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High Performance Concrete Pavement in Indiana

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JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

HIGH PERFORMANCE CONCRETE PAVEMENT IN INDIANA

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16. Abstract

Until the early 1990s, curling and warping of Portland cement concrete pavement did not concern pavement engineers in many transportation agencies. Since beginning construction of the interstate system in the United States in the late 1950s through the late 1980s, the performance of Portland cement concrete pavement has been associated with properties of concrete as a pavement material. In those years developed standards and design guidelines emphasized better concrete materials and construction control. At the time, combining curling and loading stresses was quite controversial due to the nature of the load-carrying capacity of concrete pavement and the occurrence of types of loads. Arguments developed that the types of loads (traffic and curling) rarely occurred at the same time of day. The concrete pavement design principle did not include the effects of curling and warping of concrete pavement as determining design factors in pavement performance.

This research project was initiated as a response from the INDOT Pavement Steering Committee related to the joint spacing of Jointed Plain Concrete Pavement in Indiana. There was an initiative in the Committee to reduce the joint spacing from 18 feet to 15 feet as a way to reduce premature concrete pavement deterioration. There was an indication that some newly paved JPCP had transverse cracks even before the pavement section was opened to traffic.

In this experimental study, several important conclusions were drawn from temperature analysis, stress-strain analysis, and other data analysis. The analysis from this experimental study supports the decision by INDOT to shorten the concrete pavement joint spacing to increase the performance of Jointed Plain Concrete Pavement in Indiana.

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EXECUTIVE SUMMARY

HIGH PERFORMANCE CONCRETE PAVEMENT IN INDIANA

Introduction

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Findings

Higher deflections in the concrete slab did not always mean higher stresses. Likewise, lower deflections in the slabs did not always mean lower stresses. Boundary conditions surrounding the slabs affected the slabs behavior on curling.

In the case of transverse joints with dowel bars as thick and as closer apart (with a 1.5-inch diameter dowel bar and 12-inch spacing) compared to the concrete pavement without dowel bars, looking only to the deflections on the surface of the slab will not yield correct information about the state of stress in the slabs. Lower surface deflections in this study will mean higher stress concentrations around the jointed transverse edges of slabs. In the longitudinal joints, the slabs are tied with 0.7-inch deformed steel bars with a spacing of two feet. Therefore, the restraint from the tie bars was significantly lower than that of the dowel bars, which would account for the lack of significant differences in the deflections and tilting of the slabs in transverse directions.

The followings are more detail findings from the study:

1. The temperature profile in concrete, inch by inch, depends only on seasonal changes in temperature.
2. The diurnal changes in air temperature influence the temperature profile of a concrete slab only about half-way through the thickness of the concrete pavement. Unless there is a sudden and drastic change in temperature, the temperature difference between the middle and the bottom portion of the slab is negligible.
3. The temperature profile of concrete's responses for diurnal temperature changes is not a linear profile from bottom to top as was previously assumed. Rather, it is an exponential form with a drastic change toward the surface of the concrete pavement.
4. Drastic changes in temperature in the concrete slab occur mostly during the winter and late spring or early summer seasons. These drastic changes in temperature will determine the maximum and minimum stresses in concrete pavement.
5. Built-in curling did occur as predicted by previous researchers.
6. The state of stress due to temperature curling in the concrete slabs depends significantly on the boundary conditions of the edges of the slabs.
7. The maximum and minimum stresses in concrete slabs occurred when there was a drastic, sudden change in the air temperature.
8. Shorter joint spacing gives an advantage in reducing the stresses in concrete slabs, especially stresses in the longitudinal direction that can influence the occurrence of transverse cracks. Thinner concrete slabs in combination with shorter joint spacing will significantly reduce stresses in slabs.
9. It is impractical to control built-in curling in concrete pavement by attempting to place the fresh concrete in a timely way to avoid the end of the final setting of cement hydration coinciding with the hottest temperature of the day.

Implementation

The following implementation suggestions are proposed for INDOT to be implemented in the pavement design procedures:

1. Propose to the INDOT Pavement Steering Committee that they reduce the thickness of the concrete pavement as much as possible by maximizing the pavement support layers underneath the concrete pavement layer.
2. Propose to the INDOT Pavement Steering Committee that they adopt shorter joint spacing for concrete pavement in excess of 12 inches in thickness.
3. Propose to the INDOT Portland Cement Concrete Pavement Technical Committee that they support reducing the amount of cement in the concrete mix in order to reduce the temperature of the concrete during the final setting of the cement hydration. However, the concrete strength should be in accordance to the 700 psi requirement in the INDOT MEPDG design.

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CHAPTER 1 INTRODUCTION

Until the early 1990s, curling and warping of Portland cement concrete pavement did not concern pavement engineers in many transportation agencies. Since beginning construction of the interstate system in the United States in the late 1950s through the late 1980s, the performance of Portland cement concrete pavement has been associated with properties of concrete as a pavement material. Many concrete pavement researchers in those years developed standards and design guidelines that emphasized better concrete materials and construction control. At the time, combining curling and loading stresses was quite controversial due to the nature of the load-carrying capacity of concrete pavement and the occurrence of two types of loads. Pavement experts argued that the two types of loads (traffic and curling loads) rarely occurred at the same time of day. The concrete pavement had a tendency to experience high levels of curling stress during the day while heavy trucks traveled at night.

Indications of the influence of curling stress on the performance of Portland cement concrete pavement have appeared earlier than most engineers expected. Many jointed plain concrete pavement sections with more than adequate flexural strength developed mid-slab panel cracks even before any loading was applied. Sixteen years after the construction of the AASHTO Road Test in Illinois, most of the longer concrete slabs in non-traffic section had cracks though not in shorter 15-foot slabs. In Indiana, many pavement sections with skewed joint variable spacing had mid-slab cracks in both 18 and 19-foot slabs, though not in the 12 and 13-foot slabs.

By the early 1990s, with the economic development booming and the philosophy of “get-in, get-out, and stay-out,” concrete pavements were designed and constructed for longer design life, larger Equivalent Single Axle Loads (ESALs), a thicker pavement cross section, a larger dowel bar diameter, and extended construction hours during the day. The design principle at that time did not include the effects of curling and warping of concrete pavement as determining factors in pavement performance design. The AASHTO 1986 Guide for Design of Pavement Structures indicated that the temperature and moisture differential between the surface and the bottom of the concrete pavement creates an upward curling and warping at the slab ends, which can result in pumping and structural deterioration of un-drained sections. Once again, the concern was only on the upward curling that occurred when the surface temperature was cooler than the bottom temperature, which happened mostly at night.

The increase in highway construction funding beginning in the second half of the 1990s made highway maintenance policy synonymous with reconstruction. “Band Aid” rehabilitation projects that only marginally extended the life of the pavement were switched to reconstruction projects designed with future traffic and load prediction in mind. Pavement thickness as thick as 15 inches was not uncommon. With this increase in thickness, pavement curling was becoming imminent. During those years, a few pavement sections in Indiana experienced mid-slab cracking, although those sections were not yet opened to traffic.

This pavement curling phenomenon was beginning to be explored by many states, especially in the Midwest. From responses of a questionnaire regarding curling stresses that was sent to multiple states, some states implemented a quick remedial action by shortened slab joint spacing from 18 to 15 feet. In the 1998 Supplement to the AASHTO Guide for Design of Pavement Structures Part II, Rigid Pavement Design and Rigid Pavement Joint Design, the onset of curling and warping was recognized and the computed mid-slab stress from load and climatic conditions was accounted for in the required slab thickness.

The release of the Mechanistic-Empirical Pavement Design Guide (MEPDG) by the National Cooperative Highway Research Program generated even more attention to pavement curling in pavement design and analysis. Based on the preliminary sensitivity analysis of the MEPDG software, researchers determined that pavement curling stress played a significant role in meeting the MEPDG pavement performance criteria. In many areas in the United States, based on the MEPDG analysis, transverse (or mid-slab) cracking is the most sensitive performance criterion to be considered in pavement design.

The renewed attention to pavement curling stress in pavement design and analysis has created a paradigm shift on how the pavement is supposed to be designed. Pavement engineers pay more attention to the coefficient of thermal expansion (CTE) of concrete based on the type of coarse aggregate in the concrete pavement. The CTE was found to be the dominant factor in the escalation of curling stress. Many State Highway Agencies now have to test their aggregates according to the CTE to make sure that their pavement is not over- or under-designed. In many cases, to reduce the transverse cracking result in the MEPDG, a designer must reduce the joint spacing to meet a higher percentage of reliability in the pavement performance criteria. In addition, the temperature difference between the bottom and top of the concrete pavement is becoming a more central consideration for pavement designers.

Simply speaking, curling in concrete pavement can be described as dimensional changes at the surface and bottom of a concrete slab that occur as a result of changes in diurnal temperature. When the temperature at the surface of a concrete slab is higher than the temperature at the bottom (known as the positive gradient) during the daytime, the surface dimensions will expand relative to the bottom dimensions. As a result, the concrete slabs curl down. When the slabs curl down, there is resistance to this curling action from the dead-load of the slabs. Curling stress occurs at the bottom of the slab in the form of tensile stress. When this tensile stress occurs in combination with stresses from traffic loading and other environmental loads exceed the tensile strength of concrete, cracks begin to propagate from the bottom of the slabs. Figure 1.1 shows this daytime downward curling action.

Conversely, at night, when the temperature at the surface of a concrete slab is lower than the temperature at the bottom (known as the negative gradient), the concrete surface dimensions will contract relative to the bottom dimensions. Compressive stress at the bottom of the slab and tensile stress on the surface of the slab occur as a result of these dimensional changes, and the slabs curlup. Cracks will propagate from the top of the slabs. Figure 1.2 shows this upward curling.

Classical pavement design theory does not include curling stresses as an important pavement design parameter. However, with increased efficiency in the trucking industry, peak truck traffic occurs at 3:00 in the afternoon when the positive gradient temperature is at its maximum. Therefore, curling stresses cannot be ignored in pavement design.

1.1. Temperature and Moisture Induced Stresses in Plain Concrete Slab

The onset of stresses due to temperature and moisture gradients have been recognized since as early as 1926 when Westergaard developed an equation to determine the curling stress in concrete pavement. However, the implementations to the concrete pavement design were not practical.

Temperature differentials within a concrete pavement slab cause curling stresses in in-service concrete pavement. Modern concrete pavement design practices assume 2°F to 3°F per inch depth of concrete. During the development of concrete pavement research, many sources, including the Arlington Road Test and the AASHTO Road Test, indicated a temperature differential as high as 3.7°F/inch. In modern concrete pavement as thick as 15 inches, this value is translated into a 55.5°F temperature differential between the top and bottom surface. A value this high seems untypical in the Midwest, especially during the early summer months where temperatures rarely reach 90°F.

Most modern concrete pavement is constructed with a better construction method, better specifications, better materials, and better design compared to the concrete pavement in the era from 1950s to 1980s. Concrete pavements today are more reliable in performance due to the Quality Control/Quality Assurance program and a better understanding of concrete technology. Most of the Jointed Plain Concrete Pavement (JPCP) now has better design and construction with load transfer and longitudinal ties. This design, at least, will decrease some of the curling stress. In addition, most modern concrete pavements have an

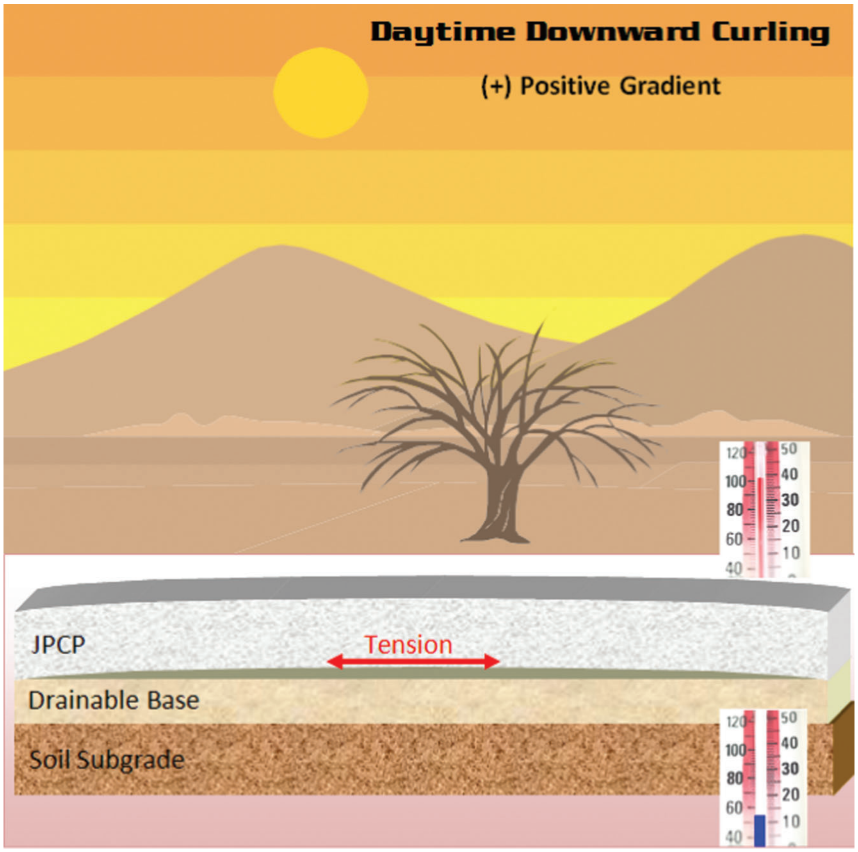


Figure 1.1 Daytime Downward Curling

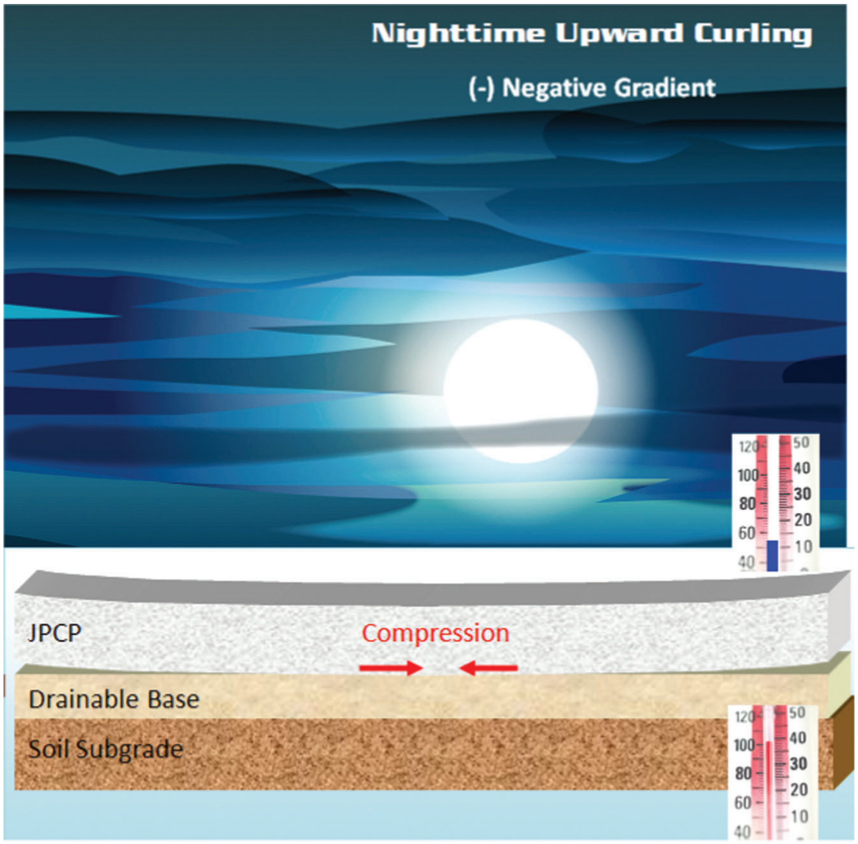


Figure 1.2 Nighttime Upward Curling

open graded drainable base that will decrease the temperature differential between the top and bottom surfaces. However, in the last ten years, more mid-slab cracks on newly constructed concrete pavement have appeared, although the pavements were not yet opened to traffic.

A lot of effort has been dedicated to temperature gradients and their relationship to curling stress. However, most of this effort was concentrated in the top, middle, and bottom of the slab only, as the temperature profile was assumed to be linear. In the case of thinner concrete pavement, this assumption may be correct; however, in the case of a thicker concrete pavement, this assumption will probably not hold up. Figure 1.3 shows the results of the KENSLAB [2] calculation of curling stresses based on joint spacing and concrete pavement thickness and width. The increase in curling stress for thicker pavement with 15 to 18-foot joint spacing is significant. For a thinner pavement, the increase of curling stresses in slabs with 18 to 20-foot joint spacing is relatively small.

Huang (2004) indicated that temperature measurements in slabs of other thicknesses at the AASHTO test site also showed that the temperature differential was not proportional to the thickness of slab and that the increase in temperature differential was not as rapid as the increase in thickness. Therefore, greater temperature gradients should be used for thinner slabs.

The form of a linear temperature profile in concrete pavement to the curling stress is easily understood. However, in the case of thicker concrete pavement, a non-linear temperature profile makes the prediction of curling stresses more difficult. The complexity of predicting curling stress and its associated damage to the concrete pavement is compounded with the issue of built-in curling during construction when concrete materials enter the cement final set time. Figure 1.4

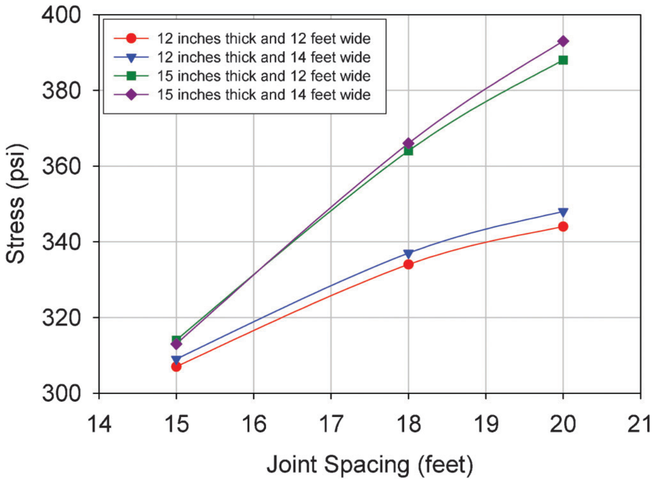


Figure 1.3 Curling Stresses Based on Joint Spacing

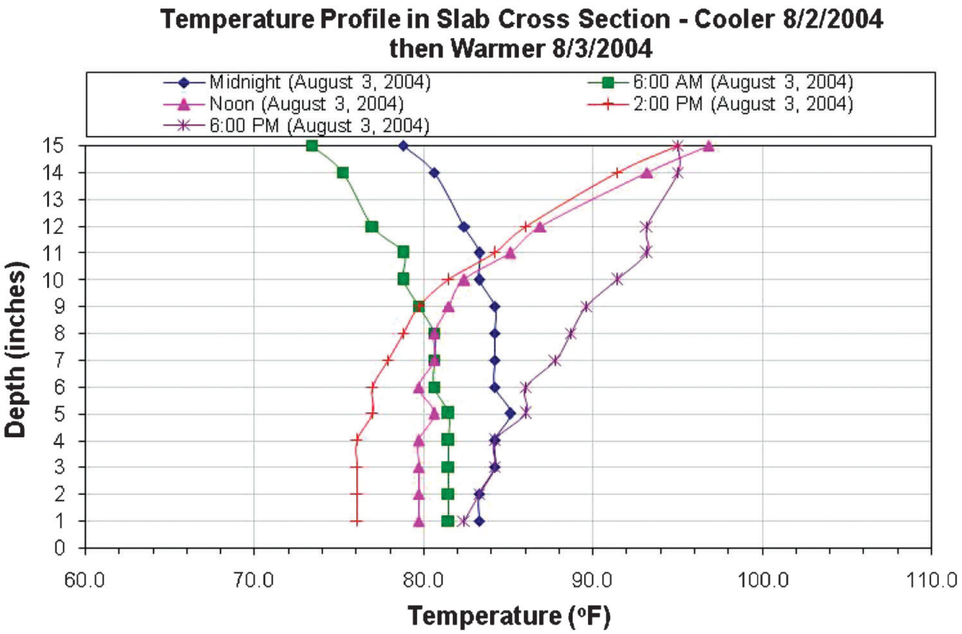


Figure 1.4 Non-Linear Temperature Profile in Concrete Pavement

shows the non-linear nature of a temperature profile in concrete pavement.

Warping as a result of moisture changes was not previously of interest to pavement engineers since the moisture gradient in concrete pavement is mostly seasonal. In addition, changes in the moisture gradients in concrete pavement are less systematic compared to those gradients in the temperature profile. Therefore, it is difficult to accurately predict the extent of concrete pavement warping for in-service concrete pavement.

For many decades, the pavement curling phenomenon was ignored by pavement practitioners in favor of traffic loading as the main cause of pavement failure in the field. Despite the fact that, in the original AASHTO Test Road, some of the concrete slabs that were never loaded with truck traffic still exhibited mid-slab cracks, practitioners ignored the role of curling stress in the propagation of cracks. It was not until the advancement of finite element analysis, changes in truck traffic loading, the advent of thicker concrete pavement, and more results from the FHWA Long Term Pavement Performance project that pavement practitioners accepted the fact that curling stress plays a major role in premature cracks.

1.2. Built-In Curling of Jointed Plain Concrete Pavement

Built-in curling is a new phenomenon in the concrete pavement community. The first extensive study of built-in curling was conducted in Chile as early as 1988. However, it was not until much later that more pavement engineers concentrated on the concept of built-in curling. The mechanism of concrete pavement built-in curling is created due to the construction time during the day or night. There are two mechanisms of built-in curling, one related to the shrinkage differential and one related to the temperature differential during construction.

The shrinkage differential involves the loss of moisture during the pavement curing process. For this reason there is a built-in moisture gradient during concrete curing. The effect of this moisture gradient on the dimension of the slab is similar to the effect of negative gradient curling (cooler surface, warmer bottom). During concrete curing, the surface of the slab will have less moisture compared to the bottom of the slab, causing the surface of the slab to shrink more compared to the bottom. As a consequence, a flat slab does not correspond to a zero-gradient slab.

The temperature differential in built-in curling involves the temperature at the time the concrete begins to set. A difference in temperature between the top and bottom of a concrete slab will trigger slab curling during concrete setting. For example, a concrete slab constructed during a hot afternoon experienced an initial higher surface temperature. However, when the concrete is about to enter its final set at night, the concrete surface temperature may be cooler than the bottom temperature because of the insulation effect by the subbase and subgrade soil to the heat of cement hydration that trapped the heat on the bottom portion of the concrete pavement. As a result, the slab curls up, similar to when a flat slab experiences a positive temperature gradient curl.

Built-in curling, however, comes not only from a temperature differential during hydration of the cement, but also from concrete shrinkage, field relative humidity, the chemistry of the cement, and other environmental conditions in the field. Since parameters other than temperature differential are difficult to obtain and analyze, those parameters are mostly ignored. However, built-in curling is an important parameter that can determine the behavior of pavement constructed in the field.

Figure 1.5 shows a scenario where a slab is constructed in the morning and has a cement hydration final set during a hot afternoon and experiences diurnal (daily) curling following the construction time. In the diurnal curling scenario, slabs that are built at a positive temperature gradient will probably never curl down in their service life. The effect of such excessive built-in curling is top-down cracking in in-service concrete.

Comprehensive knowledge of built-in curling will set up a precedent for generating strategies to implement different design features for the purpose of preventing mid-slab cracks and lengthening concrete pavement life. For example, if a curling stress can be quantified, changes in concrete slab dimensions, such as shorter joint spacing or widened pavement, will tremendously reduce the curling stress and provide economical solutions to make pavement last longer.

Implementation of the guidelines in the Mechanistic Empirical Design Guide (MEPDG) increases awareness to the pavement design engineer about built-in curling when designing a pavement section. In the northern part of the United States, built-in curling is a dominant factor in the performance criteria of the MEPDG. For example, in areas where joint faulting is not an issue, especially after the adoption of a granular sub-base drainage layer, transverse cracking because of curling stress and traffic loading stress is the only factor that determines if a pavement design can pass at a certain reliability level in the MEPDG to make the final thickness design.

In the MEPDG curling models, diurnal curling and built-in curling are integrated as one output in the calculation of transverse cracks. From the software outputs of the MEPDG analysis for Indiana's climates, transverse top-down cracking (due to pavement curling up) is a dominant factor while bottom-up cracking (due to pavement curling down) is minimal. Most truck traffic on major highways reaches its peak during the day (when a slab is most likely to curl down), when bottom-up cracking is most likely to occur. The fact that top-down cracking is dominant indicates that the majority of pavement in Indiana will experience a curl-up scenario more frequently than a curl-down one.

The majority of concrete pavement in Indiana contains crushed limestone as coarse aggregate. Based on the MEPDG material characterization, most crushed limestone in Indiana has a Coefficient of Thermal Expansion (CTE) of 5.5×10^{-6} inch/°F. Therefore, diurnal curling is kept to a minimum level with a lower CTE value. Since top-down cracking is likely to occur, this is an indication that built-in curling is an important factor in the performance of Indiana's concrete pavement. However, a typical gravel aggregate in Indiana has a CTE value of 8.6×10^{-6} inch/°F. This will exaggerate the importance of built-in curling even more.

1.3. Managing Curling in Jointed Plain Concrete Pavement

Curling of Jointed Plain Concrete Pavement (JPCP) is a natural phenomenon of pavement in the field, subject to temperature variations. There is no method to completely eliminate it, nor is there a need to do so. It is important to manage curling stresses and provide design features that will minimize propagation of mid-slab cracks, rather than blindly trying to eliminate curling stress, which may not have any definitive effect on the propagation of mid-slab cracks.

However, understanding built-in curling and diurnal curling is crucial to the selection of design features. Built-in curling is related to the early life of concrete pavement, most notably to materials and construction. Diurnal curling is mostly related to the temperature differential between the top and bottom of a concrete slab. Changes in the relative humidity of a pavement can cause warping, which has a similar effect as curling. In addition, long-term concrete creep can alter curling

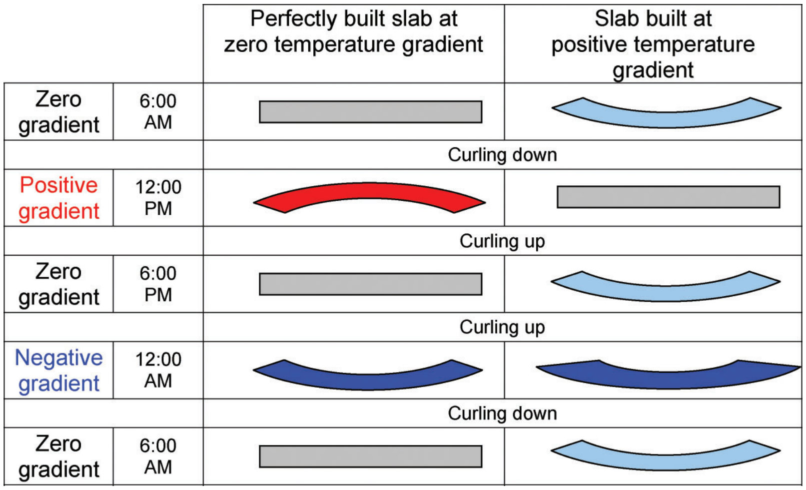


Figure 1.5 Built-In Curling of Slabs with Final Set at Positive Temperature Gradient

effects. However, the difficulty in combining all the parameters related to both of these curling effects prevents the pavement practitioner from providing economical solutions. Therefore, only those factors most influential to built-in and diurnal curling should be taken into account.

Managing built-in curling involves concrete materials selection and construction practices. Some materials or construction alternatives are difficult to implement or are less economical when it comes to construction cost. For example, altering the time of concrete placement from mid-day to very early in the morning and discouraging placement of concrete in the afternoon hours hampers construction productivity. A better alternative would be to include a higher amount of fly ash to cool down the heat of hydration of the cement in concrete. This would decrease the built-in temperature gradient when the concrete sets, as described in Figure 1.5.

In theory, built-in curling due to a built-in positive gradient (concrete placed in the afternoon hours and/or surface relative humidity higher than the bottom of the slab) is beneficial to the pavement due to the fact that the slabs will be flat in the afternoon when truck traffic is at its maximum. The primary factors that influence built-in curling are:

1. Temperature gradient between top and bottom of slab at concrete final set
2. Differential shrinkage of concrete during setting
3. Climate factors: humidity, wind speed, solar radiation, etc.

In practice, it is difficult to implement any method that would eliminate or decrease built-in curling due to the fact that air temperature, solar radiation, and relative humidity are unpredictable, especially in areas with four seasons. In addition, differential shrinkage during concrete set is also difficult to predict. During the life of concrete pavement in the field, creep and drying shrinkage will occur over time. These additional two properties of concrete make it even more difficult to predict the curling in concrete.

The most practical method to control excessive curling stress is to manage diurnal curling. Minimizing diurnal curling, especially to concrete slabs with excessive built-in curling, will help to control the total curling of concrete pavement. In other words, if built-in curling is difficult to manage, it is more beneficial to control diurnal curling instead.

1.4. Objectives of the Research Study

This research project was initiated as a response from the INDOT Pavement Steering Committee related to the joint spacing of JPCP in Indiana. There was an initiative in the Committee to reduce the joint spacing from 18 feet to 15 feet as a way to reduce premature concrete pavement deterioration. There was an indication that some newly paved JPCP had transverse cracks even before the pavement section was opened to traffic. In addition, there was a nationwide push to reduce JPCP joint spacing to reduce curling stress in concrete pavement.

The decision from the INDOT Pavement Steering Committee was to conduct field research to review the effects of shortening the joint spacing on the occurrence of curling stress. In addition, based on the curling stress calculation, reducing the curling stress can also reduce the total stress of the slab. Therefore, by shortening the joint spacing, the slab thickness can be reduced to cut the cost of initial construction.

The objectives of this field research project are:

1. To evaluate the influence of climate on the behavior of JPCP slabs.
2. To evaluate the influence of thickness and slab joint spacing on the behavior of JPCP slabs.
3. To make a decision for the department regarding whether shorter joint spacing is beneficial in terms of pavement performance and life cycle costs.
4. To justify pavement dimensional inputs in the Mechanistic Pavement Design Guide.

By monitoring the temperature of a slab and moisture contents of the subgrade, and by measuring the stress and strain responses of the slab, conclusions can be drawn about the behavior of the JPCP slab under climatic loading. Therefore, the effect of those parameters on the JPCP slab dimensions (joint spacing and thickness) can be determined in order to calculate the curling effects.

CHAPTER 2 FIELD EXPERIMENTAL PROJECT

This research study was requested and proposed by the INDOT Pavement Steering Committee as a proactive step toward adopting shorter joint spacing for thicker concrete pavement to avoid premature mid-slab transverse cracking in concrete pavement. However, before changing the INDOT Design Manual to accommodate shorter joint spacing, the committee asked the INDOT Research and Development Division to review the state of stress and strain of a concrete slab in an "ordinary" field construction. The criticality of these measurements in field construction will serve as a basis to make a final decision regarding joint spacing.

