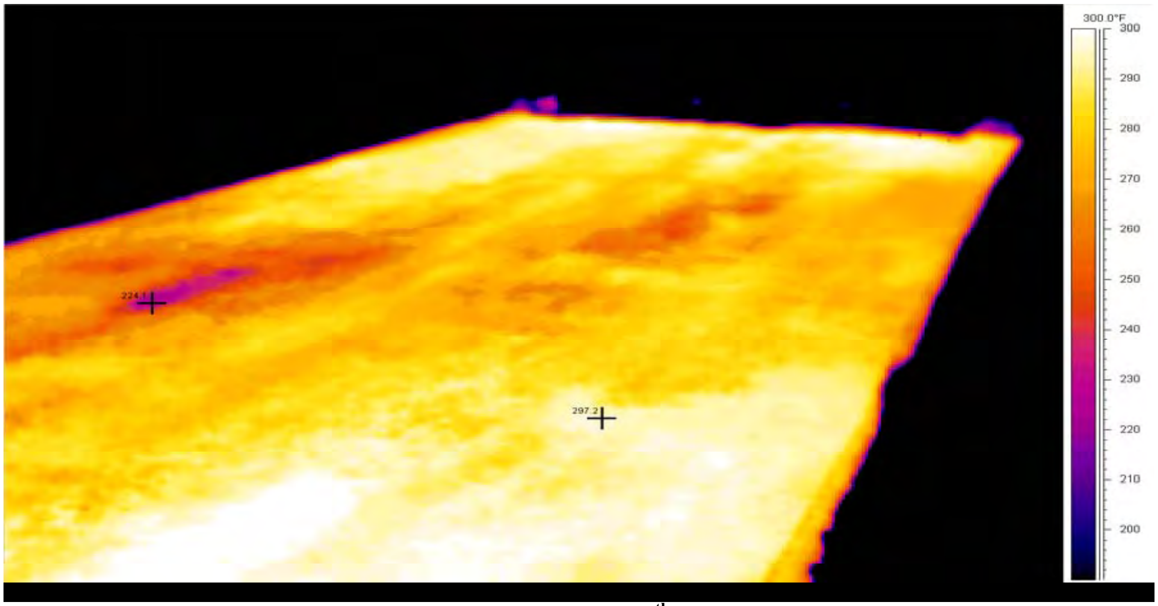


Figure A46 - Typical Thermal Image of site 19 on July 10th, Route 6.

Monitored Site 20

This site was the resurfacing of Route 196 in East Hampton. This site was monitored on July 15th and July 16th, 2002. The number for this project was 172-337K. Both days were sunny with temperatures ranging from 78°F - 90°F on the first day and in the lower to mid 70's on the second day. The base pavement temperatures ranged from 85°F - 90°F on July 15th and were in the mid 70's on July 16th. The compacted thickness of the Class 1 material was 2 inches. The plant was located approximately 55 miles away in Killingly. The trucks were loaded with either 2 or 3 drops at the plant. The haul time was approximately 60 minutes. The paving equipment consisted of a Blaw-Knox model PF3200 paver, a CAT model CB634C vibratory breakdown roller, a CAT model CB534 vibratory intermediate roller, which was also used for finish rolling and a CAT model CB224D roller for driveway entrances. The average temperature differentials on this project were 53.6°F and 53.7°F for the respective first and second days of monitoring. The average difference in density between warm and cool material was 3.9 pcf on the first day and 6.4 pcf on the second day. Figures A47-A50 show representative images of the cold spots on this project for both days and their corresponding density plots.

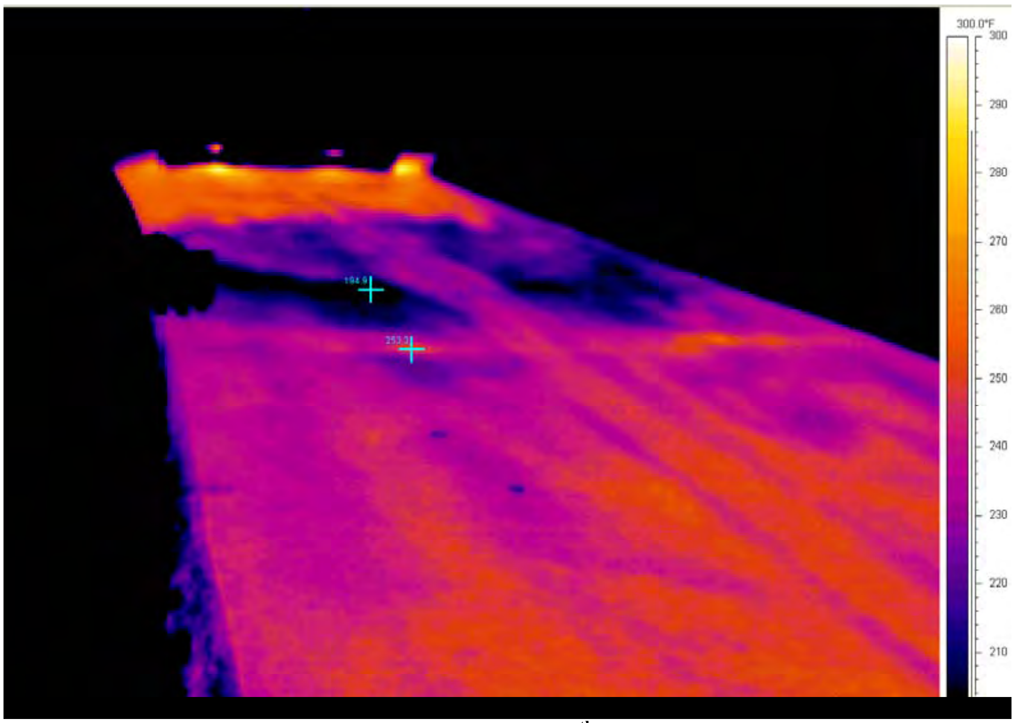


Figure A47 – Image of cold spot on July 15th, Route 196 in East Hampton

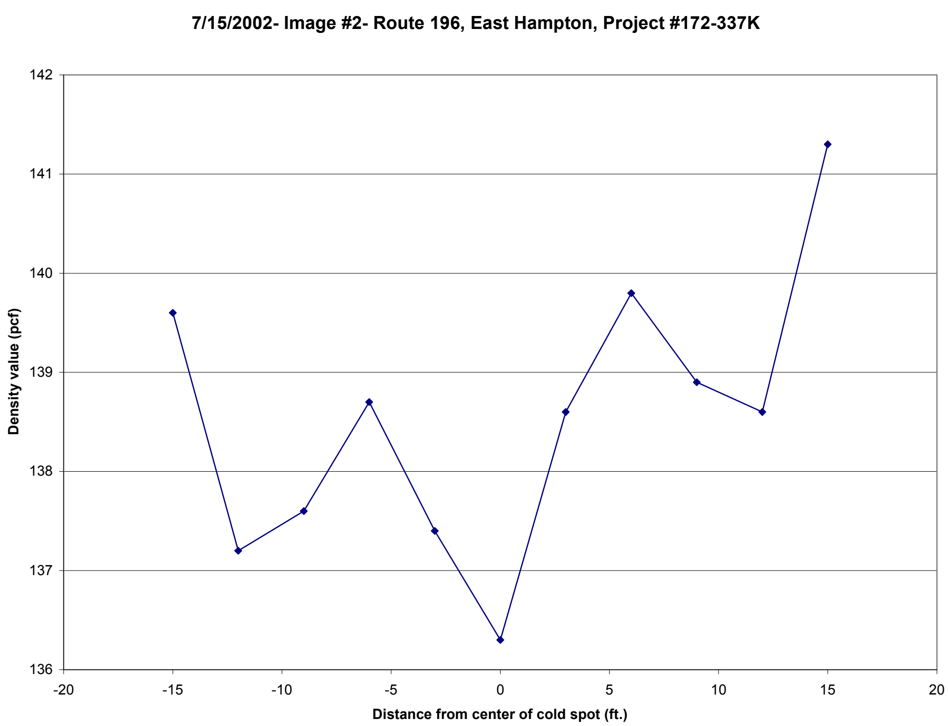


Figure A48 – Density vs Distance from cold spot

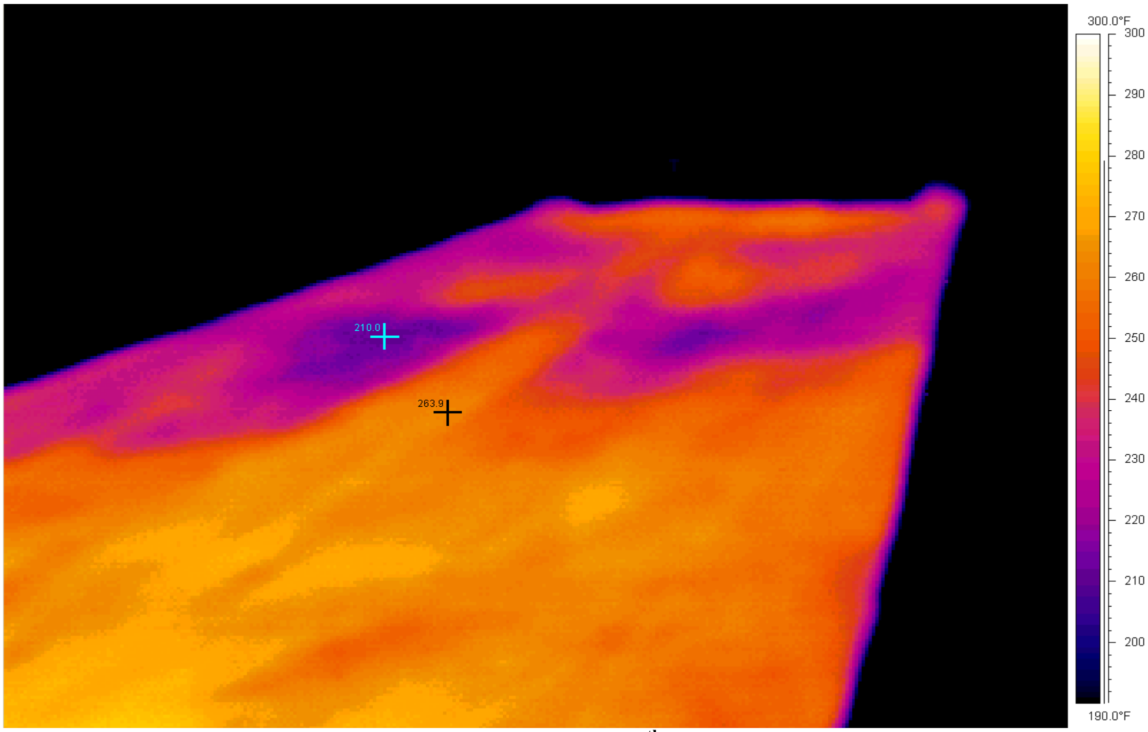


Figure A49 – Image of cold spot on July 16th, Route 196 in East Hampton.

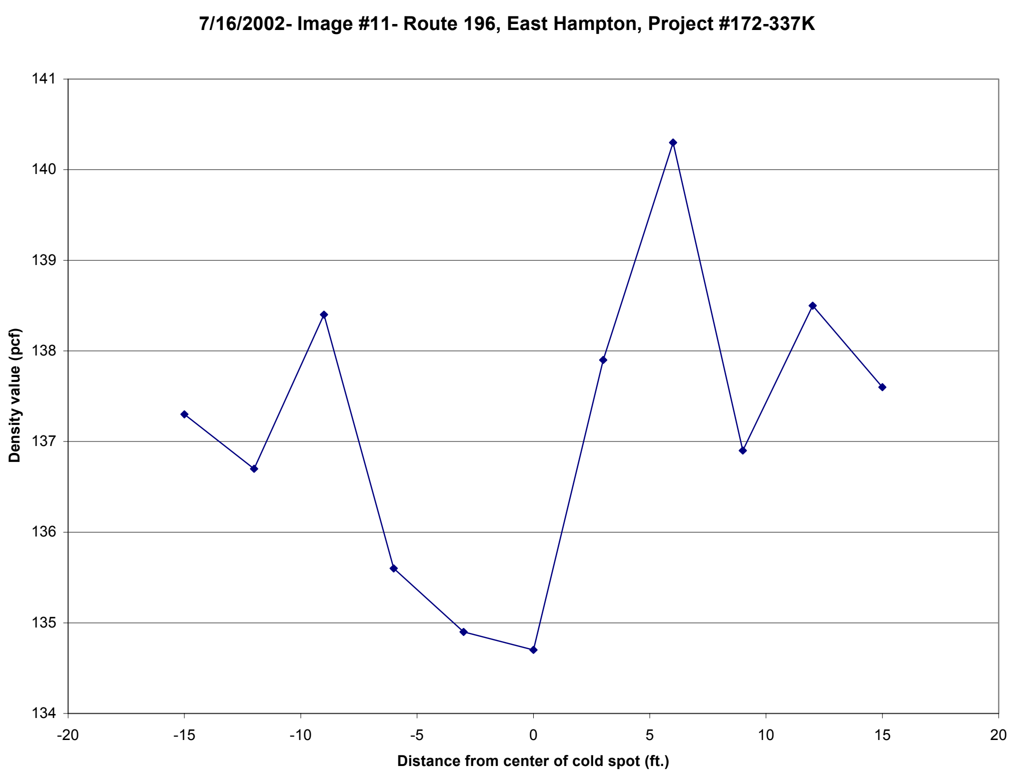


Figure A50 – Density vs Distance from cold spot

Monitored Site 21

This site was monitored on July 17, 2002 on Interstate I-91 Southbound in Wallingford. The project number was 173-348. The weather was sunny with temperatures ranging from 80°F - 90°F. The temperature of the base pavement was 100°F. The material was Superpave 12.5 mm and the compacted thickness of the mat was 2 inches. The material was being hauled from a plant in Wallingford about 5 miles from the project. Hauling time was about ten minutes. The contractor paved with a CAT model AP-1000B paver. The breakdown roller was an Ingersoll Rand model DD90HF. The intermediate and finish roller was a CAT model CB634C. The contractor also used a Roadtec model SB2000B material transfer vehicle on this project. Although the thermographic images appear to be very uniform in temperature, the densities varied from point to point as can be seen in the density plot in Figure A52. The average temperature differential on this project was 9.1°F and the average difference in density was 1.75 pcf. Figure A51 is a typical thermal image with corresponding density readings from this project.

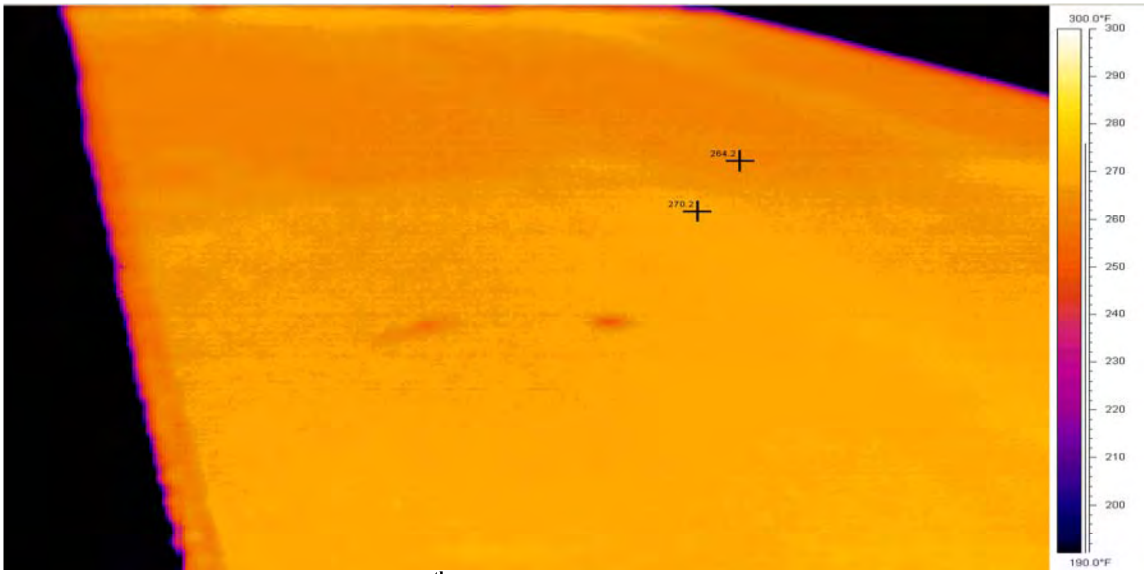


Figure A51 – Image of mat on July 17th, Interstate 91 in Wallingford.

