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Infrared Thermography-Driven Flaw Detection and Evaluation of Hot Mix Asphalt Pavements

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This research was conducted to study more realistic explanations of how variables are created and dealt with during hot mix asphalt (HMA) paving construction. Several paving projects across the state of Nebraska have been visited where sensory devices were used to test how the selected variables contribute to temperature differentials including density, moisture content within the asphalt, material surface temperature, internal temperature, wind speed, haul time, and equipment type. Areas of high temperature differentials are identified using an infrared camera whose usefulness was initially confirmed with a penetrating thermometer. A non-nuclear density device was also used to record how the lower temperature asphalt density compared to the more consistent hot area. After all variables were recorded, the locations were marked digitally via a handheld global positioning system (GPS) to aid in locating points of interest for future site revisits in order to verify research findings. In addition to the location-based database system using Google Earth, an extensive database query system was built which contains all data collected and analyzed during the period of this study. Research findings indicate that previously assumed variables thought to contribute to decreased density due to temperature differentials, like haul time and air temperature, have little impact on overall pavement quality. Additionally, the relationship between groups of temperature differentials and premature distresses one year after paving was clearly linked.</td></tr>
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The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Nebraska Department of Roads, nor the University of Nebraska-Lincoln. This report does not constitute a standard, specification, or regulation. The United States (U.S.) government and the state of Nebraska do not endorse products or manufacturers.

Chapter 1 Introduction

Generally, hot mix asphalt pavements are designed to last 15 or more years. However, many have been failing prematurely due to cracks, potholes, raveling, and other problems—thus not meeting its original design expectations (Phillips 2008). Approximately 90% of the highways and roads in the US are paved by hot mix asphalt (HMA). In 1988, the Transportation Research Board (TRB) launched a $150 million Strategic Highway Research Program to reduce premature failure of roads resulting from poor construction methods. In 1993, Superpave® (SUperior PERforming Asphalt PAVEments) was developed through the TRB program as a set of optimized mix designs and analysis methods and standards. Even after adoption of the Superpave® mixture, premature distress of HMA pavement still persisted (Phillips et al. 2003). The expected life of a segregated pavement could be less than half of its expected 15 years. The various causes of these premature distresses are numerous and lead to squandered state allocated roadway funds.

In a series of thermographic research studies performed by the University of Washington and Clemson University (Willoughby 2003; Amirkhanian 2006), it was found that excessive thermal differentials during pavement construction cause density differentials to develop. These temperature differentials lead to a lower durability of pavements than designed. The cause was attributed to the surface and boundary cooling of hot mix asphalt during transportation from an asphalt plant to a construction site. During the transport of HMA several areas of the material are prone to rapid cooling. When the material is unloaded, it is often not remixed thoroughly and portions are therefore stiffer and more resistant to compaction. These areas of cooler material typically occur again and again in the repetitive process of HMA paving, and this reoccurring problem is commonly termed “cyclic segregation.” Cyclic segregation is simply a repetitive occurrence of low-density pavement areas within the HMA paving process.

Further study by the University of Washington has detailed that the cooler areas of hot mix with a temperature differential greater than 25°F exhibited lower densities after compaction. It was also found that asphalt that is cooler than 175°F is relatively stiff, and resists compaction, which results in a lower density than hotter areas after compaction. The less dense material is therefore prone to premature distress (Willoughby 2003).

One of the major conclusions formulated by previous research projects was that some type of remixing must be performed immediately prior to the unloading of the mix. This remixing was found to be crucial in achieving a uniform temperature. The most common remixing method is the use of a material transfer vehicle (MTV). An MTV breaks up larger masses of cooler material and remixes it, resulting in a smooth mix and a consistent temperature profile (Willoughby 2003; Gilbert 2005). However, a careful and detailed cost-benefit analysis should be considered before involving the added cost of incorporating an MTV as a solution. There have been no proven results revealed thus far to indicate that all MTVs will eliminate temperature segregation to a desirable level. In fact, a 2005 Colorado Department of Transportation study found windrow elevators to be just as effective at preventing temperature segregation as material transfer vehicles (Gilbert 2005). Due to the expensive equipment, the Nebraska Department of Roads (NDOR) has not regulated the use of MTVs for paving construction. Problems leading to temperature segregation could occur with the HMA truck delivery process, dumping and rolling practices, and environmental working conditions. With these possible problems in mind, this report presents information regarding how to utilize various sensor devices to control HMA pavement quality during paving construction.

1.1 Research Objectives

The primary objective of this study is to identify and measure variables which have a significant effect on HMA temperature segregation during roadway construction in the state of Nebraska using various portable, non-destructive sensory devices. In addition, this study also further investigates the viability of the inclusion of simple non-destructive sensory devices as a means of detecting and, in turn, controlling temperature segregation within the HMA construction process.

1.2 Research Approach

In order to accomplish the goals that were set for this investigation, two phases were created for this study. Phase one included (1) a literature review of available non-destructive sensory devices that could be used for monitoring quality control in the HMA construction process, and (2) an evaluation of the possible reasons for the occurrence of thermal differentials during HMA paving. Phase two included (3) the selection and procurement of sensory devices to be used within the study, (4) the validation of the effectiveness of infrared thermography as a test modality for assessing thermal differentials in HMA, (5) the validation of the effectiveness of the other sensory devices as a test modality for assessing HMA densities, and, finally, (6) the development of a practical and economical method of preventing and managing HMA thermal differentials.

To accomplish the above objectives, this research required close collaborations with state and local contractors. A high level of cooperation has been achieved as the result of this study will ultimately help contractors mitigate temperature segregation in HMA that develops during the paving process. It is also expected that the research previously performed by other states with suitable information brings significant benefits to this research. However, due to different environments, construction methods, and regulations in different states, the outcome of applying the technology may vary. Also, the long-term implications are worth further investigation to confirm the benefits of the study and to find a means of practical application. For example, relating thermographic data with exact location data would be worth implementing to strengthen past findings by revisiting the site for data refinement.

1.3 Organization of this Report

The following report is comprised of seven chapters. Chapter 2 highlights the findings of previously published reports that deal specifically with thermography-driven HMA inspection, and the causes and effects of temperature segregation within the HMA construction process. Chapter 3 introduces and validates the sensor devices that were used throughout this investigation, in addition to the procedure used for data collection and position tracking. Chapter 4 will discuss the analysis of the collected field data including temperature differential versus density relationships and other variables. Chapter 5 introduces an audit of previous field research locations to determine what, if any, premature defects occurred at the specific locations where data had been collected the prior year. Chapter 6 briefly overviews the methods utilized as a part of this study to sort, analyze, and present data. Finally, Chapter 7 will present a summary of this investigation’s findings and conclusions derived from those findings. In addition, specific recommendations that should be considered in the attempt to mitigate temperature segregation will be made.

Chapter 2 Literature Review

Temperature segregation has received varied amounts of attention in the last three decades as a construction-related problem (Muench 1998); however, the concept has only recently gained attention from researchers (Henault 1999). There are conflicting views on the extent of thermal segregation and its impacts on the HMA construction process. To effectively understand the HMA temperature differential phenomenon being studied, it is important to first review the topics surrounding it. The following is a brief assessment of past and ongoing research dealing specifically with temperature differentials. Topics include aggregate segregation, compaction, temperature differential and equipment, and possible causes of temperature differentials.

2.1 Aggregate Segregation

"The non–uniform distribution of coarse and fine aggregate components within the asphalt mixture" is commonly agreed upon as the accepted definition for aggregate segregation according to Willoughby et al. (2001) and the American Association of State Highway and Transportation Officials (1997). Aggregate segregation has long been suspected to cause a breakdown in the overall quality of HMA that leads to premature pavement flaws. Though the effects of aggregate segregation were given attention by Bryant in 1967, it was not until two decades later that a sustained effort was generated towards understanding the issues surrounding it (Brock 1986).

The term "segregation" typically is taken to mean "coarse aggregate segregation" within HMA research. Coarse aggregate segregation is an imbalance in the gradation of pavement material that includes a disproportionate amount of coarse aggregate to fine aggregate (Williams et al. 1996). Coarse aggregate segregation often has a rough surface texture, low asphalt content, and lower density, all of which lead to premature raveling and fatigue failure (Williams et al. 1996; Amirkhanian and Putman 2006). Coarse aggregate segregation is widely discussed alongside temperature segregation because coarse aggregate cools quicker than fine aggregate (Gilbert 2005), allowing for its identification through temperature segregation. In fact, Gilbert found mix designs with larger aggregate size to be three times more likely than fine aggregate segregation to have thermal segregation. This is somewhat contrary to the findings of Henault (1999) that cold spots and hot spots in the pavement do not typically possess varied relative gradations. Though fine aggregate segregation does occur, it is rare and is typically not included within HMA segregation investigations. The Colorado study (Gilbert 2005) on thermal segregation suggests that switching to a finer gradation mix whenever possible should be done to reduce the introduction of temperature variances to the construction process.

It is important to note that the typical signs of coarse aggregate segregation do not always mean segregation is occurring. Inadequate compaction, poor mix design, and material tearing can all generate similar symptoms that mirror those of coarse aggregate segregation (Hughes 1989). Particular attention should be paid to the misdiagnosis of poor compaction as aggregate segregation.

Segregation can occur within any part of the HMA process, from mix design to transportation or compaction. Temperature differentials generated by the HMA construction process can often be controlled through proper planning and good construction practices, however, without an adequately designed mix, thermal segregation will not be fully prevented by these methods (Brock 1986). Brock (1986) points to this by finding that a properly designed mix has the greatest effect at mitigating aggregate segregation.

2.2 Compaction

As many individuals are concerned with solving the issue of exactly where temperature differentials are created within the HMA process, it is widely accepted that once HMA has cooled to specific temperatures, achieving required densities becomes difficult. Along with decreased pavement density, increases in air voids and permeability occur which, in turn, leads to a loss of pavement service life. Additionally, Henault's study in 1999 concluded that although temperature segregation may not appear to be an issue during initial lay down, it becomes more pronounced during material rolling (Henault 1999). For those reasons, significant weight is placed on proper rolling techniques.

Though the concept of studying temperature differentials is relatively new, the connection between decreased compaction temperatures has accompanied lower pavement densities for some time (Parker 1959; Kennedy et al. 1984). Willoughby et al. (2001) describe the importance material temperature plays in achieving overall density through the analysis of past researches' findings. Highlighted in this report is a study that compared the percent air voids of asphalt samples at various temperatures. Its findings showed that a sample compacted at 200℉ possessed double the amount of air voids contained in a sample compacted at 275℉, with the air void discrepancy quadrupling when the sample was compacted at 150℉. As the HMA mix cools, the asphalt binder eventually becomes stiff enough to effectively prevent any further reduction in air voids regardless of the applied compactive effort. The temperature at which this occurs is commonly referred to as cessation temperature (Pavement Interactive 2009). A recommended minimum compaction temperature of 225°F was found and has been supported through later research, and most recently by Kennedy et al. (1984). In some literature it is reported to be about 175°F for dense-graded HMA (Scherocman 1984b; Hughes 1989). Below cessation temperature, rollers can still be operated on the mat to improve smoothness and surface texture, but further compaction will generally not occur (Pavement Interactive 2009).

The air voids and permeability that accompany decreased compaction have drastic effects. Brown (1984) points out that proper density must be achieved to obtain correct percent air voids and shear strength for the material. When increased permeability is present, the material loses its waterproofing ability and the asphalt binder will break down due to oxidation (Brown 1984; Cooley and Brown 2001). A strong relationship was found to exist between permeability and pavement air voids, leading to Cooley and Brown's (2001) recommendation that field permeability should be used as a quality control method for "selected HMA construction projects." Another possible method to guard against permeability and its associated problems is to increase the lift thickness on HMA job sites (Mallick 1999).

In 1984, Scherocman and Martenson identified non-uniform material textures as often accompanying temperature segregation. This is an important point to recognize because varied HMA surface texture is typically found to cause poor compaction. The same authors reiterate that the decrease in achieved density translates to a decrease in the useful life of the pavement. They note density as being the standard indicator to how a pavement will perform. In fact, Gilbert (2005) found that temperature segregation does often lead to decreased densities, but also notes that 77% of the locations exhibiting signs of temperature segregation achieved adequate relative compaction within the Colorado study.

Although many issues underlie inadequate pavement compaction, which in turn leads to a multitude of negative pavement qualities, they can be readily combated through proper compaction techniques. Because many believe poor compaction densities are caused by decreased material temperatures, effectively pacing the correct number of rollers with the speed of the HMA paver is a key to decreasing the effects of temperature segregation (Muench 1998).

2.3 HMA Equipment

When investigating where and why temperature segregation occurs in the HMA construction process, the equipment and its operation are immediately considered. It is helpful to research past findings of equipment used within the state of Nebraska as well as others. Although it was requested that material transfer vehicles (MTV) not be included in this report's final recommendation, they should be, at a minimum, briefly covered through this literary investigation.

Three types of HMA haul trucks are used within the State of Nebraska: (1) rear dump truck, (2) belly or bottom dump truck, and (3) live belly or bottom dump truck. On the whole, material transport trucks have been widely noted as the initial cause of the temperature differentials (Read 1996). In a HMA transport truck, the surface or periphery material cools at a much faster rate than the material in the center of the load. These cooler areas of material are transferred into the paver and appear as temperature segregated pavement areas (Willoughby 2003). Steps can be taken to mitigate the rate at which the outer crust cools (Read 1996). However, the nature of the HMA construction process is such that no matter what form of truck is used, a cyclical pattern of cold material will always be introduced onsite. Because of the segregating inducing properties present in HMA trucks, it is important to properly select the appropriate haul truck.

The direct dump truck or rear dump truck has been the standard in HMA construction for several years. The rear dump truck transfers its load by directly dumping the material into the paver’s hopper. Proper staging is crucial to this process’s success because truck operators are required to constantly marry with the paver hopper to keep the construction process moving (Muench 1998). This process is rapidly losing favor among state DOTs and contractors for its temperature differential inducing properties and small capacity. It was suggested to the Colorado Department of Roads that these trucks only be utilized when coupled with a remixing device (Gilbert 2005).

Bottom dump trucks are quickly becoming the standard within the HMA construction process. Brock and Jakob (1997) have estimated a rise in construction productivity of 35-40% when using this type of truck. Bottom dump trucks are tractor-trailer style trucks that receive HMA through the top of the trailer and then distribute their load on the pavement ahead of the paver. Some form of material transfer device is required as part of this process. Instances of thermal segregation created by the truck are minimal when compared to direct dump trucks; however, many contend that dumping material onto the colder existing pavement promotes temperature segregation (Brock and Jakob 1997).

Live bottom haul trucks are not as common in Nebraska. They are similar to the bottom dump trucks mentioned above, however, instead of transferring their load to the pavement, they transfer their load directly into a transfer device through a conveyor at the bottom of the truck. Again, this truck typically sees a decrease in thermal segregation when compared to the direct dump method (Brock and Jakob, 1997).

As noted earlier, aggregate segregation is thought to be very closely tied to thermal segregation. To decrease the likelihood of aggregate segregation during transport, Kennedy et al. (1987) and Brock (1988) suggest that trucks should be loaded in multiple dumps. By following a multiple load pattern there is less of a chance for large aggregate to roll away to the sides of the truck and cause gradation and temperature problems later.

After the trucks have delivered the material to the site, it is up to transfer equipment to adequately remix and deposit the material into the paver’s hopper. There are three primary forms of material transfer equipment: (1) material transfer vehicles (MTVs); (2) material transfer devices (MTDs); and (3) windrow elevators.

MTVs and MTDs are large external remixing devices. Rather than depositing the material to be fed directly into the paver, the trucks load a staging hopper within the MTV and MTD. The material is then thoroughly remixed by large augers. This ensures a consistent gradation of the HMA and reduces temperature segregation. The use of these vehicles also allows for a smoother work process because the paver never needs to stop to receive HMA as long as the MTD or MTV has material stockpiled (Brock and Jakob 1997). Amirkhanian and Putman (2006) note that the Connecticut and Washington DOTs have seen marked decreases in the instances of thermal segregation on their job sites since these types of equipment were introduced (Read 1996; Henault 1999).

Windrow elevators are not designed for material remixing. The elevator simply collects the deposited material from the existing pavement, left behind by the haul trucks, and transfers it to the paver hopper. The paddles used to scoop up the material and the conveyor do, however, provide some level of remixing. Gilbert (2005) found windrow elevators to be just as effective at achieving proper levels of remixing as the more expensive MTVs and MTDs. Amirkhanian and Putman (2006) have also found the usefulness of windrow elevators not only for their remixing properties, but also because a decreased number of cold joints and less streaking occur when they are employed.

Finally, the paver is examined. In particular, a HMA paver's hopper wings have been tied to the generation of thermal segregation. As material is dumped into the hopper, the unfolded wings collect material that sits static and does not enter the paver unless the wings are closed. As the wings are closed, the cooled material drops into the paver and is then introduced into roadway pavement as a pronounced area of temperature segregation (Read 1996; Henault 1999; Amirkhanian 2006). It is suggested from these past findings that hopper wings not be folded during the HMA paving process because it only promotes more extreme temperature differentials.

2.4 Thermography Driven HMA Inspection

Infrared heat guns have been used in the paving industry for some time, however, their next generation counterparts, infrared cameras, are somewhat new within the industry. These cameras are incredibly efficient at identifying and quantifying temperatures' segregation. Gardiner et al. (1999) are credited as being among the first to use infrared thermography to quantify temperature differential damage. Through their analysis, they were able to identify areas of poor density and decreased asphalt content. Additionally, the Washington State and Clemson University studies on HMA segregation found the use of infrared cameras to be adequate for identifying thermal segregation

(Willoughby 2001; Amirkhanian and Putman 2006). In Gilbert's (2005) report on thermal segregation, the cameras were again found to be useful in identifying and analyzing the extent of the thermal segregation.

