Intern. J. Pavement Engineering, 2000, Vol. 1(4), pp. 265-284
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Using Infrared Thermography to Detect and Measure Segregation in Hot Mix Asphalt Pavements

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(Received September 18, 1999; Revised May 26, 2000.)

This paper summarizes the findings from the recently completed National Cooperative Highway Research Program (NCHRP) 9–11 Segregation in Hot Mix Asphalt Pavements which details the use of infrared technology for detecting and measuring segregation. Infrared thermography can be used to detect localized areas of cooler mix during typical hot mix asphalt (HMA) construction. These areas are the result of portions of mix which have cooled differentially (temperature segregation) as well as coarse aggregate-rich areas (gradation segregation). Coarse areas tend to have both more and larger air voids around the aggregate particles which allow these areas to cool faster. This is seen in the infrared image as cold spots in the freshly laid mat.

Results indicate that a temperature differential of 10, 16, 21 and greater than 21 °C from the maximum temperature in a given infrared photograph correlate with levels of segregation of none, low, medium and high, respectively. These levels of segregation are defined by statistically significant increases in air voids, decreases in mixture stiffness, increase in numbers of sieves with a greater percent retained and decreases in asphalt contents.

Keywords: HMA segregation, infrared thermography

INTRODUCTION

Recent research has shown that both gradation segregation and temperature segregation can be found in typical hot mix asphalt (HMA) paving projects. Both of these types of segregation can be seen thermally as localized areas of cooler material. In the case of gradation problems, the large percentage and size of air voids in the coarse aggregate-rich areas accelerate the cooling of the mix. Temperature segregation occurs when the mix cools differentially around the edges of the truck box during hauling and as mix sits in the paver wings. Infrared thermography has an excellent potential for detecting and measuring any type of segregation which alters the temperature profile of the pavement mat. This technology was evaluated as part of the recently completed National Cooperative Highway Research Program (NCHRP) 9–11 project (Segregation in HMA Pavements).

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Seven projects throughout the country were evaluated during construction. Cores were taken and tested and the results were used to establish relationships between changes in temperature differences and key performance-related mixture properties such as mix stiffness, air voids, asphalt content and gradation changes. The report will present a summary of these results. Follow-on work, not reported here, is being undestaren to investigate the implementation of the methodology discussed herein.

BACKGROUND

Infrared Technology

All objects emit infrared radiation in the form of heat which can be detected by an infrared scanner. These natural impulses are converted into electrical pulses then processed to create a visual image of the object's thermal energy. The colors used to represent the thermal imaging can be user-selected to represent surface temperature changes such as blue for colder regions and red for warmer regions (Brock and Jakob, 1998; Pla-Rucki and Eberhard, 1995; Weil and Haefner, 1989).

The primary component of any thermal imaging system is the optical scanner. This unit is used to detect radiation in the infrared spectrum. Other essential components are a display monitor, video camera, and computer and software for data acquisition, analysis and storage. The area surveyed by the camera is determined by minimum resolution requirements and the height of the equipment above the surface. Up to a full-lane width can be surveyed at one time (Manning and Holt, 1986) with an appropriately placed camera. Weil and Haefner (1989) noted that liquid nitrogen-cooled scanners provide improved resolution over other methods of cooling. Although current technology is vehicle-mounted, operation at highway speeds tends to blur the image. Resolution is improved substantially by operating the equipment at slower than highway speeds.

In current pavement applications, solar heating of the surface is the source of thermal energy. This means that on cloudy days or after sun down, thermal differences are minimized. The best results are obtained when used at a time of day when the rate of heating or cooling of the pavement is most rapid (Weil and Haefner, 1989). Since air voids are poor conductors of heat, areas in the pavement mat with higher voids show up as "hot spots" in thermal images. Other weather conditions such as ambient temperature, wind speed, humidity, surface moisture, and surface texture can greatly influence results. Emissivity largely depends upon surface texture with rough textures showing higher emissivity than smooth textures.

New applications of this technology have been used to identify temperature differentials in fresh hot mix during paving operations. In some instances, the temperature difference is due to a more rapid cooling of the mix along the uninsulated sides of the haul truck or the collecting (and cooling) of mix in the paver wings. This has been referred to as "temperature segregation" by Brock and Jakob (1998). In this application, the segregated areas appear as cooler areas in the thermal images.

Other researchers (Pellinen, 1991; Lahtinen, 1991) have indicated that coarse aggregate-rich areas will have a greater percentage of air voids around the particles which will promote faster cooling of the mix in these areas. Conversely, denser and more finely packed asphalt-rich and fine aggregate-rich areas will retain heat longer. These temperature differentials will then be a measure of the degree of segregation.

A Swedish company, CA Konsult (1998), has combined both infrared imaging and global positioning systems (GPS) for the data collection and analysis of these types of images for the specific purpose of locating, detecting and measuring segregation. This source of information also notes that a standard deviation of 3°C is common for projects with no visual signs of segregation.

Influence of Segregation on Pavement Performance

Gradation segregation has been linked in laboratory studies to a measurable loss of mixture stiffness, tensile strengths (both unconditioned and moisture conditioned), and fatigue life *(Khedaywi and White. 1996: Elliot* et al. *1992: Williams*, et al. *1992*). The acceptance by industry of a loss of pavement life due to high air voids is seen in the number of states which use density for pay incentives/disincentives. Temperature segregation results in air voids typically about 5 percent higher in the cooler areas than in the majority of the surrounding pavement mat (*Mahoney, 1999*).

Several studies (Khedaywi and White, 1996, Mahoney, 1999; Alabama, 1997) have used performance-related mixture properties to estimate relative changes in performance characteristics. These properties included tensile strengths, the effect of moisture on tensile strengths, diametral and beam fatigue testing, and rate of rutting from laboratory wheel track testing devices. Cross et al. (1997) found an increase of 5 percent in coarseness, measured as a change in the percent retained on the 4.75 mm sieve, corresponded to about an 11 percent decrease in tensile strength. These measurements were also strongly correlated with air voids. This suggests that any correlation between tensile strength measurements and pavement performance should include both a measure of the degree of segregation and air voids.

Cross et al. (1997) found diametral fatigue life of cores from segregated areas decreased about 50 percent with only a 10 percent increase in the percent retained on the 4.75 mm sieve. Testing of laboratory-prepared mixtures showed similar results. In the case of laboratory-prepared samples, increasing coarseness also corresponded with increasing moisture sensitivity. However, this finding was also strongly correlated with changes in voids.

Khedaywi and White (1995, 1996) tested laboratory-simulated segregated mixtures in the PurWheel tracking device. Results showed that limited coarsening of the gradation resulted in somewhat improved rut resistance when compared to the JMF. Either fine or very finely segregated mixtures showed some increase in rutting potential. However, all of these mixtures substantially out-performed the very coarsely segregated mixtures. Conducting the test in a wet environment showed that coarse segregation increased moisture damage under the simulated traffic loadings.

RESEARCH PROGRAM

Objectives

The objectives of this portion of the NCHRP 9–11 project were to:

- Evaluate the potential for using infrared thermography for detecting and measuring segregation.
- Relate infrared measurements to performance-related mixture properties.
- Develop recommendations for using infrared technology.

Scope

Test sections were evaluated one during construction in each of locations (three in the southeast, one each in the Upper Mid-West, South, Northwest and Northeast). Infrared photographs were obtained for every 10 meters of each 150 meter test section. Photographs were taken from the driver's deck of the paver during construction. Additional field testing using the Seaman Density on the Roll (DOR) nuclear density gauge was conducted on selected projects to determine if longitudinal changes in density could be correlated with either gradation or temperature segregated areas.

Cores were obtained from each project to determine the type and extent of segregation. Testing included determining changes in density, air voids, gradation, asphalt content, mixture stiffness and tensile strength due to segregation. These results were correlated with changes in the temperature distribution at each core location then this information was used to develop criteria for detecting and measuring segregation with infrared technology.

PROJECT DESCRIPTIONS

A summary of general information for each project is shown in Table I. Of the test sections evaluated during construction were either traditional or Superpave dense HMA mixtures. One project, was a stone matrix asphalt (SMA). Testing for project 5–2 was curtailed due to thunderstorms shutting the plant down.

TESTING PROGRAM

Field Testing

Projects evaluated during construction were also marked every time the paver stopped, whether or not the stoppage was due to a change in the haul truck, and the location of any hand work. Infrared photographs were obtained every 10 meters from the back of the driver's deck. An Inframetrics Thermacam PM 280 was used on all projects. Initial work with the standard 16° angle lens on project 1–2 indicated that the full width of the pavement could not be captured in one photograph from the back of the paver. Therefore, the lens was changed to a wide angle (32°) for the remainder of the projects. The Inframetrics Ther-MONITOR software was used to convert colors into temperatures per pixel.

Longitudinal paths at transverse quarter points were marked every 10 meters throughout the entire test section. The Seaman DOR was used to determine the longitudinal density profiles along each of these paths. This equipment was motor-propelled and set to move about 0.5 mph. Results from this equipment were reported as the average values for a given one meter longitudinal distance. This equipment was operated by a Seaman representative on selected projects. A moving average of 10 data points were used to smooth the data and highlight significant changes in density.