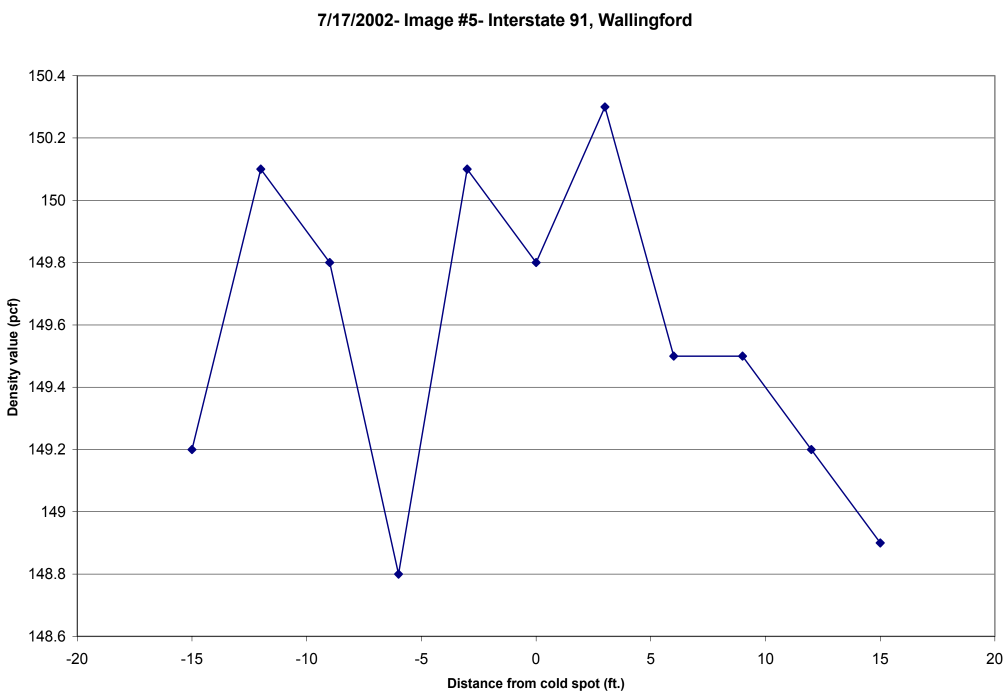


Figure A52 – Density vs Distance from cold spot

Monitored Site 22

This site was the resurfacing of Route 31 in Coventry, project number 171-302I. This site was monitored on July 19th, July 22nd and July 31st, 2002. The weather was sunny on all three days of monitoring. The ambient temperatures were 85°F, 76°F and

90°F on July 19th, 22nd and 31st respectively. The base temperatures ranged from 100°F - 125°F over the 3 days of monitoring. The plant was located 14 miles away in Manchester and the hauling time was about 25 minutes. The trucks were loaded with either 1 or 2 drops at the plant. The contractor paved with a CAT model AP1055B paver. The breakdown roller was a Hyster. The intermediate and finish roller was an Ingersoll Rand model DD-110. There was a different paver operator and also a different roller operator on the third day of monitoring. There was no material transfer vehicle used on the project.

The average temperature difference was 54.8°F, 53°F and 59.5°F for the respective first, second and third days of monitoring. Figures A53-A56 are thermal images with corresponding density readings that are typical for this project. There were no density tests performed by the CAP Lab on the first monitoring day. The average density differentials between the warm and cool material on the second and third days of paving were 4.9 pcf and 5.1 pcf respectively

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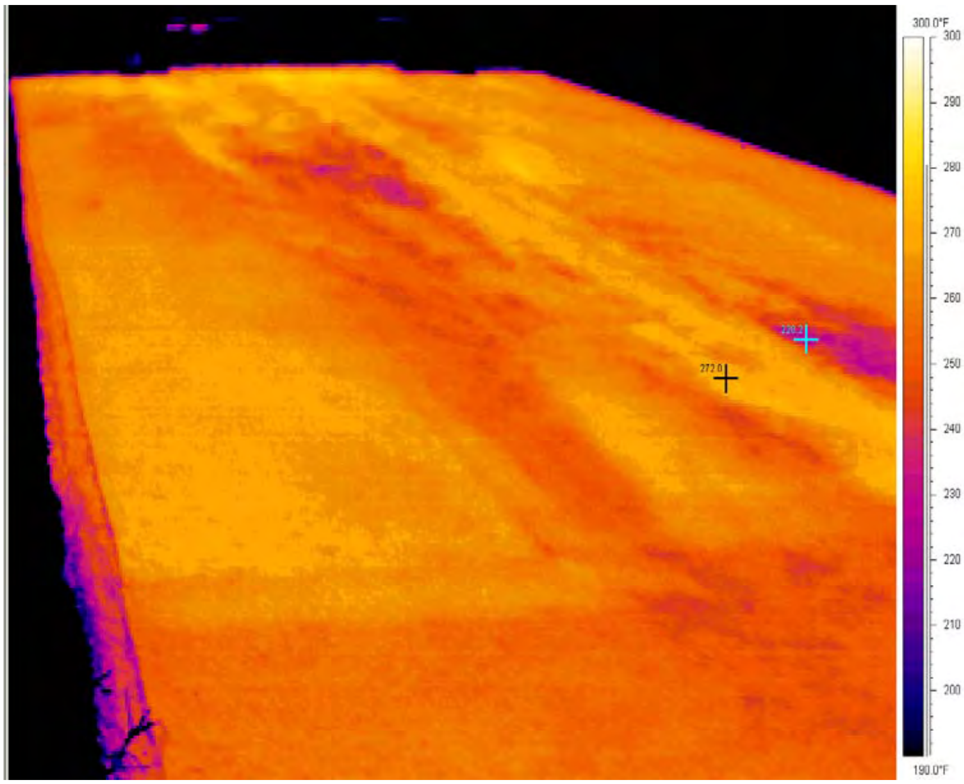

Figure A53 – Image of cold spot on July 22nd, Route 31 in Coventry.

Figure A54 – Density vs Distance from cold spot

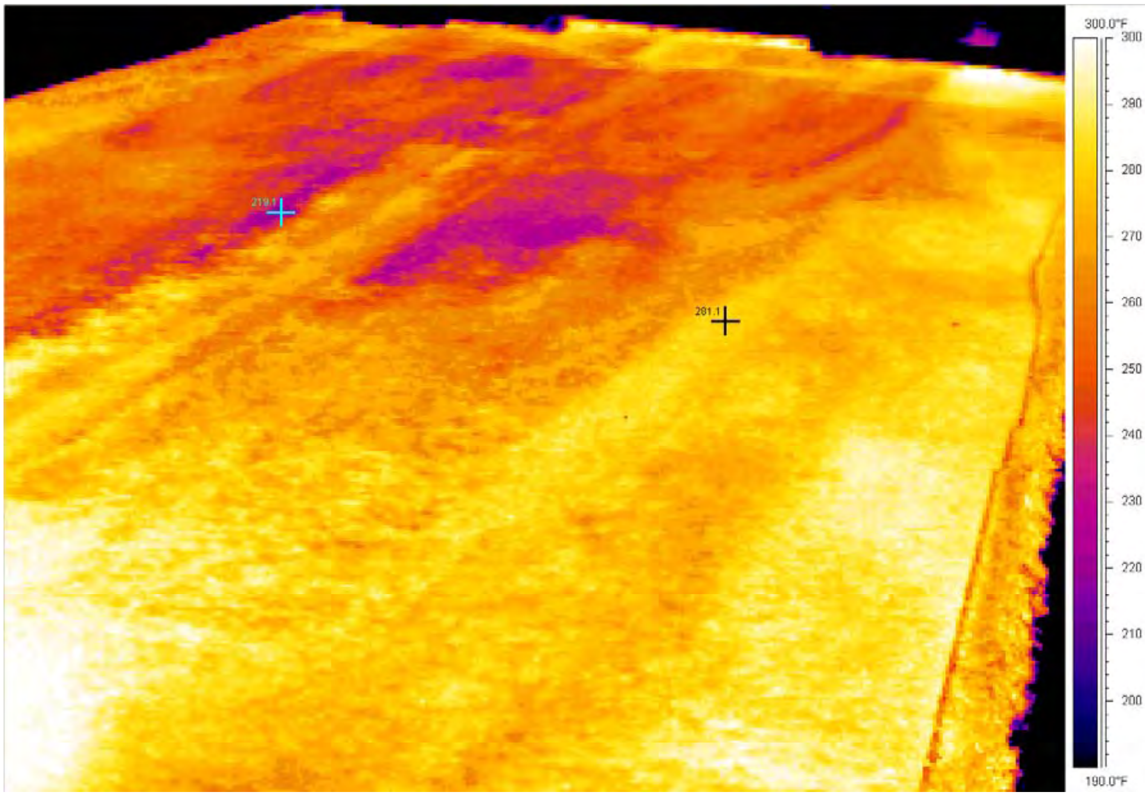

Figure A55 – Image of cold spot on July 31st, Route 31 in Coventry.

7/31/2002- Image #17- Route 31, Coventry, Project # 171-302I

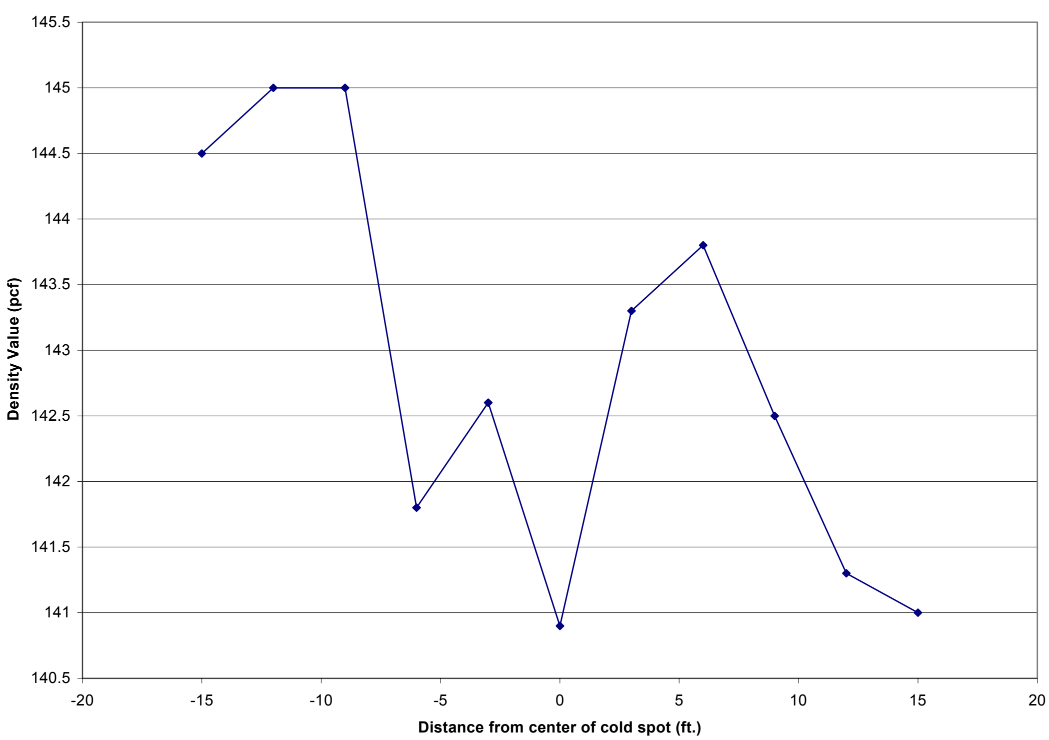

Figure A56 – Density vs Distance from cold spot

Monitored Site 23

This site was project number 172-337J on Route 195 in Storrs and it was monitored on July 25th and July 26th, 2002. The weather was sunny and ambient temperatures were 70°F-75°F both days. There was a leveling course placed on the first day from which there was a base temperature of 158°F for the pavement placed over the leveling course. The first four thermographic images on this day were taken where the wearing surface was placed on the leveling course. All images found in the database, after the first four, correspond to wearing surface being placed on a milled pavement surface. The base pavement temperature for the milled surface was 86°F.

The average temperature differential on the first day was 65.6°F and the average difference in density between warm and cool material was 8.88 pcf. The base pavement temperature on the second day of monitoring was 85°F, with an average HMA pavement temperature differential of 70.0°F.

The plant was located 21 miles away in Killingly and the haul time was 35 minutes. The trucks were loaded with 3 drops at the plant. The contractor used a Blaw-Knox model PF3200 paver, a CAT model CB634C vibratory breakdown roller, a CAT model CB534 vibratory intermediate and finish roller and a CAT model CB224D roller for driveway entrances. There was no material transfer vehicle used on this project. There were no density readings taken by the CAP Lab on the second day of monitoring due to traffic. Figure A57 is a thermal image on July 25th with Figure A58 being its corresponding density plot. Figure A59 is a thermal image taken on July 26, 2002.

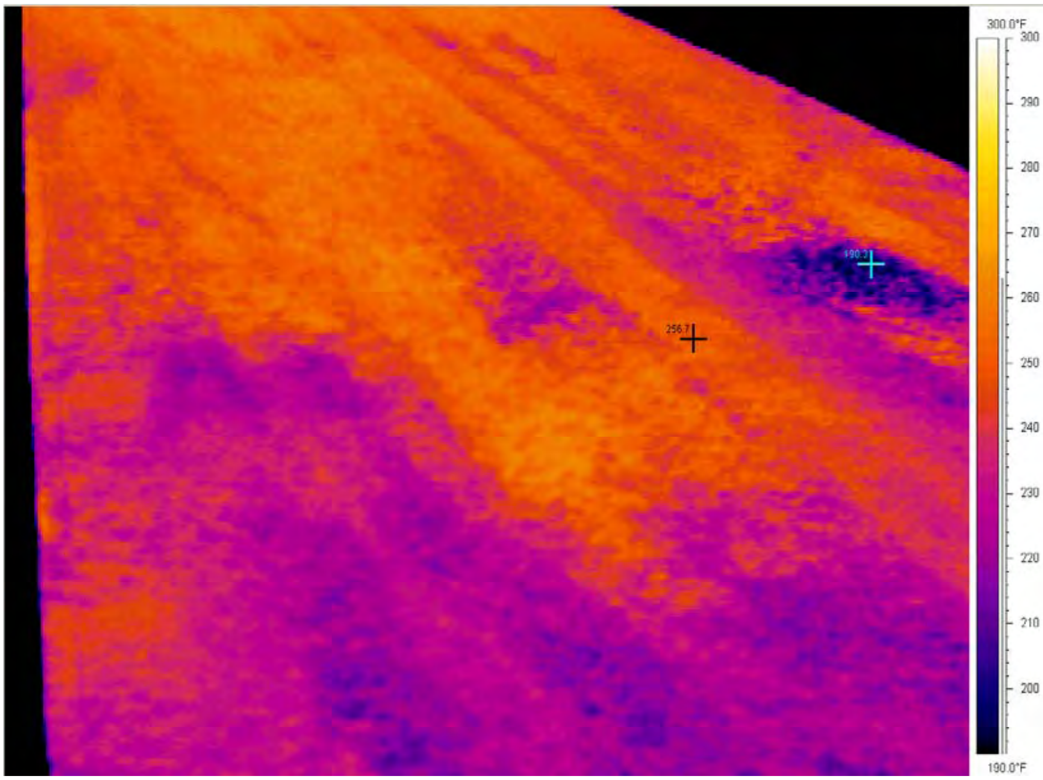

Figure A57 – Image of cold spot on July 25th, Route 195 in Storrs. 7-25-02.