The objective of this study is therefore to answer the questions from the INDOT Pavement Steering Committee and provide data to justify any decision to change the INDOT Design Manual. As the research study progresses, the new Mechanistic Empirical Pavement Design Guide (MEPDG) is released by the Transportation Research Board. This new pavement design guide is no longer a thickness-based design guide; rather, it is a design guide based on performance criteria, one of which is "Transverse Cracking %." This criterion depends on the curling and warping of concrete. In addition, in the new guide, joint spacing has become a part of design parameters, meaning that a pavement designer will determine joint spacing based on the performance prediction of the MEPDG. This new MEPDG feature makes this research study more important as a tool for helping pavement designers to understand how pavement design is affected by curling and warping of concrete pavement.

2.1. Location of Experimental Project

The committee decided to implement a reconstruction project on Interstate 65 from RP 6+73 to RP 8+14 in Clarksville, INDOT Seymour District, Indiana. The test site was a four-lane rural interstate highway to be reconstructed in order to make a six-lane highway with full-width inside and outside pavement shoulders. The roadway information in 2003 was as follows:

- Contract number: R-24550
- Average Annual Daily Traffic (AADT) in 2003 = 85,500
- Projected AADT in 2023 = 112,700
- Truck traffic = 8%
- Equivalent Single Axel Load (ESAL) = 88 million
- Speed limit = 65 miles per hour

This interstate section is busy due to its location related to the city of Louisville in Kentucky, which is located about six miles south of the project. Figure 2.1 shows the location of the experimental project on the map.

The location was selected due to the nature of the pavement contract. It is a warranty concrete pavement contract adjacent to a Performance Related Specification (PRS) pavement contract. The researchers expected that these types of contracts would yield better research results since the quality concrete and workmanship of the project are better than ordinary projects.

2.2. Pavement Features for Experimental Study

The objective of taking field measurements of the concrete pavement was to determine the stress and strain responses of the pavement due to temperature differential and traffic loading. The results obtained from studying stress and strain will determine whether the INDOT Pavement Steering Committee decides to shorten the joint spacing from 18 to 15 feet. Therefore, the arrangement of the joint spacing determines by the INDOT Pavement Steering Committee governs the arrangement of the experimental designs in the field. The following concrete pavement slab arrangement was constructed in the northbound driving lane of the I-65 project:

- Original pavement design of 15-inch thickness and 18-foot joint.
- 15-inch thickness with 15-foot joint spacing for six slabs; the second slab is instrumented (Slab A, south section).
- Original pavement design of 15-inch thickness and 18-foot joint for three slabs.
- 15-inch thickness with 18-foot joint spacing for six slabs; the second slab is instrumented (Slab B, mid-section).
- Original pavement design of 15-inch thickness and 18-foot joint for three slabs.
- 14-inch thickness with 18-foot joint spacing for six slabs; the second slab is instrumented (Slab C, north section).
- Original pavement design of 15-inch thickness and 18-foot joint spacing.

The adjacent two inside lanes were adjusted to the joint spacing. Therefore, there is no mismatch of joints between the lanes. For the 14-inch thick section, the drainable base layer was thickened by one inch from the surrounding elevation. Figure 2.2 shows the experimental sections in the plan.

2.3. Instrumentation for Experimental Study

The instrumentations of the three slabs were accomplished through the pavement contract, and a contractor was selected to perform the installations and settings of the instrumentations. Except for the moisture gages, all strain gages and tiltmeters were vibrating wire type gages suitable for concrete application. Table 2.1 shows the total channels and strain gages for the three slabs.

The instrumentation section of the slabs was accomplished by blocking out two slabs during the previous paving operation with tie bars ready for the pour of the instrumented sections. Figure 2.2 shows the block-out arrangement.

The strain gages were installed based on the principle of symmetry. Therefore, only half the slab was instrumented. The strain gages were installed along the perimeter of the pavement slab and two inches from the form or adjacent slabs. The strain gages were installed in the top and bottom perimeters of the slab, transversely in the middle of the slab top and bottom, and longitudinally in the middle of the slab top and bottom. Figure 2.3 shows the half-slab instrumentation arrangement.

The tiltmeters were installed on each corner (two tiltmeters for two perpendicular directions) and in the middle of the slab near the dowel bar basket to determine the tendency of the slab to tilt in transverse direction. Figure 2.4 shows the position of the tiltmeters.

Temperature measurements were also recorded through five sets of iButton with a capability to measure the temperature in every one-inch thickness of concrete from bottom to top. The purpose of the temperature measurement was to determine the temperature profile of the concrete pavement from bottom to top in order to explore the tendency of the concrete slab to curl up or down.

2.4. Field Construction of the Experimental Study

The construction of the experimental slabs was done by hand placement of concrete to avoid the paving machine, which would disturb and misplace the gages. The pavement construction was done first by the paving machine, and the slabs for the experimental

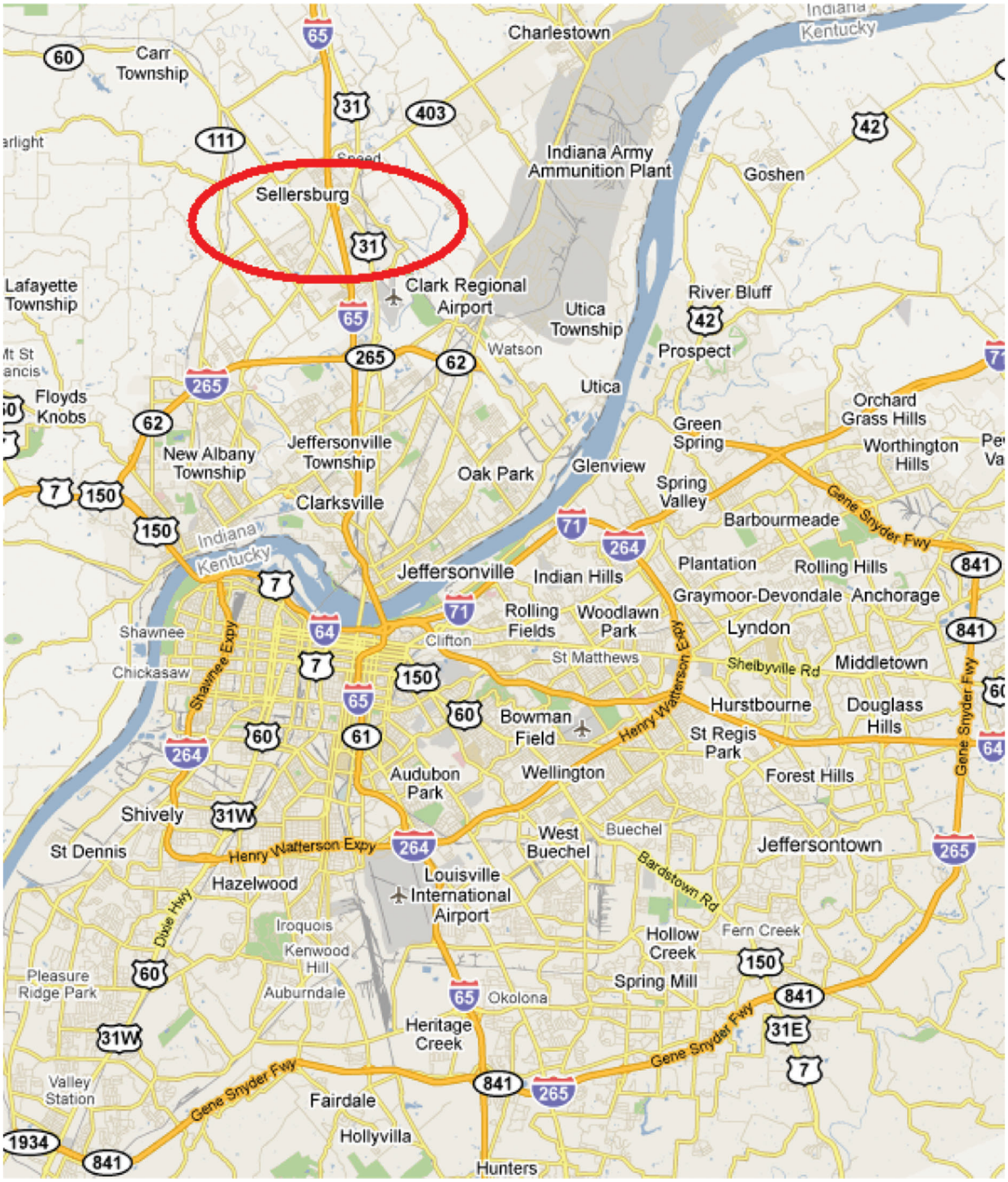


Figure 2.1 Location of Experimental Project on I-65

TABLE 2.1
Summary of Instrumentation in Slab A, B, and C

Total No. Channels	3 x 62
Total No. Strain Gages	3 x 26
Total No. Strain & Temperature Gages	3 x 12
Total No. Tilt Gages	3 x 2
Total No. Tilt & Temperature Gages	3 x 3
Total No. Moisture Gages	3 x 4

study were blocked-out along with the shoulder portions. The shoulder pavements were placed later after the experimental slabs.

The first section of the experimental slabs (two slabs) was constructed on June 23, 2004 at 6:26 AM and finished at 7:25 AM. Figure 2.5 shows the construction of the first experimental section (north) with 14-inch thickness and 18-foot joint spacing slabs. The concrete for the second section was done at 7:27 AM and finished at 8:30 AM. Figure 2.6 shows the construction

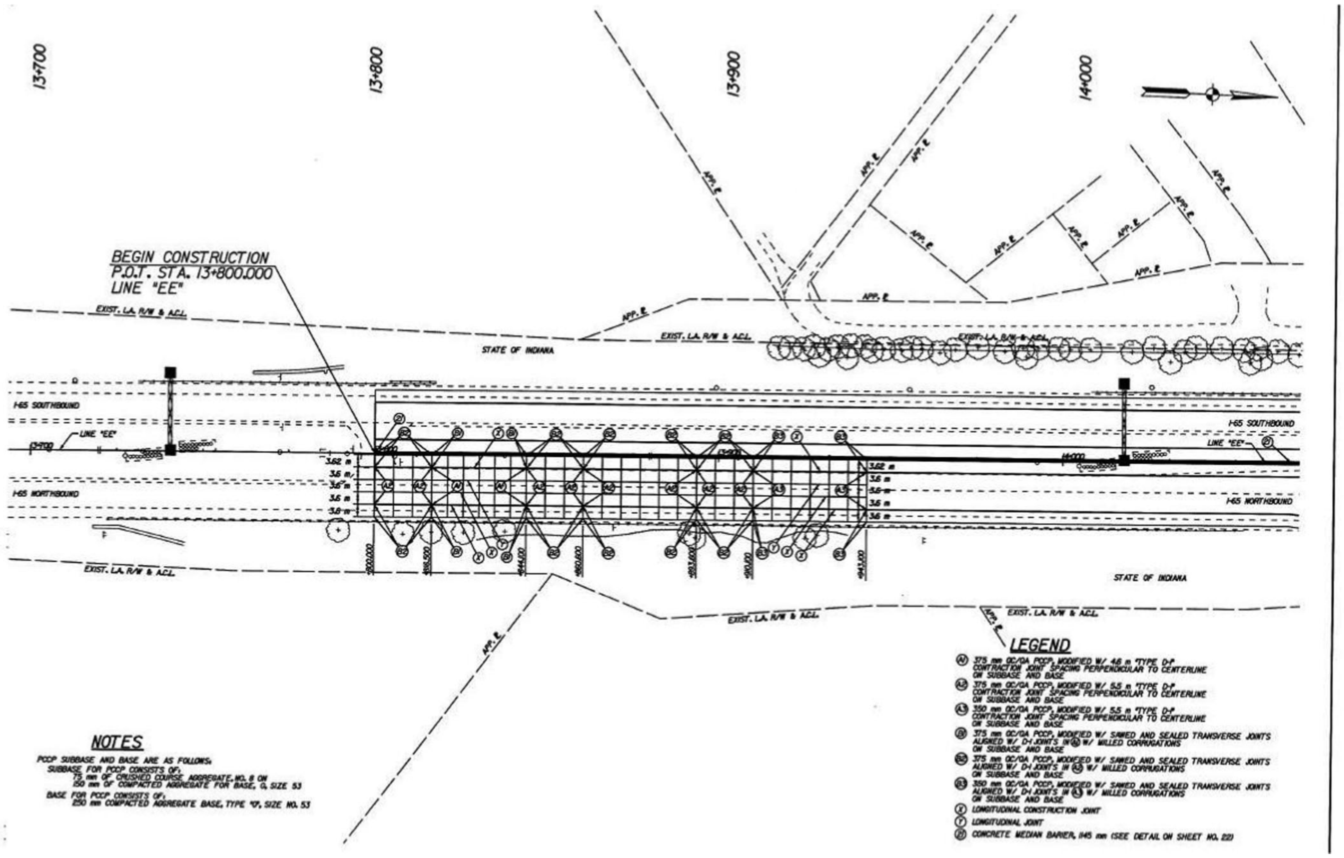


Figure 2.2 Experimental Study Sections on I-65

of the second experimental section (mid) with 15-inch thickness and 18-foot joint spacing slabs. The third section was poured at 8:35 AM and finished at 9:30 AM. Figure 2.7 shows the construction of the second experimental section (south) with 15-inch thickness and 15-foot joint spacing slabs.

The concrete material is a typical INDOT approved concrete pavement material. Its properties are as follows:

Type I Portland cement content…………………	440 lbs/yd^3 (260 kg/m^3)
Water/cementitious ratio…………………………	0.40
Fly ash content……………………………………	85 lbs/yd^3 (56 kg/m^3)
Air content…………………………………………	6.5%
Course aggregate size #8…………………………	1,875 lbs/yd^3 (1,108 kg/m^3)
Fine aggregate #23………………………………..	1,280 lbs/yd^3 (756 kg/m^3)
Slump (for hand placement)………………………	6 inches (15 cm)

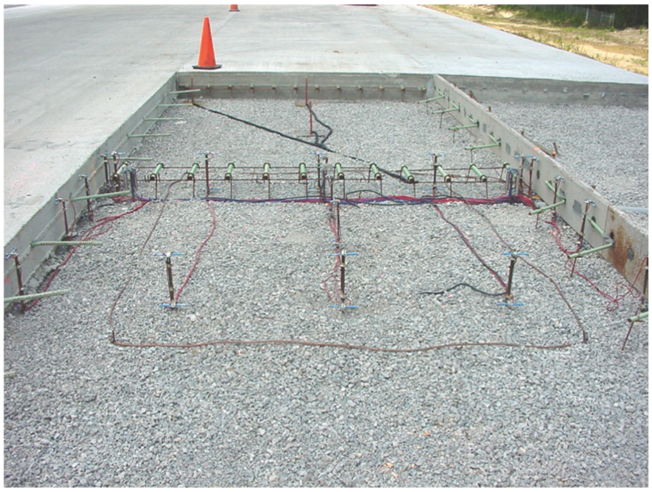


Figure 2.3 Half-slab Instrumentation Arrangement

The saw cut for transverse joints in the experimental sections were finished on the same day of the concrete pour. The seven-day compressive strength was 6,190 psi and the flexural strength was 490 psi. The modulus of elasticity of the concrete at 28 days was 4.99 million psi. Figure 2.8 shows the joint saw cutting of the first experimental section (north section) with14-inch thickness and 18-foot joint spacing slabs that was cut at 4:40 PM.

The joint saw cutting of the second (mid-section) with 15-inch thickness and 18-foot joint spacing slabs was finished at 5:50 PM and the third (south section) with 15-inch thickness, and 15-foot joint spacing slabs was finished at 6:10 PM. The results of the joint saw cutting are shown in Figure 2.9. The contractor shallowly inserted a smaller backer rod on the first joint saw cut to prevent debris from entering the joints before forming the reservoir for sealants

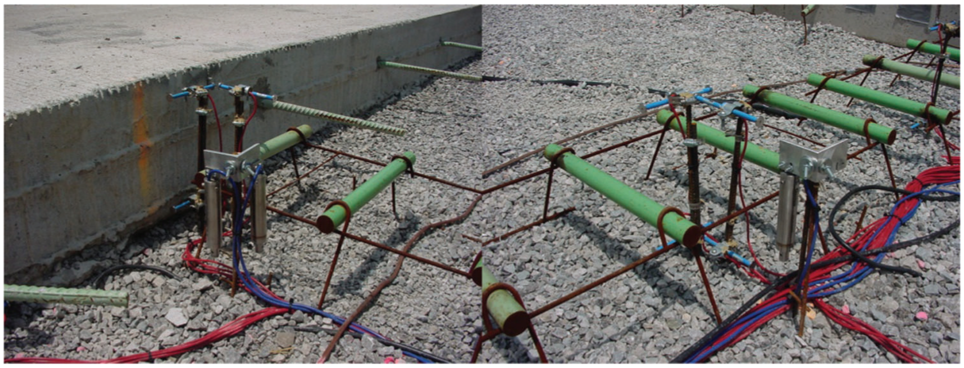


Figure 2.4 Tiltmeters in the Corner and the Middle of the Slab

Figure 2.5 Concrete placement of the 14-inch thick and 18-foot joint spacing slabs (north)

Figure 2.6 Concrete placement of the 15-inch thick and 18-foot joint spacing slabs (mid)

Figure 2.7 Concrete placement of the 15 inch-thick and 15-foot joint spacing slabs (south)

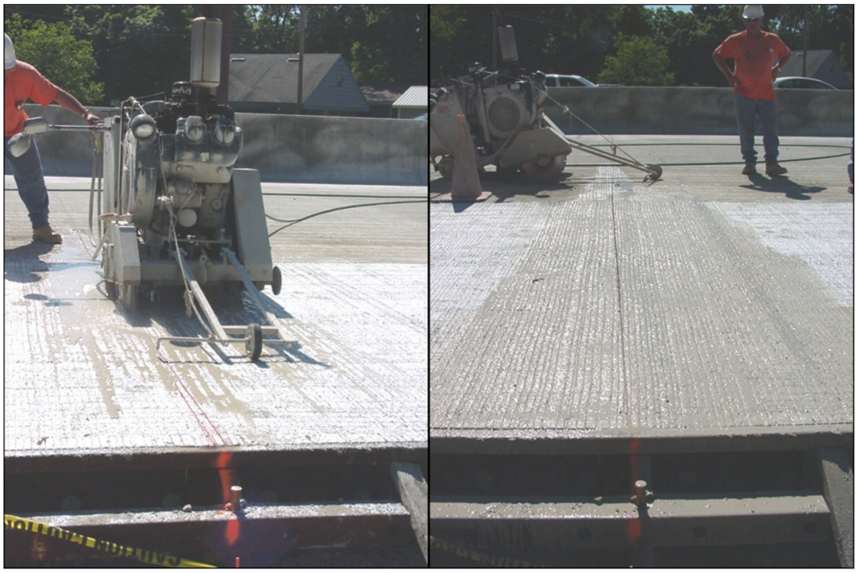


Figure 2.8 Joint saw cutting of the 14” thick and 18 foot joint spacing slabs (north)

Figure 2.9 Joint saw cut conditions the day after saw cutting

After the shoulder sections were placed seven days later, the contractor finished the joint reservoirs and filled the joints with silicon sealants. The pavement sections were opened to traffic 14 days after construction

CHAPTER 3 INSTRUMENTATION AND DATA ACQUISITION UNITS

Pavement instrumentation was a complicated issue that had to be resolved early on in the field research projects. The objectives of the measurements had to be discussed with both the instrumentation contractor and pavement contractor. The instrumentation contractor made changes to the design of the instrumentation a few months before the construction of the project. The pavement contractor made changes to how the strain gages and tiltmeter were to be set up in the block-out pavement. Most importantly, both contractors needed to know the objectives of the measurements being taken. These were as follows:

- Determine the strain of the slabs to monitor their movement due to environmental effects using strain gages.
- Determine the direction of the slabs in terms of tilting to verify the response of the slabs to the environment using tiltmeters.
- Determine the temperature profile inch-by-inch of the slabs’ thickness in both the centers and corners using iButtons.
- Determine the moisture of the subbase layer of the pavement support using a time domain reflectometer.
- Determine the traffic classifications that pass over the experimental sections.
- Determine the environment data, including air temperature, wind direction, solar radiation, precipitation, and chloride concentrations, in the pavement.

3.1. Type of Pavement Instrumentation

The instrumentation was selected based on the ruggedness and survivability of the gages in a rough environment during installation and in service. The instrumentation and data acquisition system was specified in the project contract, and an instrumentation contractor finalized all the drawings and setup of the instrumentation. The iButton to measure the hourly temperature was designed, prepared, and installed by the INDOT Division of Research and Development. The

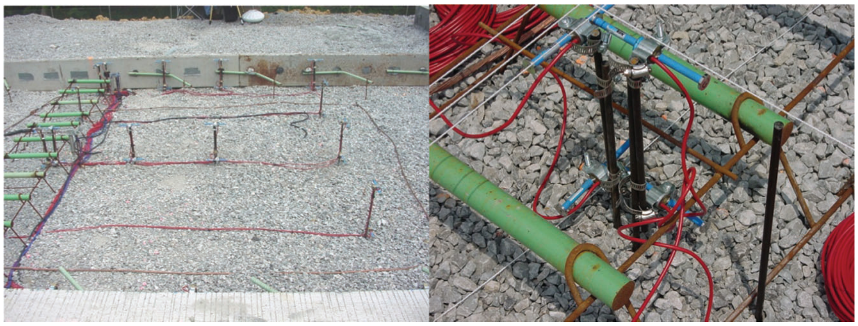


Figure 3.1 Vibrating wire strain gages along the perimeter and center of the slabs

strain gages, tiltmeters, and time domain reflectometers were subcontracted by the main instrumentation contractor to the equipment manufacturers. All the instrumentation was designed, prepared, and set up properly at least one day before the concrete pour. The traffic classification system data acquisition and the weather station were also subcontracted to manufacturers.

Figure 3.1 shows the vibrating strain gages that were installed along the perimeter of half the length of the slabs for all three experimental sections. The vibrating wire strain gages were installed in both the top and bottom portions of the slab with a distance of one inch from the top, bottom, and edges of the slabs. The strain gages were designed to record movement along the perimeter and center of the slabs.

Figure 3.2 shows the tiltmeters in the corners and centers of the slabs used to determine any tilting in X and Y directions. These tiltmeters provided qualitative data regarding any indications that the slabs were tilting. The tiltmeter in the center of the panel measured tilting only in direction X (transverse direction). The information from this center panel tiltmeter was used to determine whether there was an imbalance in the movement of the slabs because one longitudinal side was adjacent to the passing lane slabs while the other longitudinal side was adjacent to the pavement shoulders.

Figure 3.3 shows the iButton "trees" that measured the hourly temperature of the slabs from top to bottom. The iButtons were spaced in one-inch increments in order to monitor precisely the temperature profile in the slabs. The iButton "trees" were located in the corner and center of each slab. There was some concern that the corner location would dissipate heat faster than the center portion due to the joints and the law of thermodynamics that the slab extremities are cooler than other parts of the slab.

Figure 3.4 shows the "Ground Hog" traffic count and classification sensor. The intention to monitor the traffic count and classification was to determine long-term monitoring as performance criteria for the new Mechanistic Pavement Design Guide (MEPDG).

Figure 3.5 shows the weather station next to the three experimental pavement sections. The purpose of this weather station was to monitor wind speed, precipitation, air temperature, and solar radiation since these environmental parameters may significantly influence the slabs during construction and in service.

The data acquisition system was divided into three units that corresponded to the three experimental sections. The sensor terminals were enclosed in stainless steel traffic control cabinets. All three boxes were placed as close as possible to the experimental sections. The middle section contained the control unit that controls the data acquisition sequences. Figure 3.6 shows the three data acquisition boxes from the north, middle, and south sections (from left to right). All of the terminals were protected with gas tube lightning protection. The south section box included the terminal for the iButtons. All the strain gages, tiltmeters, and TDR (Time Domain Reflectometer) sensors were connected to these terminals

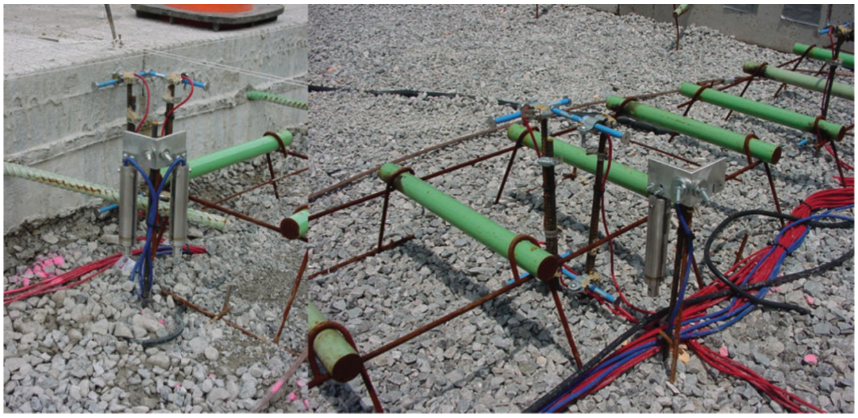


Figure 3.2 Vibrating wire tiltmeters in the corner and center of a slab

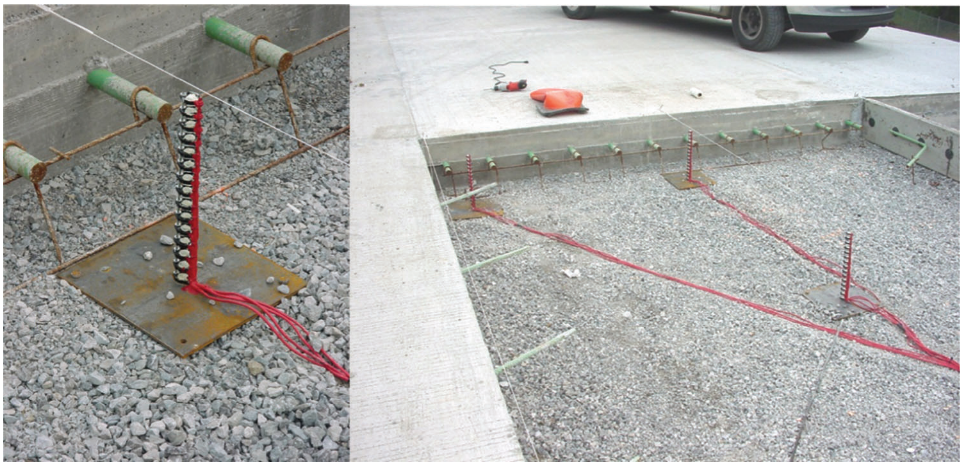


Figure 3.3 iButton trees used to measure hourly temperature

Figure 3.4 “Ground Hog” traffic count and classification sensors

Figure 3.5 Weather station

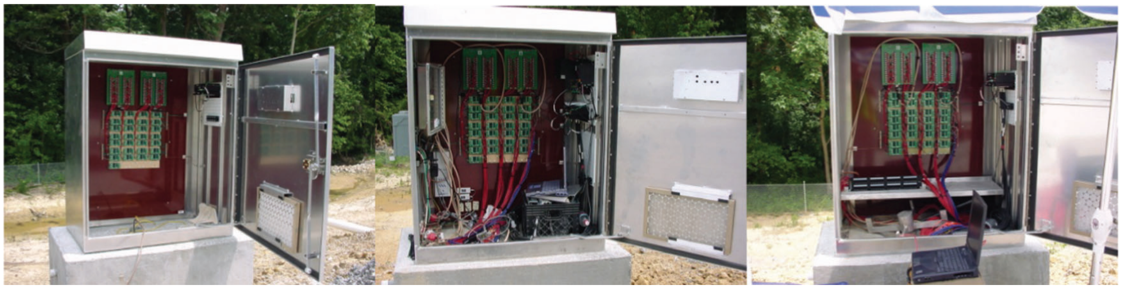


Figure 3.6 Data acquisition system for the three experimental sections

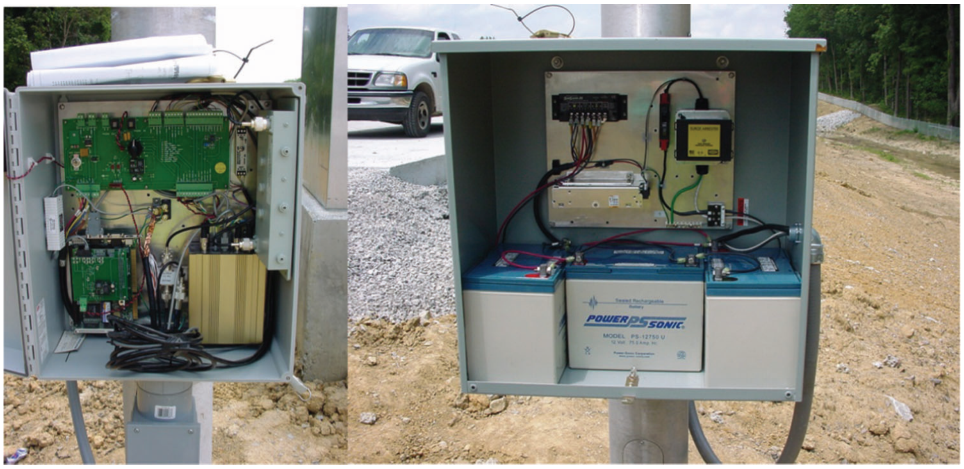


Figure 3.7 Data acquisition system for the weather station and traffic counts

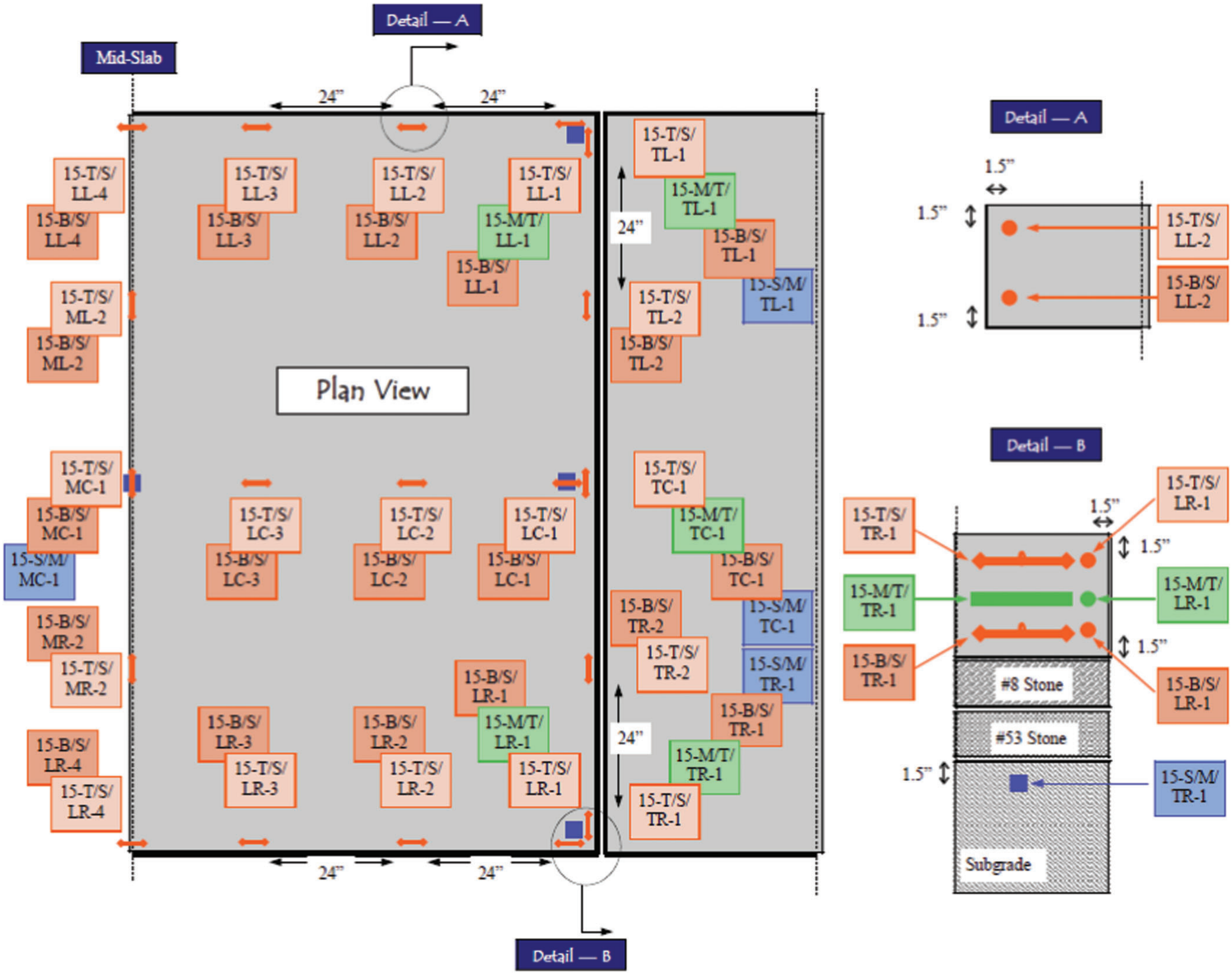


Figure 3.8 Instrumentation for Slab A, south section (15 inches thick with 15-foot joint spacing)

Legend:

15-X/Y/AB-C, Slab A

X is for location: T = Top, B = Bottom, S = Subbase

Y is for gage type: S = Strain gage, T = Tiltmeter, M = Moisture meter

A is for direction: L = Longitudinal, T = Transverse, M = Mid-slab transverse

B is for side of slab: L = Left, R = Right, C = Center

C is for the sequence number.

as well. The main data acquisition (from the control unit in the middle section) was connected to a telephone modem so that all data could be downloaded from the INDOT Division of Research and Development. The system took approximately 15 minutes to cycle the data acquisition for all the gages, tiltmeters, and TDR sensors.