Chapter 3 Research Methodology

3.1 Sensory Devices

3.1.1 Infrared Camera

For verification of the use of thermal image data in HMA applications, temperature readings were initially taken on the surface of the HMA as well as internally using a temperature probe. The internal and external temperature readings were compared to those obtained by the infrared camera. This was also done to ensure the specific infrared camera used in this study provided an accurate representation of temperature differentials. The accuracy of infrared cameras in general has already been proven in HMA applications by the University of Washington study, which notes that both temperature probes and infrared cameras are adequate tools for proving temperature differentials (Willoughby 2001). Figure 3.1 shows a Flex Cam XR2, the infrared camera used in this research. Figure 3.2 shows infrared images taken from Nebraska paving sites.

Figure 3.1 Infrared Camera

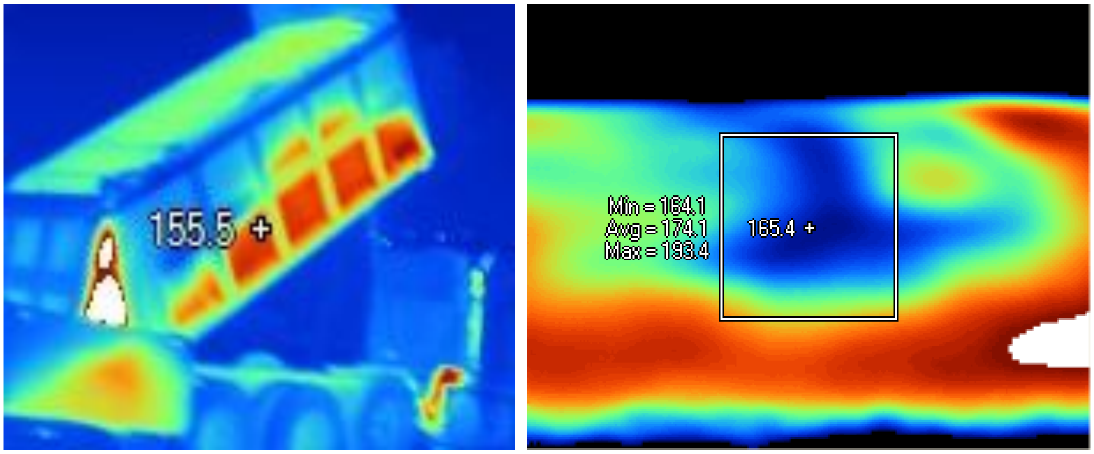


Figure 3.2 Heat Loss from a Truck (left) and Temperature Differential from an HMA Mat (right) with Temperatures Shown in °F

3.1.2 Non-Nuclear Density Gauge

For the last several decades, density of freshly laid HMA mats has been measured by contractors using nuclear density gauges. However, use of these devices requires the user to maintain an inordinate amount of records for the equipment. These requirements include calibration and recalibration records, certification records of the operators, records of radiation badges, and periodic testing of the operator's badges for radiation exposure. In addition, there is a concern about possible accidents involving the gauges that might expose the operators or other bystanders to the radiation source (Schmitt 2006; Sargand 2005). Due to these issues and concerns associated with using the nuclear gauges, this study adopted a non-nuclear density measurement method for paving quality control. After a thorough literature review, the Pavement Quality Indicator™ (PQI) 301 developed by TransTech Systems, Inc., was selected (TransTech 2008). The validation and effectiveness of the PQI has been tested in several states, including Texas (Sebesta et al. 2003), Kentucky (Allen et al. 2003), New York (Rondinaro 2003), Utah (Romero

2002), Ohio (Sargand 2005), and Nebraska (Hilderbrand 2008). Results of the investigations on the PQI have been primarily positive for quality control, especially since the release of TransTech's updated model, the PQI 301. The PQI uses electricity to measure the dielectric constant of the tested material using a toroidal electrical sensing field established by the sensing plate. The onboard electronics in the PQI then convert the field signals into material density. Once calibrated, direct density readings can be consistently obtained (TransTech 2008). In this study, the PQI is calibrated by comparing PQI's density measurements with core samples (Bulk Specific Gravity) at each site. A Maximum Theoretical Density (MTD) value (RICE# or Maximum Specific Gravity) is required for the initial device calibration, which can be provided from the asphalt mix designer. Then, the offset is adjusted after PQI calibration readings have been taken (Figure 3.3) and cores have been obtained from those same reading areas (Figure 3.4). An alternative method is also available by using a calibrated nuclear gauge to generate the offset needed by the PQI to accurately read densities. The use of nuclear gauge for calibration is especially useful when a paving job is fast-tracked to quickly open the road to public traffic. For this calibration process, a nuclear density gauge is used instead of core samples. Using a nuclear gauge to calibrate the PQI has been validated by the Wisconsin DOT (Schmitt 2006). Both methods were used as part of this study.

Figure 3.3 Taking PQI Density Readings Onsite

Figure 3.4 Taking Cores for PQI Calibration

3.1.3 Anemometer

In addition to site temperature and humidity, the wind speed was measured at each location investigated. This information was collected with the intention of correlating wind speed to the rate at which asphalt cools and develops temperature segregation.

3.2 Location Tracking

To verify the hypotheses created by the analyzed data, it was necessary to compare them against the real-world results. This research has involved the revisiting of previously investigated sites to collect the visual images needed to analyze any premature distresses or changes in density after public use of the investigated roads. This activity required marking points along the pavement where suspicious temperature and density differentials were observed.

3.2.1 Global Positioning System (GPS)

The approximate location for each mark was digitally recorded by a Garmin GPSMAP 60CSx handheld GPS device. The unit's accuracy achieves readings within about three meters of the exact location (Garmin 2007). By using GPS tags for each location, data was easily sorted during analysis and tied to digital maps, which will be discussed later. It also allowed for navigation back to selected locations, streamlining site revisitation.

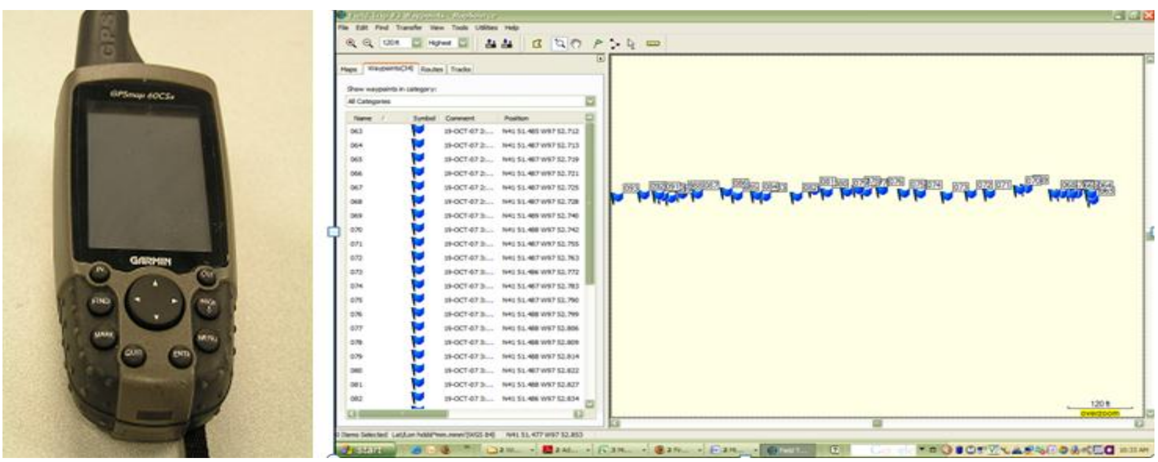


Figure 3.5 Handheld GPS Device and Jobsite Location Tags

3.2.2 Physical Markers

In addition to digital markers, physical markers were used to mark the exact location of points of particular interest to the research team. These markers were specially designed pavement marking nails similar to surveyor markers shown in Figure 3.6. The physical markers were driven into the shoulder pavement while still malleable and the distance directly across from the marker to the location was recorded.

Figure 3.6 Physical Location Markers

3.3 Other Collected Data

3.3.1 Observed Data

While onsite, the research team collected data from simple visual inspection. Though not all the data was used for analysis, its availability in comparisons may be crucial in later research. The observed data for this project includes: (1) Date, time, and location information, (2) Contractor and crew information, (3) Paving equipment, and (4) an overall jobsite description. The date, time, and location information could later be used in analyzing if temperature segregation occurs more at a certain time of year or day. It was important to collect contractor and crew information to allow for the possibility of a workmanship analysis. Unfortunately, the number of crews performing HMA work did not allow for an adequate sampling to be used for analysis due to the nature of the fast paving process. Paving equipment was noted during site visits so conclusions could be drawn about the relationships of certain equipment types involved in the HMA paving process.

3.3.2 Received Data

Data was received by the research crew through outside sources on the day of the site visit, which later proved to be pivotal to the success of the project. This information included (1) the RICE value, or maximum theoretical density (MTD), (2) the mix type, (3) and haul times and distances. The MTD was key to calibrating the device used to measure the achieved pavement density after compaction. Though current recommendations are that the PQI be used as a quality control device, pairing achieved density of the PQI with the MTD could later help establish the PQI as an accepted form of quality control or even assurance for the Nebraska Department of Roads.

The mix type of the pavement was also collected in order to analyze each type's susceptibility to temperature segregation. Haul times and distances were used to draw correlations between temperature segregation and the distance from the asphalt plants to the sites, or how different truck types were affected by varied haul times.

3.4 Data Collection Process Overview

In an effort to record trustworthy and consistent data, the method used to collect information onsite was strictly adhered to. The following describes the process that was followed while onsite:

1. Permission was obtained from the contractor and superintendent for the research crew to be onsite.
2. The MTD value was requested for gauge calibration, along with all other received data described in Section 3.3.2.
3. Six PQI readings were taken on HMA still over 120˚F for calibration purposes and marked using construction crayons to outline the footprint of the gauge.

4. The six locations were marked so they could later be cored and tested to provide a gauge offset. The offset from cores would be applied to all data after collection. Or, a calibrated nuclear gauge was used to take readings immediately after the PQI. The nuclear readings were used to create a gauge offset similar to those created by the cores.
5. An infrared camera was used to locate areas of temperature segregation. Infrared radiometric images were taken of the locations with the lens of camera facing the direction of paving. The camera was kept between five feet and 10 feet from each location being thermographed.
6. Density readings were taken using the non-nuclear density gauge at each location in a “single reading mode.”
7. Additionally, moisture values and current wind speed at each location was recorded.
8. After all characteristics of the location had been collected, the location was digitally marked using a handheld GPS unit.
9. If the location was of particular significance, a pavement marker was driven near the shoulder of the main road directly across from the area being measured.
10. A minimum of 30 locations were measured on each site whenever possible: however, on some sites inadequate temperature segregation prevented this. From the 30 points collected, a total of 60 density readings were generated. Each location generated two readings: one of the areas with a relative high temperature and the other of the areas with a relative low temperature.

11. After collecting specific material characteristics, the paving process—including pavement equipment and activity process—was visually observed and noted.
12. After each site visit, collected data was added to a pool of previously collected data, and analyses were updated.
13. Following one complete freeze-thaw season of the pavement, the site was revisited and visually inspected for changes in pavement quality where data was collected.

Chapter 4 Data Analysis

4.1 Temperature Differential vs. Density

Throughout this project, 304 unique locations have been evaluated with the primary intention of investigating the effect that temperature differentials (TD) have within the HMA paving process. As found within earlier studies, the areas possessing increased temperature differentials after final compaction are expected to yield lower densities (Figure 4.1).

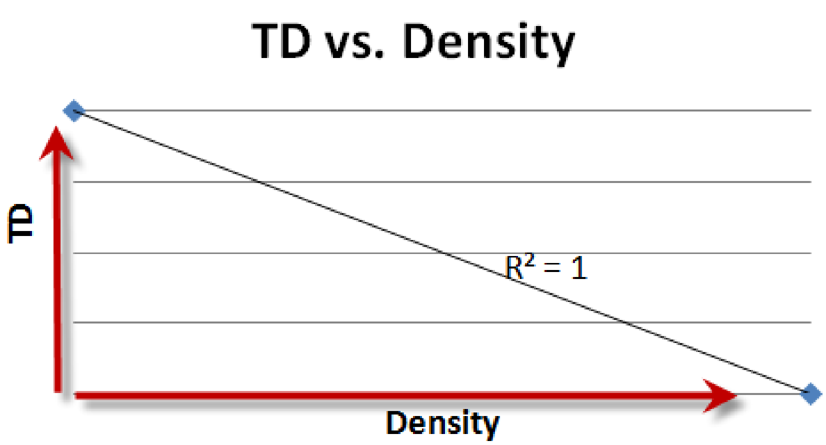


Figure 4.1 Theoretical Relationship between Temperature Differential (TD) and Pavement Density

Although a negative relationship was found, the general analysis between temperature differentials (TD) after compaction and pavement density (DEN) showed the relationship between the two variables not to be significant (Figure 4.2). This analysis included all 304 density readings obtained throughout the project and charted them against their corresponding temperature differential.

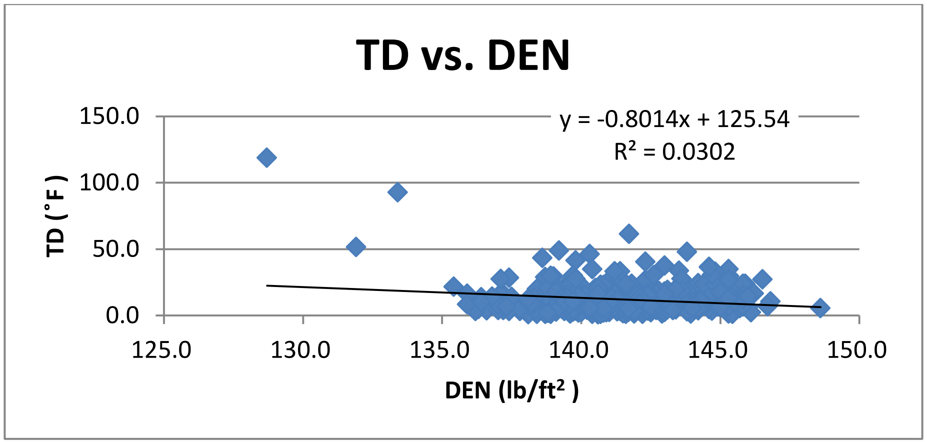


Figure 4.2 Relationship for All Collected Data between Temperature Differential (TD) and Density (DEN)

Although a direct relationship was not found between TD and density, it was useful to investigate where temperature differentials in the HMA process began to affect density. To do this, all locations were separated into sets by temperature. Each temperature group was then analyzed for its relation to TD and density; this is shown as r^2. For example, if the temperature group 20-25˚F was found to have an r^2 of 0.52, it could be assumed that if a patch of material onsite were found to be 22˚F cooler than the surrounding material after final compaction, the location would show a 52% correlation between TD and density. When developing these relationships for each temperature group, a trend line was created to show how likely the relationship between TD and density is to hold true. These analyses are graphically represented in Figure 4.3. It is easily seen that the severity of temperature differential in HMA significantly affects the negative relationship between TD and density.