Figure A58 – Density vs Distance from cold spot

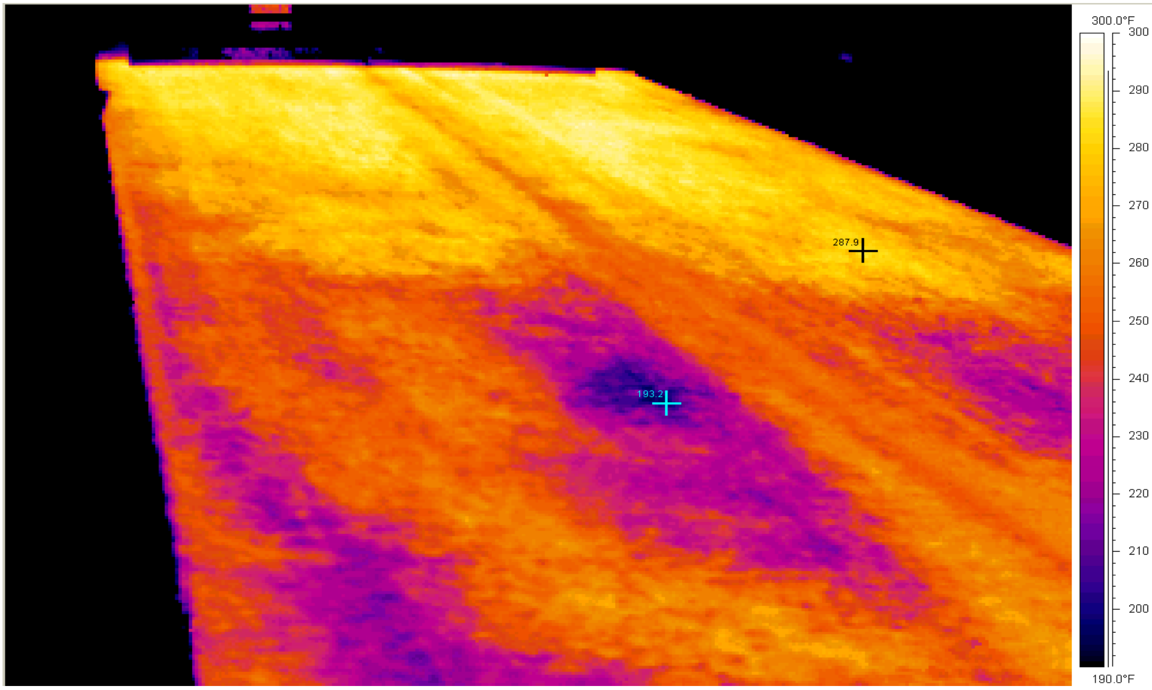

Figure A59 – Cold spot generated by spilled material on Route 195 in Storrs. 7-26-02

Monitored Site 24

Project number 171-302H was monitored for two days on August 2nd and again on August 5, 2002. The site was the resurfacing of a section of Route 6 in Manchester. The weather was sunny and the ambient temperature was 90°F on the first day of monitoring. The second day was partly cloudy and 78°F. The base temperature was 110°F and 90°F on the first and second days respectively. The material was Superpave 12.5 mm and the compacted mat thickness was 2 inches. The plant was located 15 miles from the project in Newington. Hauling time was about 20 minutes. The trucks were loaded with either 2 or 3 drops at the plant. The paver was a Blaw-Knox model PF-200. There was also a Hyster model C340 vibratory breakdown roller and an Ingersoll Rand model DD- 90HF vibratory intermediate and finish roller used. There was no material transfer vehicle used on this project. The average temperature differential observed on this project was 36.9°F on the first day and 45.9°F on the second day. The corresponding average differences in density between warm and cool spots for the first and second monitoring days were 8.75 pcf and 6.77 pcf respectively. Figures A60-A63 show typical thermographic images for the two days monitored along with their corresponding density plots.

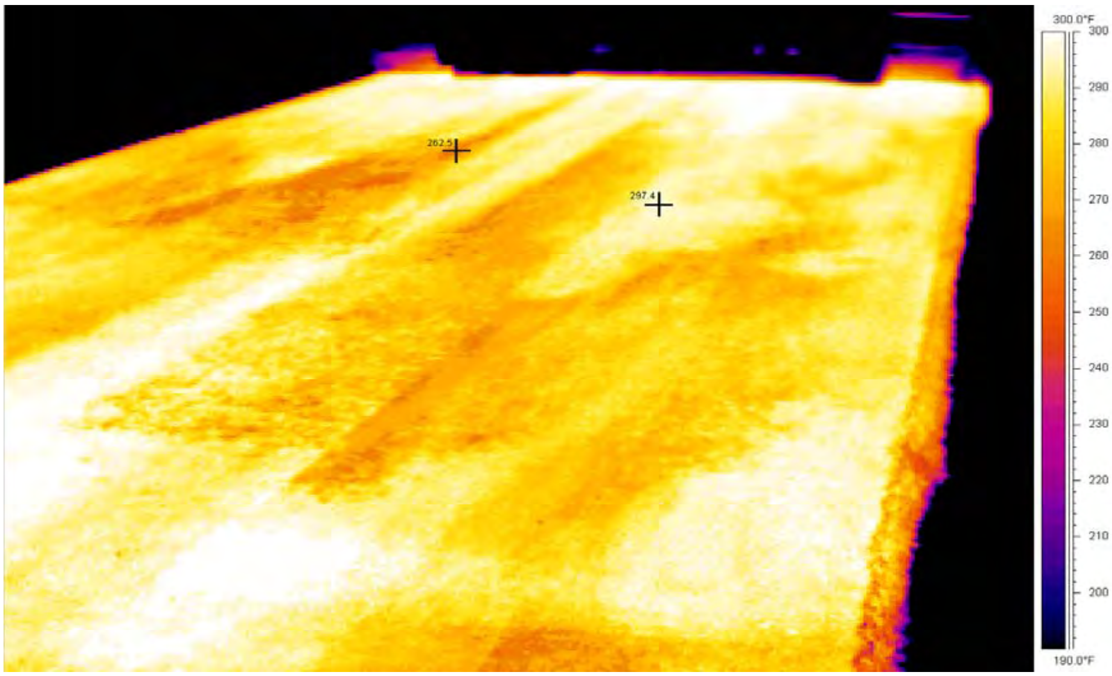

Figure A60 – Typical Image of cold spot on Route 6 in Manchester 8-2-02

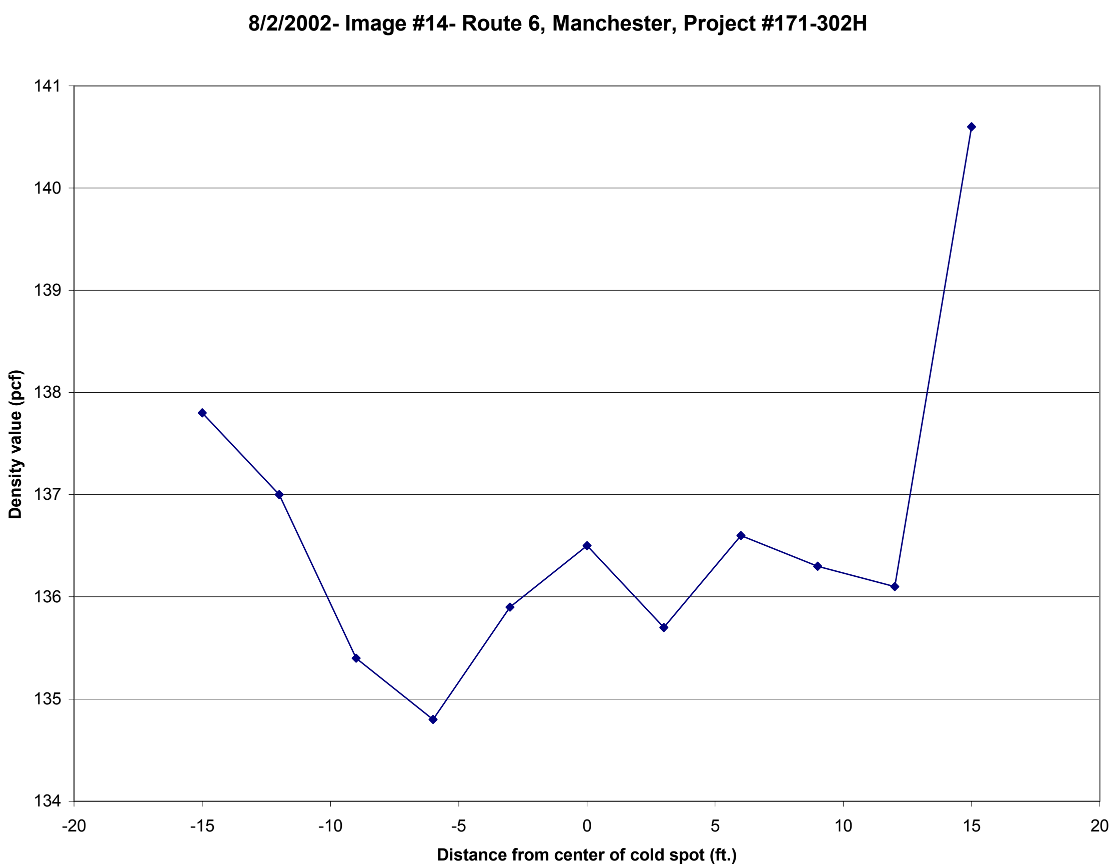

Figure A61 – Density vs Distance from cold spot

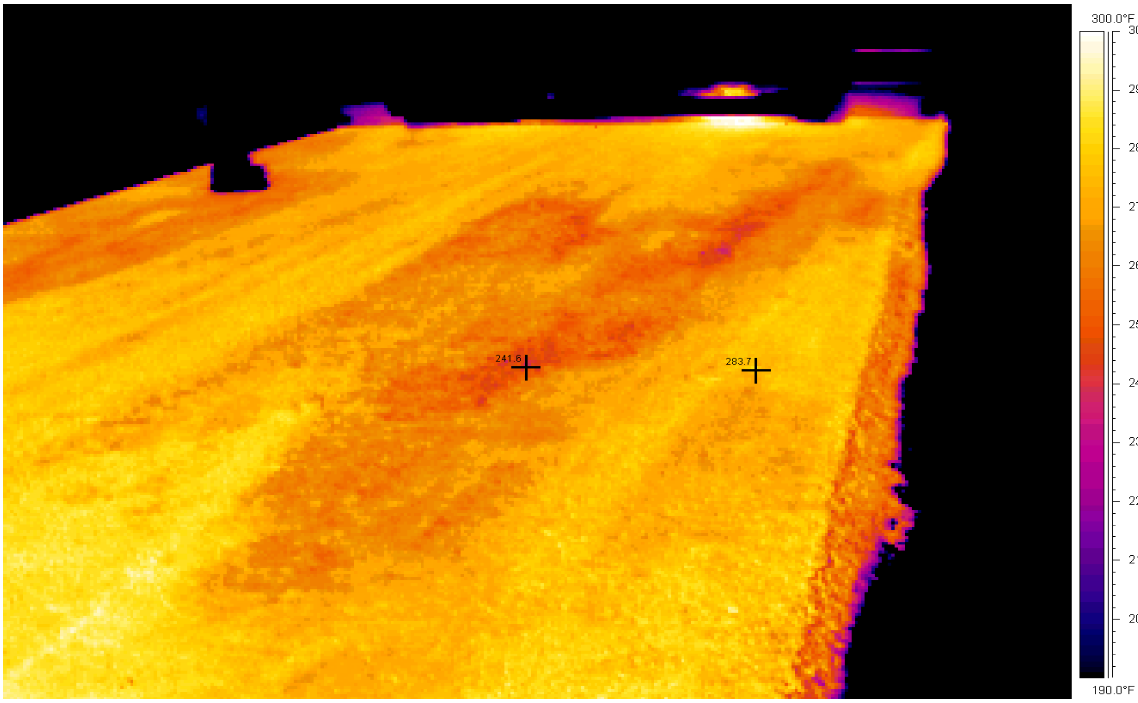

Figure A62 – Typical Image of cold spot on Route 6 in Manchester 8-5-02

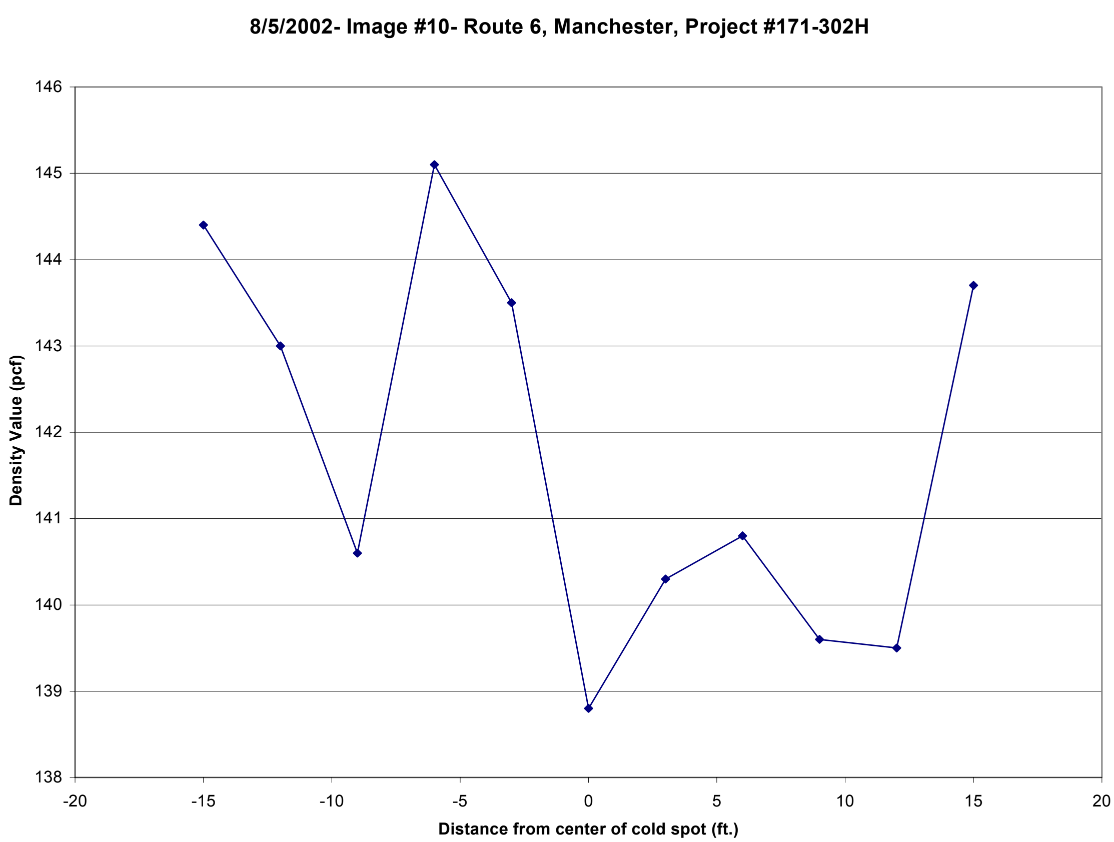

Figure A63 – Density vs Distance from cold spot

Monitored Site 25

This site was the resurfacing of Interstate 91 Southbound in Windsor on August 8, 2002. The project number was 164-224 and took place during nighttime hours. The weather was clear and the ambient temperature ranged from 70°F - 75°F. The base pavement temperature was approximately 80°F. The material being placed was Superpave 12.5 mm and the compacted thickness was 1.5 inches. The plant was located 9 miles away in East Granby. The hauling time was about 15 minutes. The trucks were loaded with either 1 or 2 drops at the plant. The contractor's equipment consisted of a CAT model AP1000B paver, a Hypac model C766C breakdown roller, a Hyster intermediate roller, a CAT model CB634 finish roller and a Roadtec model SB2500 material transfer vehicle.

The thermal images taken on this project did not show any significant temperature differentials which is typical of remixing. The average temperature differential was 11.9°F. Temperature profiles remain uniform over the scope of images for this project. Figure A64 is a thermographic image showing a typical temperature profile from this project. There were no density measurements made by the CAP Lab at this monitored site.