The data acquisition system for the weather station and traffic classifications and counts was separated from the other units in order not to delay the cycle of data acquisition due to the slow excitement-measurement process from the vibrating wire strain gages and tiltmeters. Figure 3.7 shows the data acquisition system for the weather station and traffic classifications and counts. It also includes the power supply for the data acquisition system.

The traffic classification and count signals were transmitted via wireless from the Ground Hog sensors to the weather station tower. The data acquisition accumulated the traffic data and sent the information via modem.

The complete instrumentation for all three experimental sections was complicated due to the objectives in sequencing the data acquisition for the measurements of the slabs responses in many types of gages and instruments. Figure 3.8 shows the instrumentation detail of Slab A, the south section with a slab thickness of 15 inches and joint spacing of 15 feet. Figure 3.9 shows the instrumentation detail of Slab B, the middle section with a slab thickness of 15 inches and joint spacing of 18 feet. Figure 3.10 shows the instrumentation

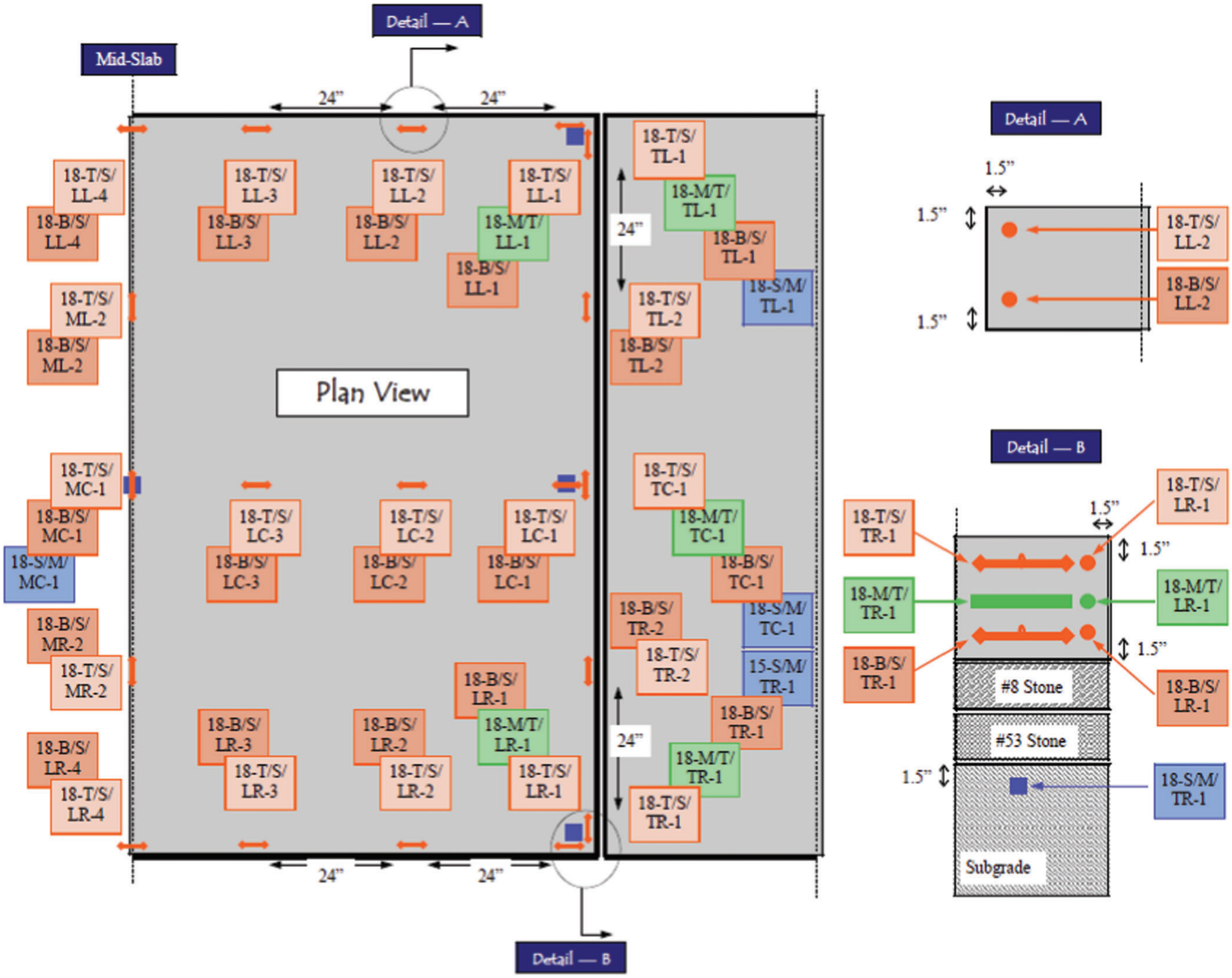


Figure 3.9 Instrumentation for Slab B, middle section 1(5 inches thick with18-foot joint spacing)

Legend:
18-X/Y/AB-C, Slab B
X is for location: T = Top, B = Bottom, S = Subbase
Y is for gage type: S = Strain gage, T = Tiltmeter, M = Moisture meter
A is for direction: L = Longitudinal, T = Transverse, M = Mid-slab transverse
B is for side of slab: L = Left, R = Right, C = Center
C is for the sequence number.

detail of Slab C, the north section with a slab thickness of 14 inches and joint spacing of 18 feet.

The instrumentation in each slab adopted a principle of symmetrical dimension in the longitudinal direction; therefore, the instrumentation was only placed along half the length of each slab. However, the strain gages were installed in both the top and bottom portions of the slabs. All the strain gages were 1.5 inches from the slab edges.

3.2. Lesson Learned from the Instrumentation and Data Acquisition Units

The instrumentation contractor did excellent work in designing, installing, and executing the system. However, the data acquisition technologies available before 2005 were not as sophisticated as newer technologies that became available in 2010. The real challenge was to make the software work with the data acquisition system by telephone modem. The weather station and traffic classifications and counts were working very well, but the software failed to collect the data properly after two weeks. In addition, the software crashed the system and erased the data in the computer.

Another issue involved the time domain reflectometer sensor and its data acquisition unit. There was a distance limitation in the length of wire between the TDR sensors and their data acquisition system, making it difficult to combine the three TDR data acquisition systems in one unit. As a result, the main data

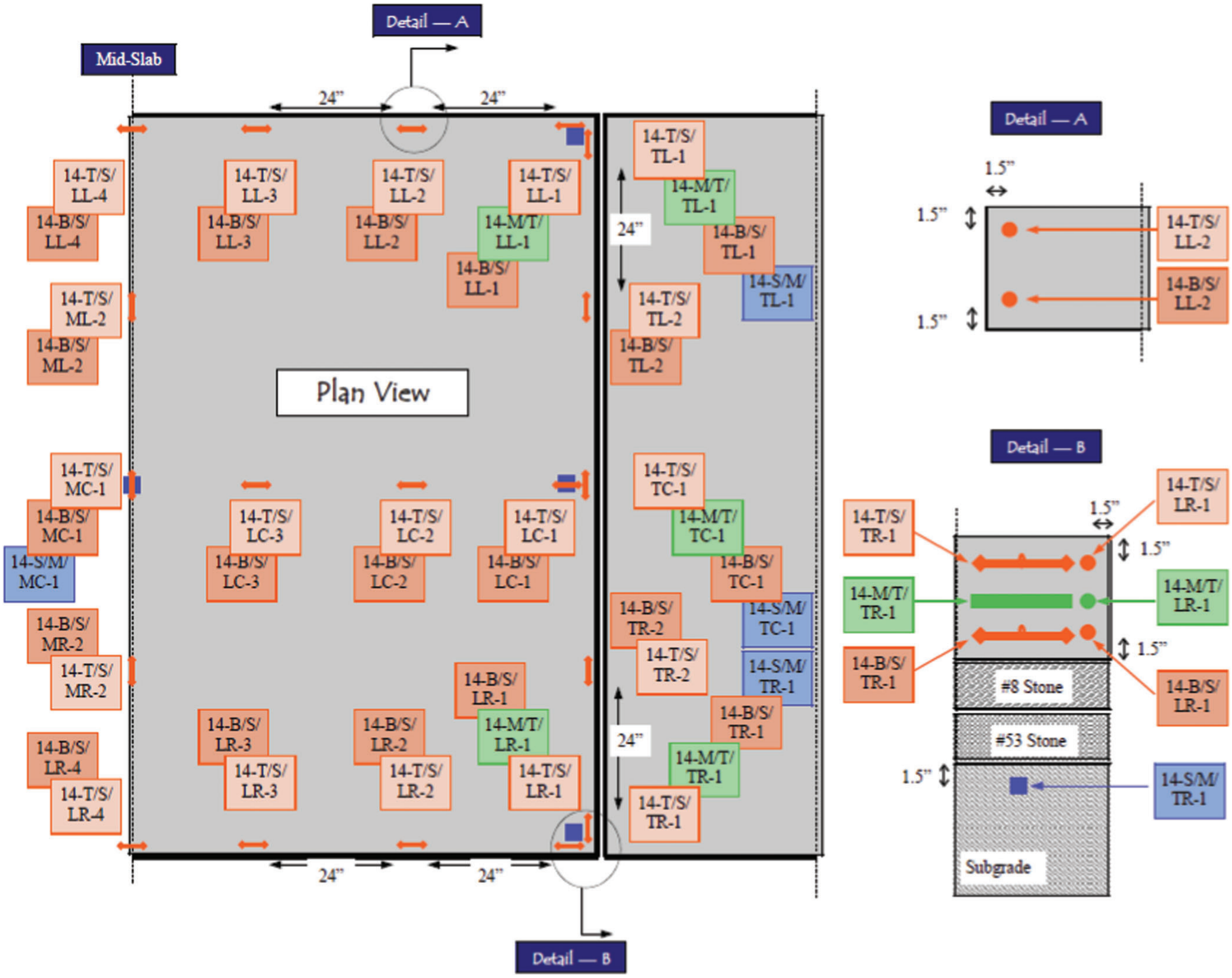


Figure 3.10 Instrumentation for Slab C, north section (14 inches thick with 18-foot joint spacing)

Legend:

14-X/Y/AB-C, Slab C

X is for location: T = Top, B = Bottom, S = Subbase

Y is for gage type: S = Strain gage, T = Tiltmeter, M = Moisture meter

A is for direction: L = Longitudinal, T = Transverse, M = Mid-slab transverse

B is for side of slab: L = Left, R = Right, C = Center

C is for the sequence number.

acquisition system needed more time to cycle the reading of the gages. In addition, the sensors for the TDR that were used to measure the moisture content in the pavement subbase (INDOT #53 stone) was difficult to install. After the installation, workers realized that was nearly impossible to measure the moisture content in INDOT #53 stone.

CHAPTER 4 DATA INTERPRETATION AND DISCUSSIONS

The data acquisition was initiated and switched on one day before the concrete placement while all the strain gages and tiltmeters were zeroed in two hours before placement. For the first 24 hours, the strain gages and the tiltmeters collected data every 15 minutes in order to capture the built-in curling of the slab during the early age of the concrete. The rest of the data for the strain gages and the tiltmeters were collected in order to monitor the diurnal movement of the slab during service. Data were collected annually by closing the lanes of the experimental sections and, at a certain time during the day, data were collected. In addition, data were also collected to review the combined strains of pavement curling and standard tandem axle loads.

The iButtons used to measure the temperatures collected hourly temperature data for every inch of concrete thickness. Each iButton has an operating life of three years for hourly data collection, which will suffice to analyze the temperature profile of the pavement for three years of different seasons.

The data acquisition for the weather station and the traffic counts and classifications experienced problems since the second week of weather and traffic monitoring. The software deleted all the data during construction and during the first two weeks of operation. The supplier of the equipment attempted to resolve the software issue in six months, but the equipment and software failed to provide reliable data; therefore, after six months, the data acquisition for weather and traffic was abandoned.

4.1. Built-in Curling of Concrete Pavement

Detection of built-in curling in concrete pavement is a very difficult process. During hydration of the cement in the first 24 hours, the concrete slabs went through temperature changes and experienced shrinkage differential, changes in humidity, and other climatic and dimensional changes. However, qualitatively, the built-in curling could be determined from the changes in the readings from the strain gages.

Built-in curling is pronounced when the concrete slab is placed in the morning and the concrete hydration reaches the final set during the highest temperature in the afternoon. In the case of this experimental study, the first slab was placed at 6:26 AM, and the final set of the cement hydration was predicted to occur around 2:00 PM. As a result, the behavior of the concrete slab should follow the scenario presented in Figure 4.1. The qualitative built-in curling measurement is presented in Figure 4.2, which shows the changes in the top strain gages in Slab A (south section) during the first 24 hours after concrete placement. The figure shows the full-slab, instead of half-slab, strain (the transverse strain gages were treated as symmetrical gages).

Figure 4.2 shows that there was built-in curling beginning after 12:00 PM on the day of the concrete placement. Green and yellow indicate tension in the strain gages, as well as curling up of the slab, while blue indicates a neutral state (the gages for these figures were zeroed in at 6:00 AM in the morning)

The difficulty in quantitatively determining the built-in curling using strain gages is the time to zero the strain gages when the concrete slabs are totally flat. The zero point will determine the reference point, or the position where a slab is assumed to be flat, as a basis of analysis of deflections and stresses of the slabs. With early shrinkage of concrete, it is almost impossible to determine the exact amount in slab deflections and curling stresses for built-in curling. Figure 4.2 shows the slab that was poured during the early morning with

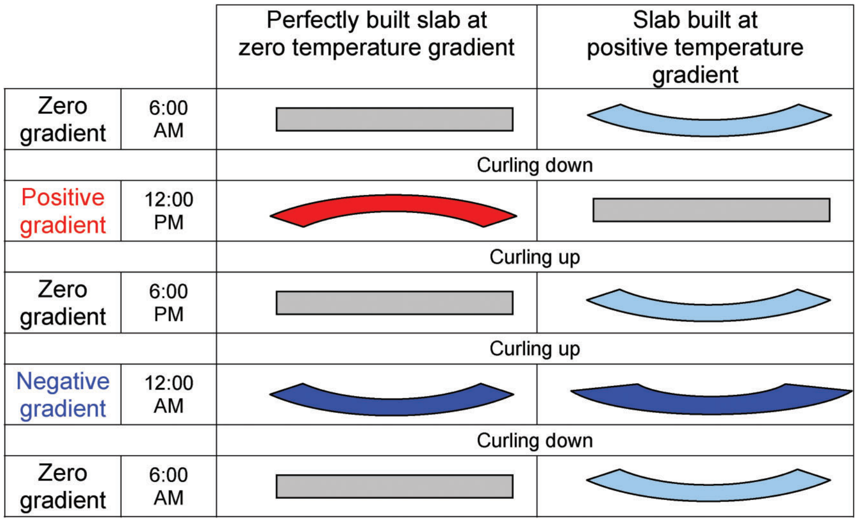


Figure 4.1 Built-In Curling of Slabs Based on Temperature Gradient

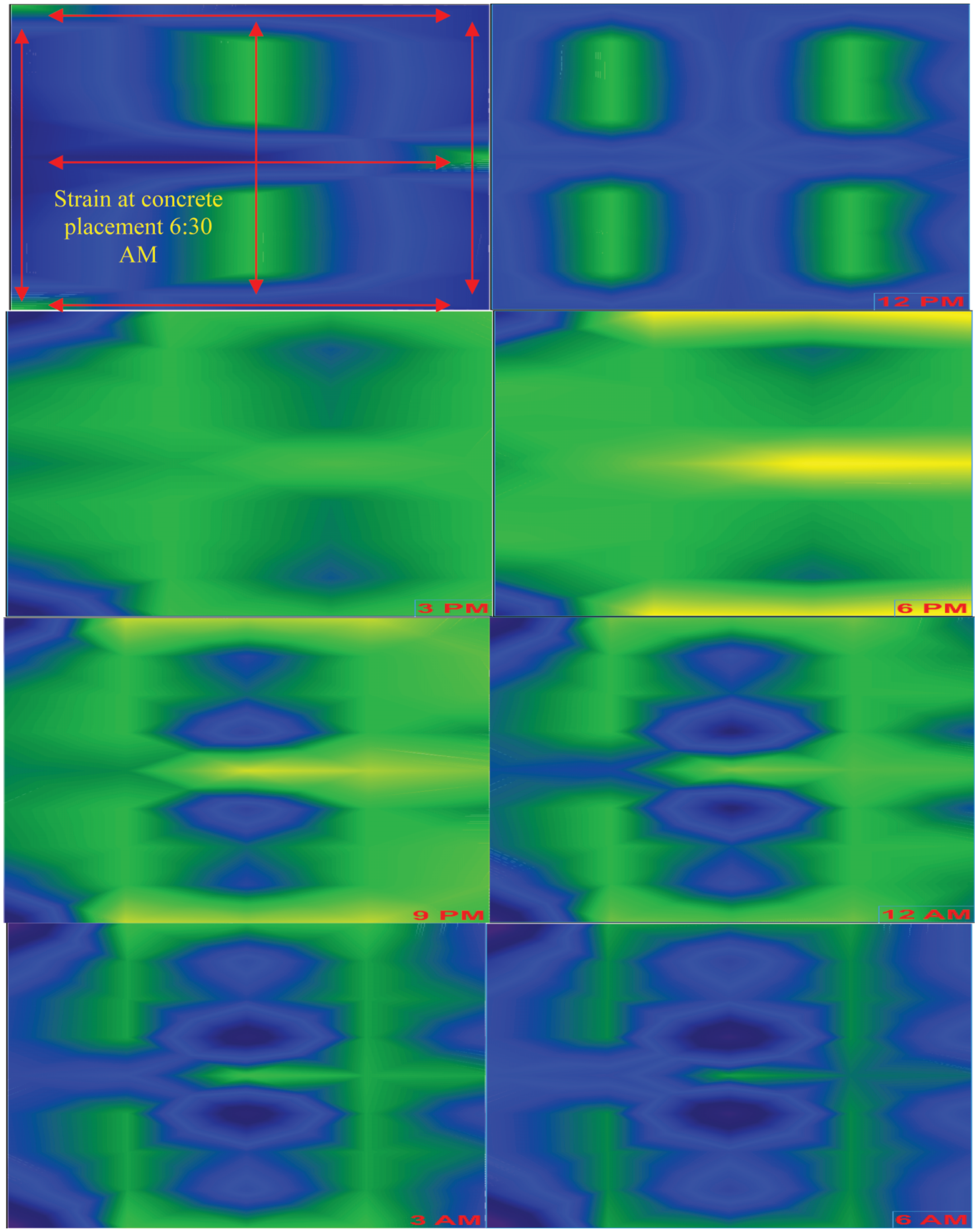


Figure 4.2 Built in Curling of Slab A

a final setting at about 2:00 PM in the summer (i.e., not during the hottest time of the day). On the other hand, Figure 4.1 shows that the slab experienced some slight built-in curling toward a form of a positive temperature gradient built-in curling as indicated in Figure 4.1. At the end of the 24-hour cycle (at 6:00 AM the next day), all of the top strain gages indicated a slight tension.

Figure 4.3 shows the stresses of all three experimental sections with the gage 14-T/S/LL-1 zeroed at 4:00 PM. The slabs experienced tension on the top portion of the pavement due to curling after construction. The stresses followed the curling scenario in Figure 4.1 with a slight deviation from the zero temperature gradient slab. This minor deviation occurred because the slab was poured at 6:30 AM and the cement hydration final set was about 2:00 PM; therefore, the slabs were not built in a totally zero temperature gradient but rather in a slightly positive temperature gradient. There was some slight built-in curling (curling up) as the switch from tensile to compressive stresses was delayed for four hours. The slab still experienced curling up and curling down in the

Figure 4.3 Stresses at the tops of slabs from strain gage LL1 calculations

diurnal climate but the length of time the slabs were curled down was less than the length of time they were curled up.

Figure 4.4 shows the stresses of the three experimental sections from the bottom slab at strain gage 14-B/S/LL-1 and illustrates a mirror image of the stresses from the top gages. The quantitative amount of stresses from curling were difficult to determine since, during the first 24 hours after construction, it is impossible to isolate those strains that resulted purely from curling.

Examining Figures 4.3 and 4.4, it is clear that the stresses after 3:00 PM the day after construction do not change. This is because the data acquisition system was instructed to stop taking readings from the gages in order to avoid recording any measurements taken while construction trucks might still be on the top of the slabs. Any subsequent data acquisition readings were collected only when a technician was present at the site to make sure that the experimental sections were closed to traffic and no vehicles were on the experimental slabs.

4.2. Concrete Slab Temperature Distribution

The temperature distribution in a concrete slab is an important issue related to curling, and it is therefore closely related to the performance of Jointed Plain Concrete Pavement (JPCP) in the field. Temperature distribution has been a controversial issue in past research efforts. Some researchers have assumed that the temperature profile across the slab depth was linear in nature. On the other hand, others have assumed that a slab was quick enough to adapt to the changing temperature so that any change in temperature at the top of the slab would alter the temperature at the bottom of the slab. In a slab thinner than eight inches, this might be the case; however, for slabs as thick as 14 to 15 inches, such temperature changes are not as drastic as researchers once thought.

Figure 4.5 shows the temperature variations on the corner of the slab recorded during the summer of 2004. The temperature on the surface of the slab closely followed the air temperature and the seasonal temperature swing. However, the mid-slab and bottom temperatures did not vary as widely as did temperatures at the top of the slab.

Figure 4.6 shows the temperature differentials between the top and bottom, top and middle, and middle and bottom of the slab, with the iButtons on the corner of the slab. It also clearly shows that the differences between the top and mid-slab thickness were the dominant differences and were almost identical to the top and bottom differences. This means that the diurnal changes in temperature influenced only the top half thickness of the slab.

Figure 4.7 shows a typical temperature profile in the summer of 2004 when there were no drastic air temperature changes in three consecutive days. The iButtons, located on the corner of the slab, revealed that the temperature profile was almost constant night and day. Figure 4.8 shows the temperature profile at the mid-slab location, which was identical to that of the corner location.

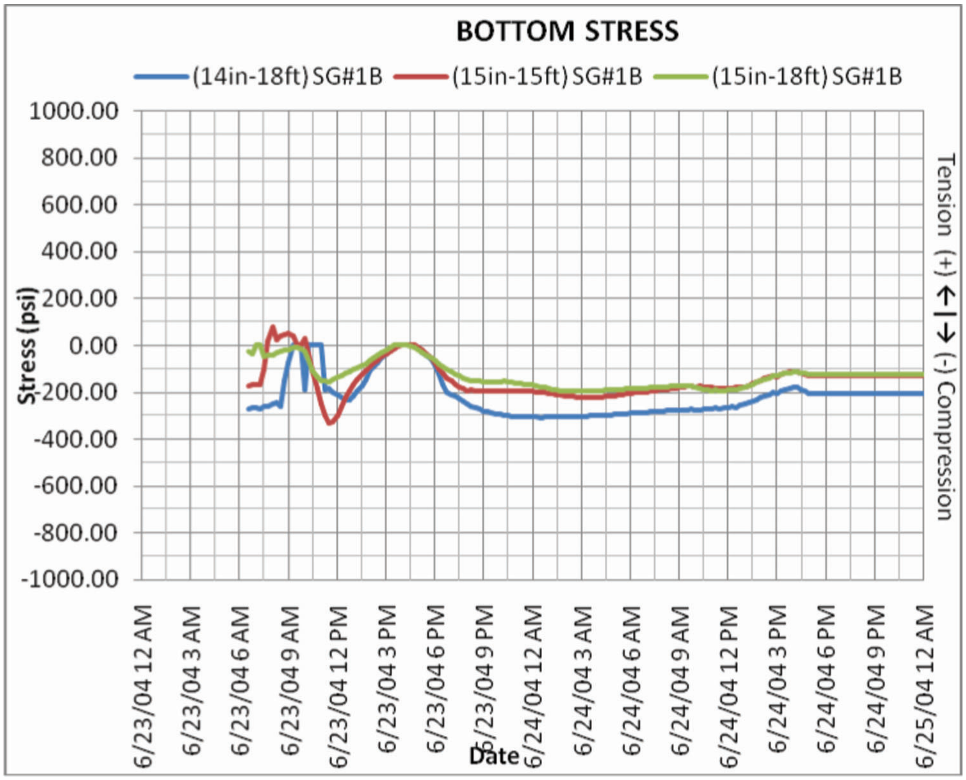


Figure 4.4 Stresses at the bottoms of slabs from strain gage LL1 calculations

Figure 4.9 shows the temperature profile of the slab when there was a sudden change in air temperature from hot to cool. The highest temperature difference occurred between the mid-depth and the top of the slab. The reaction of the slab to this drastic change in temperature influenced the bottom half of the slab by only six degrees, whereas the temperature difference between the mid-depth and bottom of the slab was only approximately three degrees.

Figure 4.10 shows the temperature profile of the slab when there was a sudden change of air temperature from cool to hot. The same phenomenon occurred in this scenario as with the change from hot to cool above. The temperature swing in the bottom half of the slab

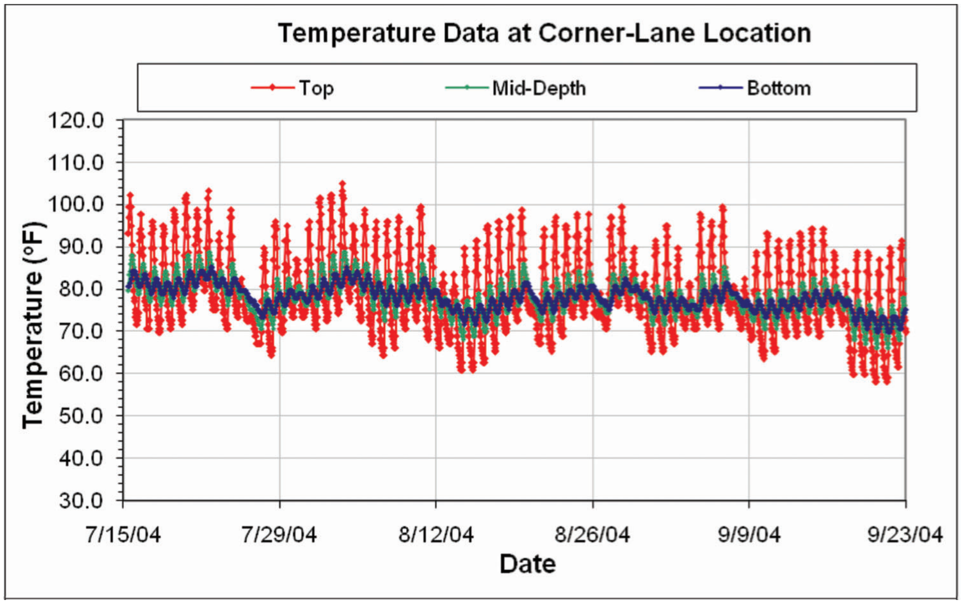


Figure 4.5 Temperature variations at the corner of the slab, summer of 2004

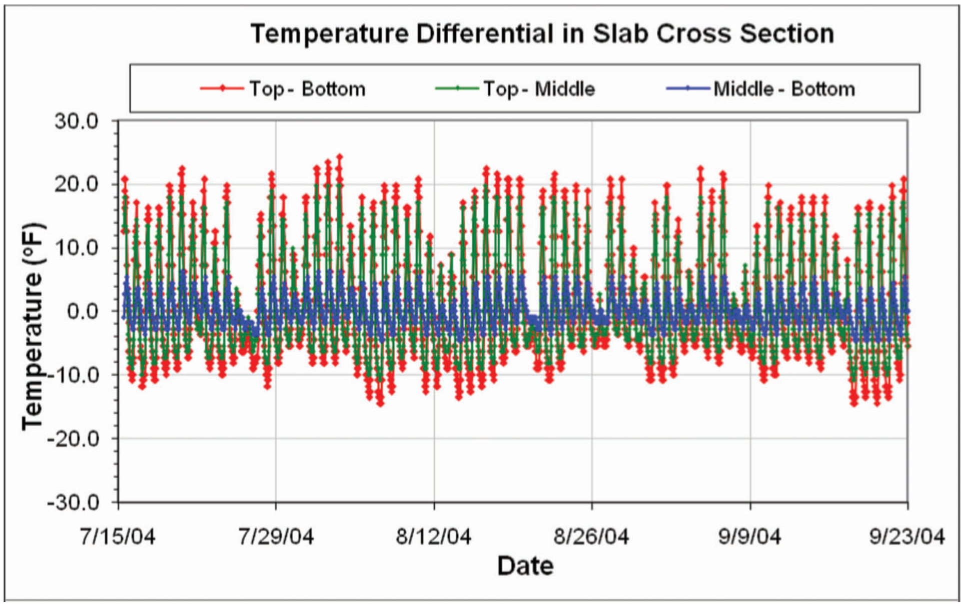


Figure 4.6 Temperature differentials between top, mid, and bottom of slab, summer of 2004

was only approximately ten degrees while the temperature difference between the mid-depth and the bottom of the slab was approximately only six degrees.

