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

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A Project in Cooperation with the U.S. Department of Transportation
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16. Abstract

This paper presents results of a study on the subject of thermal segregation of hot mix asphalt (HMA) during pavement construction. The significance of thermal segregation to pavement performance should not be overvalued, because it is not only possible, but probable, that other factors play more significant roles. For example, the authors present the concept that density achieved is more dependent upon HMA temperature (T) than temperature differentials (∆T). It is surmised that thermal segregation has a negligible effect until cold area temperatures drop below certain threshold values. This reasoning is based upon results of a five-year pavement condition survey that demonstrated little if any relationship between temperature differentials located with an infrared camera during HMA construction, and subsequent damage to a pavement's surface. While five years may be too short a period of time for some distresses to develop, it is noteworthy that extensive reflective cracking was observed at some locations, which demonstrates that it played a more prominent role than ∆T. Comparisons of asphalt contents and grain-size distributions between cold areas and their surrounding normal-temperature pavements demonstrated no significant differences, suggesting temperature differentials in the HMA during construction are not necessarily indicative of particle segregation. Finally, definitions for the terminology associated with HMA construction and infrared thermography are presented.

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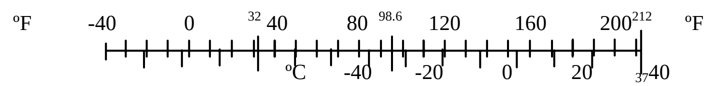
METRIC CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
mi^2	square miles	2.59	square kilometers	km^2
ac	Acres	0.405	hectares	ha
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb.)	0.907	Megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		TEMPERATURE (exact)		
ºF	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	ºC

APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
km^2	square kilometers	0.386	square miles	mi^2
ha	hectares (10,000 m^2)	2.47	acres	ac
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	Megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		TEMPERATURE (exact)		
ºC	Celsius temperature	9/5 (then add 32)	Farenheit temperature	ºF



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INTRODUCTION

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 ConnDOT 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, performed an exploratory study for Washington Department of Transportation (WSDOT) on HMA segregation with his thesis advisor, Professor Joe P. Mahoney. The proposed research was typical of other studies 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 *(1,2)*.

Data collection, including temperature readings, was adjusted to reflect this newly-found 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 *(1,2)*.

Next, various samples were taken from both the segregated 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 *(1,2)*.

The focus of the research evolved into determining the mechanism that produces these segregated appearing areas in the pavement. In his graduate thesis, entitled "Construction Related Temperature Differential Damage in Asphalt Concrete Pavements *(1)*," 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.

Read *(1)* 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 (MTV). His investigation revealed that these devices do, in fact, reduce the amount of temperature differentials in the HMA pavement *(1,2)*.

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). Brock and 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 occurrence of segregation on Connecticut roadways.

Based upon this interest, this research project was initiated in September 1998 to investigate temperature (thermal) segregation and its effect on the subsequent performance of HMA pavements. An infrared camera was rented for one month to perform the study and a preliminary Construction Report was published in November 1999 *(3)*, which provided conclusions and recommendations. One recommendation was for ConnDOT personnel to consider purchasing an infrared camera to evaluate HMA paving projects and perform additional research on the subject of thermal segregation.

Afterward, Department personnel did purchase an infrared camera and lent it to the Connecticut Advanced Pavement Laboratory (CAP Lab), of the University of Connecticut's Transportation Institute, for further research. In November 2003, Mahoney, et al. *(4)*, published a report, entitled "Application of Thermographic Imaging to Bituminous Concrete Pavements – Final Report." A discussion of their report is provided in the Literature Review.

Terminology

The following are recommended definitions for the terminology used throughout this report:

- Mat – fresh HMA pavement behind the paver following laydown, prior to or during roller compaction.
- Temperature differential – any localized HMA temperature gradient, whether at the plant, inside the truck or paver, or on the mat.
- Thermal segregation – isolated areas of the mat that differ significantly from the main body of the mat in temperature.
- Temperature differential damage (TDD) – sections of deteriorated HMA pavement that are theorized to have developed as a result of thermal segregation.
- Particle segregation – isolated areas of HMA pavement that differ significantly from the main body of pavement in grain-size distribution.
- Segregation – the former word used to describe particle segregation above; however, it has also been used to describe isolated areas of HMA pavement that differ from the main body of pavement in density/air voids, asphalt content or a combination of some or all of these components. With the advent of thermal segregation, the word segregation has become even more confusing, and it is recommended that its use be discontinued. Note: for historical purposes, the word segregation is used in this paper.

Study Objectives

The objectives of the research study as published in the study proposal, dated August 1998 *(5)*, were:

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 expected from the study included:

1. Improved understanding of thermal segregation 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 may cause to a pavement structure. At the time when the literature search was conducted for the Construction Report in 1999, 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 particle segregation was also reviewed. Since 1999, further research on thermal segregation of HMA has been conducted and will also be included in this review.

Segregation

Williams, et al. *(6)*, 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 *(6,7)*. Brown, et al. *(8)*, concluded that "segregated areas are generally 8 to 15 percent coarser than nonsegregated areas on the No. 8 [2.36 mm] sieve; the voids are typically 3 to 5 percent higher; and, the asphalt content is often 1 to 2 percent lower." Note: when they say "on the No. 8 sieve," they appear to be referring to the percent passing the No. 8 sieve, since they refer to the percent passing, rather than the percent retained, throughout their report. They observed paving projects during construction and performed tests on segregated specimens of pavement. They indicated that "segregated areas that are not overlaid tend to ravel under traffic."

Cross and Brown *(9)* 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 that “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 *(6,7)*. Khedaywi and White *(7)* 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. *(6)*, 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 *(6,10,11,12)*. These include mix design, stockpiling, mix production, storage, truck loading and unloading, and paving operations.

Brock *(10)* 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. *(12)*, 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 *(10,11)*. When a conveyor supplies material, Brock *(10)* 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. *(8)*, 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 *(13)*, 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 *(1)*. 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 *(10,11,12)*. 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 *(11)*.

During paving operations close attention to the hopper wings, hopper gates, drag slats and auger should be given. Hopper wings

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

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 *(10,11)*.

Thermal Segregation/Temperature Differential Damage

Read *(1)* 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).

Read's *(1)* work was substantiated by continued research by Professor Mahoney, et al. *(14)*, at the University of Washington. They examined four Washington State Department of Transportation (WSDOT) paving projects with an infrared camera to locate mat temperature differentials. Once located, they sampled the cooler portions of the mat along with nearby normal-temperature sections. Grain-size distributions, asphalt contents and air voids were determined for thirteen paired samples. They indicated that all of the paired samples exhibited higher air voids for the cooler mat areas (average increase of 3.9%); however, no evidence of significant segregation was found during gradation and asphalt content analyses. Note: Mahoney, et al *(14)*, used Williams, et al. *(6)*, definition of segregation: "the nonuniform distribution of coarse and fine aggregate components within the asphalt structure."

Read (1), Brock and Jakob *(2),* Mahoney et al. *(14)*, and Willoughby et al. *(15)* all indicate the mechanism that causes these compaction deficiencies is related to the paver not being able to consolidate colder portions of the mix during pavement laydown. Mahoney, et al. *(14)*, found that proper paver and roller operations could minimize compaction deficiencies for thermally segregated pavement. In addition to timely compaction, Willoughby, et al. *(15)*, recommended the use of pneumatic rollers for offsetting the effects of temperature differentials.

In 2000, Stroup-Gardiner and Brown *(16)* published a report which included recommended procedures for defining, detecting and measuring segregation. They defined segregation "… as a lack of homogeneity in the hot-mix asphalt constituents of the in-place mat of such a magnitude that there is a reasonable expectation of accelerated pavement distress (es)." These "constituents," they said, include asphalt cement, aggregates, additives and air voids. They indicated infrared thermography could be used to specify levels of segregation and for inspecting mat uniformity during construction. Stroup-Gardiner and Brown recommended pay adjustments for repeated occurrences of temperature differentials from 11 °C to 20 °C (20 °F to 36 °F), which they said were potentially segregated, and removal and replacement for temperature differentials greater than 20 °C (36 °F), which they said were probably highly segregated. While they believe infrared thermography can be used for these purposes, it is important to note they pointed out that it cannot distinguish between thermal and gradation segregation types.

During another study, Stroup-Gardiner, et al. *(17)*, investigated the use of automated equipment for collecting and recording temperature profile data. The equipment includes a transverse line of infrared sensors and a Global Positioning System (GPS). While several updates to the system were recommended, they indicated automated equipment can collect and record accurate temperature profile data comparable to that obtained with an infrared camera.

Read *(1)* 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 *(1)* also recommended that transfer devices be employed on larger projects.

Initial results of this study were published in a Construction Report in November 1999 *(3)*. The use of thermal imaging technology was verified as an effective method for monitoring temperature variations that occur in HMA during pavement construction, and researchers were able to confirm that thermal segregation does occur with conventional paving construction methods and equipment. Two different MTVs, one remixing and one with a remixing insert, were evaluated for reducing thermal segregation and were found to be effective, especially the remixing MTV.

Following this project's Construction Report publication, ConnDOT personnel purchased an infrared camera for further research conducted by CAP Lab personnel. Forty (40) ongoing HMA paving projects were selected for their study, where thermal imaging was used to monitor construction. Mahoney, et al. *(4)*, were able to confirm, from more comprehensive research, initial results published in the ConnDOT Construction Report, and they provided additional recommendations for reducing particle and thermal segregation.

Mahoney, et al. *(4)*, emphasized that identifying the problem as either particle or thermal segregation is critical because the methods employed to address each are very different, even though they may look alike. They agreed with other researchers *(1,2,3)* by encouraging the use of MTVs, especially those that remix, since they stated "remixing MTVs greatly reduce if not eliminate both types of segregation." Additional recommendations for reducing thermal segregation included removing HMA spillage prior to paving, keeping haul distances to a minimum, taking greater care during night and cold weather paving, and using heated bodies on haul units. Finally, they concurred with this project's Construction Report *(3)* that many factors play a role in influencing particle and thermal segregation and stated "… that controlling these factors to isolate a single variable would be next to impossible."

PROJECT LOCATIONS AND DESCRIPTIONS

Eleven (11) sites were selected for study from ongoing paving projects in Connecticut: nine (9) Class 1 (12.7-mm) and two (2) Class 2 (9.5-mm). Pavements for all eleven (11) sites were 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 were monitored for a period of five (5) years in order to evaluate the pavement's performance over time.

Each monitored site was approximately 150-m (500-feet) long. Monitored site locations were selected based upon safety considerations, traffic characteristics and topography. Infrared video was recorded and observations were made at the remaining five (5) non-monitored sites; however, no additional testing was performed at these locations.

Before beginning paving operations, monitored test sections were staked out and, when possible, manual distress surveys were performed in order to determine the pre-existing condition of the pavement.

Site locations and brief descriptions are provided in Table 1. Detailed site descriptions, including weather, haul time and equipment used, are provided in Appendix A.

Table 1 – Site Locations and Descriptions.

Site #	**Route**	**Dir.**	**Town**	**Pavement Type**	**Monitored Site?**	**MTV/ Remixing**
1	85	SB	Colchester	40-mm Class 1	Yes	None
2	85	NB	Colchester	40-mm Class 1	Yes	None
3	8	NB	Thomaston	40-mm Class 1	Yes	None
4	695	EB	Killingly	50-mm Class 1 over cold-in-place recycled base course	Yes	None
5	31	NB	Coventry	50-mm Class 1	Yes	None
6	Pigeon Hill Rd.		Windsor	40-mm Class 1	Yes	None
7	I-91	NB	Rocky Hill	50-mm Class 1	No	Blaw Knox MC-30 w/ Remixing Insert
8	I-91	NB	Meriden	50-mm Class 1	No	Roadtec Shuttle Buggy
9	341	NB	Warren	40-mm Class 1	No	None
10	Little Meadow Road		Guilford	40-mm Class 2	No	None
11	Linkfield Road		Watertown	40-mm Class 2	No	None

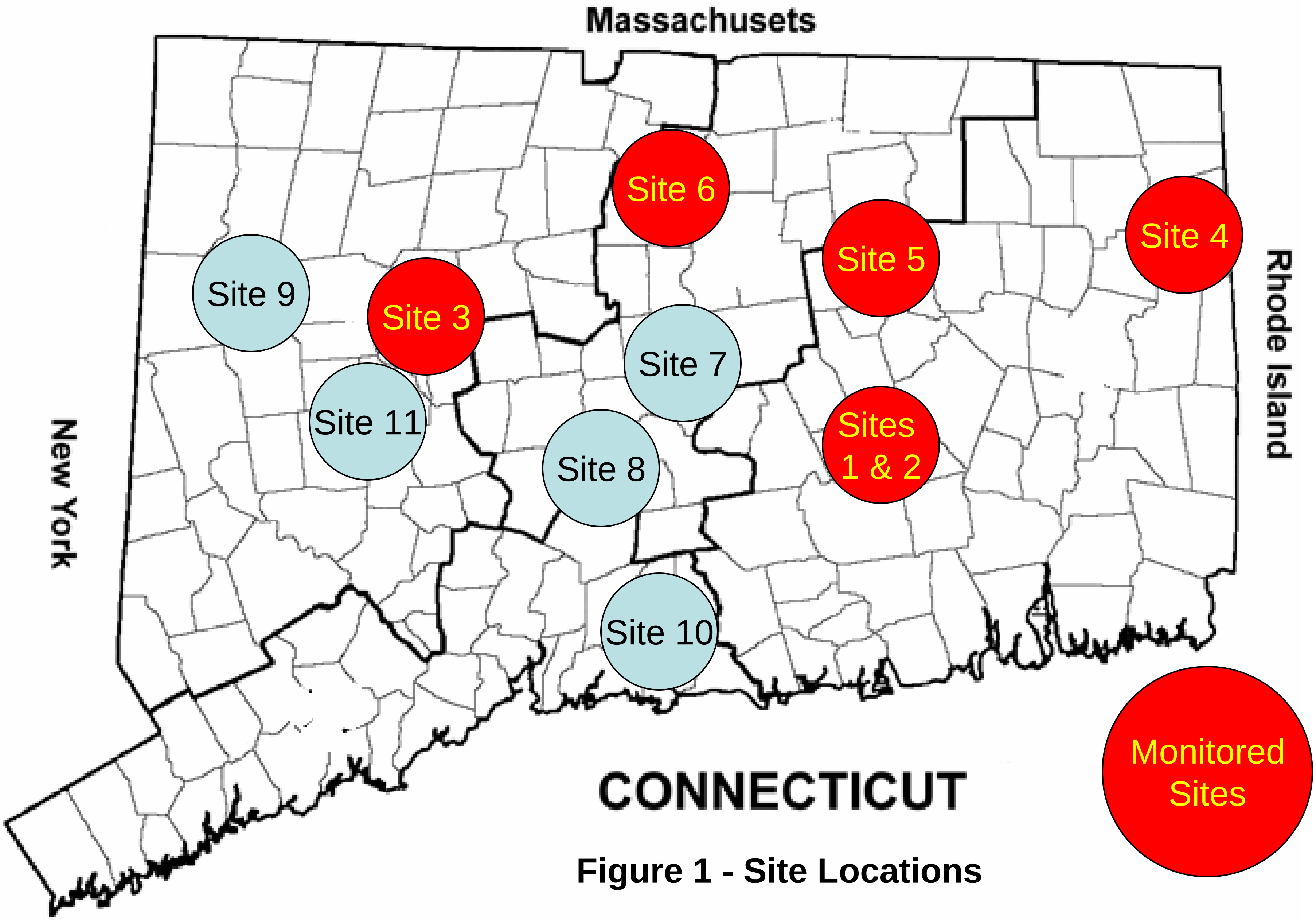


Figure 1 - Site Locations

THERMAL IMAGING

A ThermaCAM PM380 infrared camera (see Photos #1 and #2) 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.

Photo 1. Inframetrics ThermaCAM PM380.

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 x-y coordinate system within each of the monitored test sections.

The x-y coordinate system was setup by identifying a benchmark item along the roadway, such as a utility pole, which was referenced as the point where the x-axis crossed (y=0) the roadway, transverse to the centerline. The y-axis was typically setup to cross the x-axis (x=0) at the edge of pavement or at the marked shoulder line, parallel to the centerline. Site diagrams are provided in Appendix B, and x-y coordinate data are tabulated in Appendix C.

Photo 2. Infrared Camera in Use.

Sites 1 & 2 – Route 85, Colchester

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 unpredictable: sometimes strips of cooler material would appear in the center, while the sides remained hot; at 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. It should be noted, however, that water was sprayed onto the roller's drums during compaction in order to prevent HMA from sticking to them, and this water eventually worked its way onto the pavement surface. Therefore, thermal imaging results may have been disguised somewhat by the cooling effect of the water, so care was taken to consider its effect.

Site 3 – Route 8, Thomaston

The freshly placed pavement immediately behind the paver's screed was relatively uniform in temperature (see Photo #3), making the location of cold spots/areas difficult to find, but not impossible (see Photo #4). However, more local areas of cooler temperature did develop in the pavement during rolling operations as the mat cooled (see Photo #5), and they were identified and marked as such. Again, these results are suspect because of the roller's spray water, but, in some cases, these areas of cooler temperature were the only ones located.

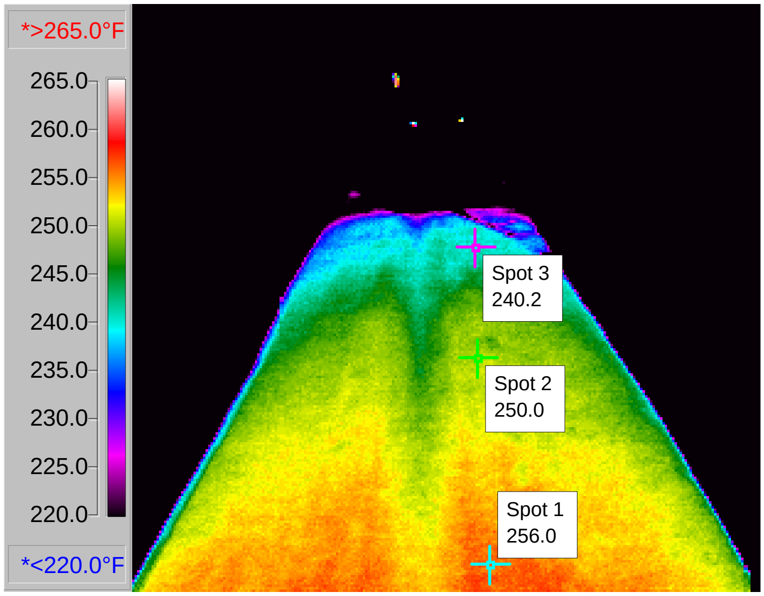


Photo 3. Site 3 - Route 8 in Thomaston.

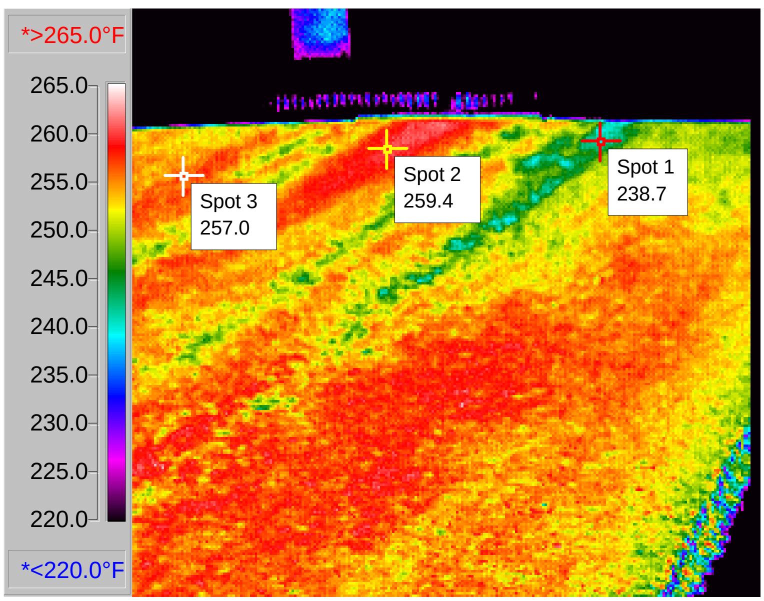


Photo 4. Site 3 - Route 8 in Thomaston, Behind Paver's Screed.

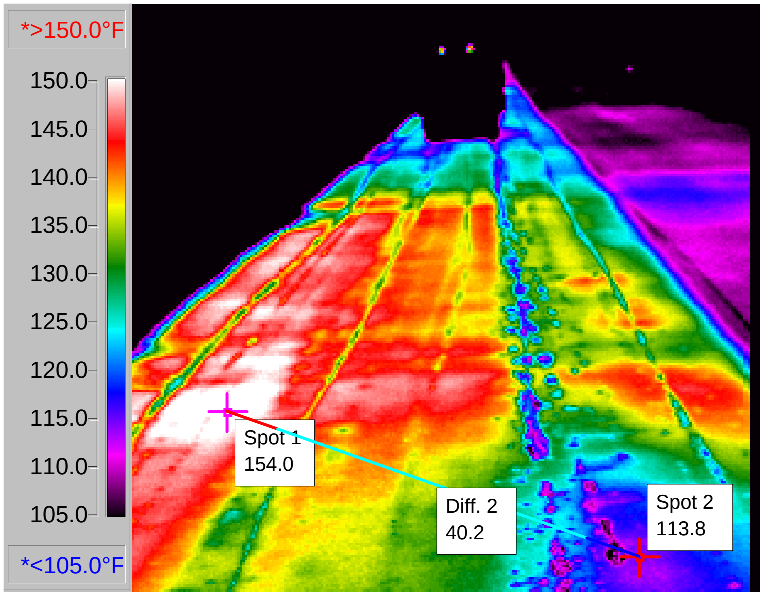


Photo 5 Site 3 - Route 8 in Thomaston.
Following Spray Water Application from Roller.

<u>Site 4 – Route 695, Killingly</u>

Temperature differentials were easily located immediately behind the paver's screed. They appeared as well-defined cold spots (see Photos #6 and #7), surrounded by warmer (normal) pavement. They occurred in a load-to-load type of pattern (see Photo #8) about every 34 meters (112 ft), and in the pavement immediately following truck changes, during which time the paver's wings were typically folded.

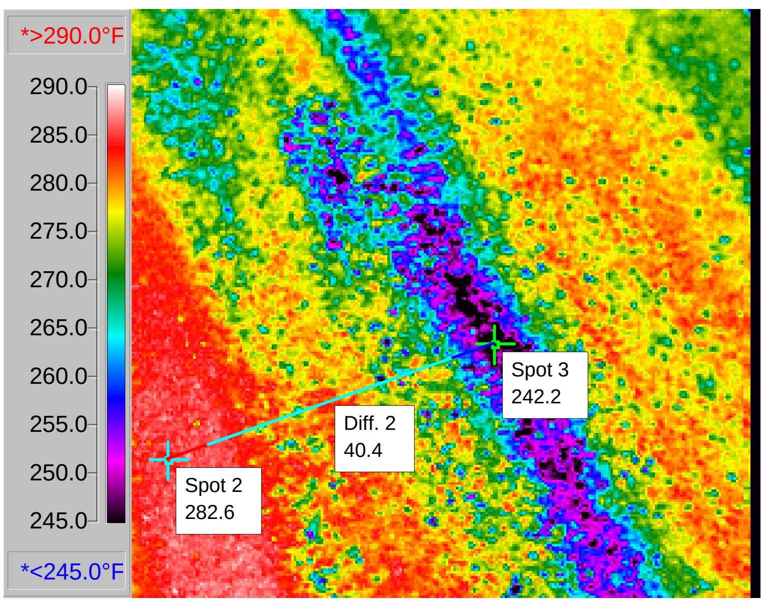


Photo 6. Site 4 - Route 695, Killingly

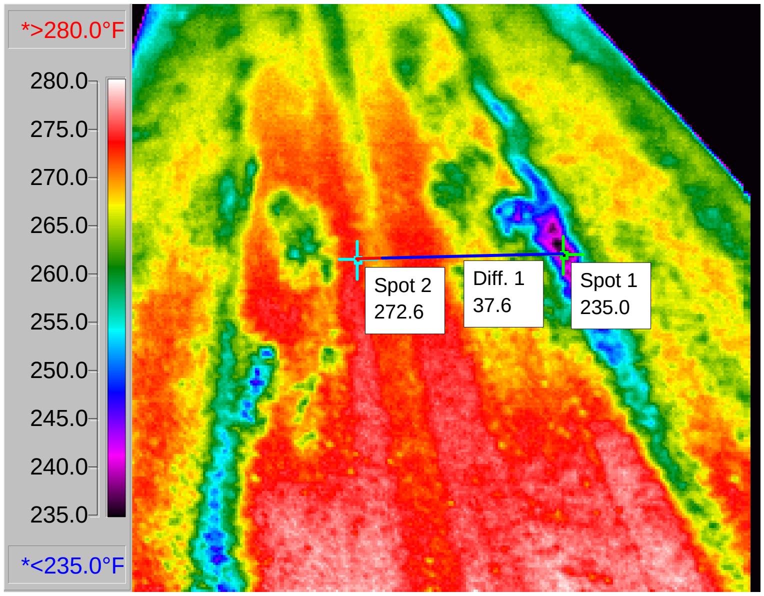


Photo 7. Site 4 - Route 695, Killingly.

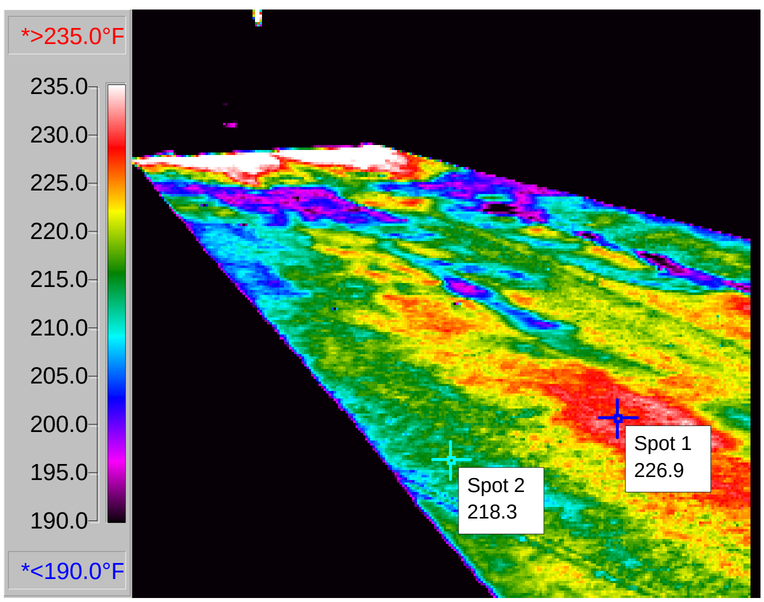


Photo 8. Site 4 - Route 695, Killingly.

Site 5 & 6 – Route 31, Coventry & Pigeon Hill Road, Windsor

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 #9). 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 #10), as opposed to longitudinal strips of hot and cool material.

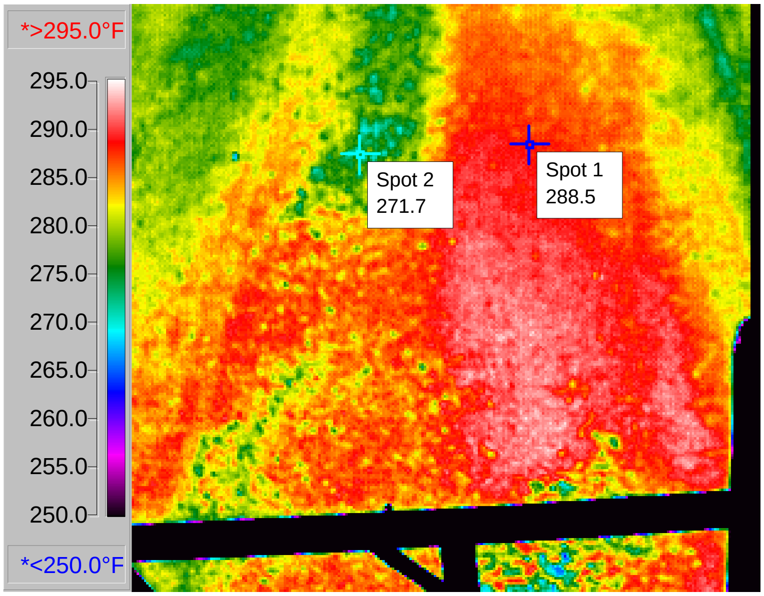


Photo 9. Site 5 - Route 31, Coventry.

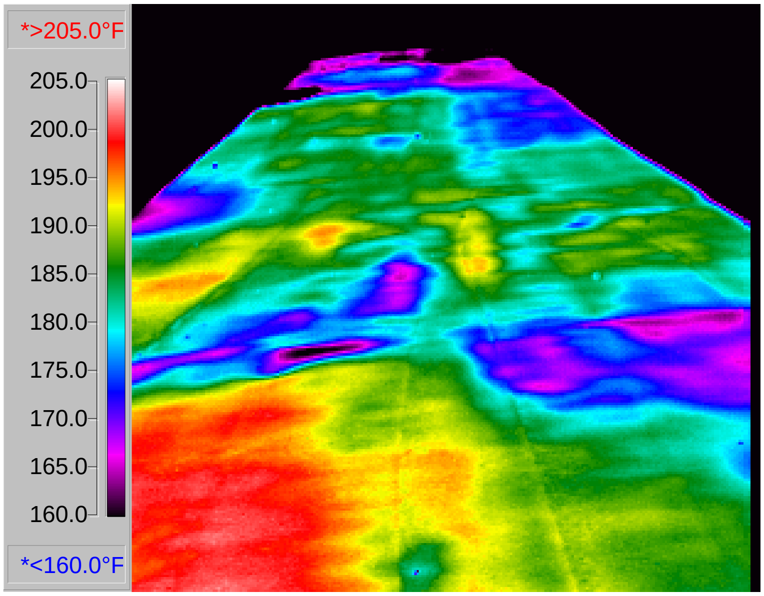


Photo 10. Site 5 - Route 31, Coventry.

Site 7 – Route I-91, Rocky Hill

For the Route I-91 Rocky Hill project, a Blaw-Knox MC-30 material transfer vehicle (see Photo #11) 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 and the ambient temperature was approximately 7 °C (45°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 thermal segregation in the 50-mm (2-inch) DOT Class 1 surface layer, but did not completely eliminate the problem (see Photo #12). 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.

Photo 11. Blaw-Knox MC-30 Material Transfer Vehicle.

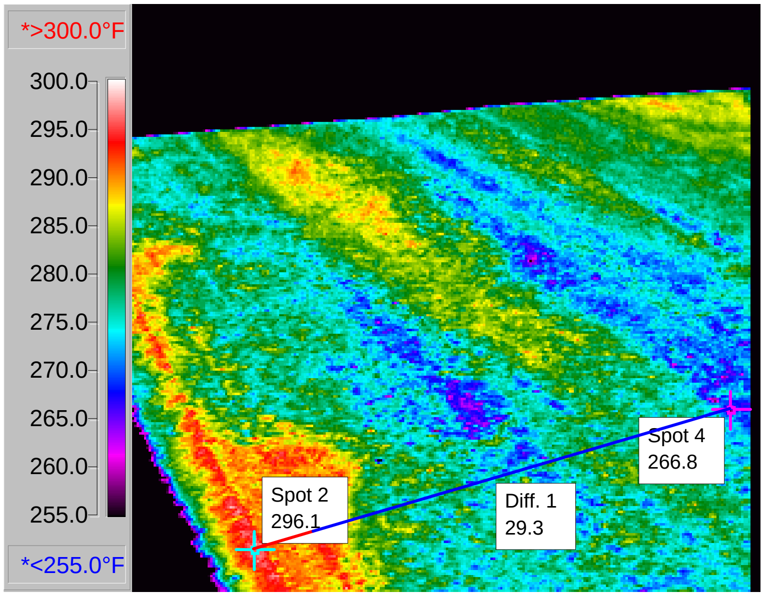


Photo 12. Route 91 – Rocky Hill

<u>Site 8 – Route I-91, Meriden</u>

On October 20, 1998, infrared video was recorded at the Route I-91 Meriden project. A Roadtec Shuttle Buggy material transfer vehicle (see Photo #13) 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. A 50-mm (2-inch) Class 1 surface layer was placed on top of a 19-mm (3/4-inch) Class 2 leveling course. 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 #14). 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.

Photo 13. Roadtec Shuttle Buggy Material Transfer Vehicle.