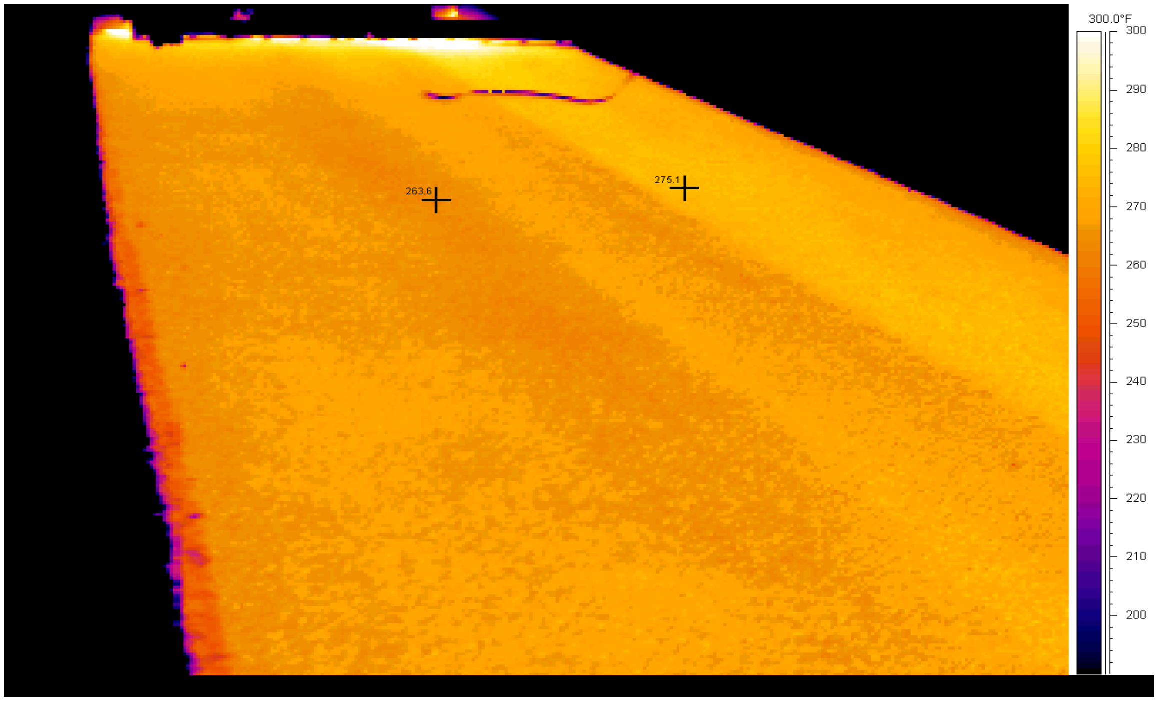

Figure A64 – Typical Thermographic Image from Interstate 91 in Windsor 8-7-02

Monitored Site 26

This monitored site was on Route 74 in Vernon on August 28th, 2002. The project number was 171-302J. The weather was cloudy with ambient temperatures in the lower 70's. The base temperature ranged from 70°F - 75°F. The material being placed was Class 1 and the compacted thickness was 2 inches. The plant was located in the town of East Granby, about 28 miles from the project and the haul time was approximately 40 minutes. The contractor paved with a Cedar Rapids paver and the rollers consisted of a Hypac model C778B breakdown roller and a Hypac model C340CW intermediate and finish roller. There was no material transfer vehicle used on this project nor were there any density measurements made by the CAP Lab. The average temperature differential observed on this project was 50.3°F. Figure A65 is a thermal image of a typical cold spot from this project.

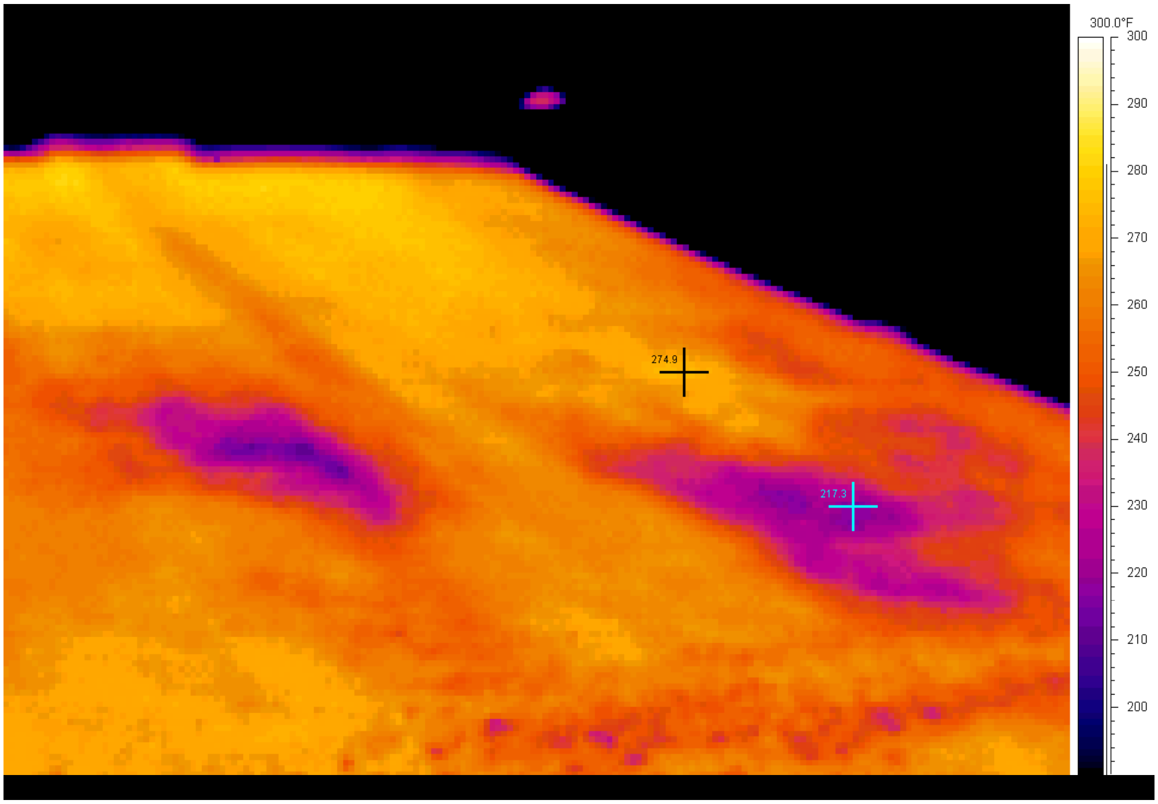

Figure A65 – Typical Thermographic Image from Route 74 in Vernon, 8-28-02

Monitored Site 27

This monitored site was Route 94 in Glastonbury, project number 171-303C. The site was monitored on 5 different days, September 3, 4, 5, 10 and 17, 2002. The weather was sunny and temperatures ranged from 65°F - 90°F over the course of the monitoring days with the exception of September 4th when the weather was overcast with intermittent sprinkles of rain. Base pavement temperatures ranged from 75°F - 110°F over the 5 days. The plant was located in Newington, about 16 miles and 20 minutes from the project. The material being placed was Superpave 12.5 mm at a compacted thickness of 2 inches. The contractor was paving with a CAT model AP1055B paver and the rollers were a Hypac model C766C vibratory breakdown roller and an Ingersoll Rand vibratory intermediate and finish roller. There was no material transfer vehicle used on September 3rd, 4th and 5th however the contractor added a Roadtec model SB-2500 material transfer vehicle to the project on September 10th and used it through September 17th.

The average temperature differential for each of the five monitoring days chronologically was 66.5°F, 51.0°F, 61.7°F, 16.0°F and 20.4°F. The temperature differentials on the last two days of monitoring reflect the use of the material transfer vehicle. There were densities recorded on the 2nd, 3rd and 5th days of monitoring. The respective average density differences between warm and cool material on those 3 days were 12 pcf, 13.7 pcf and 5.35 pcf. The last stated difference was observed on the 5th day of monitoring while the remixing material transfer vehicle was being used. Figures A66 and A67 show a typical image and corresponding density reading from this project during the monitoring days of September 3rd, 4th and 5th without the material transfer vehicle. The data and images of those days when the material transfer vehicle was used is not typical of most other monitored sites as the temperature differentials were considerably larger than most projects that used a remixing material transfer vehicle. This is particularly true for images taken on September 10th as there was a large intersection paved on that day. Figures A68 and A69 show images and densities on September 10th and 17th while the material transfer vehicle was being used.

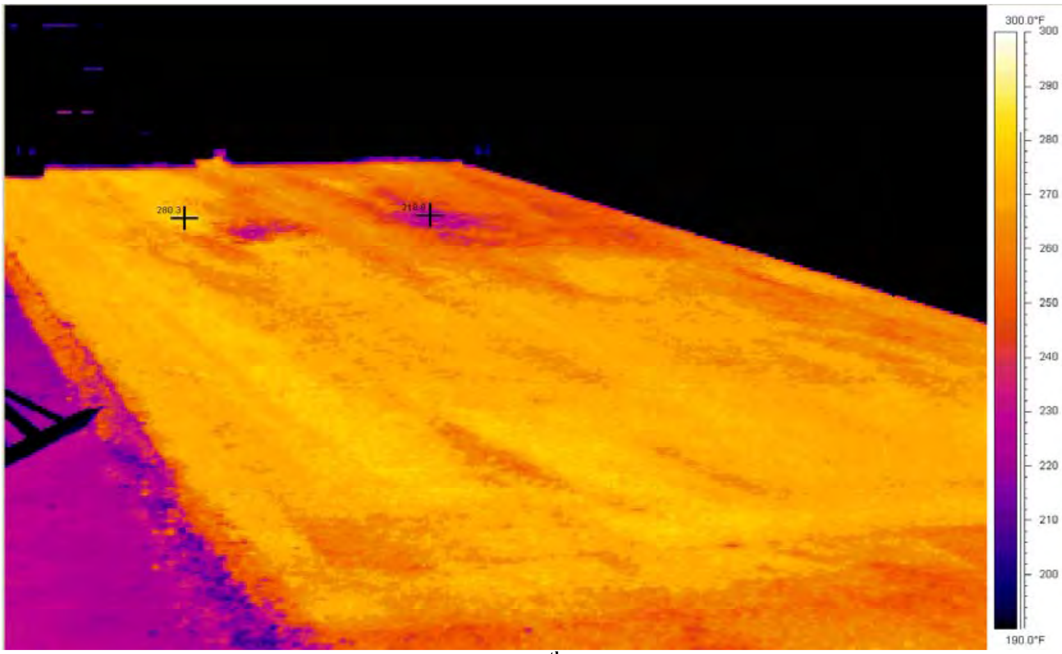

Figure A66 – Image of cold spot on September 4th, Route 94 in Glastonbury (No MTV)

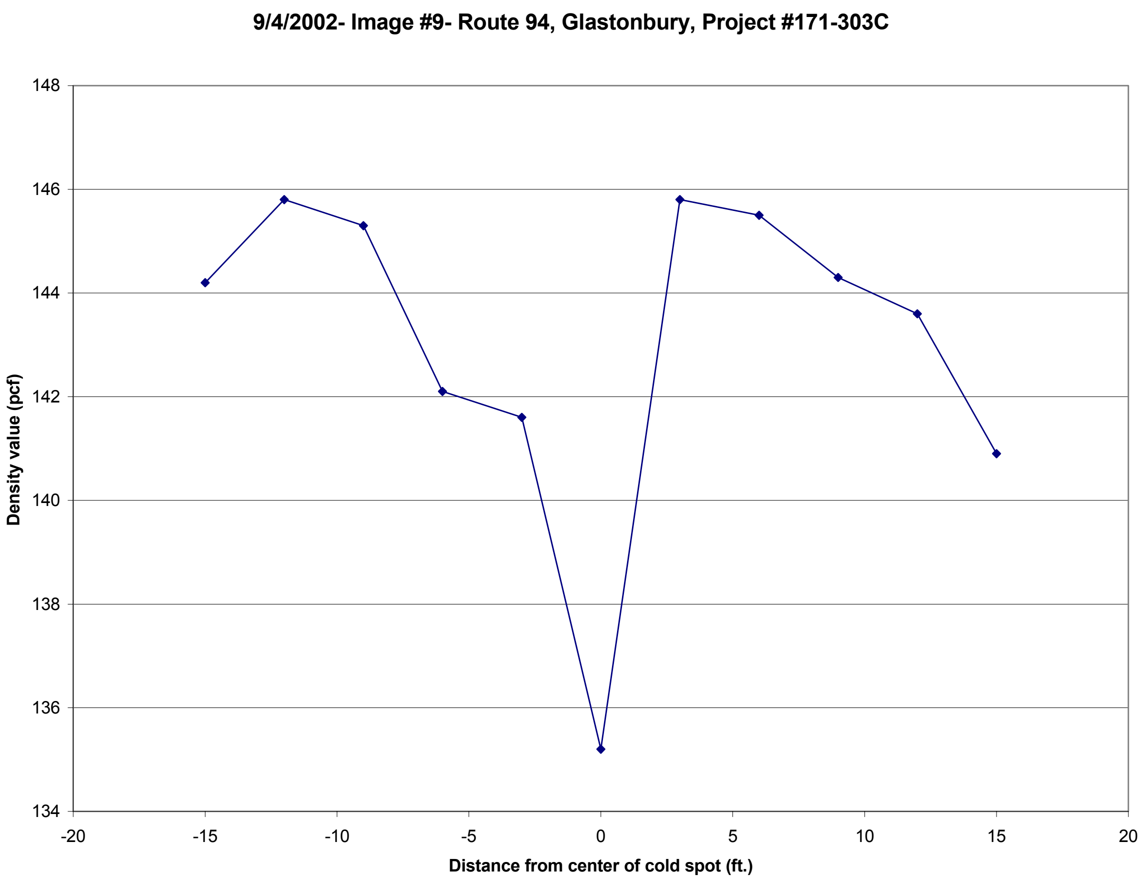

Figure A67 – Density vs. Distance from cold spot

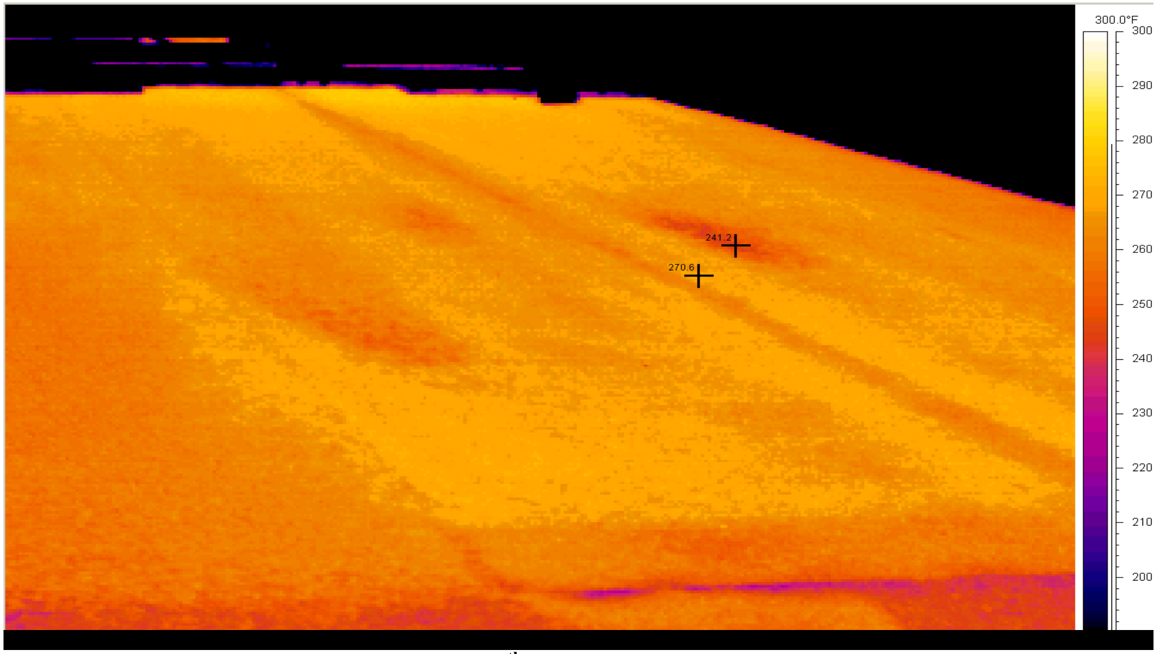

Figure A68 – Image of mat on September 17th, Route 94 in Glastonbury (MTV used)