Table 4.1 Correlation between a Given Temperature Group and the Relationship between TD and DEN

Group Number	TD Data Group	TD/DEN Relationship	Data Points	Group Number	TD Data Group	TD/DEN Relationship	Data Points
1	Whole	0.0302	408	15	14°F & Up	0.1717	121
2	1°F & Up	0.0306	407	16	15°F & Up	0.1747	109
3	2°F & Up	0.0355	389	17	16°F & Up	0.1824	102
4	3°F & Up	0.0389	369	18	17°F & Up	0.2243	87
5	4°F & Up	0.0549	342	19	18°F & Up	0.2545	77
6	5°F & Up	0.0649	313	20	19°F & Up	0.2573	69
7	6°F & Up	0.0706	281	21	20°F & Up	0.2519	65
8	7°F & Up	0.0681	250	22	21°F & Up	0.3261	53
9	8°F & Up	0.0716	234	23	22°F & Up	0.3994	48
10	9°F & Up	0.0873	218	24	23°F & Up	0.4243	45
11	10°F & Up	0.1114	194	25	24°F & Up	0.4383	37
12	11°F & Up	0.1221	175	26	25°F & Up	0.4422	34
13	12°F & Up	0.1387	156	27	30°F & Up	0.6344	22
14	13°F & Up	0.146	139	28	40°F & Up	0.5829	10

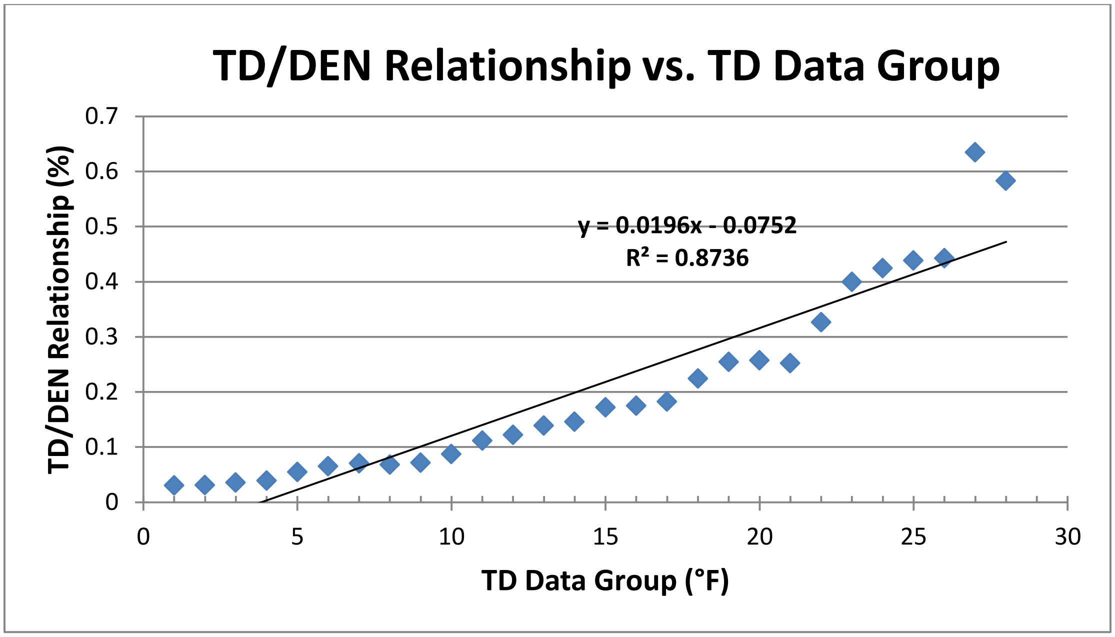


Figure 4.3 A Graphical Representation of the Relationship between Individual Temperature Groups and TD and DEN

4.2 Other Variables Investigated

4.2.1 Air Temperature

The 18 site visits carried out during this project occurred at varied times throughout the paving season across Nebraska. Sites were visited in early spring, in the middle of summer, as well as far into the fall paving season. By visiting at varied times of the year, the effect outside air temperature had on the instances of temperature differentials (TD) could be studied. It is a common practice for mix types to compensate for cold weather. Essentially boosting the mix temperature during manufacturing gives the laydown crew adequate time to use the material before it reaches its cessation point. It is still important, however, to investigate if these changes are sufficient at reducing temperature segregation. As can be seen in Figure 4.4, there was no statistically significant relationship ($r^2 = 0.026$) between the outside air temperature (AirTem) and the occurrence of temperature differentials (TD) during the typical paving seasons in Nebraska: between 50°F and 95°F.

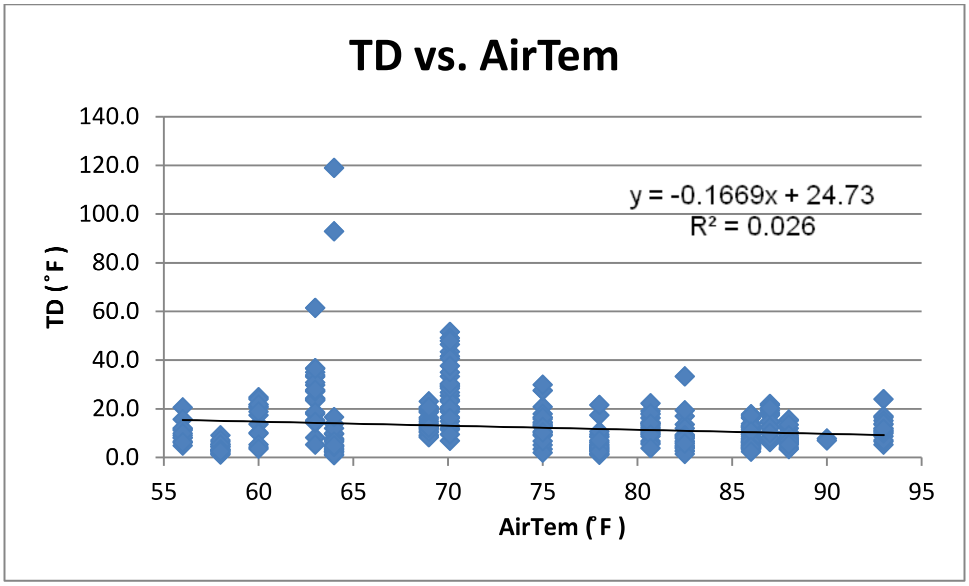


Figure 4.4 Relationship between Ambient Jobsite Air Temperature and Temperature Differential

4.2.2 Haul Time

The effect of haul time in generating temperature segregations was investigated in this study. Increased effort was placed on visiting sites with longer haul distances. It was thought that increased haul times would translate to a thicker crust being generated during transportation. The thicker crust is generated because the periphery of the material cools faster in the truck bed than the interior material. Also, varied gradation and binder content in different mix types show variations in temperature differentials after transport.

This point was proven throughout the data analysis of Site 13. Site 13 had the longest material transport time at 90 minutes (Figure 4.5); however, it exhibited decreased signs of temperature segregation. This is likely due to the gap graded crumb rubber modified binder used in the mix. These rubber modified mixes are manufactured at higher temperatures, which extends their allowable transport time. Overall, the relationship between haul time and temperature differentials was calculated at 3% (Figure 4.5). Greater than a 90-minute haul time may be required to see significant impacts on temperature differentials; longer haul distances could not be found to include as part of this study. A brief investigation of the mix types Nebraska uses and their allowable haul times would be an appropriate study to further identify which mixes can be used for sites that are at risk of developing temperature differentials due to increased haul times. Overall, this investigation indicates that current remixing practices carried out onsite are sufficient at preventing temperature segregated material.

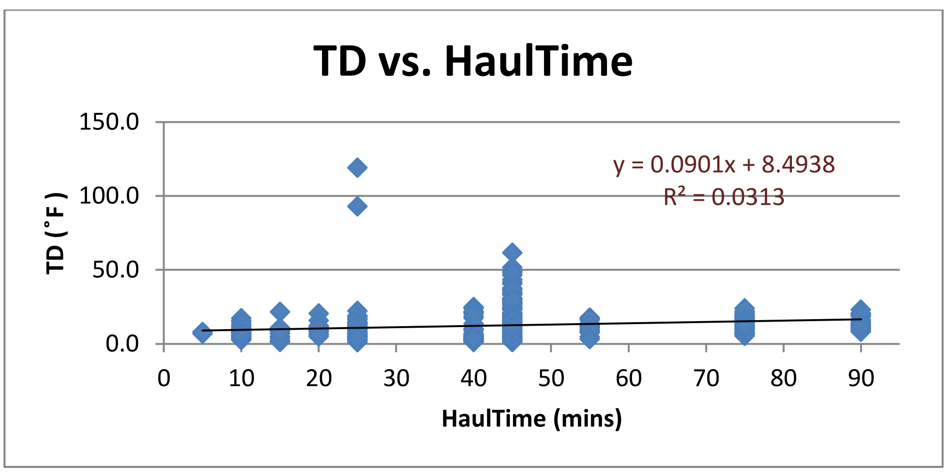


Figure 4.5 Relationship between Haul Time and Temperature Differentials

4.2.3 Material Feeding Machines

There are two types of material feeding processes from a delivery truck to a paver in Nebraska. Either HMA trucks directly dump delivered HMA into the hopper of a paver (Figure 4.6), or belly dump trucks and live belly dump trucks deposit the material ahead of a pick-up machine that scoops up the HMA and transfers it into the hopper of a paving machine (Figure 4.7). Unlike a material transfer vehicle (MTV), such as Roadtec, Inc.'s, Shuttle Buggy MTV, the pick-up machine does not have a special remixing auger or chute.

Figure 4.6 Direct Dump between Truck and Paver

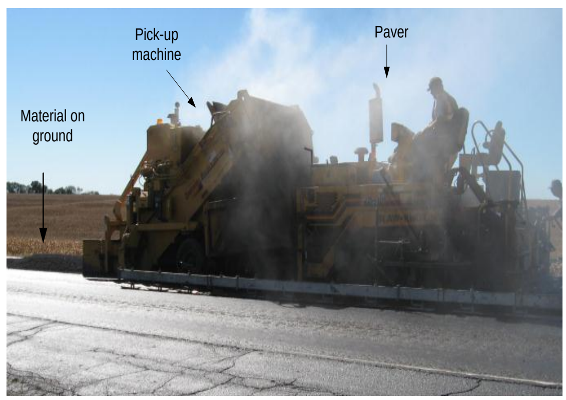


Figure 4.7 Pick-up Machine with Paver

Figure 4.8 shows the temperature differential variation for each material feeding process. When a pick-up machine is used between a belly dump truck and a paver, the completed material shows a more consistent temperature profile (standard deviation=5.3°F) than when a truck directly dumps HMA material into a road paver's hopper (standard deviation=13.1°F). The significantly smaller standard deviation demonstrates how a pick-up machine is a very cost-effective solution to reduce temperature differential of delivered HMA without using expensive MTVs.

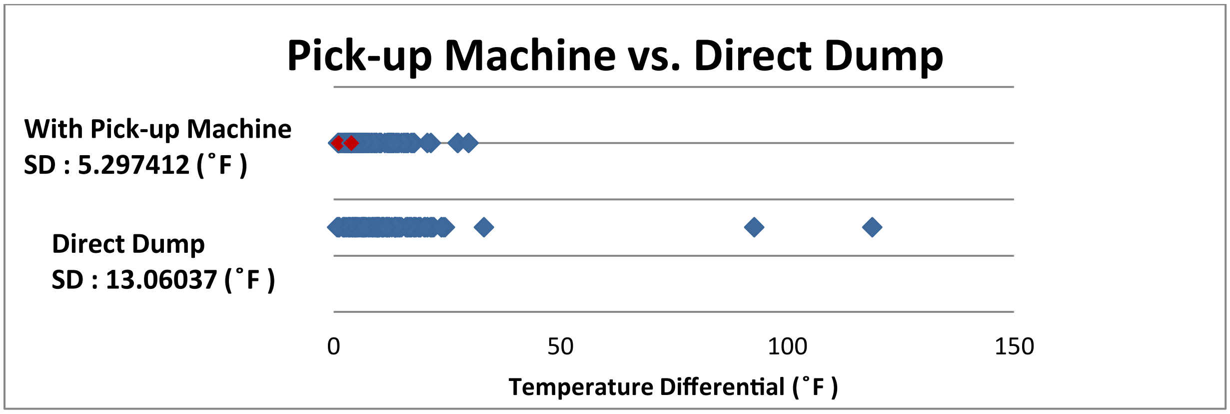


Figure 4.8 Temperature Differential Based on Feeding Types

4.2.4 Wind Speed

Wind speed was collected at each location for Sites 11-15 with a hypothesis that its effects could lead to HMA temperature segregation (Figure 4.9). The data suggests that wind speed has a negligible effect on temperature segregation, showing less than a 1% relationship. This is because the wind is likely affecting the pavement overall, rather than focalized areas.

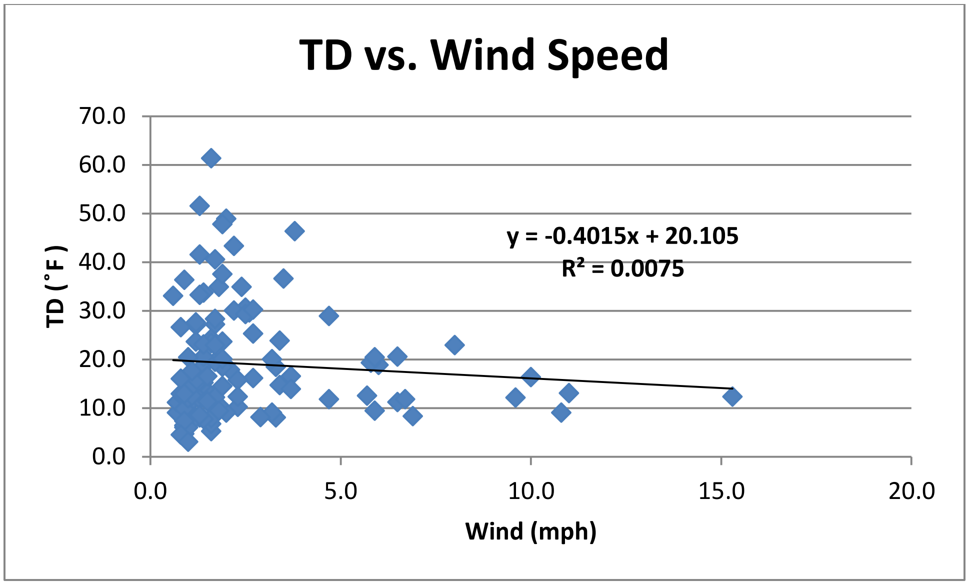


Figure 4.9 Relationship between Wind Speed and Temperature Differentials (TD)

Chapter 5 Revisit Analysis

Throughout the last two years, eighteen HMA paving projects have been visited to investigate the effects of temperature segregation. Of the 18 sites, 14 sites have weathered at least one freeze-thaw cycle. In order to fully understand the ramifications that temperature segregation has on overall pavement quality, it is important to revisit the sites throughout the pavement's lifecycle. Of the 14 sites, all have since been revisited with the exception of sites 8, 9, and 10. Sites 8 and 9 were originally paved as bypass routes and have now been demolished, and site 10 was not selected for revisiting because a limited number of data points were located during the initial visit.

As a result, of the 259 relevant data points from the 11 jobsites revisited, 76 have been notated as showing signs of premature distress. Additionally, nine locations could not be found. The remaining 174 locations were in visibly acceptable condition.

Table 5.1 Total Premature Distresses vs. Good Condition

Total Premature Distresses vs. Good Condition			
Total	Premature Distresses	Good Condition	Unknown
259	76	174	9
100.00%	29.34%	67.18%	3.47%

Of the total data points, 29% were exhibiting signs of premature distress just eight months to one and a half years later. The remaining data points are still in good overall condition while 3.5% of the points could not be located.

5.1 Types of Premature Flaws

This study classified the observed premature distresses into four types: transverse, surface void (pothole), multi-crack joint, and aggregate segregation. Table 5.2 and Figure 5.1 show a breakdown of how the 76 flaws are distributed into the four distinct categories.

Table 5.2 Instances of Premature Distress by Type

Total Instances of Premature Distress by Type				
Total	Transverse	Void	Multi-Crack joint	Segregation
76	19	28	5	24
100.00%	25.00%	36.84%	6.58%	31.58%

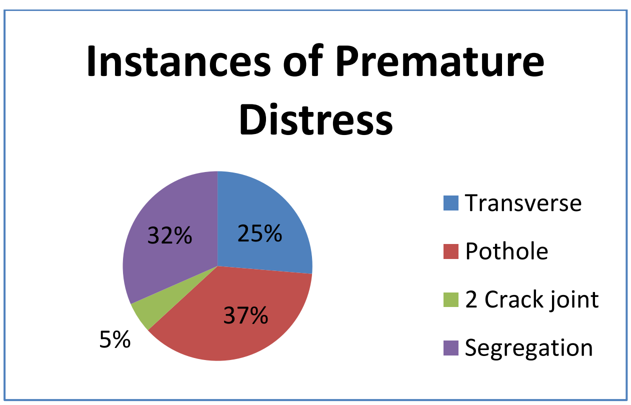


Figure 5.1 Instances of Premature Distress

5.1.1 Transverse Crack

The following picture is indicative of a transverse crack (Figure 5.2). Transverse cracks are formed perpendicular to the direction the asphalt paver, and are often the result of asphalt shrinkage. Because areas of different temperature expand and contract at different rates, transverse cracks are of particular interest in this investigation. Cracks of this type also often occur as reflective cracks, which will be discussed later.

Figure 5.2 Observed Transverse Crack

5.1.2 Multi-Crack Joint

In referencing the Asphalt Institute's article "Understanding Asphalt Pavement Distresses-Five Distresses Explained" (Walker 2009), it was found that there was no singular designation for the type of flaw shown in Figure 5.3. Because this flaw appears to be a meeting of one longitudinal crack and one transverse, it will be further identified as a multi-crack joint. The primary reasons these multi-crack flaws are formed can be assumed to be a combination of the reasons for transverse cracks and longitudinal cracks. Longitudinal cracks are often formed due to shrinkage or reflective cracking, and longitudinal segregation caused by poor paver operation. The reasons transverse cracks are formed have been stated previously (Walker 2009).

Figure 5.3 Observed Multi-Crack Joint

5.1.3 Segregation

An example of segregation can be seen from the revisit data in Figure 5.4. For clarity purposes, during this investigation's site revisit phase, areas exhibiting signs of aggregate segregation were noted simply as "segregation." AASHTO explains aggregate segregation as "the non-uniform distribution of coarse and fine aggregate components within the asphalt mixture" (AASHTO). Because a visual inspection was done to locate these flaws, only coarse aggregate segregation was located. Coarse aggregate segregation can be thought of as including a disproportionate amount of coarse aggregate as compared to fine aggregate as well as low asphalt content (Williams et. al 1996). Aggregate segregation in HMA can be caused by improper mixing. Aggregate segregation leads to flaws like accelerated rutting, fatigue failure, and potholes (Williams et. al 1996; Walker 2009).

Figure 5.4 Observed Material Segregation

5.1.4 Surface Voids (Small Pothole)

An example of an early pothole is shown in Figure 5.5. To be clear, for purposes of the first year's revisit report, a pothole was taken to be any small void larger than a quarter-sized coin. These identified surface voids have not become detrimental to overall pavement quality yet, however, it was important for the research team to tag these locations as these small surface voids have the potential of developing into major problems. It is the team's hypothesis that these small potholes have developed from large pieces of aggregate cracking or popping out of the surface of the pavement during the freeze-thaw cycle. Because these potholes have not degenerated pavement qualities to date, later data analysis deals with their inclusion at certain times.

