Development of Guidelines for Reduction of Temperature Differential Damage (TDD) for Hot Mix Asphalt Pavement Projects in Connecticut

Construction Report

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16. Abstract

Connecticut Department of Transportation personnel used an infrared camera to observe thermal segregation of hot mix asphalt during pavement construction. Several sites were selected for study from ongoing paving projects. During paving operations, the infrared camera was used to look at the mix being discharged from the truck, to the paver, and to the mat. Cold spots/areas were located, marked, and referenced to a predetermined coordinate system within each of the monitored test sections. Nuclear density tests were performed and cores were extracted for further analysis at the located cold spots/areas. Selected sites will be monitored for a period of five (5) years in order to evaluate the pavement's performance over time.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

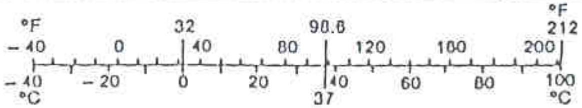
Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	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	millilitres	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 FROM 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



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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Development of Guidelines for Reduction of Temperature Differential Damage (TDD) for Hot Mix Asphalt Pavement Projects in Connecticut

Background

In November 1994, the Connecticut Department of Transportation (ConnDOT) formed a joint Task Force of State, Federal and private sector producers and other industry personnel to address several problems that have been encountered with Hot Mix Asphalt (HMA) pavements placed on Connecticut roadways. The Task Force was divided into four major sections: Specifications, Rideability, Segregation and Training. The problem of segregation of HMA has been of particular interest to Department personnel, since it has been encountered on numerous HMA pavement projects. Pavement distresses such as raveling and potholes have been observed in segregated pavements and have resulted in premature failures.

The problem of segregation of HMA is not unique to Connecticut, and research on the subject has been conducted in several states. In 1995 a graduate student at the University of Washington, Steven A. Read, was commissioned by the Washington Department of Transportation (WSDOT) to study segregation. The proposed research was typical of other studies that have been conducted; however, a midstudy change based upon a field investigation is of interest to ConnDOT personnel. He indicated that the cause of the problem being called segregation appeared to be a problem of temperature differentials in the loads of HMA at the job site.

Data collection, including temperature readings, was adjusted to reflect this newfound theory. A probe type thermometer was used to measure the temperature of freshly placed pavement that appeared to be segregated. Temperature readings of pavement directly adjacent to the segregated appearing areas were also taken. The temperature of the segregated appearing areas tended to be cooler than that of adjacent areas of pavement.

Next, various samples were taken from both the segregated (damaged) and non-segregated appearing areas of pavement. The samples were tested for binder content, gradation, Hveem stability and air voids. Based upon these test results, it was determined that the segregated appearing areas of pavement were actually not segregated after all.

The focus of the research evolved into determining the mechanism that produces these damaged (segregated appearing) areas in the pavement. In his graduate thesis, entitled "Construction Related Temperature Differential Damage in Asphalt Concrete Pavements [11]," Mr. Read concluded: the mechanism is related to temperature variations in the truckloads of HMA, and the pavement damage occurs when the paver's screed is unable to consolidate these colder portions of mix and open-segregated appearing areas show in the pavement. He named this phenomenon "temperature differential damage" (TDD). These temperature differentials in the HMA are also commonly referred to as thermal segregation.

Mr. Read suggested that remixing of the HMA prior to entry into the paver, or some type of remixing at the paver, might reduce TDD. He investigated various transfer devices to determine their effect. These were a windrow pickup device, a Blaw-Knox transfer machine, and a Roadtec Shuttle Buggy material transfer vehicle. His investigation revealed that these devices do in fact reduce the amount of temperature differentials in the HMA pavement.

Shortly following the University of Washington study, personnel from Astec Industries used an infrared camera to look at HMA during pavement construction operations. They indicated that temperature differentials in the loads of HMA were as much as 44° C (80° F). Messrs.

J. Don Brock and Herb Jakob of Astec Industries reported their findings in a technical paper entitled “Temperature Segregation/Temperature Differential Damage [2].” This technical paper was widely distributed and read by ConnDOT personnel. The technical paper was of particular interest to ConnDOT personnel because of the ongoing effort to improve the quality of HMA and to reduce the occurrence of segregation on Connecticut roadways.

Based upon this interest, this research project was initiated in September 1998 to investigate TDD during construction and its effect on the subsequent performance of HMA pavements.

Study Objectives

The objectives of the research study as published in the study proposal dated August 1998 [7] are:

1. Develop methods for the reduction of TDD to HMA pavement projects in Connecticut.
2. Determine if a relationship exists between nuclear density measurements and cold spots/areas that occur during paving operations.

Additional benefits to be expected from the study include:

1. Improved understanding of TDD and its effect on the performance of HMA.
2. Improved understanding of the relationship between nuclear density measurements and pavement temperature during placement.
3. Gain Department experience with infrared imaging technology and its applications.
4. Reduced occurrence of TDD.
5. Reduced occurrence of HMA material segregation.
6. Improved HMA pavement construction methods.

Literature Review

The purpose of the literature review was to become familiar with previous research on the subject of thermal segregation of HMA and the subsequent damage that it causes to a pavement structure. Only two studies were found which specifically looked at this phenomenon; however, it became immediately apparent that it is closely related to asphalt mixture (particle) segregation, which is commonly referred to as "segregation of HMA" or more simply "segregation." Accordingly, literature on the subject of asphalt mixture segregation was also reviewed.

Williams et al. [12] defined asphalt mixture segregation as "the non-uniform distribution of coarse and fine aggregate components." Consequently, there are two types: coarse and fine. The most common pavement distress associated with coarse segregation is raveling, and the most common distress associated with fine segregation is rutting.

Research has shown that coarse segregated areas of pavement typically have higher voids and lower asphalt content than nonsegregated areas [9,12]. Brown et al. [3] concluded "segregated areas are generally 8 to 15 percent coarser than nonsegregated areas on the No. 8 sieve; the voids are typically 3 to 5 percent higher; and the asphalt content is often 1 to 2 percent lower." They observed paving projects during construction and performed tests on segregated specimens of pavement. They indicated, "…segregated areas that are not overlaid tend to ravel under traffic."

Cross and Brown [4] studied the effect of segregation on the performance of HMA pavements. Their main objective was to determine how much segregation can be tolerated before premature raveling is the likely result. They indicated "…a variation in the percent passing the No. 4 sieve greater than 8 to 10 percent can lead to raveling."

Fine segregated areas of pavement typically have lower voids and higher asphalt content than nonsegregated areas [9,12]. Khedaywi and White [9] indicated that fine segregated areas of pavement have an increased potential for rutting because of a higher asphalt content and concentration of fine material. Williams et al. [12] performed laboratory testing to evaluate segregated pavements and concluded "…segregation results in significant asphalt content variation, which increases from very coarse to very fine segregation." They indicated that "…asphalt contents ranged from 2.1 (binder) and 3.8 (surface) percent for very coarse segregated mixes to 6.7 (binder) and 7.2 (surface) percent for very fine segregated mixes." Additionally, they concluded "…the air voids in segregated mixes increase from very fine to very coarse segregation."

It is widely agreed that asphalt mixture segregation can occur during any or all phases of the paving cycle [1,5,8,12]. These include mix design, stockpiling, mix production, storage, truck loading and unloading, and paving operations.

Brock [1] studied causes and cures for HMA segregation and concluded, "…nothing is more important to eliminating segregation than properly designing the mix." This includes the selection of an appropriate aggregate structure (size and gradation) and asphalt binder content. Kennedy et al. [8] also indicated that these have a significant effect.

Segregation can occur as a result of improper stockpiling techniques. Aggregates should be stockpiled in truckload-sized piles and be placed in a manner that prevents material from rolling down slopes [1,5]. When a conveyor supplies material, Brock [1] recommends building progressive horizontal layers. When a truck supplies material, he recommends building progressive layers on a slope. All slope angles should be less than the angle of repose[1].

Segregation can occur during production at both drum and batch mixing facilities. Brown et al. [3] indicated that less segregation generally occurs in batch plants because the plant's internal screening unit provides a gradation check immediately prior to measuring and mixing. Improper silo storage can also result in segregation. Maupin [10], however, indicated that incorporating changes in equipment and production procedures could alleviate silo storage segregation problems.

Construction related segregation occurs during truck loading, transport, unloading and paving operations. Most temperature differentials in the mix also develop during these operations [11]. Therefore, close attention to procedures for reducing segregation should be given, since implementation of these procedures will likely reduce pavement temperature variability.

Trucks should be loaded in three drops: the first in the front, the second in the back and the third in the center [1,5,8]. This prevents larger aggregate particles from rolling and segregating from the rest of the load. When trucks are loaded in one drop, end-of-load/beginning-of-load segregation often occurs because of the overlap between truckloads [5].

During paving operations close attention to the hopper wings, hopper gates, drag slats, and auger should be given. Hopper wings should be folded as infrequently as possible, or not at all. Hopper gates should be opened just wide enough and drag flight speed should be just fast enough to allow a continuous flow of material and uniform head on the augers [1,5].

[1] The steepest slope that an aggregate can attain without sliding.

Read [11] suggested that proper operation of the hopper wings is critical when there are temperature differentials in the HMA. He indicated that cool material from the sides of the load tend to accumulate along the sides of the hopper. When the wings are folded, this material falls inward and is conveyed back to the auger and is screeded out. He indicated that the screed is unable to consolidate colder portions of mix, and he observed open segregated appearing areas in the pavement at the same locations. Read named this phenomenon "temperature differential damage" (TDD).

Gardiner et al. [6] used infrared thermography to quantify TDD. They observed an increase in air voids and a decrease in asphalt content for local areas of low temperature. Pavement immediately behind the screed tended to be cooler following truck changes and paver stoppages, and they noted that a visually coarser surface texture existed for these anomalous areas.

Brock and Jakob [2] reported that the Washington Department of Transportation invited them to bring an infrared camera to study temperature segregation at several project sites. They located and marked cold (non-uniform) spots and adjacent uniform areas of pavement. They performed nuclear density tests and extracted cores for testing at the marked locations. Air voids and gradations were determined for each core. They noted that "…gradations were taken and none of the cold areas exceeded the 8 to 15% coarser on the #8 sieve. In general the gradation was very similar to that of the uniform areas. However, the air voids would exceed those [tolerances] recommended in the NCAT study." The NCAT study, conducted by Brown et al. [3], was referenced earlier in this literature review. Again, Brown et al. [3] concluded, "…air voids are typically 3-5 percent higher for segregated areas of pavement."

Read [11] studied the thermodynamics of the cooling of HMA in the trucks during transport and developed a model to predict the occurrence of TDD. He indicated that thermal barriers should be used to insulate truck bodies and found that more time is available to transport the HMA to the job site when they are employed. He recommended that more attention be given to late season paving operations and to time in transit of the HMA to the project site. Read [11] also recommended that transfer devices be employed on larger projects.

Brock and Jakob [2] concluded from their study that "…temperature variations in mix discharged from trucks have been much greater than previously thought and although undetected, has been a significant problem for many years. When looking at infrared photographs, it is apparent that random variations in density, which are quite common place, are caused by the concentration of cold material in the mat." They continued, "…to produce a long lasting smooth pavement with consistent density and thus consistent air voids, some type of device that uniformly remixes the material directly prior to placement is essential." Note: Brock and Jakob are employed by Astec Industries, Incorporated, the manufacturer and marketer of the Shuttle Buggy remixing device.

Construction Data

Eleven (11) sites were selected for study from ongoing paving projects in Connecticut: nine (9) Class 1 (12.5 mm) and two (2) Class 2 (9.5 mm). Pavement for all eleven (11) sites was placed in September and October 1998. HMA was produced at several different plants. Two (2) project sites utilized remixing transfer devices for HMA construction.

In addition to recording infrared video and making observations, six (6) of the eleven (11) sites will be monitored for a period of five (5) years in order to evaluate the pavement's performance over time. Each monitored site is approximately 500 feet long. Monitored site locations were selected based upon availability, traffic characteristics, safety, and topology. Infrared video was recorded and observations were made at the remaining five (5) non-monitored sites; however, no additional testing will be performed at these locations.