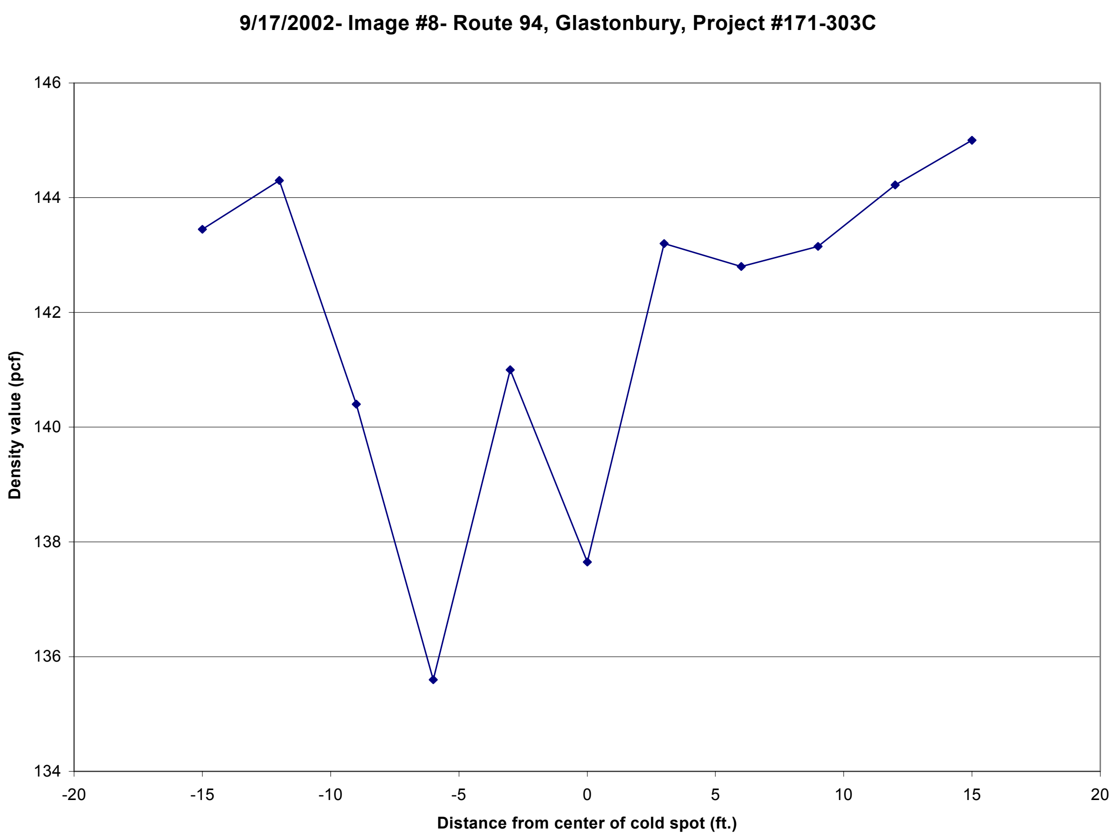

Figure A69 – Density vs. Distance from Cold Spot

Monitored Site 28

This site was project number171-303F on Route 5 and 15 Southbound in Newington. This monitoring took place on September 12, 2002. This project took place at night and the ambient temperature ranged from 45°F - 55°F with a gusty wind. The material was Superpave 12.5 mm and was being hauled 12 miles from New Britain. The haul time was about 20 minutes. The compacted thickness of the mat was 2 inches. The contractor paved with a Blaw-Knox model PF200B paver. The rollers consisted of an Ingersoll-Rand model DD-110 vibratory breakdown roller, a CAT model CB-634 vibratory intermediate roller and a Hyster finish roller. The contractor also used a Roadtec model SB2500B material transfer vehicle on this project. The mat temperatures were relatively uniform for this day of observation. The average temperature differential on this project was 14.0°F. Figure A70 is a thermographic image depicting the typical HMA temperature profile on this project. There were no density readings taken at this site by the CAP Lab.

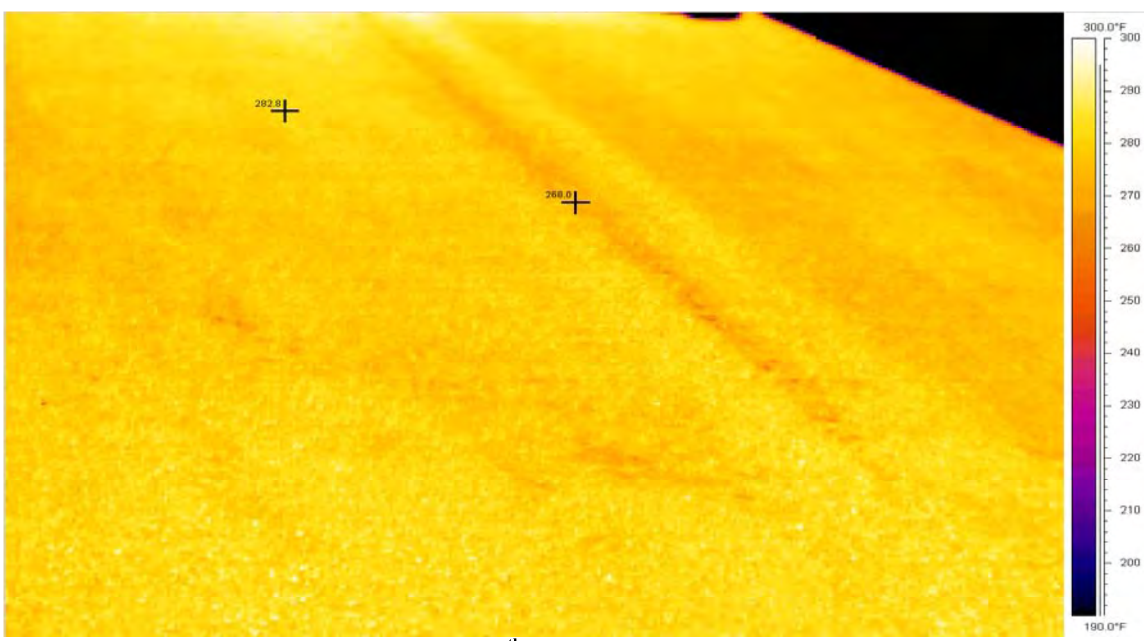

Figure A70 – Image of mat on September 12th, Route 5 & 15 in Newington (MTV used)

Monitored Site 29

The first site monitored in October of 2002 was Interstate 95 Northbound in New London, project number 94-202. This site was monitored on October 3rd, 2002. The crew on this project was the same crew that paved monitored site 27 in Glastonbury. This project took place at night with ambient temperatures between 55°F and 60°F. The base pavement temperature was approximately 67°F. The material being placed on this project was Superpave 12.5 mm and the compacted thickness of the mat was 2 inches. The material was being hauled five miles from Groton which took approximately ten minutes to haul to the project. The contractor used a CAT model AP 1055B paver, an Ingersoll Rand model DD-110 breakdown roller, a CAT model CB634C vibratory intermediate roller, a combination Rubber Tire & Steel Drum finish roller and a Roadtec model SB-2500 material transfer vehicle. There were no nuclear density readings on this day performed by the CAP Lab. The thermal images displayed consistent temperature profiles for this project. The average temperature differential on this day was 10.5°F. Figure A71 is typical of the thermal images taken on this project.

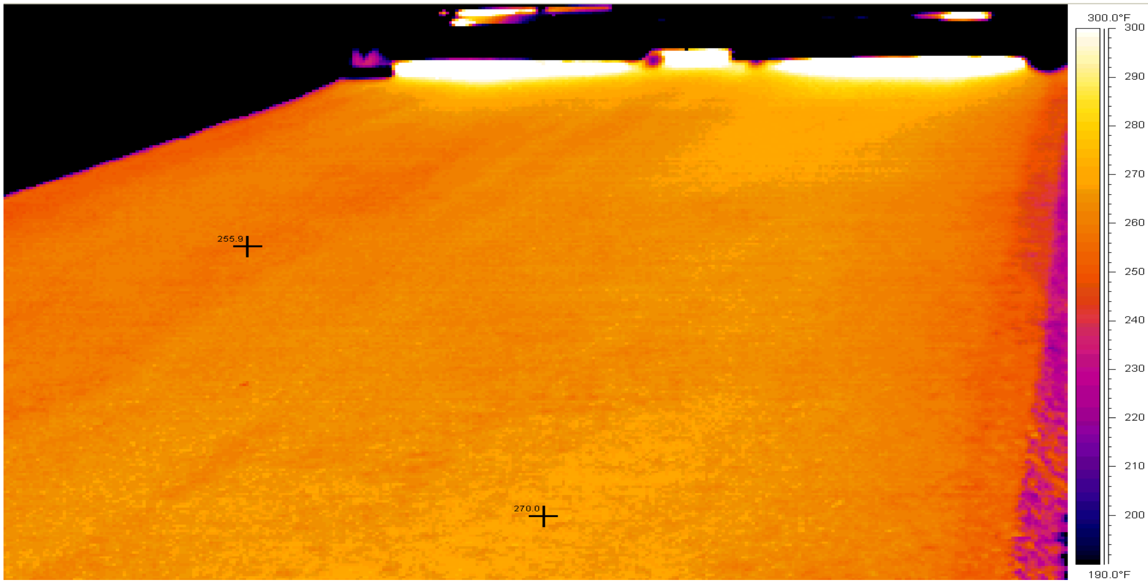

Figure A71 – Typical image of mat on October 3, Interstate 95 in New London (MTV used)

Monitored Site 30

Project number 172-338L was monitored on two occasions, October 10th and October 17th, 2002. The site was Route 184 in Groton and had the same paving crew as monitored sites 19, 21 and 35(North Crew). Ambient air temps ranged from 51°F to 62°F on the first day of monitoring and 45°F to 63°F on the second day. The base pavement temperatures were between 45°F and 50°F on both days of monitoring. The material being placed was Superpave 12.5 mm and the compacted thickness was 2.0 inches. The plant was also located in Groton, about 10 miles from the paving project. The haul time was 15 minutes. The paving equipment consisted of a CAT model AP1000B paver, a Hypac model C766C breakdown roller and a CAT model CB 634 intermediate and finish roller. There was no material transfer vehicle used on this project. The average temperature differentials were 35.2°F and 40.3°F for the respective first and second days of monitoring. Drops in densities were consistent with the cold spot locations in the thermal images. The average density difference between warm and cool material was observed at 4.95 pcf on the second day, on the first day there were no density tests performed by the CAP Lab. Figures A72 and A73 show a typical thermal image with a cold spot and corresponding nuclear density reading for this site.

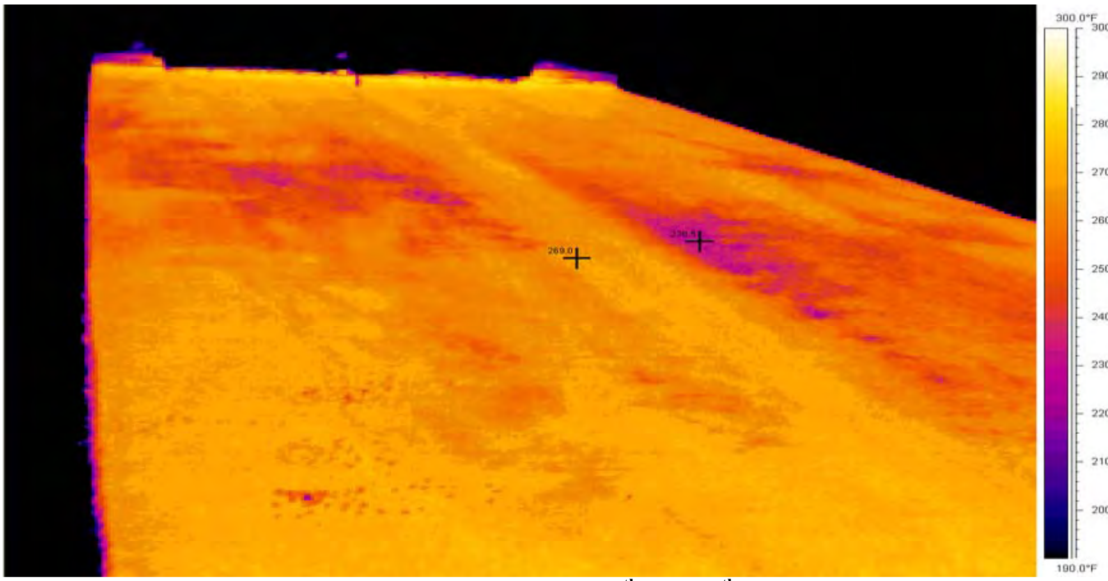

Figure A72 – Typical image of cold spot on October 10th and 17th, Route 184 in Groton

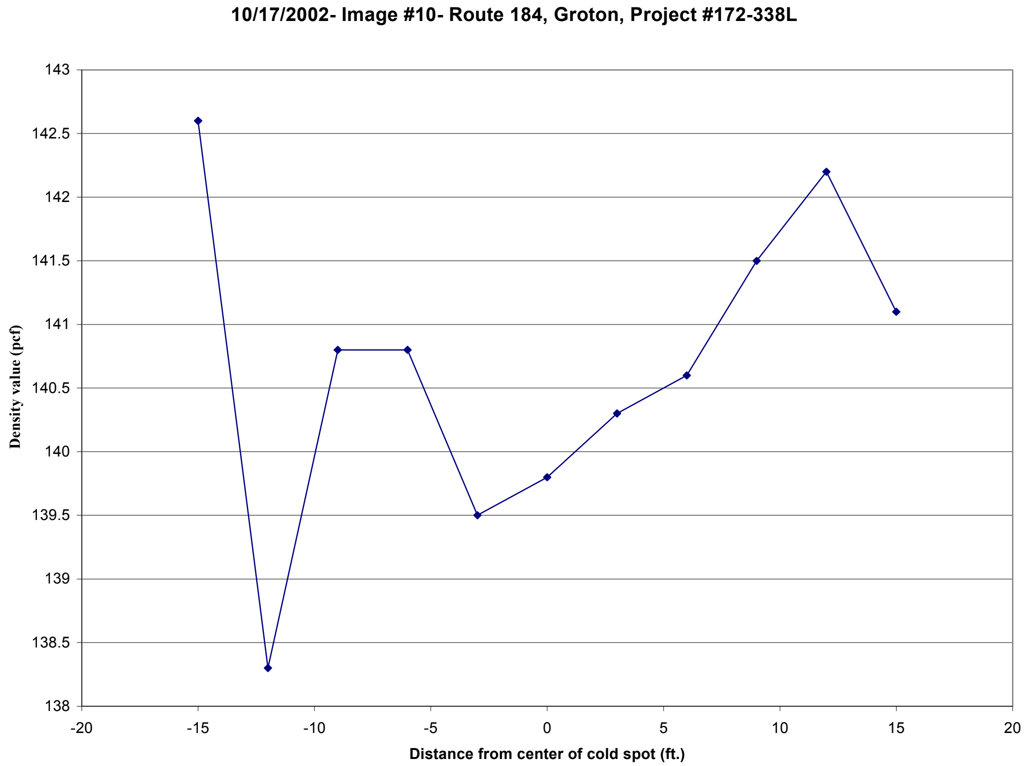

Figure A73 – Density vs. Distance from cold spot

Monitored Site 31

This project, number 51-249, on Route 4 in Farmington was monitored on 2 different days, October 15th and October 22nd, 2002. The ambient temperature was 48°F on the first day of monitoring. The second day was colder with ambient temperatures approximately 45°F. It was sunny on both days. The base pavement temperature was 40°F-45°F on both monitoring days. The plant was also located in Farmington about 5 miles from the project. The trucks had a hauling time of about 10 minutes. The material being placed was Class 1 and the compacted mat thickness was 1.5 inches. The contractor paved both days with a Blaw-Knox model PF180H paver and the rollers consisted of an Ingersoll Rand model DD-90HF breakdown roller, A Hyster model C766A Finish roller and an Ingersoll Rand model DD-24 roller used along the curbline. There was no transfer vehicle used on this project. There were no density readings taken on this project by the CAP Lab. The average temperature differential on these days was 46.3°F and 47.9°F corresponding to the first and second days of monitoring. Figure A74 is a typical thermal image of both monitoring days of this project.