Figure 4.11 shows the temperature differences between top and bottom, top and middle and middle and bottom sections of the slab. The temperature differences between the top and middle section dominated the temperature changes in the slab. The temperature differences between the middle and bottom section of the slab were relatively small compared to those of the top and middle sections. The temperature swings between the middle and bottom sections were larger in the early fall season than they were during the summer. This occurs because, during the early fall season, the air temperature differences are larger than those in the summer season. However, the temperature differences during the fall season are still relatively small compared to those in the summer season, especially the temperature differences between the middle and bottom sections after mid-October, when they are negligible.

Figure 4.12 shows a typical slab temperature during the fall season from midnight to 6:00 PM the next day. The temperature differences between the top and

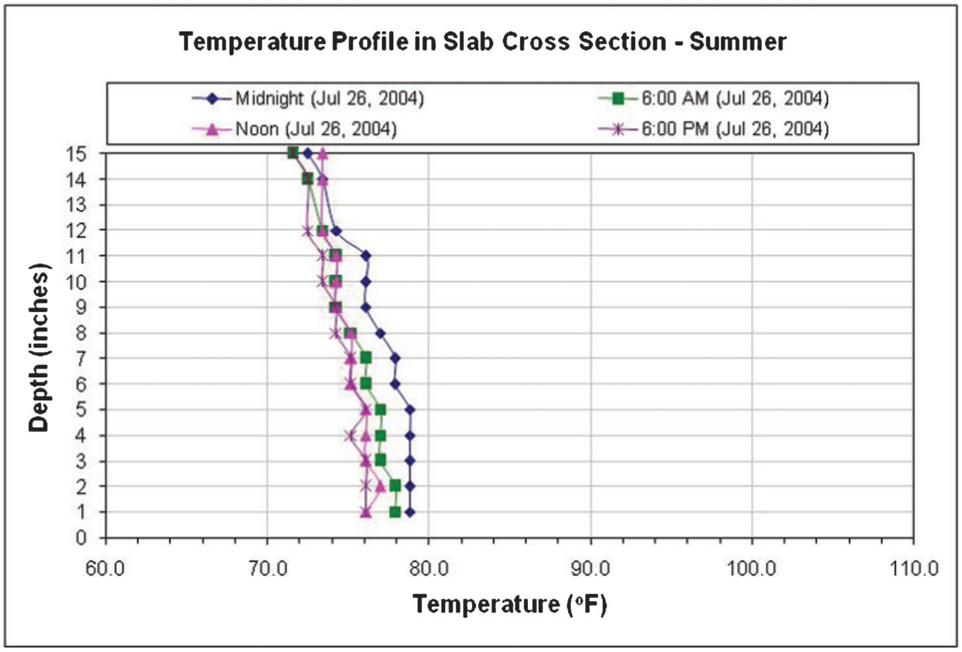


Figure 4.7 Temperature profile in a summer season at slab corner location

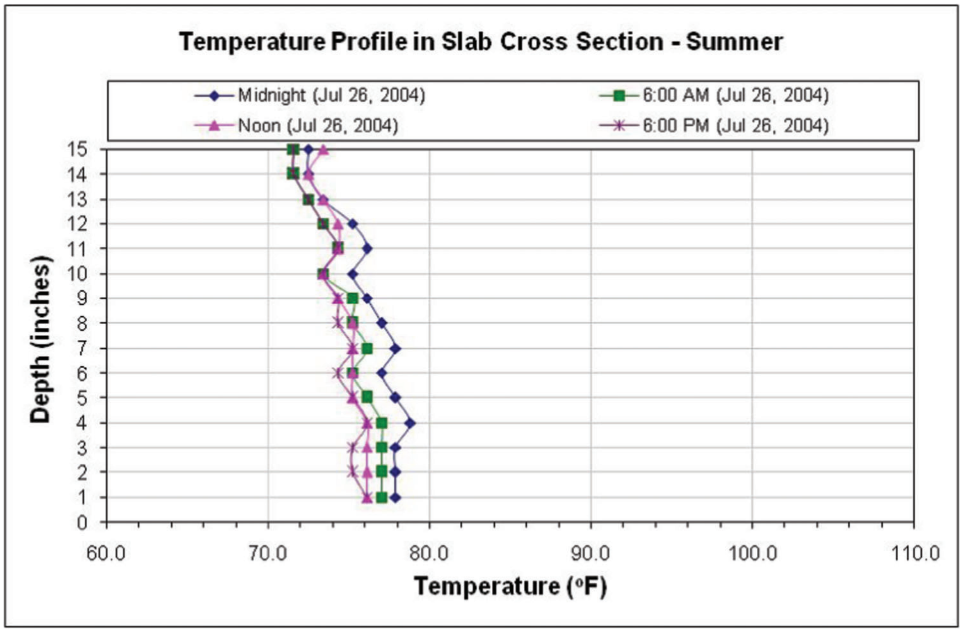


Figure 4.8 Temperature profile in a summer season at mid-slab location

bottom of the slab between midnight and noon were extremely small. Except in the case of a sudden change in air temperature, as in Figure 4.13 and 4.14, the temperature differences between the top and bottom and between night and day were very small. Examining these two figures, the temperature differences between the top and bottom sections during the night and day temperatures appear large; however, the actual temperature difference between the middle and bottom sections of the slab was approximately only less than five degrees, especially in the "cool then warm" scenario where the difference between the middle and bottom temperature was approximately only four degrees.

Figure 4.15 shows the temperature variations of the concrete slab throughout the winter season of 2005. As in the previous two seasons, the top half of the concrete

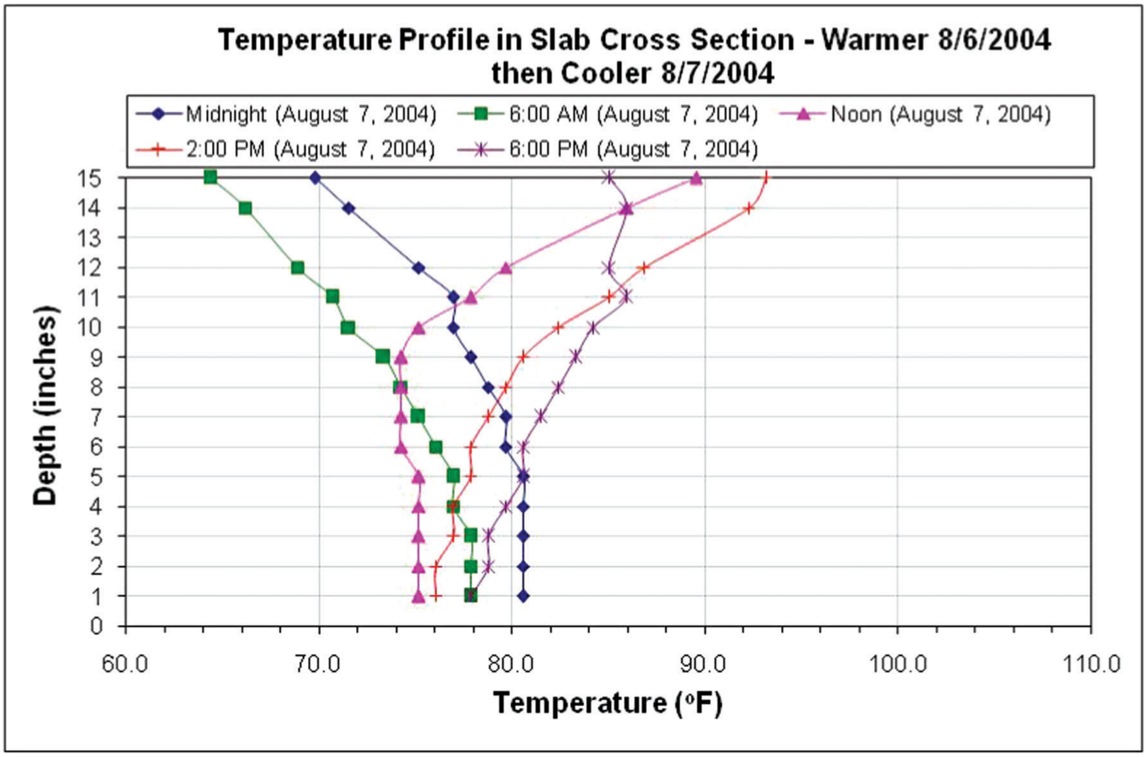


Figure 4.9 Temperature profile in a summer season with a sudden change in air temperature from warmer to cooler

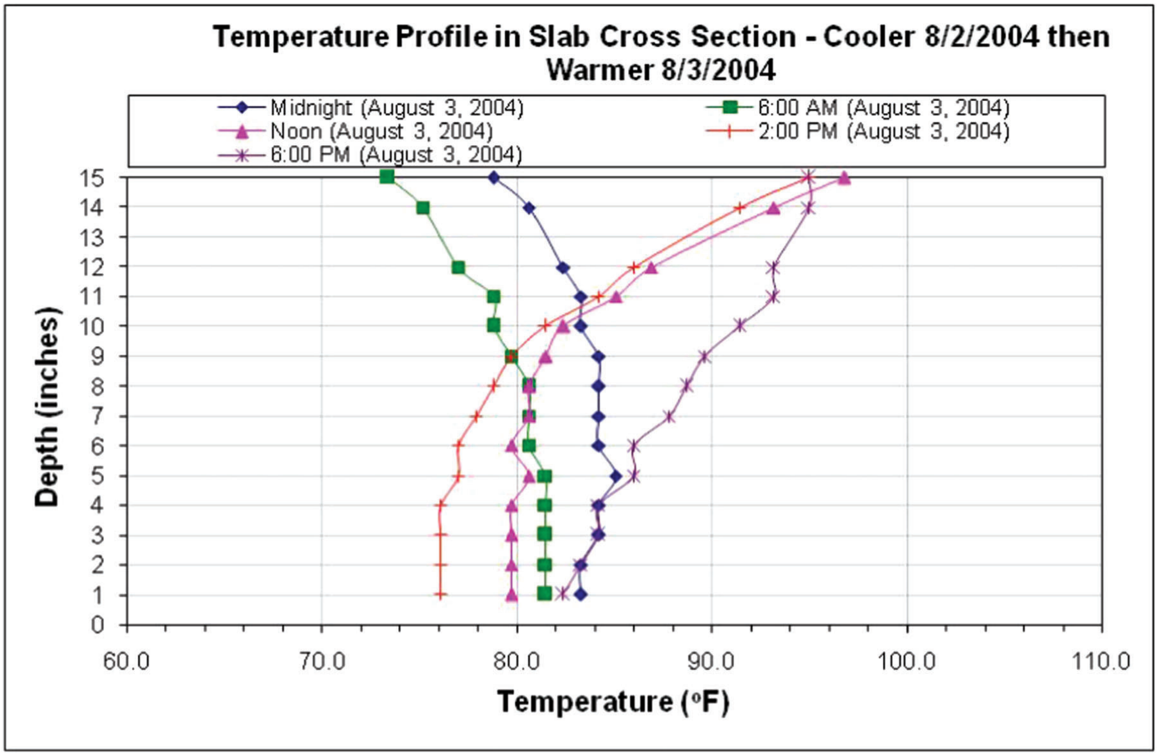


Figure 4.10 Temperature profile in a summer season with a sudden change in air temperature from cooler to warmer

slabs adapted to the air temperature while the bottom half closely followed the seasonal temperature of the soil underneath the concrete slabs.

Figure 4.16 shows the temperature differences between the top and middle portions of the slab and between the middle and bottom portions of the slab. The temperature differences between the top and middle portions were the smallest during the cold winter, nearing the spring thaw. The same effect occurred in the temperature differences between the middle and bottom

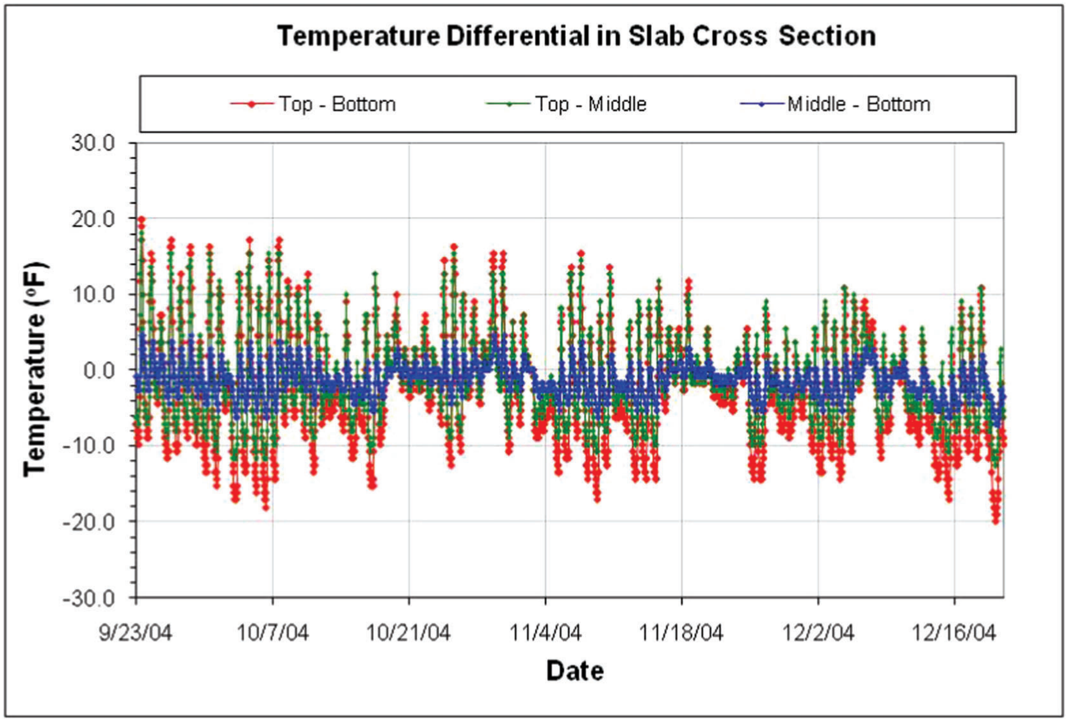


Figure 4.11 Temperature differentials between top, mid, and bottom slab, fall of 2004

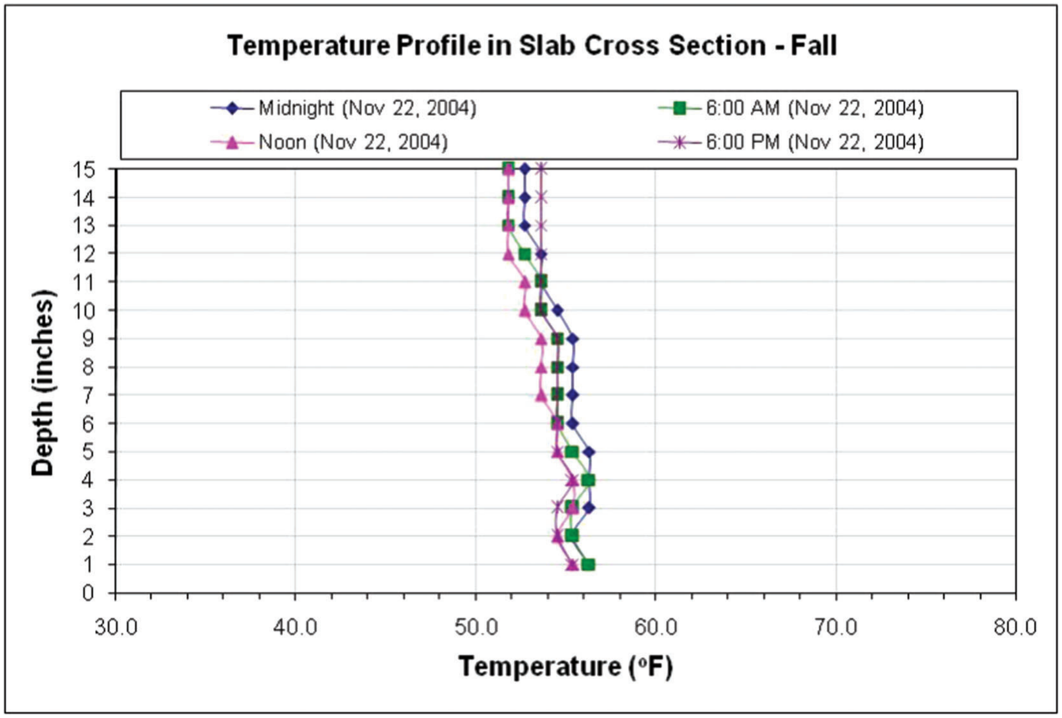


Figure 4.12 Temperature profile in a fall season at corner slab location

portions of the slab. However, in the first two weeks of January 2005, the air temperature was warmer than normal, but the temperature differences between the middle and bottom portion were still negligible.

Figure 4.17 shows a typical temperature profile for a winter season. In general, the temperature differences between the top and bottom portions of the slab were larger than the previous two seasons for both day and night air temperature swings. However, the temperature swings in the slab between day and night were negligible, in general smaller than six degrees. The temperature difference between the top and bottom

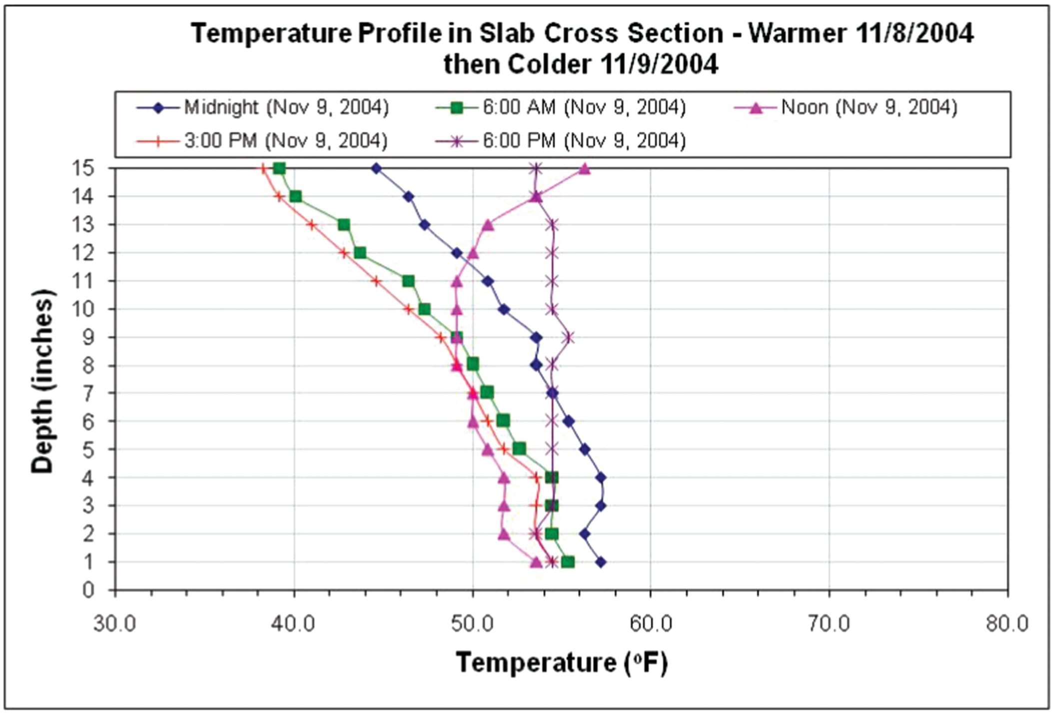


Figure 4.13 Temperature profile in a fall season with a sudden change in air temperature from warmer to colder

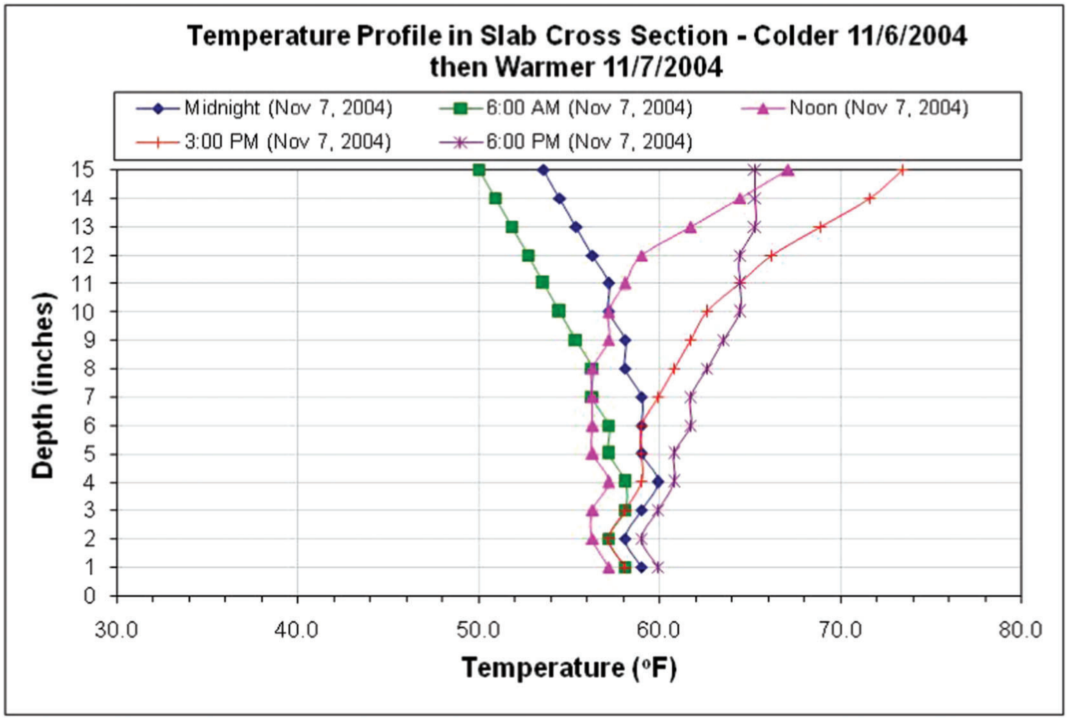


Figure 4.14 Temperature profile in a fall season with a sudden change in air temperature from colder to warmer

portions of the slab was approximately ten degrees, which was larger than the previous two seasons, although the temperature differences between the middle and bottom portions of the slab were still small, less than four degrees.

Figures 4.18 and 4.19 show the total concrete slab responses (from top to bottom) to sudden changes in air temperature during the winter season. Unlike the previous two seasons, where only the top half of the concrete slabs responded due to sudden changes in air

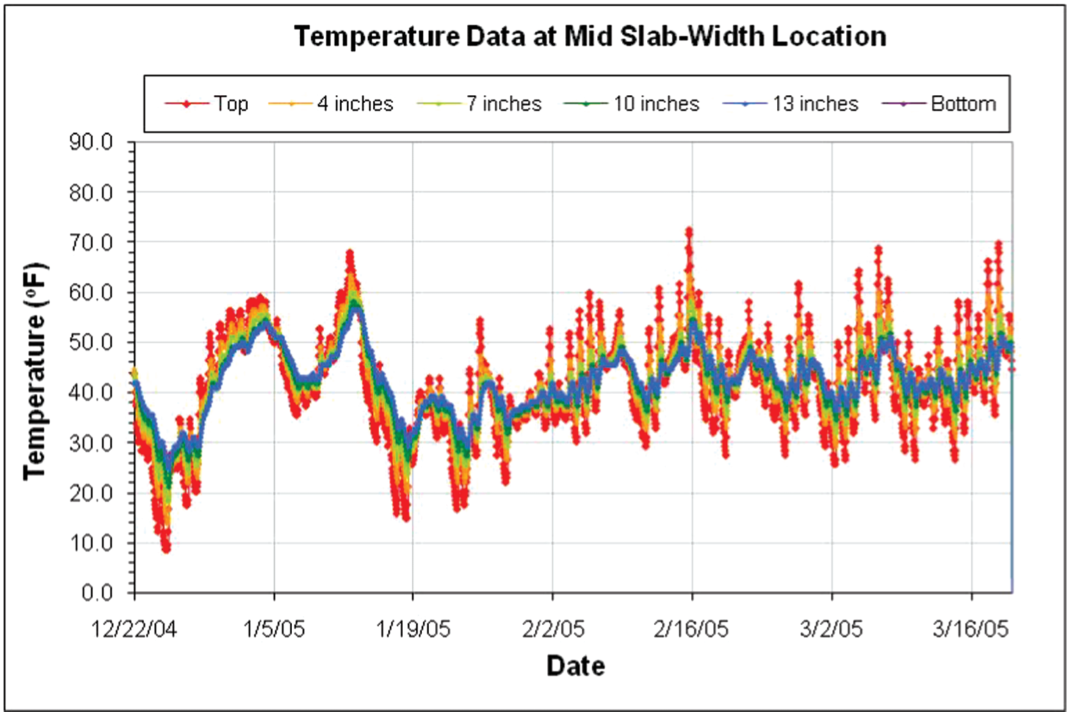


Figure 4.15 Temperature variations at the middle of the slab, winter of 2005

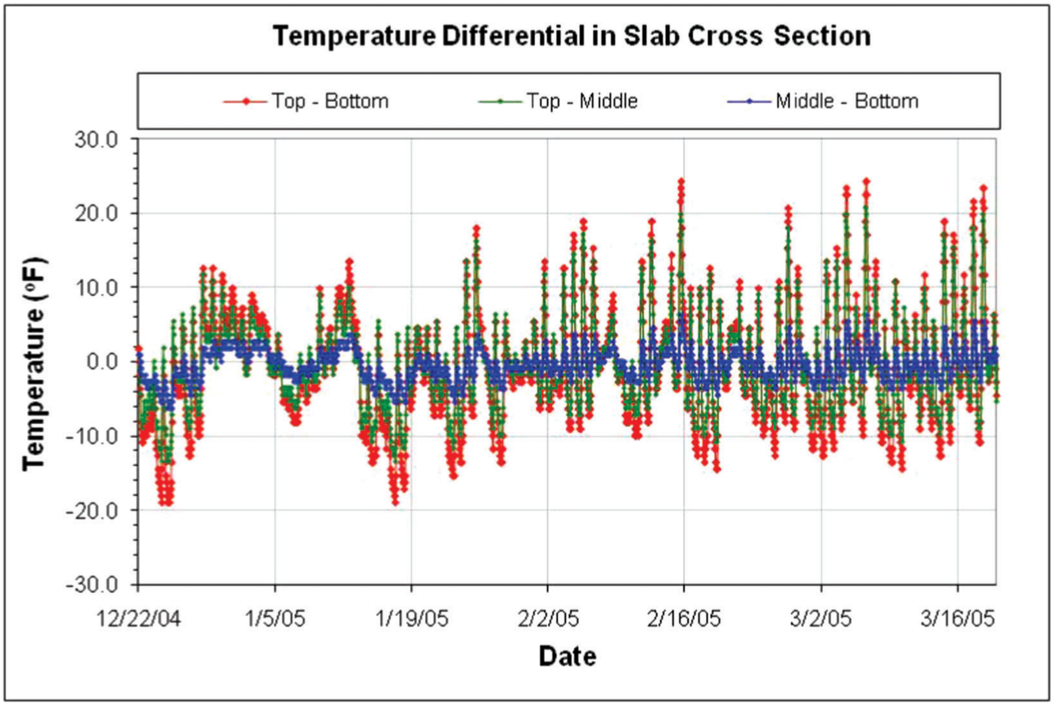


Figure 4.16 Temperature differentials between top, mid, and bottom of slab, winter 2005

temperature, during the winter season the full thickness of the slab responses to the air temperature. Such conditions triggered the highest curling stresses in the slab.

Figure 4.20 shows the temperature variations in the spring of 2005. The top of the slab quickly responded to changes in air temperature. In addition, the temperature swings in the top and bottom portions of the slab were wider compared to those in the previous three seasons. Figure 4.21 shows this temperature swing phenomenon. The temperature differences between the top and middle portions and the middle and

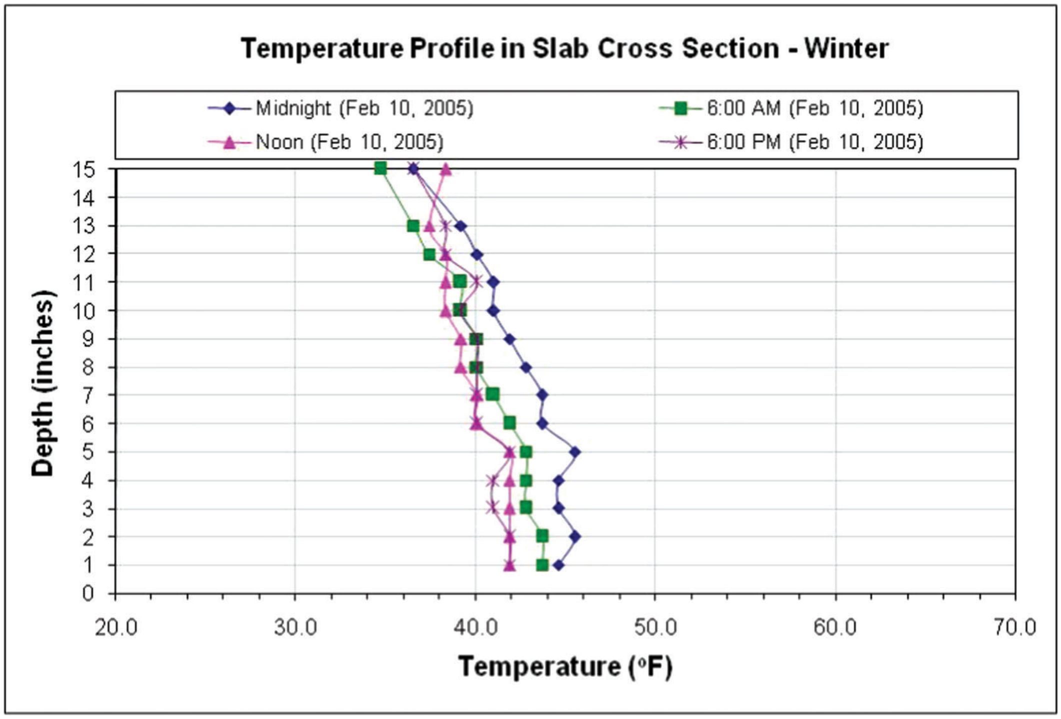


Figure 4.17 Temperature profile in a winter season at middle slab location

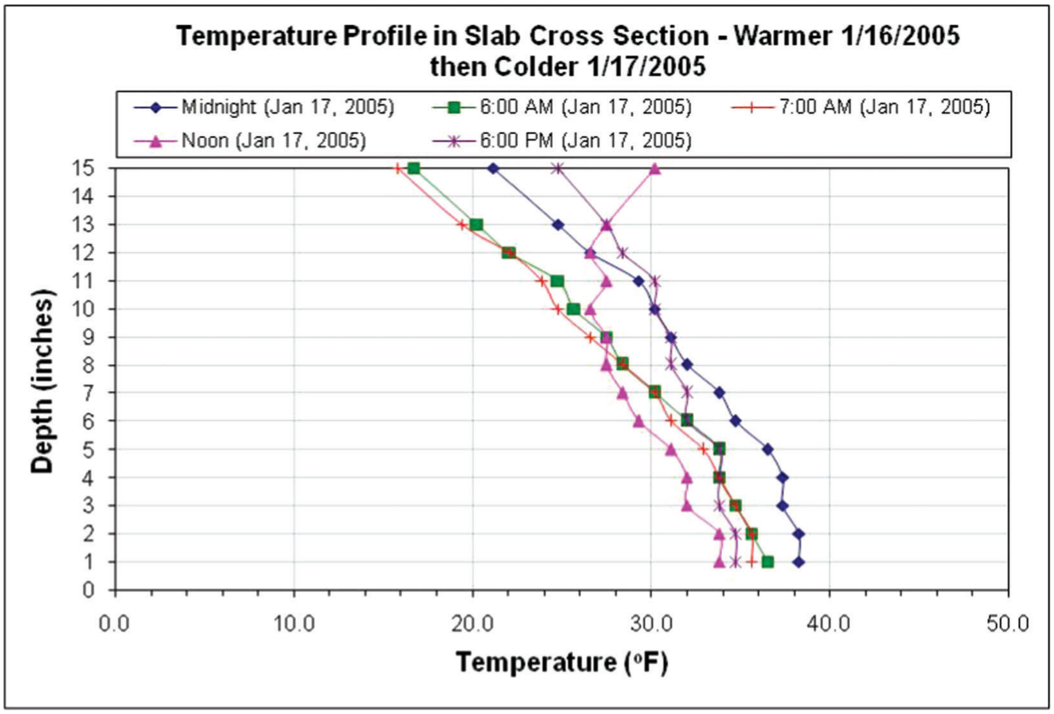


Figure 4.18 Temperature profile in a winter season with a sudden change in air temperature from warmer to colder

bottom portions were the largest compared to the previous three seasons. However, for constant and seasonably normal air temperature during the spring, the temperature swings during the spring season were low. Figure 4.22 shows the temperature swings between day and night and between the top and bottom portions. A large temperature difference occurred in the late afternoon; however, the temperature difference was only about ten degrees. Nonetheless, these temperature differences between the top and bottom and the middle and bottom portions were the largest compared to the previous three seasons.