TABLE I Summary of Project Information

Project	*Weather*	*Paving Information*	*Max. Size Agg. mm*	*Asphalt Content %*	*Asphalt Grade*	*Lift Thick. mm*
			Southeast			
1–2	Sunny, hot, humid	Paver – haul truck Day time paving	25	5.0	AC 30	45
4–2	Sunny, hot, humid	Material transfer device Day time paving	19.0	4.40	AC 30	60
5–2	Warm, humid, thunderstorms	Paver – haul truck Night time paving	19mm SMA	5.8	PG 76–22	55
			Upper Mid-West			
3–2	Sunny, warm, clear	Windrow Day time paving	12.5	5.4	NR	60
			South			
6–2	Sunny, hot, clear	Windrow paving Day time paving	37.5	3.7	AC 20	105
			Northeast			
7–2	Clear, cool (< 25°C), dry	Paver – haul truck Night time paving	19.0	5.4	NR	77
			Northwest			
2–2	Overcast, coll light showers (intermittent)	Paver – haul truck Day time paving	19.0	4.8	AR4000W	50

NR: Information not reported

The surface texture of the finished mat was visually evaluated and areas with increasingly coarser surface texture were identified. Uniformly textured areas were designated as non-segregated. A general consensus of a two-person rating team was used to further separate areas into low, medium, and high segregation based on texture differences. A visual identification of segregation could not be obtained for either the southeastern project 5–2 or northeast region test sections because of night time paving conditions; the lack of good lighting prohibited an accurate assessment of differences in surface texture.

Between 8 and 20 150-mm core locations were identified with at least three cores coming from each level of visually identified level of segregation (i.e., none, low, medium, and high). The number of cores taken depended upon the number of levels of segregation found in each project. Cold, hot and uniform temperature areas were identified with the infrared camera and used to select the core locations.

Laboratory Testing

The standard testing sequence used for determining the properties of each core is briefly described below.

- Bulk specific gravity determination (cores dried overnight at 50°C).
- Resilient modulus (stiffness) was determined at three temperatures (4, 25, and 40°C).
- Cores were initially sorted based on visual observations of segregation.
- Tensile strength, dry (unconditioned) was determined for half of the cores in each group.
- Tensile strength, wet (moisture conditioned) was determined for remaining cores.
- Cores were dried again, broken up, and the cut faces removed.
- The theoretical maximum specific gravity was then determined for each core.
- All material was retained from the theoretical maximum specific gravity testing, dried, and used to determine asphalt content and gradations.

Initial testing of cores attempted to include a measurement of permeability in the testing program, however the membrane would not seal around the cores without the use of either epoxy or grease. Since either of these methods would damage the cores, this testing was eliminated.

The ignition oven was selected for determining asphalt content and gradations for time and safety reasons (no solvents are used). Potential problems with the ignition oven degrading the aggregate were avoided by burning a core from a non-segregated area and then comparing the results to the job mix formula (JMF) reported by the agency. If a close agreement was obtained for both the asphalt content and aggregate gradation, then the ignition oven was used to determine the asphalt content. If there appeared to be a problem, at least two cores were used to determine the asphalt content and gradation with traditional solvent extraction methods. This information was used to develop correction factors for both the asphalt content and aggregate gradation on a per sieve basis.

The first step in the analysis was to determine if the visually identified non-uniformity was a function of gradation segregation. Two sieve sizes were arbitrarily selected (9.5 and 4.75 mm) for examination. These were selected based or the information presented in the literature review which suggested that a change of more than 10 percent passing one or the other of these sieves, relative to the job mix formula (JMF), was an indication of a significant (high) amount of segregation.

The percent passing each of these sieves was graphed versus the corresponding asphalt content. In most cases, there was a good correlation between changes in the asphalt cement content and gradation changes. When this was the case, the project was considered to exhibit gradation segregation. In some cases, the asphalt content changed noticeably without a change in gradation. These projects were considered to have aggregate stockpile or plant-related mixing problems.

The good correlation between asphalt content and gradation changes implies that this mix parameter can be used as a single variable to represent gradation changes. This conclusion was used to statistically re-classify the level of segregation for each core. Cores with asphalt contents near the job mix formula (JMF) were grouped together first. Natural breaks in the data were then used to further separate the data into different level of segregation. Statistics were developed for each group formed and an F-test was used to determine if the variances were statistically different. A means test (95 percent confidence level) for two independent samples with an unknown standard deviation and small sample size was then used to determine if the means were different. The classification based on significant changes in asphalt content was confirmed by evaluating each gradation for a corresponding significant change in one or more sieves. This same process was used to define the remaining levels of segregation; the data for each level of segregation for each project are shown in Table II.

TABLE II Summary of Job Mix Formula Information

Properties	*Project 1–2*			*Project 2–2*		*Project 3–2*		*Project 4–2*			*Project 5–2*	*Project 6–2*[a]			*Project 7–2*	
	No	*Low*	*Med*	*No*	*Low*	*No*	*Low*	*No*	*Low*	*Med*	*JMF*	*No*	*Low*	*Med*	*No*	*Low*
Cumulative % Passing																
37 mm												100	100	100		
25 mm	100	100	100					100	100	100		85.4	87.9	86.4		
19.5 mm	96.3	96.4	97	100	100			98.8	98.0	95	100	77.4	77.6	74.2	100	100
12.5 mm	83.7	77.8	71	97.1	95.0	100	100	81.8	78.5	74	89	61.7	62.5	57.2	99.3	100
9.5 mm	73.0	69.6	61	85.3	78.5	89.8	86.5	68.0	61.3	52	70	55.9	57.4	50.9	73.7	72.8
4.75 mm	57.0	55.0	47	52.8	44.0	50.0	45.3	43.5	39.8	31	28	39.7	40.8	35.9	55.7	51.0
2.36 mm	45.0	43.6	38	34.2	28.5	34.8	31.0	32.5	29.5	21	18	26.7	28.0	25.1	43.3	32.3
1.18 mm	36.3	33.8	32	23.2	20.5	25.8	24.0	24.3	22.8	19	16	18.4	19.7	18.1	33.7	30.3
0.60 mm	26.9	26.8	25	16.5	15.0	19.8	19.3	20.3	19.0	16	14	13.8	14.6	13.4	25.7	23.8
0.30 mm	16.0	17.0	16	12.2	11.0	13.0	12.8	16.0	15.3	13	13	10.2	11.1	10.5	18.3	16.8
0.15 mm	10.3	11.0	11	8.9	8.2	9.3	7.0	11.0	10.5	9	11	7.0	8.0	7.6	11.7	6.5
0.075 mm	6.6	7.0	6.9	6.2	5.3	4.2	4.3	6.7	6.3	5.1	10	5.2	6.2	5.6	7.5	5.3
AC Content, %	5.2	4.8	4.2	4.7	4.2	5.7	5.0	4.5	3.6	3.2	5.8	4.0	3.4	2.9	5.8	5.3
Air Voids, %	6.5	11.8	13.0	13.5	13.0	11.3	13.0	7.2	9.1	11.8	NA	8.4	7.8	8.5	7.0	10.6
Resilient Modulus MPa at 25°C	2,186	1,320	1,400	1,167	596	TS	TS	2,647	2,772	1,166	NA	3,255	3,609	2,181	1,524	2,069
Tensile Strength kPa at 25°C	NA	NA	NA	320	NA	TS	TS	776	645	NA	NA	1,150	1,084	787	55.7	448
No. of Cores	3	5	1	13	2	6	4	4	4	1	NA	2	5	3	3	4

NA: Not available or not applicable

TS: Too soft to test

a. Contractor added fine mix from hopper to top of coarse-textured areas.

While the resilient modulus was determined for three temperatures, there was little effect on the temperature susceptibility of the mixes due to segregation. This means that while there was a noticeable loss of stiffness due to segregation, the slope of the stiffness-temperature relationship did not change substantially. For brevity, only the mix stiffness determined at 25°C are shown.

The contractor on project 6–2 used a great deal of manual labor to place very fine material from the hopper over coarsely segregated areas. This tended to bias both the asphalt content and overall gradations for cores obtained from this project. That is, the gradations and asphalt content show less change due to the additional fine aggregate However, it did not influence the loss of mix stiffness, tensile strength, or increase in voids due to segregation. This indicates that other test methods than just gradation and asphalt content are needed to assess the properties of segregated areas.

RESULTS AND ANALYSIS

A comparison of the levels of segregation using asphalt content and visual observations agreed about 50 to 60 percent of the time. When there was a difference, visual observations usually indicated that the level of segregation was more severe than did the laboratory testing of cores. Segregation levels in the stone matrix asphalts (SMAs) were defined as various levels of flushing.

A comparison of the JMF to the properties of cores associated with the various levels of segregation (Table II) shows that in all cases where gradation segregation was found, there was a corresponding decrease in mixture stiffness with increasing levels of coarseness. These differences will be discussed in more detail in the following sections.

It should also be noted that while air voids also tended to increase with increasing coarseness, the standard deviations associated (about 1.2 percent) with measuring air voids made it difficult to see a statistical difference between adjacent levels of segregation.