Figure 5.5 Observed Surface Void

5.2 Site Revisit Procedure and Data Collection

The site revisits for all fourteen sites were conducted between eight and 18 months after the initial site visit. At each site, a handheld GPS unit was used to find each location that was investigated at the time of paving. Additionally, some exact locations were found based on survey markers placed along the shoulder of the road. Figure 5.6 shows what these markers looked like after one freeze thaw cycle.

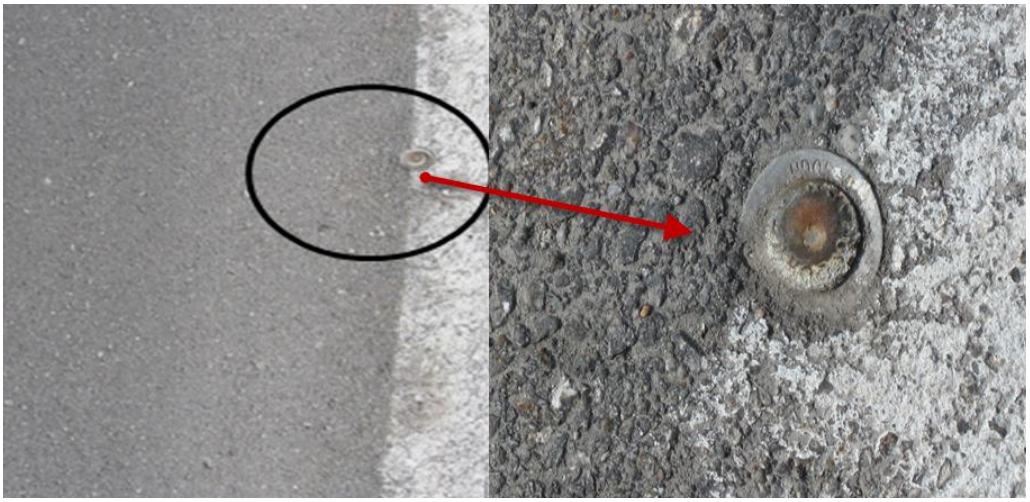


Figure 5.6 Observed Marker after One Freeze-Thaw Cycle

At each location, a visual inspection was conducted. If a flaw was noticed, the inspector briefly described the flaw, took a digital picture of the location, and visually analyzed the flaw's surroundings to determine if it was an isolated flaw or repetitive. Extra care was taken to create four distinct flaw groups and the features required to deem a location as flawed. These specific guidelines were created because classifying a location as flawed can be a somewhat subjective process.

5.3 Site Revisit Analysis

5.3.1 Site Revisit Analysis by Distress Type

All the data collected during site revisitation was separated into the four specific flaw categories as outlined above. It is important to first analyze each flaw or distress type separately because different, often unique, reasons cause failure.

5.3.1.1 Transverse Crack Premature Distress

Twenty instances of transverse cracks were noted during the first year's revisitation. As this research is primarily concerned with the overall relationship between temperature differentials and density, all 20 locations were evaluated based on that criteria. After calculating this relationship, a correlation of just greater than 27% was obtained (Figure 5.7). This correlation was lower than expected because the collected data included reflective cracks which were not affected by temperature differential.

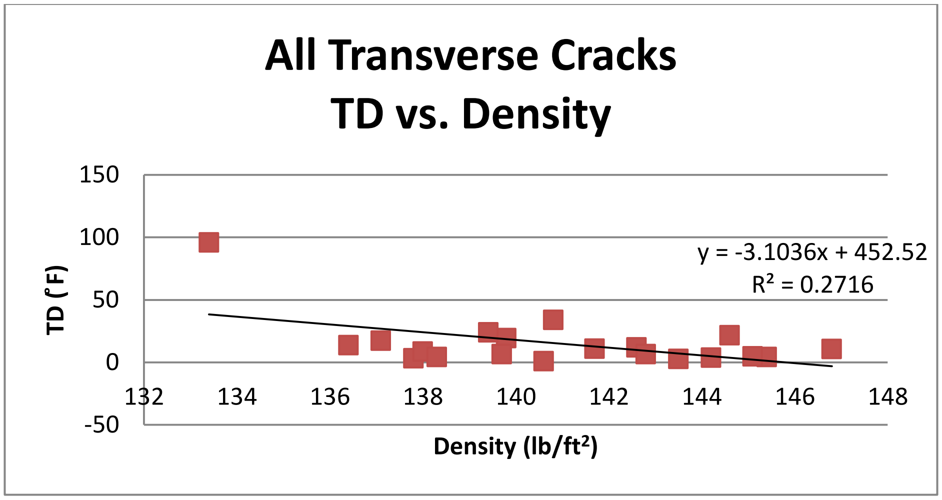


Figure 5.7 Relationship of TD and Density among Transverse Cracks

5.3.1.2 Reflective Crack Premature Distress

After collecting individual location data and conducting preliminary analyses, each site was considered as a whole. It was during this second phase of data analysis that the research team decided it was important to take a closer look at the instances of repetitive transverse cracks. Some were suspected of being reflective. Reflective cracks occur when cracks in older asphalt or concrete joints are reflected upon the new asphalt overlay. A series of graphics depicts what reflective cracking looks like in Figure 5.8.

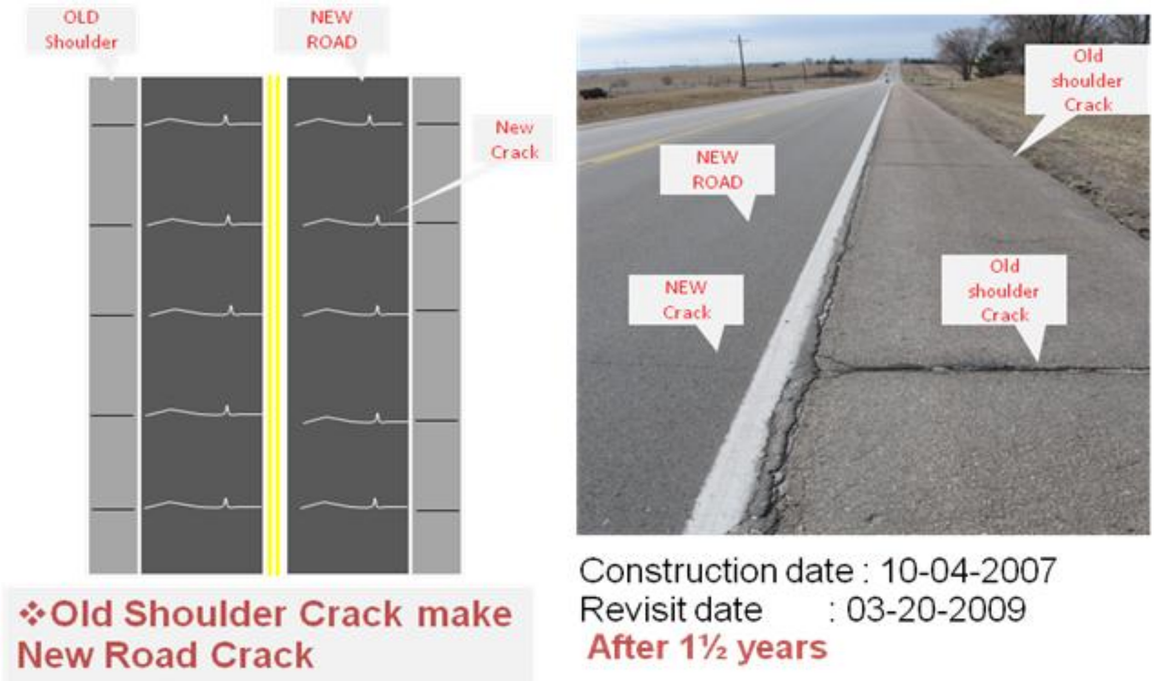


Figure 5.8 Plan View of Roadway Exhibiting Reflective Cracks (left) and Observed Reflective Cracking (right)

From the 20 observed instances of transverse cracking, 14 were found to exhibit signs of reflective cracking. When analyzing the 14 locations alone, a relationship of less than 1% was found between temperature segregation and density. This analysis further solidifies the researcher's assumption that these locations were caused by cracks permeating up through old layers of material (Figure 5.9).

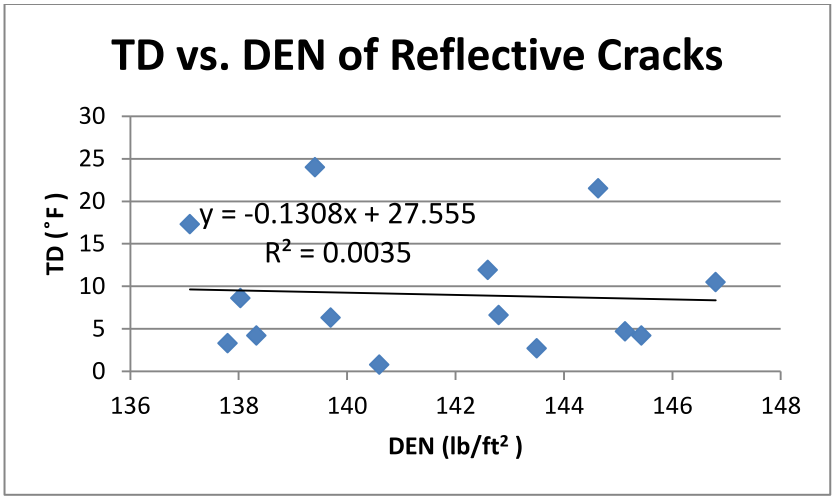


Figure 5.9 Temperature Differentials and Density Relationship among Reflective Cracks

The 14 locations were not further included in data analysis as these locations were almost certainly influenced primarily by the previous pavement underlayments. After excluding the suspected reflective cracks, the remaining six transverse cracks that had developed were found to possess an increased relationship (60.7%) between temperature differentials and density (Figure 5.10).

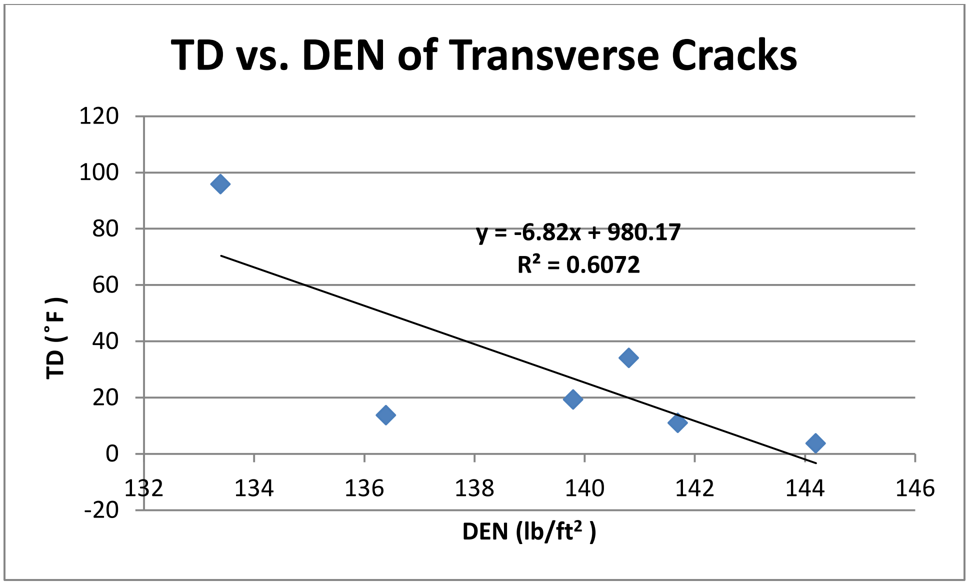


Figure 5.10 Relationship between Temperature Differentials (TD) and Density (DEN), Excluding Reflective Cracks

5.3.1.3 Surface Void Premature Distress

Small surface voids, or "potholes" for the purpose of this report, have proven to be a counterintuitive flaw. It is assumed that surface voids in the material will begin to develop at specific locations because of inadequate densities. One primary cause of inadequate density, and the focus of this research, is temperature segregation, namely cold spots. It is assumed that these cold spots would "set up" faster than the surrounding warmer temperatures, thereby increasing its ability to resist compaction. However, when analyzing locations classified as a surface void (or pothole), a positive relationship was found between temperature differentials and pavement density. This positive relationship follows counter to the assumed negative relationship where high temperature differentials would translate to low densities. This is more easily explained by Figure 5.11.

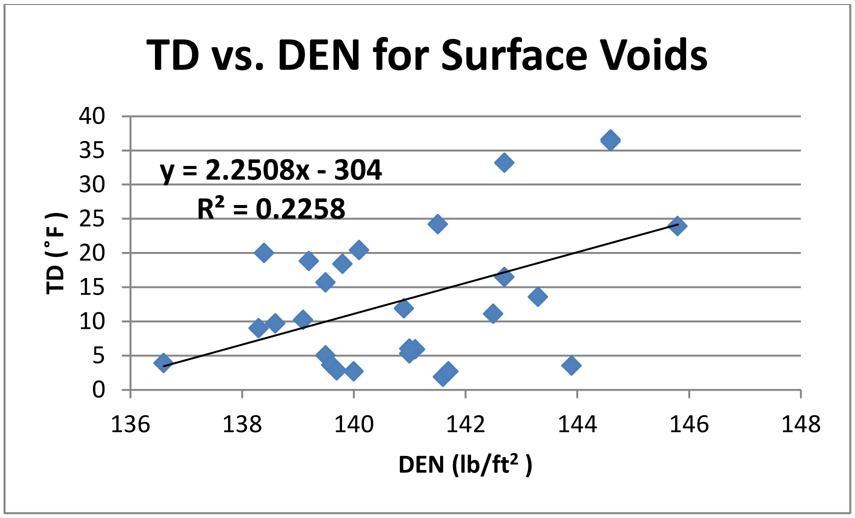


Figure 5.11 Relationship between Temperature Differentials (TD) and Density (DEN) among Surface Voids

Significant weight should not yet be put on this analysis, though, as these voids have not become pronounced enough to fully classify as premature failures. However, it is an interesting relationship, and one that might be explained more through the gradation of the mix design used rather than temperature differentials. By monitoring how these voids change in later years, time may show a decreased importance on temperature differential and an increased importance on gradation.

Due to the characteristics these voids possess in relation to other premature voids, they were intentionally excluded from some of the premature distress analysis. Later revisit data may prove their worth; however, at this time it is felt that their exclusion from the overall premature distress analysis is warranted.

5.3.1.4 Multi-Crack Joint Premature Distress

Of the four instances of multi-crack joint type of premature flaws located during visual inspections, a 98% negative relationship was calculated between temperature differential and density. Multi-crack joint distresses were only present in jobsites one and a half years old. It should be noted that if the extreme outlier with a temperature differential of 118 °F is removed from the data set, the relationship remains in the ninetieth percentile.

5.3.1.5 Aggregate Segregation Flaws

Aggregate segregation was noted at 24 locations during site revisits. Although the aggregate segregation was not yet contributing to the degeneration of roadway quality, it was noted because of its potential to eventually do so. Recall from above that aggregate segregation often means decreased binder content, which will weaken the pavement at that location. Additionally, the presence of coarse gradation on the pavement surface is more likely to crack or pop free of the pavement during freeze-thaw cycles, thereby turning into premature distresses in the form of surface voids or potholes.

Of the 24 locations with visible material segregation, a 15% negative relationship was found between temperature differential (TD) and density (DEN).

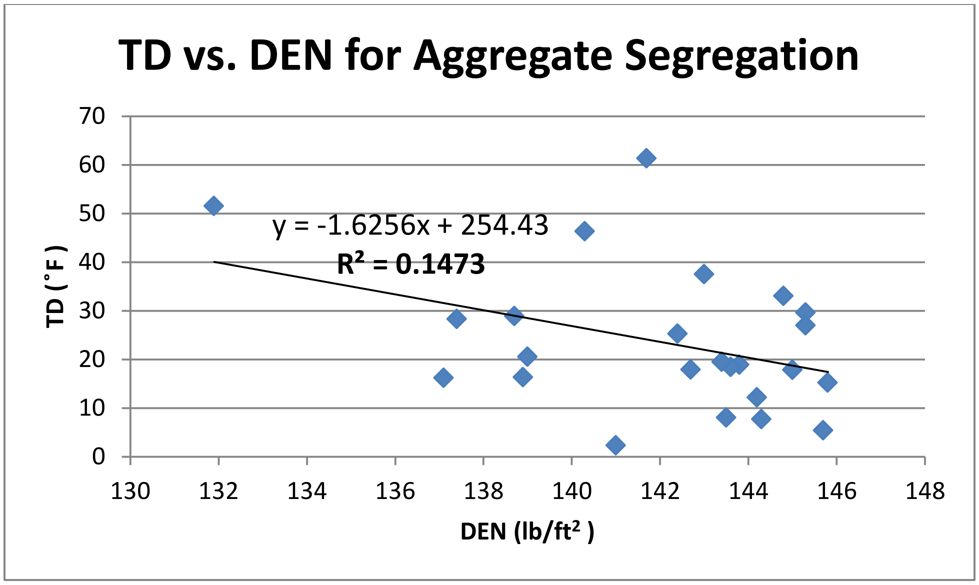


Figure 5.12 Relationship between Temperature Differentials (TD) among Aggregate Segregation

5.3.2 Overall Revisit Data Analysis

Paramount to completing the revisit analysis is the overall relationship between temperature differentials and density coupled with the instances of premature distresses. In completing the initial analysis that included the previously described pothole flaws and excluded reflective joints, a relationship of nearly 18% was discovered. Table 5.3 of the data points used for analysis is shown, accompanied with a graph showing the TD and density (DEN) relationship (Figure 5.13).