A ThermaCAM PM380 (see Photos #1 and #2, page 46) Infrared camera was rented for one (1) month from Inframetrics, Inc, the camera's inventor and manufacturer. The ThermaCAM provided a 256 x 256 pixel image, temperature measurements from –10 to 450°C, and an accuracy of +/- 2°C. It operated on a commercially available camcorder battery. Precision 12-bit measurement data were stored instantly in the field as TIFF digital files on a removable FLASH PCMCIA memory card. Inframetrics TherMonitor95 software was used in the laboratory for post-image processing and report generation.

Before beginning paving operations, monitored test sections were staked out and manual distress surveys (SHRP-P-338 [13]) were performed in order to determine the pre-existing condition of the pavement.

During paving operations, the infrared camera was used to look at the mix being discharged from the truck, to the paver, and to the mat.

Infrared video was recorded during rolling operations as the mat was compacted. Cold spots were located, marked, and referenced to a predetermined coordinate system within each of the monitored test sections.

Monitored Sites 1 & 2

The first two sites that were selected for study are located on Route 85 at 25.655-25.855 km in the Town of Colchester, Connecticut. Site 1 is in the NB direction, and Site 2 is in the SB direction. Route 85 is a two-lane undivided state route, functionally classified as a minor arterial. The ADT for this section of Route 85 is 3300 vehicles per day. The Route 85 project was completed under State Project 172-299L.

A Blaw-Knox PF-180H paver (see Photo #3), Caterpillar CB-534 breakdown roller, and Hyster C350C finish roller were employed for construction. A 40-mm (1.5-inch) DOT Class 1 surface layer was placed on top of a DOT Class 2 leveling course.

The pavements were placed on September 29, 1998. The haul time was approximately 25 minutes. It was sunny, winds were calm, the ambient temperature was 21°C (70°F), and the pavement temperature was 43°C (110°F) in the sun and 29°C (84°F) in the shade.

Temperature differentials in the freshly placed pavement were observed with the infrared camera as longitudinal strips of hot and cool material immediately behind the paver’s screed. Their occurrence was capricious: sometimes strips of cooler material would appear in the center, while the sides remained hot; other times strips of cooler material would appear on the sides, while the center remained hot. As the pavement cooled during rolling operations, cooler areas of pavement tended to concentrate into better-defined spots/areas.

Twenty (20) cold spots/areas and their respective higher temperature counterparts were located with the infrared camera. They were marked and temperatures were recorded. Each location was assigned a number and a letter designation, C for cold spots/areas and N for their adjacent (normal) areas. For example, they were labeled 1C and 1N, 2C and 2N, etc. Nuclear density tests were performed at each location, and cores were extracted at three (3) selected locations for further testing. Air voids based on nuclear density are presented in Table 1a (page 29), and air voids based on core density are presented in Table 1b (page 30).

Air voids based on nuclear density were on average 2.8 percent higher for areas of lower temperature than for their higher temperature counterparts. Air voids based on core density were 2.0 percent higher for Sample 3C vs. 3N, 2.0 percent lower for Sample 13C vs. 13N, and 5.2 percent higher for Sample 20C vs. 20N. Asphalt content based on core samples were 0.8 percent lower for Sample 3C vs. 3N and 0.2 percent lower for Sample 20C vs. 20N. The asphalt content for Sample 13C was equal to that of Sample 13N.

Sieve analyses were performed for each core that was extracted (see Table 7, page 37). The gradation for Sample 3C (cold spot/area) was slightly coarser than for 3N (normal area), and 6.5 percent more aggregate was retained on the #8 sieve for Sample 3C than for 3N. Gradations for Samples 13C and 20C were very similar to their counterparts (Samples 13N and 20N).

At Site 2, twenty-two (22) cold spots/areas and their respective adjacent areas were located with the infrared camera. They were marked, labeled and tested in the same manner as for Site 1. Air voids based on nuclear density are presented in Table 2a (page 31), and air voids based on core density are presented in Table 2b (page 32).

Air voids based on nuclear density were on average 1.0 percent higher for areas of lower temperature than for their higher temperature counterparts. Air voids based on core density were 1.4 percent higher for Sample 6C (cold spot/area) vs. 6N, 0.5 percent lower for Sample 12C vs. 12N, and 1.3 percent higher for Sample 19C vs. 19N. Asphalt content based on core samples were 0.6 percent lower for Sample 6C vs. 6N and 0.2 percent lower for Sample 19C vs. 19N. An asphalt content was not measured for Sample 12N.

Sieve analyses were performed for each core that was extracted from Site 2 (see Table 8, page 31). Gradations for the cold spot/area samples were very similar to their higher temperature counterparts. None of the cold spots/areas tested were significantly coarser on the #8 sieve than their higher (normal) temperature counterparts.

Monitored Site 3

The third site is located on Route 8 NB at 64.001-64.201 km in the Town of Thomaston, Connecticut. Route 8 is a four-lane, median-divided highway, functionally classified as a principal arterial. The ADT for this section of Route 8 is 14,900 vehicles per day. The Route 8 project was completed under State Project 151-265.

A Blaw-Knox PF-3200 paver (see Photos #4 and #5, page 47-48), breakdown roller, intermediate roller and finish roller were employed. A 40-mm (1.5-inch) DOT Class 1 surface layer was placed on top of a DOT Class 2 leveling course.

The pavement overlays were placed on October 6, 1998. The haul time was approximately 20 minutes. It was sunny, winds were calm, the ambient temperature was 18°C (64°F), and the pavement temperature was 41°C (106°F) in the sun (no shade).

The freshly placed pavement immediately behind the paver's screed was relatively uniform in temperature (see Photos #12 and #13, page 52), making the location of cold spots/areas difficult to find. However, local areas of cooler temperature did develop in the pavement during rolling operations as the mat cooled (see Photo #14, page 53). It was these local areas that were identified and marked as cold spots/areas.

Fourteen (14) cold spots/areas and their respective adjacent areas were located with the infrared camera. Nuclear density tests were performed at each location and cores were extracted at three (3) selected locations. Air voids based on nuclear density are presented in Table 3a (page 33), and air voids based on core density are presented in Table 3b (page 33).

Air voids based on nuclear density were on average 1.4 percent lower for areas of lower temperature than for their higher temperature counterparts. Air voids based on core density were 0.1 percent lower for sample 4C vs. 4N, 1.8 percent lower for Sample 7C vs. 7N, and 0.5 percent lower for Sample 13C vs. 13N. Asphalt content based on core samples were 0.2 percent lower for Sample 4C vs. 4N, 0.5 percent higher for Sample 7C vs. 7N, and 0.2 percent higher for Sample 13C vs. 13N.

Sieve analyses were performed for Samples 6N, 6C, 12N, 19N and 19C (see Table 9, page 38). Gradations for Samples 6C and 19C (cold spot/area) were slightly coarser than for Samples 6N and 19N (normal areas), and 5.7 and 3.6 percent more aggregate was retained on the #8 sieve for Samples 6C and 19C, respectively, than for their counterparts. A sieve analysis was not performed for Sample 12C and, therefore, cannot be compared to Sample 12N.

Monitored Site 4

The fourth site is located on Route 695 EB at 6.888-7.149 km in the Town of Killingly, Connecticut. Route 695 is a four-lane, median-divided highway, functionally classified as a principal arterial. The ADT for this section of Route 695 is 3400 vehicles per day. The Route 695 project was completed under State Project 68-184.

A Blaw-Knox PF-200 paver (see Photo #7, page 49), Ingersoll-Rand DD-90 breakdown roller, Caterpillar CB-534C intermediate roller, and Ingersoll-Rand ST-75 finish roller were employed. A 50-mm (2-inch) DOT Class 1 surface layer was placed on top of a cold-in-place recycled base course.

The pavements were placed on October 21, 1998. The haul time was approximately 15 minutes. It was sunny, winds were light, the ambient temperature was 18°C (64°F), and the pavement temperature was 41°C (106°F) in the sun (no shade).

Temperature differentials were easily located immediately behind the paver's screed. They appeared as well-defined cold spots (see Photos #15 and #16, page 53-54), surrounded by warmer (normal) pavement. They occurred in a load-to-load type of pattern (see Photo #17, page 54), about every 34 meters (112 ft), and in the pavement immediately following truck changes, during which time the paver's wings were typically folded.

Twelve (12) cold spots and their respective adjacent areas were located with the infrared camera. Nuclear density tests were performed at each location and cores were extracted at three (3) selected locations. Air voids based on nuclear density are presented in Table 4a, and air voids based on core density are presented in Table 4b (page 34).

Sieve analyses were performed for each core that was extracted (see Table 10, page 38). Gradations for the cold spot/area samples were very similar to their higher temperature counterparts. None of the cold spots/areas tested were significantly coarser on the #8 sieve than their counterparts.

Monitored Site 5

The fifth site is located on Route 31 WB at 8.782–8.621 km in the Town of Coventry, Connecticut. Route 31 is a two-lane undivided state route, functionally classified as a minor arterial. The ADT for this section of Route 31 is 3600 vehicles per day. The Route 31 project was completed under State Project 32-123.

A Caterpillar AP-1055B paver, Hyster 340C breakdown roller, and Ingersoll-Rand DD-110 finish roller were employed. A 50-mm (2-inch) DOT Class 1 surface layer was placed on top of a DOT Class 2 leveling course.

The pavements were placed on October 19, 1998. It was sunny, winds were light, the ambient temperature was 21°C (70°F), and the pavement temperature was 43°F (109°F) in the sun (no shade).

Temperature differentials in the freshly placed pavement were observed with the infrared camera as longitudinal strips of hot and cool material immediately behind the paver's screed (see Photo #18, page 55). The thermal pattern appeared to be random in nature, similar to sites 1 and 2. As the pavement cooled during rolling operations, cooler areas of pavement tended to concentrate into better-defined spots (see Photo #19, page 55), as opposed to longitudinal strips of hot and cool material.

Twelve (12) cold spots and their respective adjacent areas were located with the infrared camera. Nuclear density tests were performed at each location and cores were extracted at three (3) selected locations. Air voids based on nuclear density are presented in Table 5a (page 35), and air voids based on core density are presented in Table 5b (page 35).

Sieve analyses were performed for each sample that was extracted (see Table 11, page 39). Gradations for each pair of samples were similar; however, 17.5 percent more aggregate was retained on the #4 sieve for Sample 3N vs. 3C, and 4 percent more aggregate was retained on the #8 sieve for Sample 11N vs. 11C.

Monitored Site 6

The sixth site is located on Pigeon Hill Road in the Town of Windsor, Connecticut. Pigeon Hill Road is a two-lane undivided local town road. Pigeon Hill Road was paved as part of State Project 164-221.

A Cedar Rapids CR-551 paver (see Photo #8, page 49), Ingersoll-Rand breakdown roller, and Hyster C340C finish roller were employed. A 40-mm (1.5-inch) DOT Class 1 surface layer was placed on top of a DOT Class 2 leveling course.

The pavements were placed on October 15, 1998. It was sunny, winds were calm, the ambient temperature was 14°C (57°F), and the pavement temperature was 38°C (100°F), no shade.

Temperature differentials in the freshly placed pavement were observed with the infrared camera as longitudinal strips of hot and cool material immediately behind the paver’s screed. The thermal pattern of these strips appeared to be random in nature. As the pavement cooled during rolling operations, cooler areas of pavement tended to concentrate into better-defined spots, as opposed to longitudinal strips of hot and cool material.

Ten (10) cold spots and their respective adjacent areas were located with the infrared camera. Nuclear density tests were performed at each location and cores were extracted at three (3) selected locations. Air voids based on nuclear density are presented in Table 6a, and air voids based on core density are presented in Table 6b (page 36).

Sieve analyses were performed for each core that was extracted (see Table 12, page 39). The gradation for Sample 1N was significantly coarser than for 1C, and 11.1 percent more aggregate was retained on the #8 sieve for Sample 1N than for 1C. Samples 3N and 5N were similar in gradation to their counterparts (Samples 3C and 5C). Samples 3C and 5C had 3.8 and 0.5 percent more aggregate retained on the #8 sieve than Samples 3N and 5N, respectively.

Additional Sites

Five additional sites for which infrared video was recorded and observations were made include: Route I-91 in Rocky Hill, Route I-91 in Meriden, Route 341 in Warren, Little Meadow Road in Guilford and Linkfield Road in Watertown. No additional testing or monitoring will be performed for these locations. Pavement for all five (5) of these additional sites was placed in September and October 1998.