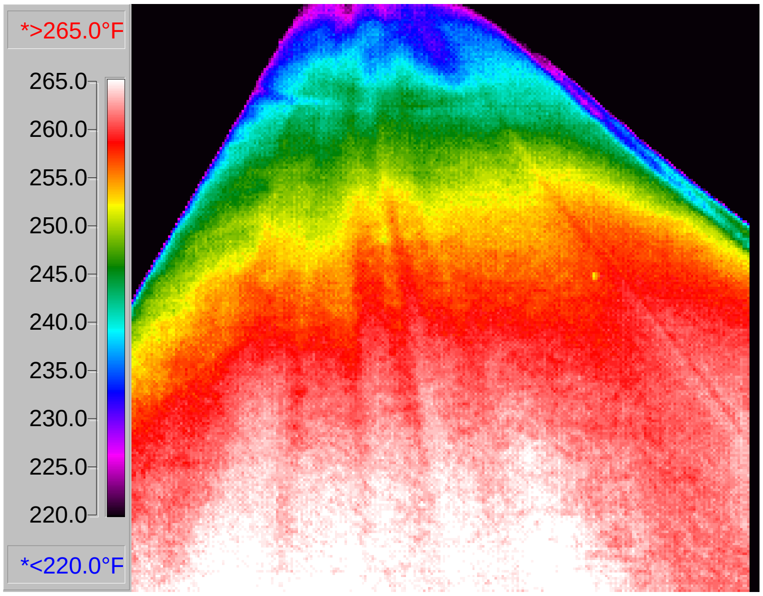


Photo 14. Route 91 – Meriden.

<u>Site 9 – Route 341, Warren</u>

On October 16, 1998, the infrared camera was brought to Route 341 in Warren, Connecticut, where a 38-mm (1.5-inch) DOT Class 1 surface layer was being placed on top of a 19-mm (3/4-inch) DOT Class 2 leveling course. 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 #15). 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.

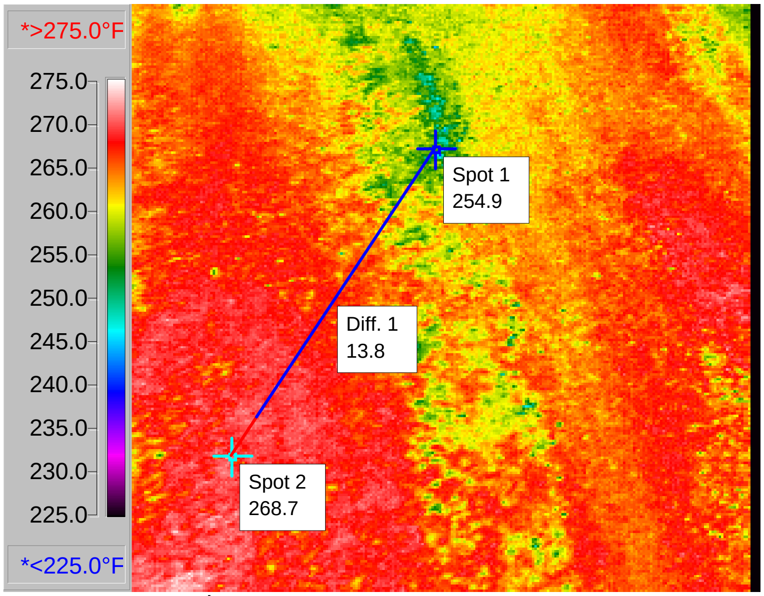


Photo 15. Route 341 – Warren.

<u>Site 10 – Little Meadow Road, Guilford</u>

On October 5, 1998, a 38-mm (1.5-inch) 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 #16).

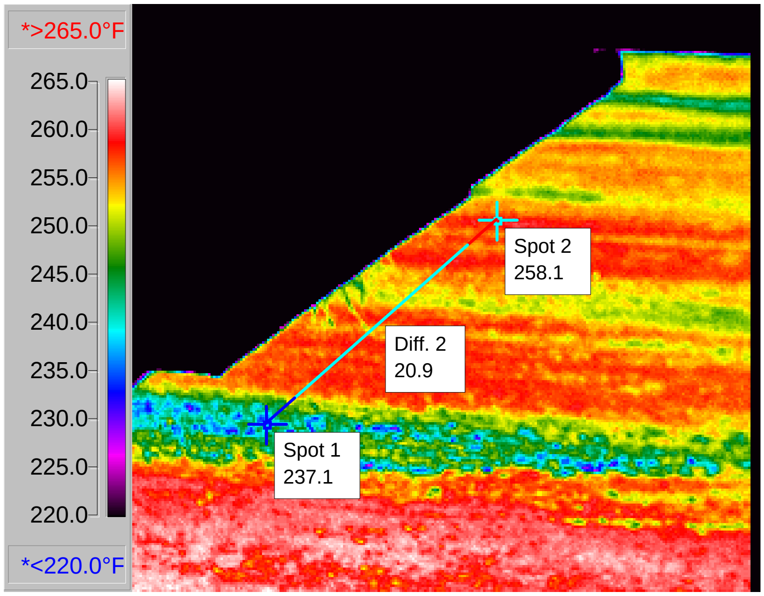


Photo 16. Little Meadow Road – Guilford.

Site 11 – Linkfield Road, Watertown

On October 13, 1998, another 38-mm (1.5-inch) 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. No significant differences in terms of temperature were observed between this Class 2 mix and the Class 1 mixes.

Note the thermal effects associated with raking (see Photo #17), which demonstrates how these images exclude temperatures of material immediately beneath the mat surface.

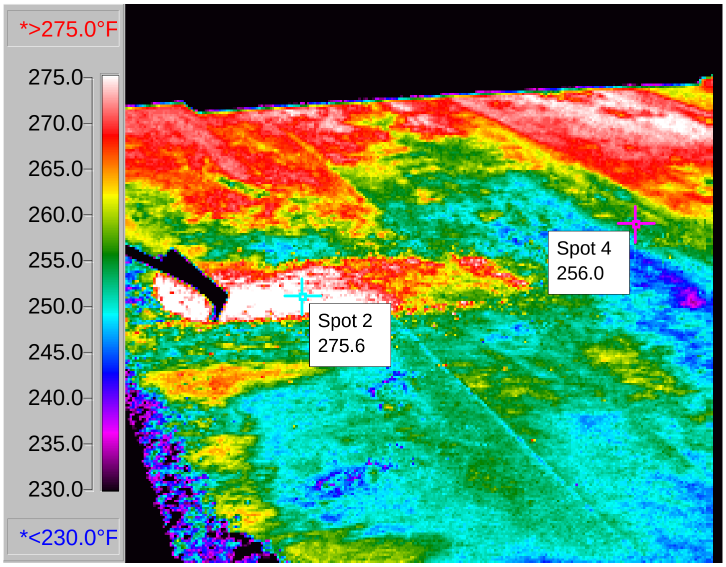


Photo 17. Linkfield Road – Watertown.

DATA ANALYSIS

For each monitored site, 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 each monitored site.

Core samples were tested for percent air voids in accordance with AASHTO T269, asphalt content in accordance with AASHTO T308 and gradation in accordance with AASHTO T30. Results of these and nuclear density tests are tabulated in Appendix D.

Percent Air Voids of Cored Samples

For cored samples, comparisons of air voids between normal and cold temperature spots are shown in Figure 2. Air voids of normal temperature spots are shown in red, and air voids of cold temperature spots are shown in blue. Air void differences between cold and normal temperature spots ($(\text{Air Void})_{diff}$ = $(\text{Air Voids})_{cold}$ – $(\text{Air Voids})_{normal}$) are shown in Figure 3; where, positive differences are shown in blue, and negative differences are shown in red. Note that twelve (12) out of eighteen (18) cold spots had higher air voids than their normal temperature counterparts, one (1) was the same, and a reverse trend was observed for five (5) others. Also note that five (5) cold spots had at least two percent (2%) higher air voids than their normal temperature counterparts, while only one (1) normal temperature spot had air voids at least two percent (2%) higher than its cold temperature counterpart.

Looking at Figures 2 & 3, one might expect significant problems to develop at Sites 1 and 6 because of high air voids. Air voids for samples 3C (C represents cold spot) and 20C at Site 1 were 10.7% and 12.0%, respectively, and air voids for sample 5C at Site 6 were 10.1%. Air voids for Sites 2 and 4 were slightly elevated for the cold spots, as they ranged from 7.8% to 9.5% for Site 2 and from 7.4% to 8.0% for Site 4. Air void differences for Site 3 suggest a trend reversal because air voids were actually higher for normal temperature areas (differences ranged from 0.1% to 1.8%). Finally, based solely on air voids, one would expect Site 5 to perform well because air voids were within a desirable range (from 4.9% to 6.6%).

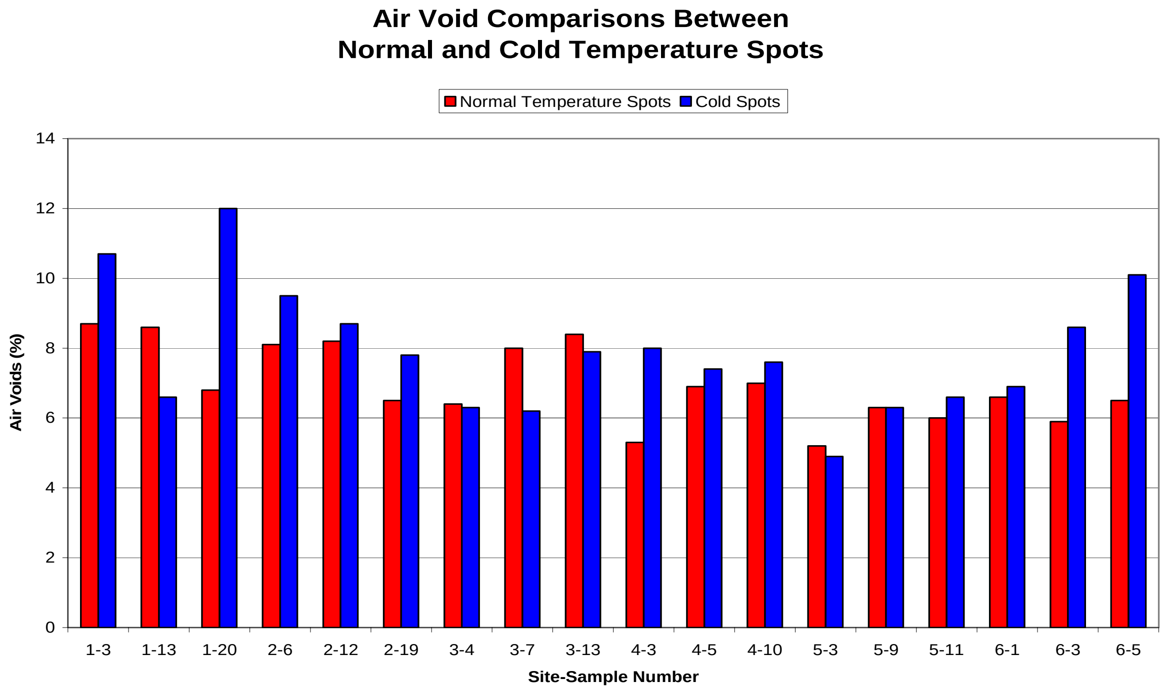


Figure 2 – Air Void Comparisons Between Normal and Cold Temperature Spots for Cored Samples.

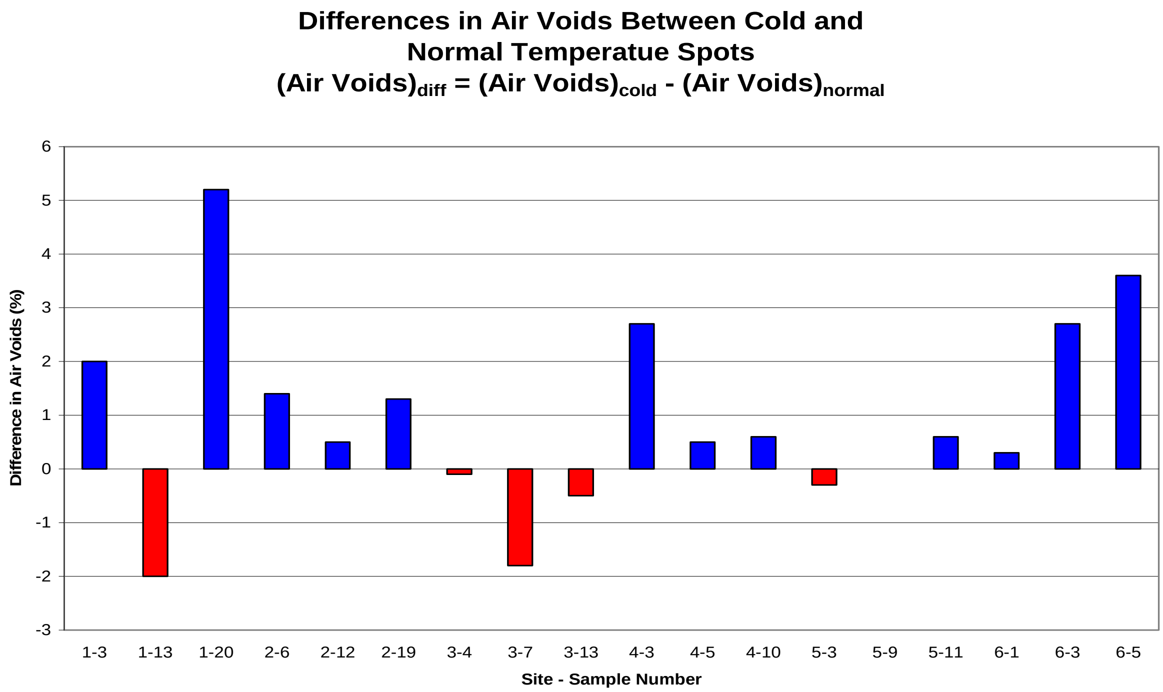


Figure 3 – Differences in Air Voids Between Cold and Normal Temperature Spots for Cored Samples.

Asphalt Contents of Cored Samples

Comparisons of asphalt contents between normal and cold temperature spots are shown in Figure 4. Asphalt contents for normal temperature spots are shown in red, and asphalt contents for cold temperature spots are shown in blue. Asphalt content differences between normal and cold temperature spots ($AC_{diff} = AC_{normal} - AC_{cold}$) are shown in Figure 5; where, positive differences are shown in red, and negative differences are shown in blue. Only nine (9) out of seventeen (17) normal temperature spots had higher asphalt contents than their cold temperature counterparts, four (4) were the same, and a reverse trend was observed for four (4) others. Note: reverse trends observed for asphalt contents did not coincide with those observed for air voids.

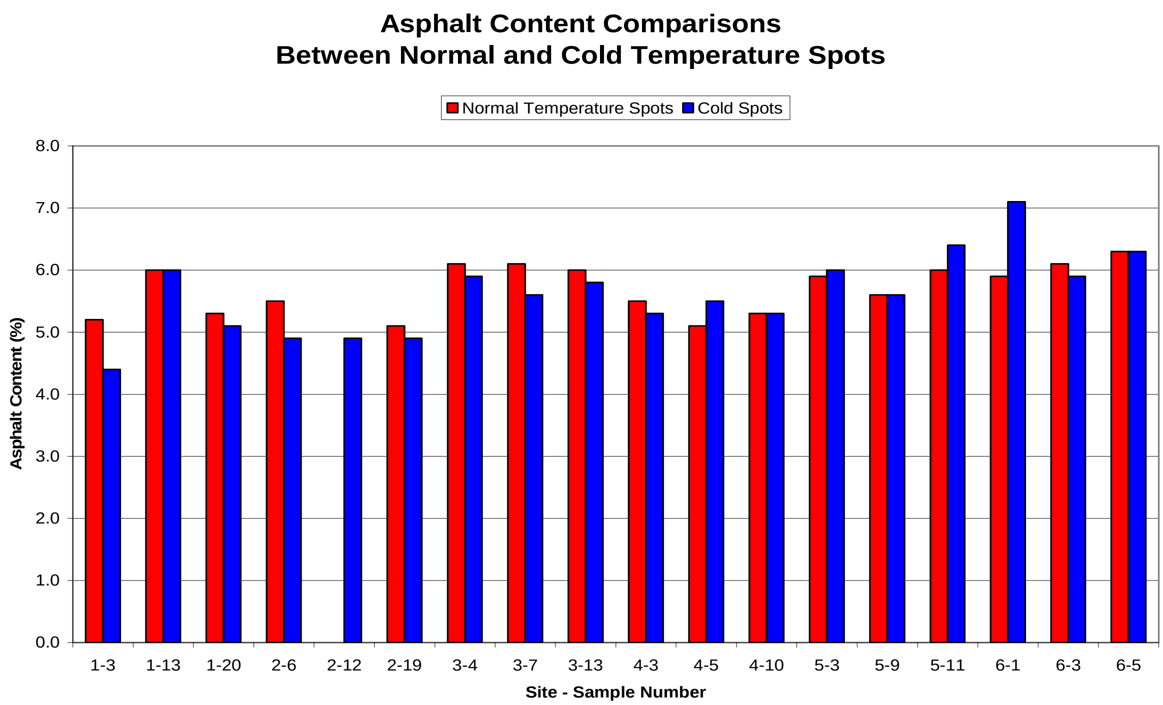


Figure 4 – AC Comparisons Between Normal and Cold Temperature Spots for Cored Samples.

Next, temperature differentials observed with the infrared camera were plotted versus changes in asphalt content between normal and cold temperature cored samples. The randomness of the scatter in Figure 6 shows poor correlation between them, and the coefficient of simple correlation was low ($r = 0.30$).

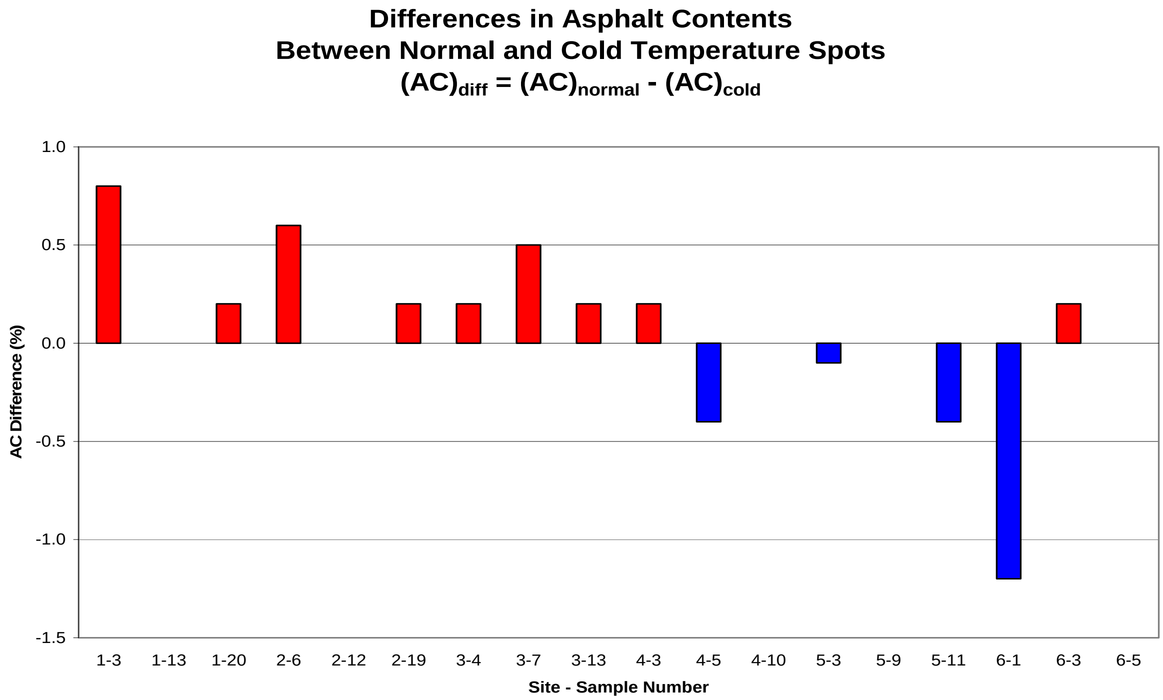


Figure 5 – AC Differences Between Normal and Cold Temperature Spots for Cored Samples.

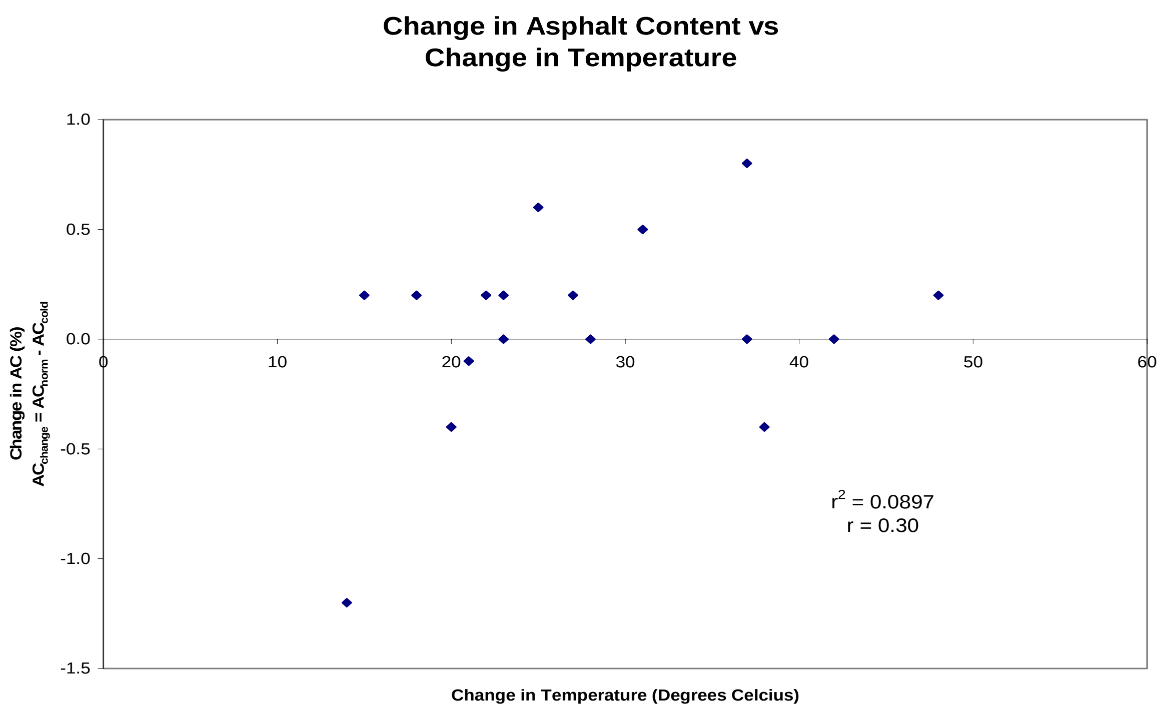


Figure 6 – Relationship Between Temperature Differentials and Change in Asphalt Content.

Grain-Size Distributions of Cored Samples

Sieve analyses were performed for each core that was extracted, and grain-size distribution curves for each site are plotted logarithmically in Figures 7-12. Normal (N) and Cold (C) samples plotted are paired by color. For each site, the first pair of companion core samples are plotted in blue, the second pair in green and the third in red. Overall, grain-size distributions of companion cored samples were similar to one another. Particular attention was given to the 4.75 mm (No. 4) and 2.36 mm (No. 8) sieves when comparing sample counterparts, since Brown, et al. [3,4] concluded that differences greater than 8% passing these sieves indicate the presence of segregation. These threshold differences were generally not exceeded; however, there were two exceptions.

At Site 5, 75.1 percent aggregate passed the 4.75 mm (No. 4) sieve for Sample 3C, versus 57.6 percent for Sample 3N (see Figure 11). In addition, significantly more aggregate passed the 9.50 mm (3/8”) sieve for Sample 3C. At first glance, it appears the occurrence of fine-particle segregation existed at the Sample 3C location; however, a closer look at the Sample 3C curve reveals that the percents passing the 2.36 mm (No. 8) and finer sieves were similar to the other curves, so it does not appear that it was segregated throughout the entire distribution. Furthermore, this condition was not observed at the other two companion core locations, so it appears segregation was not prevalent.

At Site 6, grain-size distribution curves for Samples 1N and 1C differed from the other curves at either end of the spectrum; coarse and fine (see Figure 12). Sample 1N was coarser than the norm, while Sample 1C was finer. The fact that they differed oppositely provides further evidence of localized segregation, and differences between 1N and 1C passing the 4.75 mm (No. 4) and 2.36 mm (No. 8) sieves were 16.1 percent and 11.1 percent, respectively. Finally, the asphalt content for Sample 1C was higher (7.1%) than the norm, which also suggests the presence of fine segregation at that location. The other companion cored sample distributions were similar to one another, which suggest segregation was not widespread at Site 6.

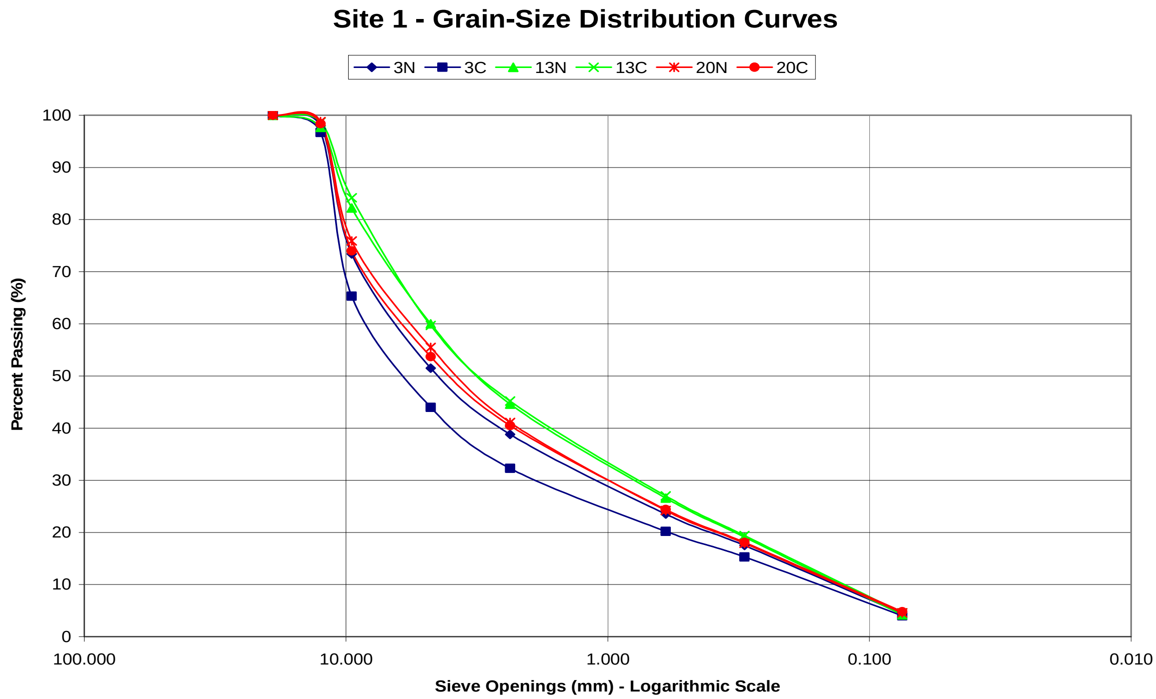


Figure 7 – Grain-Size Distribution Curves for Site 1.

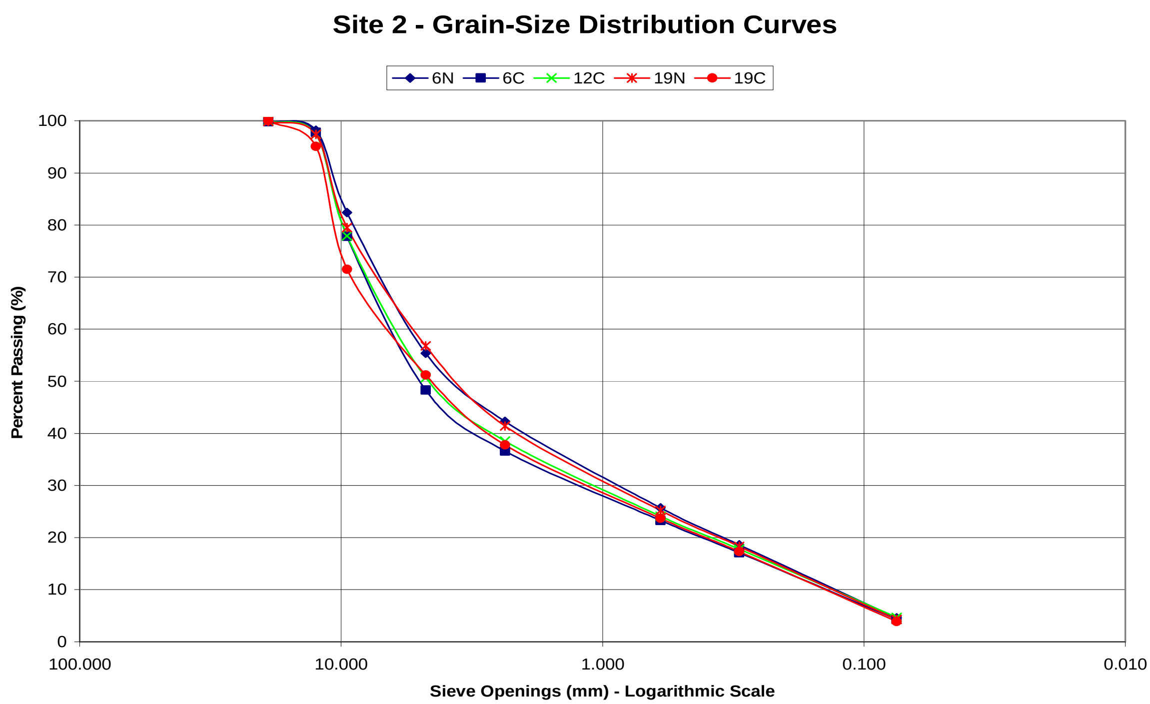


Figure 8 – Grain-Size Distribution Curves for Site 2.

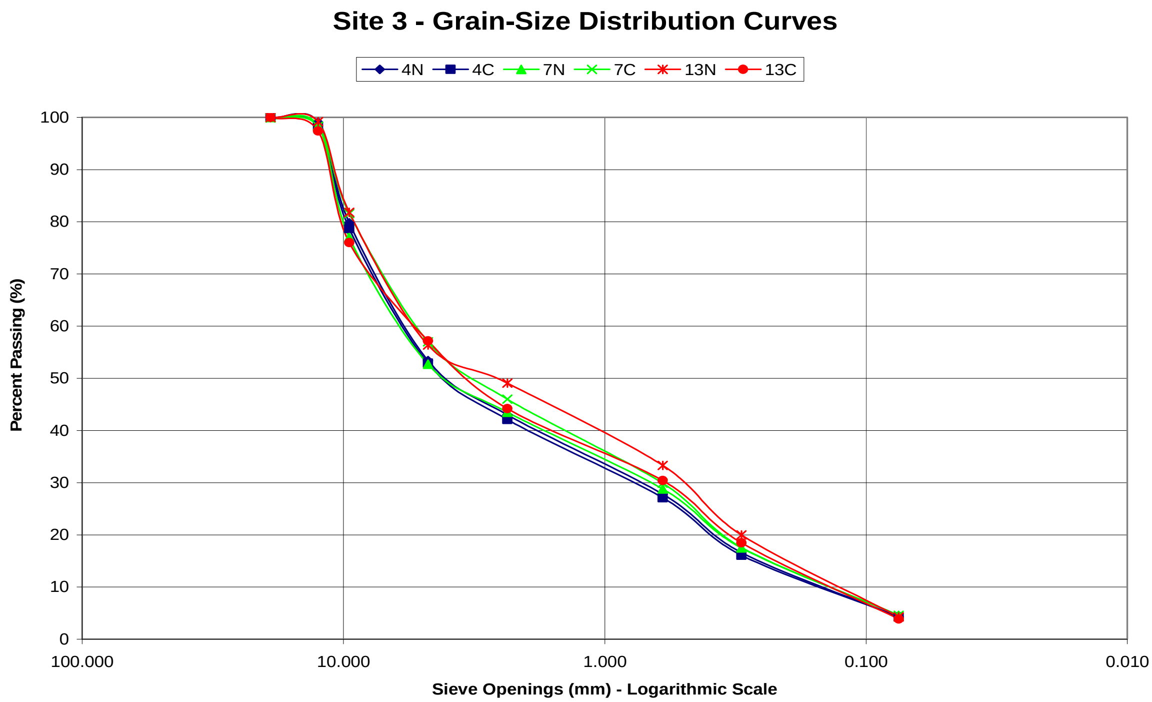


Figure 9 – Grain-Size Distribution Curves for Site 3.