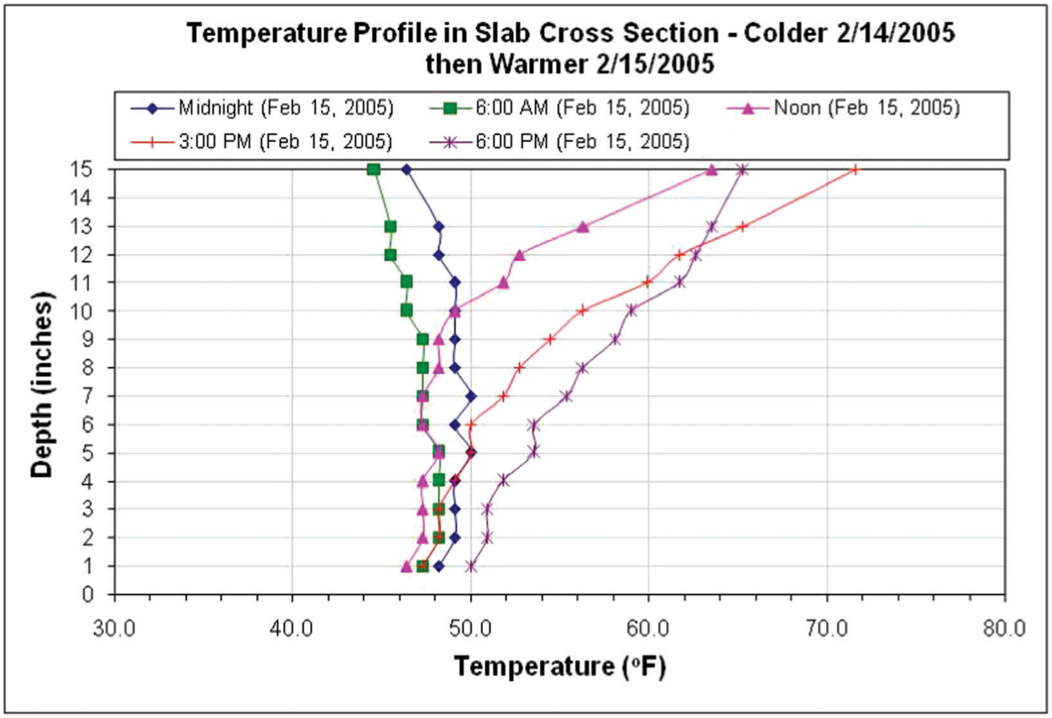


Figure 4.19 Temperature profile in a winter season with a sudden change in air temperature from colder to warmer

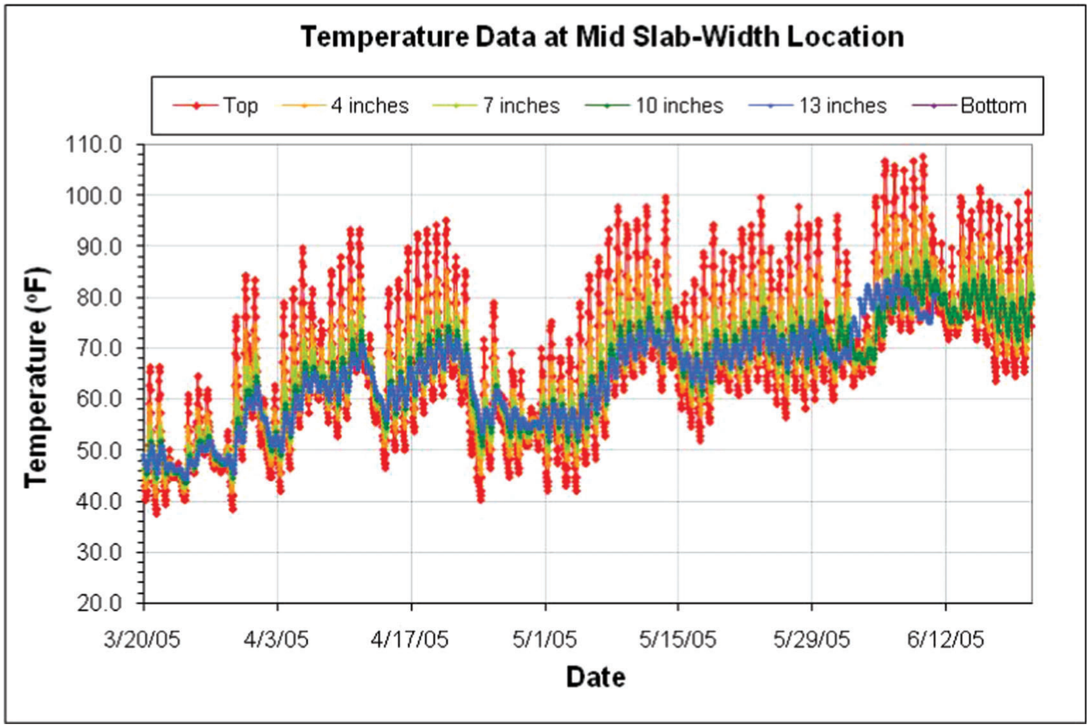


Figure 4.20 Temperature variations at the middle of the slab, spring of 2005

Figures 4.23 and 4.24 show the responses of the concrete slab to sudden changes in air temperature during the spring season. The temperature differences between the top and bottom were large compared to those in the previous three seasons. The differences were in the range of 30 degrees, which can trigger severe concrete slab curling. The temperature differences between the middle and bottom portions of the slab were also large, more than ten degrees. Although the top half of the slab responded more to the sudden

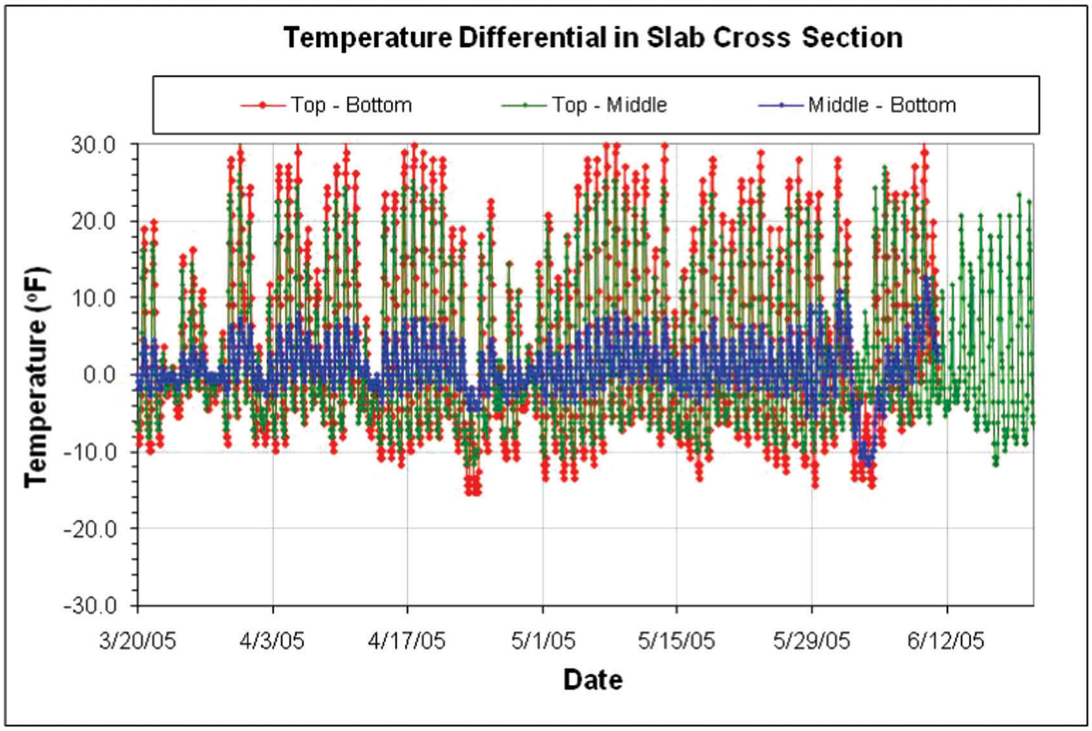


Figure 4.21 Temperature differentials between top, mid, and bottom of slab, spring 2005

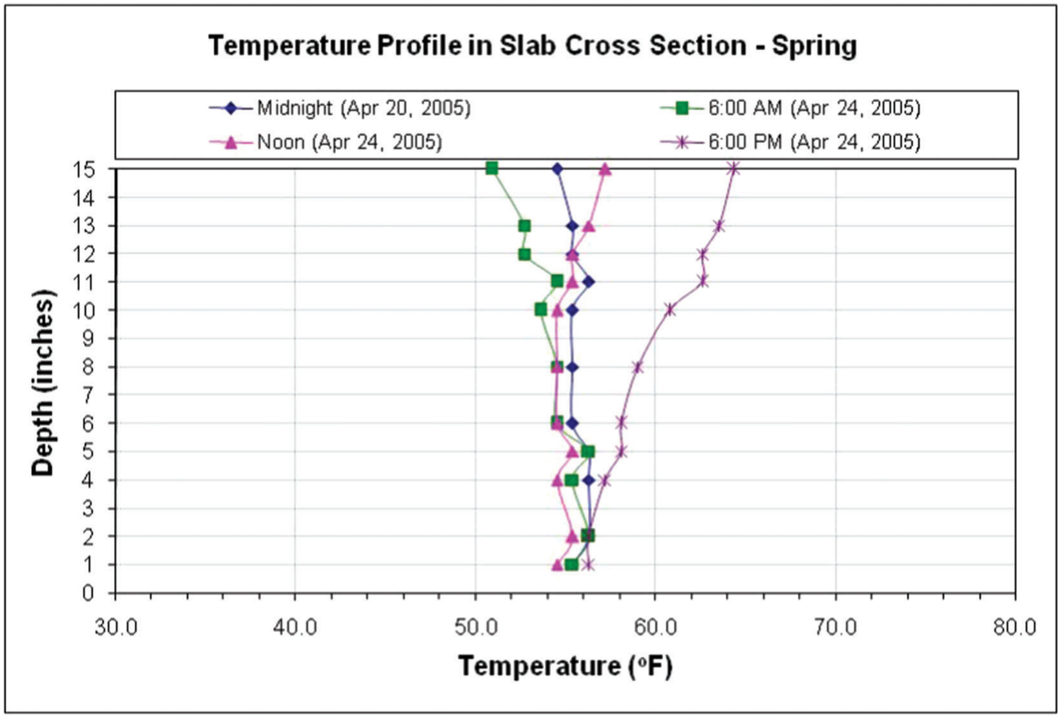


Figure 4.22 Temperature profile in a spring season at middle slab location

change of temperature, the bottom half also responded quickly. Together, these two figures illustrate that the slab's most severe responses to temperature changes occurred when the air temperature changed from cold to hot. The temperature swings in the slab that occurred due to changes during the day and night were also rather large.

Data and analysis of the temperature profiles detailing how the slabs responded to air temperature, daily and seasonably, suggested that during the season

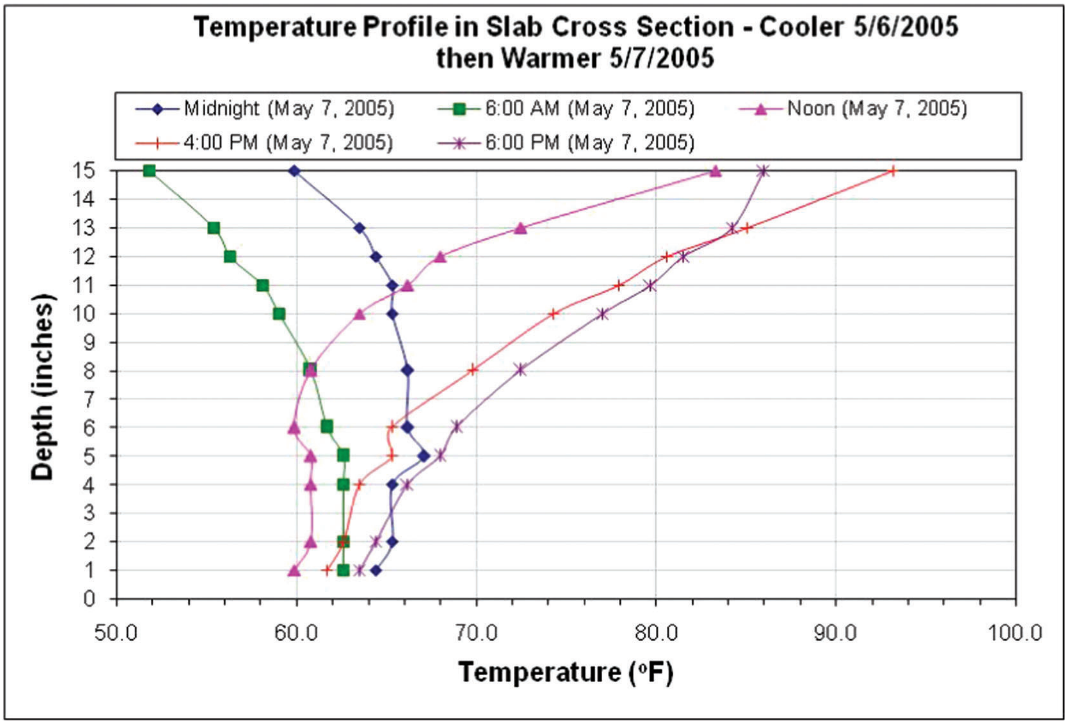


Figure 4.23 Temperature profile in a spring season with a sudden change in air temperature from cooler to warmer

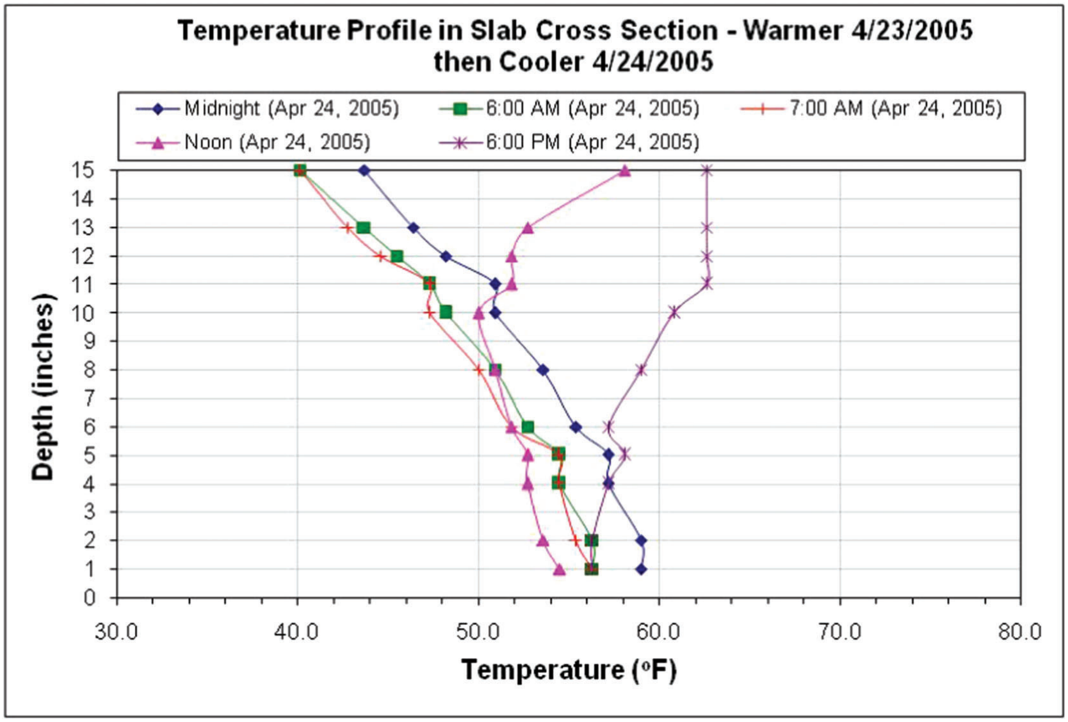


Figure 4.24 Temperature profile in a spring season with a sudden change in air temperature from warmer to cooler

the concrete slabs experience small temperature differences between the top and bottom portions of the slabs with daily air temperature variations only affect the top half thickness of the slabs. In addition, the temperature swings in the slabs between night and day were significantly smaller than previously expected. However, sudden changes in air temperature, especially during the spring season, created large temperature differences between the top and bottom portions of the slab. The most severe difference occurred when the air temperature changed drastically from cold to hot.

The analysis of the concrete slab temperatures yields significant knowledge regarding how the slab behaved and the expected curling stress that the concrete slab experienced. The next section will discuss the stresses and strains of the concrete due to the curling of the slab, with data taken from different seasons.

4.3. Concrete Slab Surface Deflections

Deflections of the concrete slab due to built-in curling and diurnal curling are still a controversial issue. From a structural engineering point of view, the dowel bars and tie bars provide enough anchoring of the concrete slab to avoid any deflection due to self-weight of the concrete in curling conditions. However, structural engineers agree that stresses in built-in curling and diurnal curling did occur in the concrete slab due to the restraints created by the dowel and tie bars. Many experts believe that curvatures in the slabs due to deflection occurred but it is not significantly high to increase the pavement roughness during diurnal curling.

The challenges in measuring the deflections in concrete slabs due to diurnal curling involve the reference points and the directions of the curvature. Physically measuring the surface curvature of the slabs is always an issue due to the lack of reference point. Even with strain gages inside the concrete slabs, forming the surface curvature of the slab is difficult to achieve. Therefore, in this research project, the surface curvatures of the slabs were built by modeling the surface from readings taken from the strain gages. Using the mid-slab as the reference point, surface curvatures can be formed.

As indicated in the slab temperature analysis, the largest temperature differentials (those between the top and bottom portions of the slab) occurred during colder air temperatures when there was a sudden change in air temperature. The deflection analysis revealed that the maximum deflection of the slab occurred during the month of November in 2005. Unfortunately, at that time of year, the iButtons had already stopped collecting temperature data due to battery power. Therefore, the temperature profiles in the slabs could not be determined.

Figures 4.25 to 4.28 show the deflections of the three experimental slabs at their maximum deflections. The deflections were modeled based on the center of the slab in the longitudinal and transverse directions; the reference points were the strain gages in the middle of each slab. These figures indicated that the deflections between the left and right longitudinal edges of the slabs were not identical. The reasons for the asymmetrical deflections were: (a) the right hand side of the slab (shoulder) was not cast at the same time as the slab, and

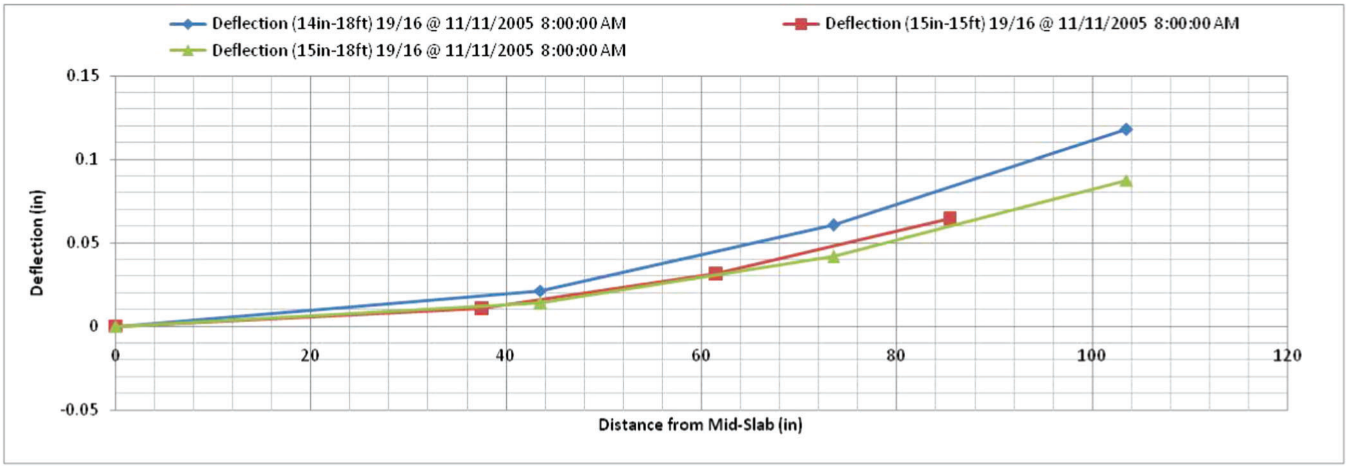


Figure 4.25 Comparison of the slab deflections in left-side longitudinal direction in late fall

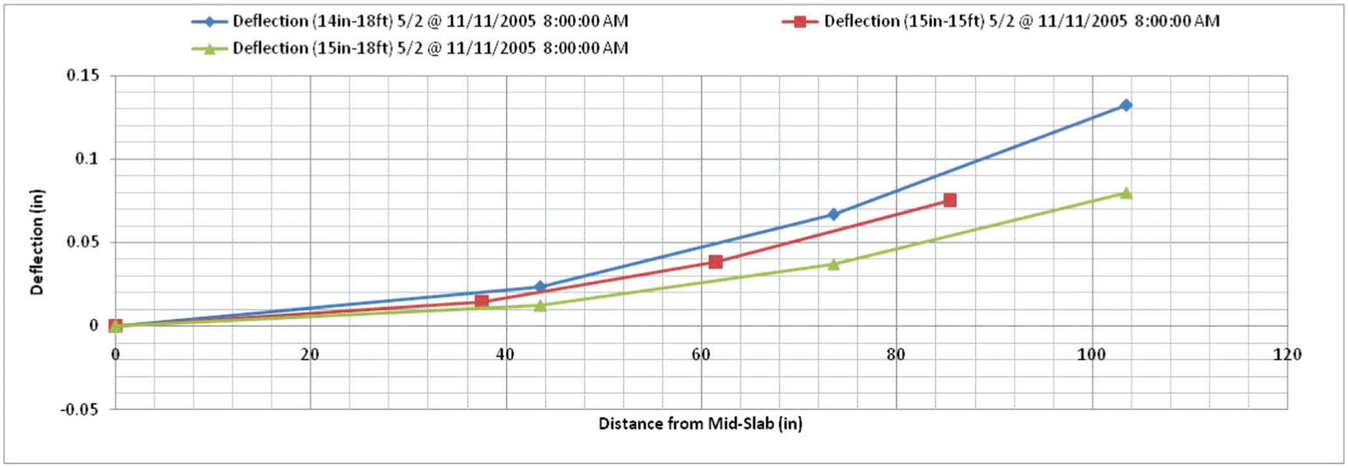


Figure 4.26 Comparison of the slab deflections in right-side longitudinal direction in late fall

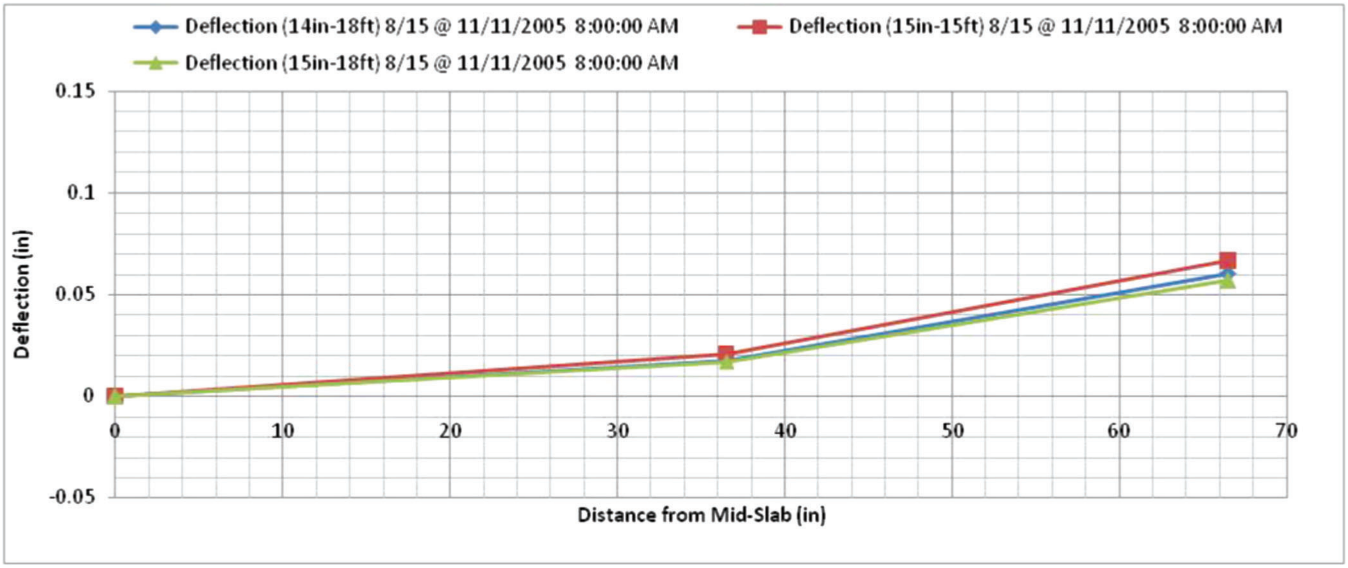


Figure 4.27 Comparison of the slab deflections at the left-half panel transverse direction in the late fall

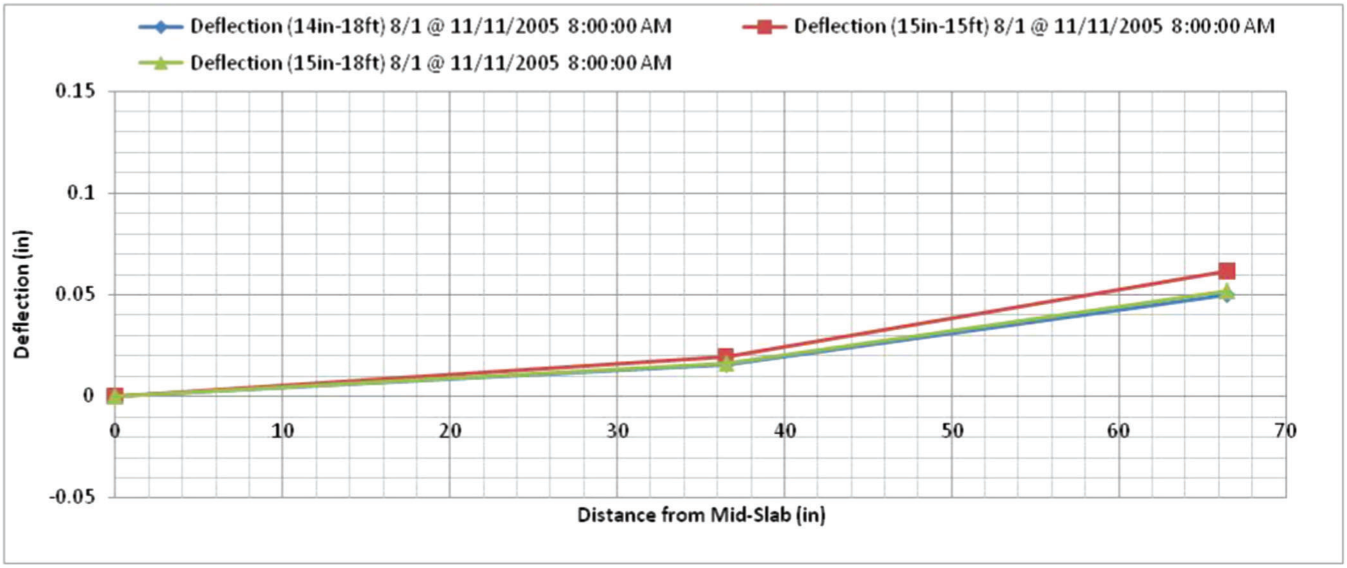


Figure 4.28 Comparison of the slab deflections at the right-half panel transverse direction in the late fall

(b) the left hand side was the passing lane, which could hold the experimental slab more firmly compared to the shoulder side.

From these maximum deflections, one can see that the left longitudinal deflections were lower than the right longitudinal deflections (Figures 4.25 and 4.26). While in the transverse direction of the slab, the left side transverse direction did not have significantly lower deflections compared to those from the right transverse direction (Figures 4.27 and 4.28). These figures indicated that the curling up or "bowl shape" of the slab during curling was asymmetrical.

Figures 4.25 and 4.26 show that, although the thicker but shorter slab (with 15-inch thickness and 15-foot joint spacing) had lower deflections at the edge, the thicker and longer slab (with 15-inch thickness and 18-foot joint spacing) had even lower deflections. This occurred because the self-weight of the slab countered the upward movement of the slab edges to form the "bowl shape." The same phenomenon also occurred in the transverse direction (see Figures 4.27 and 4.28). However, the restraint from the self-weight generated more stresses for the longer, thicker slab. In addition, the thicker slabs had a larger moment of inertia (I) to counteract the bending of the slab upward.

Figures 4.27 and 4.28 show that the longer slabs (with 14-inch thickness and 18-foot joint spacing, and 15-inch thickness and 18-foot joint spacing) had lower deflections compared to the shorter, thicker slab (15-inch thickness and 15-foot joint spacing). However, the differences were negligible. In this transverse direction, where the slab width was only 12 feet, the difference in the curling shape was also negligible.

Based on the analysis of the strains from the measurements recorded during the late fall and early summer, one can see that the shorter, thicker slab (with 15-inch thickness and 15-foot joint spacing) experienced less curling deflection in the longitudinal direction compared to the thinner slab with longer joint spacing (i.e.,14-inch thickness and 18-foot joint spacing). The thicker slab with longer joint spacing (15-inch thickness and 18-foot joint spacing) had a lower deflection. However, considering this phenomenon, this may not equal less curling stress.