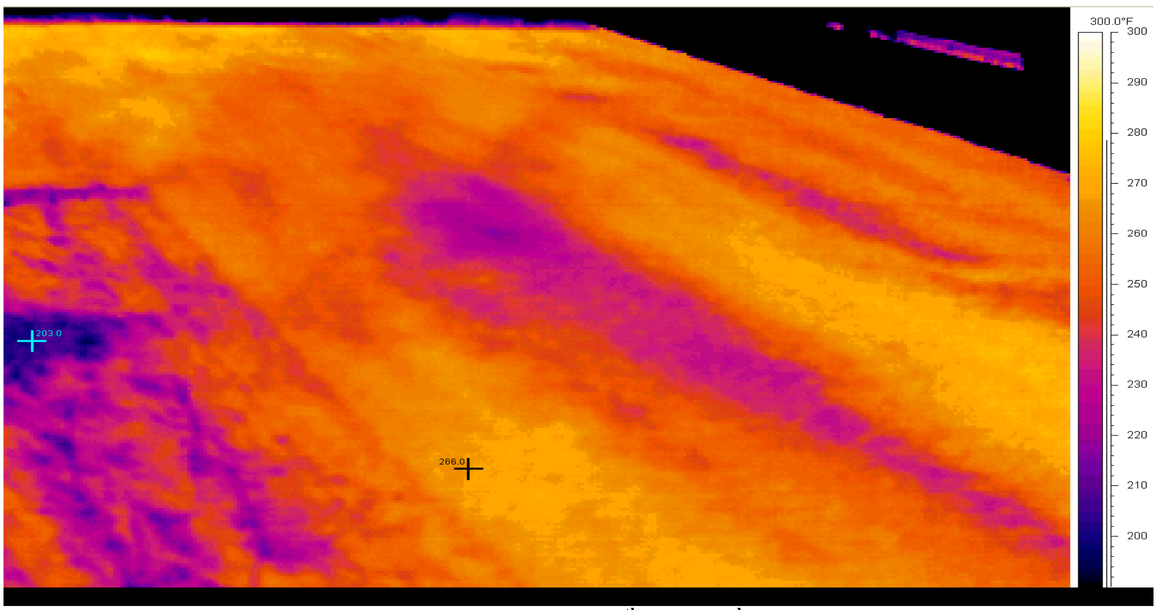

Figure A74 – Typical image of cold spot on October 15th and 22nd, Route 4 in Farmington

<u>Monitored Site 32</u>

This site was also monitored on October 15th, 2002. The project was number 131-62 on Route 10 in Southington and it took place during nighttime hours. The weather was drizzly and on the brink of rain so short passes were made. There were 4 passes observed within 3 hours. The ambient temperature was 45°F - 50°F. The base pavement temperature on this project also ranged from 45°F - 50°F. The material was Class 1 and the compacted thickness of the mat was 2 inches. The plant was located in New Britain, 10 miles from the project. The trucks had a hauling time of 20 minutes. The contractor paved with a Blaw-Knox model PF172 paver. The breakdown roller was a Hyster model C340A. An Ingersoll Rand model DD-70 vibratory roller was used for intermediate and finish rolling. There was no material transfer vehicle used on this project and there were no density tests performed by the CAP Lab. The average temperature difference on this site was 52.9°F. Figure A75 is a typical thermal image of a truck change on this project.

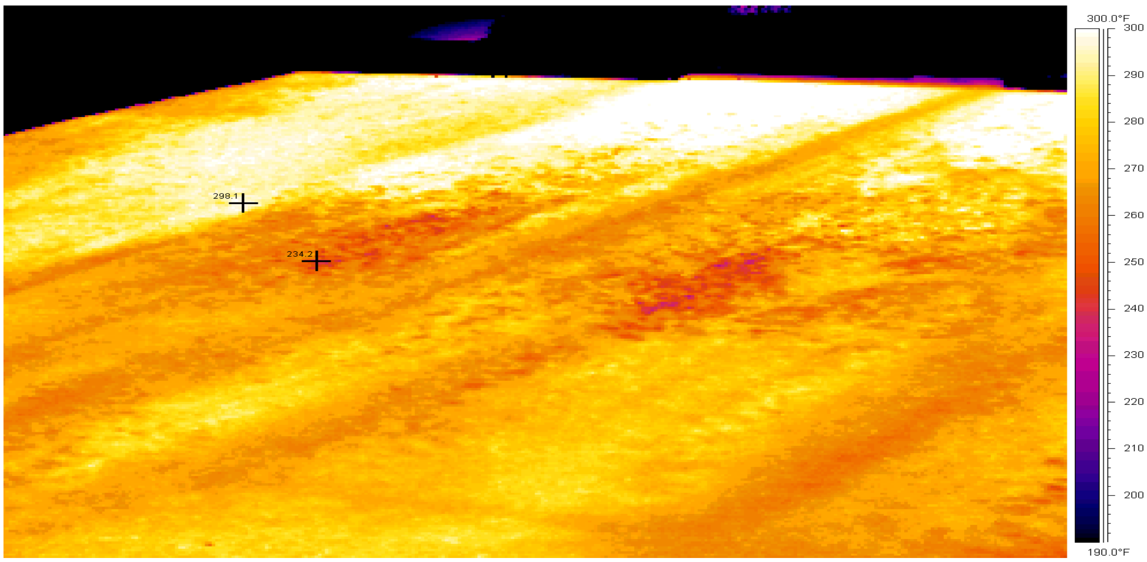

Figure 75 – Typical image of truck change on October 15th, Route 10 in Southington (night paving)

<u>Monitored Site 33</u>

This project (173-348H) was the resurfacing of Route 22 in North Haven. This site was monitored on both October 28th and 29th, 2002. The ambient temperature on this project was 50°F - 55°F on the first monitoring day and 45°F - 50°F and windy on the 2nd day of monitoring. The base temperature was measured as being 70°F. The contractor was placing a leveling course early the first and second day prior to resurfacing, however all images are of wearing course. The material being placed was Class 1 and the compacted mat thickness was 1.5 inches. The material was hauled from North Haven the first day of paving which was about 5 miles from the project and the hauling time was approximately 10 minutes. The material was hauled from North Branford the second day, which was about 8 – 9 miles from the project and haul time was approximately 15 minutes. The contractor paved with a Blaw-Knox model PF200 paver. The rollers consisted of a Hyster model C340 static breakdown roller and an Ingersoll Rand model DD110 vibratory intermediate and finish roller. There was no material transfer vehicle used on this project and there were no recorded densities. The average temperature differences on this site for the first and second days were 37.4°F and 43.6°F respectively. Figures A76 and A77 are typical of the temperature profiles for the first and second day of paving respectively.

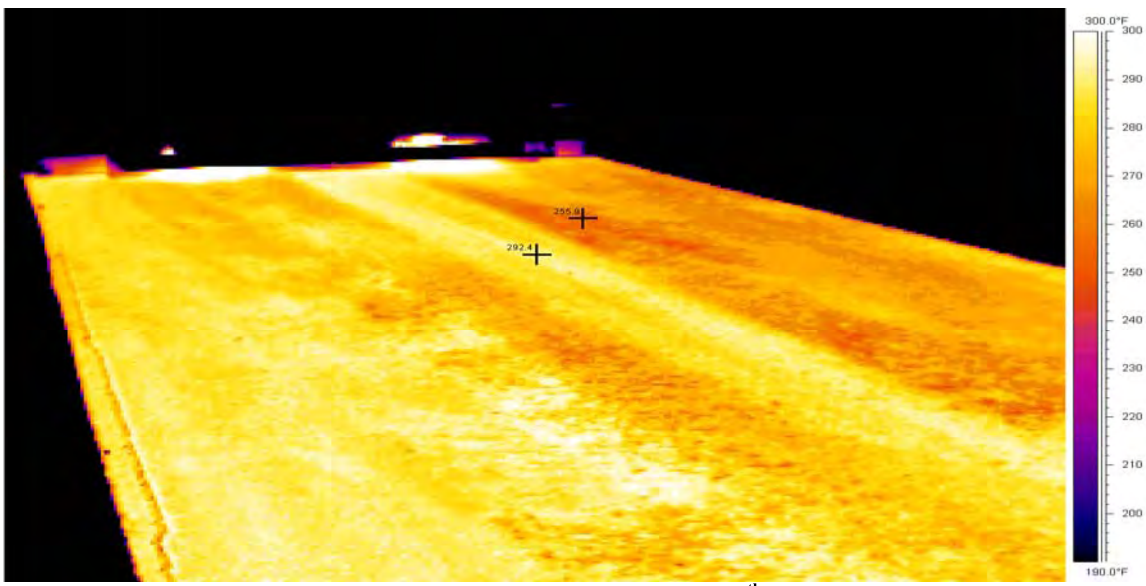

Figure A76 – Typical image of temperature profile on October 28th , Route 22 in North Haven

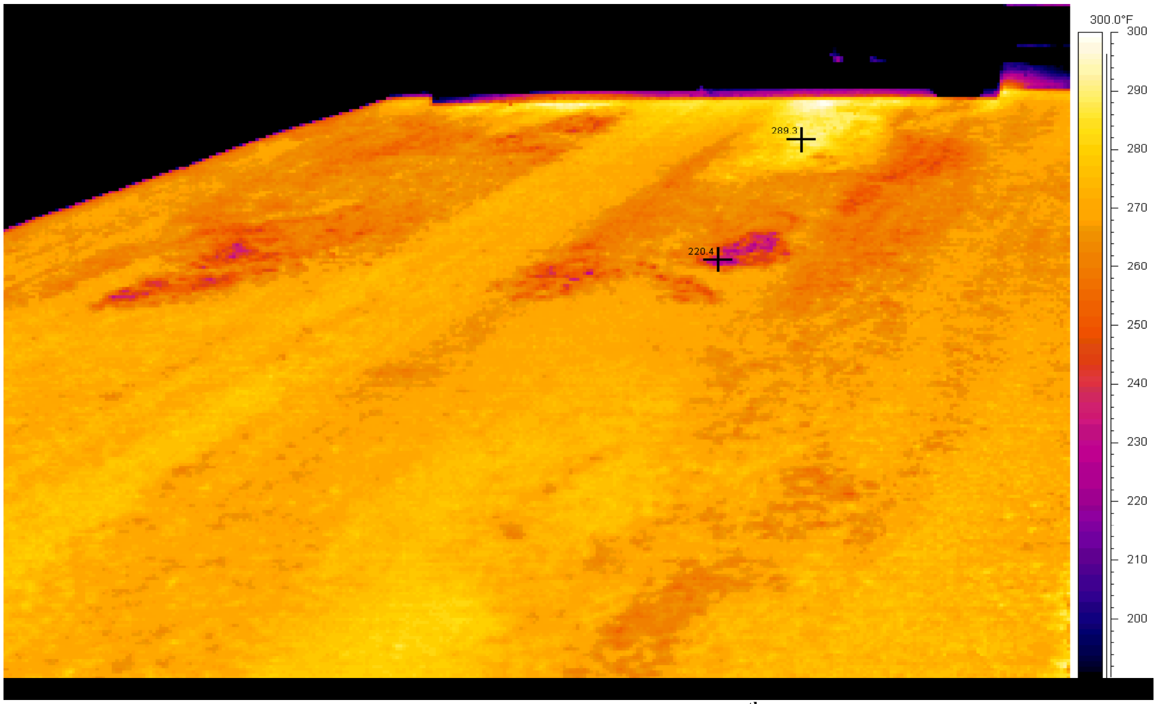

Figure A77 – Typical image of temperature profile on October 29th , Route 22 in North Haven

Monitored Site 34

The first monitored site in November 2002 was on Route 8 in Winchester on November 1st. The project number was 162-131. The day was cloudy with an ambient temperature of 40°F - 45°F. The temperature of the base pavement was 50°F. The material for this job was Superpave 37.5 mm and was being placed as a base course. The plant was located in Torrington, about 11 miles from the project. Trucks had a haul time of approximately 20 minutes. The paver was a Blaw-Knox model PF115 and the breakdown roller was an Ingersoll Rand model DD-90HF. Data from this project was excluded from all calculations as it was a base mix.

Monitored Site 35

This site was the resurfacing of Route10 in Farmington, project number 174-305E, on November 2nd, 2002. The weather was sunny and unseasonably cold with ambient temperatures ranging from 25°F - 35°F. The temperature of the base pavement on this project also ranged from 25°F - 40°F. The contractor implemented two paving crews on this project, one for paving in the southern half of the project and one for paving in the northern half of the project. Both crews were placing Class 1 material at a compacted thickness of 1.5 inches and there was no material transfer vehicle used on this project.

The southern paving crew was receiving material from a plant in New Britain, which was about 10 miles from the project giving the trucks a haul time of about 15 minutes. The southern crew was paving with a CAT model AP1000 paver, a Hyster breakdown roller and an Ingersoll-Rand model DD110 intermediate and finish roller. The observed average temperature differential for the southern crew was 42.1°F. The average difference in density between warmer and cooler material placed by this crew was 3 pcf.

The northern crew was receiving material from a plant, which was located in Farmington about 4 miles from the project. The hauling time from that plant was about 8 minutes. The northern crew paved with a Blaw-Knox model PF-200B paver, a Hyster breakdown roller and a CAT model CB634C intermediate and finish roller. The material being placed by the northern crew had an average temperature difference of 49.7°F and an average difference in density of 8.0 pcf between warm and cool material. Figures A78-A81 give typical thermal profiles of the mat on this project with their corresponding cold spot density analyses for both the northern and southern crews.