For the Route I-91 Rocky Hill project, a Blaw-Knox MC-30 material transfer vehicle (see Photo #10, page 50) was employed with a Blaw-Knox PF-180H paver. Additionally, a remixing insert was placed inside the paver’s hopper. Infrared video was recorded on October 6, 1998. It was a night project, winds were calm, and the ambient temperature was approximately 1°C (33°F). The haul time to the project was approximately 15 minutes.

The MC-30 material transfer vehicle in combination with the remixing insert did appear to reduce the occurrence of temperature differentials, but did not completely eliminate the problem (see Photo #20, page 56). An occasional cold spot did show in the pavement during construction. It was observed that the freshly laid pavement cooled quickly during rolling operations, and that additional temperature differentials developed in the mat during this cooling process. Compaction of the mat continued as the pavement cooled to the cessation temperature of 79°C (175°F). Cooler areas of pavement (cold spots), as seen with the infrared camera, were as low as 66°C (150°F) during compaction.

On October 20, 1998 infrared video was recorded at the Route I-91 Meriden project. A Roadtec Shuttle Buggy material transfer vehicle (see Photo #11, page 51) was employed with a Blaw-Knox PF-3200 paver. It was a night project, the ambient temperature was approximately 9°C (48°F) and winds were calm. The haul time was approximately 20 minutes.

Once paving operations had been established and all the equipment was warm, temperature differentials were virtually eliminated through remixing in the Shuttle Buggy (see Photo #21, 56). It should be noted, however, that some temperature differentials did appear in the mat at the beginning of paving operations, when the equipment was cold. Also, it should be noted that the pavement cooled more quickly at night than had typically been observed for daytime construction. Remixing, obviously, has no affect on the rate at which a pavement cools after being placed.

On October 16, 1998, the infrared camera was brought to Route 341 in Warren, Connecticut where a DOT Class 1 pavement was being constructed. Conventional paving methods and a Blaw-Knox PF-180H paver were used. It was sunny, winds were light, the ambient temperature was 13°C (55°F), and the pavement temperature was 32°C (90°F) in the sun and 18°C (64°F) in the shade. The haul time was approximately 25 minutes.

Infrared video and still photos were recorded. It was observed that temperature differentials in the freshly laid pavement occurred infrequently and were not as severe as had been seen on other projects (see Photo #22, page 57). When temperature differentials did appear, it was typically following paver stoppages and truck changes. Additionally, it was observed that temperature differentials appeared on the mat shortly following the paver's wings being folded.

On October 5, 1998, a DOT Class 2 project was observed with the infrared camera. It was a Town project located on Little Meadow Road in Guilford, Connecticut. It was sunny, winds were calm, the ambient temperature was 18°C (64°F), and the pavement temperature was 35°C (95°F) in the sun and 20°C (68°F) in the shade. The haul time was approximately 15 minutes.

The DOT Class 2 (9.5 mm) mix is finer than the Class 1 (12.5 mm) mix and is often used on town roads. A Class 2 project was sought in order to evaluate and compare the thermal behavior of Class 2 vs. Class 1. No significant differences between the mixes were seen. Temperature differentials appeared in longitudinal strips in the same type of random pattern that was observed at sites 1, 2, 5 and 6 (see Photo #23, page 57).

On October 13, 1998, another Class 2 project was observed with the infrared camera. It was also a Town project. The project was located on Linkfield Road in Watertown, Connecticut. It was cloudy, winds were calm, the ambient temperature was 13°C (55°F), and the pavement temperature was 18°C (64°F).

Temperature differentials appeared in the same type of longitudinal strips that were described for the Class 2 project in Guilford (see Photo #24, page 58). No significant differences in terms of temperature were observed between this Class 2 mix and the Class 1 mixes.

Observations, Comments and General Discussion

Temperature variations consistently appeared in the loads of HMA, as seen through the infrared camera, and it was observed that a low temperature crust formed in the loads during transport to the job sites. Severe temperature differences appeared as the loads broke and hot insulated material underneath the crust was exposed. The low temperature crust material was conveyed through the paver and out the screed. Some remixing was accomplished at the paver's auger, but not enough to completely eliminate the temperature variations. Variations of high and low temperatures appeared in longitudinal strips on the pavement.

While most of the HMA was conveyed directly through the paver, some of it accumulated along the edges of its wings and cooled to lower temperatures. When the wings were folded, this cooler material fell to the center of the hopper where it was conveyed out through the screed. Spots of low temperature appeared in the pavement shortly thereafter. On jobs where the wings were folded between truckloads, a cyclic load-to-load occurrence of these low temperature spots were observed. It was also observed that less temperature segregation generally occurred when the paver's wings were folded less frequently, as observed on Route 341 in Warren.

A significant reduction in temperature segregation was observed for the project paved with the Roadtec Shuttle Buggy material transfer vehicle. Department personnel stood on the paver during construction and noted that its operation was much smoother than had been observed for conventional projects, where the paver was in direct contact with the truck. They looked at the freshly placed pavement immediately behind the paver's screed and observed that it was uniform in temperature across the width of pavement. No local areas of cold temperature were seen. It should be noted that the paving train was in full operation at this point and all of the equipment was warmed-up.

A reduction in temperature segregation was also noted for the project paved with the Blaw-Knox MC-30 transfer vehicle; however, an occasional cold spot/area did appear during construction.

Conclusions

As described earlier in this report, the study objectives were to develop methods for the reduction of TDD to HMA pavement projects in Connecticut, and to determine if a relationship exists between nuclear density measurements and cold spots/areas that occur during paving operations. The latter will be addressed in this section of the report. The former will be addressed in the following section, Recommendations.

Preliminary results of this study indicate that a well-defined statistical relationship does not exist between change in density ($\Delta\sigma$), as measured with the nuclear gauge, and change in temperature (ΔT), as measured with the infrared camera. The coefficient of simple correlation (r) between $\Delta\sigma$ and ΔT was low for each of the monitored sites, indicating little or no linear association between them. Observations of scatter plots of $\Delta\sigma$ vs. ΔT (see Figures 1-6, pages 40-45) do not point to any type of linear or curvilinear relationships.

It should be noted that the dependent variable ($\Delta\sigma$) is not uniquely determined when the level of the independent variable (ΔT) is specified. This is because other factors play a role. These factors can vary from project to project or even within an individual project. They include materials, mix designs, lift thickness, climate, and available paving and compaction equipment. It is possible that one or more of these factors may have a more profound effect on the pavement’s density than ΔT.

Therefore, care should be taken when drawing conclusions from these statistical relationships.

At site 1, there appeared to be a general tendency for the density (σ) to be lower for the cold spots/areas than for their adjacent areas. On average, the cold spot/areas were 70 kg/m^3 less dense, as measured with the nuclear gauge, than their higher temperature counterparts. However, the linear association between ΔT and $\Delta\sigma$ was poor, and the coefficient of simple correlation (r) was 0.2. Note: a coefficient of simple correlation of r=0 indicates that there is no linear association, while a coefficient of r=–1 or 1 indicates that the variables have perfect linear association. These data suggest that while the density did tend to be less for the cold spots/areas, the density did not tend to increase or decrease linearly with ΔT. Also note that the scatter plot (see Figure 1) shows no pattern between ΔT and $\Delta\sigma$.

At site 2, the tendency for σ to be lower for the cold spots/areas was less evident, as the average density was only 25 kg/m^3 less for the cold spots/areas than their adjacent areas. The coefficient of simple correlation between ΔT and $\Delta\sigma$ was low (r=0.4). The scatter plot for site 2 is contained in Figure 2.

At site 3, a reverse trend occurred, as there was a general tendency for σ to actually be higher for the cold spots/areas than for their adjacent areas. The linear association between ΔT and $\Delta\sigma$ was poor (r=-0.4), and the scatter plot (see Figure 3) shows no pattern between the variables.

During field observations, well-defined temperature differentials were seen in the pavement at site 4 in Killingly. It was believed that if there were to be a relationship between ΔT and $\Delta\sigma$, this relationship would be most prevalent at this site. This was not the case, however, as there was poor linear association between them (r=-0.05), and the scatter plot (see Figure 4, page 43) shows no pattern. As was the case for sites 1 & 2, there was a general tendency for σ to be lower for the cold spots/areas than for their adjacent areas. On average, the cold spot/areas were 40 kg/m^3 less dense, as measured with the nuclear gauge, than their higher temperature counterparts.

Results were similar at sites 5 and 6. No linear associations between ΔT and $\Delta\sigma$ were evident in the scatter plots (see Figures 5 & 6) and the coefficients of simple correlation were low. Cold spots/areas at both sites did tend to have slightly lower densities than their adjacent higher temperature counterparts.

In general, cold spots/areas did tend to be less dense than their surrounding (normal) pavement, as five (5) out of the six (6) sites evaluated had lower average densities for these anomalous spots/areas. It is not clear as to why site 3 had a reverse trend. It can be hypothesized that a temperature tender zone exists in a freshly placed pavement for which the HMA is not at its optimal temperature for compaction. The existence of a temperature tender zone may explain site 3's trend reversal, since the surrounding hotter (normal) pavement may have been in the tender zone while the cold spot/area was below this temperature range.

Asphalt contents between the cold spots/areas and their higher temperature counterparts were very similar. Only one (1) set of cores tested and compared exceeded a 1 percent difference. The coefficient of simple correlation between change in asphalt content and ΔT was low (r=0.3). Based upon these data, it appears that there is no correlation between pavement laydown temperature and asphalt content.

Gradations were also very similar, as only one (1) set of cores that were tested and compared exceeded 8 percent coarser on the #8 sieve.

Considering these data, it may be concluded that the cold spots/areas were not segregated. This is in keeping with a Washington study noted in Brock in Jakob's report where "…gradations were taken and none of the cold areas exceeded the 8 to 15 percent coarser on the #8 sieve." The coefficient of simple correlation between change in material retained on the #8 sieve and ΔT was low (r=-0.3). It appears, based upon these data, that there is also no correlation between pavement laydown temperature and gradation.

While the author agrees that a pavement's density will tend to vary because of concentrations of cold material, a valid linear or curvilinear statistical relationship could not be shown (see Figures 1-6, pages 40-45). The author does not agree that the cause of the problem being called cyclic (particle) segregation is a problem of temperature differentials in the loads of HMA at the job site. The author believes that the problem of particle segregation is a very real problem, capable of existing independently of temperature differentials.

Recommendations

It is recommended that some type of remixing transfer equipment be employed on larger projects. Their use is recommended for two reasons.

The first reason is based upon observations made with the infrared camera during this study. A substantial reduction in temperature segregation was observed on projects paved with remixing equipment, particularly that paved with the Roadtec Shuttle Buggy. Since less temperature segregation occurs on projects paved with remixing equipment, the likelihood of a project to exhibit TDD is also reduced. It may also be stated that HMA that is well mixed for temperature must necessarily be well mixed for particle size. Therefore, the likelihood of a project to exhibit particle segregation is also reduced when remixing equipment is employed.

The second reason is based upon specifications being proposed to use pavement smoothness as criteria for incentive/disincentive payments. A recent report prepared by the Connecticut Transportation Institute indicated, "…these proposed specifications stipulate the use of IRI (International Roughness Index), a statistic developed by the World Bank. The IRI statistic employed is based on a 'quarter-car' simulation of a drive over a measured profile, and actually represents the vertical displacement that a passenger in a car would experience in units of in/mile or m/km." The use of a shuttle buggy type of device does not make contact with the paver and will, therefore, eliminate the "bump" that typically occurs when hauling units backup to a paving machine. This will provide a smoother pavement.

The author agrees with additional recommendation provided by Read [11]. These include giving more attention to late season paving operations, folding the hopper wings as infrequently as possible, and using insulated or heated hauling units.

It is recommended that an appropriate number of hauling units be employed in order to ensure that delays in paving operations are minimized. When paving machines are not in operation, the HMA sits and cools in the hopper. Once the next truck arrives, this material is conveyed to the auger and screeded out. Cold spots/areas appear in the pavement shortly thereafter.

Department personnel ought to give consideration to purchasing an infrared camera. The Department's Pavement Advisory Team (PAT) could use it on a regular basis to evaluate paving operations on projects throughout the state. When temperature differentials are observed, PAT personnel would be able to provide contractors with recommendations to reduce them, immediately, at the job site. These recommendations would include those discussed in this report, as well as additional recommendations that they would be able to make based upon their own experiences.