INFRARED THERMOGRAPHY

Figure 1 shows a typical thermal photograph from an area with uniform temperature obtained during construction. The area of the thermal photograph in the foreground which does not include the edges of the pavement mat was converted to temperatures per pixel without any normalization of data. At about 5 meters behind the paver, the full width of the pavement can be seen but this area has a trapezoidal shape due to the focal length of the lens. Temperatures in the trapezoidal region shown in Figure 1 were then normalized to a standard pavement width of 3.3 meters (12 feet). The result was an ASCII data file of temperatures 123 lines long by 23 data points wide. This approach weights the temperatures near the paver heavier than those in the last half of the area. For analysis purposes, the assumption was made that the data obtained from each image would have this same bias. Therefore, changes in the temperature histogram developed for each image would be relative to any other image since the camera location was fixed and the images were obtained at incremental (10 m) distances.

These data were then used to develop temperature histograms for each photograph. An examination of the histograms showed that there were three general types of temperature profiles 1) single mode, narrowly distributed, 2) single mode, widely distributed, and 3) bi-modal. The single, narrowly distributed histogram indicates a uniform mat temperature. The single but widely distributed histogram is due to localized cooler areas associated with raising the paver wings. Normally, two populations with different characteristics would be seen as a bimodal histogram. However, in this case the mean temperatures of each population are not so different as to make them easily distinguishable. The bi-modal distribution occurs when the paver has been stopped for a length of time and there is a significant area of the mat which is cooler. Two distinct histogram areas with a wide distribution indicate the cooler area due to end-of-truck changes, flipping the paver wings, and the new hot mix (Figure 2).

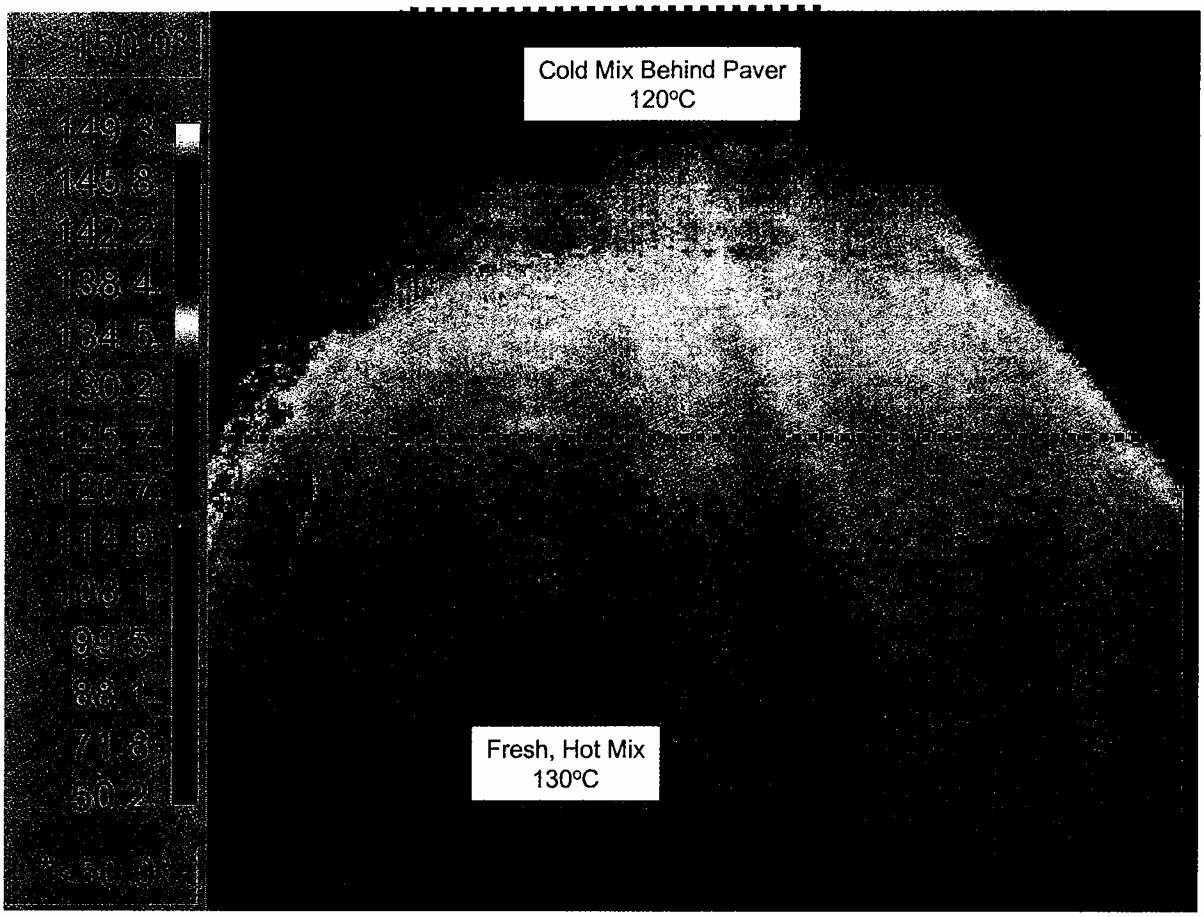

FIGURE 1 Typical Infrared Image and Area Over Which Temperatures are Normalized to the Pavement Width

The simplest way to represent the width of the spread of any distribution is to use the range. For any given photograph, the cumulative percent of the mat in a 10 meter length that was cooler than the maximum temperature in each photograph minus 10, 15, 20, 25 and 30°C were calculated from each histogram. Figure 3 shows this distribution for project 1–2. Construction processes which were expected to produce areas of segregated mix are also noted on this figure. This figure shows that there was a wide range of temperatures both before and after haul trucks were changed and after paver stopped to adjust the equipment. In between these points, less than 10 percent of the mat was cooler than the maximum temperature minus 15°C (second set of bars from the back of figure).

An examination of the thermal photographs reveled that the wide distribution of temperatures in front of the paver stop were the result of flipping the paver wings. The Seaman DOR longitudinal density data (Figure 4) shows that the wider range of temperatures immediately behind the paver produced a localized region of very low density. This is because while the roller operator was working close to the back of the paver, it could not roll 100 percent of the mat behind the paver since the equipment was in the way.

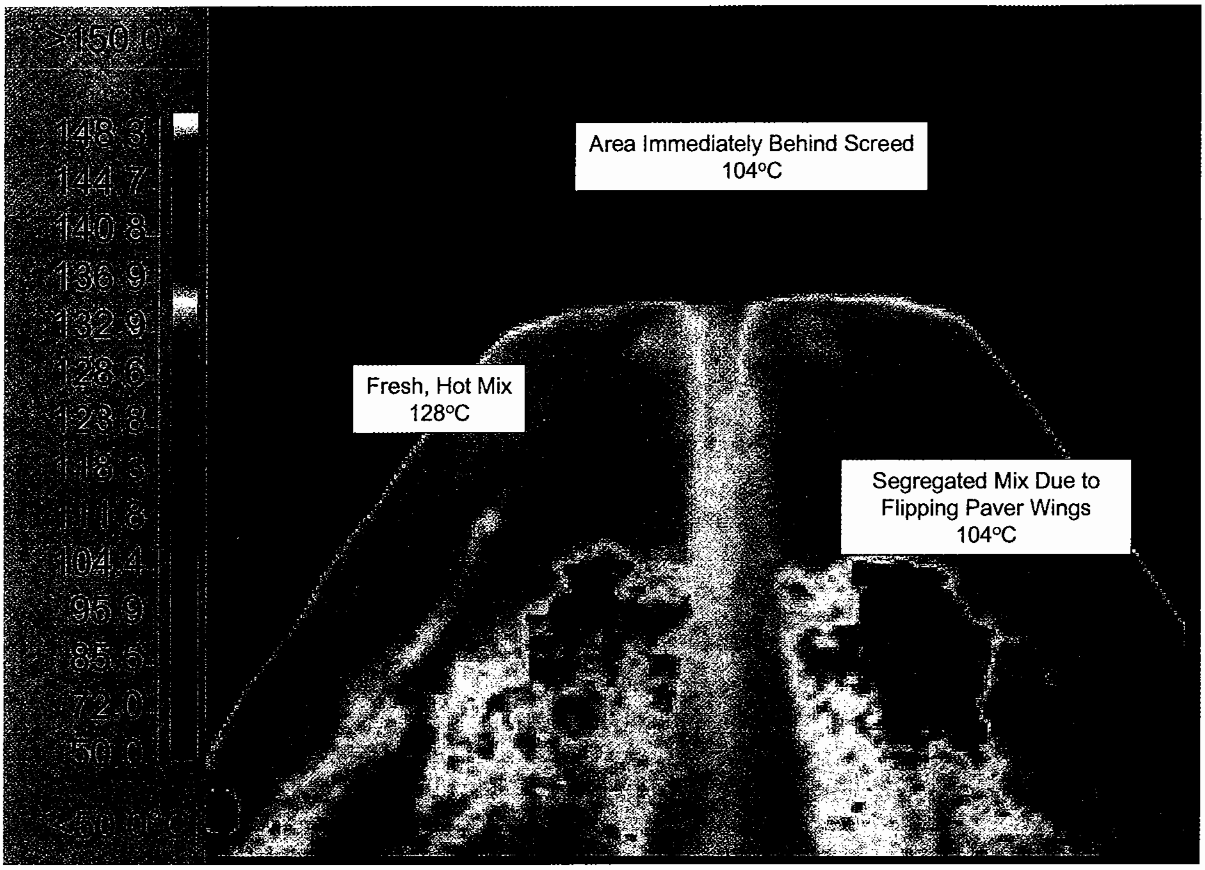

FIGURE 2 Actual Temperature Differentials Represented by Histogram Characteristics

These results suggest that there are two types of temperature segregation. The first is that noted by Brock and Jakobs (1998) which is due to localized cold or gradation segregated mix in the truck or hopper. The second is due to a paver stop long enough to result in a temperature differential of more than 20°C.