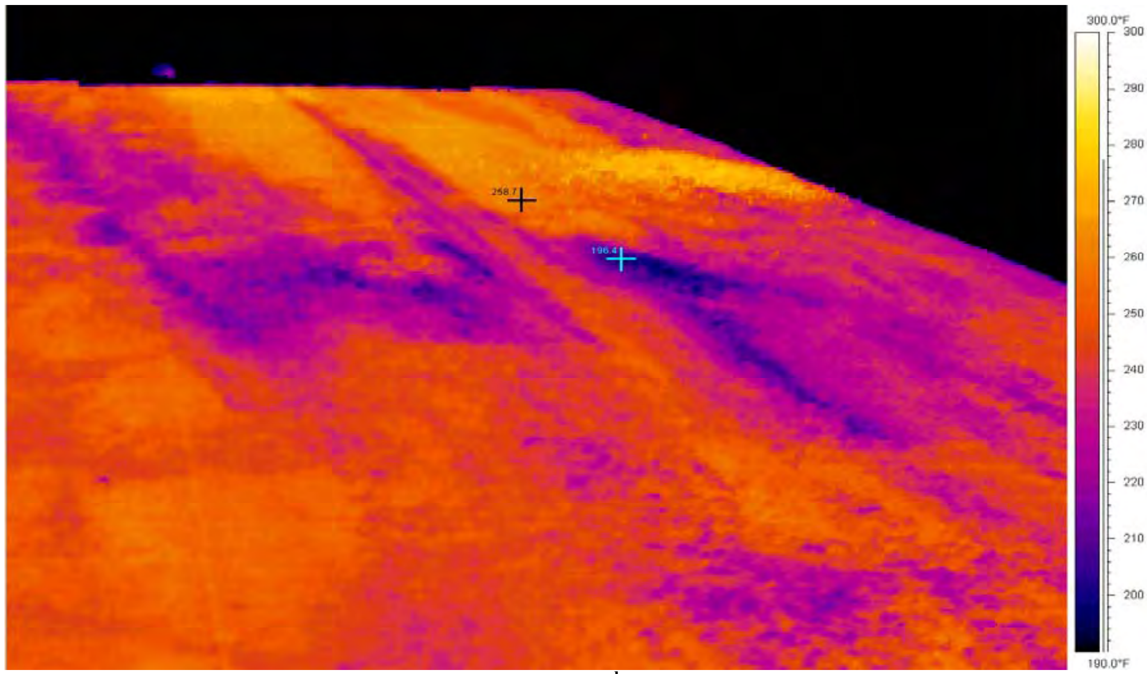

Figure A78 Typical thermal profile, November 2nd, north crew, Route 10 Farmington

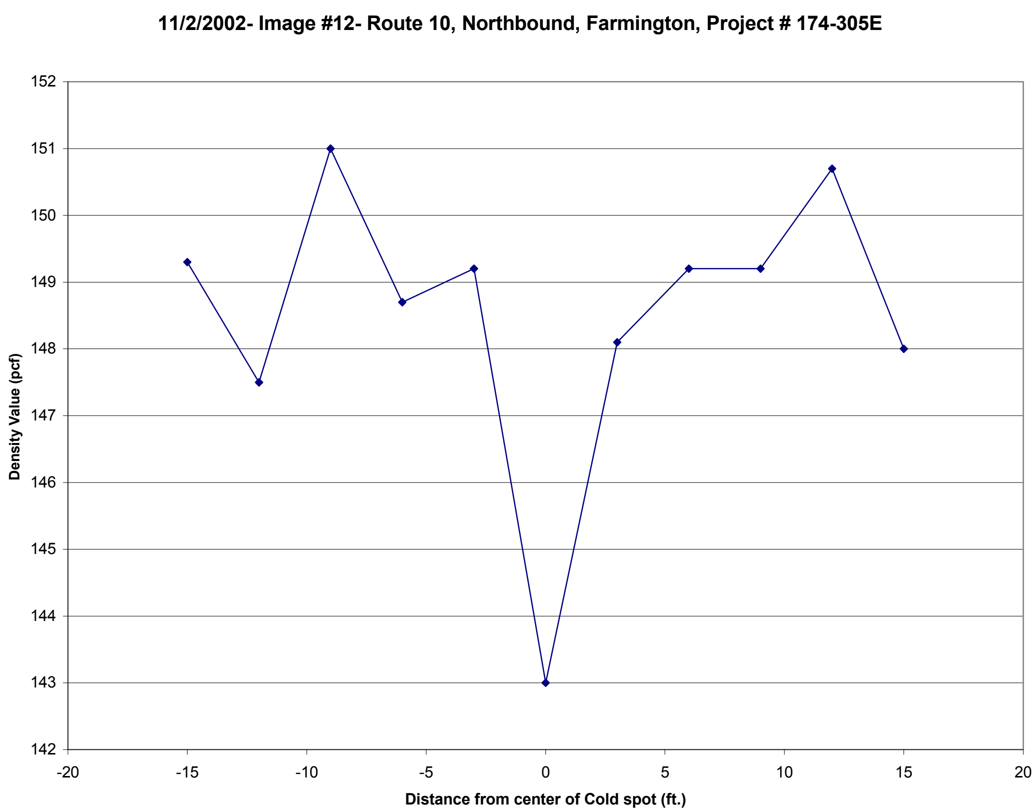

Figure A79 – Density vs. Distance from cold spot

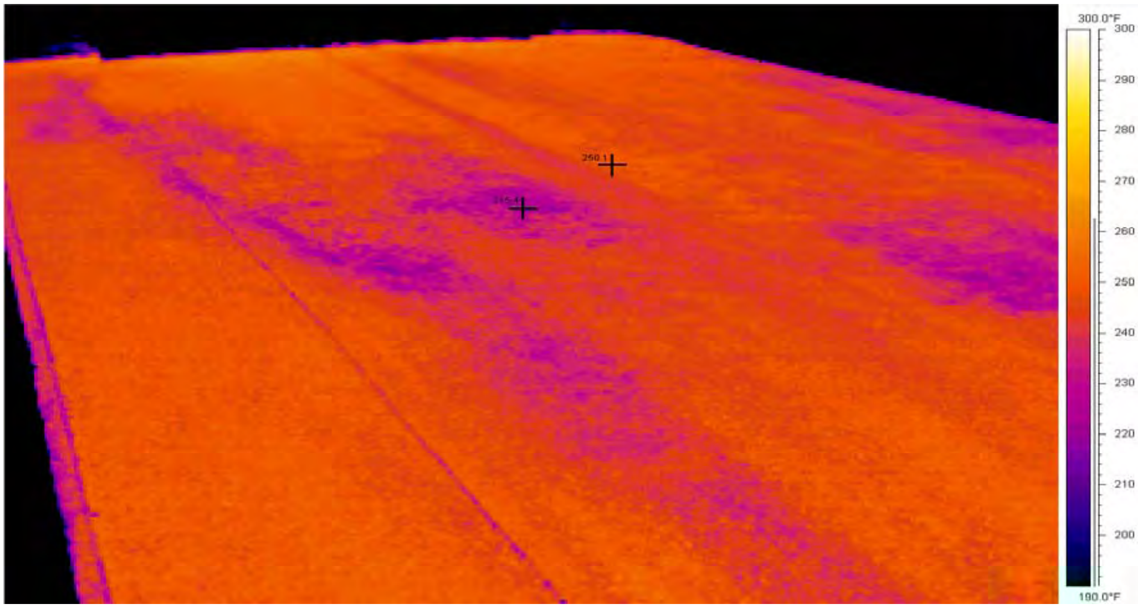

Figure A80 - Thermal profile, November 2nd, south crew, Route 10 Farmington.

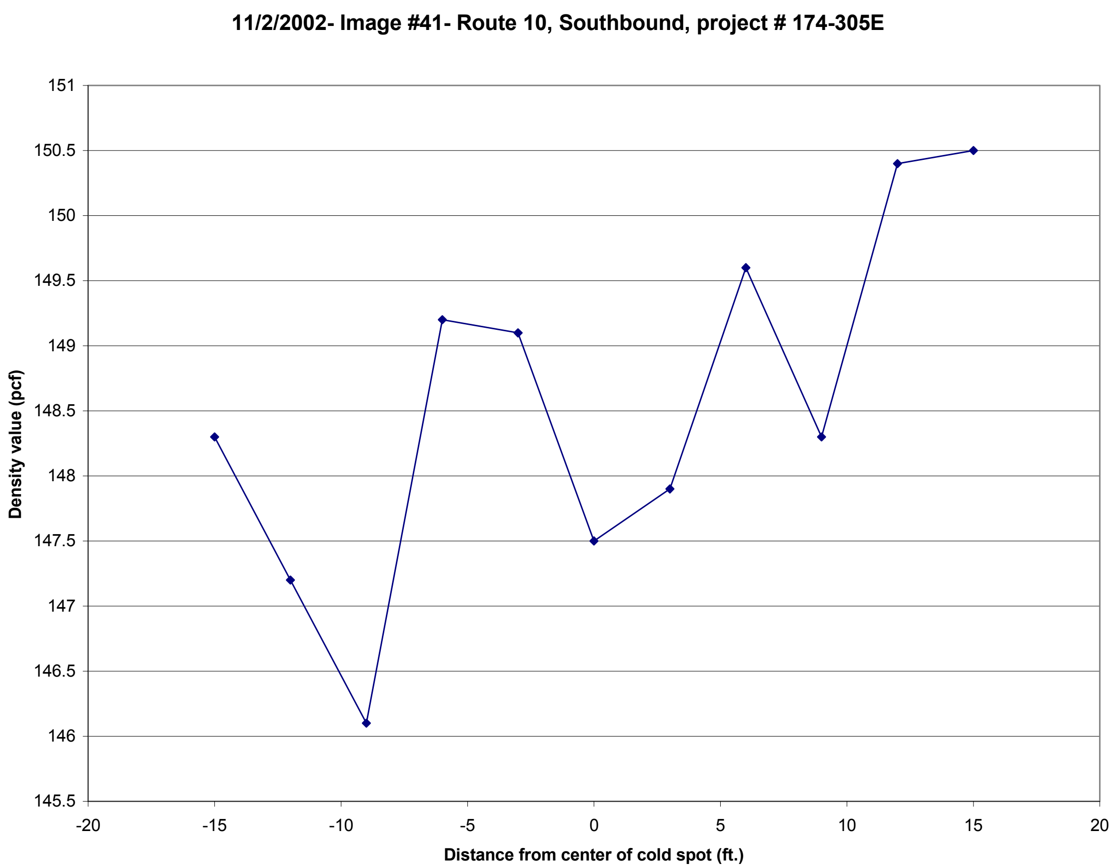

Figure A81 – Density vs. distance from cold spot

Monitored Site 36

This site was on Farmington Avenue in West Hartford on November 5, 2002 project number 155-149. The ambient temperature was 45°F as was the temperature of the base pavement. The plant was in New Britain about 10 miles from the project. The trucks had a hauling time of about 15 minutes. The material that was being placed on this project was Class 1 and the compacted mat thickness was 2 inches. The contractor used a Blaw-Knox model PF3200 paver, a Hyster model C340 breakdown roller and a Hypac model C766C vibratory intermediate and finish roller. The average temperature differential of the placed material on this site was 53.3°F. There was only one density profile taken on this project and its difference was 7.5 pcf between warm and cool material, however, it's corresponding thermal image is very representative of the rest of the project and both are shown in Figures A82 and A83.

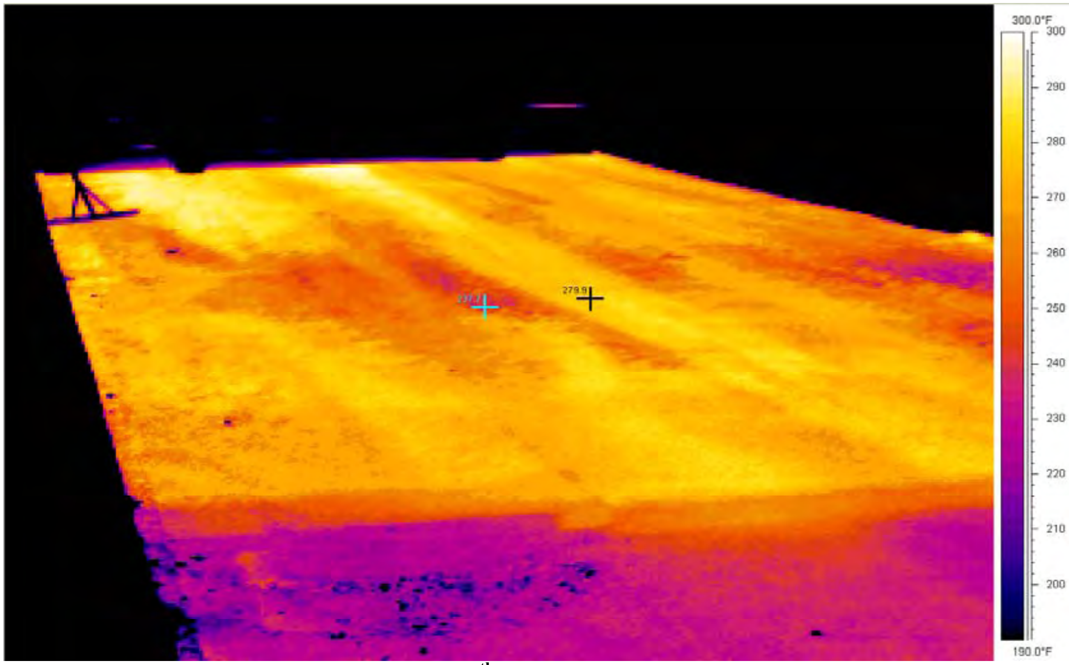

Figure A82 - Thermal profile, November 5th, Farmington Avenue, West Hartford.

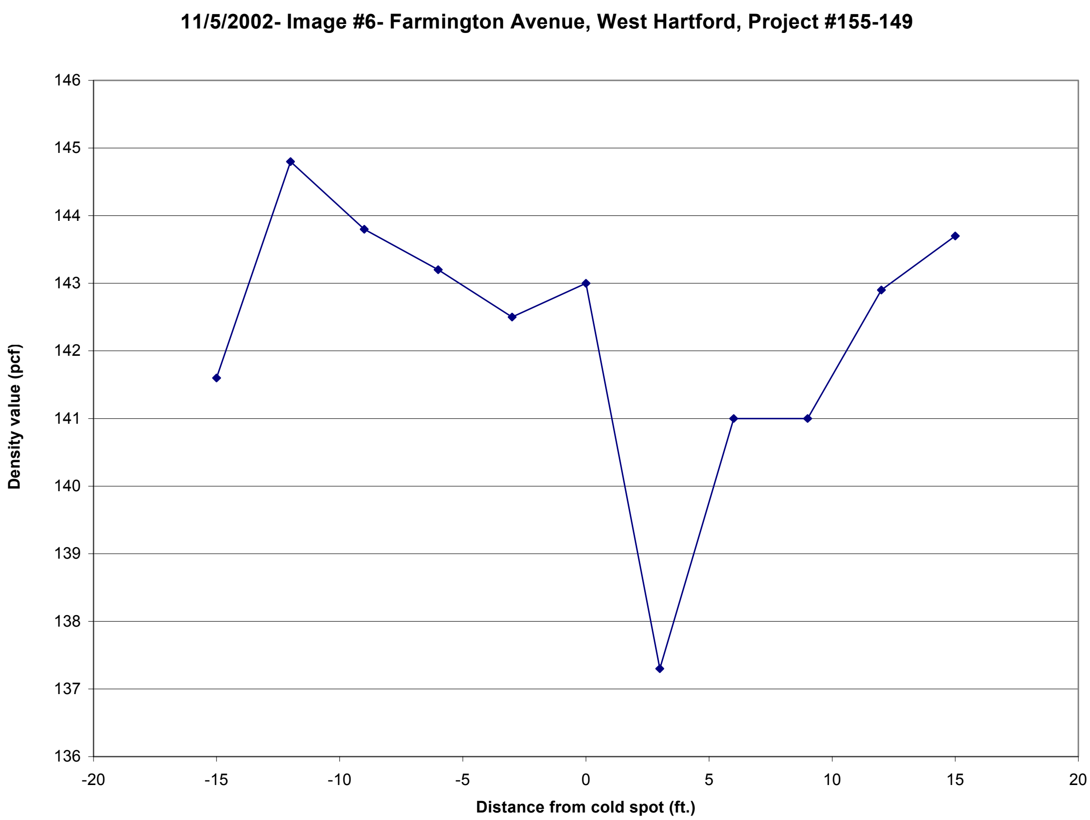

Figure A83 – Density vs. distance from cold spot

Monitored Site 37

Continuation of monitoring sites resumed on June 6th, 2003 on Route 320 in Willington. The project number was 171-306C and this site as well as all other sites monitored in 2003 pertained exclusively to the study of the effects of heated truck bodies on thermal properties of HMA. The material on this day was Class 1 and was being hauled approximately 45 minutes from a HMA plant in Killingly. The compacted thickness of the material was 2 inches and paving was proceeding in the northern direction. The base pavement temperature was 80°F and the ambient air temperature was 65°F at the start of monitoring. The paving equipment used consisted of a Blaw-Knox model PF3200 paver, a CAT model CB-634 vibratory breakdown roller and a CAT model CB-534 vibratory intermediate and finish roller. The average temperature differential for that day was 45.6°F. Figure A84 is an image of material and a cold spot on this project from a truck with an activated heated body. The CAP Lab did not perform any nuclear density testing on this site.