Figures 4.29 and 4.30 show the maximum deflections of the slab by comparing several measurements during the spring, summer, and fall of 2005. The maximum deflections occurred in late fall of 2005. As was shown in the temperature analysis, a sudden air temperature change during the late fall or early winter will result in maximum temperature differences between the top and bottom portions of the slabs. Those two figures show the same phenomena as previously described in Figures 4.25 and 4.26 regarding the deflections of the slab with an efficient dimension of 15-inch thickness and 15-foot joint spacing. Although the thicker but shorter slab (with 15-inch thickness and 15-foot joint spacing) had lower deflections at the edge, the thicker and longer slab (with 15-inch thickness and 18-foot joint spacing) had even lower deflections.

Figures 4.31 and 4.32 show the minimum deflections of the slab during the very late spring/early summer of 2005. The deflections show that, at about the time the cement hydration finished its final set during construction (between 2:00 to 4:00 PM) in the afternoon, the slabs should be relatively flat and there should be no curling occurring. Although there were differences among the deflections of the slabs in those three experimental sections, they were very small. Therefore, for practical purposes the slabs were considered flat.

Figures 4.33 and 4.34 show the maximum deflections of the slab in the transverse directions on the left and right side of the slabs. There was no significant difference among the three experimental sections in this transverse direction because the width of the slab was only 12 feet. The deflections were minimal in this

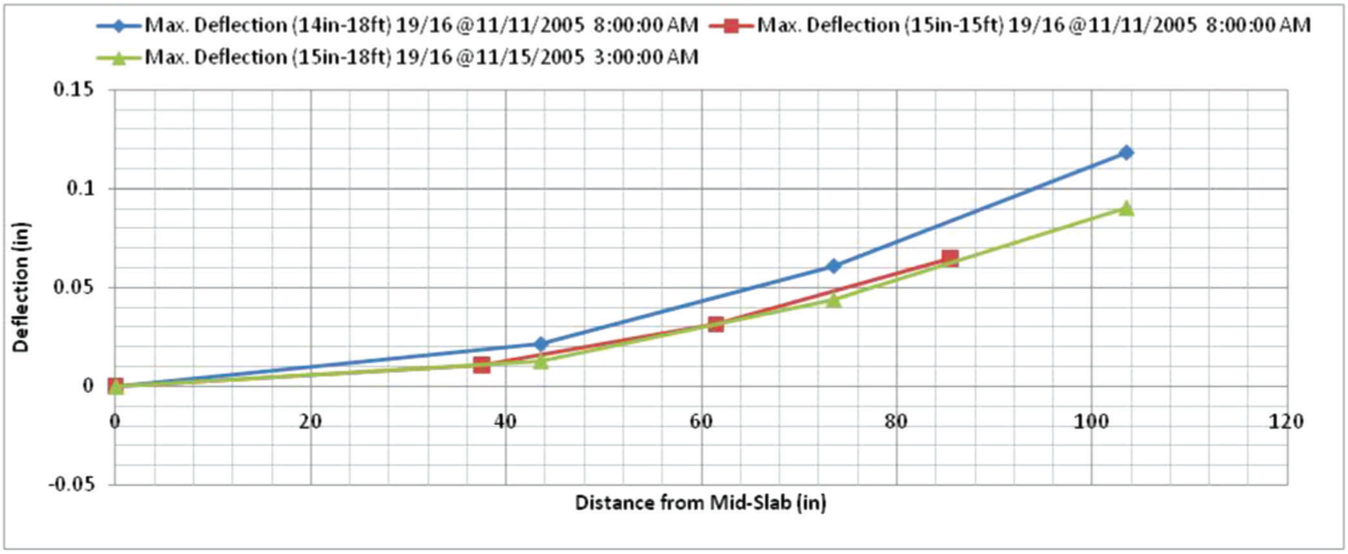


Figure 4.29 Comparison of maximum slab deflections in left-side longitudinal direction

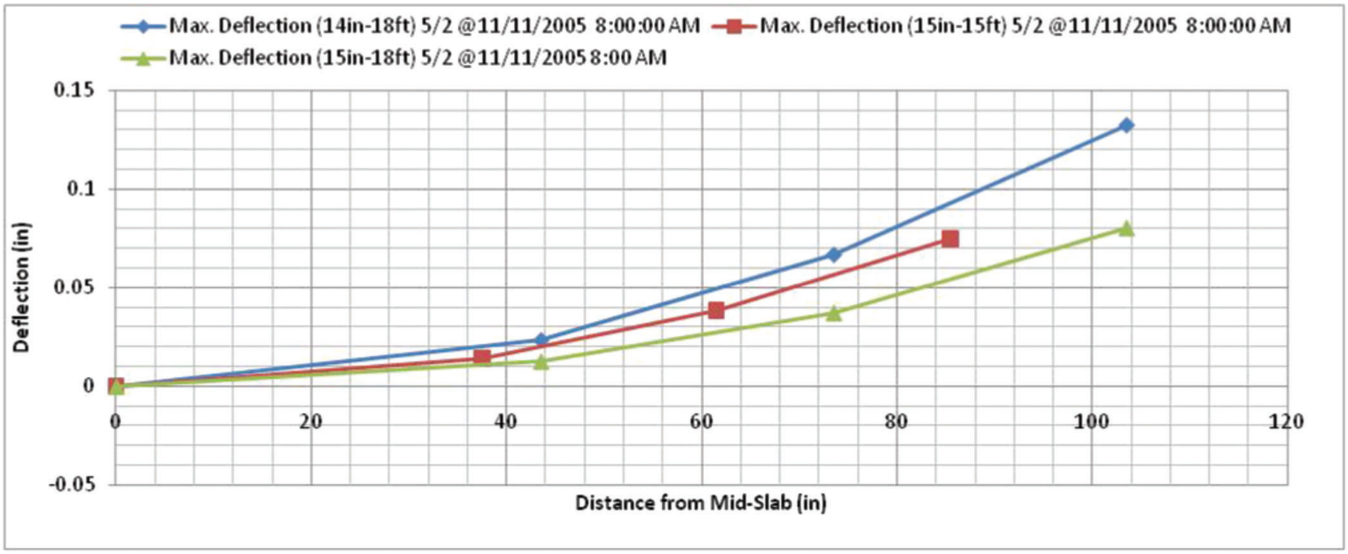


Figure 4.30 Comparison of maximum slab deflections in right-side longitudinal direction

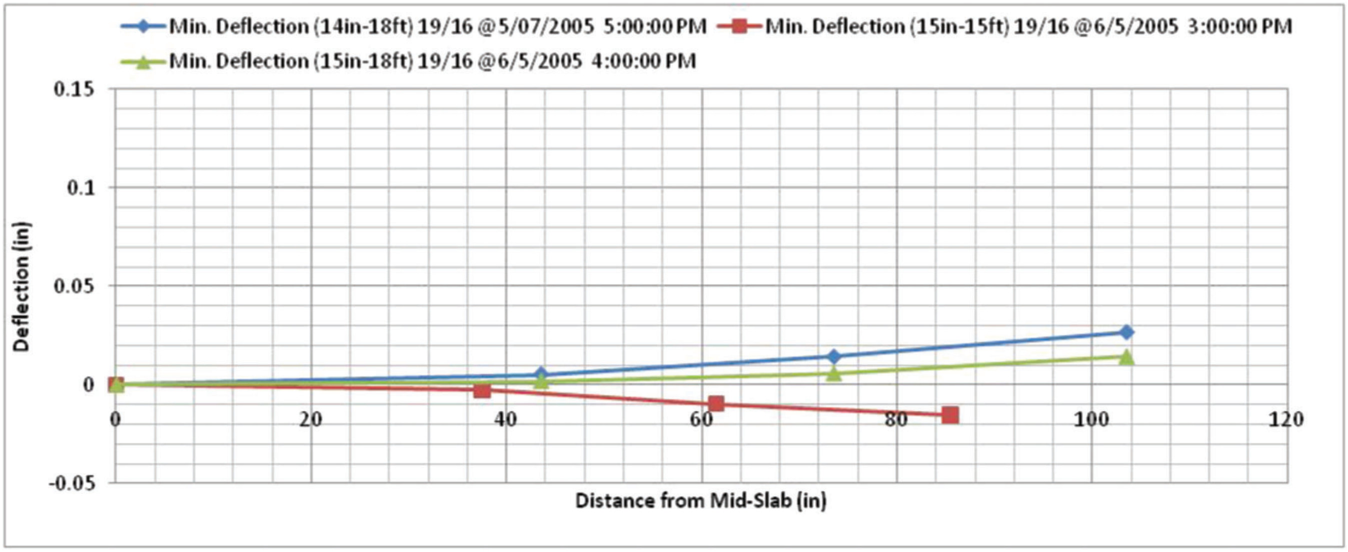


Figure 4.31 Comparison of minimum slab deflections in left-side longitudinal direction

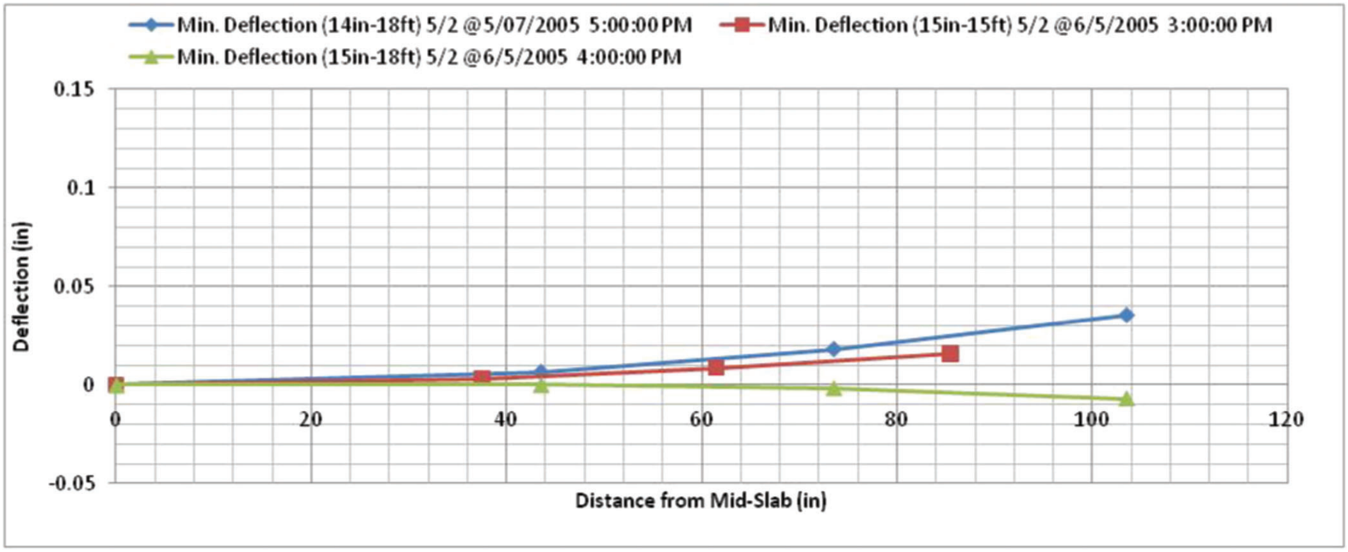


Figure 4.32 Comparison of minimum slab deflections in right-side longitudinal direction

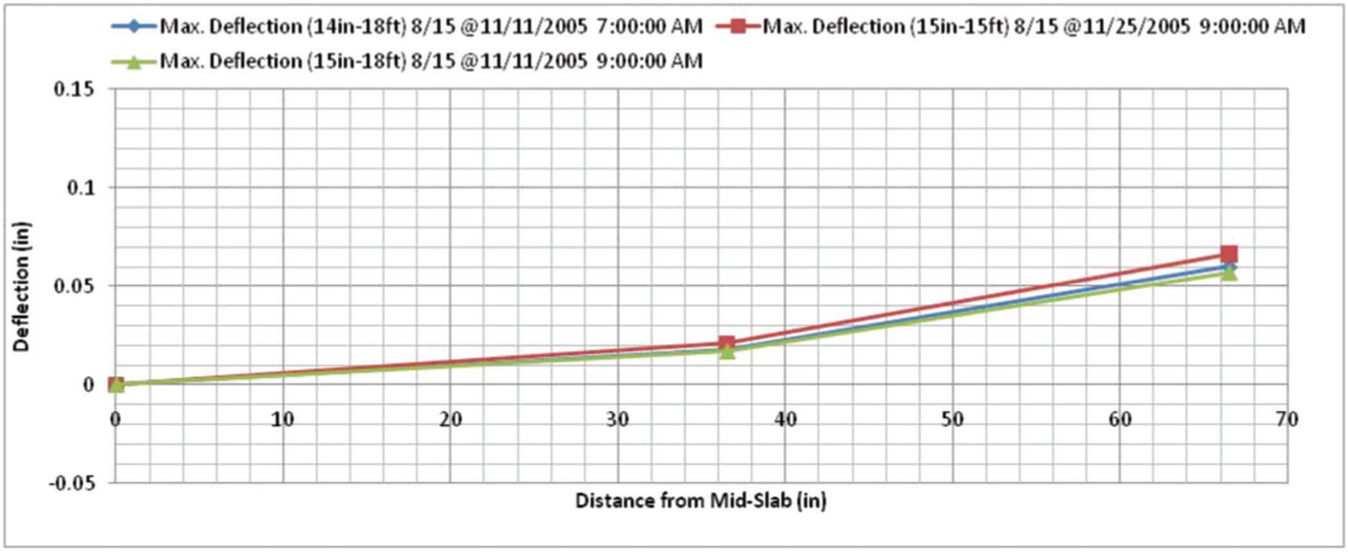


Figure 4.33 Comparison of maximum slab deflections in the left-half panel transverse direction

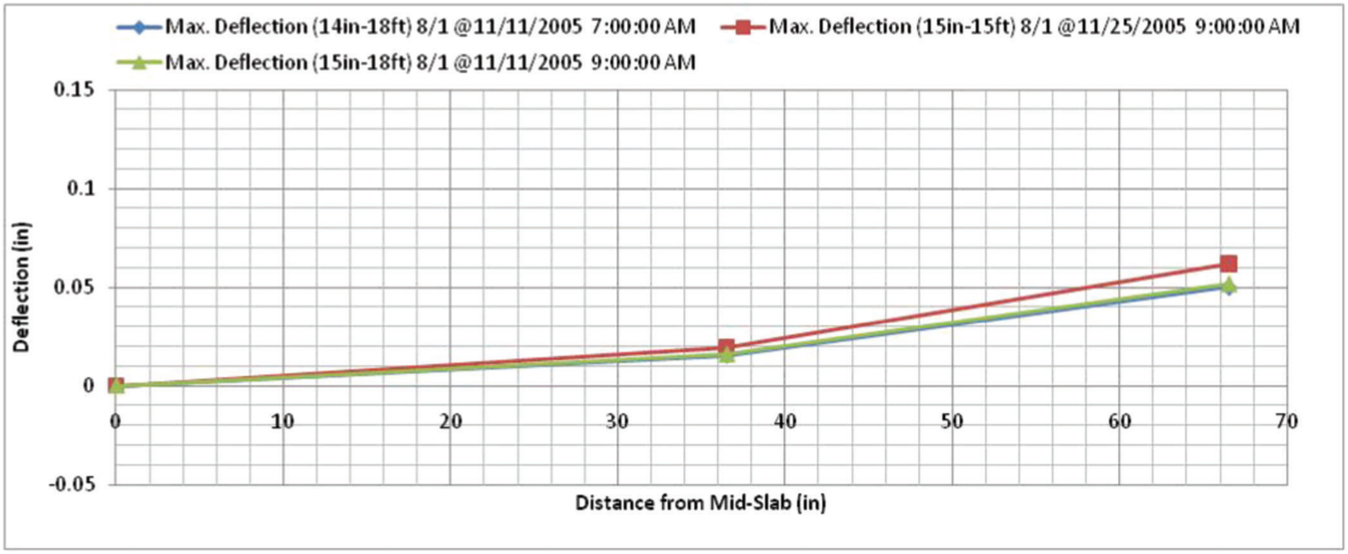


Figure 4.34 Comparison of maximum slab deflections in the right-half panel transverse direction

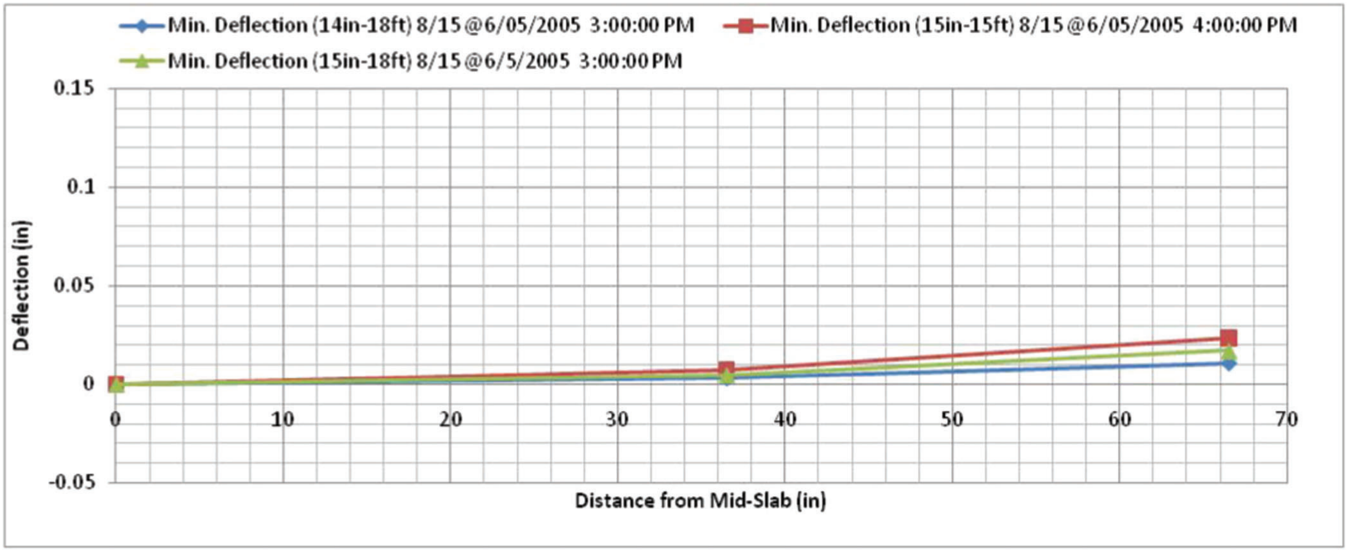


Figure 4.35 Comparison of minimum slab deflections in the left-half panel transverse direction

transverse direction, and the slabs were practically flat. However, once again, the maximum deflections occurred during the late fall in 2005.

Figures 4.35 and 4.36 show the minimum deflections of the slabs in the transverse direction on the left and right sides of the slabs. There was no significant difference among the deflections of the three experimental sections. In addition, the deflection was extremely small, and the slabs were practically flat. These minimum deflections occurred during the late spring/early summer of 2005, as already predicted in the temperature analysis. The minimum deflections occurred at almost the same time, when the slabs finished their final set of cement hydration during construction in 2004.

The analysis above indicates that the slabs never experienced curling down because of negative gradients (where top surface temperature is lower than bottom surface). However, the measurements were sampled only at certain times of the year because of traffic in the experimental sections. There is a probability that curling down occurred in other times when there was no measurements were taken.

Figures 4.26 to 4.36 already show the typical deflections and maximum and minimum deflections in the slab. In accordance with the prediction in the temperature analysis, extreme temperature differences between the top and bottom of the slab occurred when there was a sudden change in air temperature. The deflections in the slabs followed this trend of the temperature profile.

The maximum deflection (curling up) occurred on November 11, 2005. From the temperature profile in Figure 4.37, one can see that during that time there was

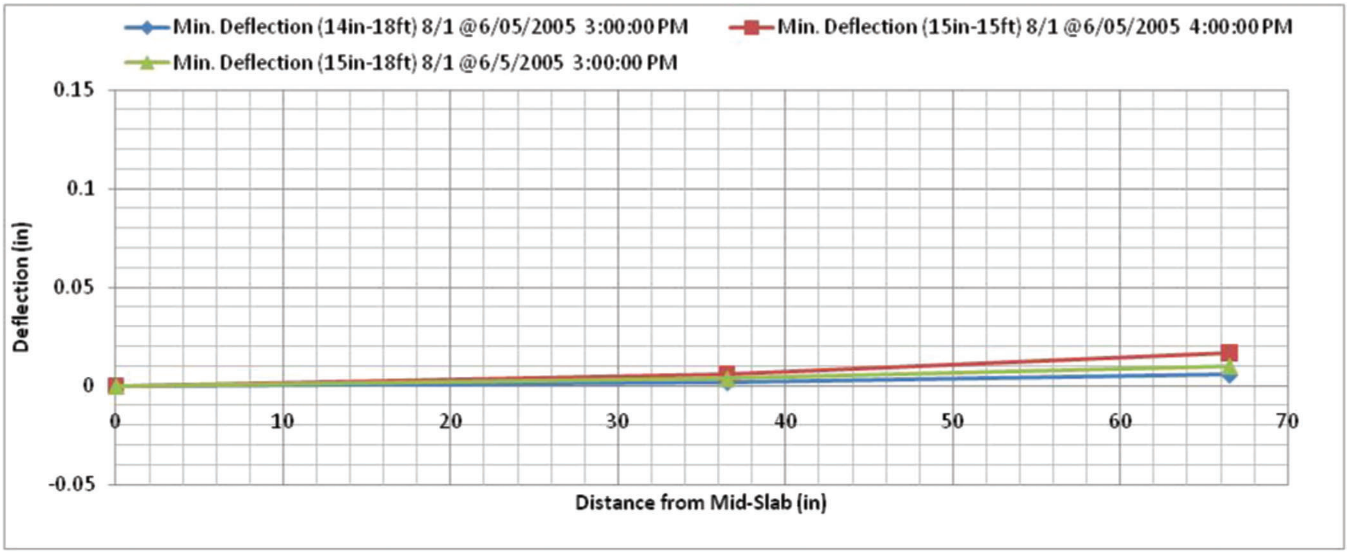


Figure 4.36 Comparison of minimum slab deflections in the right-half panel transverse direction

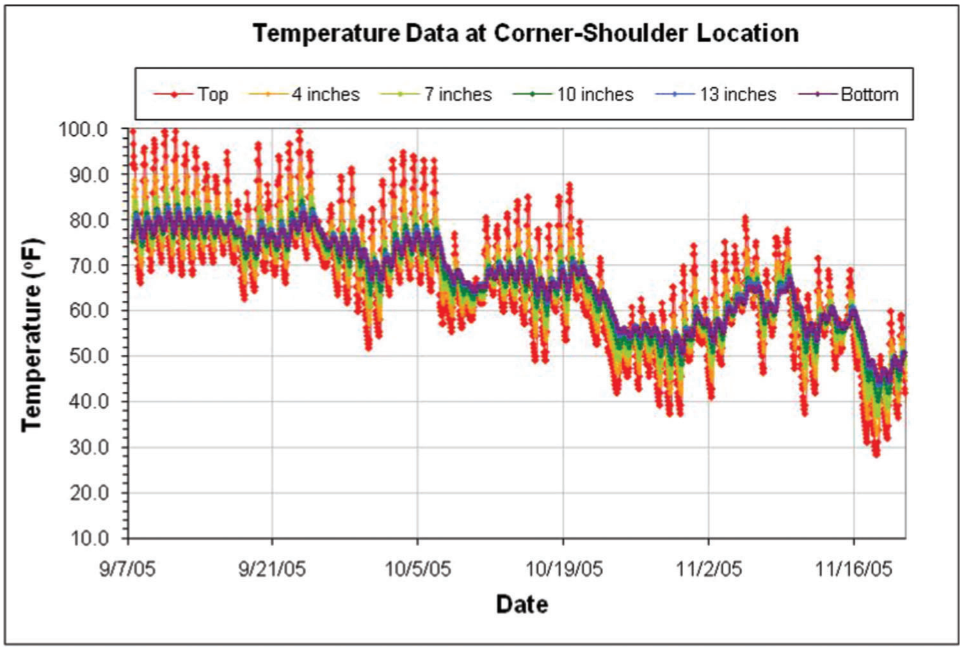


Figure 4.37 Temperature profile for fall 2005

a large swing in air temperature. The figure shows sudden changes in temperature from warm to cold. This warm-to-cold phenomenon in air temperature will trigger curling up in the slabs, and the slabs will form a "bowl" shape. Figure 4.38 shows the temperature profile in the slab on November 11, 2005, with extreme temperature differences between the top and bottom portions of the slab.

Figure 4.39 shows the temperature in the slab on May 7, 2005, when minimum deflections occurred. It also shows a sudden change of air temperature from cold to hot. As expected, the slab had a large temperature difference between its top and bottom portions. Figure 4.40 shows the temperature in the slab on June 5, 2005, when the deflections for the 15-inch thick slabs were in the minimum values. Once again,

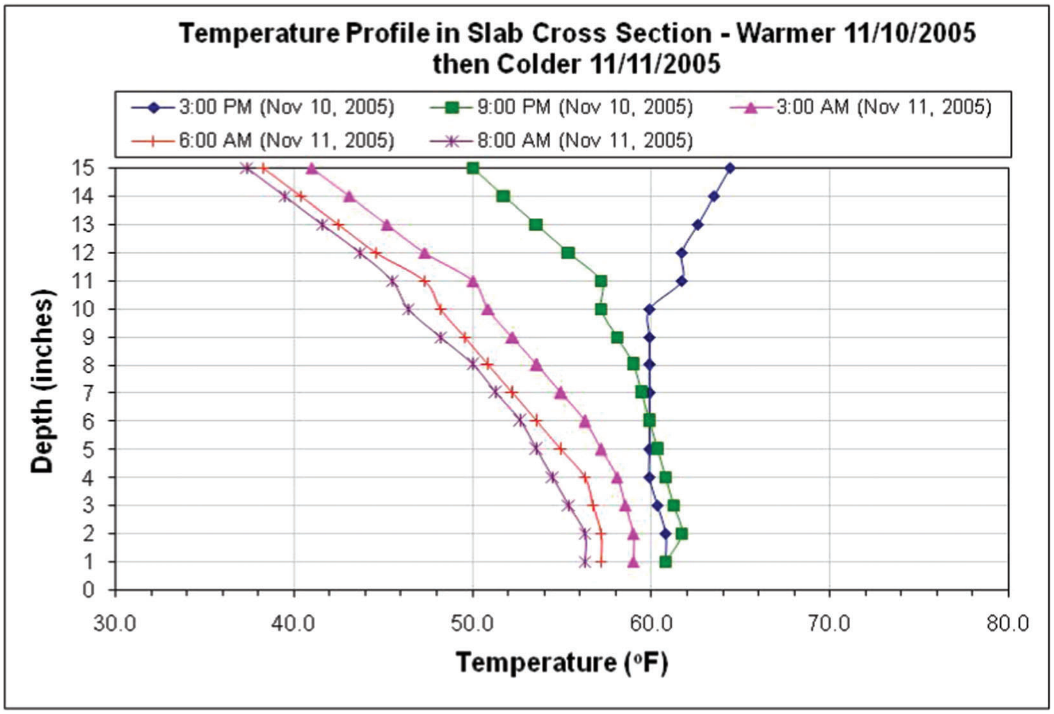


Figure 4.38 Temperature in the slab on November 11, 2005

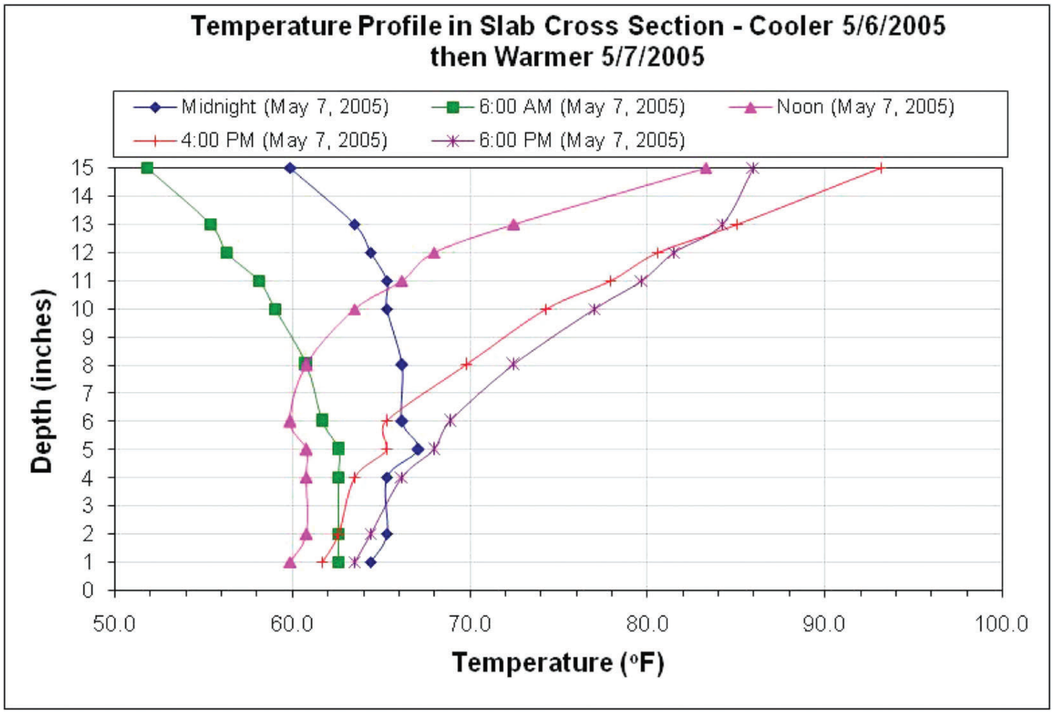


Figure 4.39 Temperature in the slab on May 7, 2005

this minimum deflection occurred when there was a sudden change in air temperature from cold to very hot.