Enfrared data for project 2–2 was limited to temperature readings at each core location. Therefore, no temperature distribution information was available.

Figure 5 shows the same representation of the analysis for project 3–2. This project used windrow paving to place a tapered 40 to 70 mm first course of Superpave mix over a PCC pavement. The uniformity of the temperature profile can be attributed to a continuous and consistent windrow paving operation but the there was also a consistently wide range of temperatures throughout the new lift. Figure 5 shows that between 40 and 60 percent of the mat consistently is more than 20°C cooler than the maximum temperature. This may reflect a combination of moderate ambient temperatures and the tapered lift thickness (cooler lifts cool more quickly). It may also be a due to the long windrow placed in front of the paver which would allow a significant amount of cooling of the mix on the surface. This project had generally high voids which appears to reflect the high percentage of the mat cooler than 20°C.

Figure 6 shows the temperature profile for project 4–2. This project used a material transfer device but experienced problems with haul trucks arriving in time to prevent the paving operation from stopping. As with project 1–2, every time a paver stop was

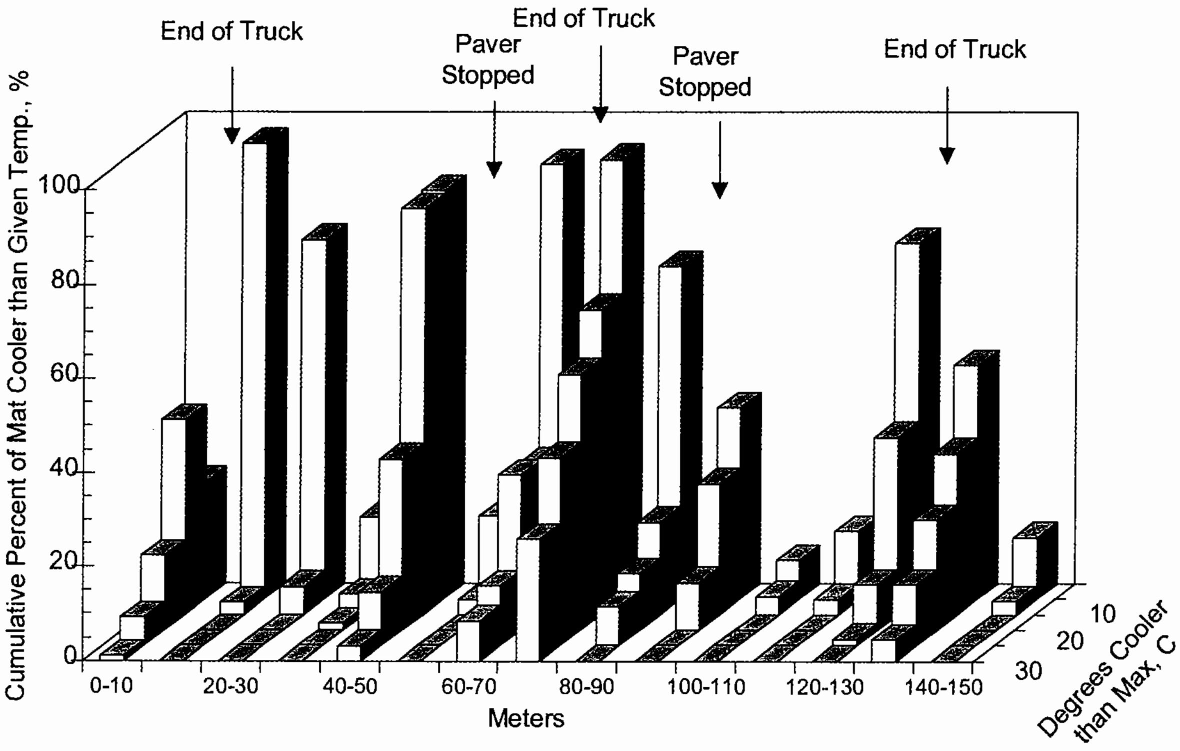

FIGURE 3 Cumulative Frequency Distribution for Project 1–2 (Southeastern Region)

noted there was wider temperature distribution behind the paver. Even though there was a surge bin in the hopper and the wings could not be raised there was an occasionally wider range of temperature in front of the paver stop. This would suggest that the material in the surge bin was cooling sufficiently so that this temperature change was apparent once paving started again. The large temperature range at the end of the test section was the result of an extended delay in the arrival of the haul truck.

Laboratory results indicated there was a strong correlation between gradation and asphalt content changes. Cores with coarser gradations and lower asphalt contents were found at the beginning of the test section (0 to 20 meters, Figure 6). Cores with high voids were found at the end of the test section which would be consistent with temperature segregation due to the paver stop.

Figure 7 shows the temperature distribution for the one SMA project evaluated during construction. At the start of this project, the plant operator had the mixing temperature set very high to compensate for the higher viscosity polymer modified asphalt being used. Initial mix temperatures behind the paver were around 180°C ("smoking" of the mix was obvious). Individual infrared photographs indicated that there may be some initial auger problems (i.e, longitudinal segregation); this conclusion is based on the longitudinally cooler areas in the center of the mat (Figure 8). As these longitudinal anomalies began to disappear, the temperature differentials decreased.

Only three cores could be taken because of an approaching thunderstorm. These coring locations were selected so that the transverse properties of the test section at about the mid-point were obtained. Air voids were 5.3, 4.2, and 4.7 percent at quarter points transversely the lane. The 4.2 percent voids corresponds with the higher temperature area.

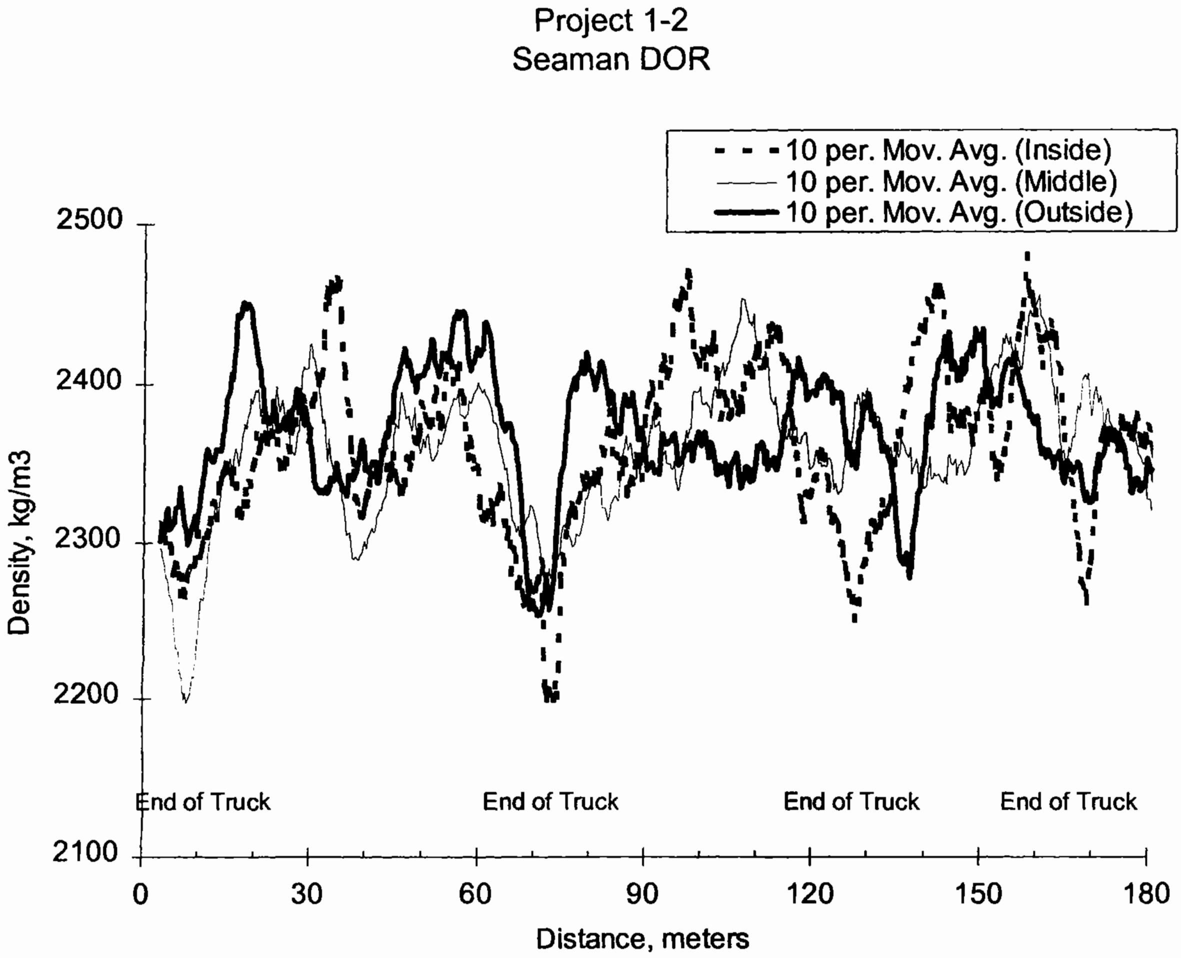

FIGURE 4 Seaman DOR Longitudinal Density Profiles for Project 1–2

Figure 8 shows the temperature distribution for project 6–2. This project used windrow paving but there was routinely a 20 to 50 minutes wait for the next haul trucks. Sometimes three haul trucks would show up at the same time while only one would arrive at other times. The contractor had assigned two workers to periodically take fine mix out of the hopper and use it to cover the coarser textured areas behind the paver. All of these construction factors (except the time intervals between haul trucks) are identified on Figure 8.