If Department personnel decide to invest in an infrared camera, it is recommended that additional research on the subject of thermal and material segregation be conducted. This research should include investigating whether any more or less TDD occurs at plants using silo storage or when ambient temperatures fall below 10°C (50°F). While some of the plants did use silo storage during this research, it cannot be determined from the collected data if they had a significant effect.

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Table 1a. Site 1 – Route 85 Colchester

Sample	IR Temp. (C°)	IR Temp. Difference (C°)	Nuclear Density (kg/m³)	Nuclear Density Difference (kg/m³)	% Air Voids Based on Nuclear Density	Difference in Air Voids (%)
1N 1C	128 124	4	2337 2246	91	6.5 10.1	3.6
2N 2C	121 118	3	2318 2273	45	7.2 9.0	1.8
3N 3C	114 77	37	2174 2143	31	13.0 14.2	1.2
4N 4C	113 84	29	2220 2182	38	11.2 12.7	1.5
5N 5C	111 104	7	2223 2217	6	11.0 11.3	0.3
6N 6C	114 93	21	2235 2199	36	10.6 12.0	1.4
7N 7C	111 99	12	2238 2185	53	10.4 12.6	2.2
8N 8C	109 106	3	2288 2182	106	8.4 12.7	4.3
9N 9C	98 87	11	2265 2158	107	9.4 13.6	4.2
10N 10C	96 80	16	2244 2185	59	10.2 12.6	2.4
11N 11C	103 78	25	2273 2084	189	9.0 16.6	7.6
12N 12C	89 75	14	2337 2148	189	6.5 14.0	7.5
13N 13C	84 56	28	2246 2273	-27	10.1 9.0	-1.1
14N 14C	92 86	6	2331 2236	95	6.7 10.5	3.8
15N 15C	92 77	15	2284 2236	48	8.6 10.5	1.9
16N 16C	74 62	12	2265 2174	91	9.4 13.0	3.6
17N 17C	83 74	9	2288 2198	90	8.4 12.0	3.6
18N 18C	99 87	12	2284 2260	24	8.6 9.6	1.0
19N 19C	100 87	13	2328 2262	66	6.8 9.5	2.7
20N 20C	96 69	27	2235 2172	63	10.6 13.1	2.5
Average	94	15	2236	70	10.5	2.8
Standard Deviation	+/-17	+/-10	+/-59	+/-53	+/-2.3	+/-2.7

Table 1b. Site 1 – Core Data

Sample	IR Temp (C°)	IR Temp. Difference (C°)	Air Voids (%)	Difference in Air Voids (%)	AC Content (%)	Difference in AC Content (%)
3N 3C	114 77	37	8.7 10.7	2.0	5.2 4.4	0.8
13N 13C	84 56	28	8.6 6.6	-2.0	6.0 6.0	0.0
20N 20C	96 69	27	6.8 12.0	5.2	5.3 5.1	0.2

Table 2a. Site 2 – Route 85 Colchester

Sample	IR Temp. (C°)	IR Temp. Difference (C°)	Nuclear Density (kg/m^3)	Nuclear Density Difference (kg/m^3)	% Air Voids Based on Nuclear Density	Difference in Air Voids (%)
1N 1C	121 108	13	2304 2217	87	7.8 11.3	3.5
2N 2C	113 102	11	2169 2257	-88	13.2 9.7	-3.5
3N 3C	108 92	16	2239 2124	115	10.4 15.0	4.6
4N 4C	107 86	21	2233 2074	159	10.6 17.0	6.4
5N 5C	111 96	15	2238 2139	99	10.4 14.4	4.0
6N 6C	110 85	30	2195 2129	66	12.2 14.8	2.6
7N 7C	113 101	12	2233 2227	6	10.6 10.9	0.3
8N 8C	104 88	16	2267 2280	-13	9.3 8.8	-0.5
9N 9C	99 80	19	2308 2278	30	7.6 8.8	1.2
10N 10C	93 86	7	2230 2252	-22	10.8 9.9	-0.9
11N 11C	106 91	15	2182 2140	42	12.7 14.4	1.7
12N 12C	96 77	19	2249 2230	19	10.0 10.8	0.8
13N 13C	96 84	12	2259 2233	26	9.6 10.6	1.0
14N 14C	90 79	11	2267 2276	-9	9.3 8.9	-0.4
15N 15C	89 79	10	2249 2166	83	10.0 13.3	3.3
16N 16C	89 79	10	2198 2252	-54	12.0 9.9	-2.1
17N 17C	89 77	12	2167 2265	-98	13.3 9.4	-3.9
18N 18C	89 82	7	2169 2241	-72	13.2 10.3	-2.9
19N 19C	98 76	22	2342 2278	64	6.3 8.8	2.5
20N 20C	98 86	12	2369 2283	86	5.2 8.6	3.4
21N 21C	97 78	19	2238 2321	-83	10.4 7.1	-3.3
22N 22C	86 70	16	2273 2163	110	9.0 13.4	4.4
Average	93	15	2232	25	10.7	1.0
Standard Deviation	+/-12	+/-5	+/-61	+/-74	+/-2.4	+/-2.9

Table 2b. Site 2 – Core Data

Sample	IR Temp (C°)	IR Temp. Difference (C°)	Air Voids (%)	Difference in Air Voids (%)	AC Content (%)	Difference in AC Content (%)
6N 6C	85 110	25	8.1 9.5	1.4	5.5 4.9	0.6
12N 12C	77 96	19	8.2 8.7	0.5	NA 4.9	NA
19N 19C	76 98	22	6.5 7.8	1.3	5.1 4.9	0.2

Table 3a. Site 3 – Route 8 Thomaston

Sample	IR Temp. (C°)	IR Temp. Difference (C°)	Nuclear Density (kg/m^3)	Nuclear Density Difference (kg/m^3)	% Air Voids Based on Nuclear Density	Difference in Air Voids (%)
1N 1C	116 103	13	2340 2419	-79	8.9 5.9	-3.0
2N 2C	116 99	17	2395 2435	-40	6.8 5.3	-1.5
3N 3C	115 104	11	2366 2419	-53	7.9 5.9	-2.0
4N 4C	119 96	23	2340 2416	-76	8.9 6.0	-2.9
5N 5C	118 94	24	2377 2412	-35	7.5 6.1	-1.4
6N 6C	117 109	8	2360 2360	0	8.2 8.2	0.0
7N 7C	108 77	31	2332 2420	-88	9.3 5.8	-3.5
8N 8C	99 76	23	2315 2390	-75	9.9 7.0	-2.9
9N 9C	116 101	15	2417 2368	49	6.0 7.9	1.9
10N 10C	109 102	7	2353 2396	-43	8.4 6.8	-1.6
11N 11C	97 82	15	2393 2435	-42	6.9 5.3	-1.6
12N 12C	88 74	14	2392 2340	52	6.9 8.9	2.0
13N 13C	84 69	15	2387 2425	-38	7.1 5.6	-1.5
14N 14C	105 98	7	2382 2404	-22	7.3 6.5	-0.8
Average	100	16	2385	-35	7.2	-1.4
Standard Deviation	+/-15	+/-7	+/-34	+/-43	+/-1.3	+/-1.7

Table 3b. Site 3 – Core Data

Sample	IR Temp (C°)	IR Temp. Difference (C°)	Air Voids (%)	Difference in Air Voids (%)	AC Content (%)	Difference in AC Content (%)
4N 4C	119 96	23	6.4 6.3	-0.1	6.1 5.9	0.2
7N 7C	108 77	31	8.0 6.2	-1.8	6.1 5.6	0.5
13N 13C	84 69	15	8.4 7.9	-0.5	6.0 5.8	0.2

Table 4a. Site 4 – Route 695 Killingly

Sample	IR Temp. (C°)	IR Temp. Difference (C°)	Nuclear Density (kg/m^3)	Nuclear Density Difference (kg/m^3)	% Air Voids Based on Nuclear Density	Difference in Air Voids (%)
1N 1C	102 87	15	2342 2150	192	6.1 13.8	7.7
2N 2C	125 101	24	2313 2278	35	7.2 8.6	1.4
3N 3C	127 79	48	2337 2223	114	6.3 10.8	4.5
4N 4C	124 91	33	2292 2300	-8	8.1 7.7	-0.4
5N 5C	122 84	38	2273 2291	-18	8.8 8.1	-0.7
6N 6C	121 91	30	2294 2235	59	8.0 10.3	2.3
7N 7C	123 98	25	2315 2270	45	7.1 8.9	1.8
8N 8C	119 94	25				
9N 9C	121 88	33	2281 2244	37	8.5 10.0	1.5
10N 10C	121 79	42	2231 2188	43	10.5 12.2	1.7
11N 11C	117 91	26	2267 2246	21	9.1 9.9	0.8
12N 12C	116 97	19	2225 2236	-11	10.8 10.3	-0.5
13N 13C	116 95	21	2247 2271	-24	9.9 8.9	-1.0
Average	105	29	2265	40	9.2	1.6
Standard Deviation	+/-16	+/-9	+/-45	+/-62	+/-1.8	+/-2.5

Table 4b. Site 4 – Core Data

Sample	IR Temp (C°)	IR Temp. Difference (C°)	Air Voids (%)	Difference in Air Voids (%)	AC Content (%)	Difference in AC Content (%)
3N 3C	127 79	48	5.3 8.0	2.7	5.5 5.3	0.2
5N 5C	122 84	38	6.9 7.4	0.5	5.1 5.5	-0.4
10N 10C	121 79	42	7.0 7.6	0.6	5.3 5.3	0

Table 5a. Site 5 – Route 31 Coventry

Sample	IR Temp. (C°)	IR Temp. Difference (C°)	Nuclear Density (kg/m^3)	Nuclear Density Difference (kg/m^3)	% Air Voids Based on Nuclear Density	Difference in Air Voids (%)
1N 1C	101 82	19	2427 2371	56	7.0 9.2	2.2
2N 2C	93 74	19	2286 2332	-46	12.4 10.7	-1.7
3N 3C	103 82	21	2406 2412	-6	7.9 7.6	-0.3
4N 4C	97 82	15	2465 2230	235	5.6 14.6	9.0
5N 5C	91 76	15	2483 2433	50	4.9 6.8	1.9
6N 6C	90 78	12	2420 2427	-7	7.3 7.0	-0.3
7N 7C	93 74	19	2255 2411	-156	13.6 7.7	-5.9
8N 8C	89 74	15	2432 2379	53	6.9 8.9	2.0
9N 9C	79 56	23	2428 2444	-16	7.0 6.4	-0.6
10N 10C	107 74	33	2187 2390	-203	16.2 8.5	7.7
11N 11C	93 73	20	2411 2398	13	7.7 8.2	0.5
12N 12C	95 74	21	2440 2256	184	6.5 13.6	7.1
Average	85	19	2380	13	8.8	0.5
Standard Deviation	+/-12	+/-5	+/-80	+/-122	+/-3.0	+/-4.7

Table 5b. Site 5 – Core Data

Sample	IR Temp (C°)	IR Temp. Difference (C°)	Air Voids (%)	Difference in Air Voids (%)	AC Content (%)	Difference in AC Content (%)
3N 3C	103 82	21	5.2 4.9	-0.3	5.9 6.0	-0.1
9N 9C	79 56	23	6.3 6.3	0.0	5.6 5.6	0.0
11N 11C	93 73	20	6.0 6.6	0.6	6.0 6.4	-0.4

Table 6a. Site 6 – Pigeon Hill Road

Sample	IR Temp. (C°)	IR Temp. Difference (C°)	Nuclear Density (kg/m^3)	Nuclear Density Difference (kg/m^3)	% Air Voids Based on Nuclear Density	Difference in Air Voids (%)
1N 1C	107 93	14	2417 2355	62	7.2 9.6	2.4
2N 2C	104 92	12	2382 2278	104	8.6 12.6	4.0
3N 3C	110 92	18	2467 2299	168	5.3 11.7	6.4
4N 4C	101 73	28	2339 2428	-89	10.2 6.8	-3.4
5N 5C	100 63	27	2441 2363	78	6.3 9.3	3.0
6N 6C	89 64	25	2470 2328	142	5.2 10.6	5.4
7N 7C	93 66	27	2329 2379	-50	10.6 8.7	-1.9
8N 8C	95 66	29	2291 2376	-85	12.1 8.8	-3.3
9N 9C	92 68	24	2419 2318	101	7.1 11.0	3.9
10N 10C	83 63	20	2278 2488	-210	12.6 4.5	-8.1
Average	86	23	2372	22	8.9	0.8
Standard Dev.	+/-16	+/-8	+/-66	+/-123	+/-2.5	+/-4.7