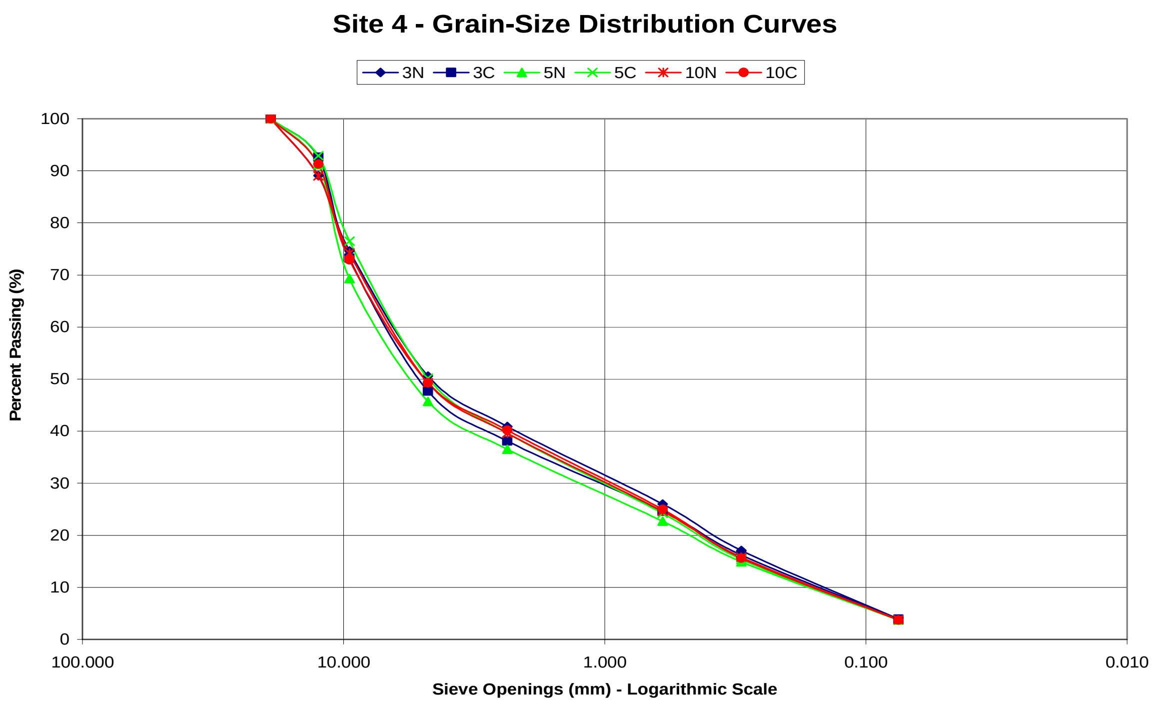


Figure 10 – Grain-Size Distribution Curves for Site 4.

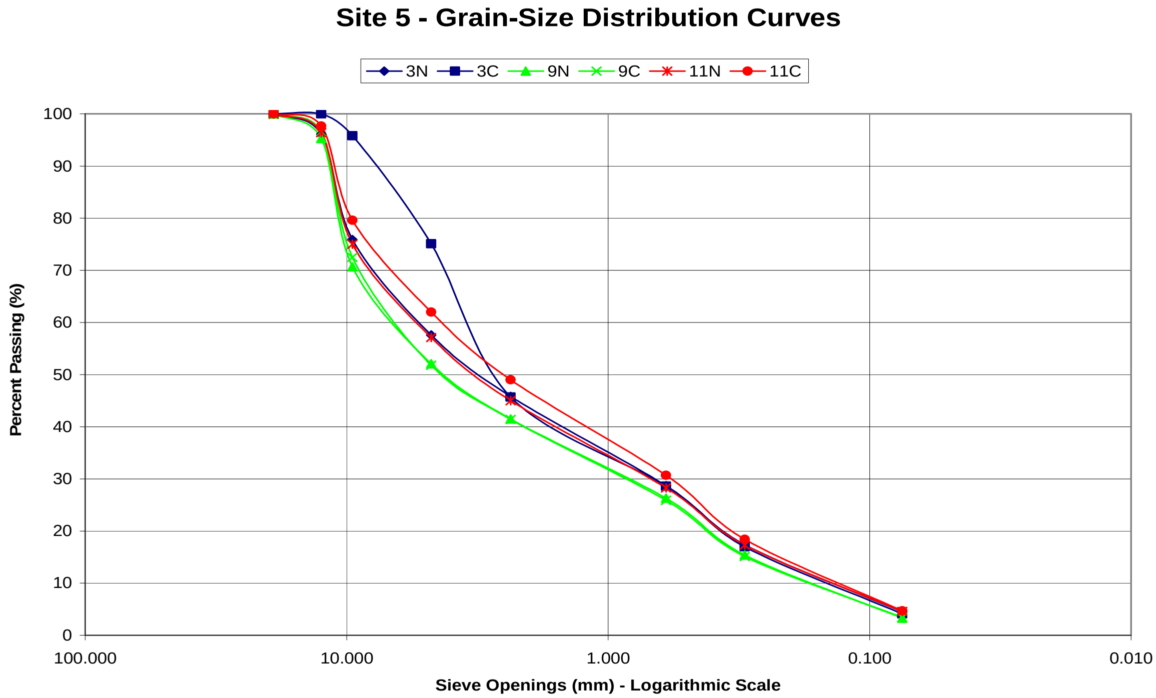


Figure 11 – Grain-Size Distribution Curves for Site 5.

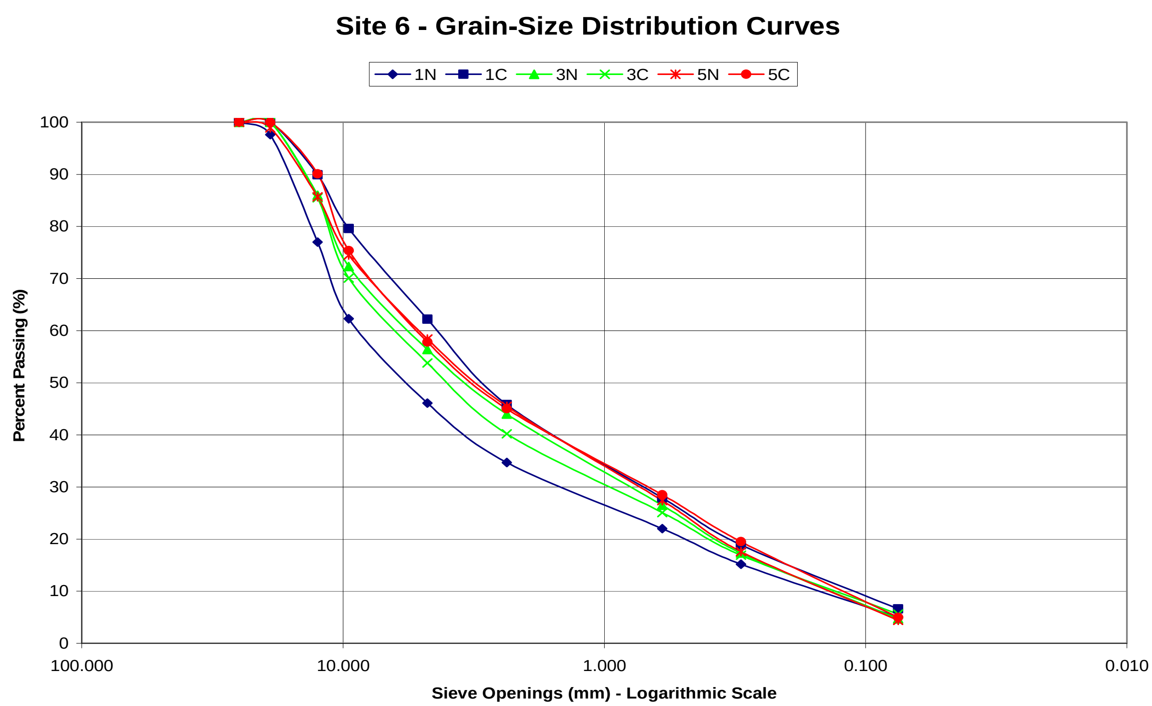


Figure 12 – Grain-Size Distribution Curves for Site 6.

Lastly, in order to see if there was a relationship between temperature differentials and particle segregation, differences between percents passing the 2.36-mm (No. 8) sieve for each companion core were plotted against ΔT (see Figure 13). Based upon observations of this scatter plot, it can be seen that a linear or curvilinear relationship between them did not exist, and the correlation was poor (r = 0.17).

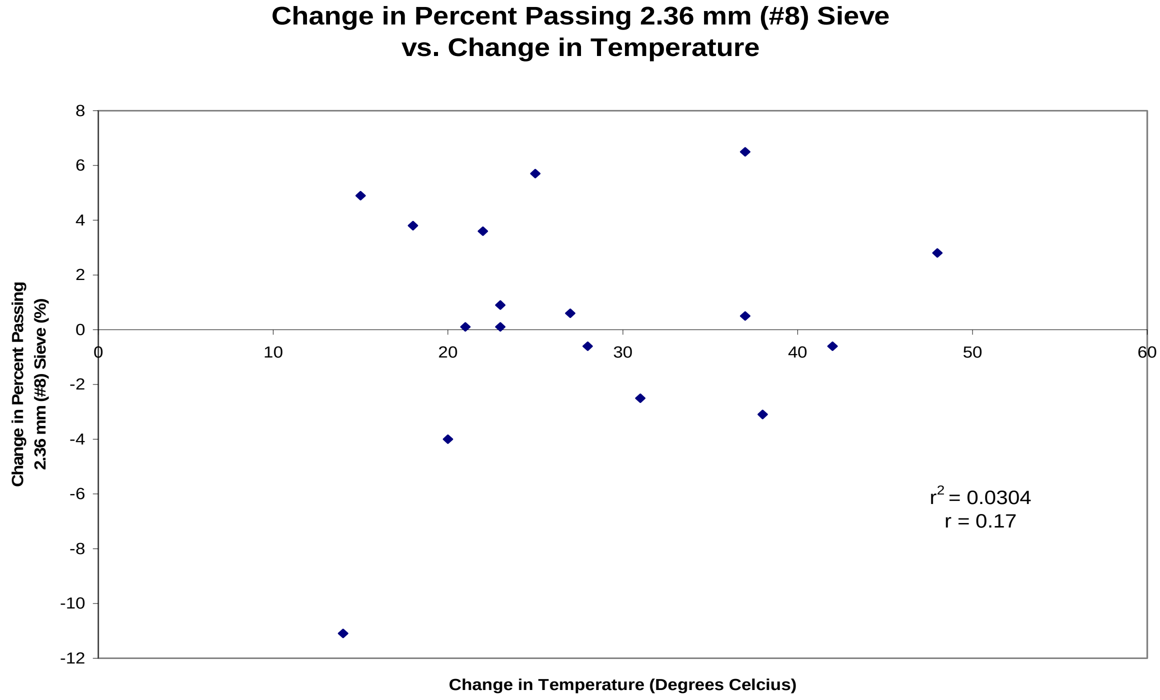


Figure 13 – Relationship Between Temperature Differentials and Particle Segregation

<u>Nuclear Density Test Comparisons</u>

At each site, cold spots/areas and their respective higher temperature counterparts were located with the infrared camera. Nuclear density tests were performed at each location. Density comparisons between normal and cold temperature areas are shown in Figures 14-24 (even numbered figures). Normal temperature area densities are shown in red, while cold temperature area densities are shown in blue. Density differences between normal and cold temperature areas ($\sigma_{diff} = \sigma_{normal} - \sigma_{cold}$) are shown in Figures 15-23 (odd numbered figures); where, positive differences are shown in red, and negative differences are shown in blue. Note: graph types are staggered in order to keep test sites in sequence.

Upon review of these comparisons, there appeared to be a general tendency for the density (σ) to be lower for the cold spots/areas than for their adjacent normal temperature spots; however, this tendency was not observed at every site. Overall, fifty-five (55) out of ninety (90), or sixty-one percent (61%), cold spots/areas had lower densities than their normal temperature counterparts. The tendency for σ to be lower for the cold spots/areas was most prevalent at Site 1, where nineteen (19) out of (20) had lower densities than their counterparts (see Figures 14 & 15). A reverse trend existed at Site 3, where only two (2) out of fourteen (14) cold temperature areas had lower densities than their counterparts (see Figures 18 & 19). Sites 2 (see Figures 16 & 17) and 4 (see Figures 20 & 21) demonstrated a tendency for σ to be lower for the cold areas, while no tendencies were evident for Sites 5 and 6 (see Figures 24 – 25).

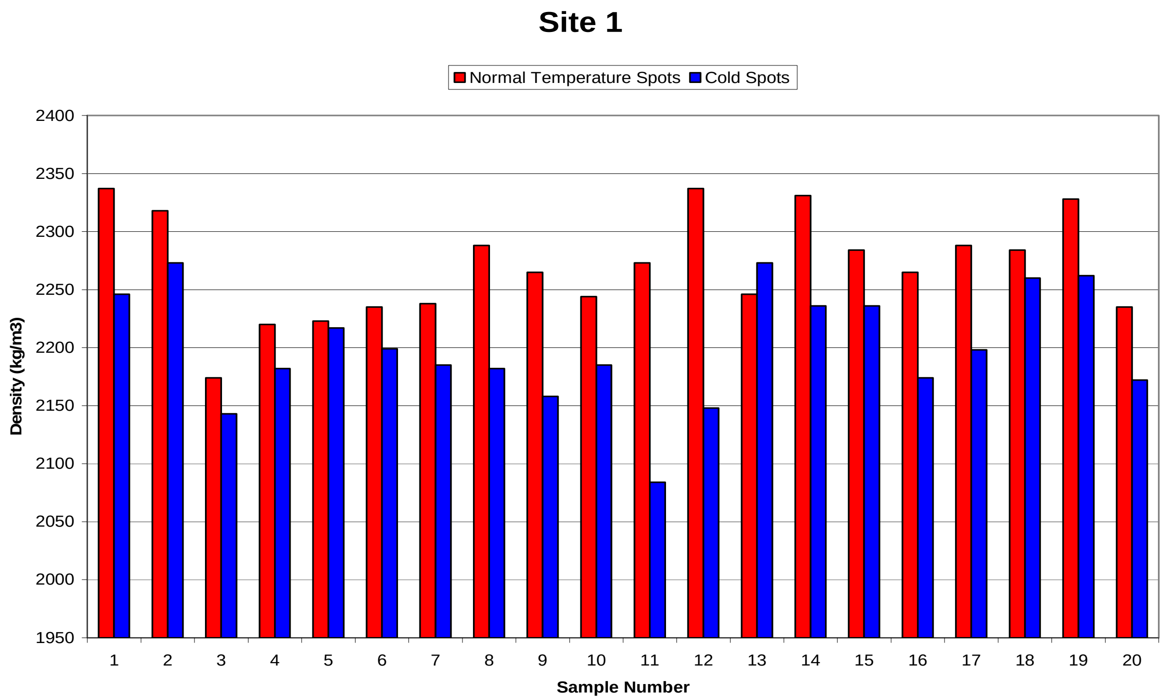


Figure 14 – Nuclear Density Comparisons Between Normal and Cold Temperature Spots at Site 1.

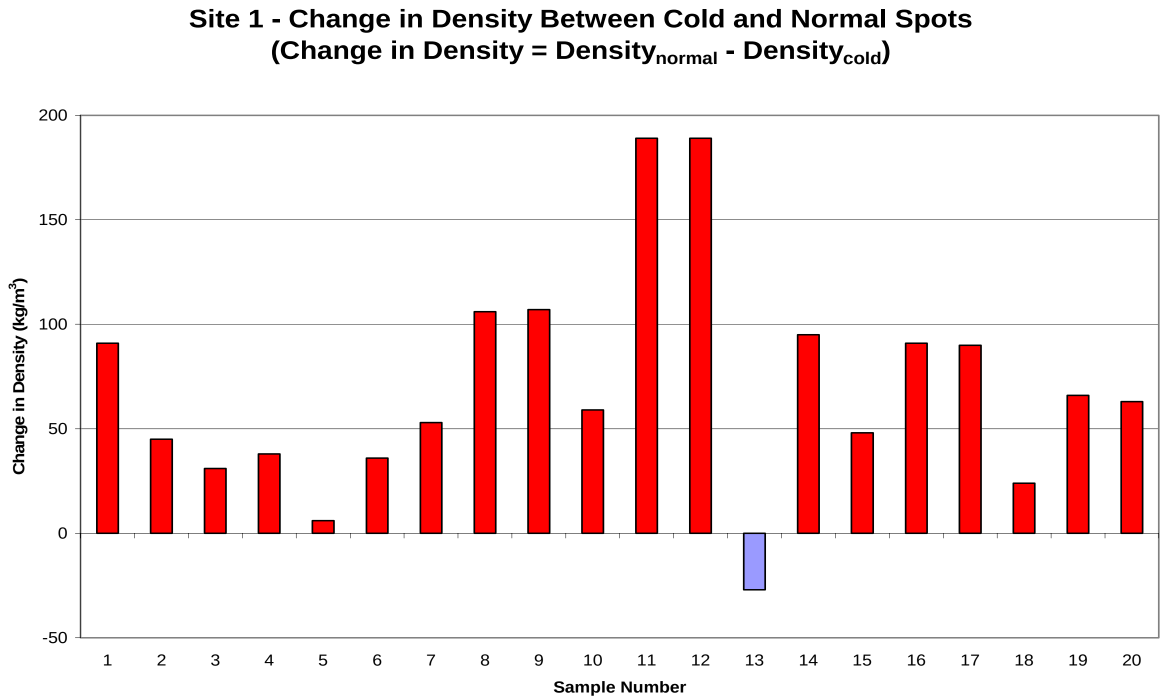


Figure 15 – Change in Density Between Cold and Normal Temperature Spots at Site 1.

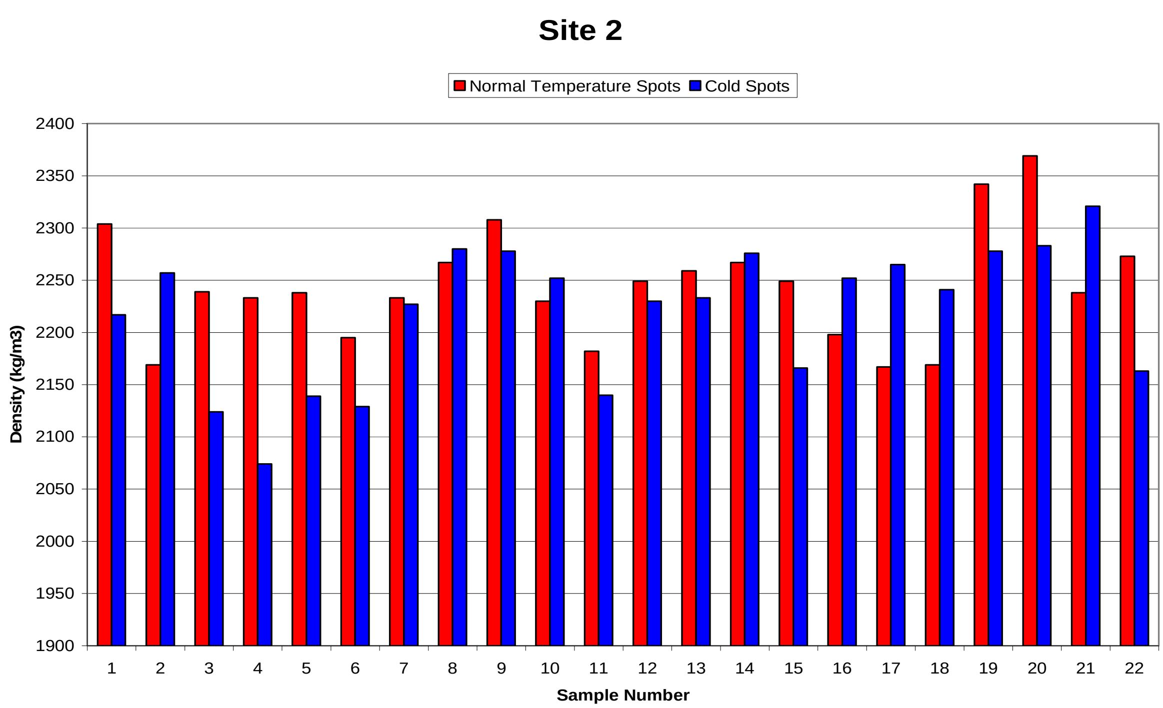


Figure 16 – Nuclear Density Comparisons Between Normal and Cold Temperature Spots at Site 2.

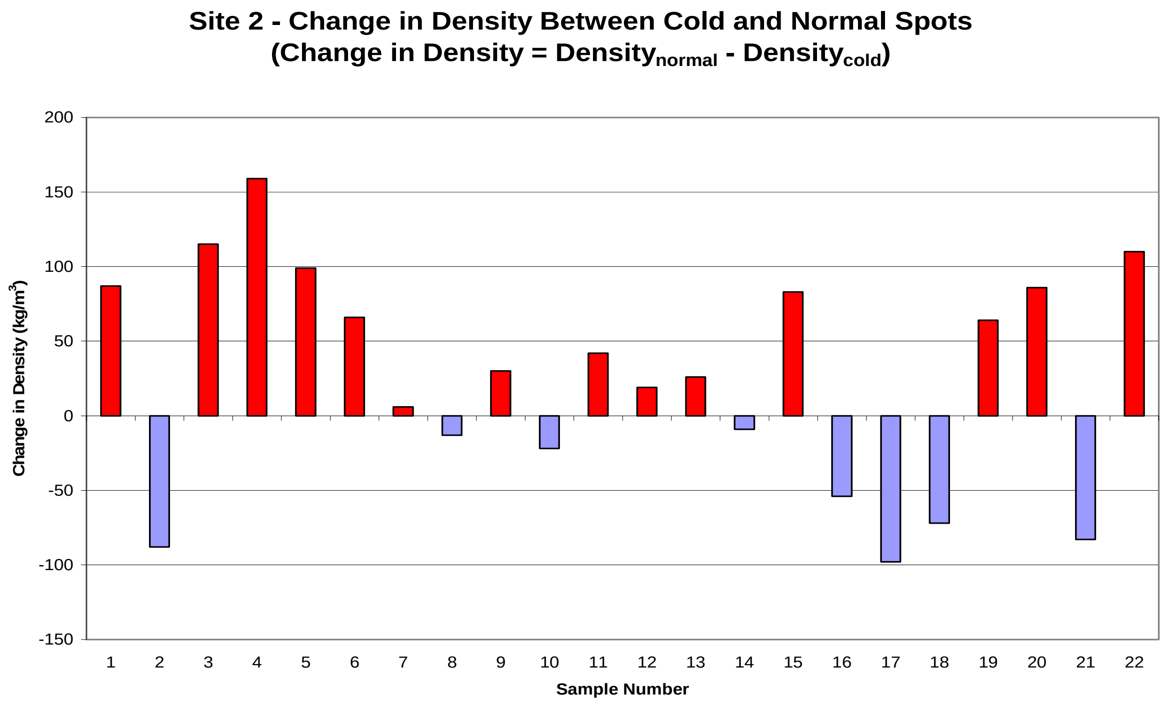


Figure 17 – Change in Density Between Cold and Normal Temperature Spots at Site 2.

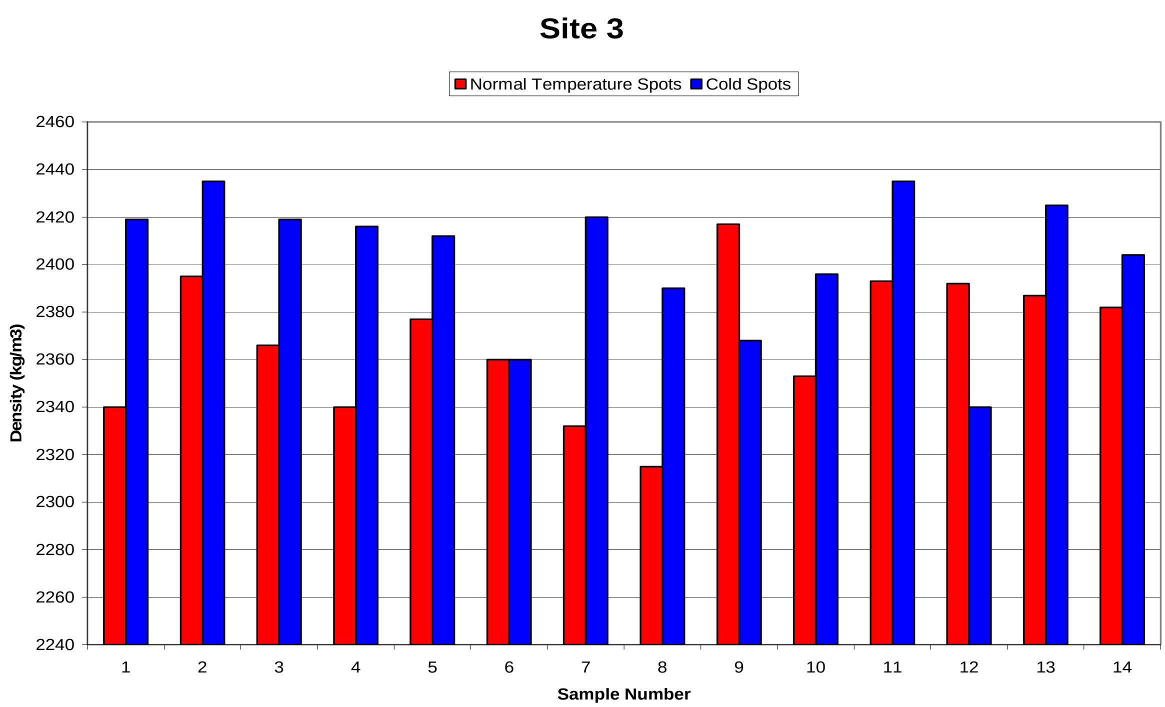


Figure 18 – Nuclear Density Comparisons Between Normal and Cold Temperature Spots at Site 3.

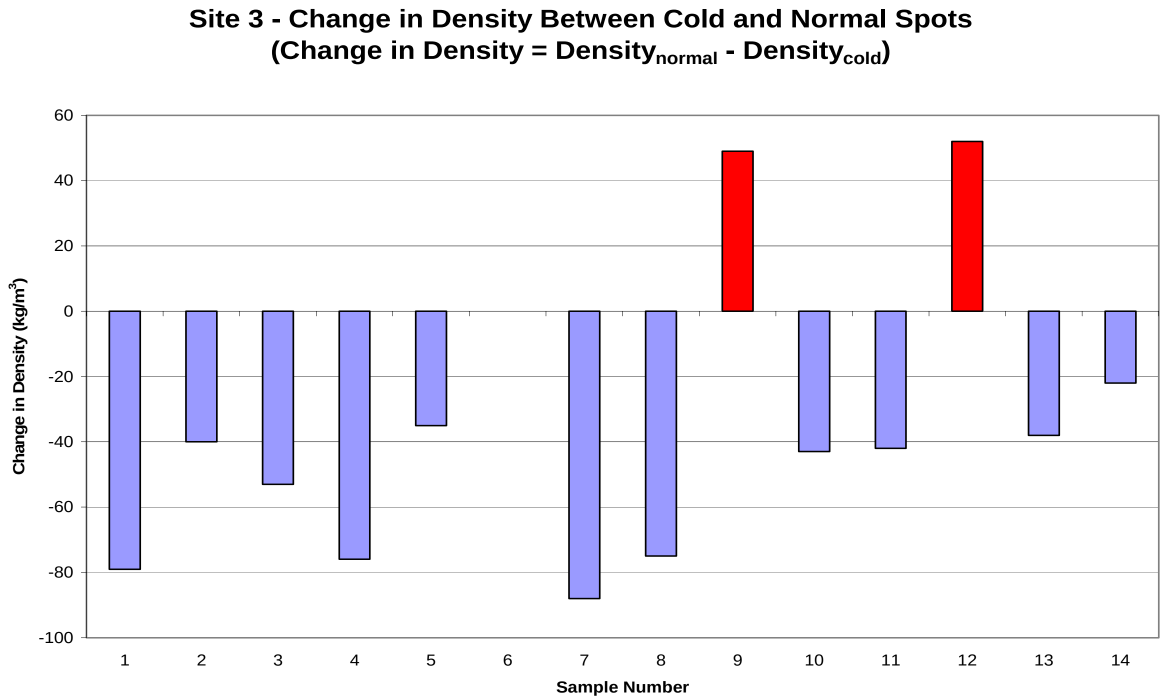


Figure 19 – Change in Density Between Cold and Normal Temperature Spots at Site 3.

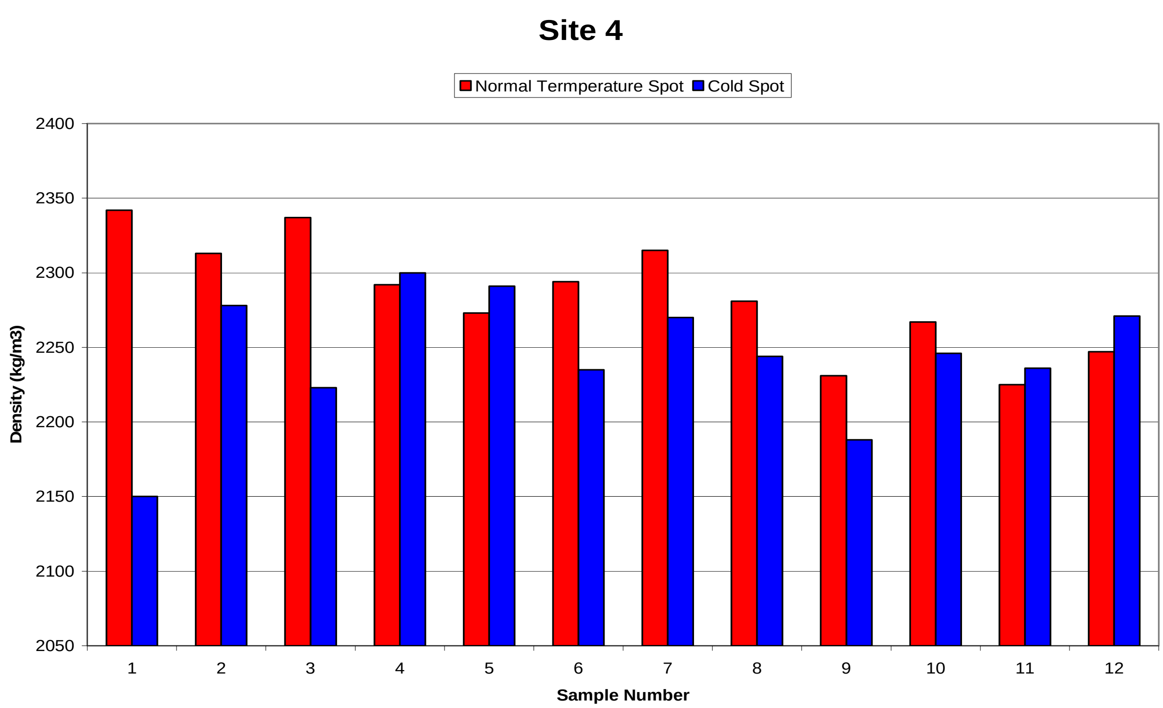


Figure 20 – Nuclear Density Comparisons Between Normal and Cold Temperature Spots at Site 4.

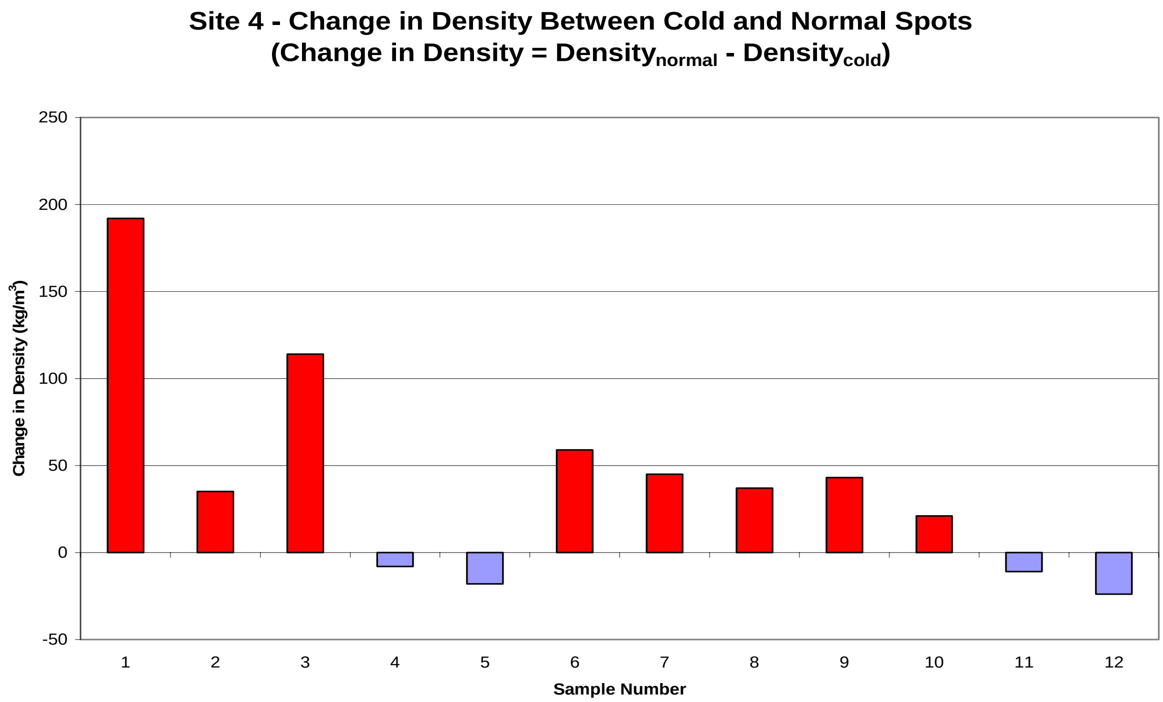


Figure 21 – Change in Density Between Cold and Normal Temperature Spots at Site 4.