Based on the temperature profiles in Figures 4.38 and 4.39 and the minimum deflections profiles in Figures 4.31 and 4.32, sudden changes in air temperature from cold to hot will trigger curling in a downward direction. However, the minimum deflections are extremely small. Since the temperature differences between the top and bottom portions of the slab in Figures 4.38 and 4.39 and the negative deflections in Figures 4.31 and 4.32 are extremely small, this indicates that the built-in curling in the slab will result in the slab

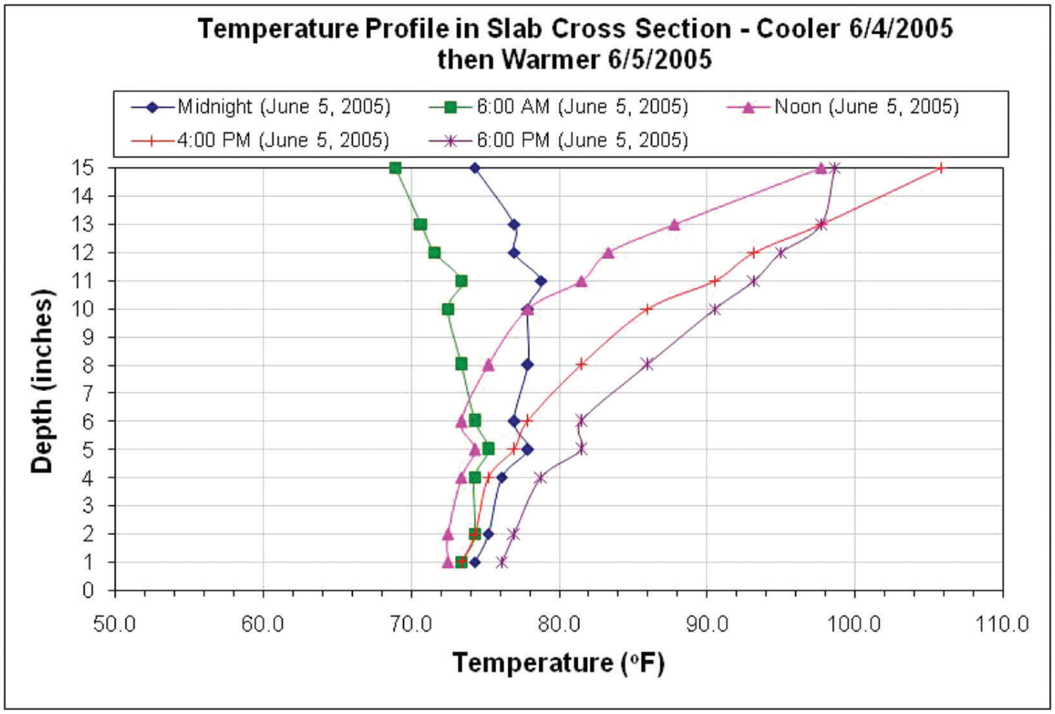


Figure 4.40 Temperature in the slab on June 5, 2005

curling up. This supports the theory that slab curling is related to the time of the final set of the cement hydration in concrete. Since the experimental slabs during construction were placed in the early morning hours and their final set occurred between 2:00 to 4:00 PM (the hottest time of the day, positive temperature gradient), the slabs most likely have built-in curling in the upward direction (curling-up) as in Figure 4.1.

4.4. Concrete Slab Stress Analysis

The behavior of the experimental slabs in response to changes in air temperature has been explained in terms of the distribution of the temperature within the slab and in terms of the slab deflections in relation to slab temperature. However, the most important parameters that determine the performance of Jointed Plain Concrete Pavement in the field are those stresses created by built-in curling, diurnal curling, warping of the slabs due to moisture, shrinkage of the concrete, and lastly, the loading from the traffic on the slabs.

The stress distributions in the slabs were calculated based on the data from the strain gages, meaning that the stresses were not measured directly from the slabs. Rather, the stresses were calculated from the models of the dimensional changes of the slabs that were measured by the strain gages. The most extreme dimensional changes in the slabs occurred during the late fall and late spring seasons.

Figures 4.41 and 4.42 show the stresses at the top and bottom portions of the slabs in a typical winter season with diurnal changes in a temperature. The information presented matches what had been predicted in theory thus far, that is, that shorter joint spacing creates less diurnal curling stresses in the slab, especially when the slab is curling up. Figure 4.41 shows that the slab did not curl down during the late fall and winter. Because the slabs have a built-in curling in the form of curling-up. Unless there is a sudden change in air temperature from very cold to very hot, the slabs do not curl down. In addition, the temperature in the bottom half of the slab did not change much in response to the diurnal temperature.

Figure 4.42 shows the stresses at the bottom portions of the slabs. Practically speaking, the bottoms of the slabs were in tension. This phenomenon is the opposite of curling up. In a situation where the slabs were curling up, the bottom portions of the slabs have to be in compression. Researchers suspected that, since the bottom portion of the slab did not respond well to fluctuations in diurnal temperature and the moisture at the bottom of the slabs was higher during the fall and winter seasons, then the bottom half of each slab would expand and create tension instead of compression.

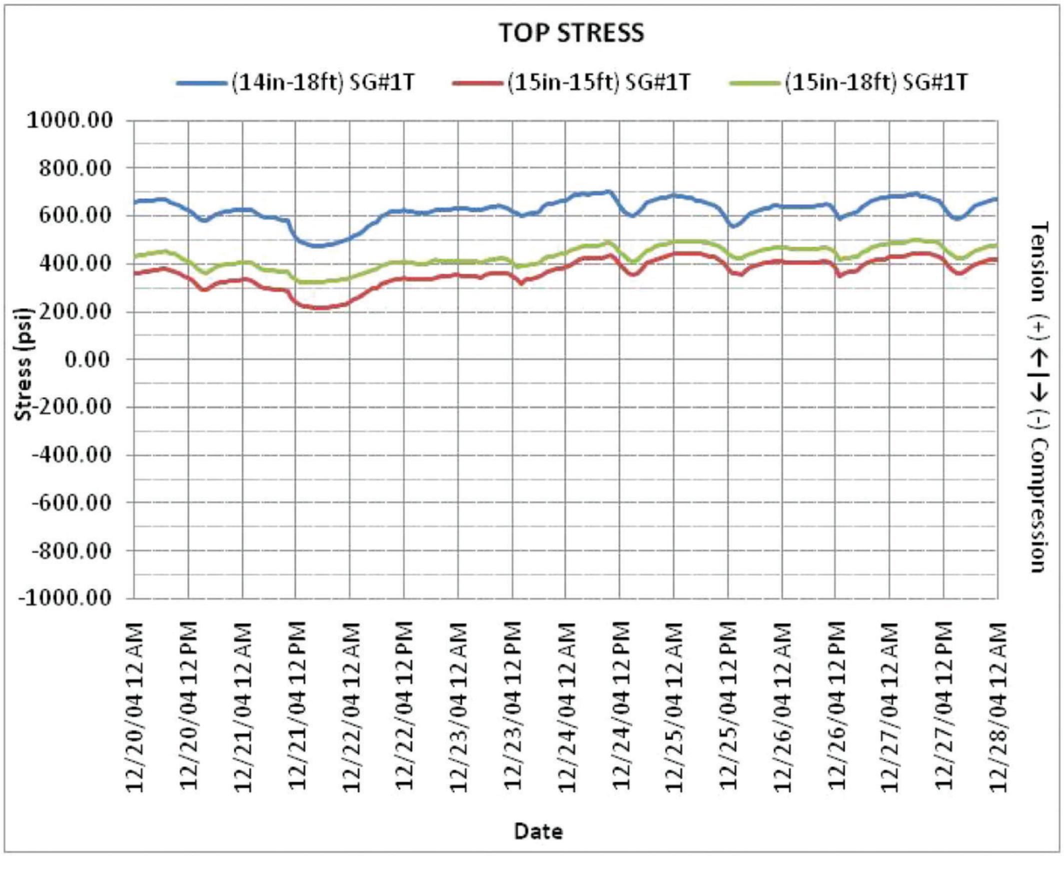


Figure 4.41 Stresses on the top of the slab, typical winter season

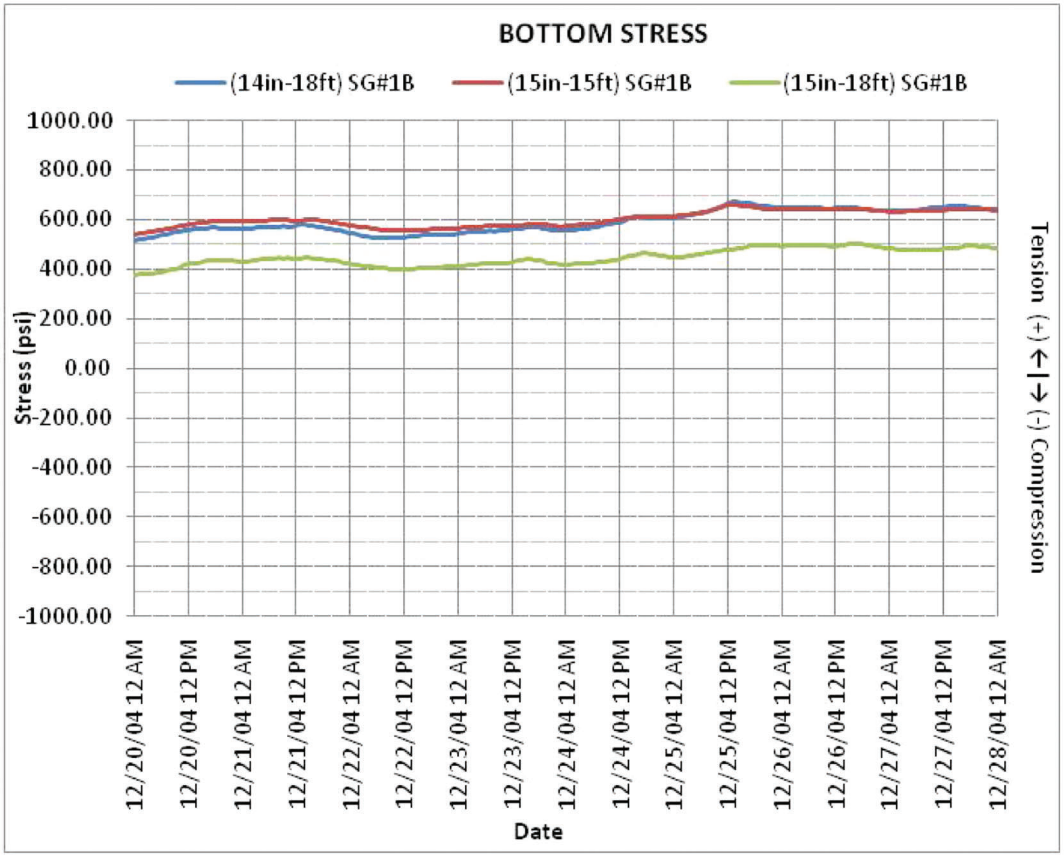


Figure 4.42 Stresses on the bottom of the slab, typical winter season

Figures 4.41 also shows that the 15-inch thick slabs had lower stresses than the 14-inch slabs due to the fact that the moment of inertia in the thicker slabs was higher than in the thinner slabs, that is, it was harder to bend a thicker slab than a thinner one.

Figures 4.43 and 4.44 show stresses in the slabs in a typical late spring/early summer season when the air temperature swings are greatest. During late spring and early summer, the slabs experienced curling up and curling down based on changes in air temperature. Figure 4.43 shows that the longer slabs (with 14-inch thickness and 18-foot joint spacing, and 15-inch thickness and 18-foot joint spacing) were mostly curling up and only slightly curling down in the afternoon just past noon. At night, those longer slabs curled up. However, for the shorter slab (with 15-inch thickness and 15-foot joint spacing), the slab curled down when the air temperature was warm, and it curled up when there was a cooler air temperature on the surface.

Figure 4.44 shows the stress at the bottom portion of the slabs. As in the winter season, the temperature in the bottom half of the slabs was almost constant, unless there was a sudden change in air temperature. Since the moisture at the bottom of the slab was higher than it was at the top, the bottom of the slab experienced tension instead of compression. To truly analyze the effect of curling, the maximum stresses need to be determined.

Figure 4.45 shows the maximum and minimum stresses on the top portions of the three experimental slabs. The left side of the slabs, which were connected to the passing lane, on average, the stresses along that edge of the slabs with shorter joint spacing (with 15-inch thickness and 15-foot joint spacing) are smaller. Therefore, the slab with a shorter joint spacing experienced lower tensile stresses in the curling-up condition.

The same phenomenon occurred in the transverse direction at the edge of the slab where the dowel bars were located. Except for the right sides of the slabs, which were tied to the pavement shoulder, on average, the shorter slabs experienced lower stresses compared to the longer joint slabs. The differences in stresses on the left side (tied to the passing lane) and the right side (tied to the shoulder) is due to the way the slabs were placed (without a shoulder) during construction; the pavement shoulders were placed later on. With the imbalance between the weight of the passing lane and the weight of the shoulder and the absence of shoulder during construction, the slabs have different constraints to the built-in curling. The minimum stresses (curling down, compressive stresses) follow that pattern for the stresses as in the maximum stresses, the responses in the left side and right side are different.

Figure 4.46 shows the maximum and minimum stresses on the bottom portions of the slabs. In general,

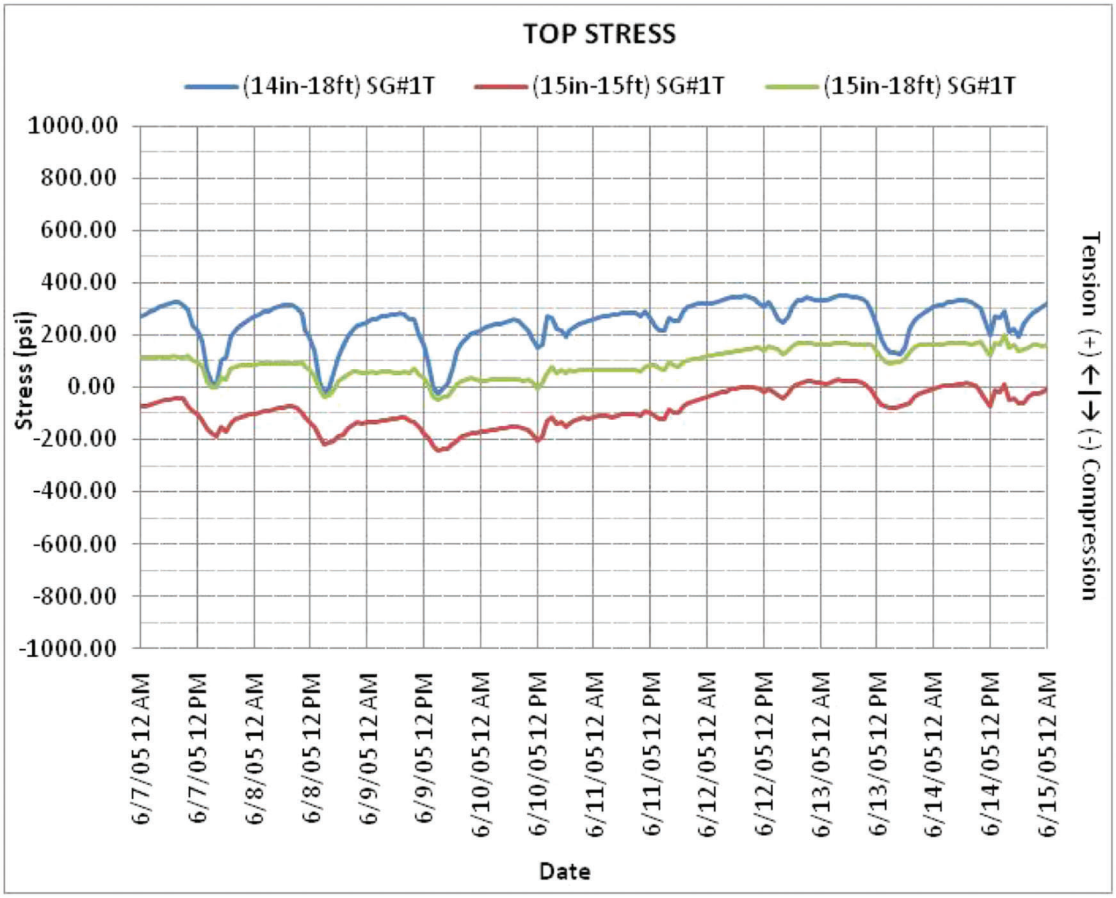


Figure 4.43 Stresses on the top of the slab, typical spring season

the stresses along the perimeters of the slabs favored shorter joint spacing. On average, shorter joint spacing experienced lower stresses in the curling-up condition. However, in general, slabs with longer, thinner joint spacing (e.g., 14-inch thickness and 18-foot joint spacing) had lower minimum stresses (curling down, compressive stresses).

4.5. Concrete Slab Rotation Analysis

Figures 4.47 and 4.48 show the tilting of Slab A (with 15-inch thickness and 15-foot joint spacing) during the winter and summer seasons according to the tiltmeter data on the left corner of the slab in the longitudinal direction, and reveal a small angle of rotation on the left corner of the slab. During the winter season, the slab seems to be continuously curled up. The data from the tiltmeters conforms to the data from the strain gages. During the summer season, the diurnal curling is more pronounced, as seen in Figure 4.48.

Figures 4.49 and 4.50 show the tilting of Slab A during the winter and summer seasons in the left corner of the slab in the transverse direction. The same phenomena occurred in the longitudinal direction. The rotations were extremely small. However, the tilting in this transverse direction was smaller than in the longitudinal direction due to the dimension of the slab (i.e., the width of the slab was shorter than the length of the slab).

Figures 4.51 and 4.52 show the tilting of the Slab A in the right corner in the longitudinal direction during the winter and summer seasons. Once again, the summer season shows a more pronounced diurnal curling. This right corner area shows slightly more rotations than the left corner area of the slab because the right corner was tied to the pavement shoulder while the left was tied to the passing lane pavement.

Figures 4.53 and 4.54 show the tilting of the slab on the right corner in the transverse direction. In general, the rotations in this transverse right corner were almost identical to those on the left side.

Figures 4.55 and 4.56 show the tilting of Slab B (with 15-inch thickness and 18-foot joint spacing) in the longitudinal direction on the left corner in typical winter and summer seasons. As already predicted in the strain gage data, Slab B has less deflection due to self-weight, which will counter the curling. As a result, the rotation for this longer slab was less than that for the shorter one. As with the shorter slab (Slab A), the diurnal curling was more pronounced during the summer season.

Figures 4.57 and 4.58 show the tilting of Slab B in the transverse direction on the left corner, and illustrate that diurnal curling was more pronounced in the

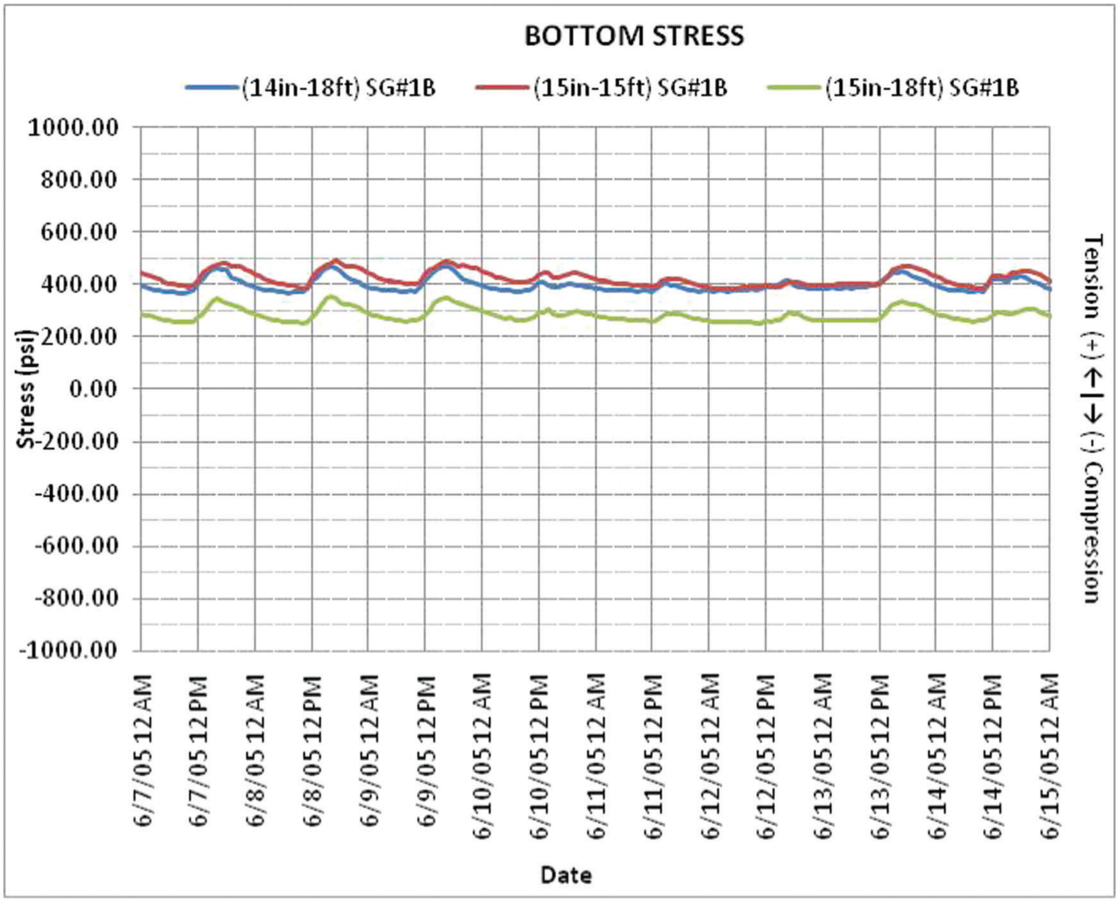


Figure 4.44 Stresses on the bottom of the slab, typical spring season

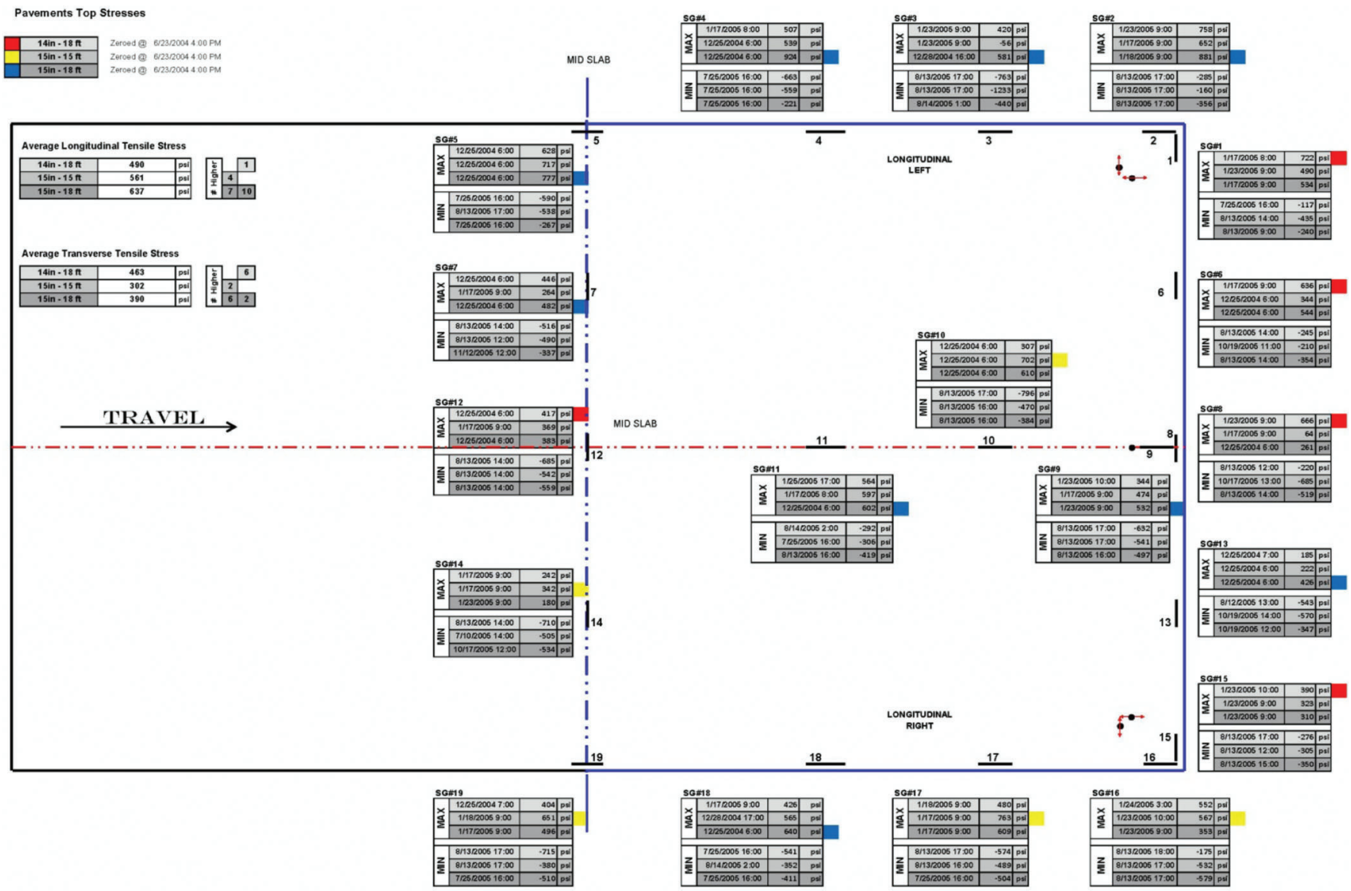
summer than in the winter season. The up and down pattern in Figure 4.58 shows almost to the "true" diurnal curling, curling-up and curling-down following the diurnal air temperature.

Figures 4.59 and 4.60 show the tilting of the Slab Bin the longitudinal direction on the right corner. The rotations were slightly more pronounced in this right corner because the right side was tied to the pavement shoulder, which also occurred in the shorter slab during the Winter season; that is, there was no significant diurnal curling occurred in the slabs.

Figures 4.61 and 4.62 show the tilting of Slab B on the right corner in the transverse direction. Compared to the left corner, the peak of the rotations was almost identical, but the left corner had more pronounced diurnal curling. Once again, this was because the right side was connected to the pavement shoulder instead of a traffic lane. In addition, the pavement shoulder was placed later in construction; therefore, the curling profile of the slab was slightly different. Nevertheless, this construction sequence was chosen because it was the most likely sequence to occur in multi-lane pavement constructions.

Data and rotations from the tiltmeters provided information about the behavior of the slabs regarding seasonal and diurnal curling. However, similar to the deflection information from the strain gages, information the from tiltmeters needed to be incorporated with the stress analysis of the slabs. Higher deflections in the concrete slab did not always mean higher stresses. Likewise, lower deflections in the slabs did not always mean lower stresses. Boundary conditions also affected the slabs.

In the case of transverse joints with dowel bars as thick and as closer apart (with a 1.5-inch diameter dowel bar and 12-inch spacing) compared to the concrete pavement without dowel bars, looking only to the deflections on the surface of the slab will not yield correct information about the state of stress in the slabs. Lower surface deflections in this study will mean higher stress concentrations around the jointed transverse edges of slabs. In the longitudinal joints, the slabs are tied with 0.7-inch deformed steel bars with a spacing of two feet. Therefore, the restraint from the tie bars was significantly lower than that of the dowel bars, which would account for the lack of significant differences in the deflections and tilting of the slabs in transverse directions. The widths of the slabs were also the same.



Pavements Top Stresses

🟥	14in - 18 ft	Zeroed @ 6/23/2004 4:00 PM
🟨	15in - 15 ft	Zeroed @ 6/23/2004 4:00 PM
🟦	15in - 18 ft	Zeroed @ 6/23/2004 4:00 PM

Average Longitudinal Tensile Stress

14in - 18 ft	490	psi
15in - 15 ft	561	psi
15in - 18 ft	637	psi

# Higher		1
	4	
	7	10

Average Transverse Tensile Stress

14in - 18 ft	463	psi
15in - 15 ft	302	psi
15in - 18 ft	390	psi

# Higher		6
	2	
	6	2

SG#4

MAX	1/17/2005 8:00	507	psi	
	12/25/2004 6:00	539	psi	
	12/25/2004 6:00	924	psi	🟦
MIN	7/25/2005 16:00	-663	psi	
	7/25/2005 16:00	-559	psi	
	7/25/2005 16:00	-221	psi	

SG#3

MAX	1/23/2005 9:00	420	psi	
	1/23/2005 9:00	-56	psi	
	12/28/2004 16:00	581	psi	🟦
MIN	8/13/2005 17:00	-763	psi	
	8/13/2005 17:00	-1233	psi	
	8/14/2005 1:00	-440	psi	

SG#2

MAX	1/23/2005 9:00	758	psi	
	1/17/2005 9:00	652	psi	
	1/18/2005 9:00	881	psi	🟦
MIN	8/13/2005 17:00	-285	psi	
	8/13/2005 17:00	-160	psi	
	8/13/2005 17:00	-356	psi	

SG#5

MAX	12/25/2004 6:00	628	psi	
	12/25/2004 6:00	717	psi	
	12/25/2004 6:00	777	psi	🟦
MIN	7/25/2005 16:00	-590	psi	
	8/13/2005 17:00	-538	psi	
	7/25/2005 16:00	-267	psi	

SG#1

MAX	1/17/2005 8:00	722	psi	🟥
	1/23/2005 9:00	490	psi	
	1/17/2005 9:00	534	psi	
MIN	7/25/2005 16:00	-117	psi	
	8/13/2005 14:00	-435	psi	
	8/13/2005 9:00	-240	psi	

SG#7

MAX	12/25/2004 6:00	446	psi	
	1/17/2005 9:00	264	psi	
	12/25/2004 6:00	482	psi	🟦
MIN	8/13/2005 14:00	-516	psi	
	8/13/2005 12:00	-490	psi	
	11/12/2005 12:00	-337	psi	

SG#6

MAX	1/17/2005 9:00	636	psi	🟥
	12/25/2004 6:00	344	psi	
	12/25/2004 6:00	544	psi	
MIN	8/13/2005 14:00	-245	psi	
	10/19/2005 11:00	-210	psi	
	8/13/2005 14:00	-354	psi	

SG#10

MAX	12/25/2004 6:00	307	psi	
	12/25/2004 6:00	702	psi	🟨
	12/25/2004 6:00	610	psi	
MIN	8/13/2005 17:00	-796	psi	
	8/13/2005 16:00	-470	psi	
	8/13/2005 16:00	-384	psi	

SG#12

MAX	12/25/2004 6:00	417	psi	🟥
	1/17/2005 9:00	369	psi	
	12/25/2004 6:00	383	psi	
MIN	8/13/2005 14:00	-685	psi	
	8/13/2005 14:00	-542	psi	
	8/13/2005 14:00	-559	psi	

SG#8

MAX	1/23/2005 9:00	666	psi	🟥
	1/17/2005 9:00	64	psi	
	12/25/2004 6:00	261	psi	
MIN	8/13/2005 12:00	-220	psi	
	10/17/2005 13:00	-685	psi	
	8/13/2005 14:00	-519	psi	

SG#11

MAX	1/25/2005 17:00	564	psi	
	1/17/2005 8:00	597	psi	
	12/25/2004 6:00	602	psi	🟦
MIN	8/14/2005 2:00	-292	psi	
	7/25/2005 16:00	-306	psi	
	8/13/2005 16:00	-419	psi	

SG#9

MAX	1/23/2005 10:00	344	psi	
	1/17/2005 9:00	474	psi	
	1/23/2005 9:00	532	psi	🟦
MIN	8/13/2005 17:00	-632	psi	
	8/13/2005 17:00	-541	psi	
	8/13/2005 16:00	-497	psi	

SG#14

MAX	1/17/2005 9:00	242	psi	
	1/17/2005 9:00	342	psi	🟨
	1/23/2005 9:00	180	psi	
MIN	8/13/2005 14:00	-710	psi	
	7/10/2005 14:00	-505	psi	
	10/17/2005 12:00	-534	psi	

SG#13

MAX	12/25/2004 7:00	185	psi	
	12/25/2004 6:00	222	psi	
	12/25/2004 6:00	426	psi	🟦
MIN	8/12/2005 13:00	-543	psi	
	10/19/2005 14:00	-570	psi	
	10/19/2005 12:00	-347	psi	

SG#15

MAX	1/23/2005 10:00	390	psi	🟥
	1/23/2005 9:00	323	psi	
	1/23/2005 9:00	310	psi	
MIN	8/13/2005 17:00	-276	psi	
	8/13/2005 12:00	-305	psi	
	8/13/2005 15:00	-350	psi	

SG#19

MAX	12/25/2004 7:00	404	psi	
	1/18/2005 9:00	651	psi	🟨
	1/17/2005 9:00	496	psi	
MIN	8/13/2005 17:00	-715	psi	
	8/13/2005 17:00	-380	psi	
	7/25/2005 16:00	-510	psi	