Table 6b. Site 6 – Core Data

Sample	IR Temp (C°)	IR Temp. Difference (C°)	Air Voids (%)	Difference in Air Voids (%)	AC Content (%)	Difference in AC Content (%)
1N 1C	107 93	14	6.6 6.9	0.3	5.9 7.1	-1.2
3N 3C	110 92	18	5.9 8.6	2.7	6.1 5.9	0.2
5N 5C	100 63	37	6.5 10.1	3.6	6.3 6.3	0.0

Table 7 – Site 1

Sieve Passing	3N	3C	13N	13C	20N	20C
200	4.4	4.0	4.2	4.6	4.6	4.8
50	17.5	15.3	19.1	19.4	17.9	18.1
30	23.5	20.2	26.6	27.0	24.2	24.4
8	38.8	32.3	44.6	45.2	41.1	40.5
4	51.5	44.0	60.0	59.7	55.5	53.7
3/8″	73.4	65.3	82.2	84.2	75.9	74.0
½″	98.0	96.7	97.7	98.7	98.8	98.4
¾″	100	100	100	100	100	100

Table 8 – Site 2

Sieve Passing	6N	6C	12N	12C	19N	19C
200	4.6	4.3	NA	4.7	4.3	3.9
50	18.6	17.1	NA	17.8	18.3	17.3
30	25.7	23.3	NA	24.1	25.2	23.7
8	42.3	36.6	NA	38.5	41.4	37.8
4	55.4	48.3	NA	50.7	56.8	51.2
3/8″	82.4	77.8	NA	77.9	79.5	71.5
½″	98.2	97.8	NA	97.4	97.4	95.1
¾″	100	99.8	NA	100	99.9	100

Table 9 – Site 3

Sieve Passing	4N	4C	7N	7C	13N	13C
200	4.3	4.3	4.6	4.6	4.3	3.9
50	16.6	16.1	17.5	17.6	20.0	18.5
30	27.8	27.1	28.8	29.9	33.3	30.4
8	43.0	42.1	43.5	46.0	49.1	44.2
4	53.4	52.9	52.7	57.0	56.4	57.2
3/8″	79.8	78.7	77.0	81.6	81.8	76.0
½″	99.1	98.3	98.4	98.3	99.2	97.4
¾″	100	100	100	99.9	100	100

Table 10 – Site 4

Sieve Passing	3N	3C	5N	5C	10N	10C
200	3.9	3.9	3.7	3.8	3.8	3.7
50	17.1	16.2	14.9	15.4	15.8	15.6
30	26.0	24.6	22.7	24.2	24.6	25.0
8	40.9	38.1	36.5	39.6	39.6	40.2
4	50.6	47.7	45.7	50.2	49.3	49.3
3/8″	74.6	73.2	69.3	76.5	74.2	72.9
½″	89.1	92.6	91.2	92.9	89.0	91.3
¾″	100	100	100	100	100	100

Table 11 – Site 5

Sieve Passing	3N	3C	9N	9C	11N	11C
200	4.5	4.1	3.3	3.4	4.6	4.7
50	17.4	17.0	15.4	15.1	17.3	18.4
30	28.7	28.6	26.3	25.9	28.3	30.7
8	45.8	45.7	41.5	41.4	45.0	49.0
4	57.6	75.1	52.1	51.8	57.1	62.0
3/8″	75.9	95.8	70.7	72.5	75.0	79.6
½″	96.1	100	95.3	96.6	96.4	97.7
¾″	100	-	100	99.9	100	100

Table 12 – Site 6

Sieve Passing	1N	1C	3N	3C	5N	5C
200	5.0	6.6	4.7	5.6	4.4	5.0
50	15.2	18.9	17.3	16.9	17.6	19.5
30	22.0	27.9	26.5	25.1	27.4	28.5
8	34.7	45.8	44.0	40.2	45.5	45.0
4	46.1	62.2	56.4	53.8	58.4	57.8
3/8″	62.3	79.6	72.3	70.1	74.5	75.4
½″	77.0	89.9	86.0	85.5	85.7	90.1
¾″	97.6	100	100	100	98.9	100
1″	100	-	-	-	100	-