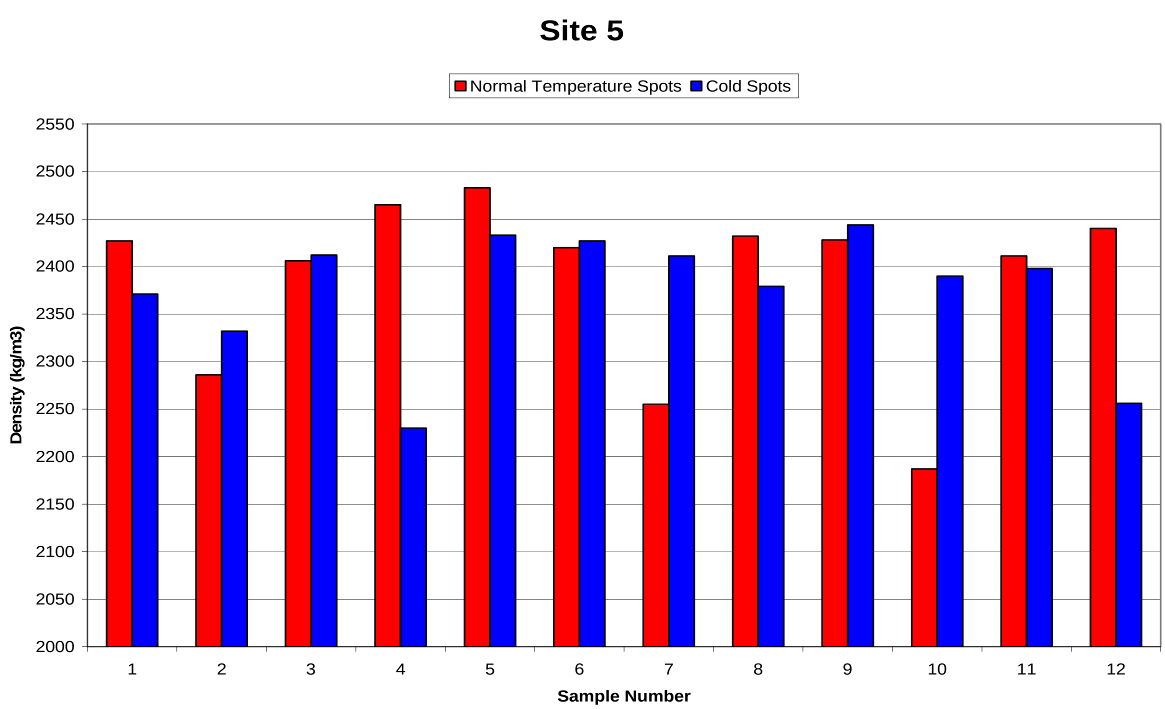


Figure 22 – Nuclear Density Comparisons Between Normal and Cold Temperature Spots at Site 5.

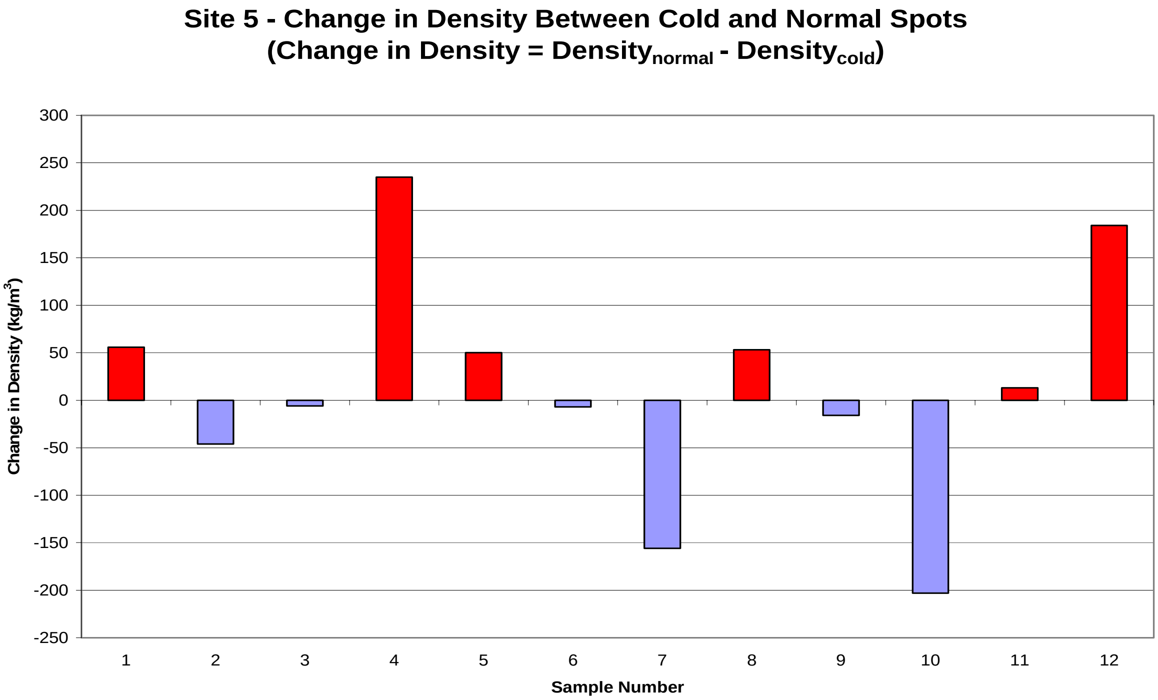


Figure 23 – Change in Density Between Cold and Normal Temperature Spots at Site 5.

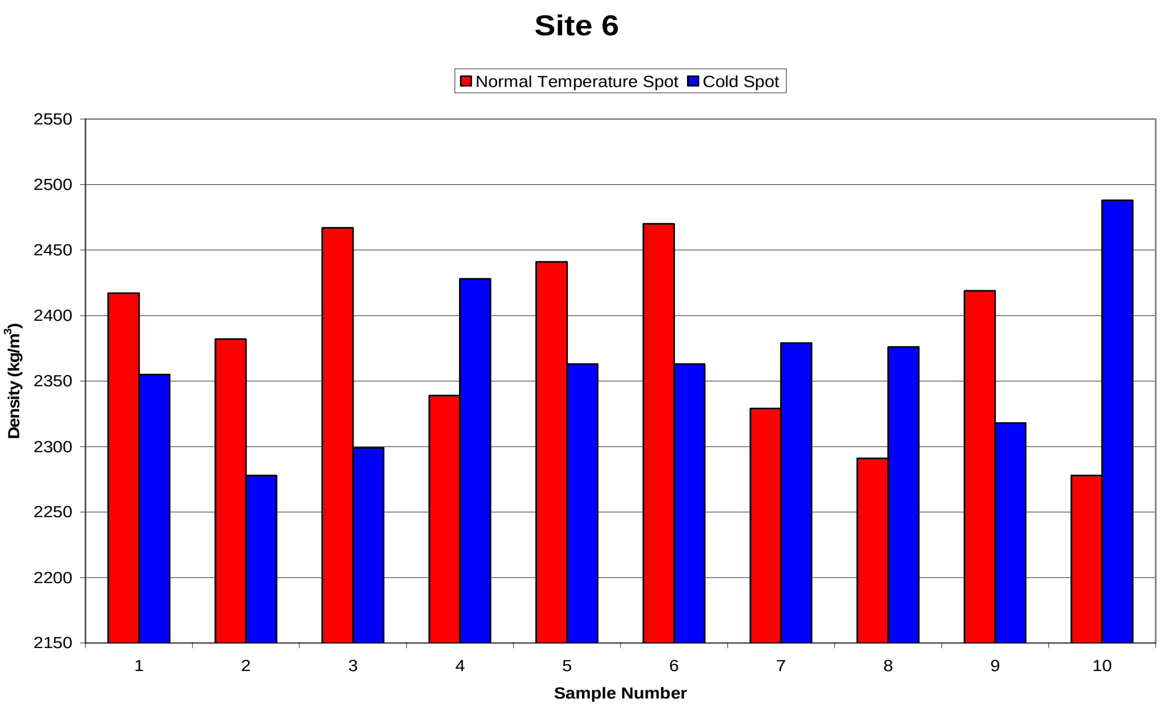


Figure 24 – Nuclear Density Comparisons Between Normal and Cold Temperature Spots at Site 6.

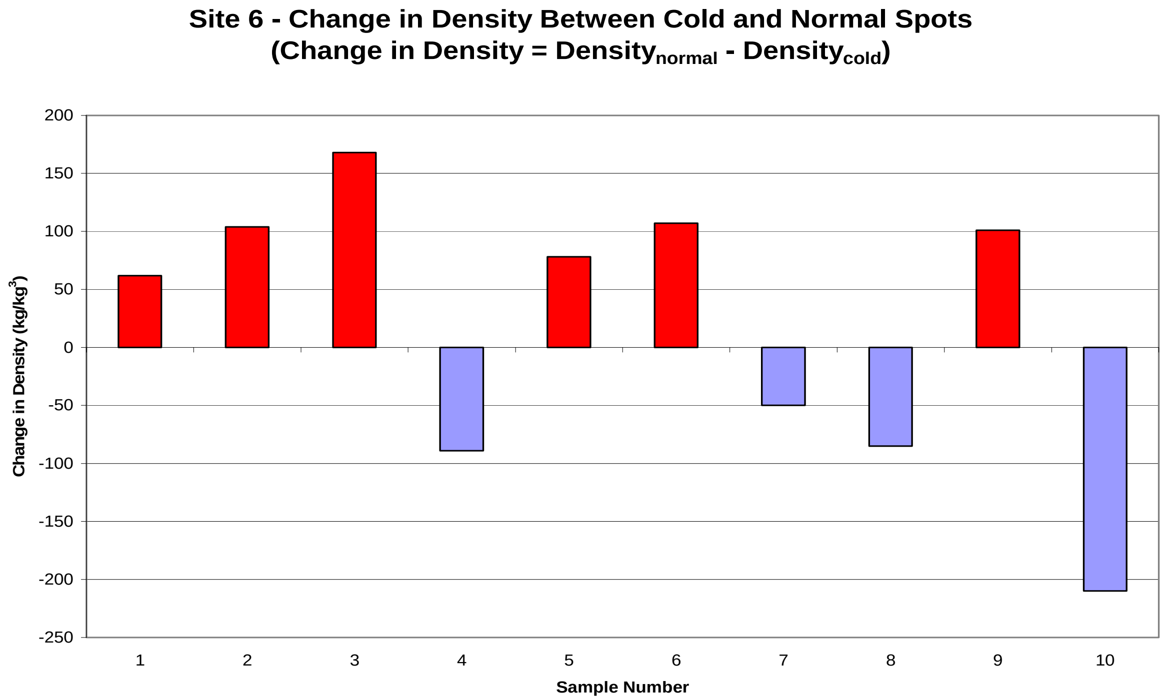


Figure 25 – Change in Density Between Cold and Normal Temperature Spots at Site 6.

<u>Nuclear Density Test Correlations</u>

Scatter plots for each site showing relationships between change in density ($\Delta\sigma$) and change in temperature (ΔT) are provided in Figures 26 – 31. While there appeared to be a general tendency for the cold spot/area densities to be lower than their counterparts, the linear association between ΔT, as measured with the infrared camera, and $\Delta\sigma$, as measured with the nuclear gauge, was poor. At each site, the coefficient of simple correlation (r) was low. The highest absolute value for r was 0.54 (Site 5), and r approached 0 at Site 4. 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. Ultimately, the scatter plots indicate very little definable relationships between ΔT and $\Delta\sigma$.

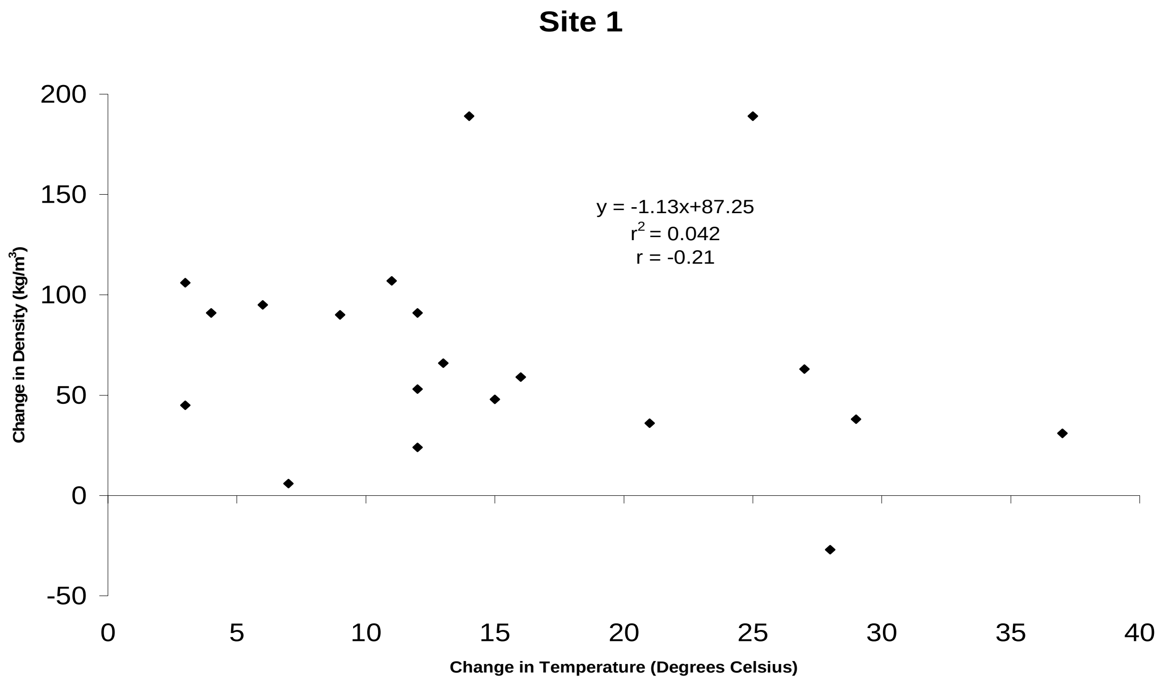


Figure 26 – Relationship Between Δσ and ΔT at Site 1.

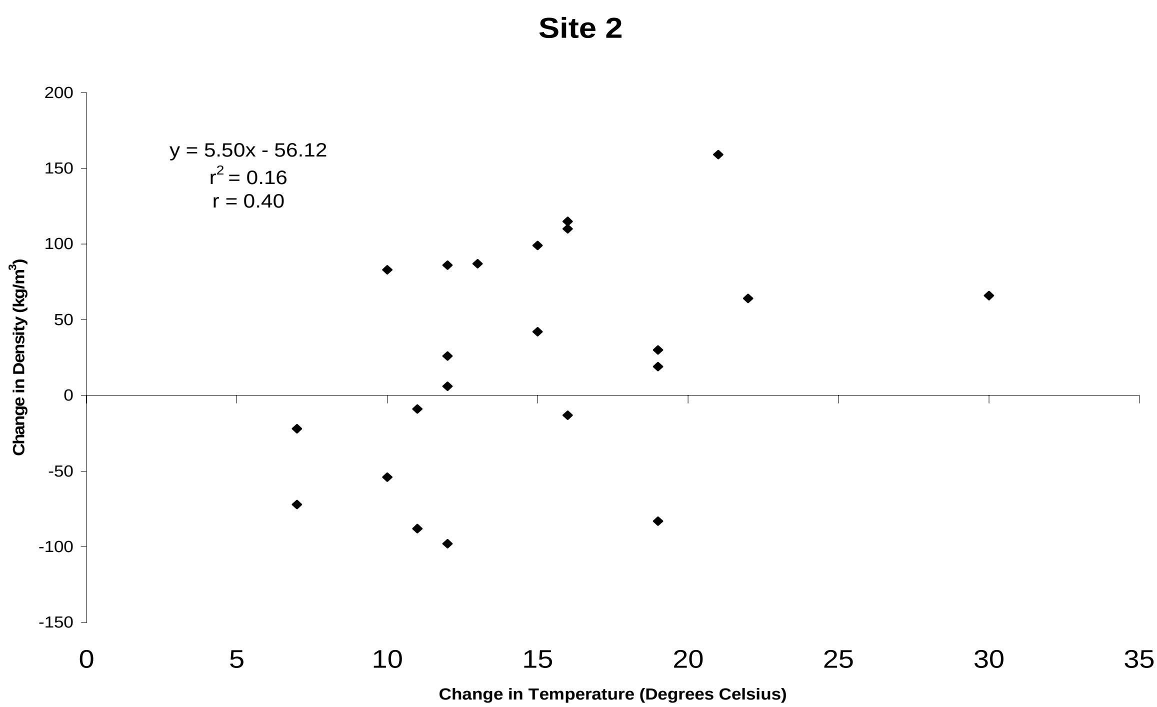


Figure 27 - Relationship Between Δσ and ΔT at Site 2.

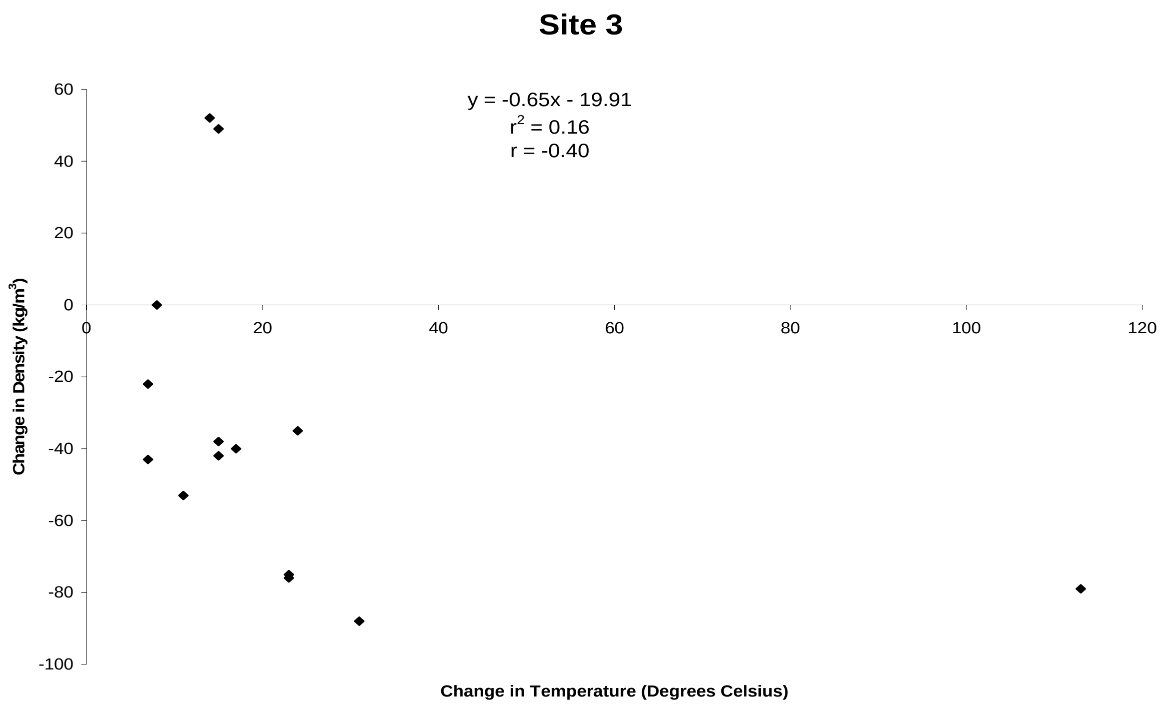


Figure 28 - Relationship Between Δσ and ΔT at Site 3.

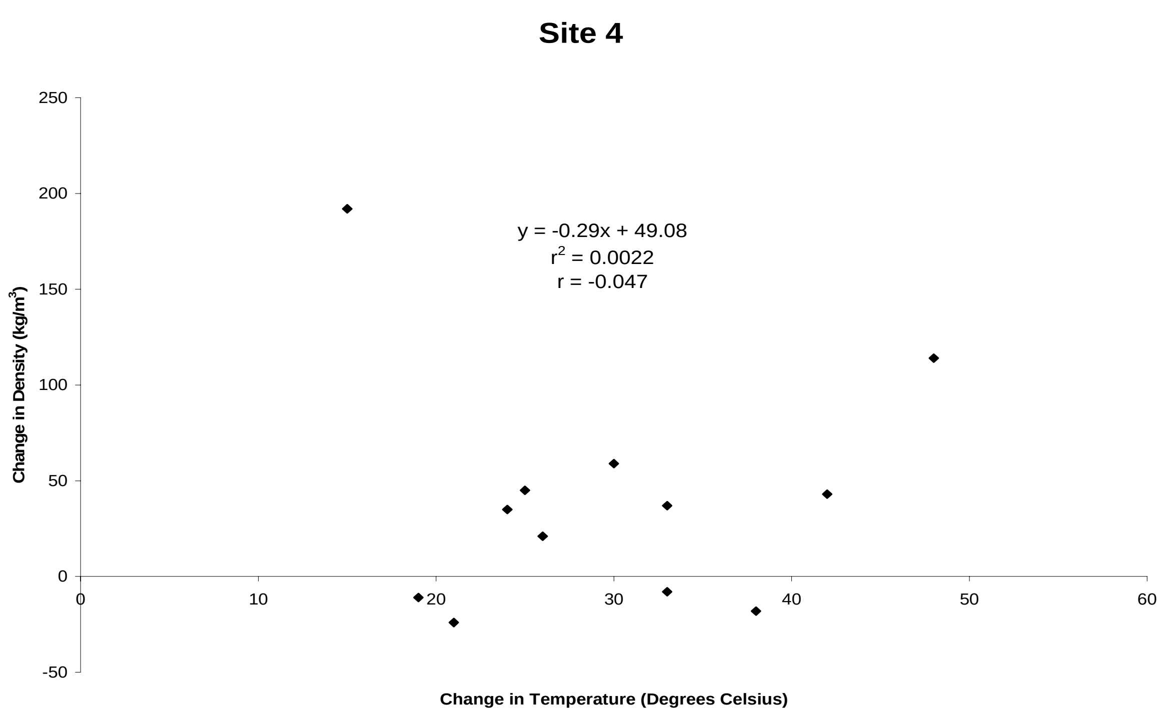


Figure 29 - Relationship Between Δσ and ΔT at Site 4.

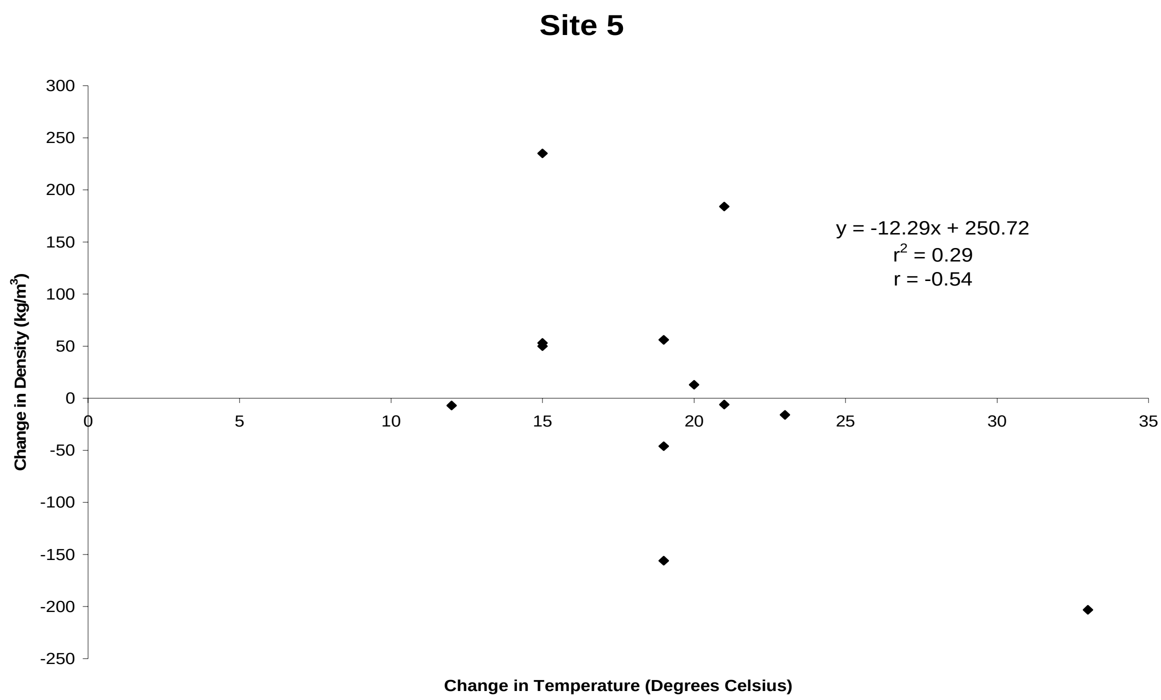


Figure 30 - Relationship Between Δσ and ΔT at Site 5.

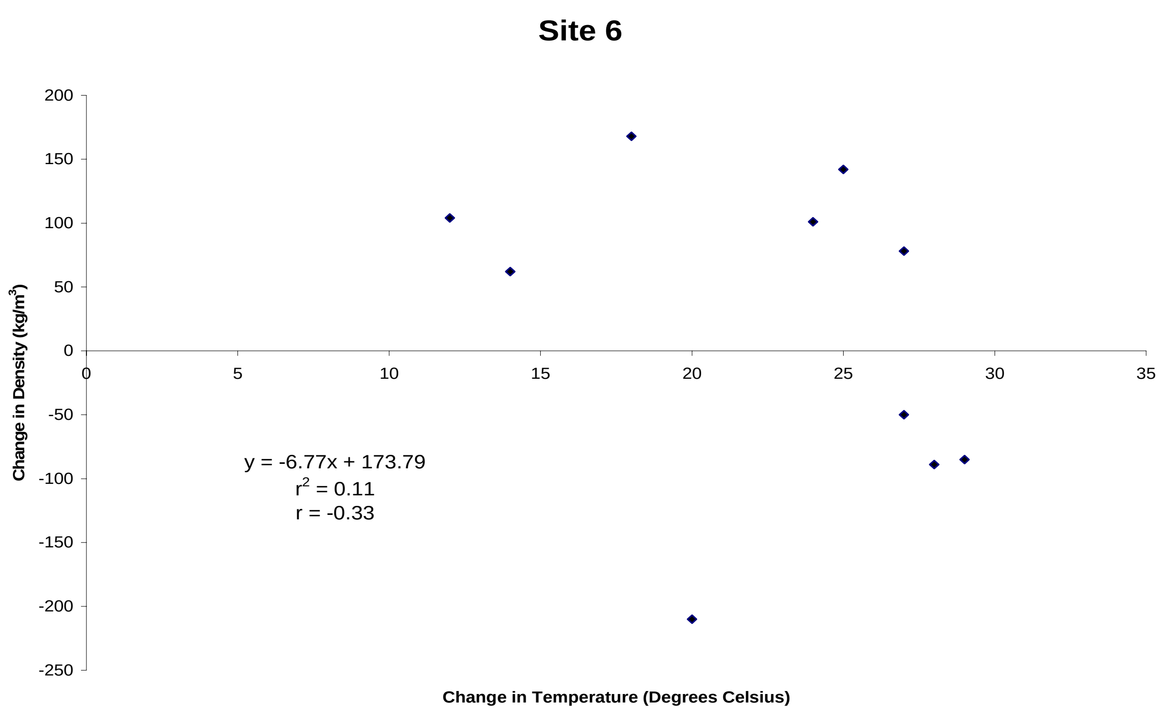


Figure 31 – Relationship Between Δσ and ΔT at Site 6.

CONDITION SURVEY

Six (6) of the eleven (11) sites were monitored for a period of five (5) years for areas of pavement distress. The other five (5) sites were not monitored because they were either located on busy sections of interstate highways and posed safety concerns, or were represented by similar sites already selected for monitoring. Coordinates of cold spot/areas, for each monitored site, in relation to described bench marks are provided in Appendix C. Research staff performed manual distress surveys by walking each side of the sections using a measuring wheel and documenting, to scale, crack lengths and types on graph paper. Each site (1-6) was surveyed on August 1999, August 2000, October-November 2001, December 2002 and November 2003. Final pavement distress survey plots, performed in November 2003, are shown in Appendix B. In addition, WiseCrax and DigitalHiway software were used to survey pavements.

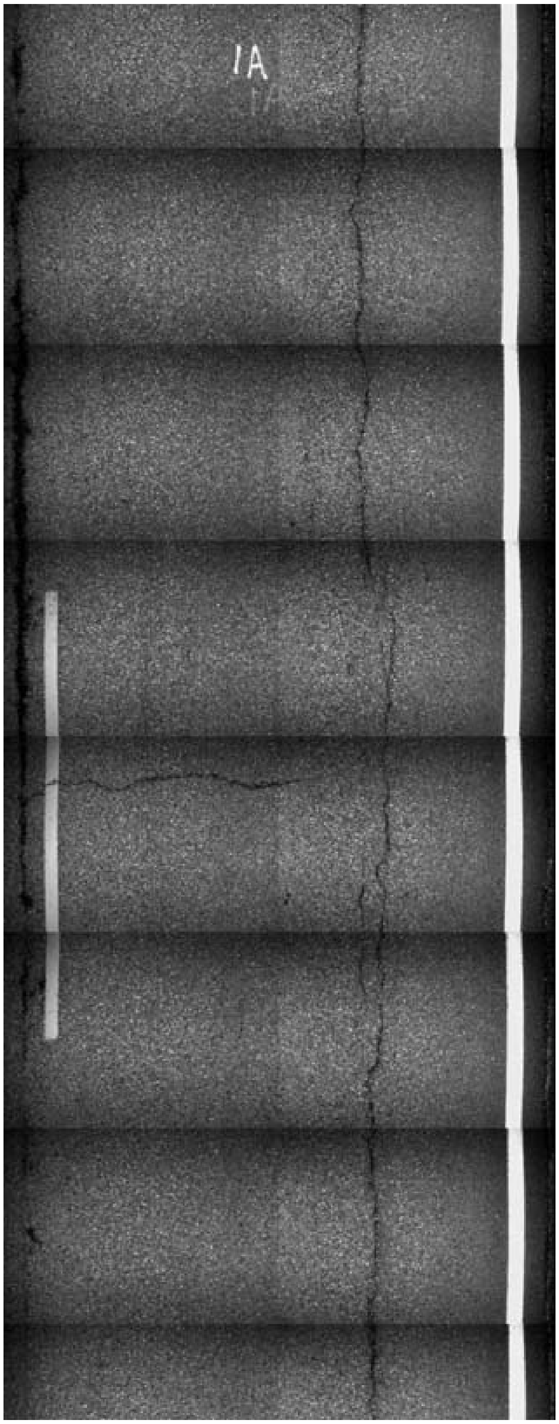
Sites 1 & 2

At Sites 1 & 2 (see Photo 18), few areas of pavement distress were observed for the first three years. Low severity (0 mm < crack width < 6 mm) longitudinal and transverse cracks appeared in the fourth year. During the fifth year survey, areas of pavement distress became much more apparent, possibly due to a harsh winter, as low and medium severity (6 mm ≤ crack width < 12 mm) longitudinal and transverse cracks were observed (see Photos 19-33). Many of the cracks reflected through from the underlying pavement, as can be seen by looking at the pre-existing condition of pavement in Photo 34. It is noteworthy that this occurred, in spite of the fact that the top 2-inches of pavement were milled off during resurfacing operations. Most significantly, relationships between areas of pavement distress and cold spot/areas observed with the infrared camera were not evident during the survey. Additional time (2 to 5 years) may be necessary for TDD to present itself in a pavement distress survey.