Table 5.3 Revisit Data Analysis

n	TD	DEN	n	TD	DEN	n	TD	DEN
1	1.9	141.6	22	10.2	139.1	42	20.0	138.4
2	2.3	141	23	10.9	141.7	43	20.4	140.1
3	2.7	140	24	11.1	142.5	44	20.5	139
4	2.7	141.7	25	11.9	140.9	45	23.9	145.8
5	2.8	139.7	26	12.2	144.2	46	24.2	141.51
6	3.5	143.9	27	13.6	143.3	47	25.3	142.4
7	3.6	139.6	28	13.7	136.4	48	27	145.3
8	3.7	144.2	29	15.2	145.8	49	28.3	137.4
9	3.9	136.6	30	15.7	139.5	50	28.9	138.7
10	5	139.5	31	16.2	137.1	51	29.6	145.3
11	5.3	141	32	16.3	138.9	52	33	144.8
12	5.4	145.7	33	16.5	142.7	53	33.2	142.7
13	5.9	141.1	34	17.8	145	54	34	140.81
14	6.0	141.0	35	17.9	142.7	55	36.3	144.6
15	7.1	139.2	36	18.4	139.8	56	36.6	144.6
16	7.3	138.7	37	18.4	143.6	57	37.5	143
17	7.7	144.3	38	18.8	139.2	58	46.3	140.3
18	8	143.5	39	18.9	143.8	59	51.5	131.9
19	9.0	138.3	40	19.3	139.8	60	61.3	141.7
20	9.6	137.4	41	19.5	143.4	61	95.8	133.4
21	9.7	138.6				62	118.8	128.7

NOTE: TD in(℉), DEN in lb/ft^2

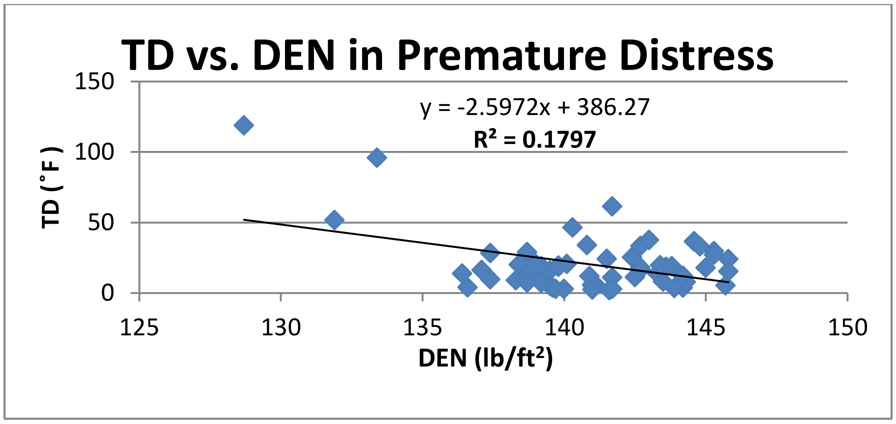


Figure 5.13 Relationship between Temperature Differentials and Density among Total Instances of Observed Premature Distresses

Recall, however, that when analyzed individually the pothole type of flaw exhibited a positive relationship between TD and density. Because all other flaw types show signs of being affected by temperature differentials in regard to their corresponding densities, while the locations with small voids do not, they were removed from the data set. The remaining 34 premature distresses or flaw locations were analyzed with regard to TD and density and were found to have a relationship of 37% (Figure 5.14): an improvement of 19% over the inclusion of small voids.

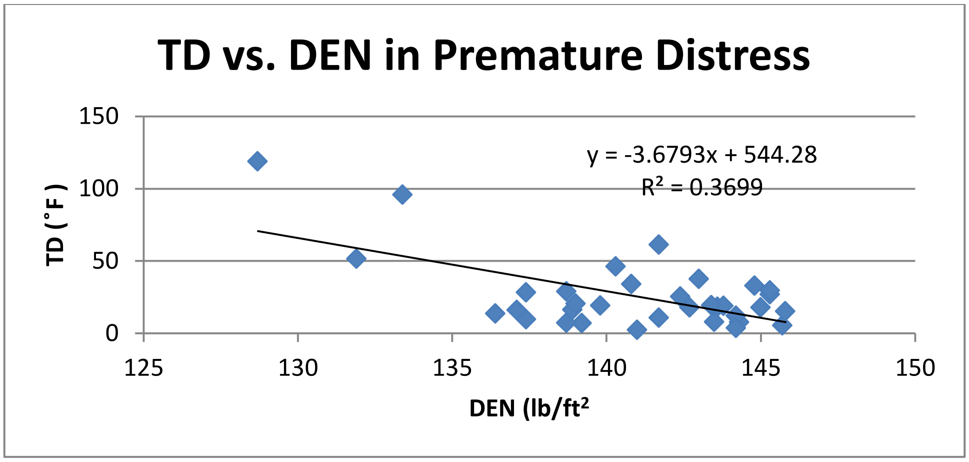


Figure 5.14 Relationship between Temperature Differentials and Premature Distresses, Excluding Small Surface Voids

Although the above graph gives insight to how the density of hot mix asphalt is affected by temperature differentials overall, it does not paint a complete picture. It is helpful to sort the locations showing signs of premature distresses into temperature differential groups as shown in Table 5.4. After sorting, the relationship (r^2) between TD and density according to a temperature range is nearly perfect (99.76%), as shown in Figure 5.15. This illustrates that the prematurely distressed material caused by a higher temperature differentials has a higher probability of possessing lower densities.

Table 5.4 Relationship between R^2 and Corresponding TD Groups for Premature Distresses

Num	Temperature Diff. Range (˚F)	R^2	Included Premature Distresses Data Points
1	5 F and Up	0.3682	32
2	10 F and Up	0.4333	26
3	15 F and Up	0.4941	23
4	20 F and Up	0.5474	14
5	25 F and Up	0.5953	13
6	30 F and Up	0.6634	8

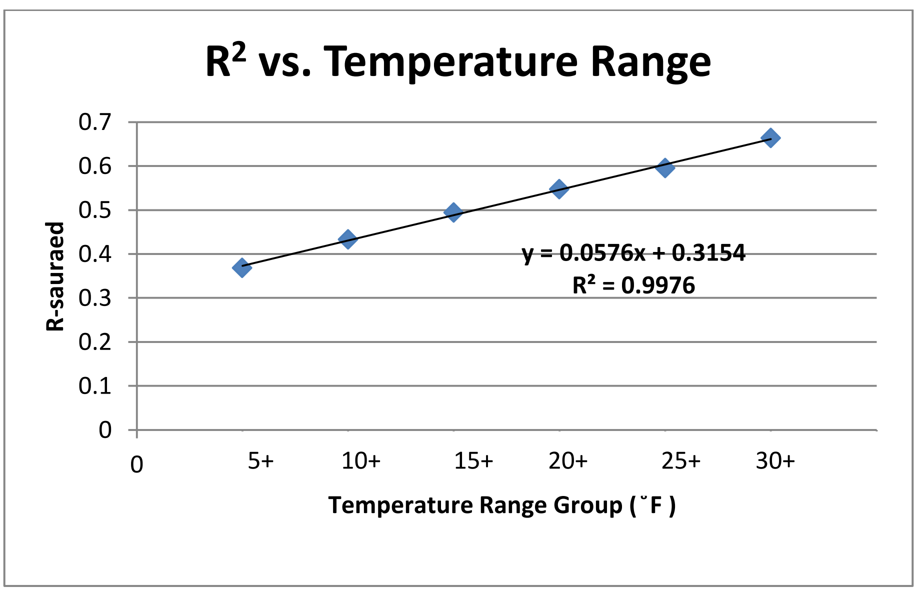


Figure 5.15 Relationship between the Correlation of TD and DEN for a Given Temperature Range and the Temperature Range Group

It is useful to also investigate the simple relationship between temperature differentials and the occurrence of premature flaws. In order to do this, all premature distresses and noted flaws were separated into the corresponding temperate differential range that was documented at the time of paving (Table 5.5). These ranges were simply charted against how often premature distresses or flaws were noted out of all data points falling within the specified range (Figure 5.16). For example, when looking at all the locations investigated within the 15˚F to 20˚F temperature range, 39% of those locations have shown signs of premature distress or flaws between eight months and one and a half years later.

In these analyses, graphs are provided both with small surface voids (potholes) and without. These graphs highlight the importance of including the voids in some analyses as their relationship to TD and density has been ruled out based on their positive relationship, but the simple relationship between TD and premature flaws has not been. That is to say, there is a marked trend between the occurrence of premature pavement flaws and increasing temperature differentials. When looking at Figures 5.16 and 5.17, a more distinct relationship between temperature differentials and pavement flaws was found when surface voids were included. This finding indicates that although density was unaffected by temperature differentials among noted surface voids, it is still important to consider temperature differentials as leading to surface void premature distresses. This relationship is useful to note because the current quality control and quality assurance practices within the State of Nebraska do not account for temperature differentials and would therefore fail to identify certain future premature distresses in the form of surface voids. Additionally, it should be noted that the relationship between TD and premature distress increases to nearly 70% when the one extreme outlier in the 20˚F to 25˚F temperature range is excluded (Figure 5.17).

Table 5.5 Temperature Differential Range (TD) vs. Type of Premature Distress (PD), with Surface Voids

TD (˚F)	Trans-verse	%	Small Voids	%	Agg. Seg.	%	Multi-Crack	%	Total	Data Total	%
1~5	1	11.1%	7	77.8%	1	11.1%	0	0.0%	9	74	12. %
5~10	0	0.0%	6	50.0%	3	25.0%	3	25.0%	12	76	15.79%
10~15	2	28.6%	4	57.1%	1	14.3%	0	0.0%	7	60	11.67%
15~20	1	7.7%	4	30.8%	8	61.5%	0	0.0%	13	33	39.39%
20~25	0	0.0%	4	80.0%	1	20.0%	0	0.0%	5	30	16.67%
25~30	0	0.0%	0	0.0%	5	100.0%	0	0.0%	5	9	55.56%
30~40	1	16.7%	3	50.0%	2	33.3%	0	0.0%	6	12	50.00%
40~	1	20.0%	0	0.0%	3	60.0%	1	20.0%	5	10	50.00%
Total	6		28		24		4		62	304	20.39%

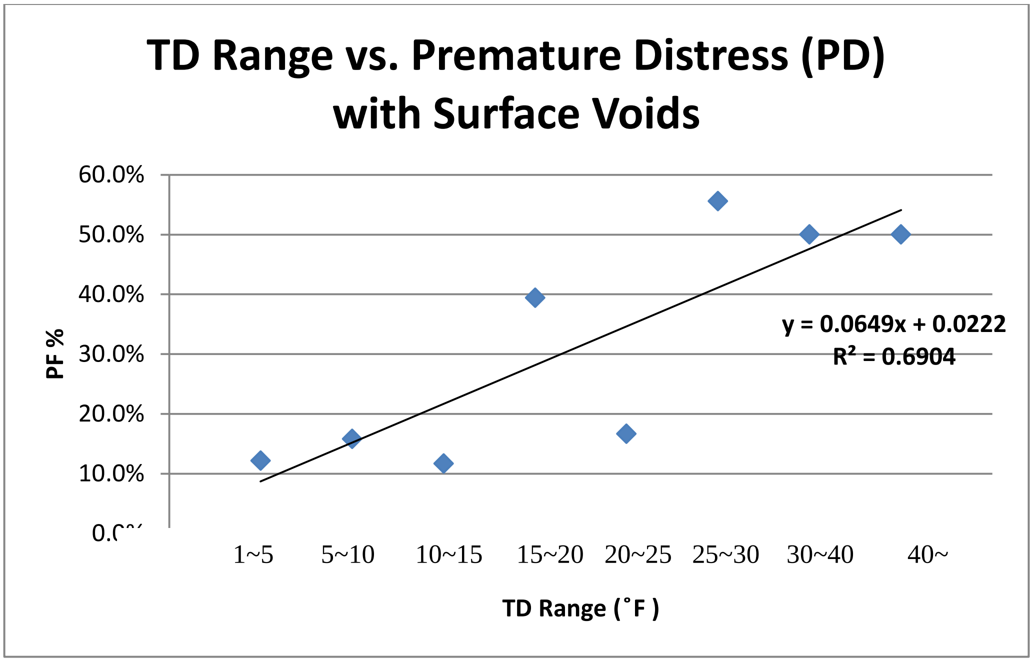


Figure 5.16 Correlation between the Percentages of Premature Distresses, Including Surface Voids, Found within a Specified Temperature Range

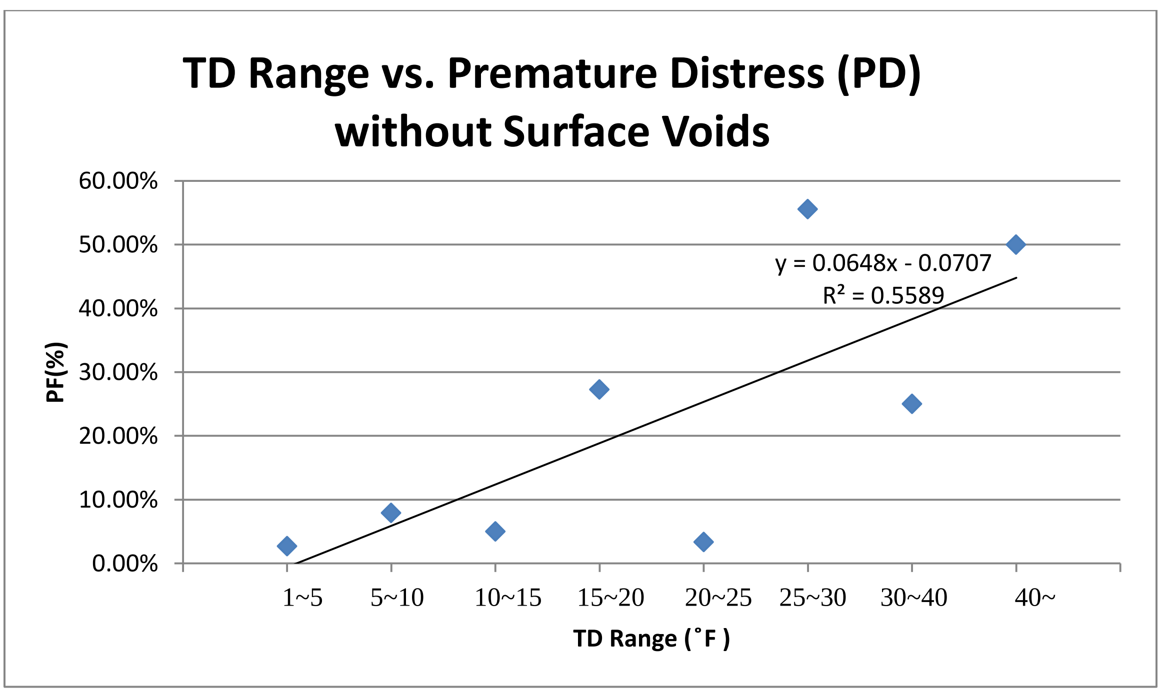


Figure 5.17 Correlation between the Percentages of Premature Flaws, Excluding Surface Voids, Found within a Specified Temperature Range

Chapter 6 Data Management

It became apparent that this project necessitated a system to efficiently manage the growing amount of collected and analyzed. The research group set out to develop a system to sort and represent data in a highly visual and intuitive manner. The developed system can be used to aid the current pavement construction and maintenance management system.

6.1 Google Earth based Visualization of Pavement Data

In order to perform this investigation, a number of devices were utilized. Those devices included (1) a portable anemometer to record current weather conditions, (2) portable GPS unit to digitally mark areas of interest for later revisit, (3) a thermal imaging camera to locate areas of HMA temperature segregation, (4) a penetrating thermometer to validate the thermal camera, (5) a digital camera to record site conditions and procedures, and (6) nuclear and non-nuclear pavement density devices to measure the compacted density of the material. In addition to data collected via portable devices, site-specific information was collected, including (1) pavement or mix type, (2) lift thickness, (3) haul time, (4) equipment used, and (5) location.