Site 1 - Relationship Between Change in Temperature and Change in Density

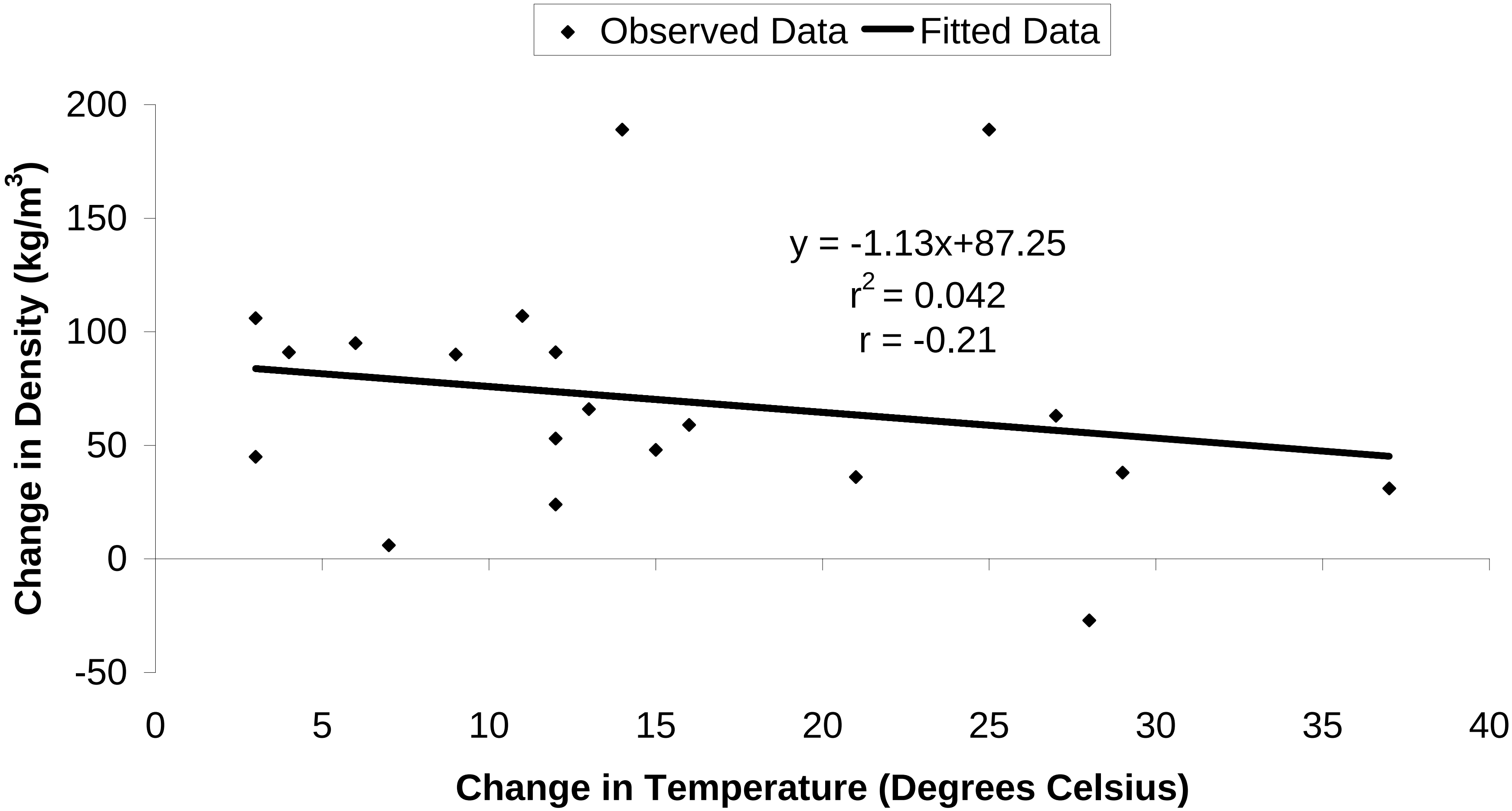

Figure 1

Site 2 - Relationship Between Change in Temperature and Change in Density

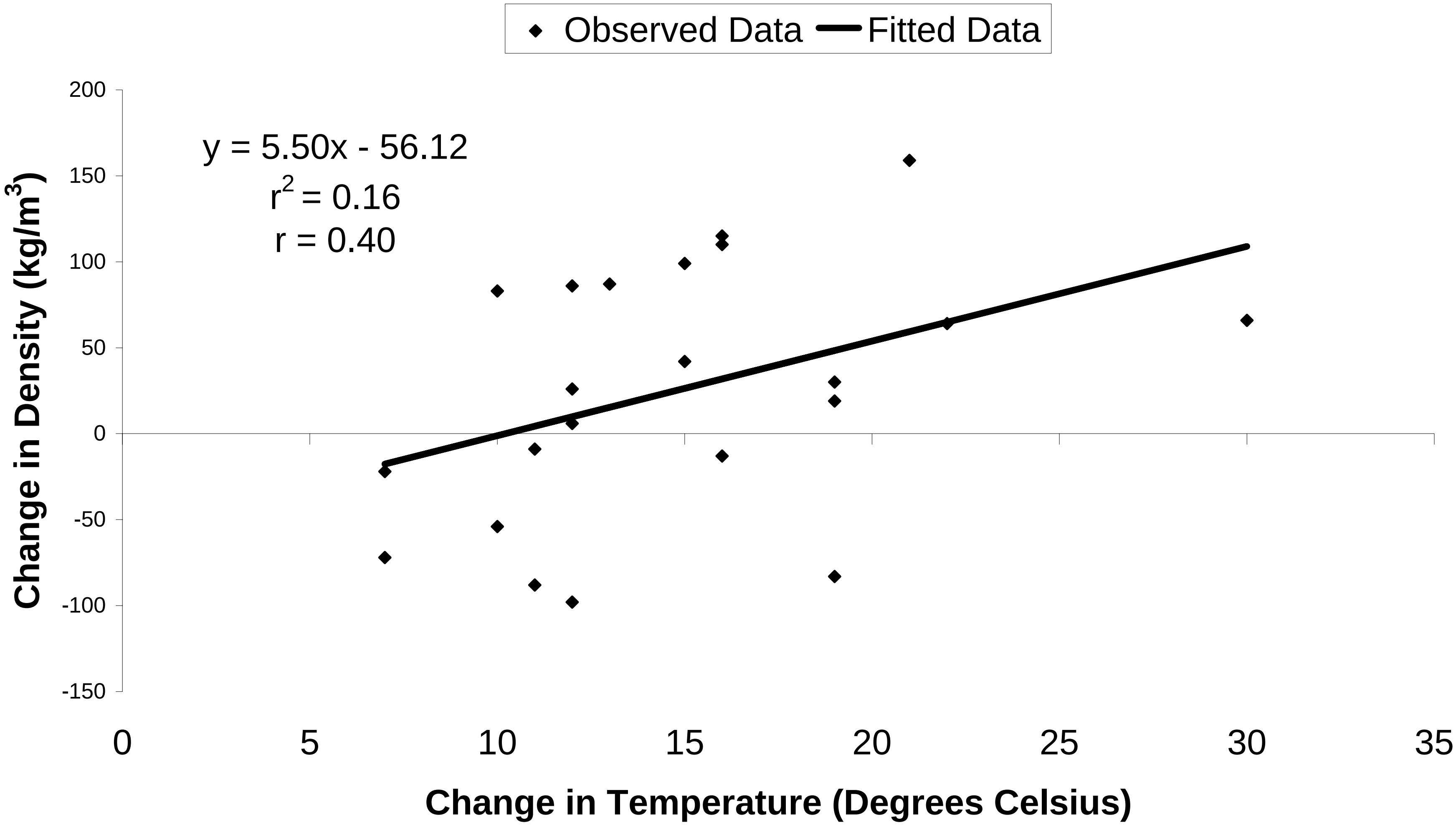

Figure 2

Site 3 - Relationship Between Change in Temperature and Change in Density

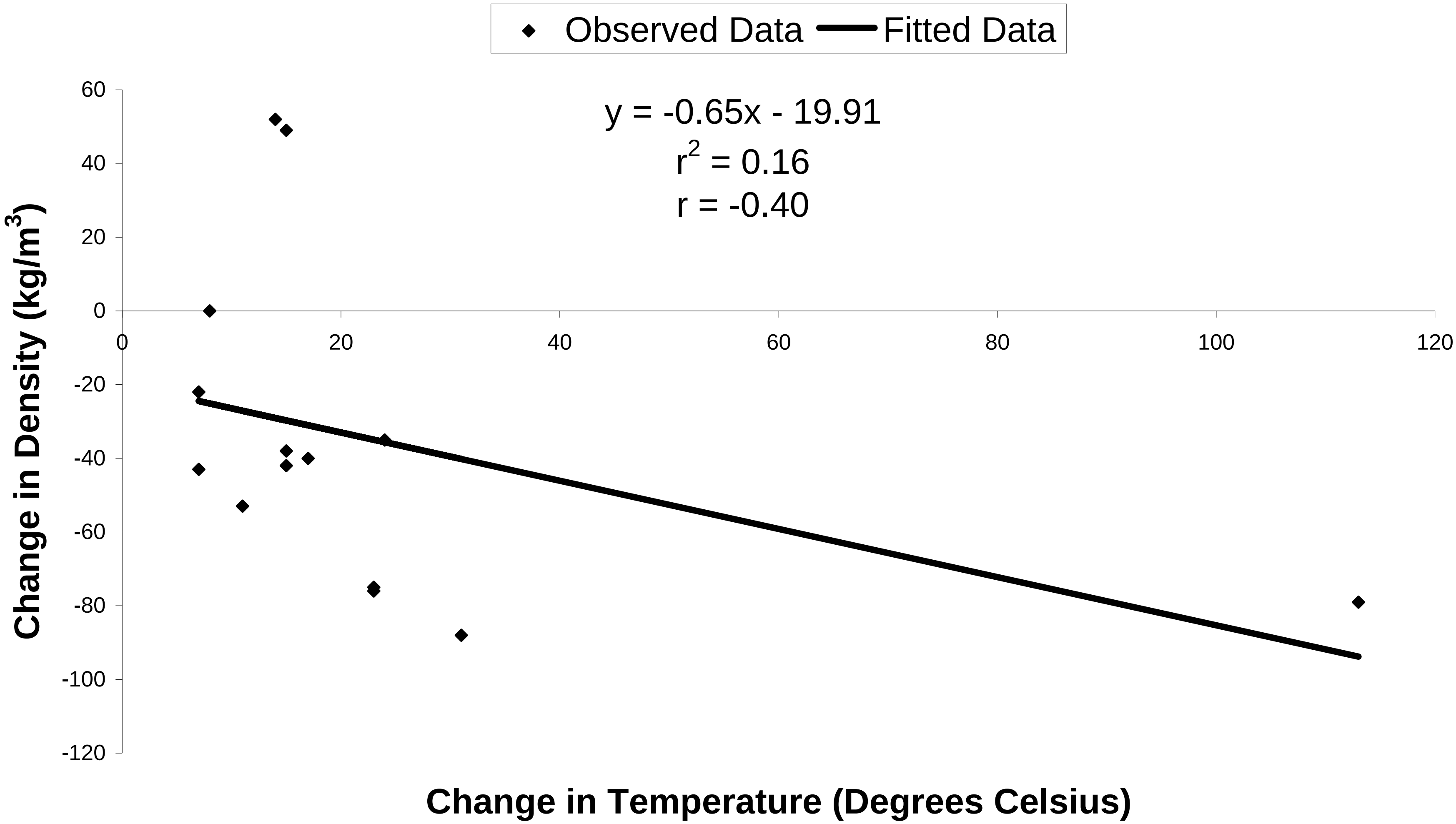

Figure 3

Site 4 - Relationship Between Change in Temperature and Change in Density

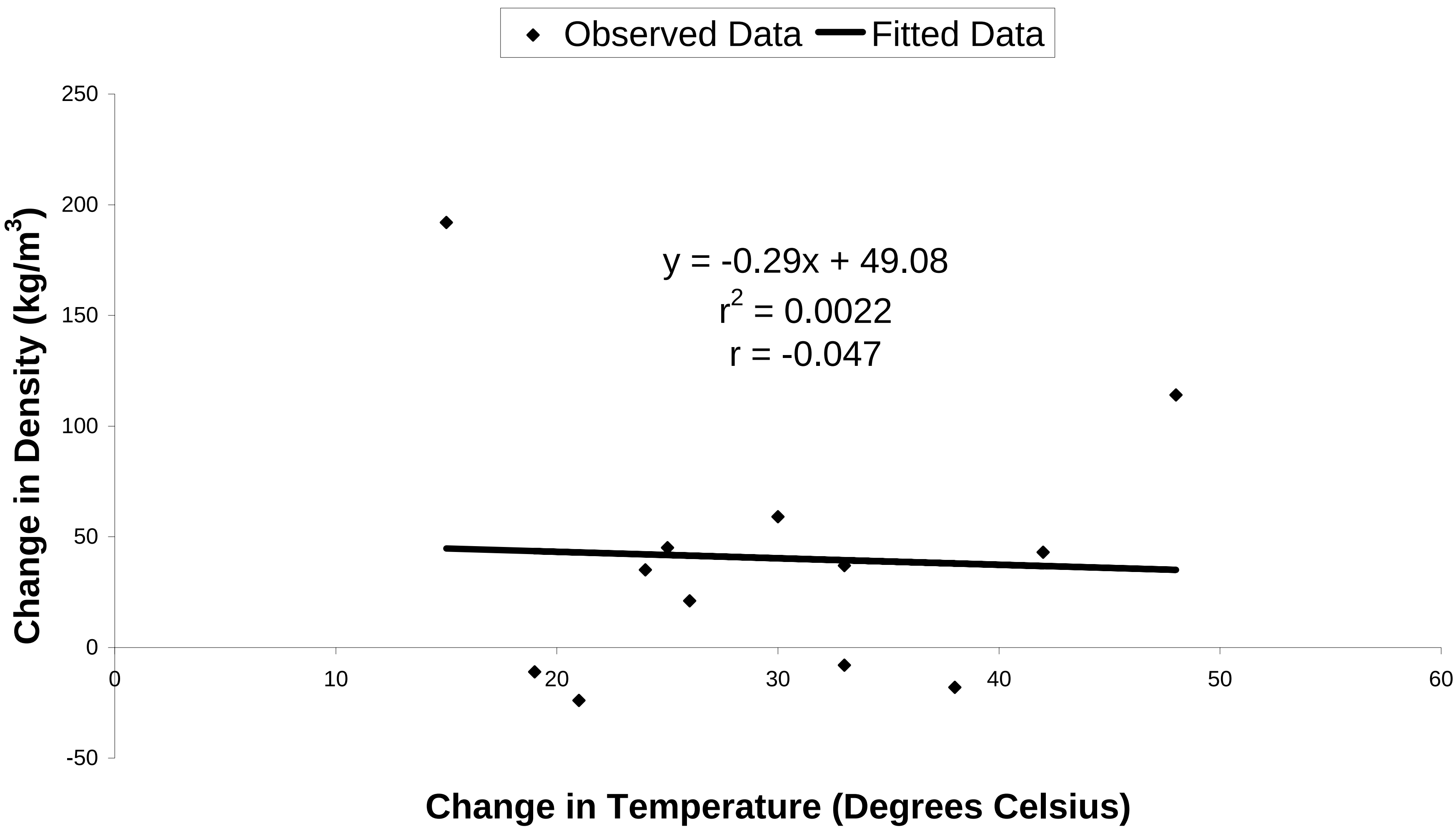

Figure 4

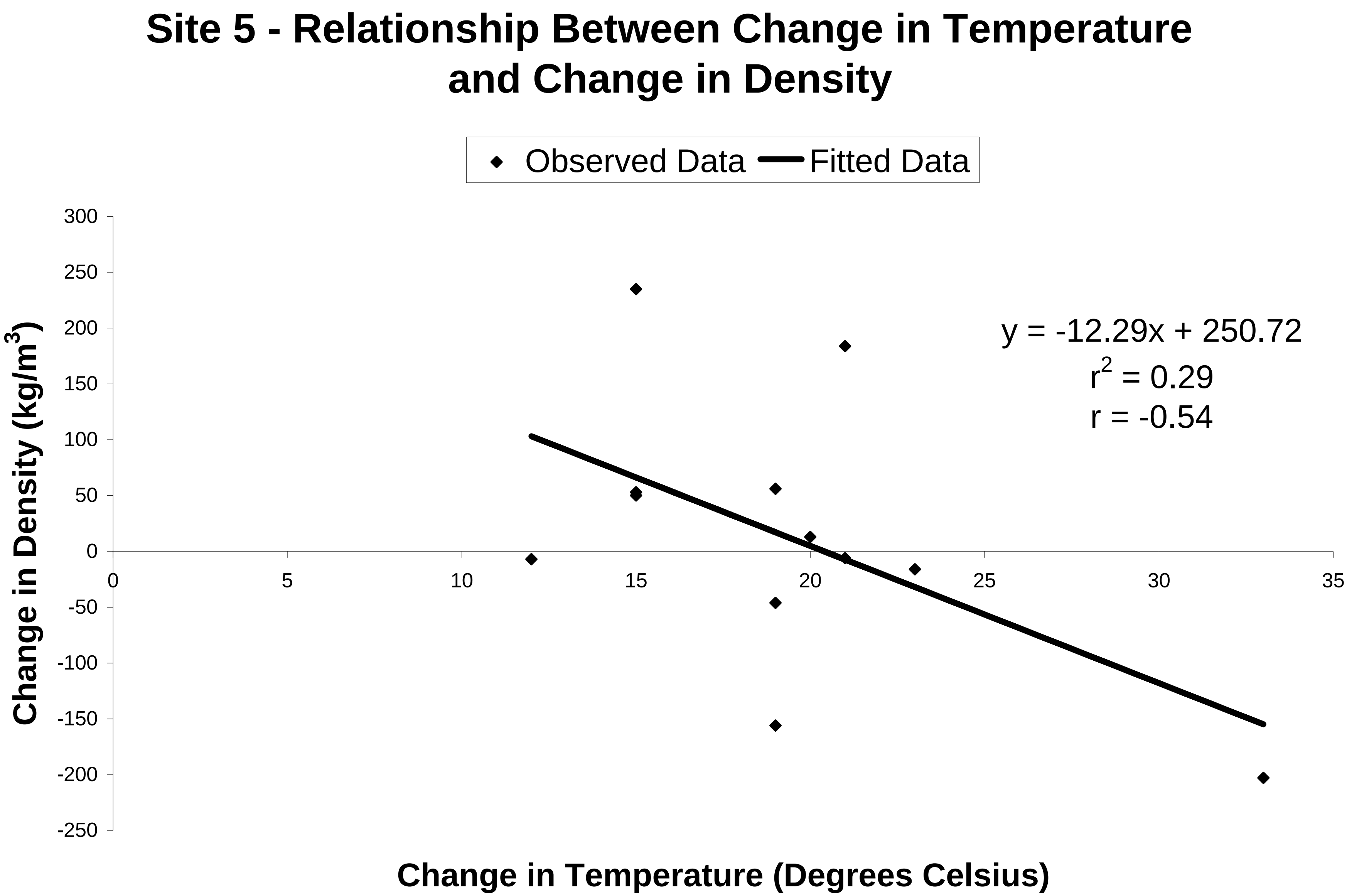
Site 5 - Relationship Between Change in Temperature and Change in Density
Observed Data
Fitted Data
y = -12.29x + 250.72
r2 = 0.29
r = -0.54
Change in Density (kg/m3)
Change in Temperature (Degrees Celsius)
300
250
200
150
100
50
0
-50
-100
-150
-200
-250
0
5
10
15
20
25
30
35