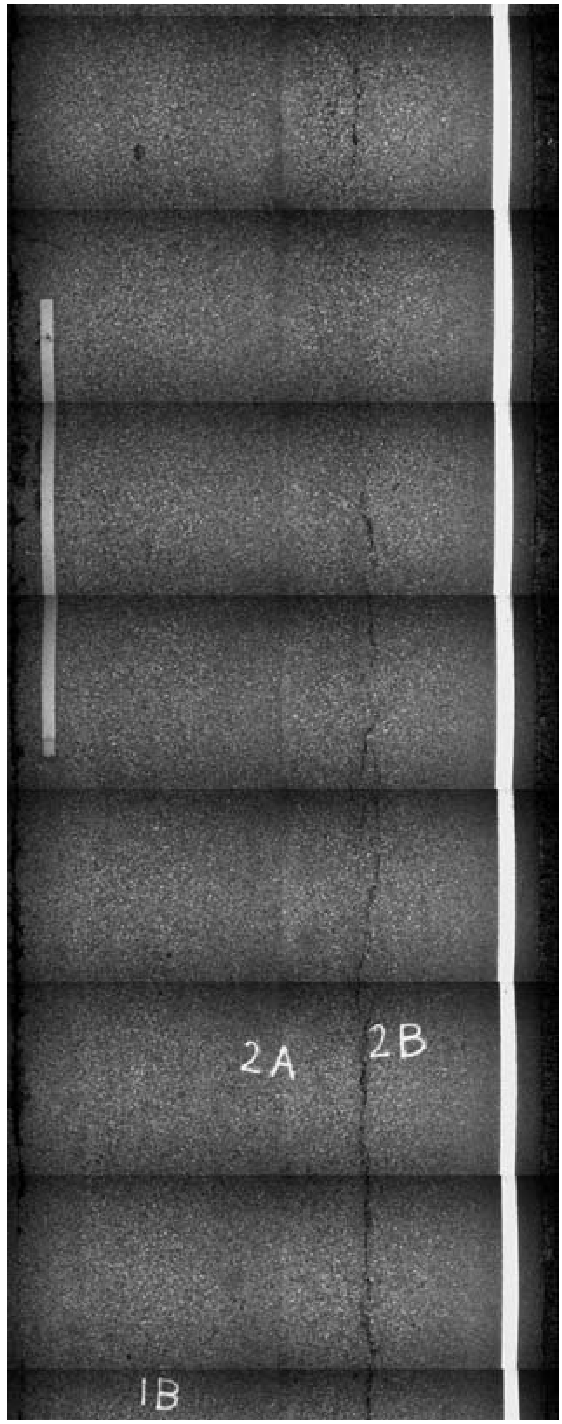
WiseCrax images of Sites 1 and 2 are shown in Photos 19-26 and Photos 27-33, respectively. Samples marked “A” represent cold spots, while those marked “B” represent normal temperature pavement. It should be noted that slight shading can be seen between the left and right sides of the WiseCrax images as a result of merging two separate photos (from separate booms equipped with cameras), and it does not represent pavement distress of any kind. At Site 2, core holes can be seen at locations for Samples 3 (Photo 27, not marked, but to the left and slightly below Samples 4), Samples 13 (Photo 29) and Samples 20 (Photo 31); and, at Site 2, they can be seen at locations for Samples 12 (Photo 23) and Samples 19 (Photo 24). Comparisons between areas marked “A” and “B” do not demonstrate a tendency for cold spots to deteriorate at a faster rate than normal temperature pavement. In fact, when looking at photos for Site 1, one may draw the conclusion that normal temperature areas (marked “B”) deteriorate at a faster rate than the cold spots. At Site 1 (see Photos 19-26), several normal temperature samples (2B, 5B, 6B, 9B, 10B, 12B, 13B, 15B, 16B, 19-23B) were located along longitudinal crack lines, while their cold temperature counterparts show little or no deterioration. Upon examination of pre-1998 DigitalHIWAY images (see Photo 34 for example), however, it appears that many of the areas marked “B” are located along longitudinal crack lines that existed prior to 1998 pavement reconstruction. Therefore, conclusive statements regarding rates of deterioration between cold and normal temperature areas cannot be made, since other factors, such as reflective cracking, play significant roles in the pavement’s performance.

Photo 18 – 1998 Photo of Sites 1 & 2, Route 85 SB & NB in Colchester

2003 WiseCrax Images of Site 1

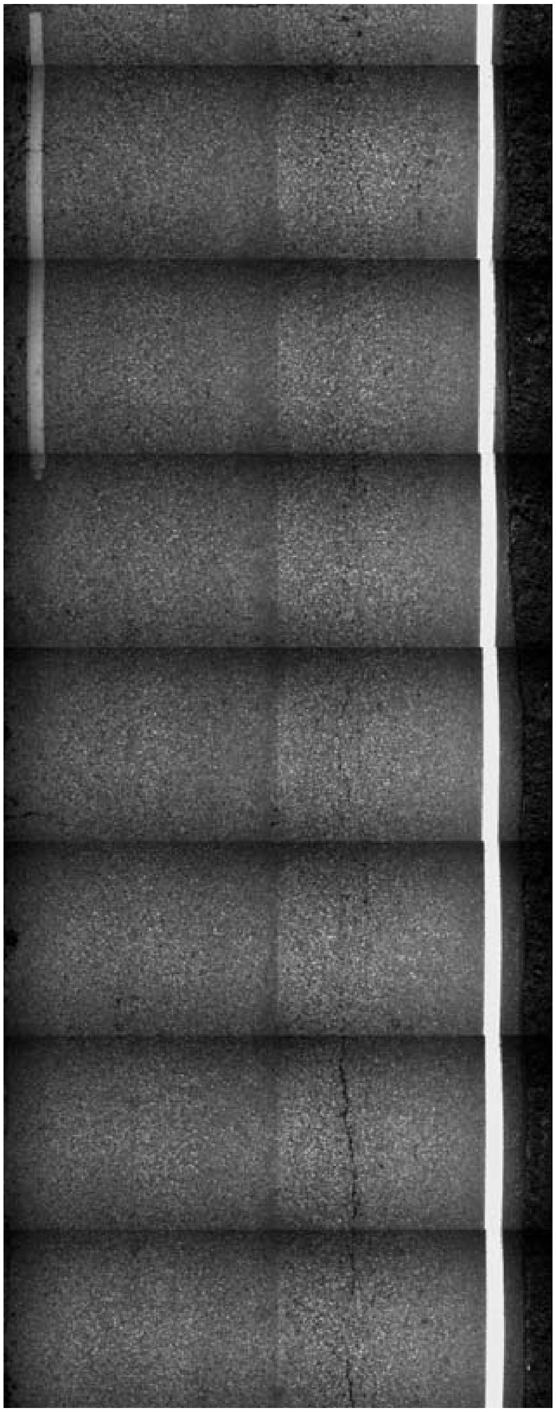


Sample 1A

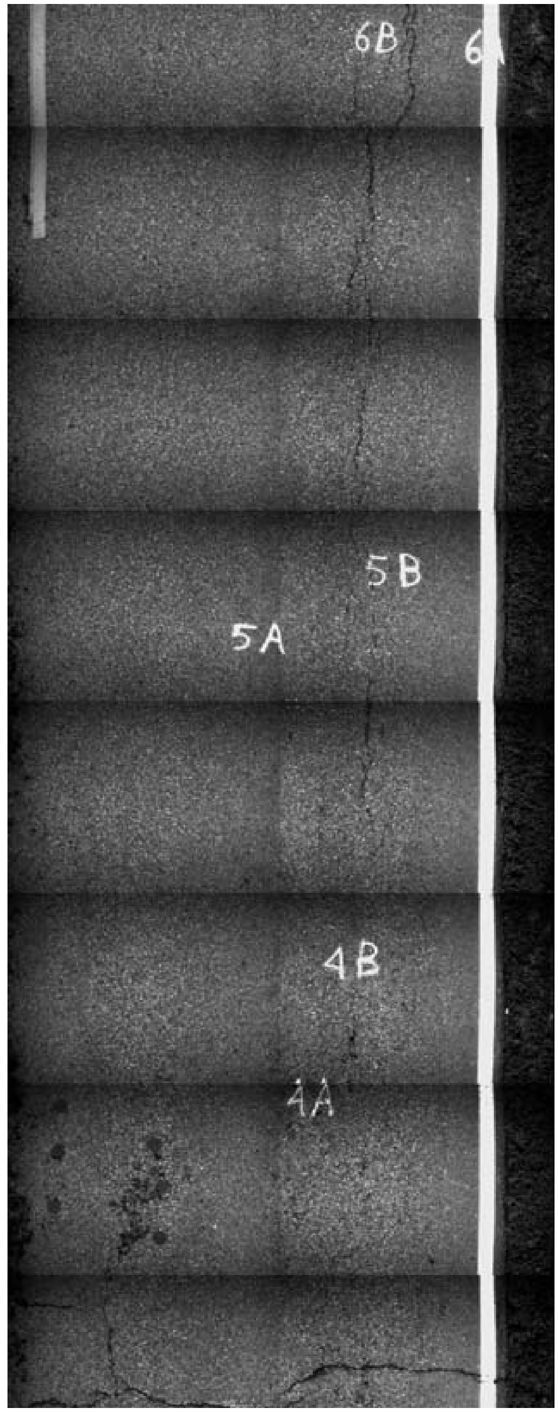


Samples 1B, 2A & 2B

Photo 19 – Route 85 SB in Colchester, Samples 1 - 2



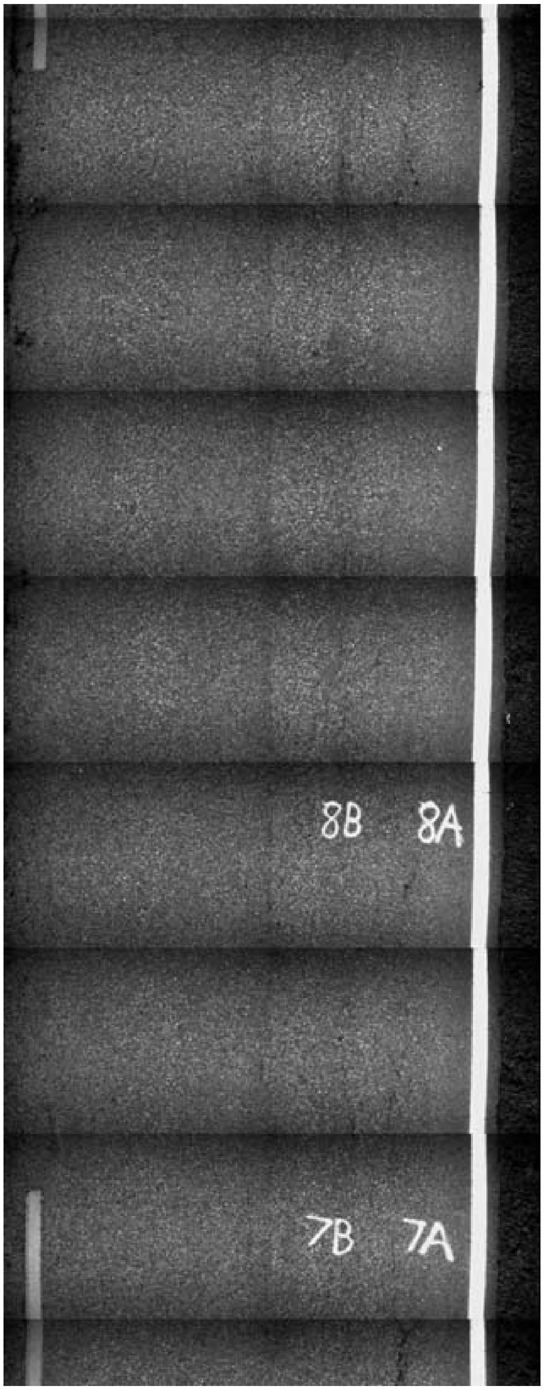
No Samples Within Area Shown



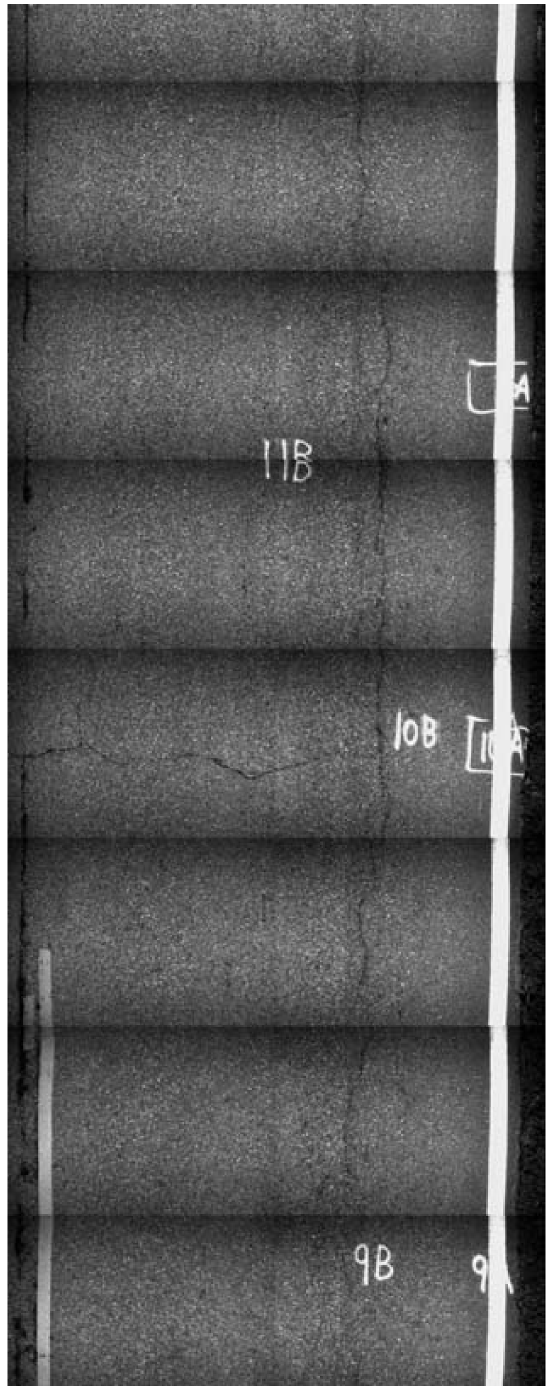
Samples 3 (not labeled) – 6 (A&B)

Photos 20 – Route 85 SB in Colchester, Samples 3 - 6

2003 WiseCrax Images of Site 1 (Continued)



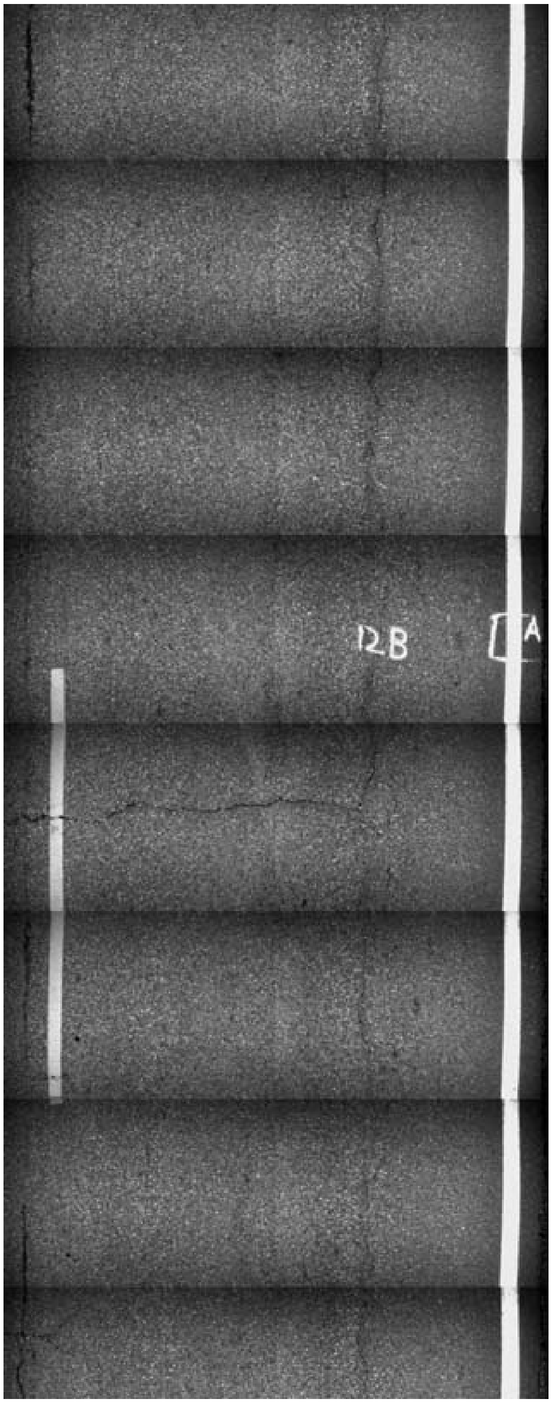
Samples 7 & 8 (A & B)



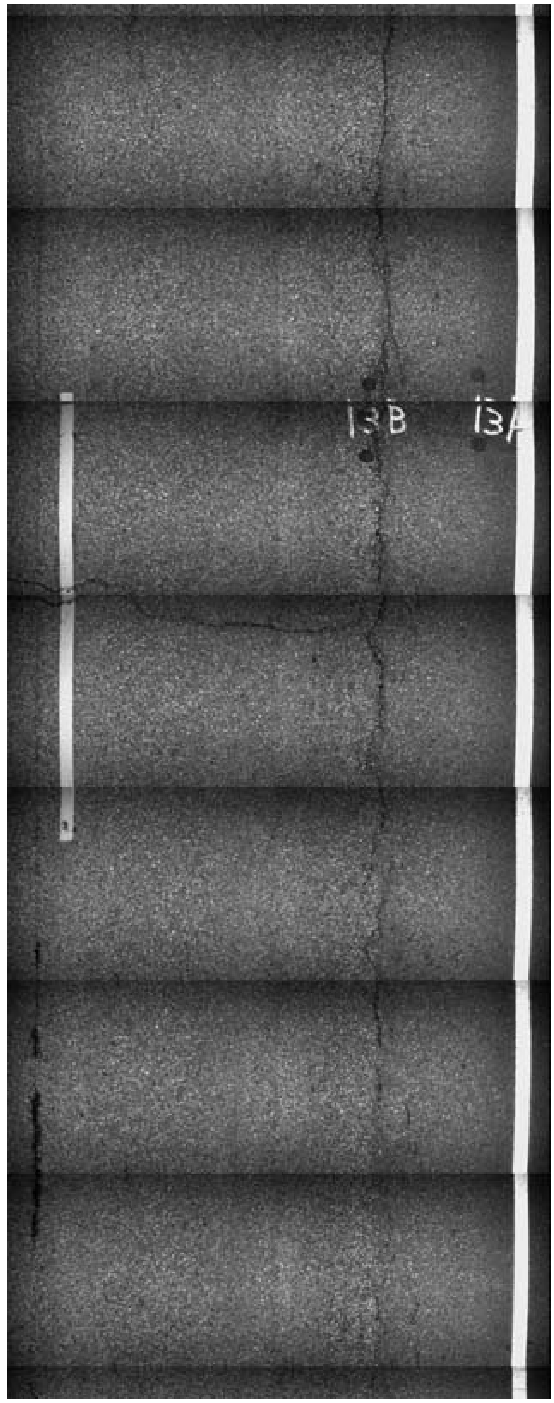
Samples 9 – 11 (A & B)

Photos 21 – Route 85 SB in Colchester, Samples 7 - 11

2003 WiseCrax Images of Site 1 (Continued)



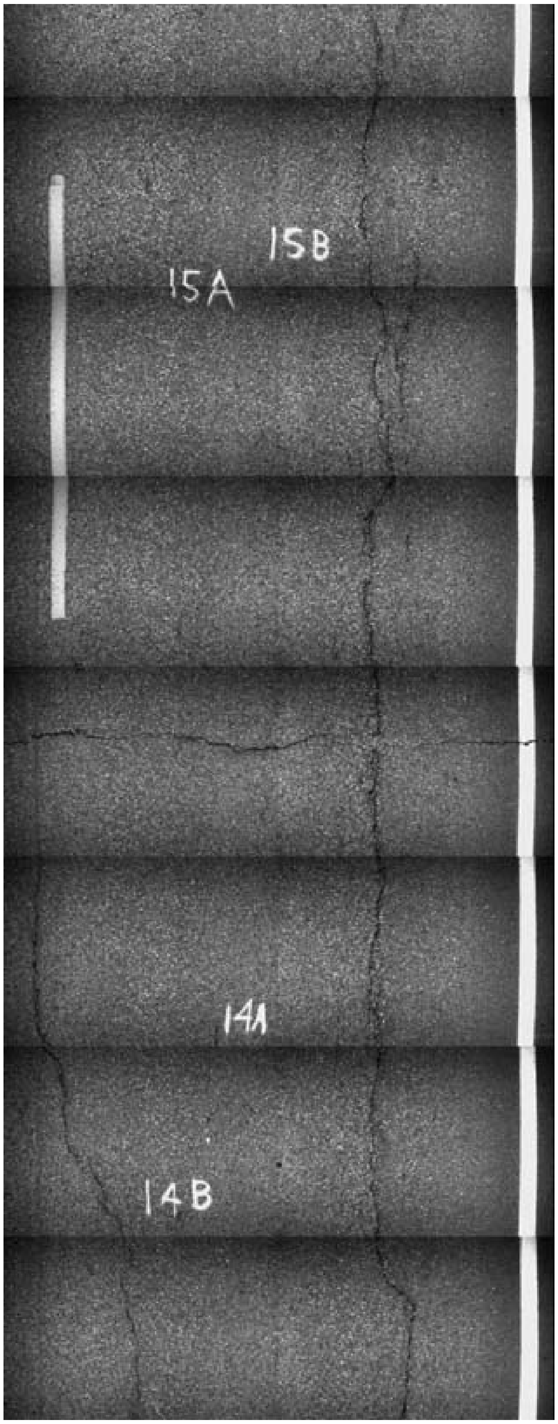
Samples 12 (A & B)



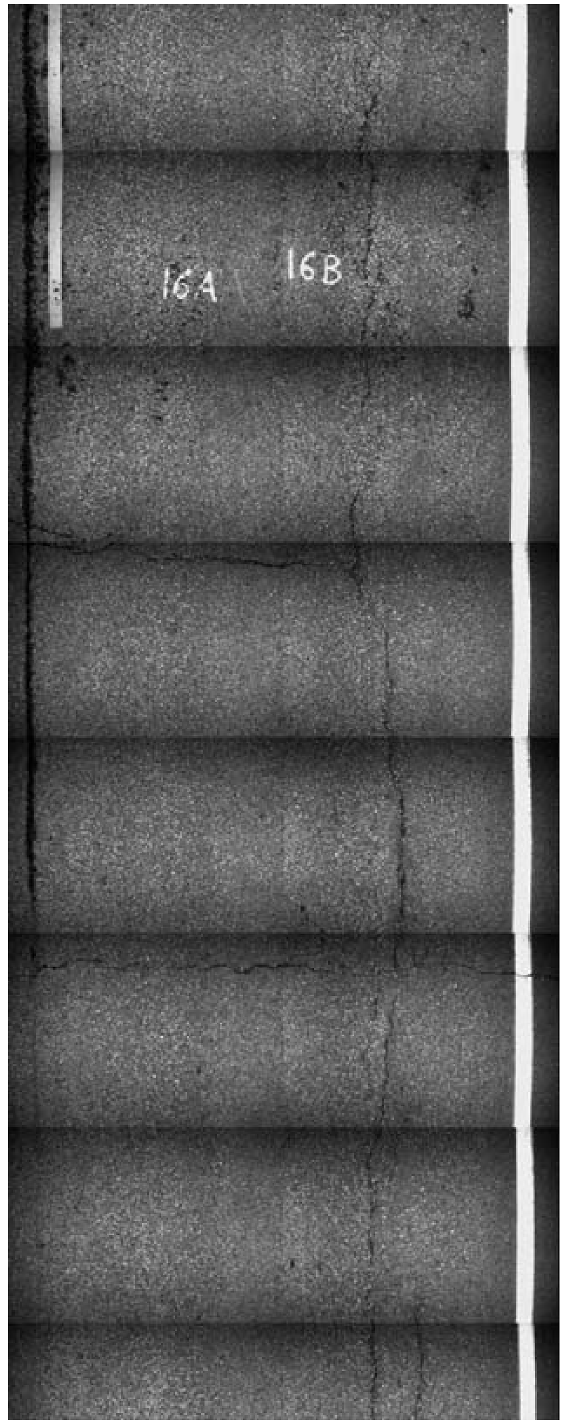
Samples 13 (A & B)

Photos 22 – Route 85 SB in Colchester, Samples 12 - 13

2003 WiseCrax Images of Site 1 (continued)



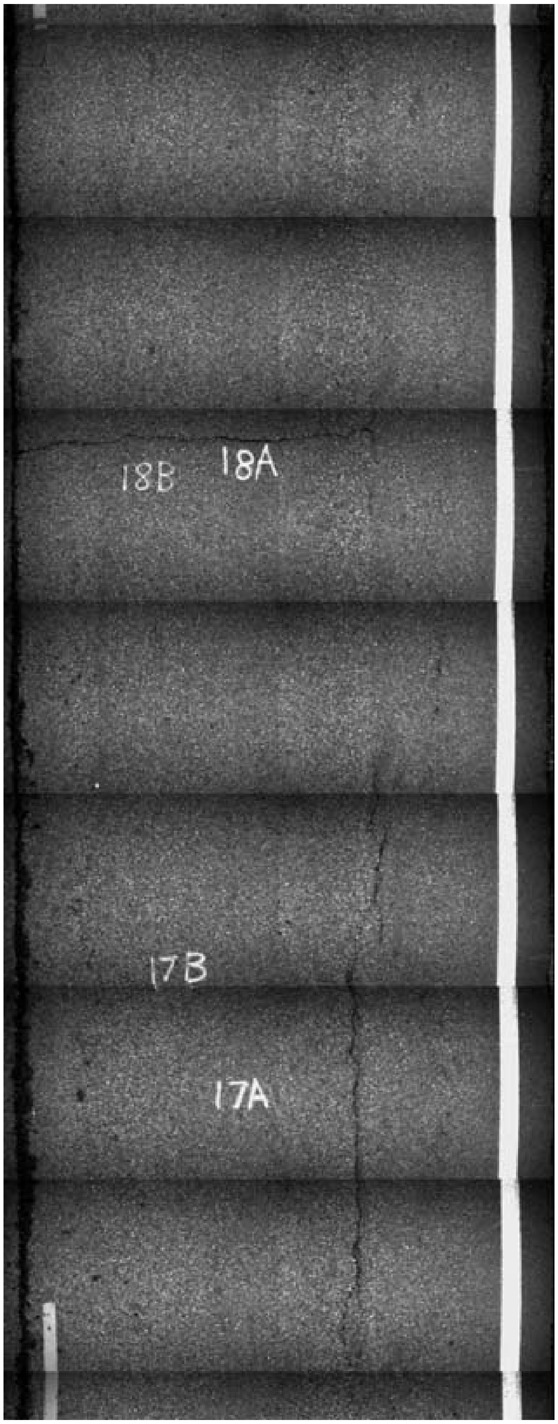
Samples 14 & 15 (A & B)



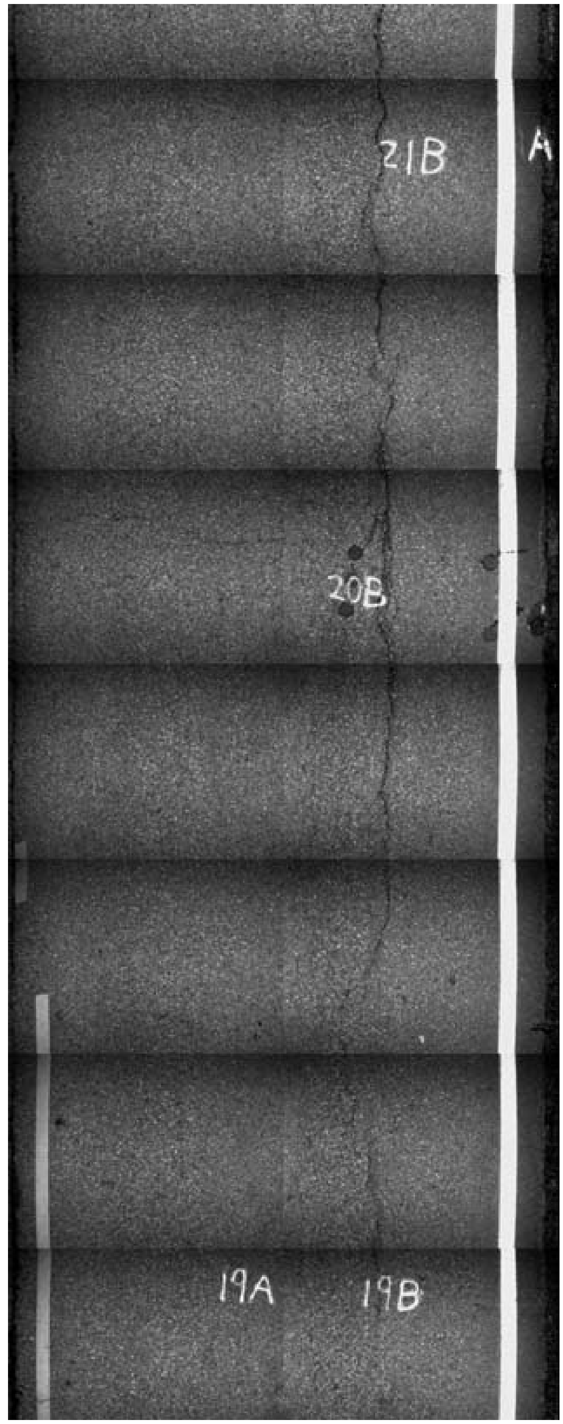
Samples 16 (A & B)

Photos 23 – Route 85 SB in Colchester, Samples 14 - 16

2003 WiseCrax Images of Site 1 (continued)



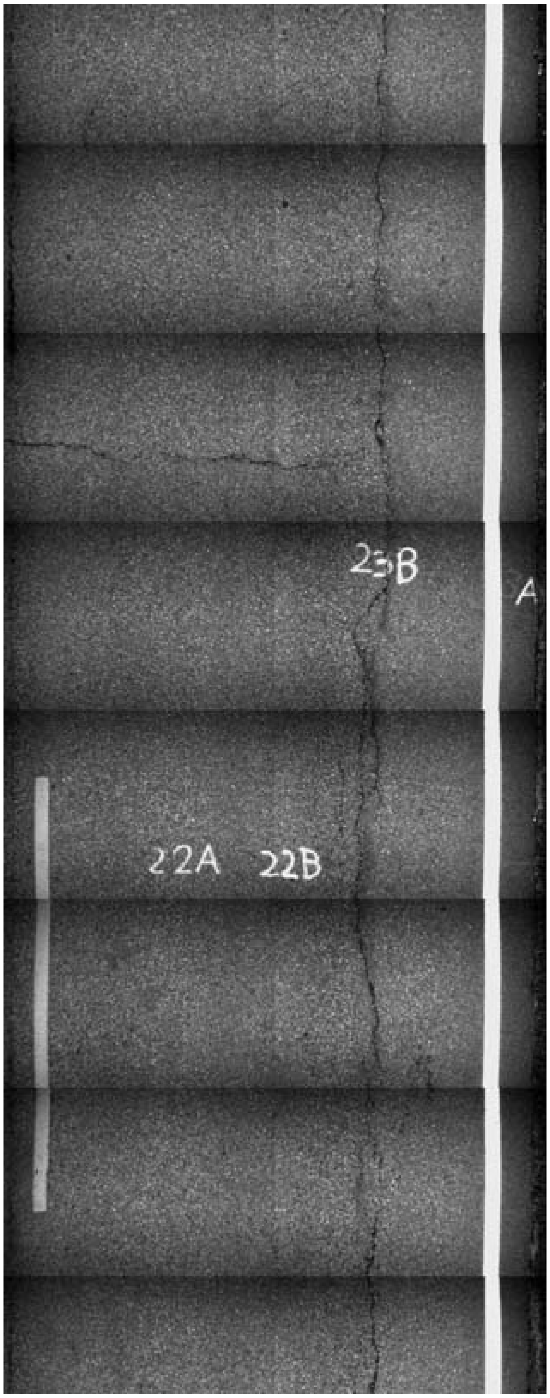
Samples 17 & 18 (A & B)



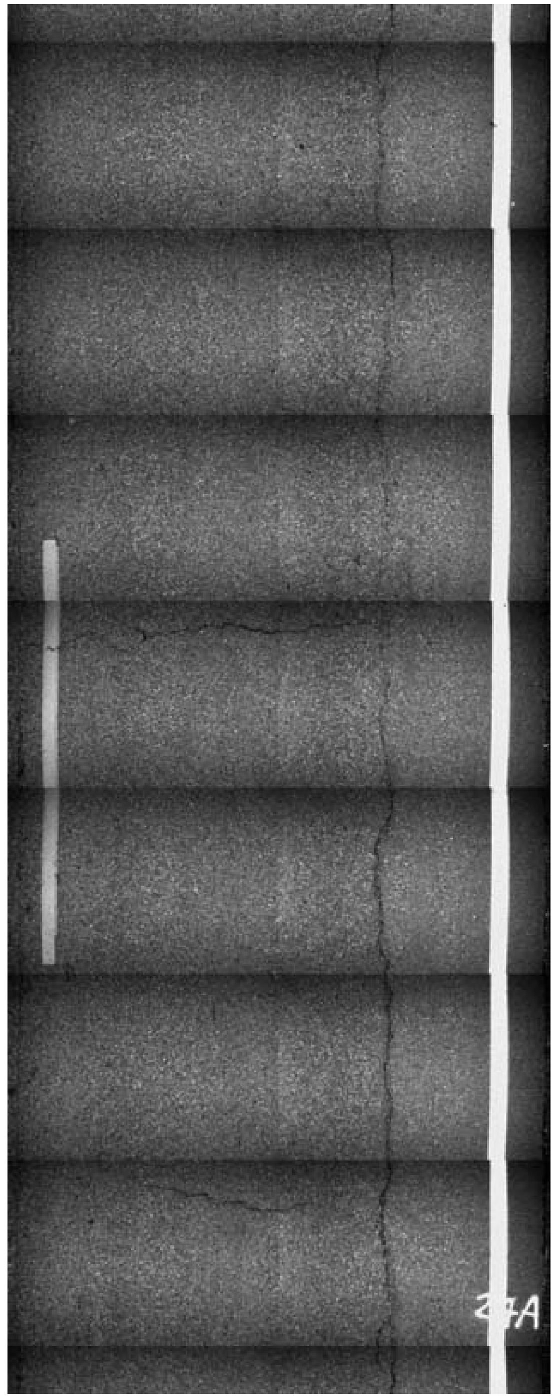
Samples 19 – 21 (A & B)