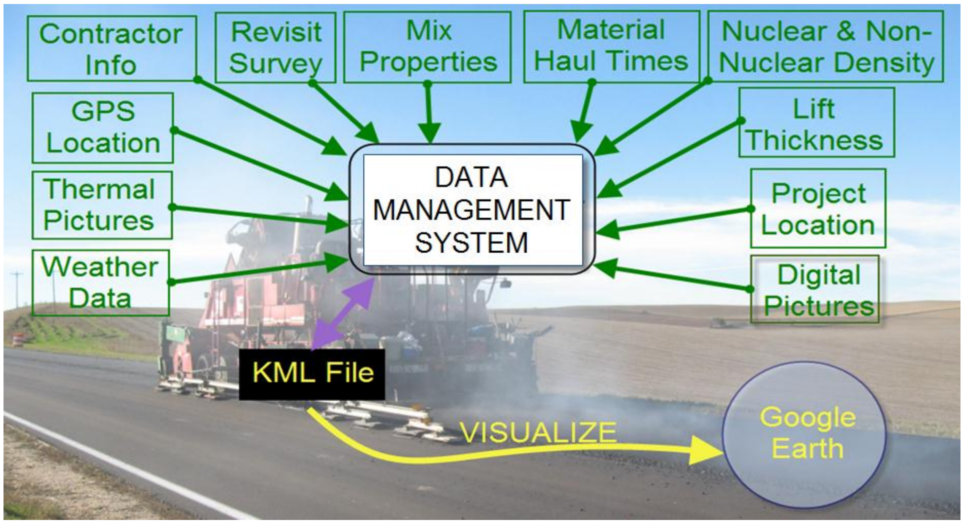


Figure 6.1 Developed Data Management System

The system was constructed during the paving offseason and ready for use at the start of the 2009 paving season in Nebraska. That spring, all previous sites were revisited in an effort to measure or identify a change in overall pavement quality. Any changes in quality were documented and imported into the Google Earth (KML) format database system that was created. After all information from the revisit had been uploaded, users were able to simply "fly" around the Google Earth program and select individual sites to find site properties like the contractor, mix properties, or even site data analyses (Figure 6.2). Once a particular site had been selected, users were able to further focus on a site-specific data point (Figure 6.3). For example, when a flaw was noted at a specific location during site revisitation, users were able to immediately call up that exact location to view relevant information that was logged at the time of construction that might explain the pavement's premature distress. Information that might explain the pavement's distress could have included decreased density readings or thermal images showing drastic temperature segregation.

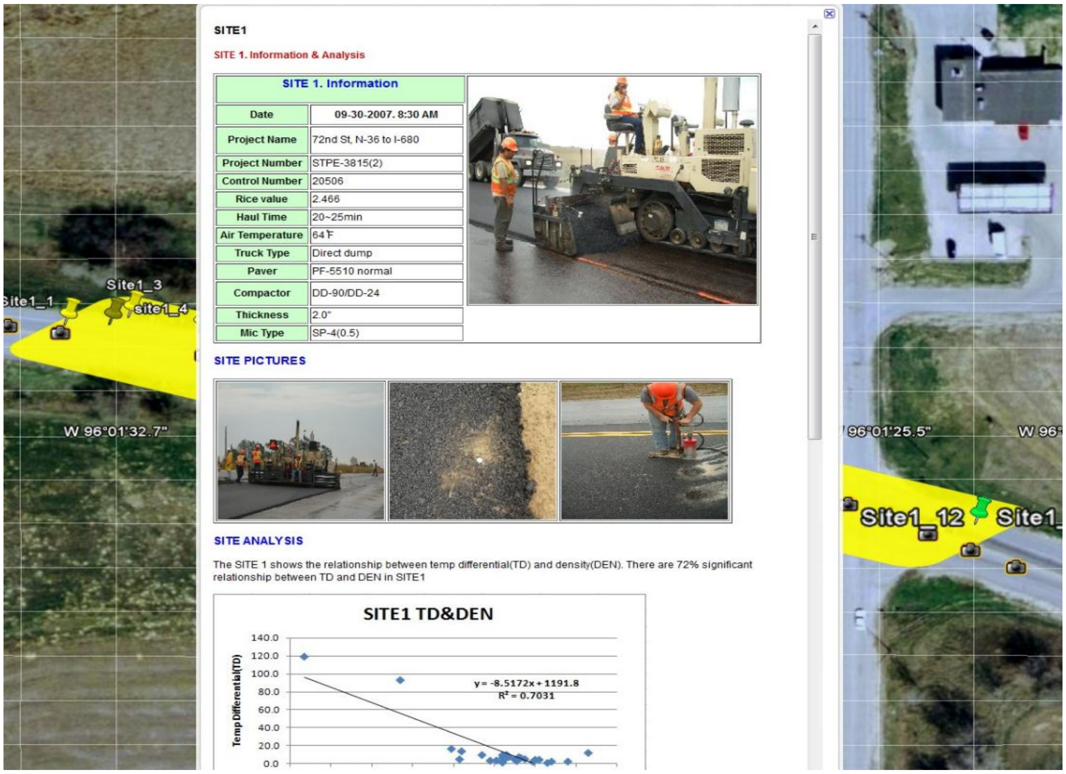


Figure 6.2 Google Earth Based Database

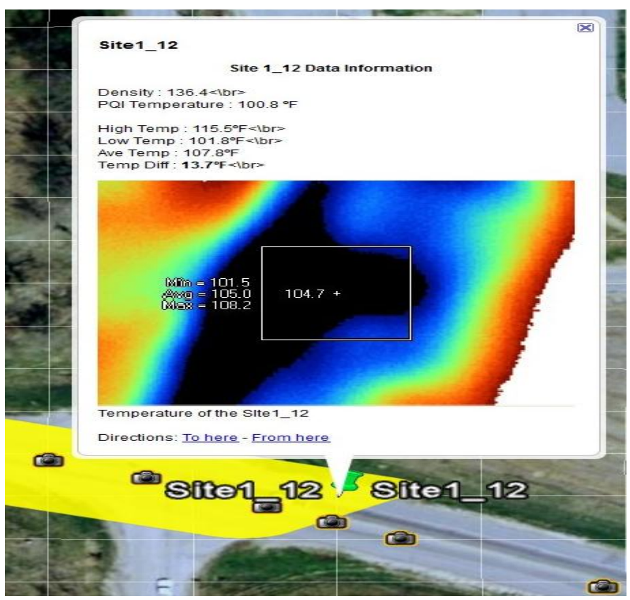


Figure 6.3 Location-Specific Data via Google Earth

Those working on the project were able to instantly recall location-specific data, typically in a highly visual manner, enabling more fluent and reliable decision-making. Not only was this system easy to use and understand, but it was easily accessible from any computer with Google Earth installed. Changes to project-specific data could be made on the road and reflected back to users in the lab.

6.1.1 Google Earth File Type

This study has shown Google Earth holds a valuable place as a pavement construction database tool; however, it is important to consider how it will be integrated with existing and future pavement or asset management systems. The Texas Transportation Institute of Texas A&M University highlighted this issue in its development of a web-based tracking system for flexible pavement. The Institute noted that a system based on the XML schema promoted easy data or file exchange (Krugler et al. 2008).

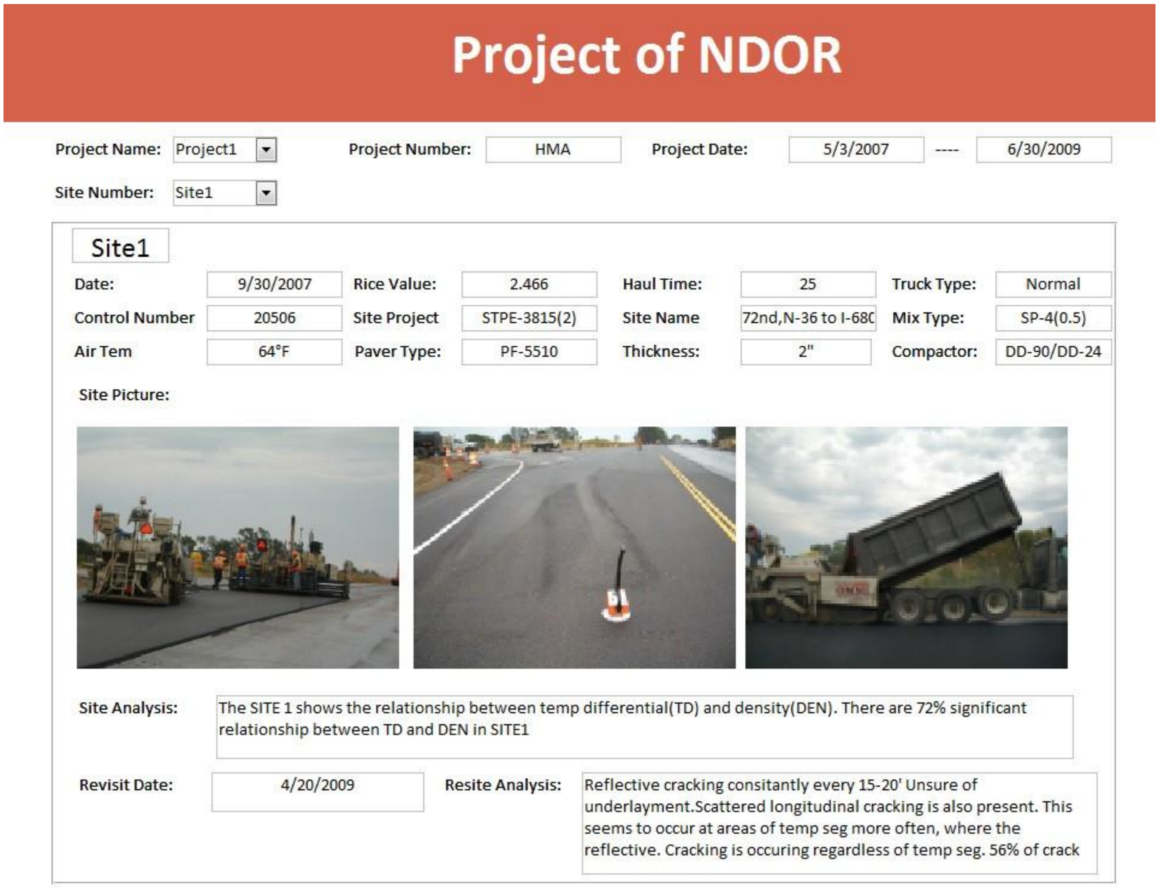
The current Google Earth program is built on a Keyhole Markup Language (KML) 2.2 Schema. In turn, the KML language schema is based on XML and was created specifically for the representation of geographic data (Open Geospatial Consortium 2009). Most Google Earth users are familiar with the KMZ file format, which is simply a zipped KML file. Though there is a number of software applications specifically designed to convert KML files to XML files and vice versa, it is simply done by opening the KML file in a text file and then opening and saving that text file in Excel as XML Data.

6.2 Database in Microsoft Access

The wide array of data types within this project necessitated NDOR's request of a proprietary database in which to store all research data as part of the project's deliverables. The database allows the state to access historical data for later analysis if necessary. This is an important aspect of this type of research, as later findings will enhance the validity of previously collected data.

The database information is similar to the information included within the Google Earth application. In the database, site information includes RICE value, haul time, truck type, control number, site project number, site project name, mix type, air temperature, paver type, lift thickness, roller type, site analysis summary, revisit date, revisit analysis summary, and three images of each site. Additionally, all 408 investigated locations have unique data stored in the database that includes data number, hot temperature, cold temperature, temperature differential, pavement density, moisture content, wind speed, GPS location, infrared image, located premature distress type, and two images of each data point.

The database was constructed using Microsoft Access. The file extension generated by Microsoft Access is .accdb, which is easily transferred into the versatile XML schema. The database consists of four primary units, one data table called from Excel, and three user-integrated design forms (Figures 6.4, 6.5). The design forms are utilized via simple drop down menus that then call the appropriate data.



Project of NDOR

Project Name: Project1 | Project Number: HMA | Project Date: 5/3/2007 ---- 6/30/2009

Site Number: Site1

Site1

Date:	9/30/2007	Rice Value:	2.466	Haul Time:	25	Truck Type:	Normal
Control Number	20506	Site Project	STPE-3815(2)	Site Name	72nd,N-36 to I-68C	Mix Type:	SP-4(0.5)
Air Tem	64°F	Paver Type:	PF-5510	Thickness:	2"	Compactor:	DD-90/DD-24

Site Picture:

Site Analysis: The SITE 1 shows the relationship between temp differential(TD) and density(DEN). There are 72% significant relationship between TD and DEN in SITE1

Revisit Date: 4/20/2009

Resite Analysis: Reflective cracking consitantly every 15-20' Unsure of underlayment.Scattered longitudinal cracking is also present. This seems to occur at areas of temp seg more often, where the reflective. Cracking is occuring regardless of temp seg. 56% of crack

Figure 6.4 Site Designed Database Form

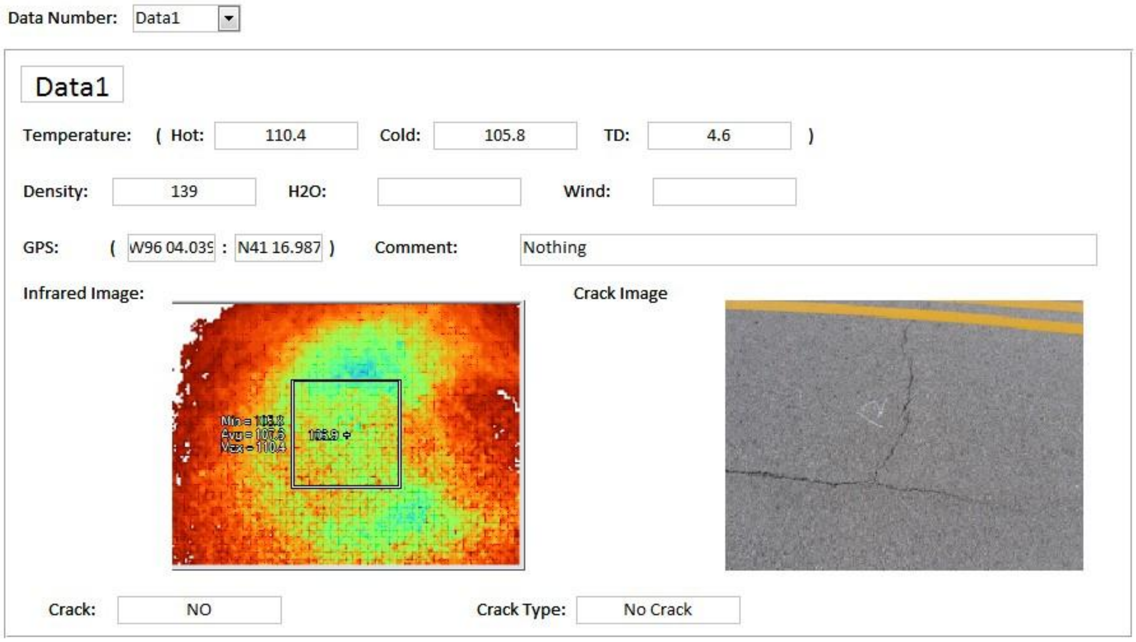


Figure 6.5 Data Designed Database Form

Chapter 7 Conclusions and Recommendations

7.1 Conclusions

The primary objective of this report was to identify and measure variables which could have a significant effect on HMA temperature segregation during roadway construction in the state of Nebraska. The study also investigated the viability of including simple non-destructive sensory devices as a means of detecting and controlling temperature segregation. The following is a brief overview of the findings generated in the pursuit of each of the study's proposed sub-objectives.

1. *Evaluating the possible reasons for thermal differentials during HMA construction process*

The overall relationship between pavement temperature differentials and density was not readily apparent when areas of temperature segregation were identified after compaction. When taken as a whole, the data did not show a significant relationship between temperature differentials and density, exhibiting only a 3% correlation. However, when separating the data into increasing temperature groups, a clear trend in the relationship between temperature differentials and density was found. For example, when a temperature differential is 2˚F, the TD/DEN relationship is less than 10%, but when the temperature differential is increased to 30˚F after compaction the relationship is nearly 70%.

When analyzing independent construction variables within the HMA process, a limited correlation was found. Jobsite air temperature at the time of paving was not found to be a significant indicator of increased or decreased air voids, showing a relationship of less than 3%. The activity of material hauling--particularly, haul time--was also not found to be a good indicator of overall temperature segregation, again showing a 3 % relationship. Instead, the different material transport methods were more likely to lead to areas of temperature segregation. It was discovered that belly dump trucks that incorporated the use of a pick-up machine were far superior to the direct dump paving process of traditional HMA trucks. The belly dump process was found to have a temperature variance of 5˚ F, while the direct dump process was found to have a temperature variance of 13˚ F.

The key to successfully drawing conclusions about the effects of temperature segregation within the HMA process was the revisiting of past paving sites. Through these site visits, it was discovered that of the 259 investigated locations, 76 were exhibiting signs of premature distress one year later. It should be noted, however, that 14 of these flaws showed signs of reflective cracking. The reflective cracks were found to hold less than a 1% relationship to temperature differentials and density and were excluded from analysis on that basis.

Transverse cracks, multi-crack joints, and aggregate segregation, were all found to have a significant relationship between temperature differentials and density, with relationships being 60.7 %, 98%, and14.73%, respectively.

On the other hand, surface voids (potholes) were not found to follow the typical relationship between temperature segregation and density. Later analysis did show that although surface voids did not show a relationship in regard to density, it was still important to consider temperature differentials as possible causes of surface void premature distresses. If this trend continues, it can be assumed that under current quality control and quality assurance procedures in the state of Nebraska, this flaw will be unaccounted for.

By organizing the collected premature distress data into discrete temperature ranges, the relationship between temperature differentials and density was found to be more than 99%. Additionally, when temperature groups are compared to the instances of premature distresses, there is a clear trend of nearly 70%, implying increases in temperature differentials lead to an increase in premature distresses.

2. *Developing a practical and economical method of preventing and managing HMA thermal differentials*

The results of this objective are discussed in Section 7.2.

3. *Validating the effectiveness of infrared thermal images as a test modality for assessing thermal differentials in HMA*

The use of an infrared camera in identifying areas of temperature segregation was a simple process. The research team was able to quickly focus on areas of temperature segregation and how they were created within the HMA construction process. The infrared readings generated by the infrared thermography consistently showed relatively similar results to those of the onboard thermometer device on the non-nuclear density gauge (PQI) as well as HMA temperature probes.