As with both projects 1–2 and 4–2, there is a noticeable increase in the percent of the mat 20°C cooler than the maximum temperature immediately behind the paver. The Seaman DOR data shown in Figure 9 confirms that these broader temperature ranges correspond with localized areas of low density although the areas are not always as obvious as in the other projects. This may be due to the artificially altered surface texture as a result of all of the hand work by the contractor. That is, the density measurements tend to vary based on changes in the coarseness of the surface texture which has been shown to affect the gauge results.

Figure 10 shows the temperature distribution for the last project (7–2). The length of this project was

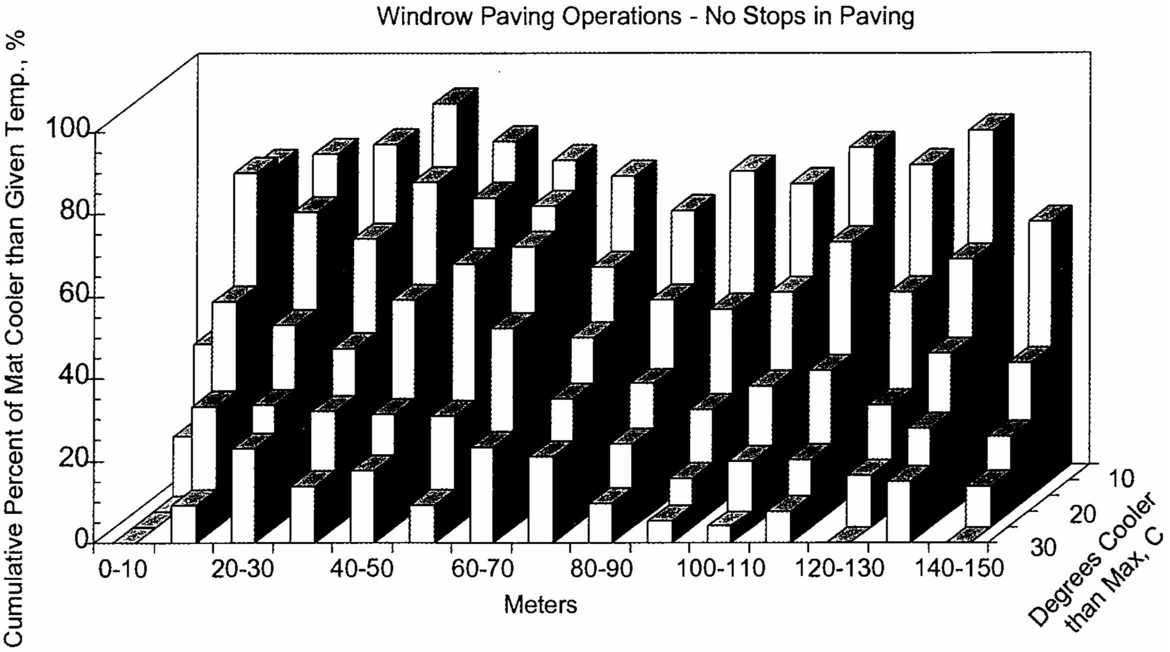

FIGURE 5 Cumulative Frequency Distribution for Project 3–2 (Upper Mid-West Region)

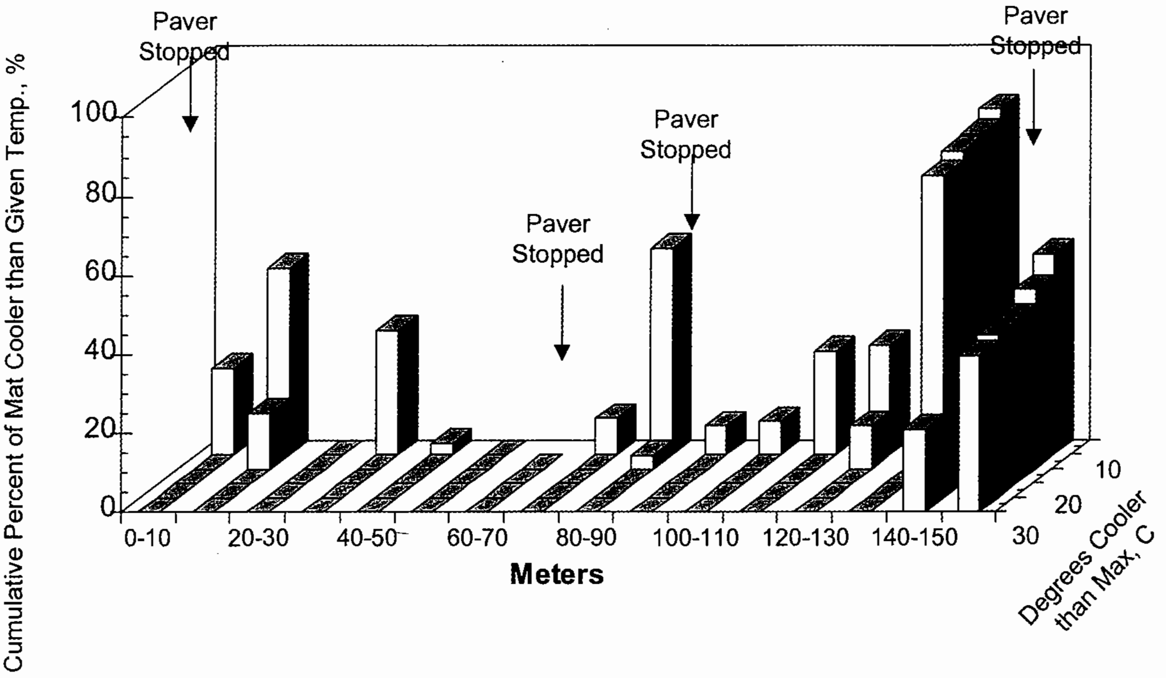

FIGURE 6 Cumulative Frequency Distribution for Project 4–2 (Southeastern Region)

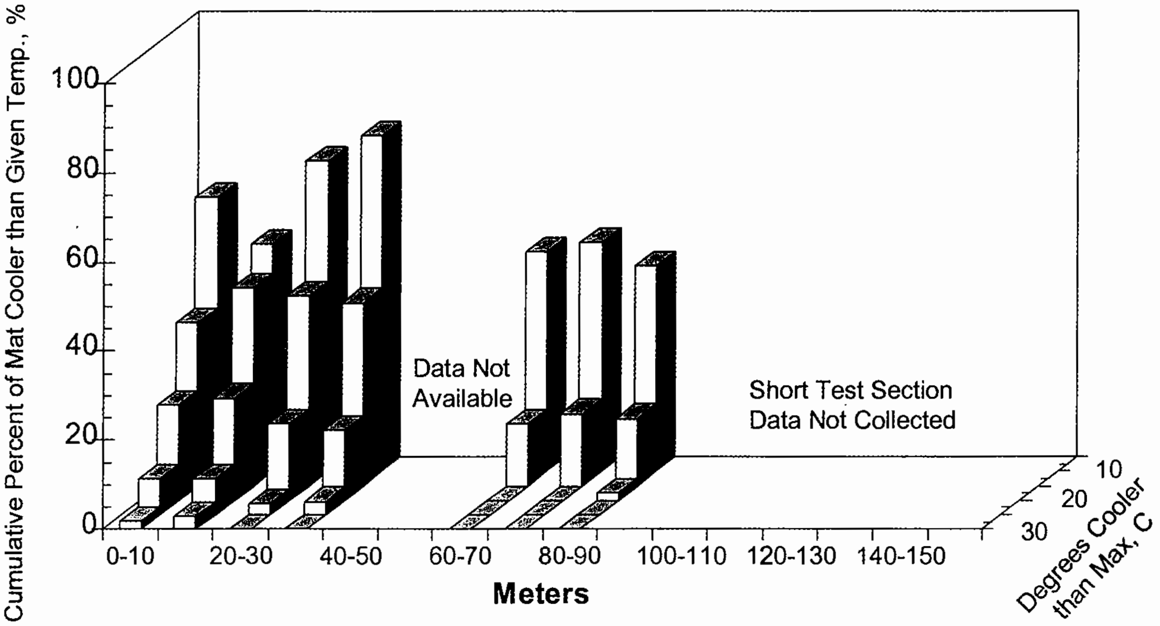

FIGURE 7 Cumulative Frequency Distribution for Project 3–2 (Upper Mid-West Region)