Photos 24 – Route 85 SB in Colchester, Samples 17 - 21

2003 WiseCrax Images of Site 1 (Continued)

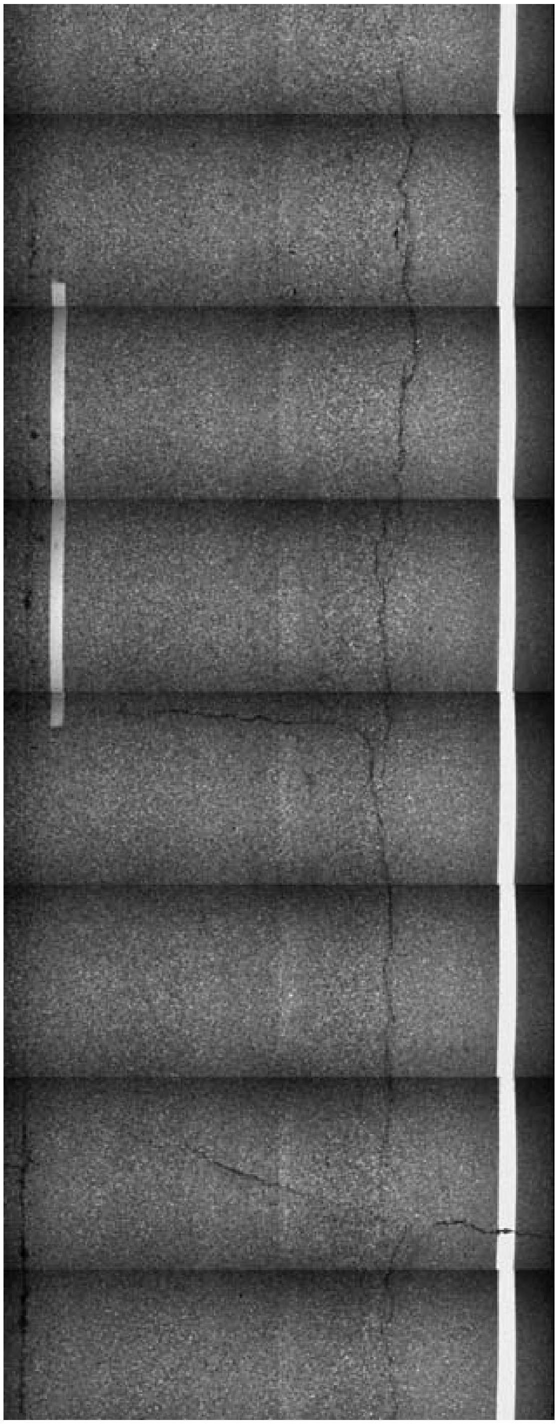


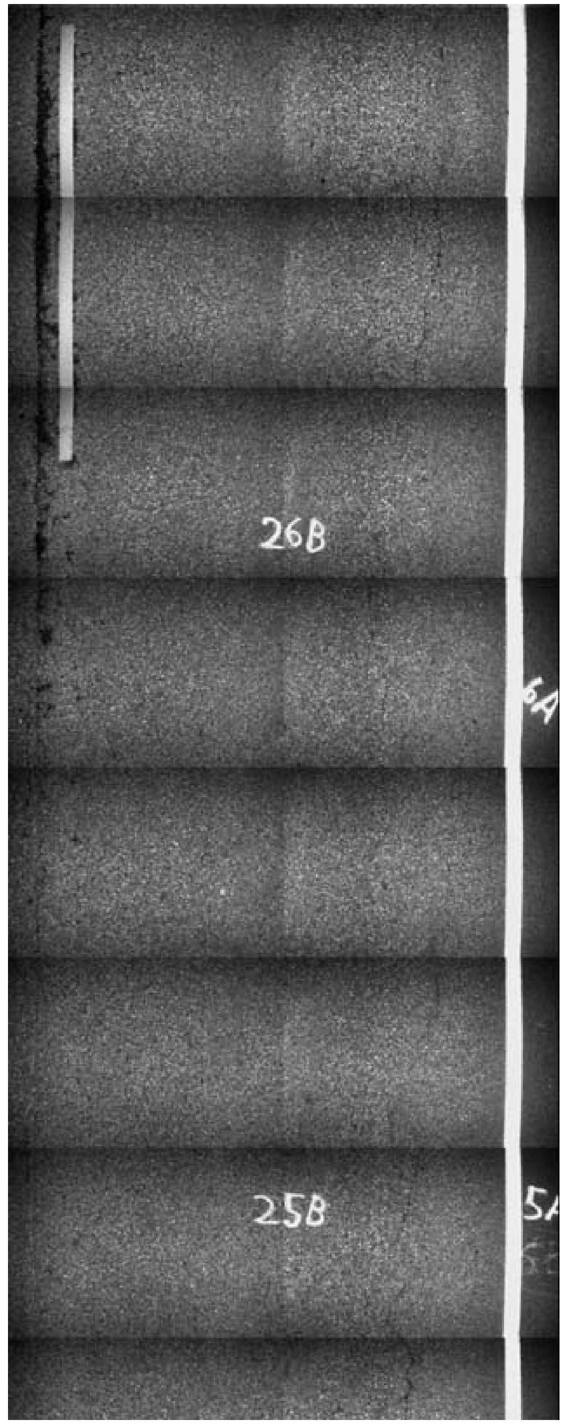
Samples 22 & 23 (A & B)



Sample 24A

Photos 25 – Route 85 SB in Colchester, Samples 22 - 24

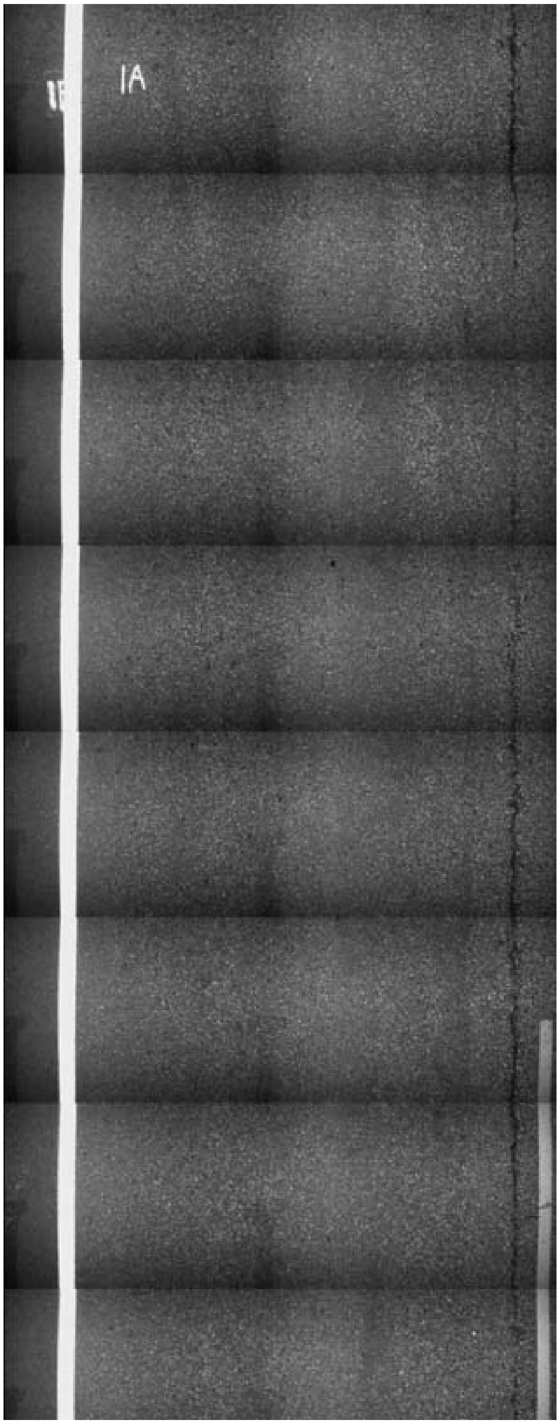




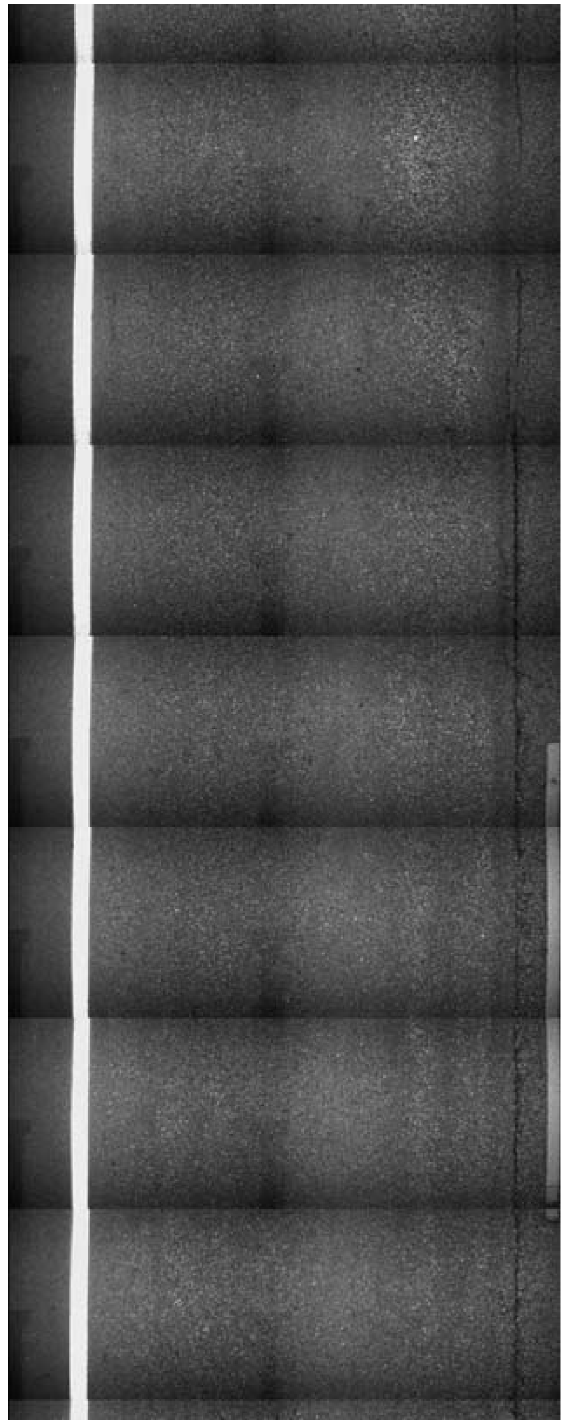
Samples 25 and 26 (A & B)

Photos 26 – Route 85 SB in Colchester, Samples 25 - 26

2003 WiseCrax Images of Site 2



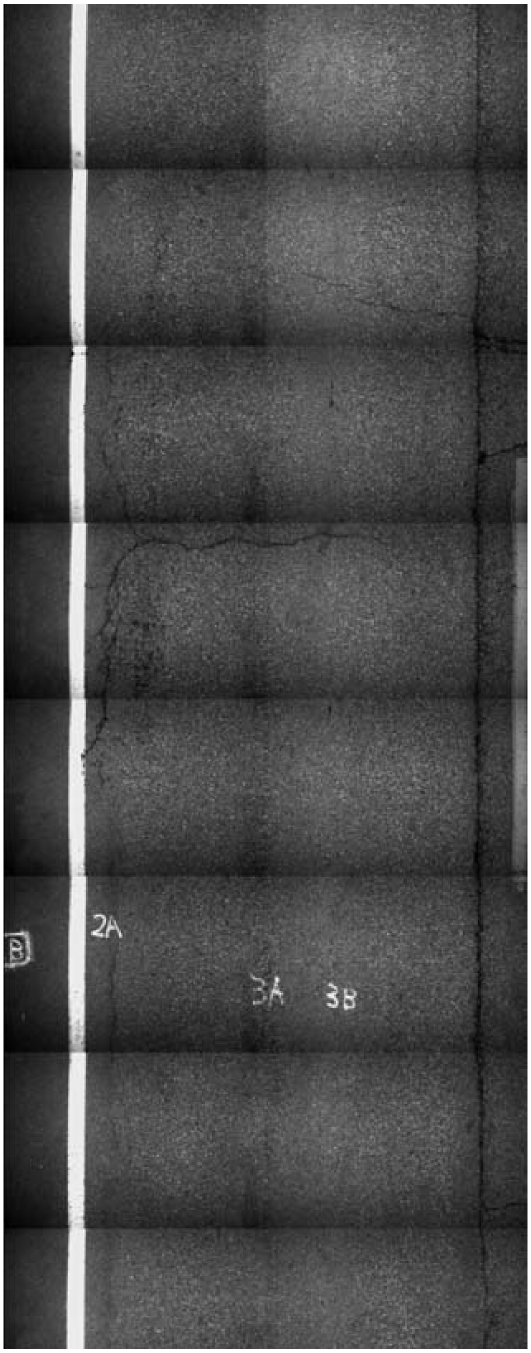
Samples 1 (A & B)



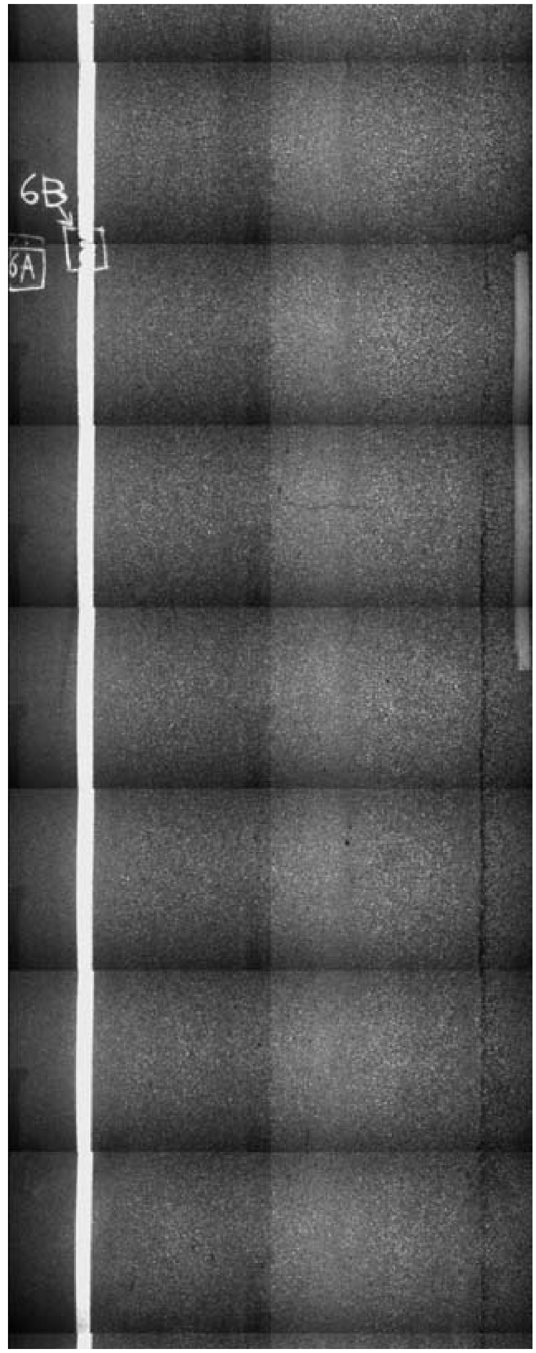
No Samples Within Area Shown

Photos 27 – Route 85 NB in Colchester, Samples 1

2003 WiseCrax Images of Site 2 (Continued)



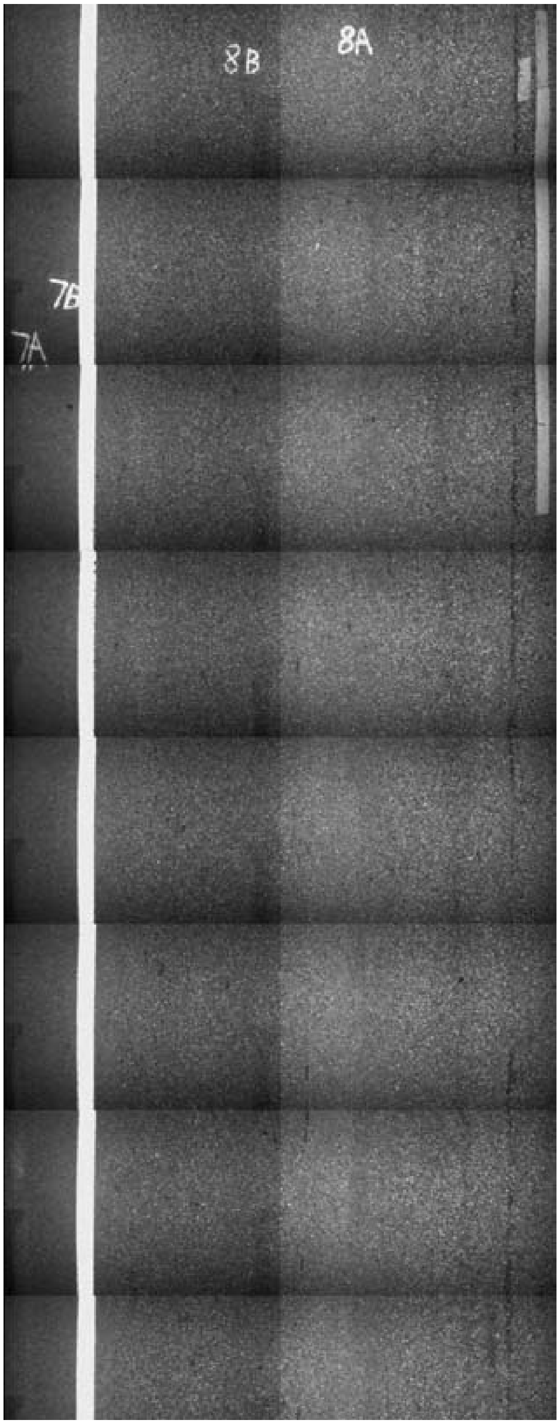
Samples 2 & 3 (A & B)



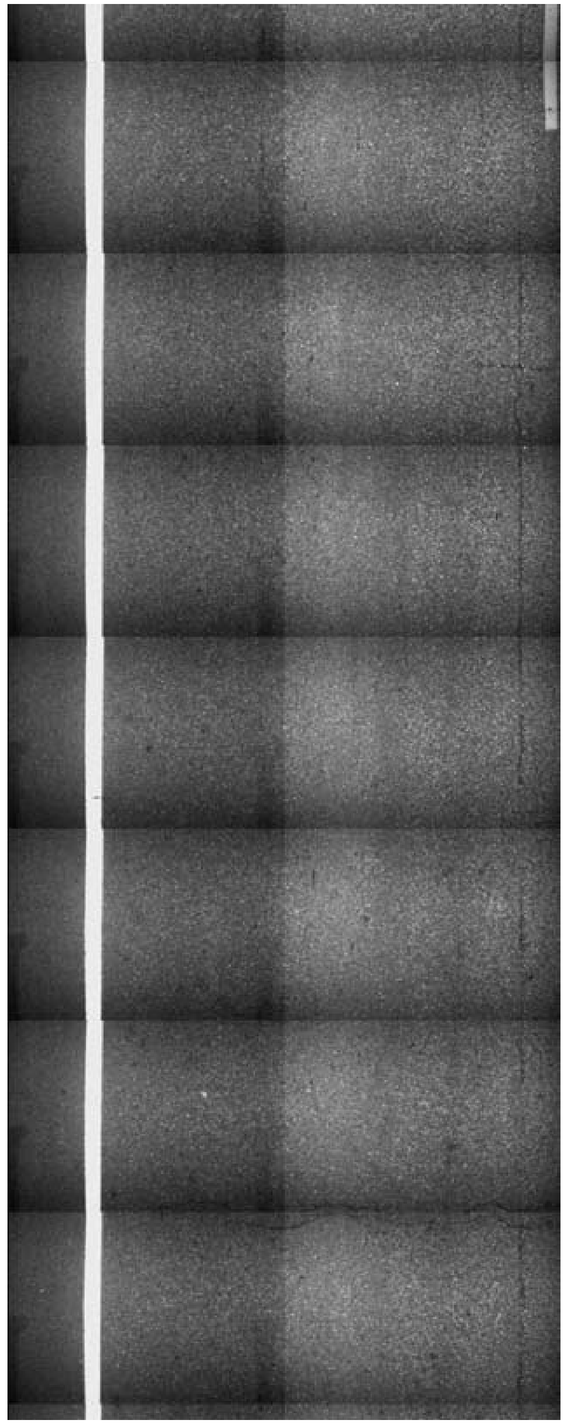
Samples 6 (A & B)

Photos 28 – Route 85 NB in Colchester, Samples 2 – 6 (4 & 5 not shown)

2003 WiseCrax Images of Site 2 (Continued)



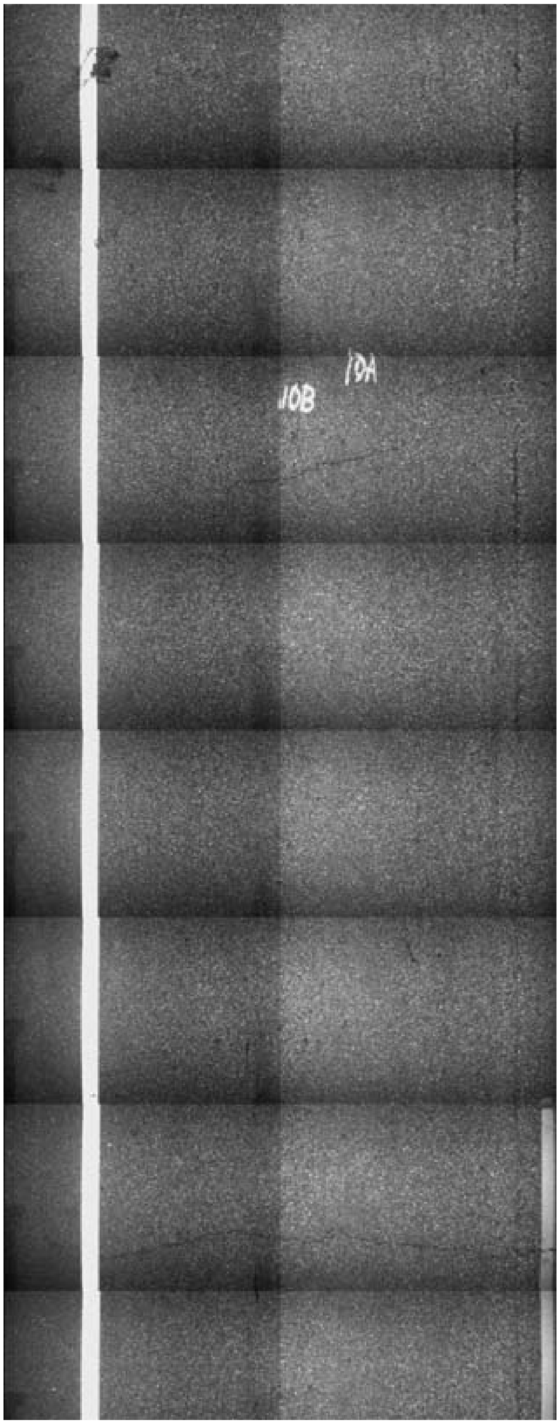
Samples 7 & 8 (A & B)



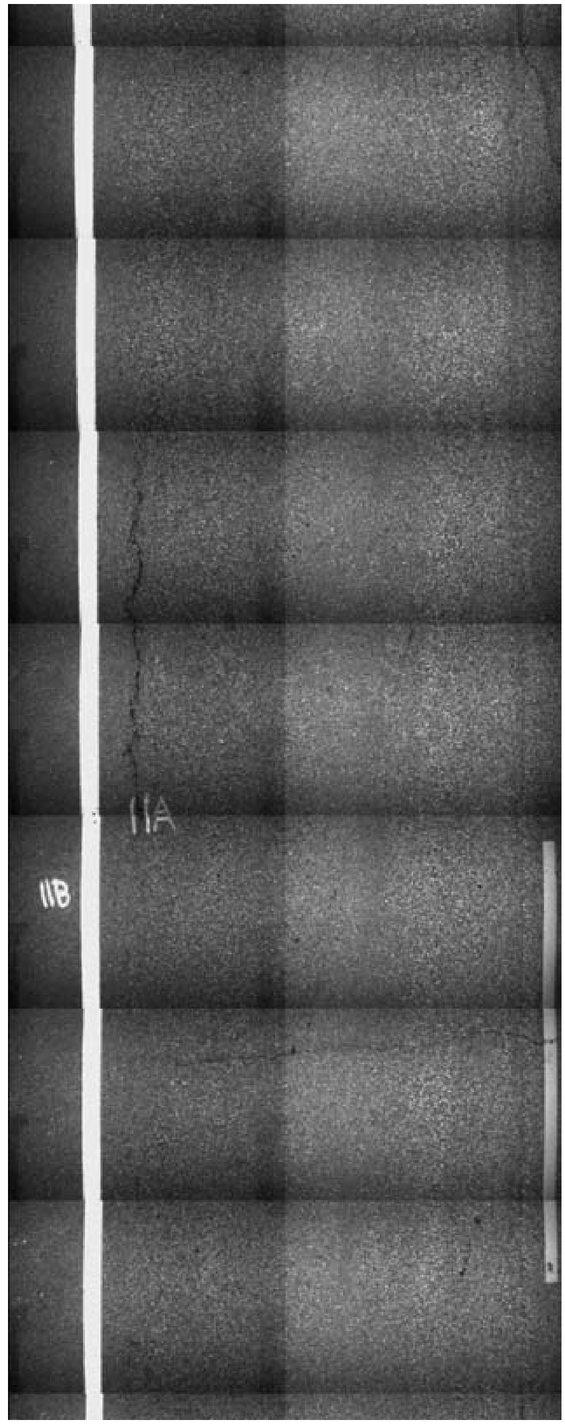
No Samples Within Area Shown

Photos 29 – Route 85 NB in Colchester, Samples 7 - 8

2003 WiseCrax Images of Site 2 (Continued)

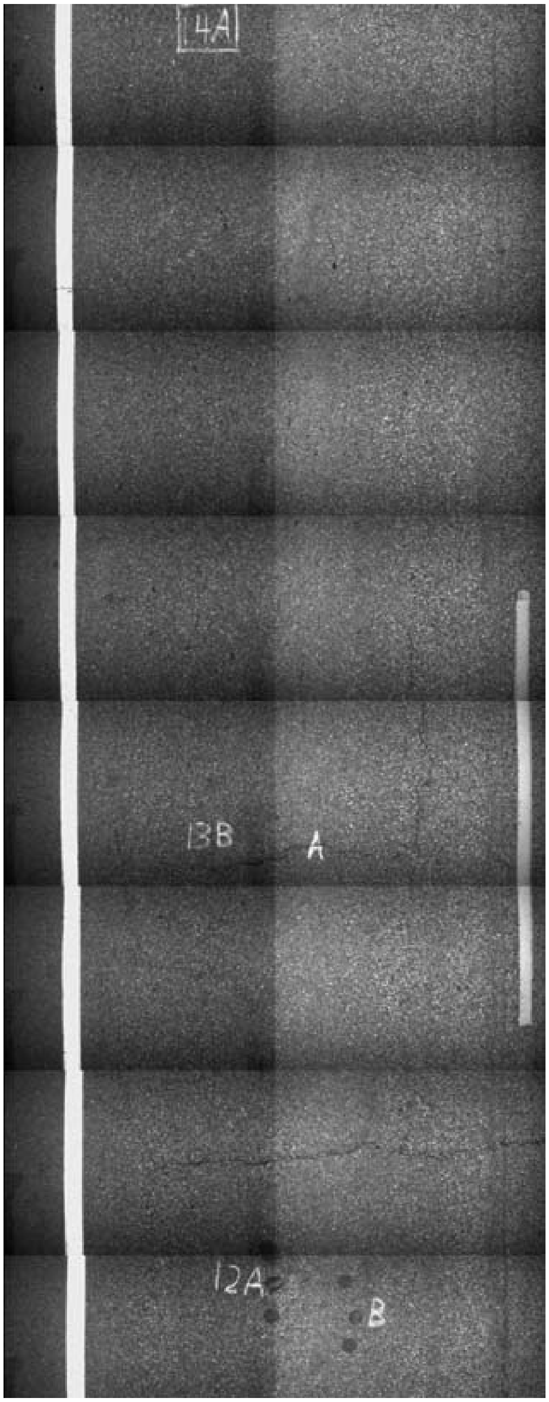


Samples 10 (A & B)

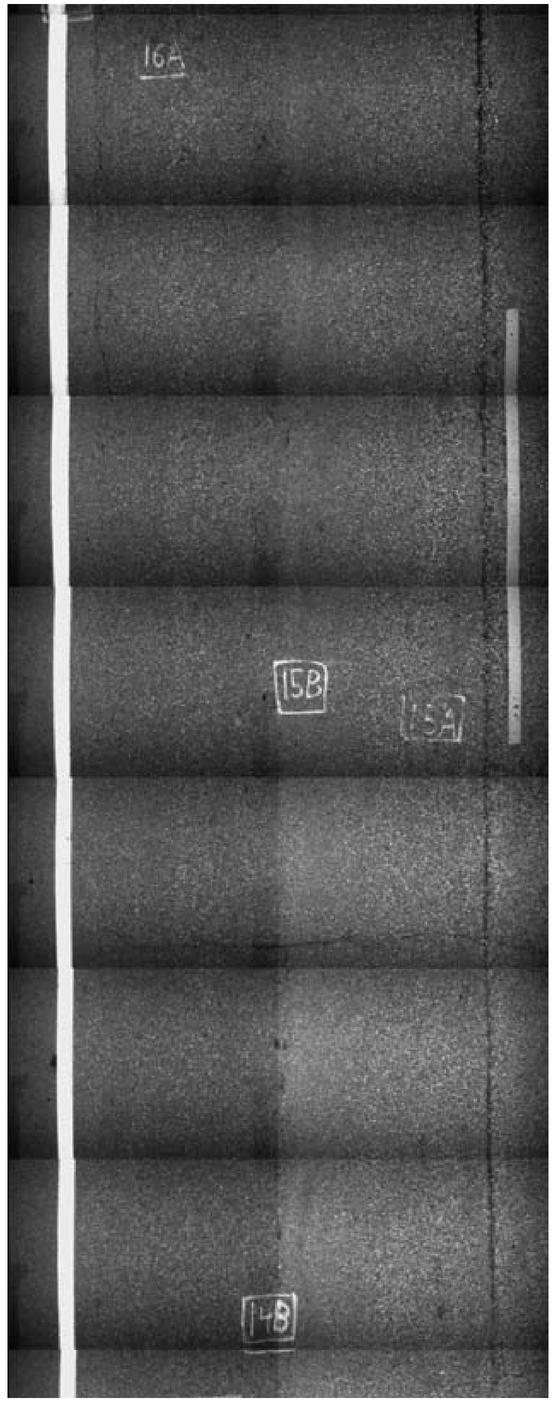


Samples 11 (A & B)