4. *Validating the effectiveness of non-nuclear density gauge as a test modality for assessing HMA densities*

The non-destructive sensory devices selected by the research team were found to be very intuitive to potential users. The PQI 301 proved to be an effective tool in collecting HMA density readings. Its straightforward interface and ability to rapidly take HMA density readings illustrated its effectiveness as a quality control device.

5. *Other Findings*

The location tracking system utilized as part of this study was proven adequate. The physical location markers were still highly visible after one year of pavement use. However, some locations that were only marked digitally could not be located for revisit. These locations were not included as part of the site revisit analysis.

Finally, the use of a database system that incorporated the visualization of collected data through Google Earth was useful in analyzing and reviewing information. The XML platform that Google Earth's KML file type is based upon makes its incorporation into existing programs and database nearly seamless.

7.2 Recommendations

The clear relationship between temperature segregation and premature distresses underlines the importance of identifying thermal differences. The variability of each jobsite coupled with inexpensive thermography devices suggests that thermography's inclusion as a quality control device for state inspectors would be useful and economical. The funds spent on maintaining or replacing pavement failing due to temperature segregation would likely far exceed that of the purchase price of infrared equipment.

The use of rear dump trucks as a means of transporting HMA to the site should be prohibited unless a remixing machine is used. At a minimum, due to the relationship between material temperature and outside air temperature, tight tarping of truck beds with proper side insulation should be required year-round when using rear dump trucks.

Training or educational programs for the roller operators is recommended. Many compact roller operators observed in this study seemed to lack adequate knowledge on situational rolling patterns in terms of the number of required rolling passes, timing, and required minimum mat temperature for rolling.

The inclusion of GIS-based software like Google Earth or Microsoft Bing Map (Virtual Earth) could be useful as an aid to state pavement or asset management systems as a means of visualizing useful data through the Internet.

Possible methods of incorporating temperature segregation as a means of payment should be incorporated to the current pay structure.

7.3 Future Studies

Further research is needed to investigate the extent of some premature flaws such as surface voids (potholes), which were identified to be the result of temperature segregation rather than lower density. Again, current quality control and assurance activities focus on changes in material density rather than temperature segregation.

Further research is needed to investigate the economic impacts reflective cracks have on newly placed pavements' service life, as well as methods to mitigate reflective cracking in general.

Compaction is an important factor of producing a durable pavement in the construction process. Even without temperature segregation, the mat can still have lower density due to the incorrect rolling practices. To achieve optimum load-bearing and weathering characteristics, an asphalt mix must be compacted to a specific range of density within a certain time. Additionally, roller settings such as amplitude, frequency, and number of rolling passes should be determined based on given site factors including weather and mix types.

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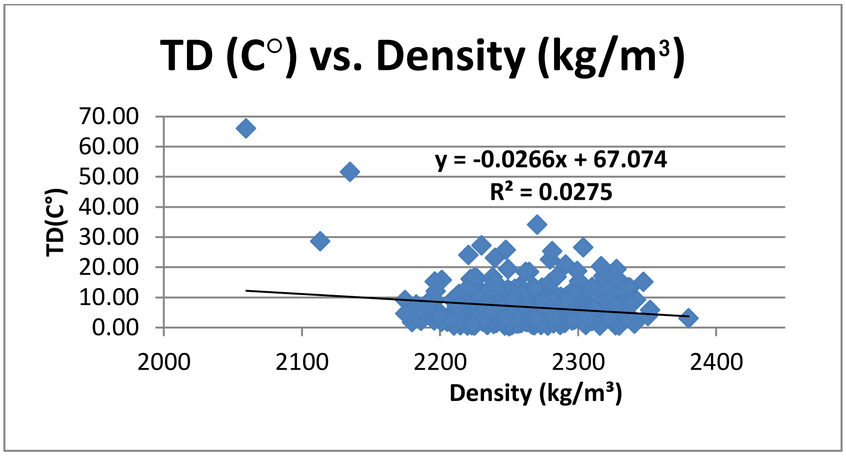

Figure 4.2 Relationship for All Collected Data between Temperature Differential (TD) and Density (DEN)

Table 4.1 Shows the Correlation between a Given Temperature Group and the Relationship between TD and Den

TD GROUP OVER X °C	R-SQUARED	# OF DATA POINTS	TD GROUP OVER X °C	R-SQUARED	# OF DATA POINTS
Whole	0.0105	408	12°C	0.3394	51
1°C	0.0318	389	13°C	0.4242	43
2°C	0.0473	350	14°C	0.4371	34
3°C	0.069	297	15°C	0.4354	33
4°C	0.064	245	16°C	0.5291	27
5°C	0.082	217	17°C	0.6664	21
6°C	0.115	176	18°C	0.6562	20
7°C	0.1377	143	19°C	0.6507	16
8°C	0.1615	115	20°C	0.6547	14
9°C	0.1682	98	25°C	0.5932	10
10°C	0.2473	76	30°C	0.9882	3
11°C	0.2635	64	Total : R^2 = 0.9337		

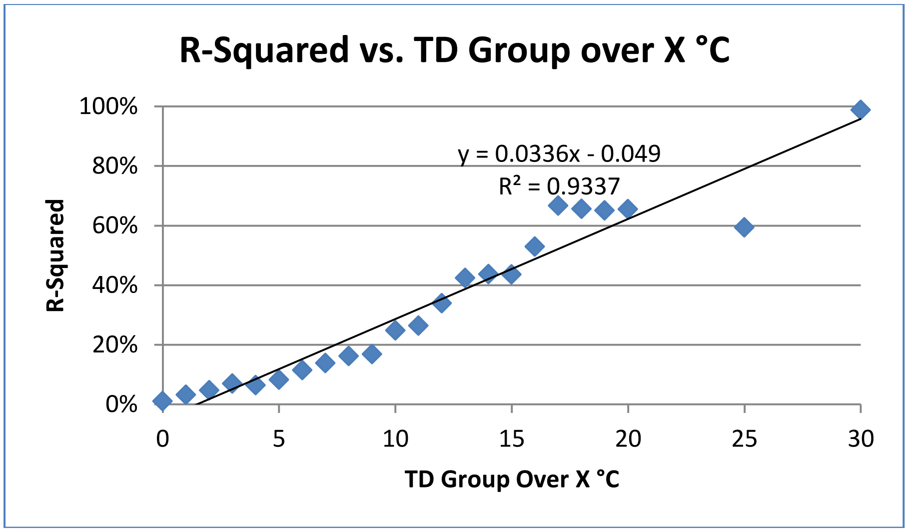

Figure 4.3 A Graphical Representation of the Relationship between Individual Temperature Groups and TD and DEN

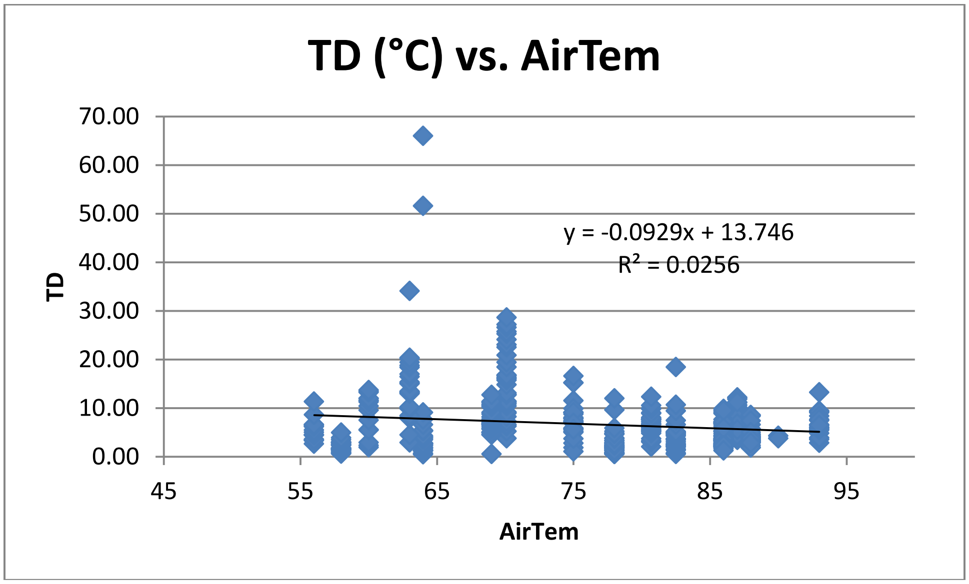

Figure 4.4 Relationship between Ambient Jobsite Air Temperature and Temperature Differential

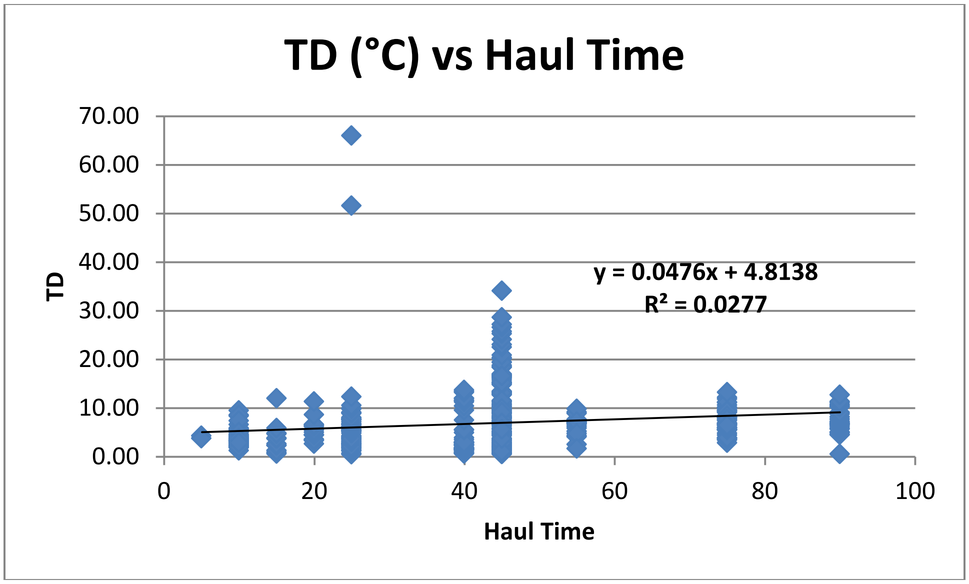

Figure 4.5 Relationship between Haul Time and Temperature Differentials

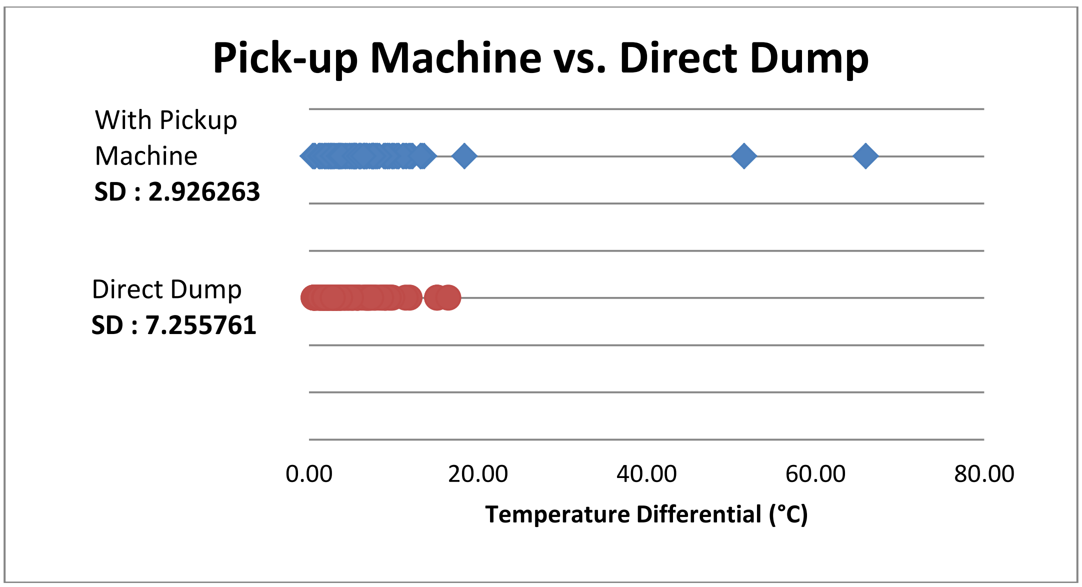

Figure 4.8 Temperature Differential Based on Feeding Types

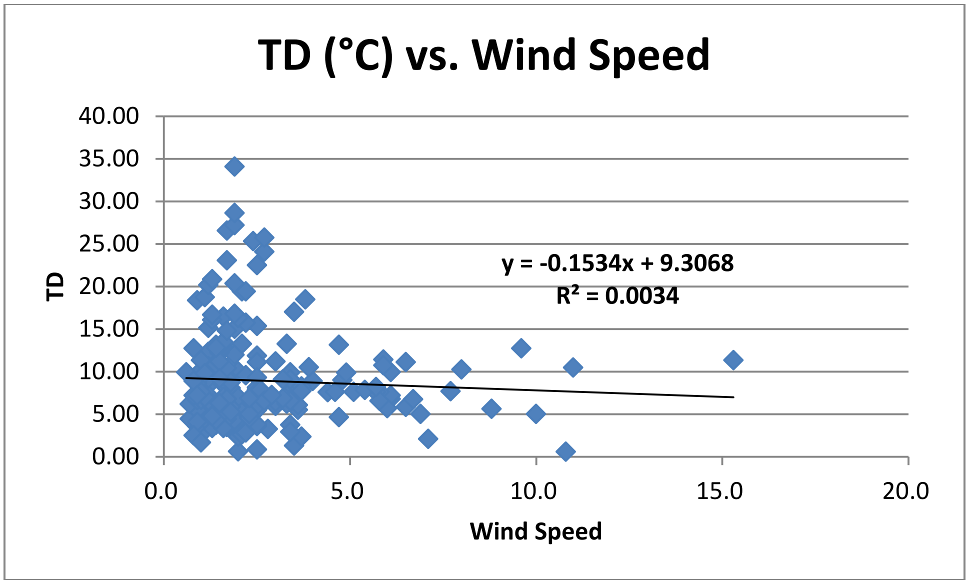

Figure 4.9 Relationship between Wind Speed and Temperature Differentials (TD)

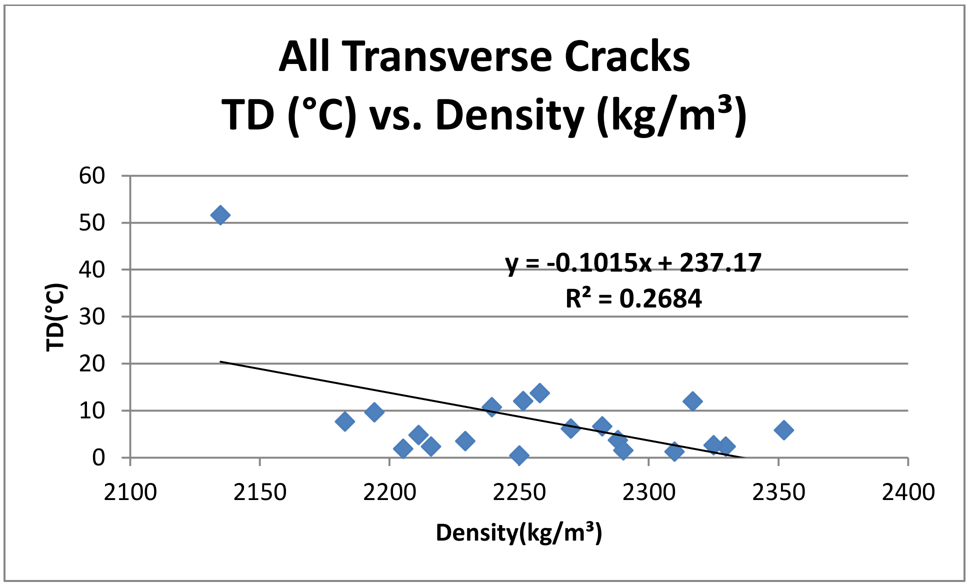

Figure 5.7 Relationship of TD and Density among Transverse Cracks

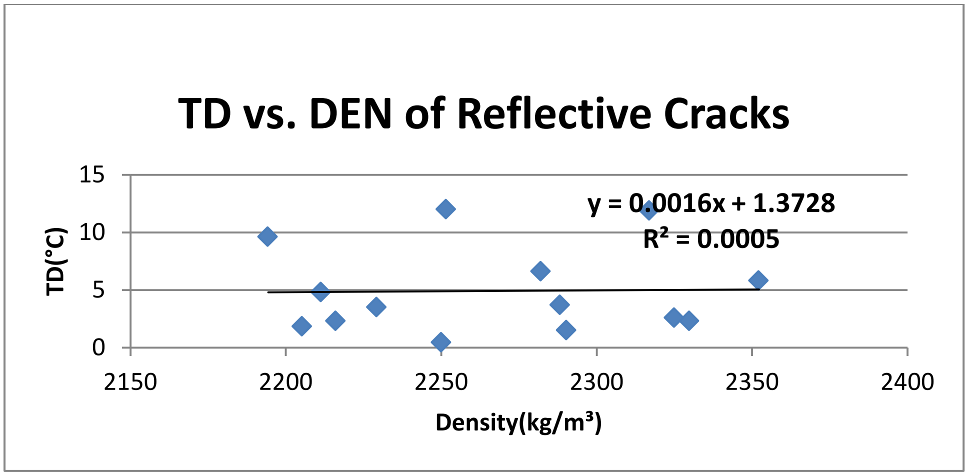

Figure 5.9 Temperature Differentials and Density Relationship among Reflective Cracks