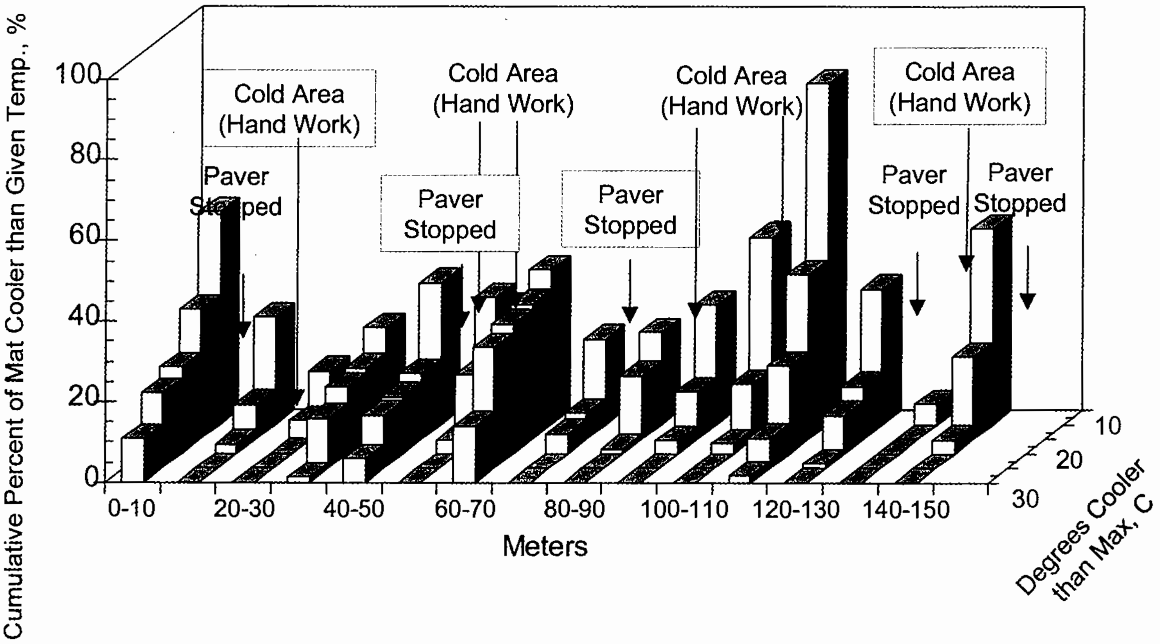

FIGURE 8 Cumulative Frequency Distribution for Project 6–2 (Southern Region)

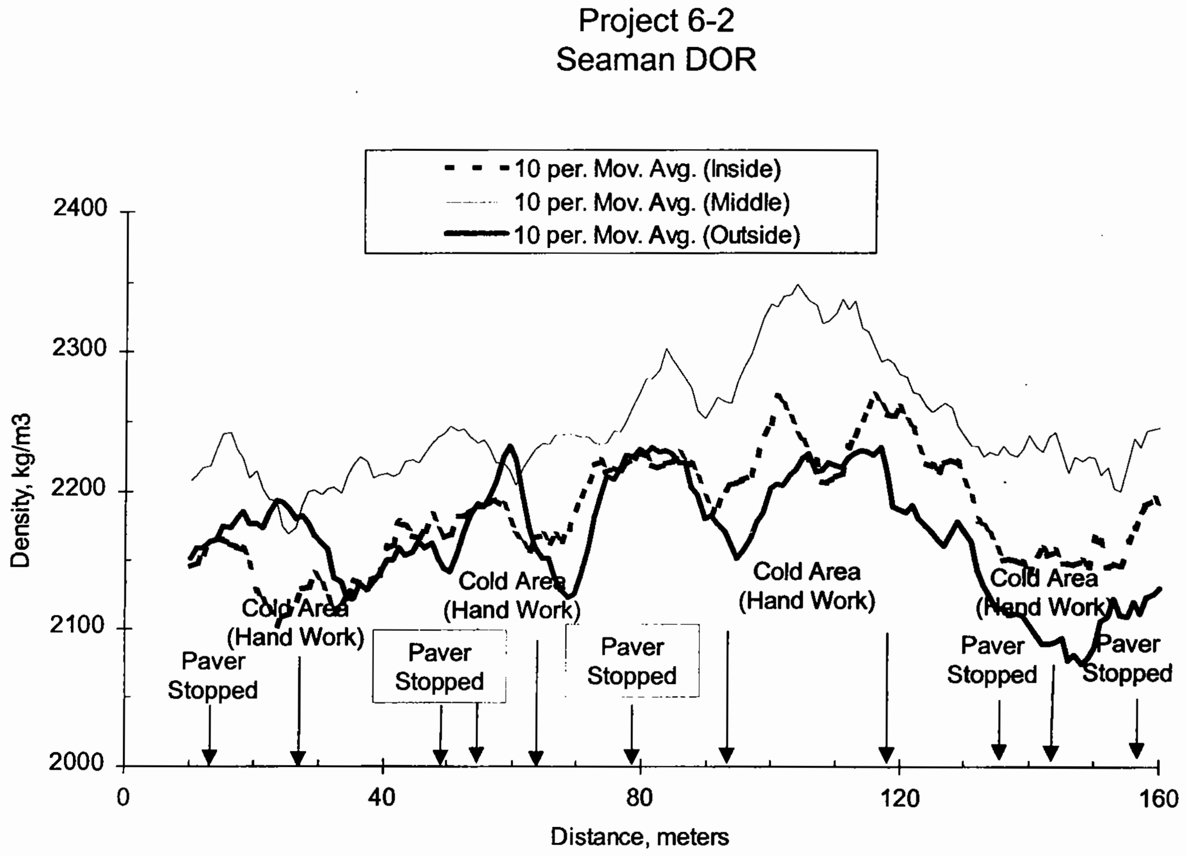

FIGURE 9 Seaman DOR Longitudinal Density Profiles for Project 6–2 (Southern Region)

shortened as the result of the contractor deciding to pave less of the lane prior to dropping back and placing the adjacent lane. Laboratory test results of cores only indicated a limited level of low gradation segregation but there was a fair relationship between cold spots and localized areas of low density. These results indicate that both gradation and temperature segregation were found on this night time paving job in the northeastern part of the country.

CORRELATION OF INFRARED TEMPERATURE DATA WITH MIXTURE PROPERTIES

The preceding data were used to estimate the mean temperature difference at each core location for a given project. These data are shown in Table III.

Temperature differences were then correlated with key mixture properties (stiffness, air voids, and asphalt content; Figures 11, 12, and 13). The magnitude of resilient modulus measurements (stiffness) have a strong dependency on the stiffness of the binder used for each mixture. Since most projects used different grades of asphalt cement, a single parameter was needed so that all of the data could be

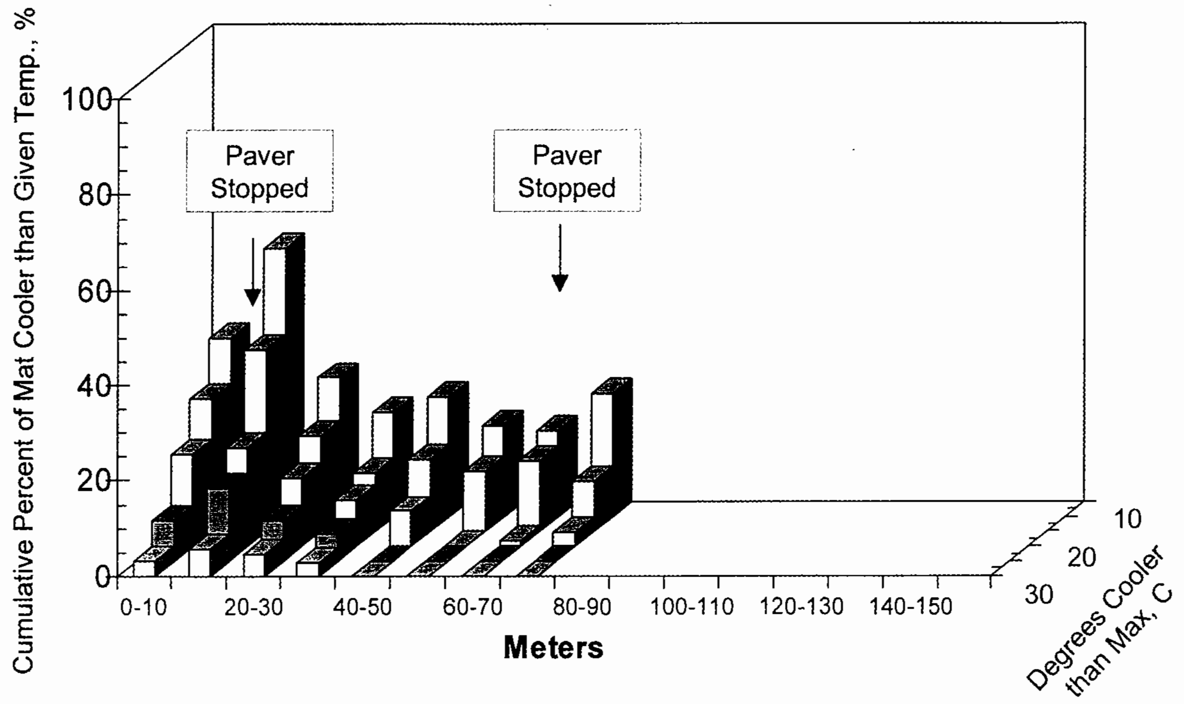

FIGURE 10 Cumulative Frequency Distribution for Project 7–2 (Northeastern Region)

compared at once. The hypothesis used to develop this parameter was that while the magnitude of the stiffness is dependent upon the asphalt grade, the change in stiffness due to segregation should be proportional. Therefore, the ratio of the stiffness of the segregated to the non-segregated mix was used. Figure 11 shows that this parameter did a good job of providing a correlation between the level of segregation and the mean temperature difference determined from the infrared thermography. Two outliers are circled; both of these are from project 6–2 with the contractor hand-work in the segregated areas. There are four values that are not shown that are all for the highly segregated areas which signified their low stiffness by falling apart upon coring. All of these cores had temperature differences greater than 25°C.