Photos 30 – Route 85 NB in Colchester



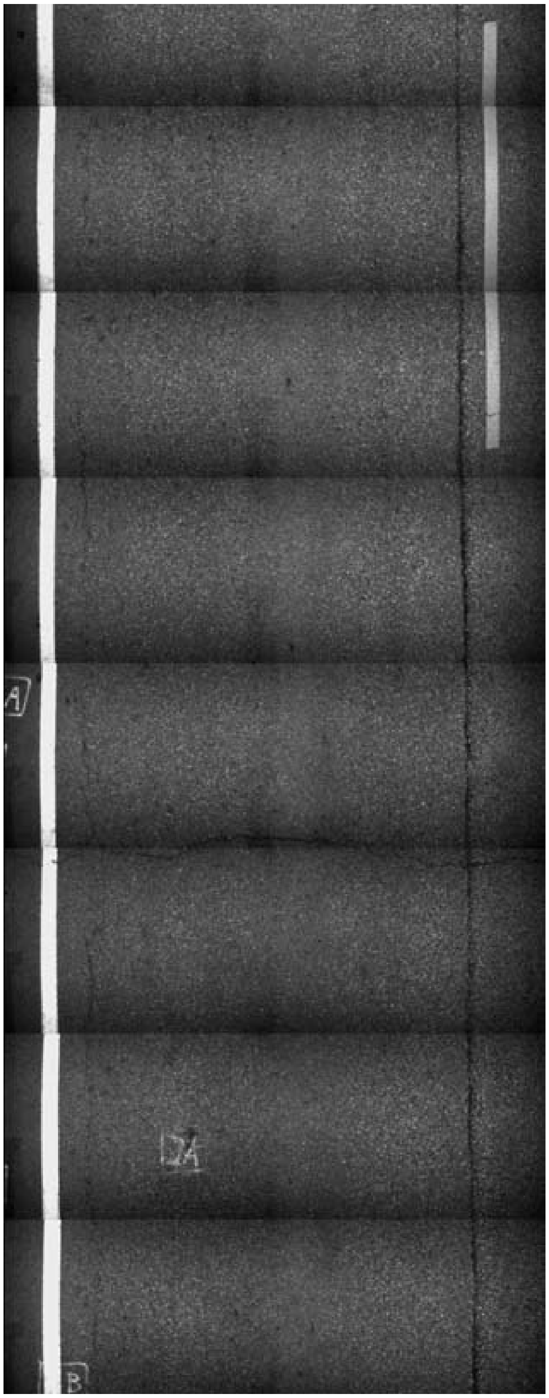
Samples 12 & 13 (A & B), 14 A



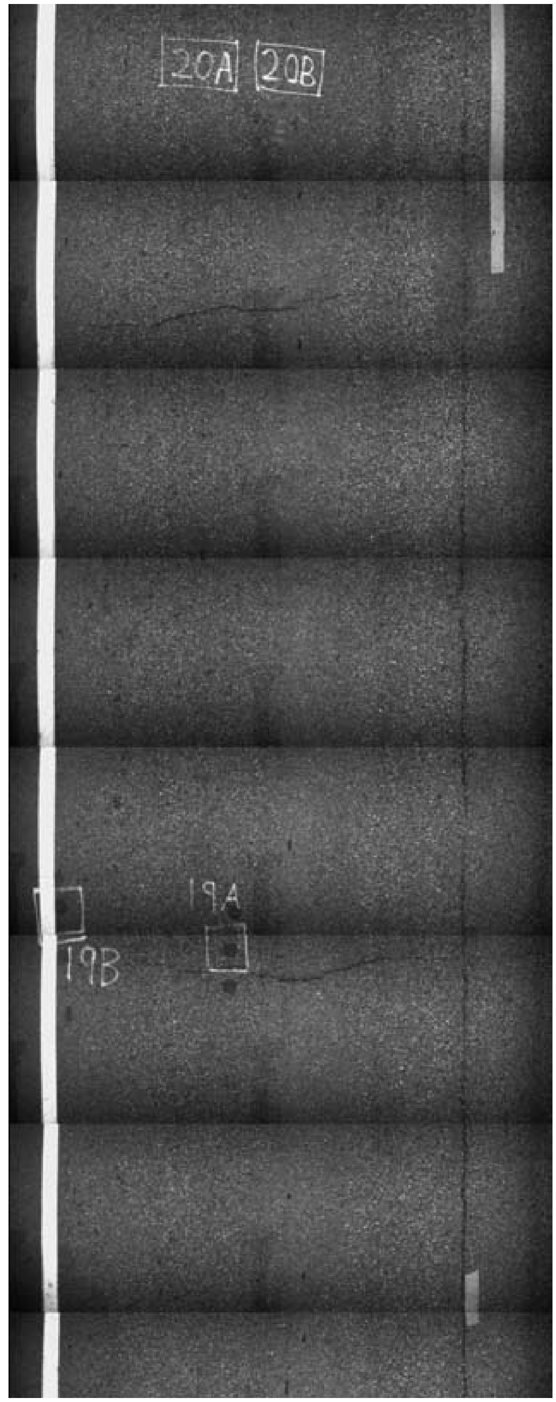
Samples 14 B, 15 (A & B), 16 A

Photo 31 – Route 85 NB in Colchester, Samples 12 - 16

2003 WiseCrax Images of Site 2 (Continued)

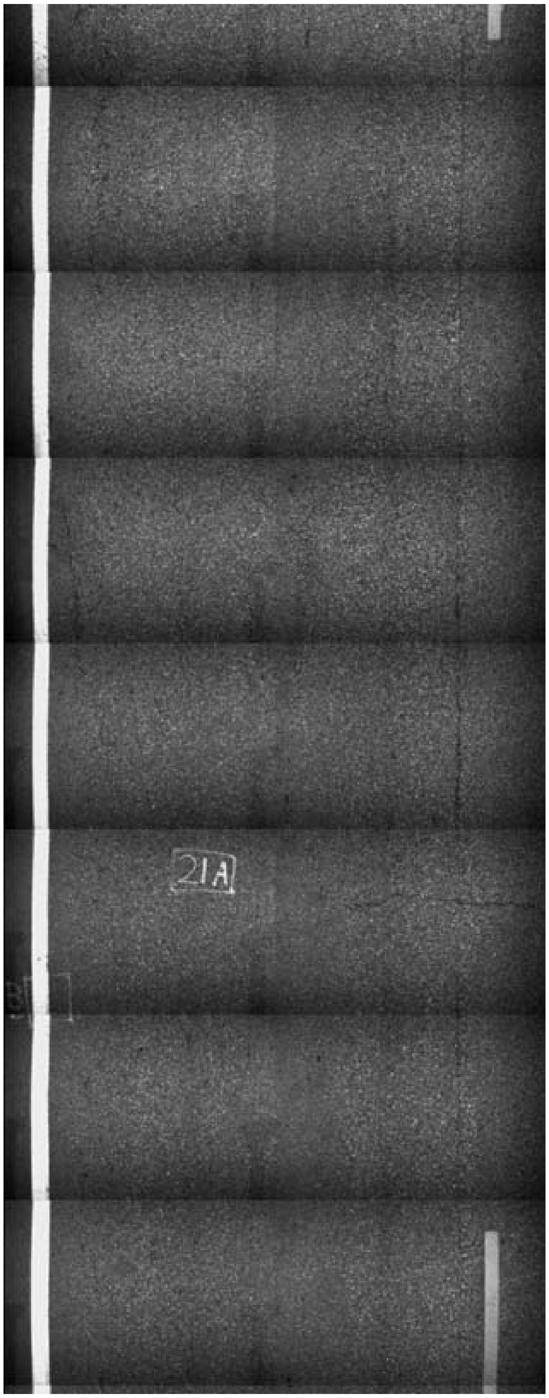


Samples 16B, 17A, 18A (counterparts not visible)

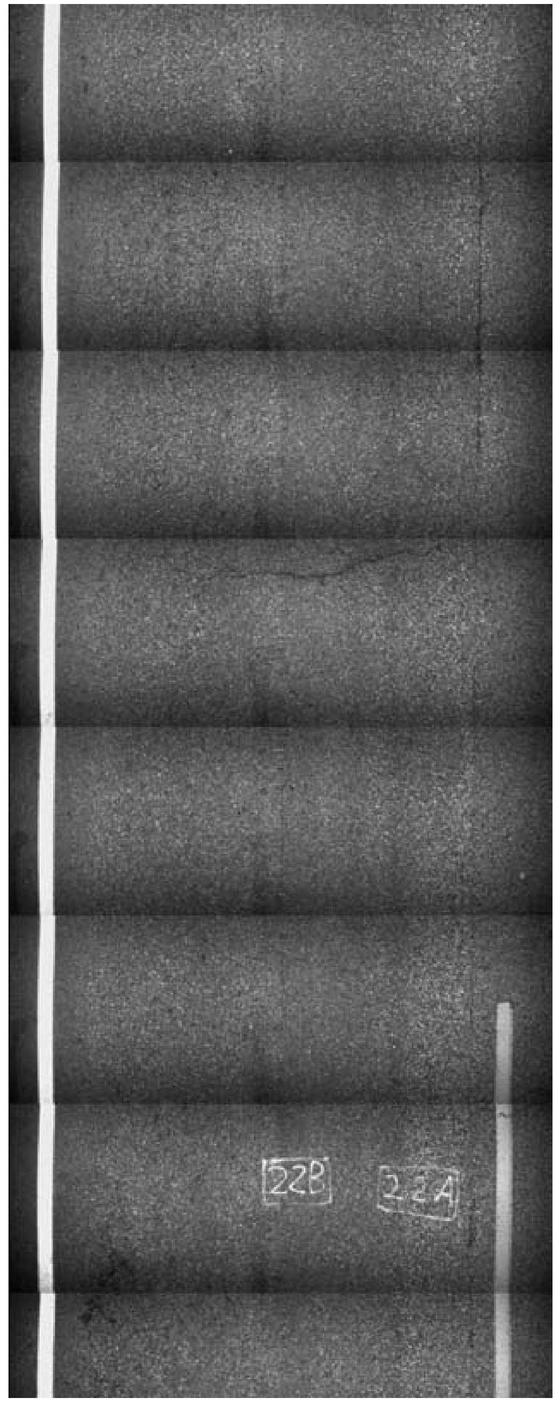


Samples 19 & 20 (A & B)

Photo 32 – Route 85 NB in Colchester, Samples 16 - 20



Samples 21 (A & B)



Samples 22 (A & B)

Photo 33 – Route 85 NB in Colchester, Samples 21 - 22

Photo 34 – 1996 DigitalHIWAY Image
Note Location of Longitudinal Crack on Right

Site 3

Route 8 was originally constructed with a jointed portland cement concrete (PCC) pavement. In 1988, it was overlaid with HMA. This overlay was milled off to the PCC pavement in 1998, prior to repaving with HMA. PCC joint locations were marked and staked off, so that following paving operations, joints could be saw-cut into the HMA overlay at these same locations. This was done in order to provide relief and control cracking at the joints. Finally, the saw-cut joints were sealed with asphaltic joint sealant material.

Viewing DigitalHIWAY images from 1997, prior to 1998 resurfacing operations, it can be seen that the preexisting condition of pavement within the limits of Site 3 was good (see Photos 35). During the 5-year monitoring period, Site 3 pavement performed well, and few areas of distress were located. Some low severity longitudinal cracks developed at the longitudinal joints, outside the wheel paths, and three (3) full width medium severity transverse cracks were found within the limits of Site 3. One (1) of the transverse cracks appeared slightly offset from the saw-cut joint, suggesting the saw-cut joint was misplaced in relation to the PCC joint. As was the case for Sites 1 & 2, a clear relationship between pavement distress and cold spot/areas observed with the infrared camera was not evident.

1997 – Prior to Milling and Paving

1998 – After Milling and Paving

2001 – Three (3) Years Later

2003 – Five (5) Years Later

Photos 35 – Route 8 NB in Thomaston (Site 3) at approximately 64.015 km.

Site 4

Interestingly, Site 4 was observed to have the fewest areas of pavement distress of all the sites monitored, even though it had the most profound and well defined occurrences of thermal segregation. This may be explained by the fact that a 50-mm (2-inch) DOT Class 1 surface layer was placed on top of a cold-in-place recycled base course, while the other sites were placed on top of existing pavements. Longitudinal cracks were observed along the length of the test site at the longitudinal joint locations, which occurred primarily outside the wheel paths (see Photos 36). One crack developed between three core holes drilled for Sample 3, most likely caused by a fracture line created by the core holes. Little or no additional cracking was seen during the surveys. None of the cracks appeared to be related in any way to thermal segregation or to the cold spot/areas monitored. Continued monitoring of Site 4 for TDD is recommended.

1997 – Before Paving Operations. Note: pavement was cold-in-place recycled for base.

1998 – Immediately after Paving Operations. Surface paved over cold-in-place recycled base.

2001 – 3-years After Paving Operations

2003 – 5-years After Paving Operations

Photos 36 – Route 695 EB in Killingly (Site 4) at approximately 6.930 km.

Site 5

In 1998, the top three inches of pavement at Site 5 were milled off and then paved over with HMA. During the 5-year monitoring period, underlying cracks began to reflect through to the new surface layer. By the fifth year (2003), low to moderate fatigue cracking could be seen (see Figure B-4) during the distress survey. In addition, low to moderate longitudinal cracks appeared at the longitudinal joints, outside the wheel paths. With all the areas of pavement distress, it was difficult to tell whether the cold spot/areas had any effect. No trends or relationships between areas of distress and cold spot/areas were evident.

1997 – Prior to Paving Operations

1998 – After Paving Operations

2001 – Three (3) Years Later

2003 – Five (5) Years Later

Photos 37 – Route 31 WB in Coventry (Site 5) at approximately 8.797 km.

Site 6

Results of the condition survey for Site 6 indicated that pavement distresses consisted primarily of low and medium severity longitudinal cracks located along the longitudinal joints. Once again, there did not appear to be any relationship between areas of pavement distress and cold spot/areas observed with the infrared camera. Note: Site 6 is not part of the state-maintained roadway network and, consequently, was not photologged, so WiseCrax and DigitalHiway software were not available for further analysis.

DISCUSSION

Density/Air Voids

In general, cold spots/areas tended to be slightly less dense than their surrounding (normal) pavement, as five (5) out of six (6) sites evaluated had lower average (nuclear) densities (see Appendix D); and, fifty-five (55) out of ninety (90) (or 61%) cold spot/areas were less dense than their normal temperature counterparts, as measured with the nuclear density gauge.

This tendency was substantiated by the percent air voids of cored samples measured, since twelve (12) out of eighteen (18) (or 67%) cold spots had higher air voids than their normal temperature counterparts. Similar to nuclear density results, a reverse trend was observed at Site 3, as all three (3) cold temperature cored samples had lower air voids (higher density) than their counterparts.

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.

A well-defined statistical relationship could not be established 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 26-31) do not point to any type of linear or curvilinear relationships. Combining data from all six sites, the same statement can be made for the relationship between increases in air voids and temperature differentials measured with the infrared camera ($r = 0.1$). This supports results presented by Mahoney, et al. *(14)*, as their data demonstrated a "very limited trend" too.

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, base courses, mix designs, lift thickness, climate, actual temperature when compacting, and available paving and compaction equipment. It is not only possible, but probable, 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.

The density achieved may be more dependent upon HMA temperature (T) than change in temperature (ΔT). For example, if N1 = 280 °F and C1 = 210 °F, ΔT = 70 °F; and, if N2 = 205 °F and C2 = 135 °F, ΔT = 70 °F. ΔT equals 70 °F for each location, but, during compaction, the density achieved will be much different when T = 210 °F versus 130 °F.

This having been said, scatter plots between $\Delta\sigma$ and ΔT would have been more meaningful if a consistent baseline temperature, of say 280°F, was used for the normal temperature pavement. This, at least, would have eliminated one variable (T), albeit a significant one.

Asphalt Content

Asphalt contents between 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 (see Figure 5). The coefficient of simple correlation (r = 0.30) between change in asphalt content and ΔT was low (see Figure 6). Based upon these data, it appears that there is no correlation between asphalt content and temperature differentials that occur during HMA construction.

Similar to scatter plots between Δσ and ΔT, the scatter plot (see Figure 6) between change in asphalt content and ΔT would have been more meaningful if a consistent baseline temperature was used for the normal temperature pavement. Unlike density, however, asphalt contents between cold spots/areas and their higher temperature counterparts were similar, so it is unlikely that a trend exists between them.

Gradations

Gradations were also very similar, as only two (2) sets of cores that were tested and compared exceeded 8 percent coarser in passing the 2.36 mm (No. 8) sieve. Considering these data, it may be concluded that the cold spots/areas were not segregated in particle size. This is similar to a Washington study noted in Brock and Jakob's report [2] where "… gradations were taken and none of the cold areas exceeded the 8 to 15 percent coarser on the No. 8 sieve." It also supports conclusions by Mahoney, et al. *(14)*, as they found no significant particle segregation for their four projects. The coefficient of simple correlation (r = 0.17) between change in material retained on the 2.36 mm (#8) sieve and ΔT was low (see Figure 13).

Thermal Imaging

Considering the many variables involved, it is difficult to quantify conclusions via statistics, but thermal imaging did provide researchers an opportunity to perform a qualitative analysis. The following is a discussion of this analysis, which generally supports initial work by Read *(1)*, Brock and Jakob *(2)*, and follow-up work in Washington State *(14,15)*.

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 material insulated by 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 typically appeared in longitudinal strips, although, they also appeared as well-defined spots on the pavement surface.

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 truck loads, such as Site 4 in Killingly, cyclic load-to-load occurrences of these low temperature spots were observed. It was also observed that less thermal segregation generally occurred when the paver's wings were folded less frequently, as observed on Route 341 in Warren.

A significant reduction in temperature differentials were observed for the project paved with the Roadtec Shuttle Buggy material transfer vehicle. ConnDOT personnel stood on the paver during construction and noted that its operation went more smoothly 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 differentials were also noted for the project paved with the Blaw-Knox MC-30 transfer vehicle; however, an occasional cold spot/area did appear during construction.

<u>Temperature Differential Damage (TDD)</u>

Results of the five-year condition survey did not conclusively demonstrate a relationship between temperature differentials and pavement distress, but as stated previously, there are many variables involved that may have a more profound effect than ΔT. These variables are difficult to control and isolate in order to draw statistically valid conclusions. Case in point, it was observed that Site 4 had the most severe temperature differentials of the sites monitored, but held up the best of all the sites, most likely because it was paved over a cold-in-place recycled base course, whereas the other sites were paved over existing pavements.

Nevertheless, to restate more specifically, the results of the study did not prove that TDD exists, since no pavement damage or deterioration was observed during the condition surveys for the first five years. Furthermore, no statistically valid evidence of changes in asphalt content or particle size was proven to be related to HMA temperature differentials. There did appear to be a tendency for density to be lower for cold spots/areas, but this, also, was not conclusively proven.

For the six sites monitored, during the first five years, the cold areas have not deteriorated faster than the warmer (normal) areas. Five years might not be a sufficient amount of time for pavement distress to develop. Based upon feedback from the reviewers of this paper, it has been decided that ConnDOT will continue to monitor some or all of these sites.

CONCLUSIONS

The following conclusions were drawn from this five-year study:

- While densities of cold areas (average σ_{cold}=2283 kg/m^3) tended to be slightly lower than their surrounding higher temperature areas (average σ_{normal}=2309 kg/m3) of pavement, a well-defined statistical relationship did not exist between pavement density and local areas of cold temperature in the fresh HMA mat.
- For the eighteen cores tested, the air voids of the cold areas slightly exceeded their surrounding higher temperature areas of pavement by an average of 0.9%, well below the 3 to 5 percent Brown, et al. *(8)*, observed for segregated areas of pavement during their study. This average increase in air voids (0.9%) is significantly less than the increase observed by Mahoney (3.9%), et al. *(14)*, but this may have been the result of good construction practices by the contractors, which Mahoney, et al. (14), and Willoughby, el al. (15), indicated could eliminate the theorized damage due to temperature differentials.

- Grain-size distributions were similar between the cold areas and surrounding higher temperature areas of pavement, and differences did not exceed 8 percent on the 2.36 mm (No. 8) sieve.
- Asphalt contents (AC) were similar between the cold areas and surrounding higher temperature areas of pavement, and AC differences did not exceed 1%.

Based upon these conclusions, the following are theorized:

- While the presence of temperature differentials in the mix can be problematic to achieving desired levels of compaction, its significance to pavement performance should not be overvalued. HMA pavement density is more dependent upon temperature (T) than change in temperature (∆T), and density will not be significantly altered until cold spots/areas drop below certain threshold values. For instance, it is likely that HMA paved at T = 100°C (212°F) will be affected more by ∆T = 20°C (36°F) than HMA paved at T = 150°C (302°F).
- Thermal segregation and particle segregation are independent conditions, and each is capable of existing without the presence of the other. This supports Read's *(1)* initial observations and continued research by Mahoney, et al. *(14)*, and Willoughby, et al. *(15)*.
- The difference between thermal and particle segregation cannot be distinguished through the use of thermal imaging. This supports conclusions of previous research by others *(4,14,15,16)*.
- Based upon statements in the literature review, it is also theorized that pavement smoothness can be adversely affected by temperature differentials. Researchers seem to agree that a paver's screed is unable to fully consolidate isolated areas of cooler material, which are then stretched, so there is less material available for compaction *(1,2,4,14,15)*. Mahoney, et al. *(14)*, and Willoughby, et al. *(15),* indicated that these areas could still be adequately compacted with timely rolling operations. Since there is less material available in the cooler regions, in order to achieve a uniform density across the mat, a slight depression or dip would have to be created.
- Finally, considering the results of the pavement distress surveys and extent of reflective cracking observed, it appears the condition of underlying pavements play a much more significant role in overall pavement performance than temperature differentials in the HMA.

RECOMMENDATIONS

Based upon this research, the following recommendations are offered:

- HMA pavement construction incentive/disincentive payments, penalties, repairs and/or replacement should not be specified by identification of temperature differentials (∆T) alone. The temperature (T) of the mat during compaction is more significant to pavement performance; therefore, ∆T and T must be used together to identify or screen for problem areas. Once these areas are identified, they must be sampled by coring and tested for air voids, asphalt content and gradation. Then, using all of the data above, decisions can be made regarding payments, repairs and/or replacement.

- Remixing material transfer vehicles (MTVs) should be employed on larger HMA paving projects that permit long, continuous pulls. 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 thermal segregation was observed on projects paved with remixing MTVs. Note: this was also observed in Washington *(1,2)*. Less temperature variation provides an indication of improved uniformity. The second reason is based upon specifications being proposed to use pavement smoothness as criteria for incentive/disincentive payments. A) Remixing MTVs do not make direct contact with the paver and will, therefore, eliminate the "bump" that typically occurs when hauling units back up to the paver. B) Remixing MTVs reduce occurrences of temperature differentials, which were theorized to adversely affect pavement smoothness. Thus, remixing MTV usage will improve uniformity and smoothness – two highly desirable HMA pavement characteristics.
- Inspectors should continue to use a combination of probe-type and infrared thermometers to monitor temperatures during HMA pavement construction. Infrared thermometers provide inspectors with the capability to take quick surface temperature measurements from short distances. Measuring pavement temperature with probe-type thermometers is more difficult, but they provide inspectors with the capability to measure temperatures beneath the mat surface.
- Infrared cameras can be used as an effective method for detecting and measuring temperature differentials during the construction of HMA pavements. Note: care should be taken when interpreting these images because they provide surface data only. Once rollers begin compacting the pavement, water is then placed on the surface, and its cooling effect must be considered.
- Infrared camera thermographic images should not be used for detecting and measuring particle segregation during the construction of HMA pavements.
- The authors agree with additional recommendations provided by Read *(1)*. These included giving more attention to late season and night paving operations, folding the hopper wings as infrequently as possible, and using insulated or heated hauling units. Note: Mahoney et al. *(4)* of the CAP Lab also agreed with these recommendations, except for hopper wing operations. Mahoney et al. recommended that either: (1) the hopper wings not be folded at all, or (2) the hopper wings be folded frequently, after each load; but not infrequently, because "… colder material from the wings is then incorporated into the mat forming a large cold spot and decreasing the density in that specific area."
- It is recommended that an appropriate number of hauling units be employed in order to minimize delays in paving operations. All phases of mix delivery must be considered when determining the number of hauling units. These include truck capacities, plant production rates (tons per hour), speed of paving operations, and rates of compaction *(18)*. 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.
- Since five years may be too short a period of time for some pavement distresses to develop, longer monitoring periods are recommended.

Similarly, more time (than 5 years) is recommended for warranty specifications. A period of seventy (70%) or eighty percent (80%) of the expected pavement life may be more appropriate. So, for a 12-year pavement, a 9-year warranty may be suitable.

- In order to properly quantify the relationship between HMA temperature differentials and pavement density, it is recommended that future research be conducted inside a laboratory, where variables can be controlled. A standard HMA mix could be studied by applying the same compaction effort at various temperatures. Then, samples could be extracted and densities determined. Temperature tender zones would be revealed. Finally, scatter plots of temperature differences vs. density could be plotted to quantify their relationship.

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APPENDIX A

MONITORED SITE LOCATIONS AND DESCRIPTIONS

Photo A-1. Blaw-Knox PF-180H Paver Used at Sites 1 and 2.

Sites 1 & 2 - Route 85, Colchester

The first two sites were located on Route 85 at 25.655 – 25.855 km in the Town of Colchester, Connecticut. Site 1 was in the SB direction, and Site 2 was in the NB direction. Route 85 is a two-lane, undivided, state route, functionally classified as a minor arterial. Traffic volumes for 1997 and 2002 are provided in Table A7 of Appendix A. The Route 85 project was completed under State Project 172-299L.

A Blaw-Knox PF-180H paver (see Photo #1), 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 25-mm (1-inch) 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.

Site 3 – Route 8, Thomaston

The third site was 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. Traffic volumes for 1997 and 2002 are provided in Table A7 of Appendix A. The Route 8 project was completed under State Project 151-265.

A Blaw-Knox PF-3200 paver (see Photos #3 and #4), 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 25-mm (1-inch) 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).

Photo A-2. Truck Used at Site 3, Route 8 in Thomaston.

Photo A-3. Blaw-Knox PF-3200 Paver Used at Site 3.

Photo A-4. Infrared Video Recorded From Top of Blaw-Knox PF-3200 Paver at Site 3.

Site 4 – Route 695, Killingly

The fourth site was 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. Traffic volumes for 1997 and 2002 are provided in Table A7 of Appendix A. The Route 695 project was completed under State Project 68-184.

A Blaw-Knox PF-200 paver (see Photo #5), 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 4-inch, rejuvenated cold-in-place recycled base course. Note: a recycling train was used to mill, rejuvenate and replace the existing asphalt 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).

Photo A-5. Blaw-Knox PF-200 Paver Used at Site 4.

Site 5 - Route 31, Coventry

The fifth site was 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. Traffic volumes for 1997 and 2002 are provided in Table A7 of Appendix A. 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 25-mm (1-inch) DOT Class 2 leveling course.

The pavement was placed on October 19, 1998. The haul time varied between 20 and 35 minutes. It was sunny; winds were light; the ambient temperature was 41°C (70°F); and, the pavement temperature was 43°C (109°F) in the sun (no shade).

Site 6- Pigeon Hill Road, Windsor

The sixth site was 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 #6), 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 25-mm (1-inch) DOT Class 2 leveling course.

The pavements were placed on October 15, 1998. The haul time was approximately 25 minutes. 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.

Photo A-6.   Cedar Rapids CR-551 Paver Used at Site 6.

<u>Additional Sites (7-11)</u>

Five (5) additional sites for which infrared video was recorded and observations were made included: Route I-91 in Rocky Hill, where a Blaw-Knox MC-30 material transfer vehicle was employed (see Photo #7); Route I-91 in Meriden, where a Roadtec Shuttle Buggy Material Transfer Vehicle was used (see Photo #8); Route 341 in Warren; Little Meadow Road in Guilford; and Linkfield Road in Watertown. No additional testing or monitoring was performed for these locations. Pavement for all five (5) of these additional sites was placed in September and October 1998.

APPENDIX B

PAVEMENT DISTRESS SURVEYS

Sites 1 (NB) & 2 (SB)