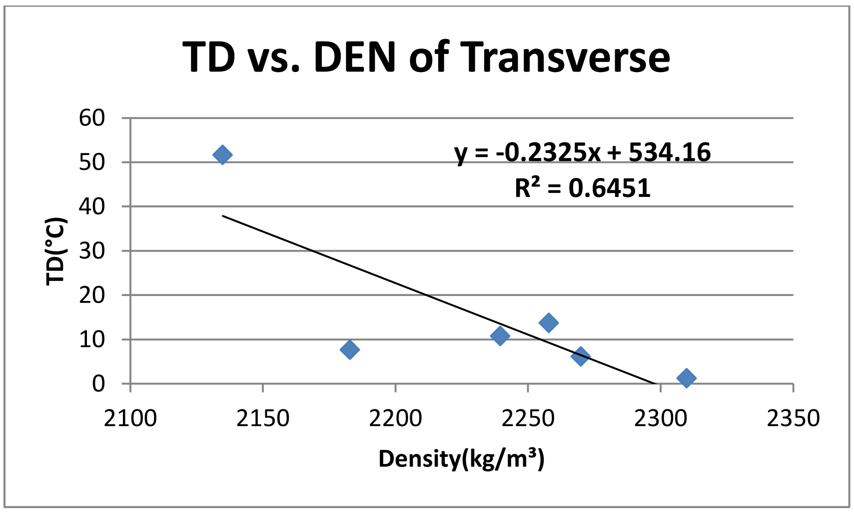

Figure 5.10 Relationship between Temperature Differentials (TD) and Density (DEN), Excluding Reflective Cracks

Table 5.3 Revisit Data Analysis

Num	TD (°C)	DEN(kg/m³)	Num	TD (°C)	DEN(kg/m³)	Num	TD (°C)	DEN(kg/m³)
1	1.1	2268.4	22	5.7	2228.382	43	11.3	2244.4
2	1.2	2310	23	6.1	2270	44	11.4	2227
3	1.3	2266.1	24	6.2	2282.9	45	13.3	2336.3
4	1.5	2130.7	25	6.6	2257.2	46	13.4	2267.6
5	1.5	2270	26	6.8	2321.3	47	13.7	2258
6	1.6	2236	27	7.6	2295.7	48	14.1	2281.5
7	1.9	2317.6	28	7.6	2182.9	49	15.0	2328
8	2.0	2237.6	29	8.4	2336.3	50	15.7	2201.4
9	2.2	2186.3	30	8.7	2234.79	51	16.1	2222.3
10	2.8	2232.5	31	9.0	2196.342	52	16.4	2328.3
11	2.9	2258.8	32	9.1	2225.178	53	18.3	2320.2
12	3.0	2334.114	33	9.2	2286.3	54	18.4	2264.7
13	3.3	2258.4	34	9.9	2286.054	55	20.2	2316.8
14	3.3	2258.8	35	9.9	2323.2	56	20.3	2316.8
15	3.9	2227.7	36	10.2	2300.8	57	20.8	2291.1
16	4.1	2219.7	37	10.2	2239.596	58	25.7	2247.9
17	4.3	2320.8	38	10.4	2229.984	59	28.6	2113.3
18	4.4	2299.2	39	10.5	2303.676	60	34.1	2270.3
19	5.0	2215.566	40	10.7	2239.596	61	51.6	2134.9
20	5.3	2198.9	41	10.8	2297.5	62	66.0	2059.7
21	5.4	2218.1	42	11.1	2217.168			

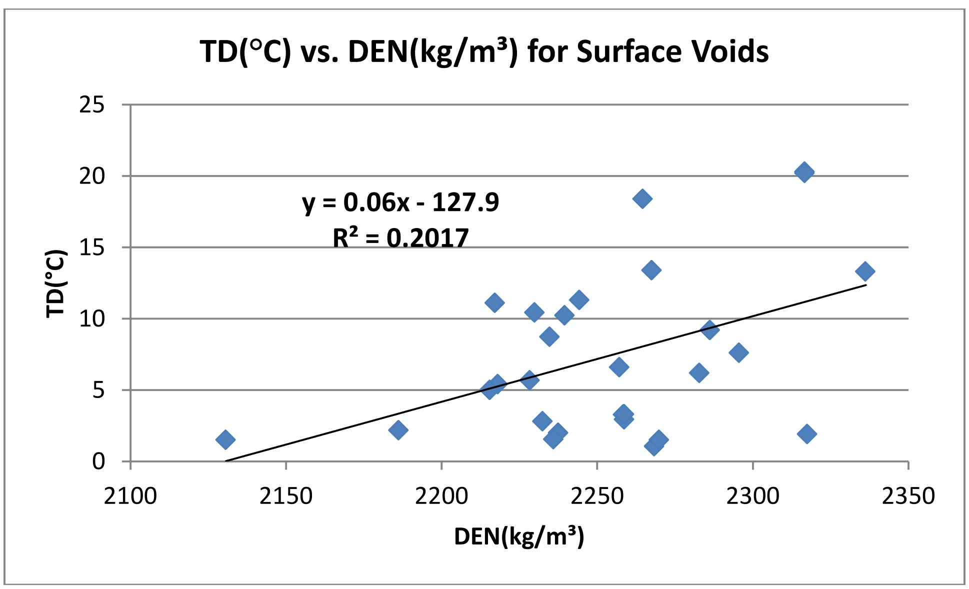

Figure 5.11 Relationship between Temperature Differentials (TD) and Density (DEN) among Surface Voids

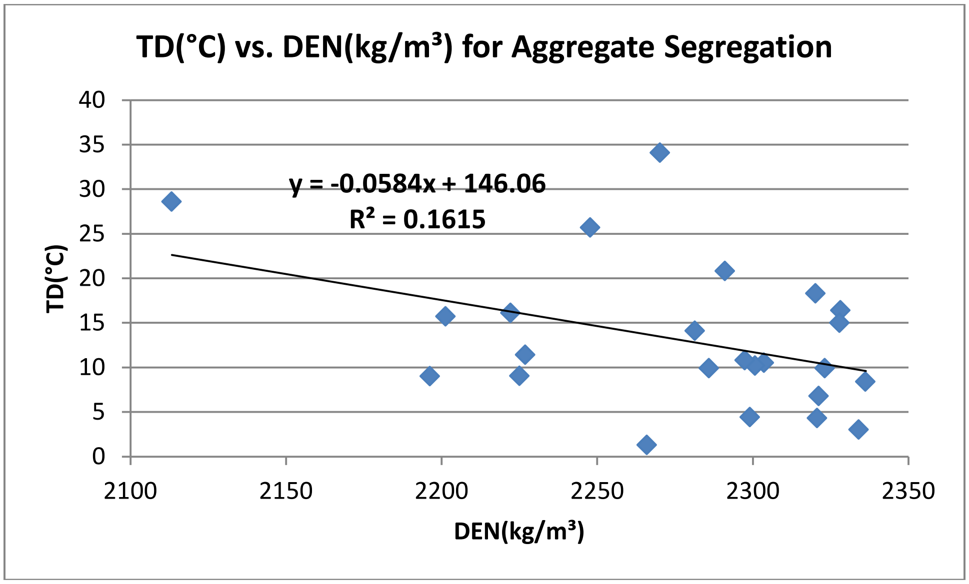

Figure 5.12 Relationship between Temperature Differentials (TD) among Aggregate Segregation

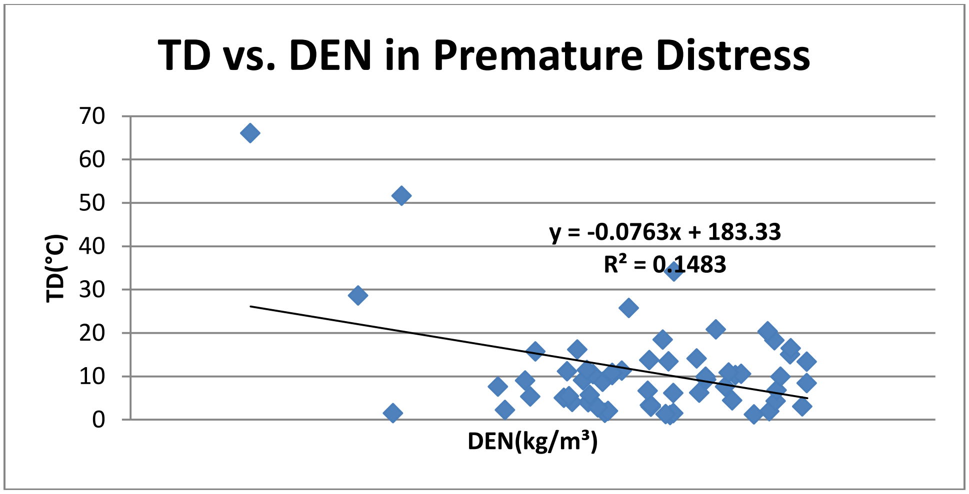

Figure 5.13 Relationships between Temperature Differentials and Density among Total Instances of Observed Premature Distresses

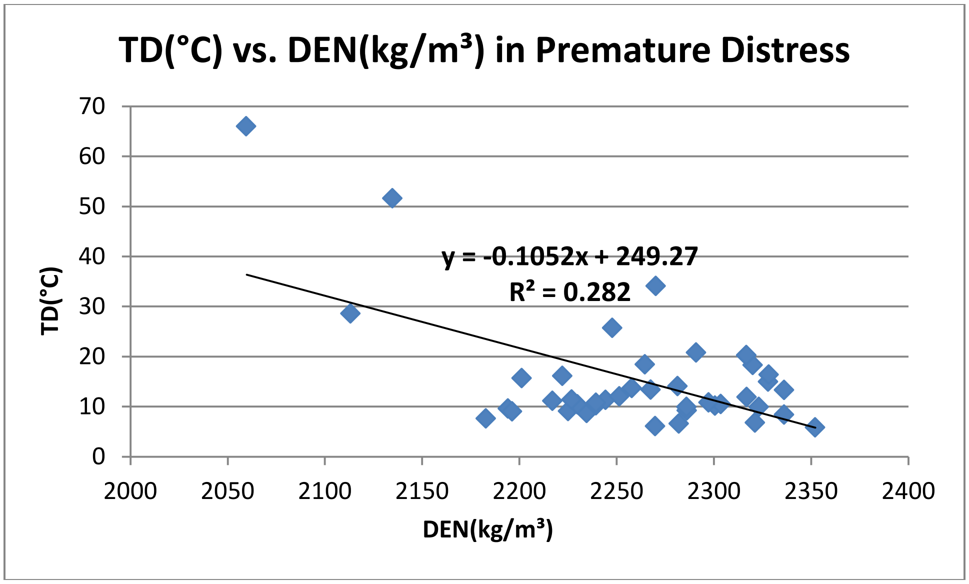

Figure 5.14 Relationship between Temperature Differentials and Premature Distresses, Excluding Small Surface Voids

Table 5.4 Relationship between R^2 and Corresponding TD Groups for Premature Distresses

Num	Temperature Diff. Range(°C)	R-Squared	Included Premature Distress Data Points
1	whole	0.282	48
2	5°C and Up	0.3693	32
3	10°C and Up	0.5707	20
4	15°C and Up	0.5904	11
5	20°C and Up	0.5966	6
6	30°C and Up	0.9885	3

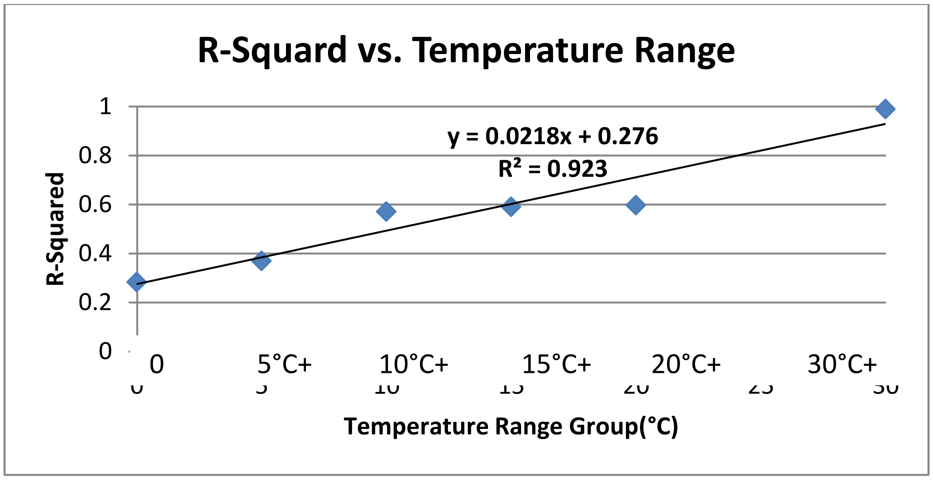

Figure 5.15 Relationship between the Correlation of TD and DEN for a Given Temperature Range and the Temperature Range Group

Table 5.5 Temperature Differential Range (TD) vs. Type of Premature Distress (PD), with Surface Voids

TD (°C)	Transverse	Small Voids	Agg. Segregation	Multi-Crack	Total	DATA Total	%
1~5	1	11	4	2	18	123	14.6%
5~10	2	8	6	1	17	75	22.7%
10~15	2	6	5	0	13	34	38.2%
15~20	0	1	5	0	6	16	37.5%
20~25	0	2	1	0	3	6	50.0%
25~30	0	0	2	0	2	5	40.0%
30~	1	0	1	1	3	3	100.0%
Total	6	28	24	4	62	262	43.3%

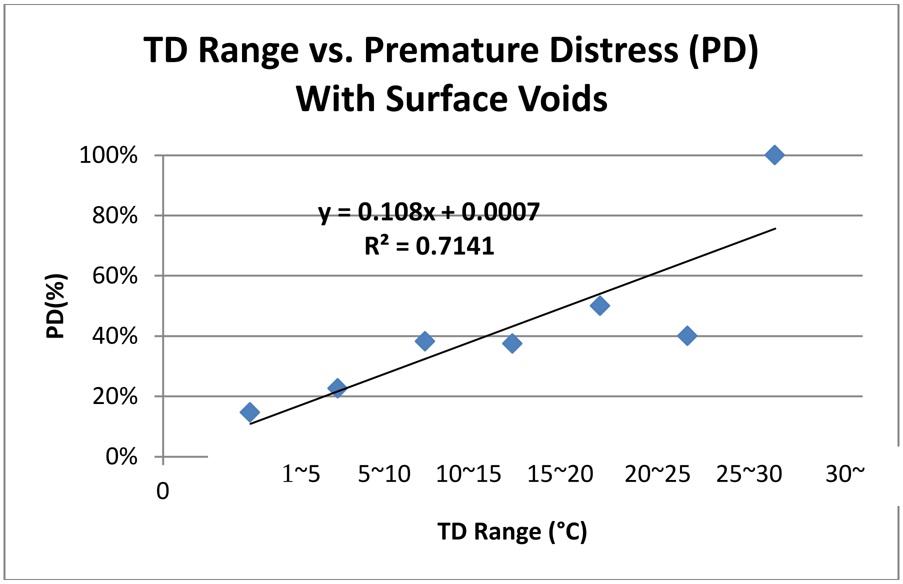

Figure 5.16 Correlation between the Percentages of Premature Distresses, Including Surface Voids, Found within a Specified Temperature Range

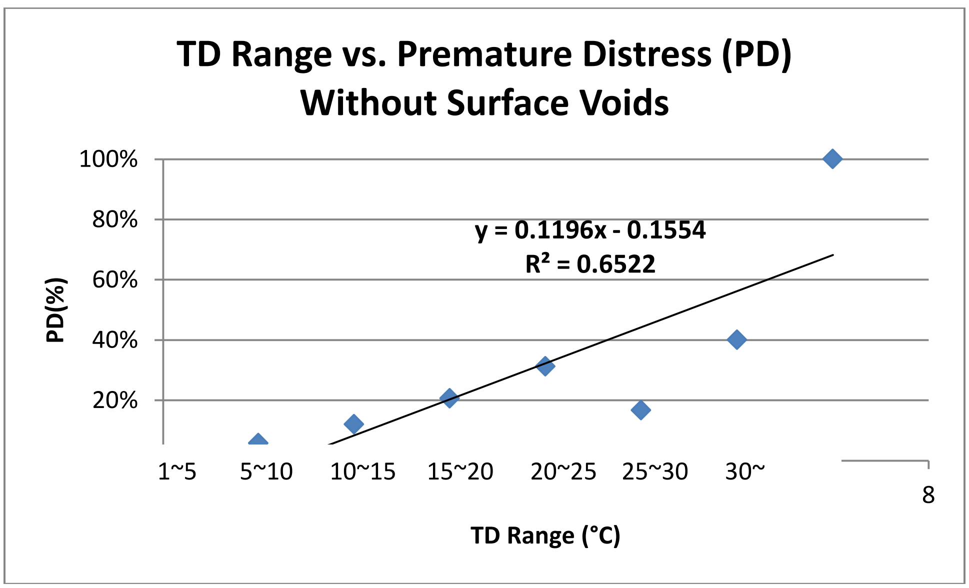

Figure 5.17 Correlation between the Percentages of Premature Flaws, Excluding Surface Voids, Found within a Specified Temperature Range

Appendix B Database

See the enclosed CD for Microsoft Access database and Google Earth database. Site by site field data collection and analysis results are included in the database. Tutoring movie clips for using Access and Google Earth are included in the CD as well.