TABLE III Mean Infrared Temperature Difference from the Maximum for Each Level of Segregation

Level of Segregation	*Southeastern Region*			*Southern Region*	*Upper Mid-Western Region*	*Northeastern Region*	*Northwest*
	Mean Infrared Temperature Difference for Project No.:						
	Proj. 1–2	*Proj. 4–1*	*Proj. 5–2*	*Proj. 6–2*	*Pro. 302*	*Proj. 7–2*	*Proj. 2–2*
None	8.9	5.2	9.0	24.5	5.9	3.5	5.6
Low	12.8	11.4	20.0	19.7	18.2	18.8	13.0
Medium	16.0	1.8	--	27.2	--	--	--
High	--	--	--	--	--	--	--

-- This level of segregation was not seen; no data available

Figure 11 shows that areas with fine or no segregation typically had resilient modulus ratios of 90 percent or greater and temperature differentials of 10°C or less. Areas with low and medium segregation had stiffness values between about 70 to 90 percent and from 50 to 70 percent of the non-segregated areas, respectively. These changes in stiffness agree with the information presented in the Background section which suggested that there was a loss of about 50 percent of stiffness with a 10 percent change in the percent passing coarser sieve size(s). This level of gradation change would correspond with the designation of "medium" segregation for this research. Based on previous research which show that within-laboratory testing variability for resilient modulus testing is less than 10 percent (Stroup-Gardiner and Newcomb, 1992) and the statistics generated in this testing program (Stroup-Gardiner and Brown, 2000) showed that these ranges will approximately split the buyers-sellers risk at about 30 percent.Temperature differentials between 10 and 16°C indicate a low level of segregation while a difference between 16 and 21°C is associated with a medium level of segregation. Mixtures with differentials greater than 21°C signify highly segregated mixtures. For this relationship, the levels of segregation include both gradation and temperature segregation since either type will influence mixture stiffness.

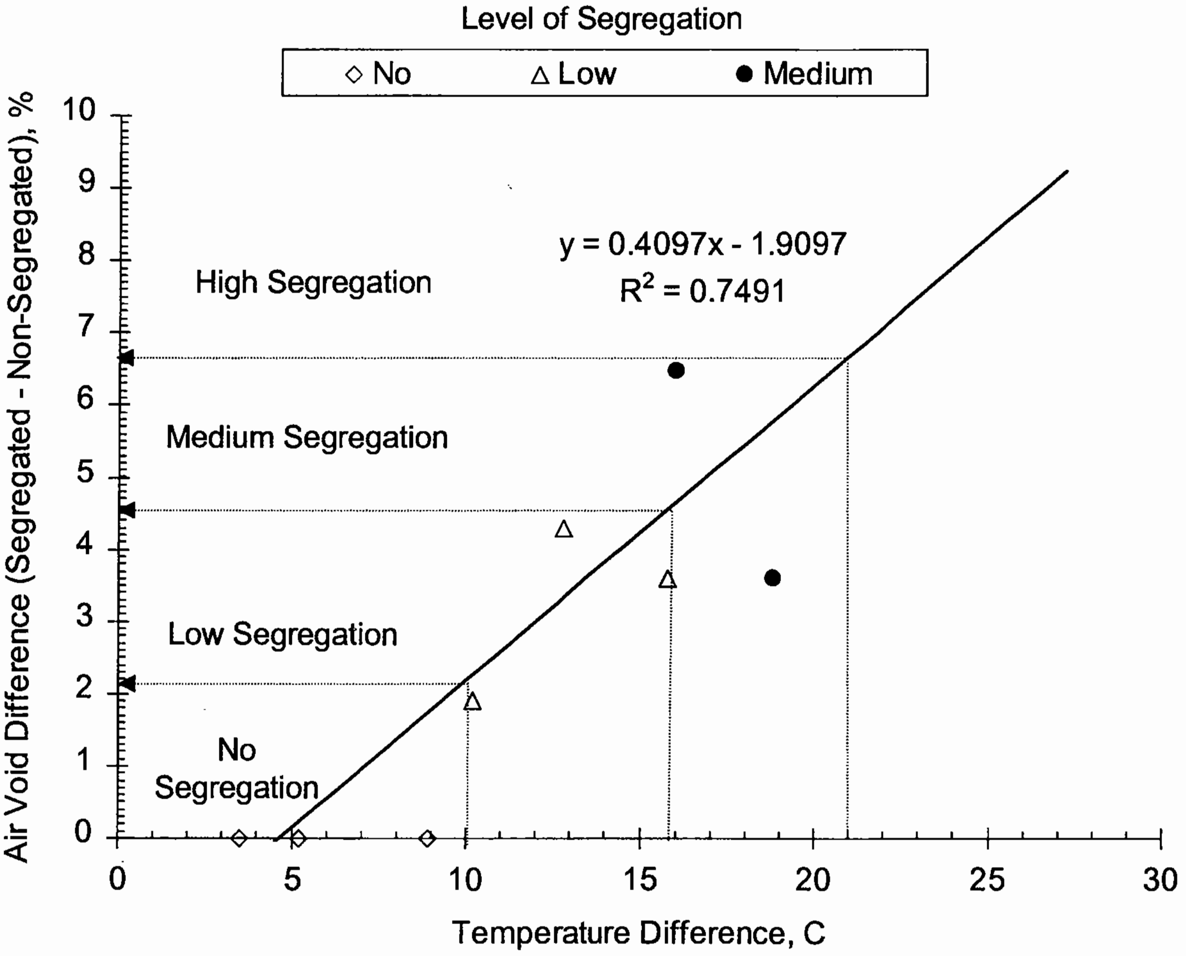

FIGURE 11 Correlation Between Infrared Temperature Differences and Loss of Stiffness Due to Segregation

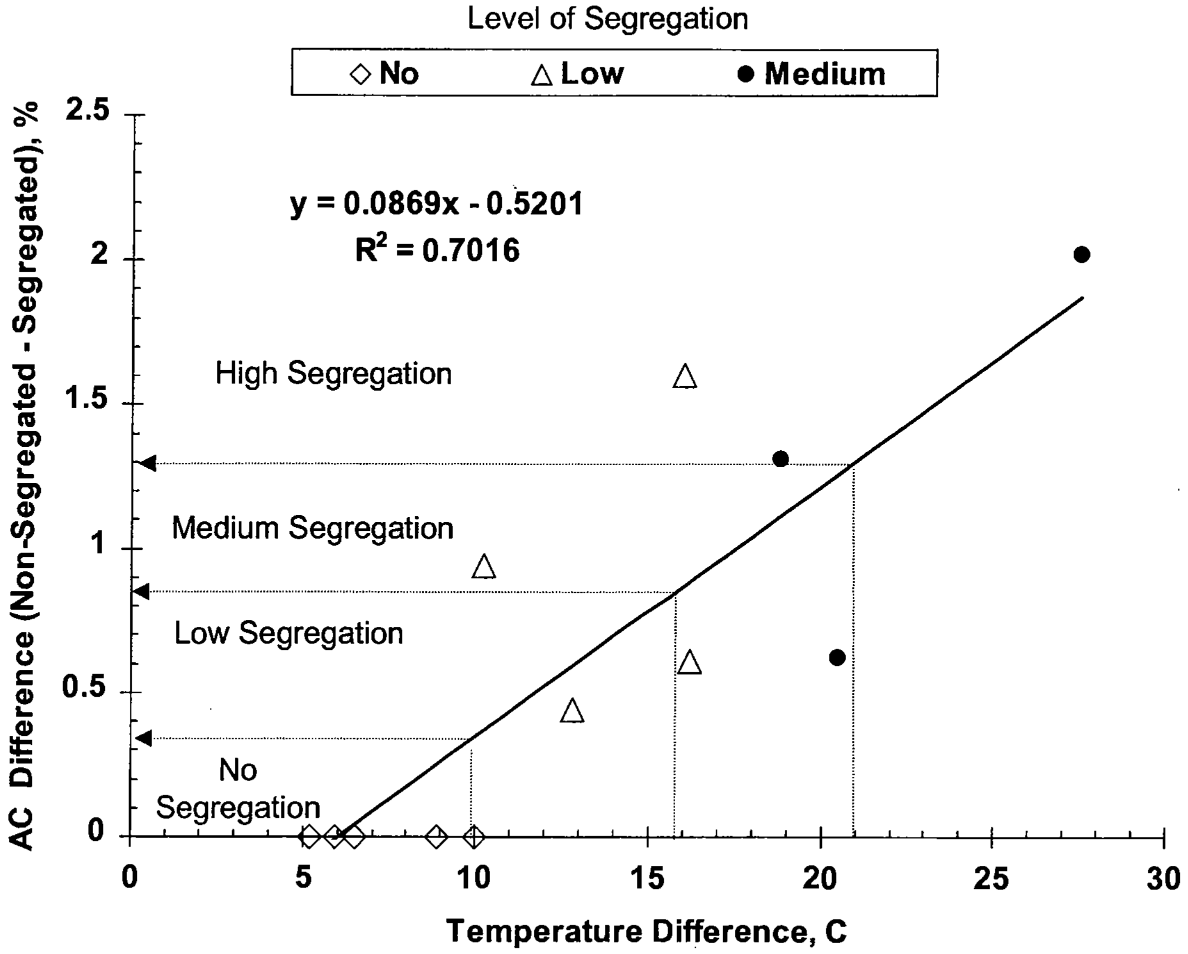

FIGURE 12 Correlation Between Changes Infrared Temperature Differences and Air Void Differences