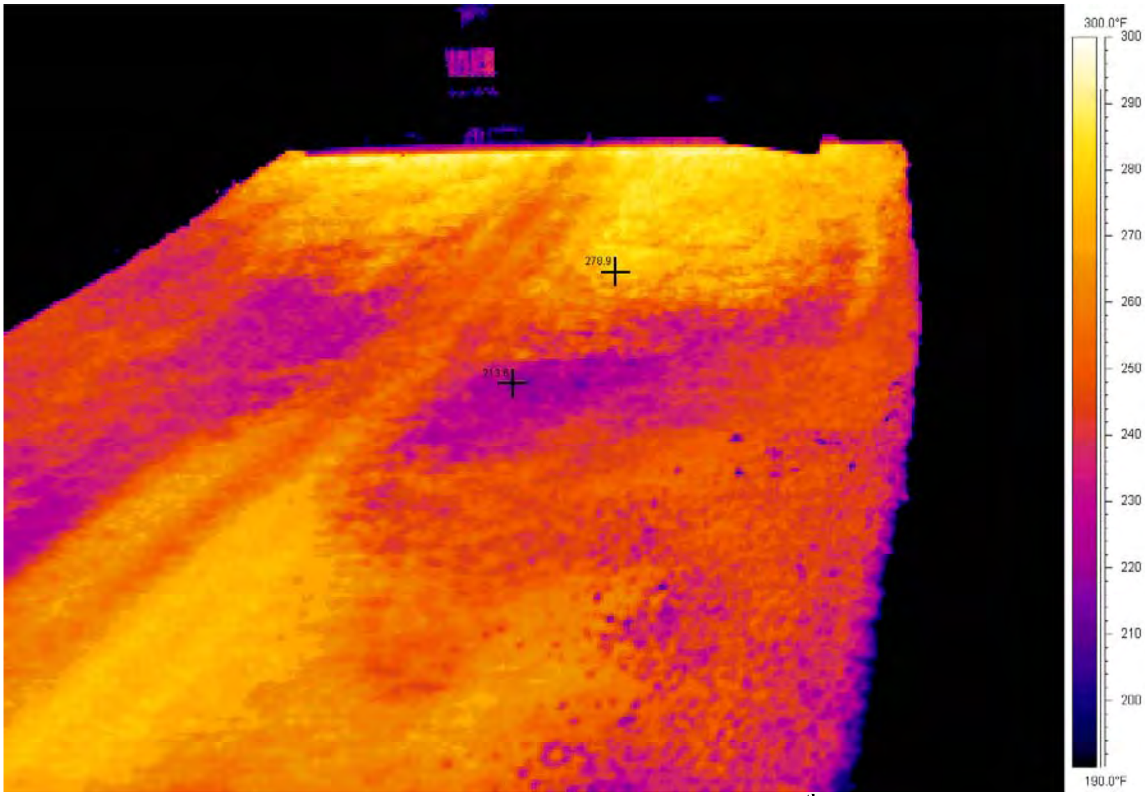

Figure 84 – Image of Cold spot from truck with heated body on June 6th, 2003.

Monitored Site 38

The next monitored site was project number 171-307H on Route 176 in Newington on June 9th, 2003. This project was also monitored exclusively for the heated body study. The material on this project was Class 1 and it was being placed at a compacted thickness of 2 inches. The haul time from the plant to this project was approximately 8 – 10 minutes as the plant was located just 5 miles away and also in the town of Newington. The base pavement temperature was 80°F-85°F and the ambient temperature ranged from 65°F-70°F. The paving equipment consisted of a Blaw-Knox model PF200B paver, a Hyster model C340 Static breakdown roller, and an Ingersoll Rand model DD-110 vibratory intermediate and breakdown roller. There was no MTV used on this project. Again there was no significant change in the thermal nature of the HMA as cold spots appeared regardless of whether or not the bodies were heated. Figure

A85 is a typical thermal profile of a heated body load on this monitoring day. The CAP Lab did not perform and nuclear density testing on this site.

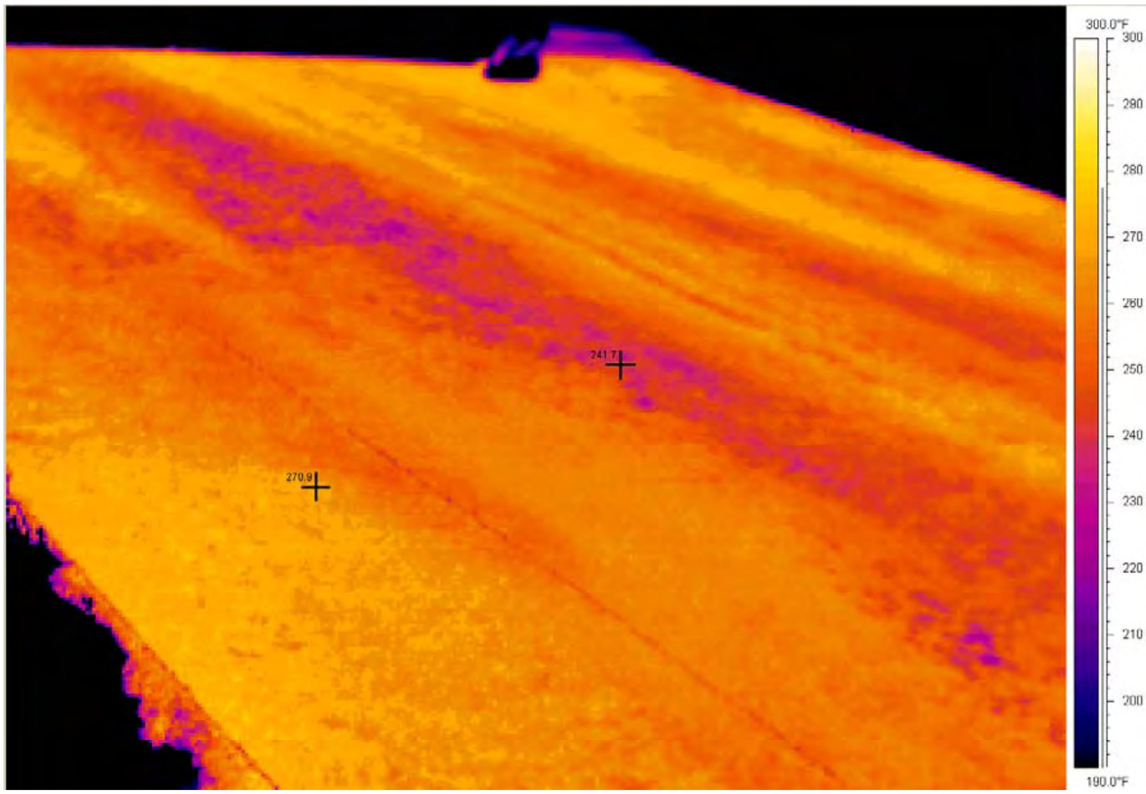

Figure A85 – Typical thermal profile from Route 176 in Newington (Heated Body Study)

Monitored Site 39

This project number was 129-107. The site was Route 186 in Somers and it was monitored on June 11th, 2003. This site was again exclusively monitored for the heated truck body study. The material being placed on this project was Class 1 and it was being placed at a compacted thickness of 1.5 inches. The weather was cloudy and very humid with intermittent sprinkles of rain. The base pavement temperature was 85°F-90°F and the ambient temperature was approximately 75°F. The HMA was being hauled about 15 miles from a plant in Springfield, Massachusetts, with a haul time of twenty minutes. The paver was a Blaw-Knox model PF200B. The compacting equipment consisted of a

Galion static breakdown roller and an Ingersoll Rand vibratory intermediate and finish roller. There were 13 trucks on the project. There was no significant difference seen in the mat with the thermal camera from truckloads that used heated bodies. Figure A86 shows a truckload from this site that was delivered with a heated body.

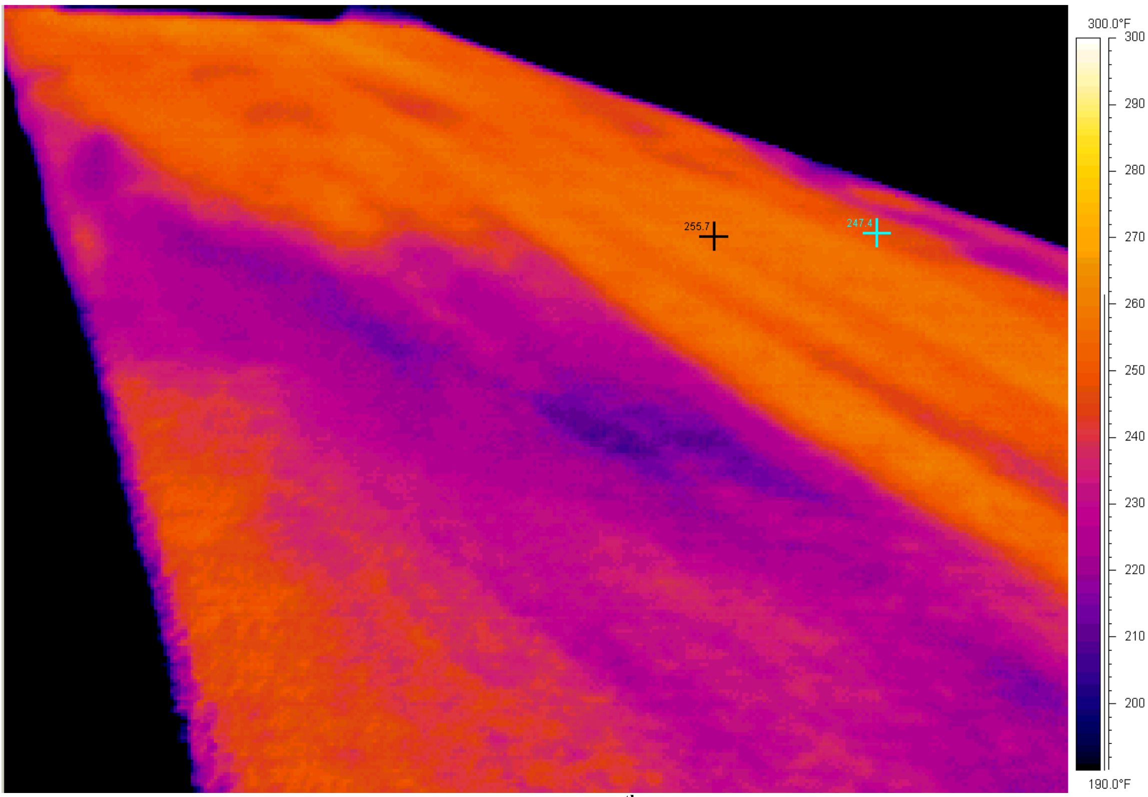

Figure A86 – Typical thermal image of mat on June 11th, 2003 with applied heated body.

Monitored Site 40

The final monitored site was also conducted exclusively for the heated body study. This project was numbered 57-106 and was monitored on both June 16th and June 17th of 2003. The site was the resurfacing of Route 201 in Griswold. The material was Class 1 and was being hauled approximately 25 minutes from Killingly. There were no density tests performed on this project by the CAP Lab and there was no MTV used on either of the 2 monitoring days. June 16th was a standard monitoring day with thermal images taken of the mat. June 17th was different in that the trucks bodies themselves were viewed through the thermal camera to compare thermal images of heated vs. non-heated bodies.

On June 16th, there were no significant changes from loads which came from heated bodies to loads which came from non-heated bodies. The cold spots seen on this project were as random as on any other project regardless of the nature of the truck body.

On June 17th, thermal images were taken of the truck bodies to measure differences in the skin temperature between heated and non-heated bodies. A significant notable feature of these thermal images was that one could make out very distinctly where the load was in the body of the truck irregardless of the type of body. The heat of the HMA mass in the truck reflects through the body and is very distinguishable in the thermal image. Figure A87 shows a typical thermal image of the mat on June 16th, Figure A88 shows a typical thermal image of a heated truck body while Figure A89 shows a typical thermal image of a non-heated truck body.

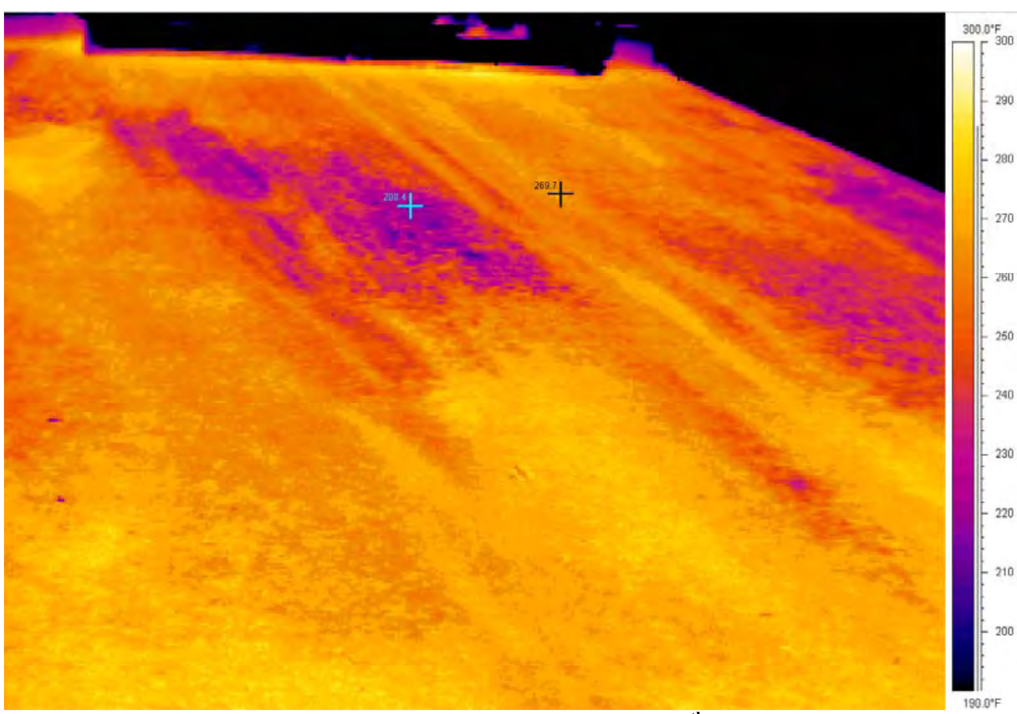

Figure A87 - Typical thermal image of the mat on June 16th with heated body

Figure A88 - Typical thermal image of a heated truck body

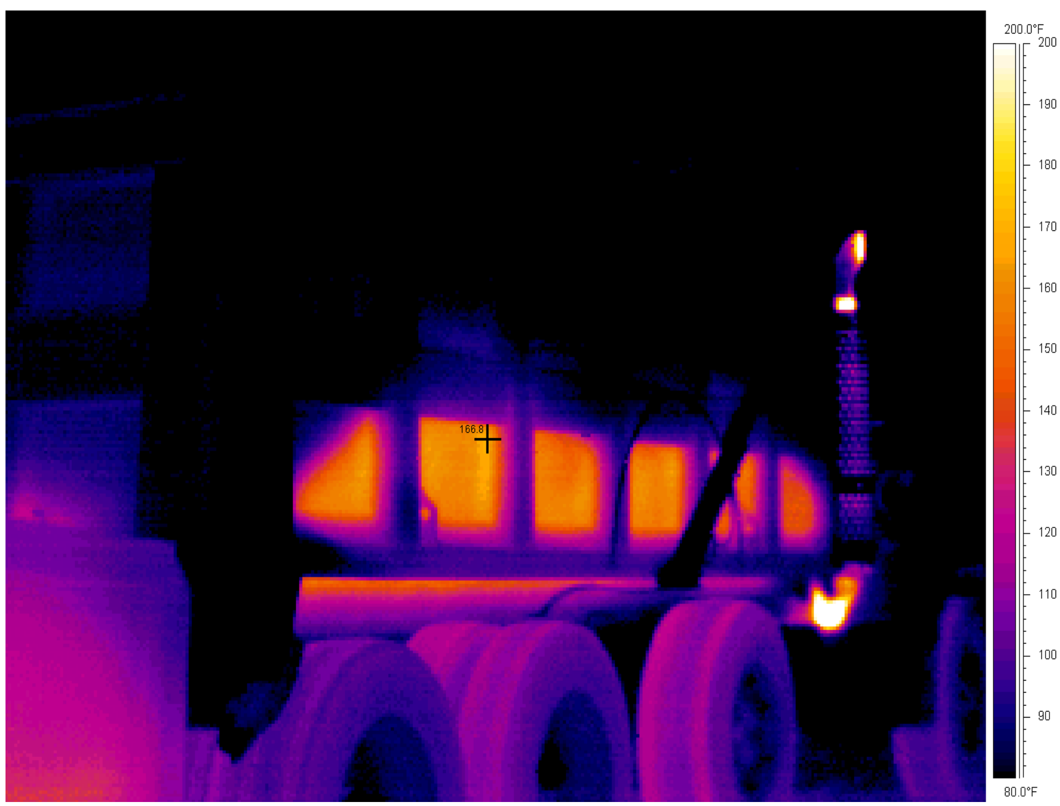

Figure A89 - Typical thermal image of a non-heated truck body