Figure 5

Site 6 - Relationship Between Change in Temperature and Change in Density

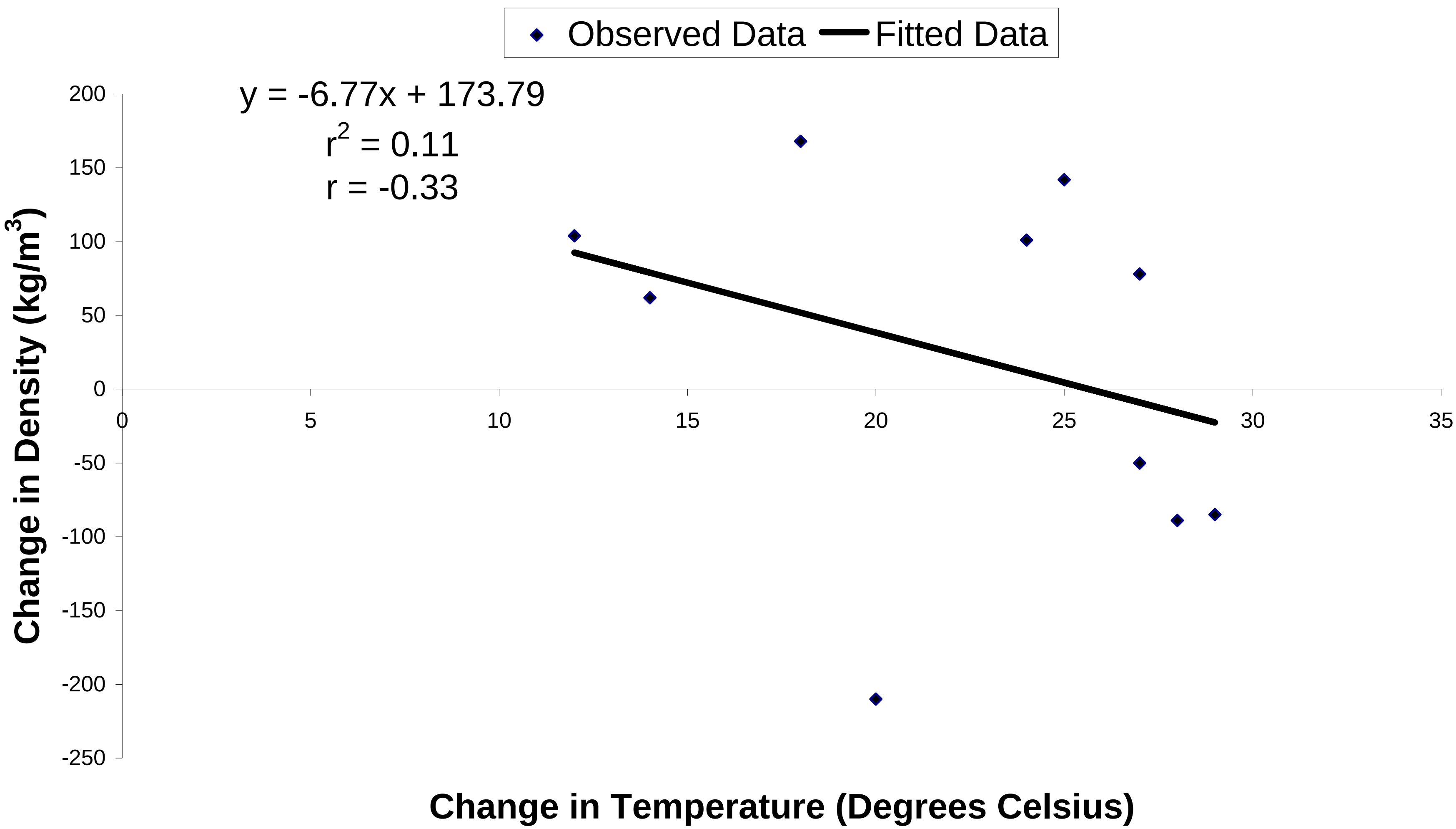

Figure 6

Photo #1. Inframetrics ThermaCAM PM380.

Photo #2. Infrared Camera in Use.

Photo #3. Blaw-Knox PF-180H Paver Used on Sites 1 and 2.

Photo #4. Blaw-Knox PF-3200 Paver Used on Site 3.

Photo #5. Infrared Video Being Recorded From Top of Blaw-Knox PF-3200 Paver at Site 3.

Photo #6. Truck Used at Site 3 Project, Route 8 in Thomaston.

Photo #7. Blaw-Knox PF-200 Paver Used on Site 4.

Photo #8. – Cedar Rapids CR-551 Paver Used on Site 6.

Photo #9. Department Personnel Use Infrared Camera to Look at Truckload of HMA.

Photo #10. Blaw-Knox MC-30 Material Transfer Vehicle.

Photo #11. Roadtec Shuttle Buggy Material Transfer Vehicle.