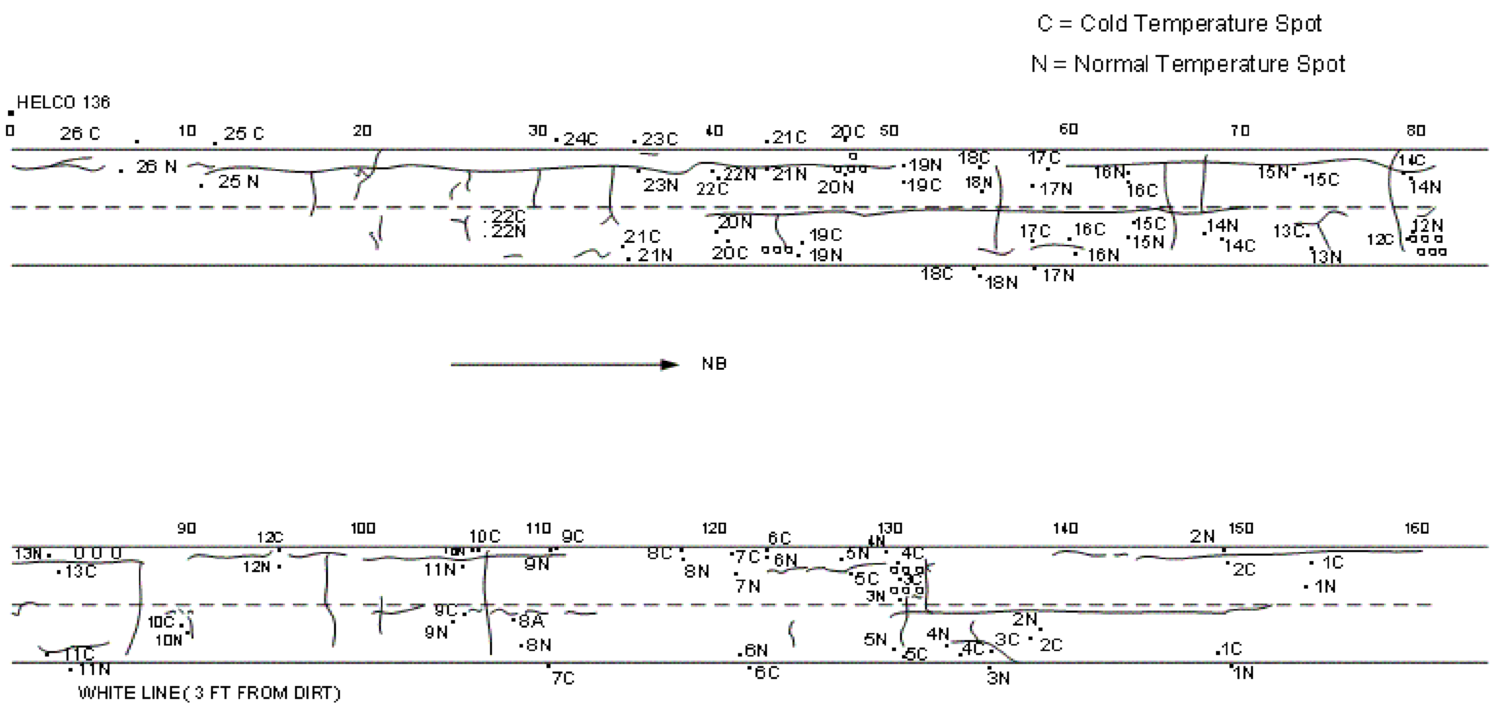


Figure B-1 – Sites 1 & 2, Route 85 Both Directions, Colchester

Site 3

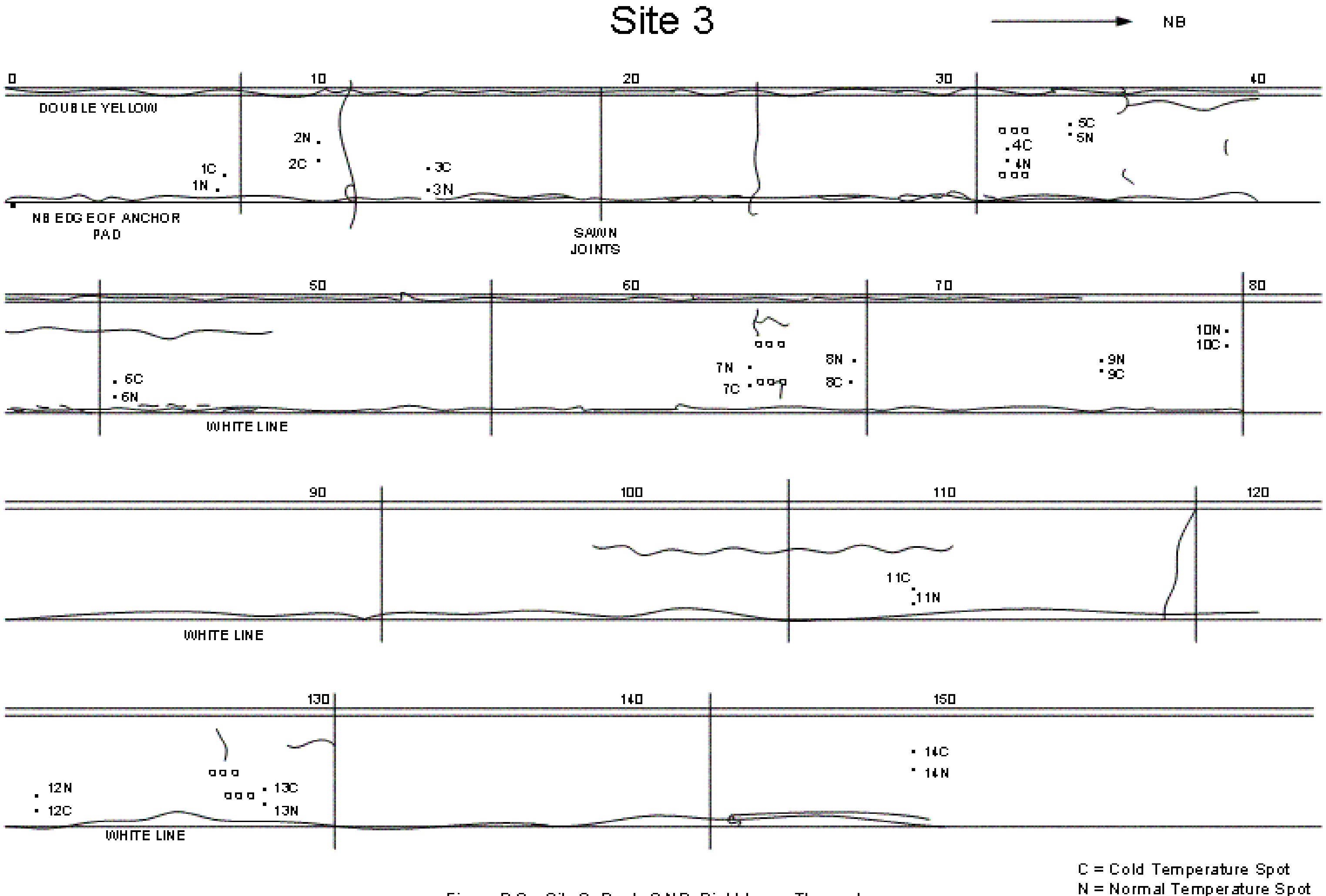


Figure B-2 – Site 3, Route 8 NB, Right Lane, Thomaston

Site 4

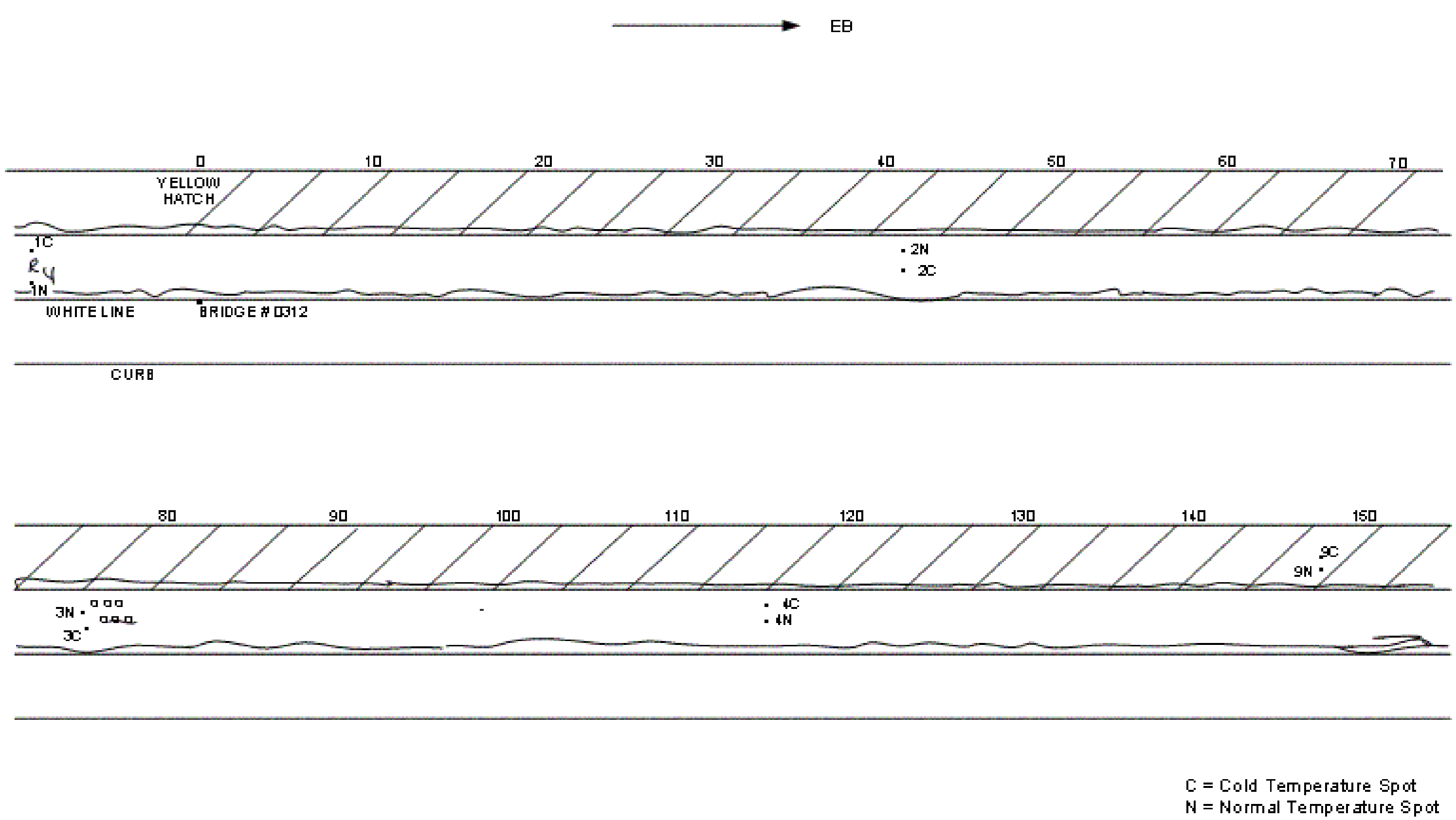


Figure B-3 – Site 4, Route 695, Killingly

Site 4 (Continued)

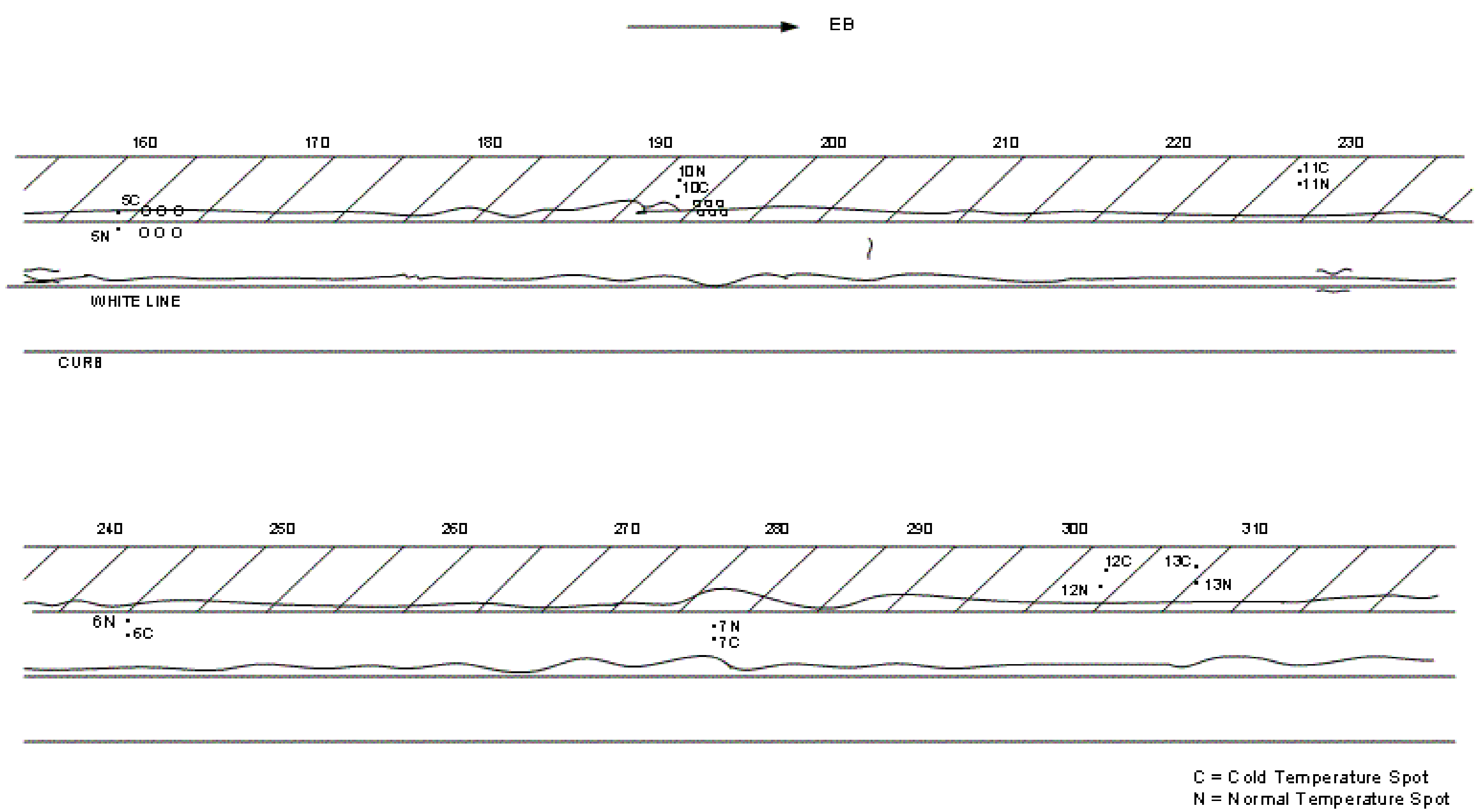


Figure B-3 (Continued) – Site 4, Route 695 EB, Killingly

Site 5

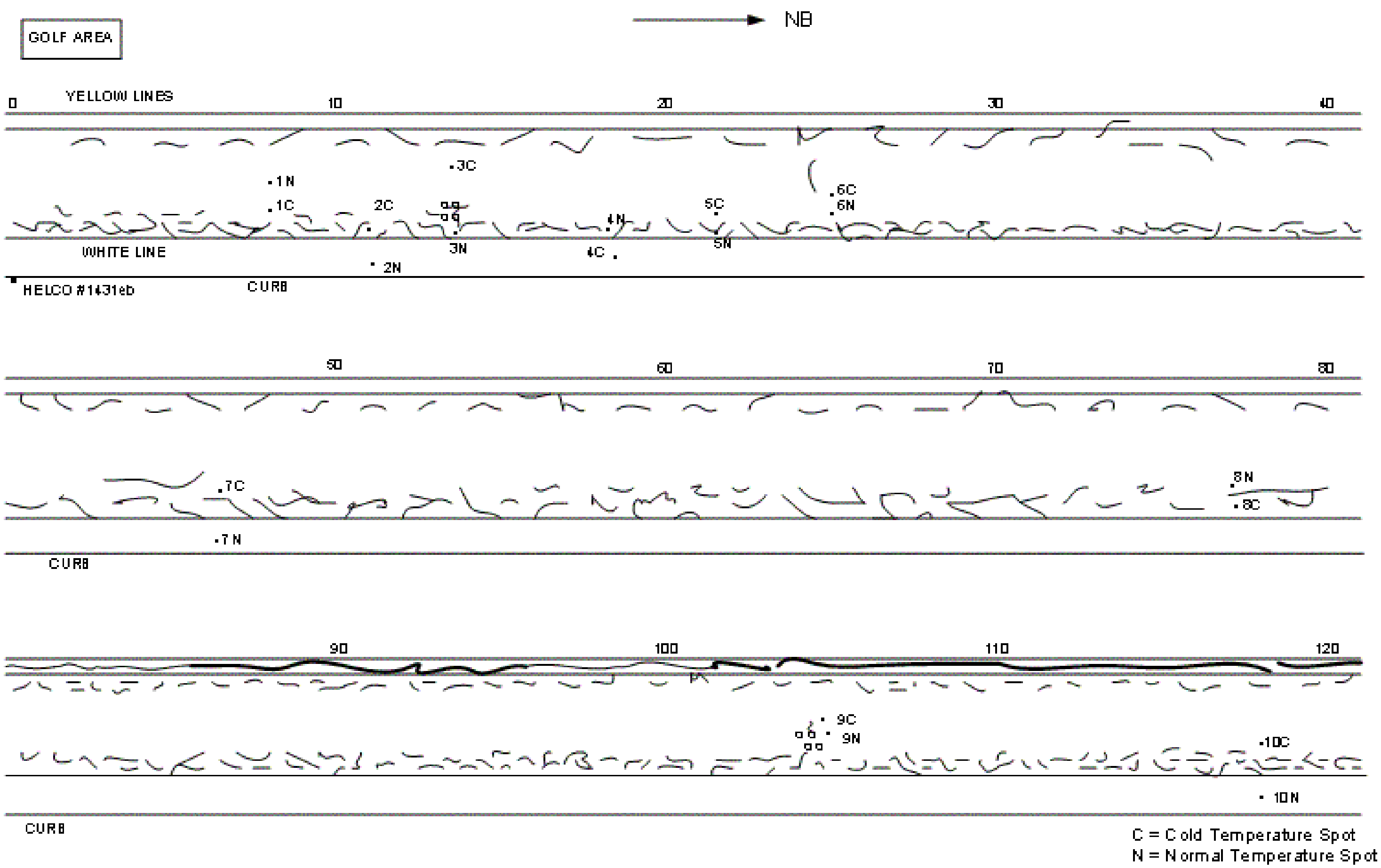
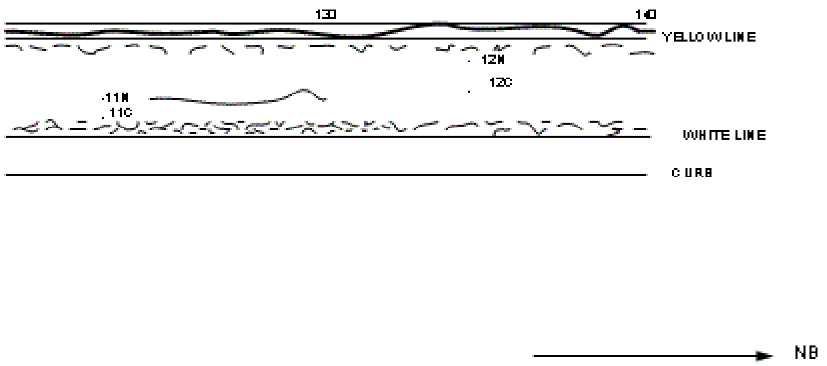


Figure B-4 – Site 5, Route 31 NB, Coventry

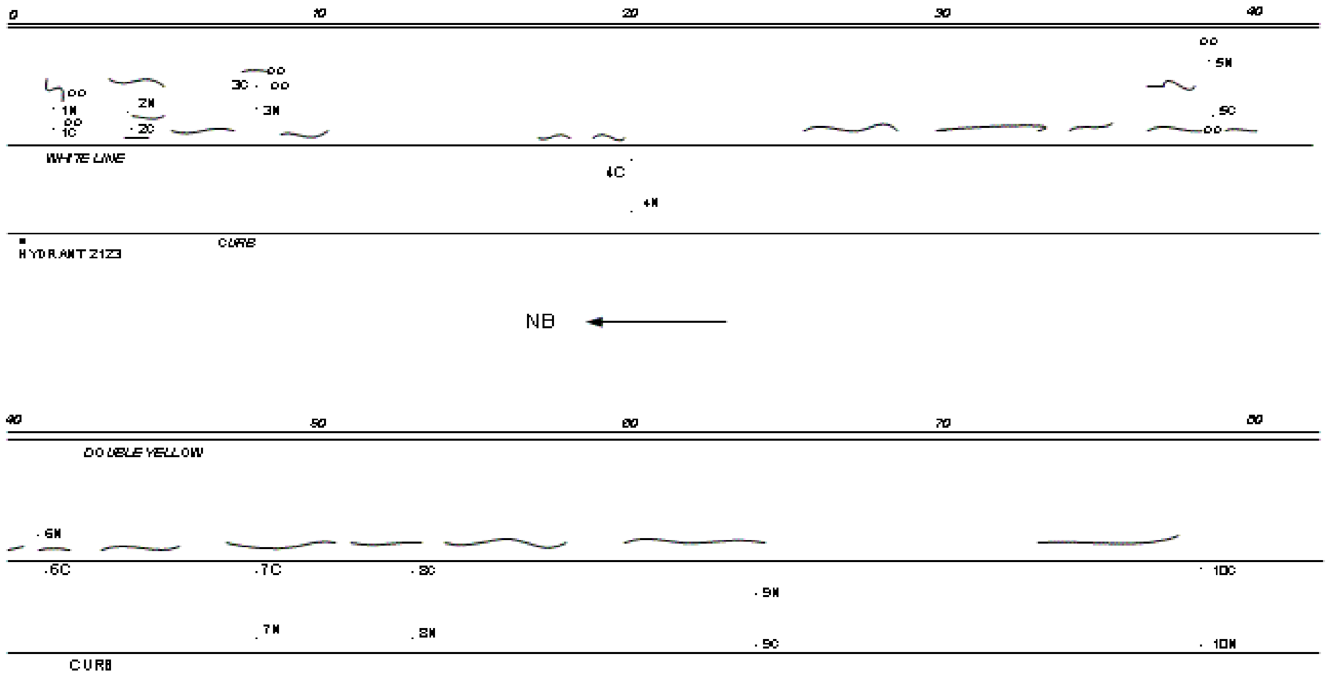
Site 5 (Continued)



C = Cold Temperature Spot
N = Normal Temperature Spot

Figure B-4 – Continued – Site 5, Route 31 NB, Coventry

Site 6



C = Cold Temperature Spot
N = Normal Temperature Spot

Figure B-5 – Site 6, Pigeon Hill Road, Windsor

APPENDIX C

MONITORED SPOT/AREA X-Y COORDINATES

Site 1, Route 85 NB, Colchester

The survey area starts at HELCO Pole 136 (SB side). X is the lateral distance from the white shoulder line (NB side). Y is the distance along the roadway from Pole 136 and increases towards the NB direction.

Table C-1
Location of Monitored Pavement Segments at Site 1.

C/N	X	Y
	(m)	(m)
22C	2.8	27.0
22N	1.8	27.0
21C	1.2	34.7
21N	0.0	35.9
20C	1.2	39.3
20N	1.7	39.3
19C	1.3	45.7
19N	0.0	45.3
18C	-0.3	53.9
18N	-0.5	54.5
17C	0.9	57.1
17N	-0.5	57.5
16C	-0.7	59.4
16N	0.0	58.9
15C	2.8	64.2
15N	1.8	63.9
14C	1.0	70.0
14N	1.4	68.2
13C	1.7	74.9
13N	1.0	74.9
12C	1.5	78.0
12N	2.1	78.4

C/N	X	Y
	(m)	(m)
11C	0.4	83.6
11N	-0.2	85.2
10C	1.9	91.4
10N	1.5	91.7
9C	2.9	105.3
9N	1.9	104.9
8C	1.9	109.1
8N	1.1	109.2
7C	-0.4	111.4
7N	-0.1	110.9
6C	-0.5	120.7
6N	0.0	120.7
5C	0.6	131.1
5N	1.2	131.0
4C	0.5	134.1
4N	0.6	133.1
3C	0.2	135.9
3N	-0.5	136.0
2C	1.5	136.3
2N	2.0	136.5
1C	0.4	149.5
1N	-0.1	149.6

Site 2, , Route 85 SB, Colchester

The survey area starts at HELCO Pole 136. X is the lateral distance from the white shoulder line, SB side. Y is the distance along the roadway from Pole 136 and increases towards the NB direction.

Table C-2
Location of Monitored Pavement Segments at Site 2.

C/N	X	Y
	(m)	(m)
26C	-0.2	6.4
2N	1.6	5.3
25C	-0.2	10.8
25N	1.6	10.3
24C	-0.2	31.2
24N	NA	NA
23C	-0.2	36.0
23N	0.7	35.9
22C	2.2	38.1
22N	1.2	38.1
21C	-0.1	42.9
21N	0.7	42.9
20C	-0.2	46.0
20N	1.1	46.0
19C	1.8	50.9
19N	0.8	50.9
18C	1.8	55.1
18N	2.5	55.1
17C	1.8	59.5
17N	2.4	58.7
16C	2.2	63.7
16N	1.5	63.6

C/N	X	Y
	(m)	(m)
15C	2.2	73.5
15N	1.6	73.3
14C	1.9	79.1
14N	2.5	80.1
13C	1.8	84.7
13N	1.0	24.7
12C	0.0	96.2
12N	0.9	96.2
11C	NA	104.2
11N	1.5	105.1
10C	0.0	107.1
10N	0.5	107.1
9C	0.0	110.6
9N	0.8	110.6
8C	0.2	117.8
8N	0.9	117.8
7C	0.3	120.8
7N	1.0	120.8
6C	0.1	122.2
6N	0.8	122.2
5C	1.6	126.8
5N	0.6	125.9

C/N	X	Y
	(m)	(m)
4C	1.2	129.8
4N	0.9	128.7
3C	2.3	130.1
3N	3.1	130.1
2C	1.7	149.2
2N	0.7	149.2
1C	1.7	152.5
1N	2.5	151.7

Site 3, Route 8, Thomaston

The survey area is located in the low speed lane and starts at the NB edge of a metal beam rail (MBR) end anchor pad. Y is the distance from the NB edge of the MBR anchor pad and increases NB. X is the lateral distance from the joint at the shoulder/right lane.

Table C-3
Location of Monitored Pavement Segments at Site 3.

C/N	X	Y
	(m)	(m)
1C	0.9	7.0
1N	0.3	6.3
2C	1.2	10.0
2N	1.9	10.0
3C	1.2	12.8
3N	0.6	12.8
4C	2.1	32.4
4N	1.9	32.9
5C	2.9	34.7
5N	2.7	34.3
6C	1.1	43.9
6N	0.8	43.8
7C	1.3	64.0
7N	1.8	64.0
8C	1.3	67.5
8N	1.7	67.5
9C	1.2	75.5
9N	2.2	75.5
10C	2.5	79.3
10N	3.0	79.1

C/N	X	Y
	(m)	(m)
11C	1.0	108.9
11N	0.2	108.6
12C	0.5	121.4
12N	1.2	121.4
13C	1.2	128.3
13N	0.9	128.5
14C	3.1	148.9
14N	2.3	148.9

Site 4, Route 695, Killingly

The survey area starts at the end of a concrete wall on the overpass of Quadock Brook, Bridge Number 0312. X is the lateral distance away from the white line (12’ from curb). Y is the distance along the Roadway from the wall and increases EB.

Table C-4
Location of Monitored Pavement Segments at Site 4.

C/N	X	Y
	(m)	(m)
1C	1.3	-11.5
1N	2.9	-11.5
2C	2.0	40.9
2N	3.2	40.9
3C	1.6	75.0
3N	2.3	75.0
4C	2.8	115.5
4N	2.2	115.5
5C	3.5	159.4
5N	4.0	159.4
6C	2.2	240.7
6N	2.7	240.7
7C	2.6	276.0
7N	3.0	276.0
8C	NA	NA
8N	NA	NA

C/N	X	Y
	(m)	(m)
9C	5.3	147.9
9N	4.8	147.9
10C	5.2	191.1
10N	6.0	191.1
11C	5.7	226.8
11N	5.1	226.8
12C	6.1	302.7
12N	5.0	302.7
13C	6.1	306.4
13N	5.6	306.4

Site 5, Route 31 Coventry

The survey area starts two feet north of CL&P Pole 1431E6. X is the lateral distance from the white curb line. Y is the distance along the roadway from Pole 1431E6 and increases towards the NB direction.

Table C-5
Location of Monitored Pavement Segments at Site 5.

C/N	X	Y
	(m)	(m)
1C	2.3	8.2
1N	2.7	8.2
2C	1.9	10.6
2N	.25	10.6
3C	3.8	13.6
3N	1.3	13.6
4C	0.4	18.2
4N	1.7	18.2
5C	2.1	21.7
5N	1.7	21.7
6C	2.8	25.0
6N	2.3	25.0

C/N	X	Y
	(m)	(m)
7C	2.2	46.9
7N	0.4	46.9
8C	2.1	77.3
8N	2.6	77.3
9C	3.0	104.9
9N	2.3	104.9
10C	2.3	118.5
10N	0.3	118.5
11C	2.0	122.9
11N	2.7	122.9
12C	3.1	122.9
12N	4.4	134.9

Site 6, Pigeon Hill Road, Windsor

The survey area starts at the Fire Hydrant on the Southbound side across from the entrance to Imperial Industrial. X is the distance from the white line. Y is the distance from the hydrant and increases towards Route 305.

Table C-6
Location of Monitored Pavement Segments at Site 6.

C/N	X	Y
	(m)	(m)
1C	3.4	1.8
1N	4.2	1.8
2C	3.6	4.2
2N	4.2	4.2
3C	5.5	8.2
3N	4.3	8.2
4C	2.4	20.0
4N	0.8	20.0
5C	3.6	37.6
5N	5.6	37.6
6C	2.8	40.9
6N	4.2	40.9
7C	3.0	48.2
7N	0.8	48.2
8C	3.0	53.4
8N	0.5	53.4
9C	0.5	63.8
9N	1.8	63.6
10C	2.4	78.8
10N	0.3	78.8

Table C-7
Traffic Volume (Average Daily Traffic) 1997 and 2002.

Site	1997	2002
1	3300	3600
2	3300	3600
3	14900	17600
4	3400	3300
5	3600	4900
6	NA	NA

APPENDIX D
TABULATED DATA

Table D-1
Site 1 - Nuclear Density Test Data for Cold/Normal Temperature Spots.

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	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 N Average Average C	101 86	 15	2271 2201	 70	9.1 11.9	 2.8

Table D-2
Site 1 - Additional Information from Locations with 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 D-3
Site 1 - Grain-Size Distributions from Cores.

Sieve Passing	Sieve Opening (mm)	3N (%)	3C (%)	13N (%)	13C (%)	20N (%)	20C (%)
200	0.075	4.4	4.0	4.2	4.6	4.6	4.8
50	0.300	17.5	15.3	19.1	19.4	17.9	18.1
30	0.600	23.5	20.2	26.6	27.0	24.2	24.4
8	2.360	38.8	32.3	44.6	45.2	41.1	40.5
4	4.750	51.5	44.0	60.0	59.7	55.5	53.7
3/8″	9.500	73.4	65.3	82.2	84.2	75.9	74.0
1/2″	12.500	98.0	96.7	97.7	98.7	98.8	98.4
3/4″	19.000	100	100	100	100	100	100

Table D-4
Site 2 - Nuclear Density Test Data for Cold/Normal Temperature Spots.

Sample	IR Temp. (C°)	IR Temp. Difference (C°)	Nuclear Density (kg/m^3)	Nuc. Dens. Difference (kg/m^3)	% Air Voids Based on Nuc. Dens.	Diff. in Air Voids (%)
1N	121	13	2304	87	7.8	3.5
1C	108		2217		11.3	
2N	113	11	2169	-88	13.2	-3.5
2C	102		2257		9.7	
3N	108	16	2239	115	10.4	4.6
3C	92		2124		15.0	
4N	107	21	2233	159	10.6	6.4
4C	86		2074		17.0	
5N	111	15	2238	99	10.4	4.0
5C	96		2139		14.4	
6N	110	25	2195	66	12.2	2.6
6C	85		2129		14.8	
7N	113	12	2233	6	10.6	0.3
7C	101		2227		10.9	
8N	104	16	2267	-13	9.3	-0.5
8C	88		2280		8.8	
9N	99	19	2308	30	7.6	1.2
9C	80		2278		8.8	
10N	93	7	2230	-22	10.8	-0.9
10C	86		2252		9.9	
11N	106	15	2182	42	12.7	1.7
11C	91		2140		14.4	
12N	96	19	2249	19	10.0	0.8
12C	77		2230		10.8	
13N	96	12	2259	26	9.6	1.0
13C	84		2233		10.6	
14N	90	11	2267	-9	9.3	-0.4
14C	79		2276		8.9	
15N	89	10	2249	83	10.0	3.3
15C	79		2166		13.3	
16N	89	10	2198	-54	12.0	-2.1
16C	79		2252		9.9	
17N	89	12	2167	-98	13.3	-3.9
17C	77		2265		9.4	
18N	89	7	2169	-72	13.2	-2.9
18C	82		2241		10.3	
19N	98	22	2342	64	6.3	2.5
19C	76		2278		8.8	
20N	98	12	2369	86	5.2	3.4
20C	86		2283		8.6	
21N	97	19	2238	-83	10.4	-3.3
21C	78		2321		7.1	
22N	86	16	2273	110	9.0	4.4
22C	70		2163		13.4	
Average N	100		2244		10.2	
Average		14		25		1.0
Average C	86		2219		11.2	

Table D-5
Site 2 - Additional Information from Locations with 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 D-6
Site 2 - Grain-Size Distributions from Cores.

Sieve Passing	Sieve Opening (mm)	6N (%)	6C (%)	12N (%)	12C (%)	19N (%)	19C (%)
200	0.075	4.6	4.3	NA	4.7	4.3	3.9
50	0.300	18.6	17.1	NA	17.8	18.3	17.3
30	0.600	25.7	23.3	NA	24.1	25.2	23.7
8	2.360	42.3	36.6	NA	38.5	41.4	37.8
4	4.750	55.4	48.3	NA	50.7	56.8	51.2
3/8″	9.500	82.4	77.8	NA	77.9	79.5	71.5
1/2″	12.500	98.2	97.8	NA	97.4	97.4	95.1
3/4″	19.000	100	99.8	NA	100	99.9	100

Table D-7
Site 3 - Nuclear Density Test Data for Cold/Normal Temperature Spots.

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 N Average Average C	108 92	 16 	2368 2403	 -35 	7.9 6.5	 -1.4

Table D-8
Site 3 - Additional Information from Locations with 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 D-9
Site 3 - Grain-Size Distributions from Cores.

Sieve Passing	Sieve Opening (mm)	4N (%)	4C (%)	7N (%)	7C (%)	13N (%)	13C (%)
200	0.075	4.3	4.3	4.6	4.6	4.3	3.9
50	0.300	16.6	16.1	17.5	17.6	20.0	18.5
30	0.600	27.8	27.1	28.8	29.9	33.3	30.4
8	2.360	43.0	42.1	43.5	46.0	49.1	44.2
4	4.750	53.4	52.9	52.7	57.0	56.4	57.2
3/8″	9.500	79.8	78.7	77.0	81.6	81.8	76.0
1/2″	12.500	99.1	98.3	98.4	98.3	99.2	97.4
3/4″	19.000	100	100	100	99.9	100	100

Table D-10
Site 4 - Nuclear Density Test Data for Cold/Normal Temperature Spots.

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
Ave N Average Ave C	120 90	 29 	2285 2244	 40 	8.4 10.0	 1.6

Table D-11
Site 4 - Additional Information from Locations with 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 D-12
Site 4 - Grain-Size Distributions from Cores.

Sieve Passing	Sieve Opening (mm)	3N (%)	3C (%)	5N (%)	5C (%)	10N (%)	10C (%)
200	0.075	3.9	3.9	3.7	3.8	3.8	3.7
50	0.300	17.1	16.2	14.9	15.4	15.8	15.6
30	0.600	26.0	24.6	22.7	24.2	24.6	25.0
8	2.360	40.9	38.1	36.5	39.6	39.6	40.2
4	4.750	50.6	47.7	45.7	50.2	49.3	49.3
3/8″	9.500	74.6	73.2	69.3	76.5	74.2	72.9
1/2″	12.500	89.1	92.6	91.2	92.9	89.0	91.3
3/4″	19.000	100	100	100	100	100	100

Table D-13
Site 5 - Nuclear Density Test Data for Cold/Normal Temperature Spots.

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 N Average C	94 75	19	2387 2374	13	8.6 9.1	0.5

Table D-14
Site 5 - Additional Information from Locations with 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 D-15
Site 5 - Grain-Size Distributions from Cores.

Sieve Passing	Sieve Opening (mm)	3N (%)	3C (%)	9N (%)	9C (%)	11N (%)	11C (%)
200	0.075	4.5	4.1	3.3	3.4	4.6	4.7
50	0.300	17.4	17.0	15.4	15.1	17.3	18.4
30	0.600	28.7	28.6	26.3	25.9	28.3	30.7
8	2.360	45.8	45.7	41.5	41.4	45.0	49.0
4	4.750	57.6	75.1	52.1	51.8	57.1	62.0
3/8″	9.500	75.9	95.8	70.7	72.5	75.0	79.6
1/2″	12.500	96.1	100	95.3	96.6	96.4	97.7
3/4″	19.000	100	-	100	99.9	100	100

Table D-16
Site 6 - Nuclear Density Test Data for Cold/Normal Temperature Spots.

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
Ave N Ave C	97 74	23	2383 2361	22	8.5 9.4	0.8

Table D-17
Site 6 - Core Additional Information from Locations with Core Data.

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

Table D-18
Site 6 - Grain-Size Distributions from Cores.

Sieve Passing	Sieve Opening (mm)	1N (%)	1C (%)	3N (%)	3C (%)	5N (%)	5C (%)
200	0.075	5.0	6.6	4.7	5.6	4.4	5.0
50	0.300	15.2	18.9	17.3	16.9	17.6	19.5
30	0.600	22.0	27.9	26.5	25.1	27.4	28.5
8	2.360	34.7	45.8	44.0	40.2	45.5	45.0
4	4.750	46.1	62.2	56.4	53.8	58.4	57.8
3/8″	9.500	62.3	79.6	72.3	70.1	74.5	75.4
1/2″	12.500	77.0	89.9	86.0	85.5	85.7	90.1
3/4″	19.000	97.6	100	100	100	98.9	100
1″	25.000	100	100	100	100	100	100