The slope of the relationship between air void difference and the mean temperature difference indicated that, as expected, air voids increased with the level of segregation as indicated by the increasing temperature difference (Figure 12). The air void difference was used to compare projects so that relative changes could be determined. The temperature differentials used to define none, low, medium and high levels of segregation on Figure 11 are also shown on this figure. There is a good relationship between changes in air voids due to segregation and a given level of segregation identified by these temperature ranges. The overlap in air void ranges represented by each temperature differential range is the result of the large standard deviation (about 1.2%) associated with measuring air voids.

Since asphalt content was found to be a good single-factor representation of gradation segregation, then there should be a good correlation between temperature differentials and asphalt content changes when the cold areas are the result of gradation segregation. Figure 13 confirms this hypothesis. Project 3–

2 was not included in this analysis because the changes in asphalt content for this project were related to production problems and not gradation segregation. Projects 5–2 and 7–2 were eli*minated because of both limited data and a strong indication that temperature differences were related only to temperature segregation. That is, no correlation between the asphalt content and temperature would be expected. In the case of project 6–2, it is suspected that the −0.5 and −1.0 percent asphalt values should actually be shifted to one level higher of segregation. This is because of the effort by the contractor to cover up coarse areas with asphalt-rich finely graded mix which artificially increased the asphalt content determined for the cores. In general, this figure shows that infrared temperature differentials are also reasonably related to gradation segregation.

Changes in a specific sieve size or a set of sieve sizes were difficult to quantify due to the wide range of gradation curve shapes and maximum aggregate sizes. That is, fine mixtures may segregate but they will show changes on finer sieve sizes than a large maximum-sized aggregate coarse gradation. The best way found to handle this problem was to determine the number of sieves with statistically significant changes.

Based on an evaluation of the data for all of the projects (7 projects, 6 states, > 100 cores), it was found that gradations with low levels of segregation had between 1 and 3 sieves with percent passing decreases of 5 percent or more when compared to the non-segregated areas (i.e., more material retained on a sieve). When mixtures were classified as having medium segregation, between 2 and 4 sieves were more than 10 percent coarser. Highly segregated mixtures had at least 4 sieve sizes that were more than 15 percent coarser.

CONCLUSIONS

The following conclusions can be drawn from this research:

1. Infrared thermography can be used to detect and measure segregation. However, it cannot discriminate between the types of segregation (i.e., gradation and temperature segregation). This technology can be used to define various levels of segregation as follows:

- *Non-segregated* areas will have temperatures less than 10°C cooler than the maximum temperature in a photograph indicating either non-or finely segregated mixes with a stiffness within 90 percent of the anticipated value and air voids of less than 8 percent.
- *Low level segregation* will show up as areas with temperatures between 10 and 16°C cooler than the maximum temperature. These areas will have a mix stiffness between 10 and 30 percent less, and air voids between 0 and about 4 percent greater, than in the non-segregated areas. If the temperature difference is due to gradation segregation, these areas will also have a gradation with at least one sieve size which is at least 5 percent coarser than the non-segregated areas with a corresponding decrease in asphalt content of between 0.3 and 0.75 percent.
- *Medium level segregation* will have temperatures between 17 and 21°C of the maximum. The mix stiffness will be between about 30 and 50 percent less, and air voids between 2 and 6 percent greater, than in the non-segregated areas. If the temperature difference is due to gradation segregation, these areas will also have a gradation which is at least 10 percent coarser than in the non-segregated areas, at the sieve sizes, with a corresponding decrease in asphalt contents of between 0.75 and 1.3 percent.
- *High level segregation* will have temperature variations greater than 21°C. Cores will likely fall apart upon coring if the problem is due to gradation segregation. These areas will have air voids at least 4 percent greater than the non-segregated areas. If the temperature difference is due to gradation segregation, these areas will also have a gradation which is at least 15 percent coarser than in the non-segregated areas at least three sieves, with a corresponding decrease in asphalt contents of greater than 1.3 percent.

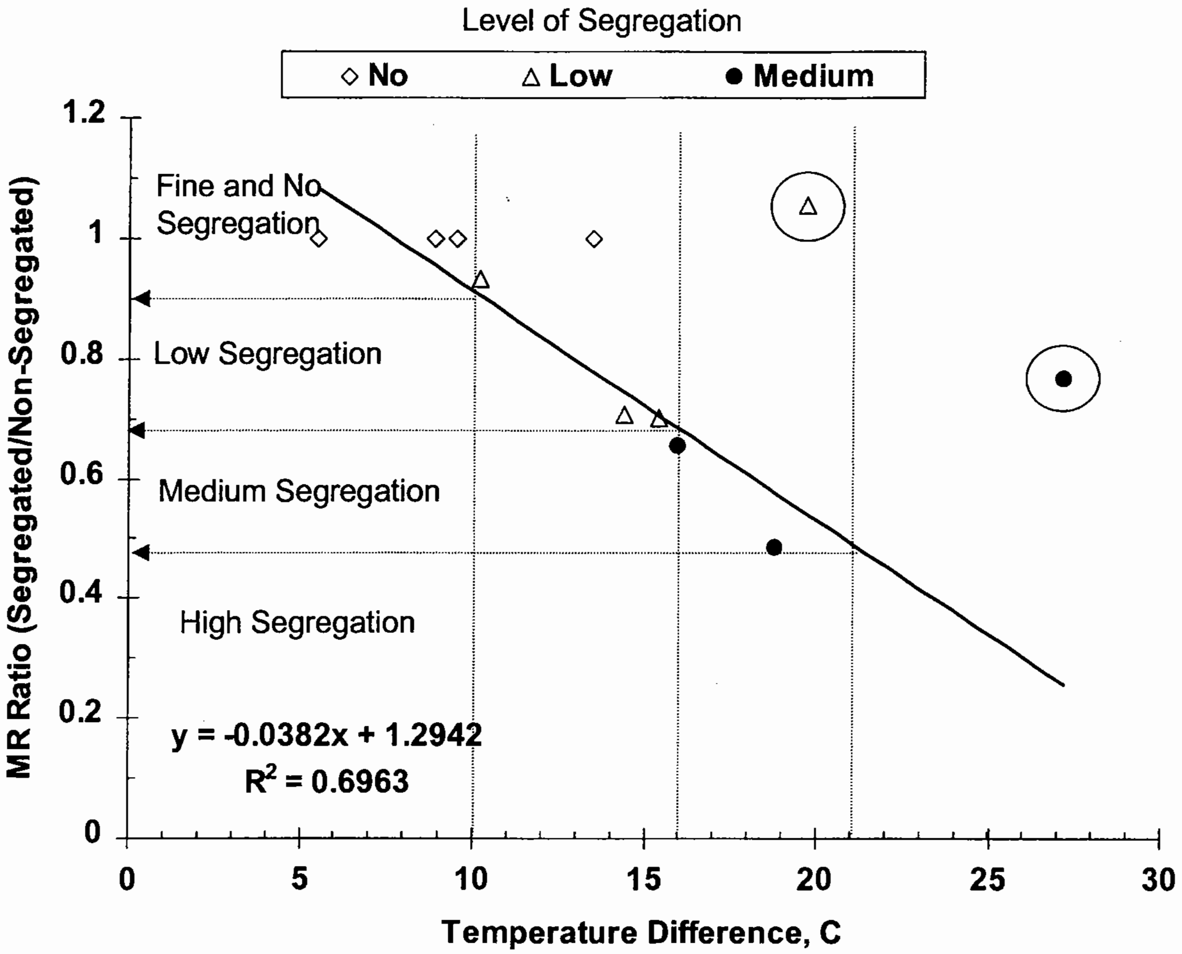

FIGURE 13 Correlation Between Changes in Infrared Temperature Differences and Asphalt Cement Content Differences

All observations with regards to air voids assumes that proper compaction temperatures and procedures have been used and that the non-segregated areas of the mat have acceptable properties.

2. Localized areas of non-uniformity with either temperature or gradation segregation can be seen as cold spots after the paver wings are flipped.
3. Clear transverse domarcations are observed between just-laid but cooling mix immediately behind the screed and fresh mix placed once the paver starts moving after a stop. Temperature differences of about 10 to 15°C or less do not appear to have a large affect on decreased density. However, differences of 40°C correlate with air voids approximately 5 percent higher in the cold areas as compared to the hot, fresh mix. These areas of poor compaction can be seen in the longitudinal density profiles obtained with the rolling nuclear density gauge.

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