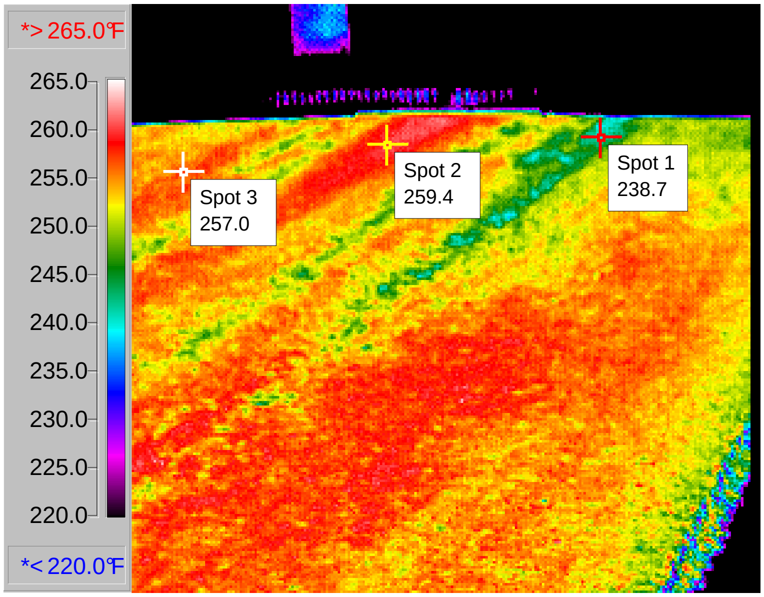

Photo #12. Route 8 in Thomaston

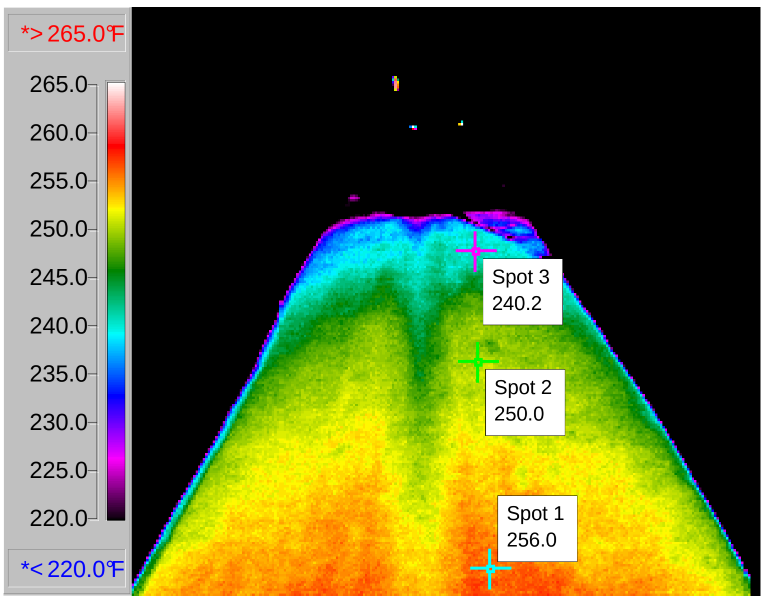

Photo #13. Route 8 in Thomaston

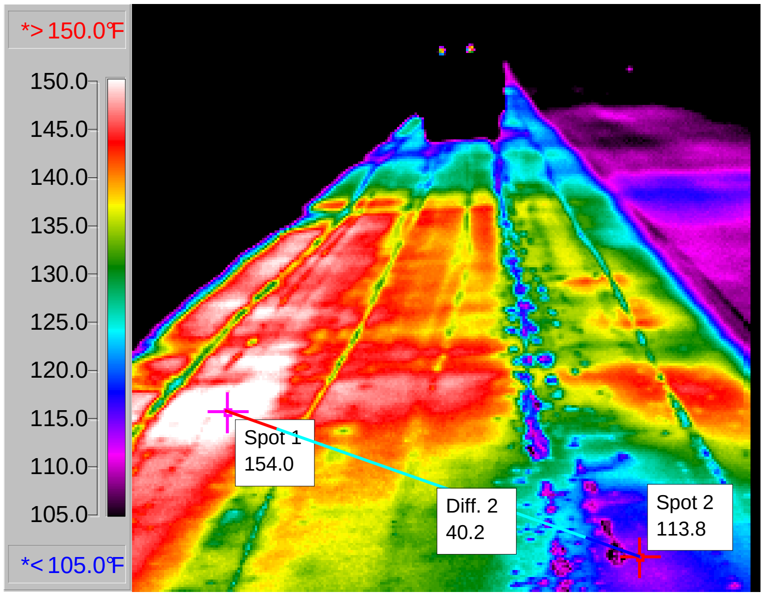

Photo #14. Route 8 in Thomaston

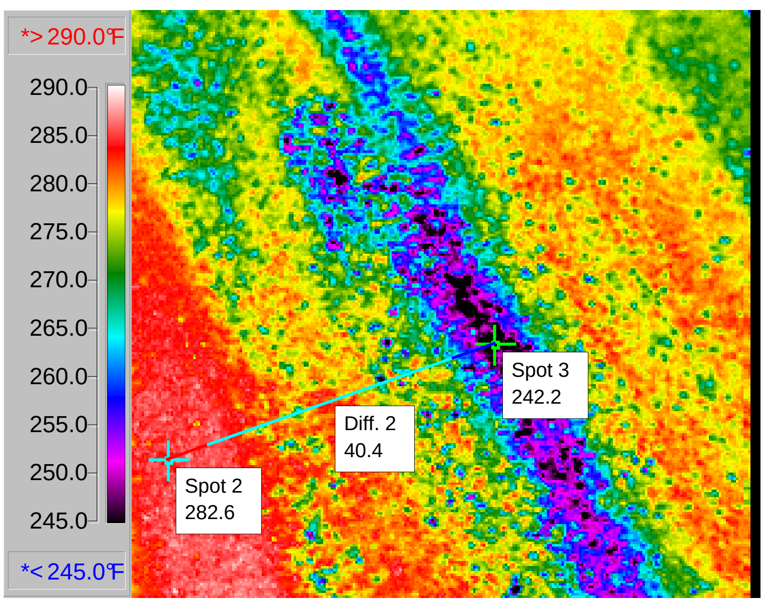

Photo #15. Route 695 – Killingly

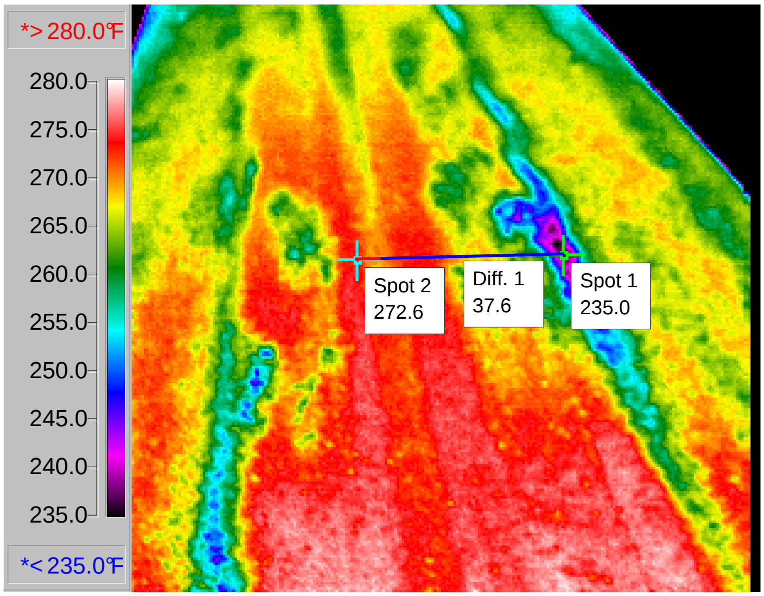

Photo #16. Route 695 – Killingly

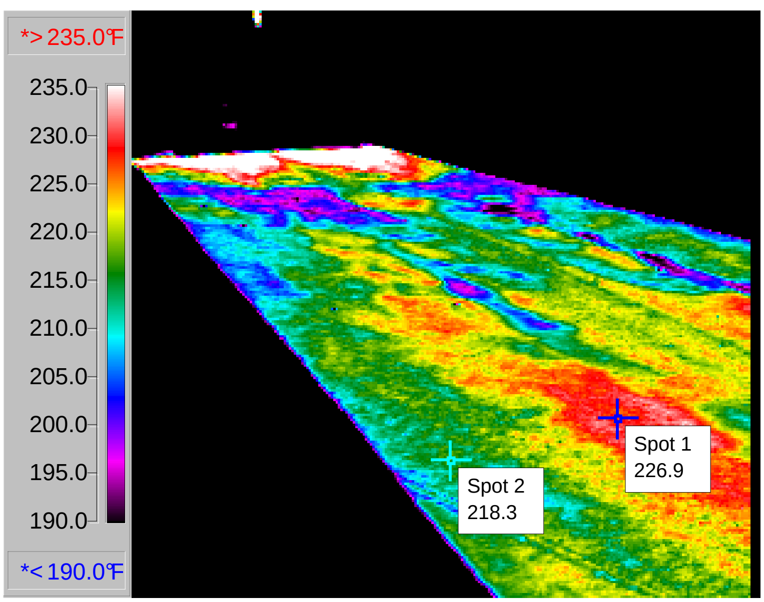

Photo #17. Route 695 – Killingly

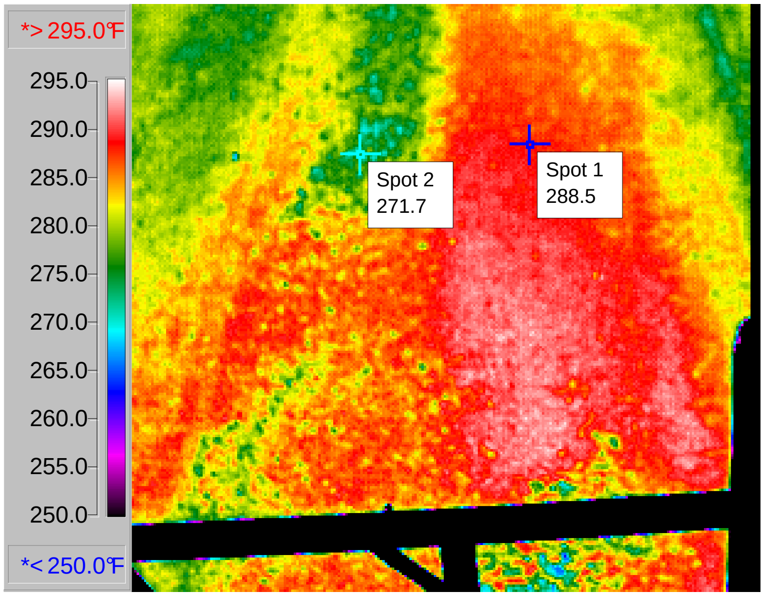

Photo #18. Route 31 – Coventry

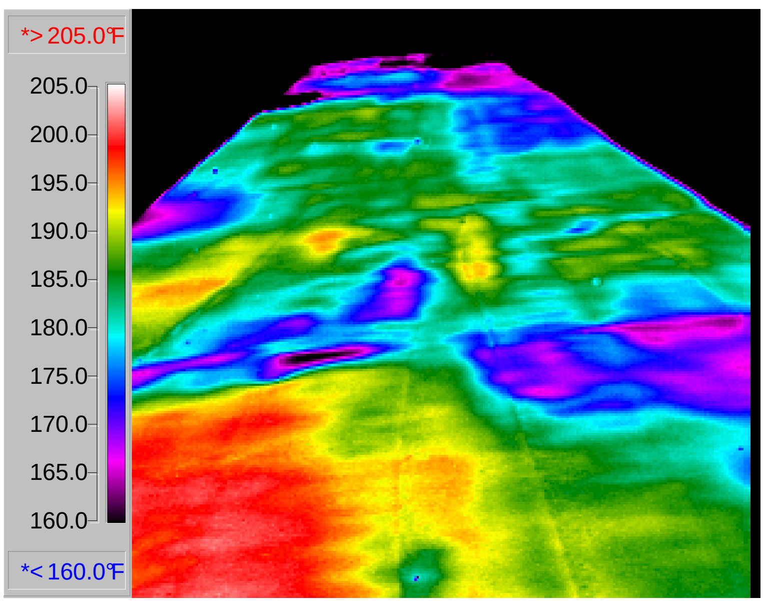

Photo #19. Route 31 – Coventry

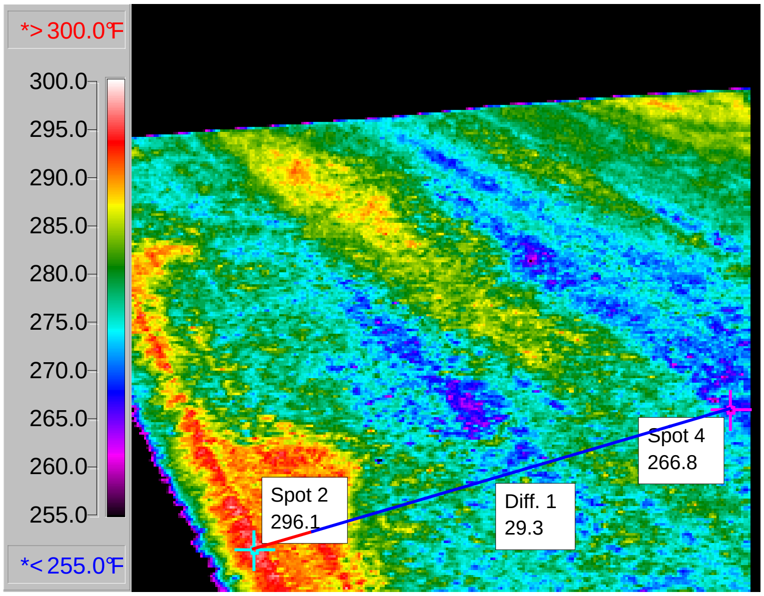

Photo #20. Route 91 – Rocky Hill

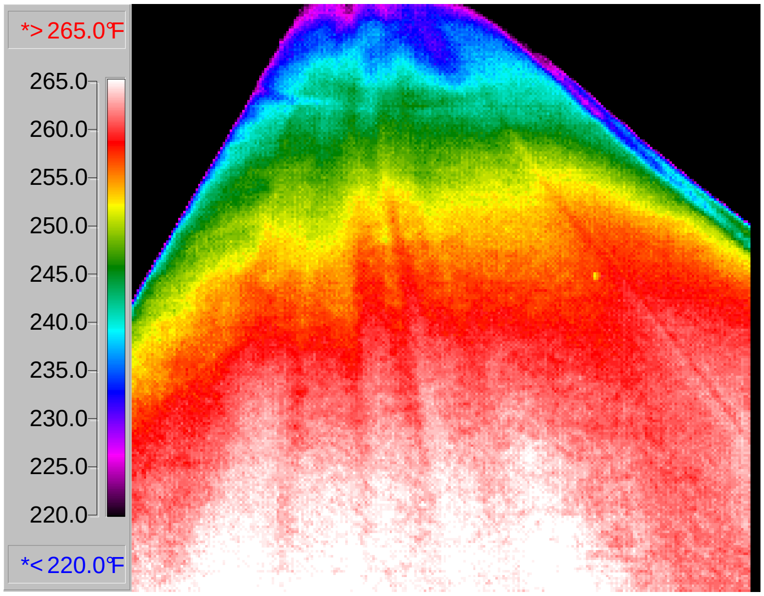

Photo #21. Route 91 – Meriden

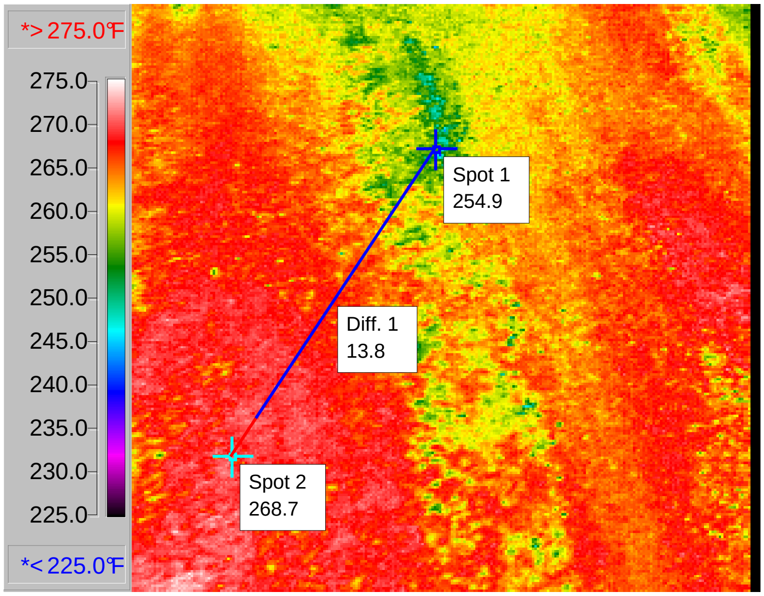

Photo #22. Route 341 – Warren

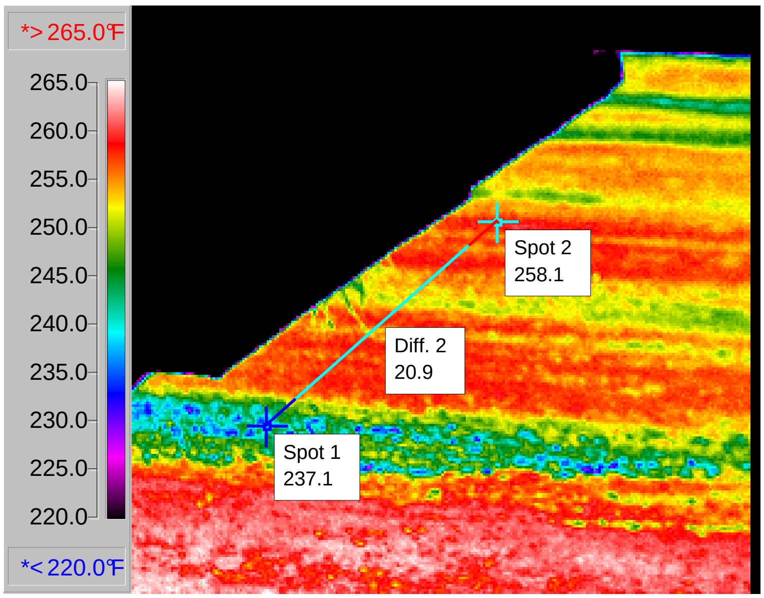

Photo #23. Little Meadow Road – Guilford

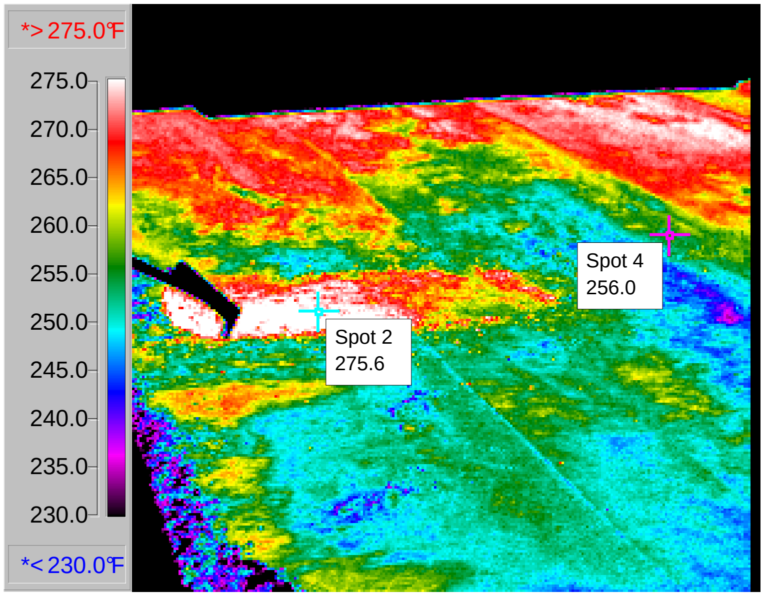

Photo #24. Linkfield Road - Watertown