SG#18

MAX	1/17/2005 9:00	426	psi	
	12/28/2004 17:00	565	psi	
	12/25/2004 6:00	640	psi	🟦
MIN	7/25/2005 16:00	-541	psi	
	8/14/2005 2:00	-352	psi	
	7/25/2005 16:00	-411	psi	

SG#17

MAX	1/18/2005 9:00	480	psi	
	1/17/2005 9:00	763	psi	🟨
	1/17/2005 9:00	609	psi	
MIN	8/13/2005 17:00	-574	psi	
	8/13/2005 16:00	-489	psi	
	7/25/2005 16:00	-504	psi	

SG#16

MAX	1/24/2005 3:00	552	psi	
	1/23/2005 10:00	567	psi	🟨
	1/23/2005 9:00	353	psi	
MIN	8/13/2005 18:00	-175	psi	
	8/13/2005 17:00	-532	psi	
	8/13/2005 17:00	-579	psi	

Figure 4.45 Maximum and minimum stresses on the top portions of slabs

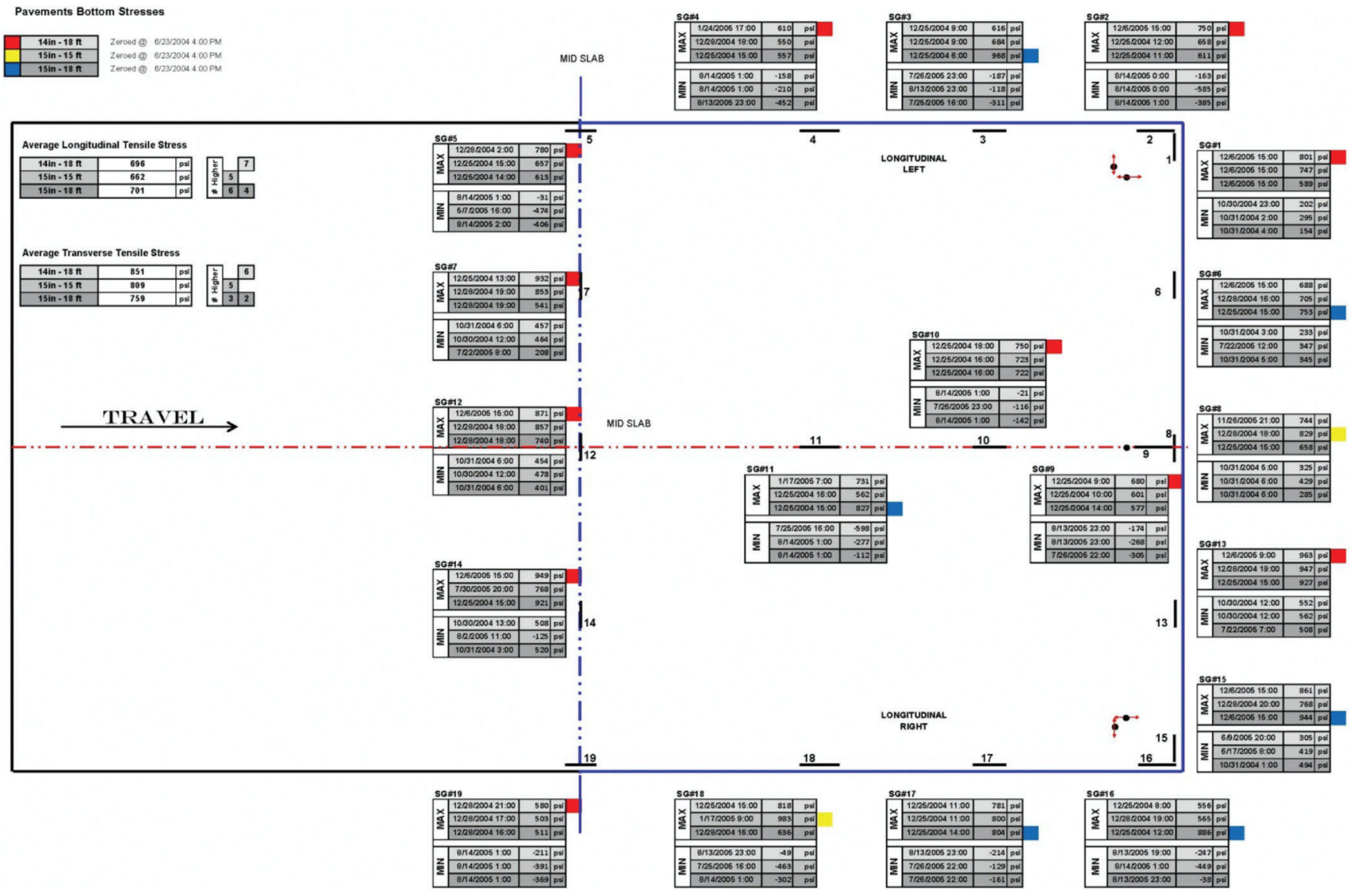


Figure 4.46 Maximum and minimum stresses on the bottom portions of slabs

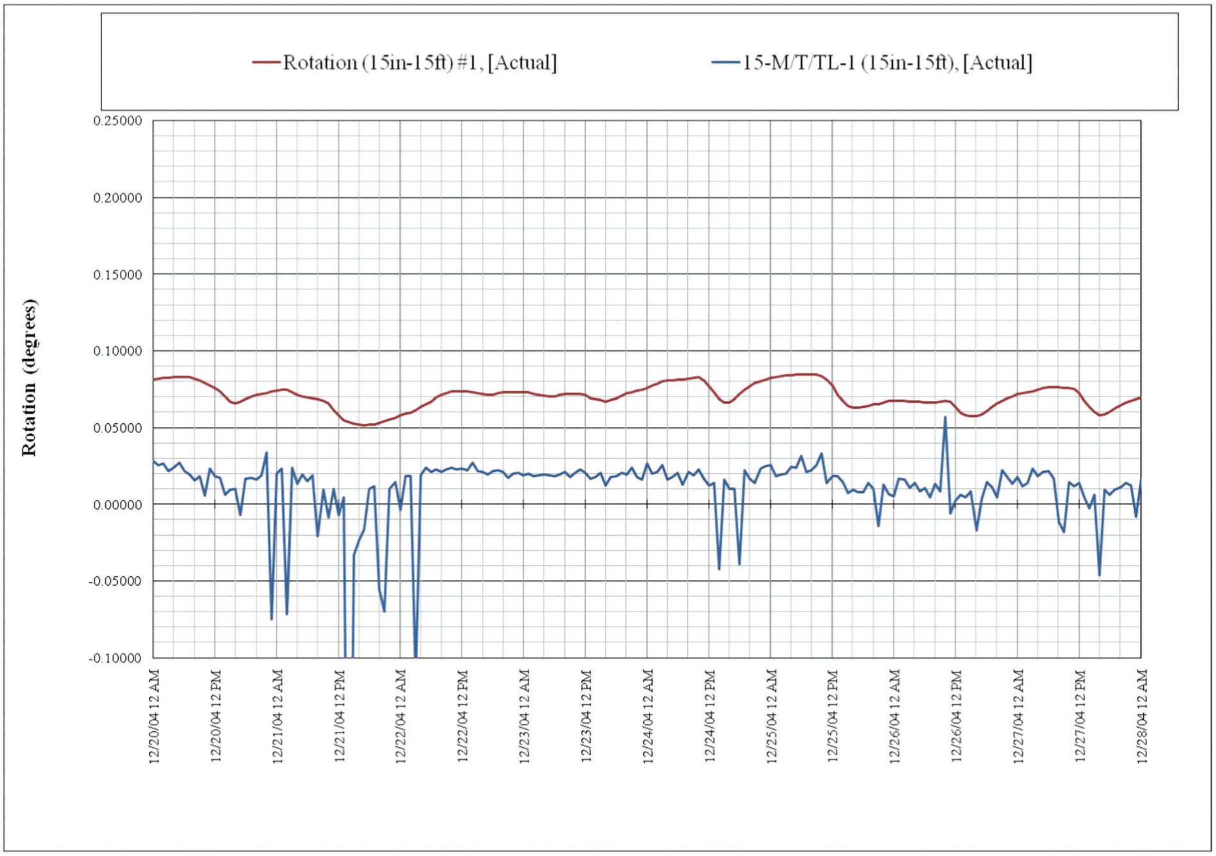


Figure 4.47 Tilting of Slab A on longitudinal left corner, typical winter

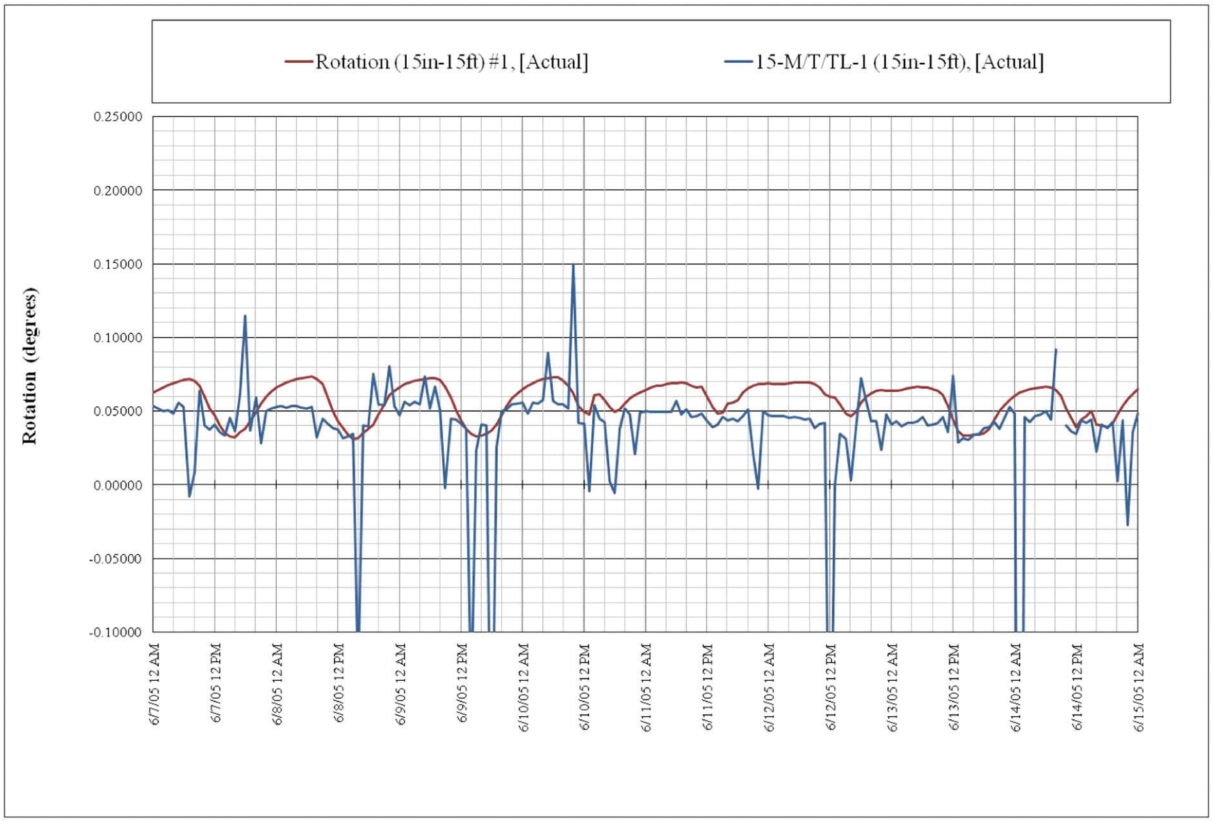


Figure 4.48 Tilting of Slab A on longitudinal left corner, typical summer

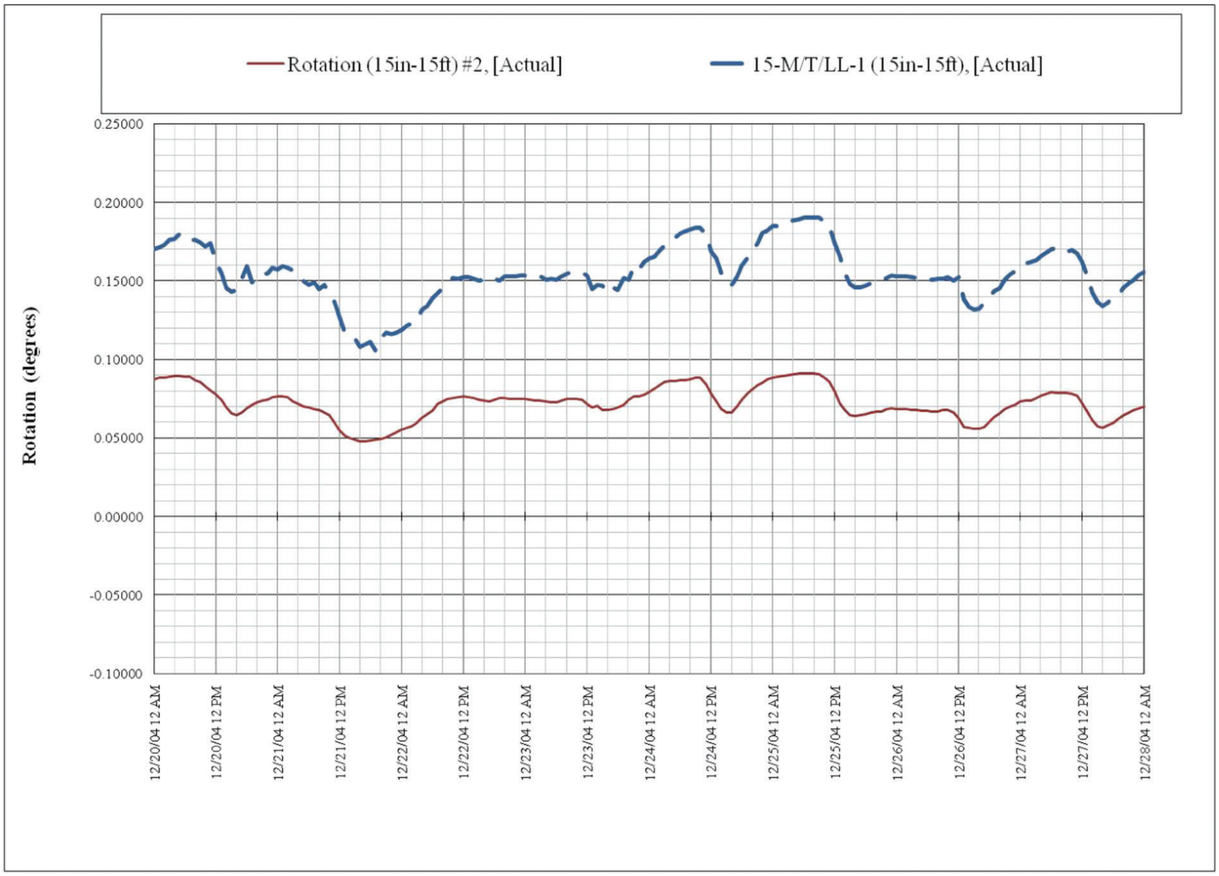


Figure 4.49 Tilting of Slab A on transverse left corner, typical winter

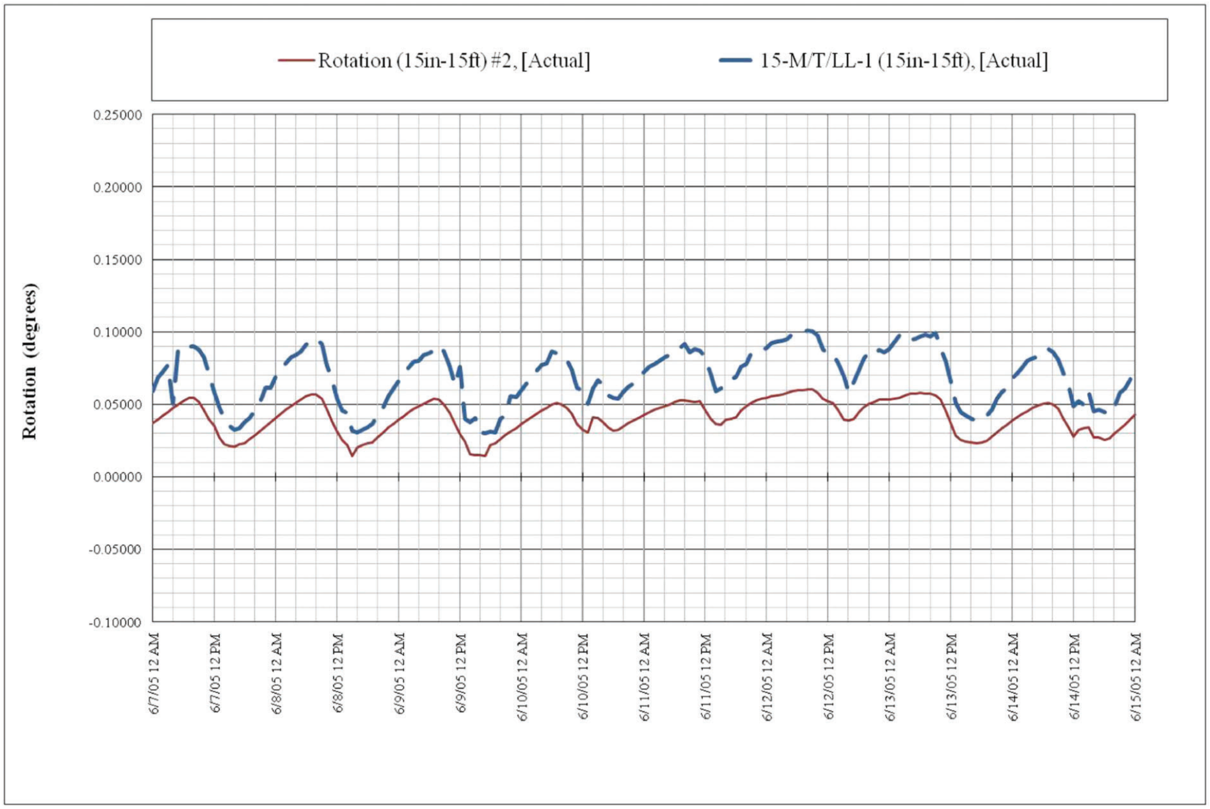


Figure 4.50 Tilting of Slab A on transverse left corner, typical summer

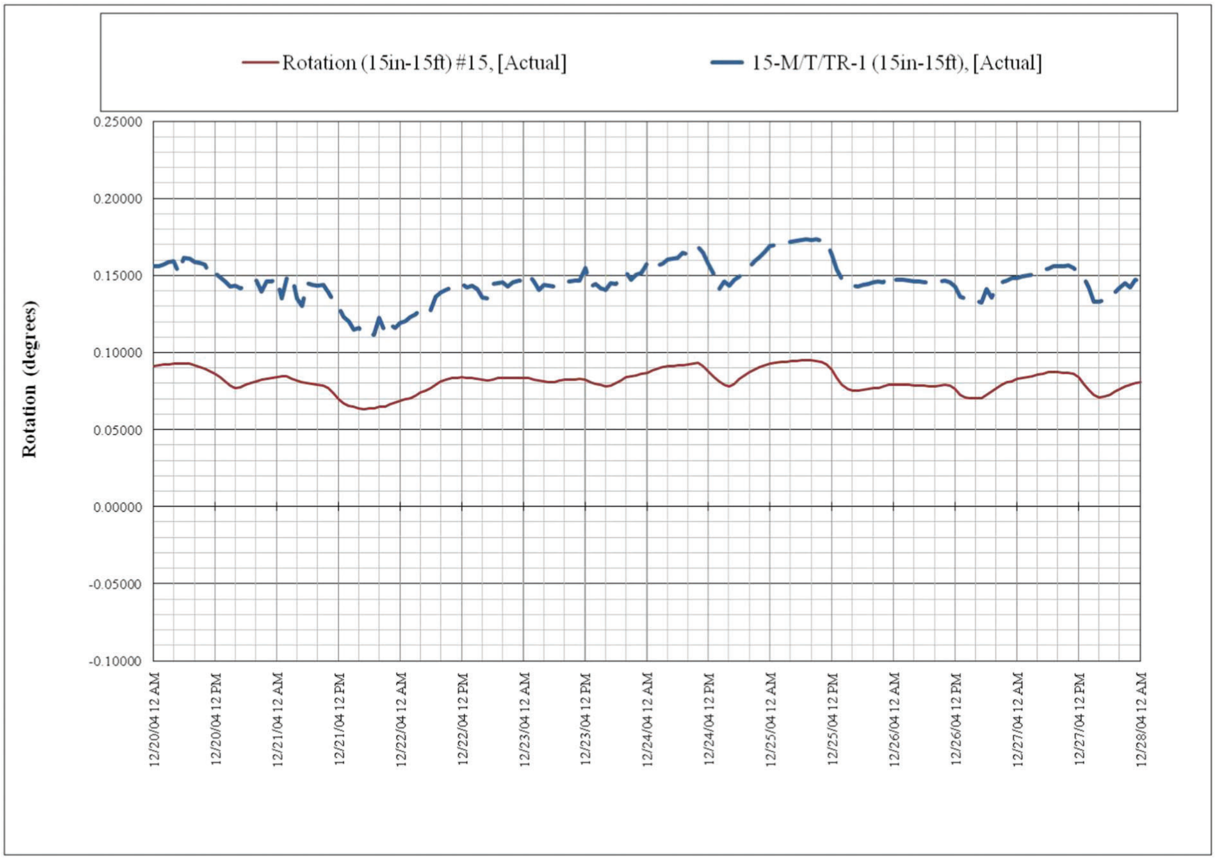


Figure 4.51 Tilting of Slab A on longitudinal right corner, typical winter

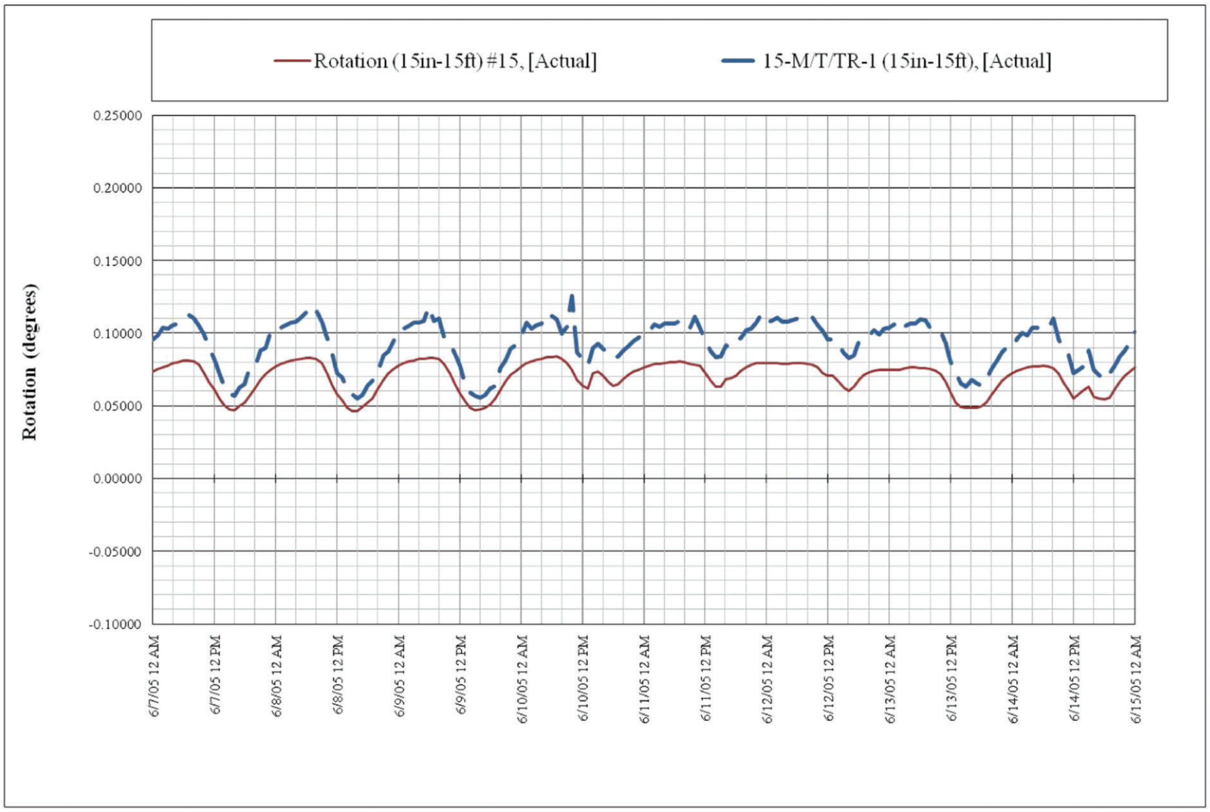


Figure 4.52 Tilting of Slab A on longitudinal right corner, typical summer

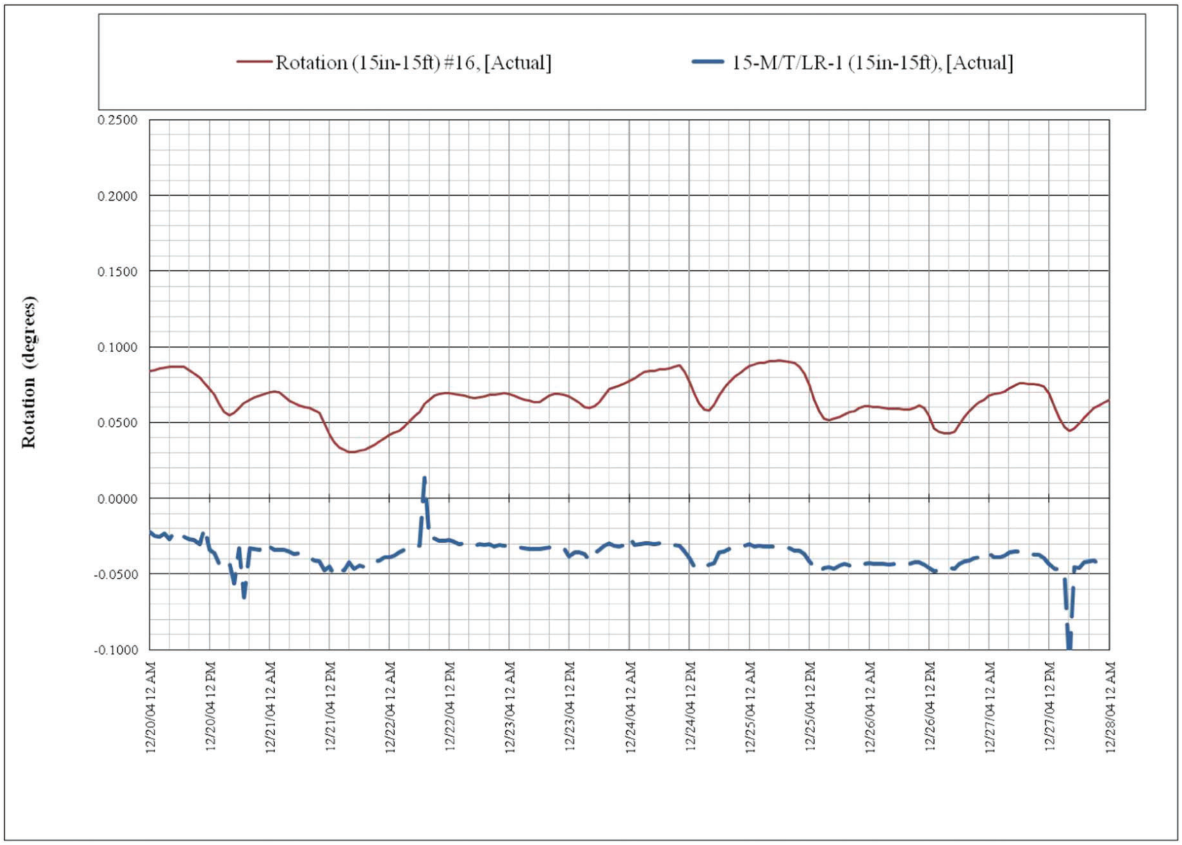


Figure 4.53 Tilting of Slab A on transverse right corner, typical winter

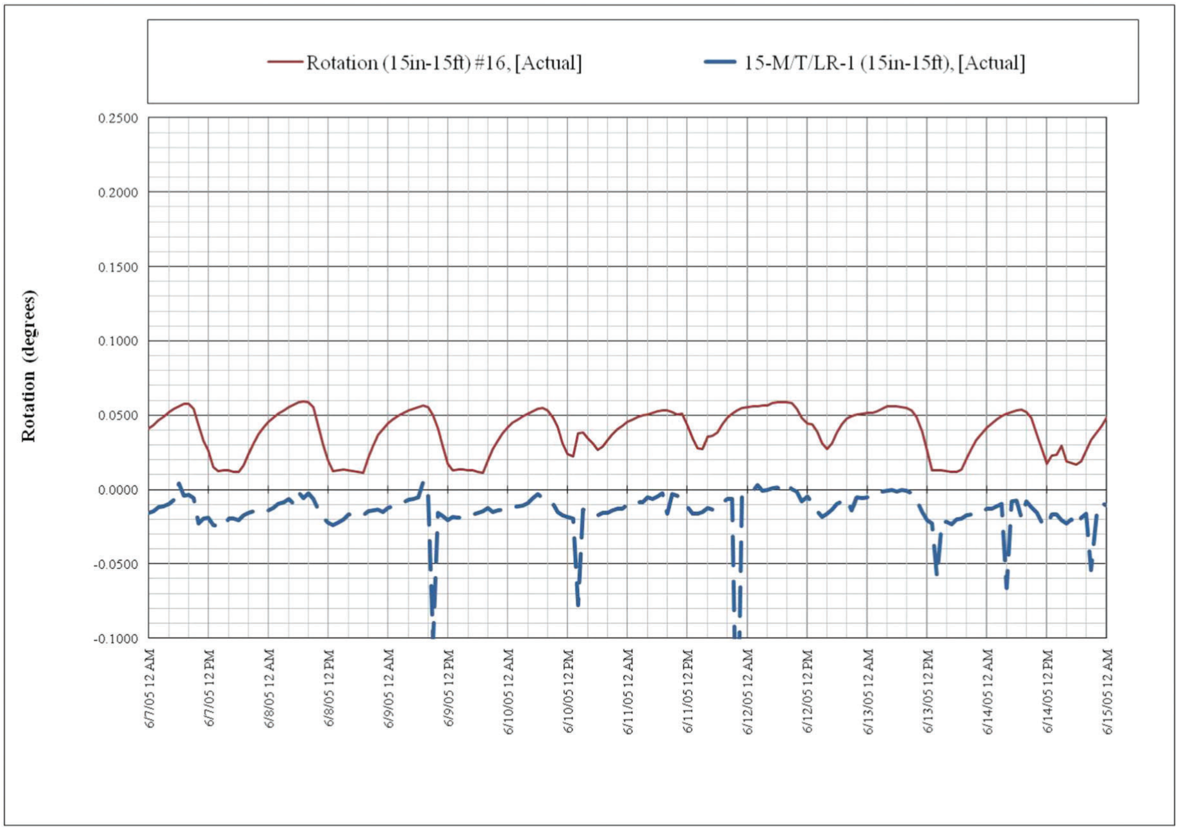


Figure 4.54 Tilting of Slab A on transverse right corner, typical summer

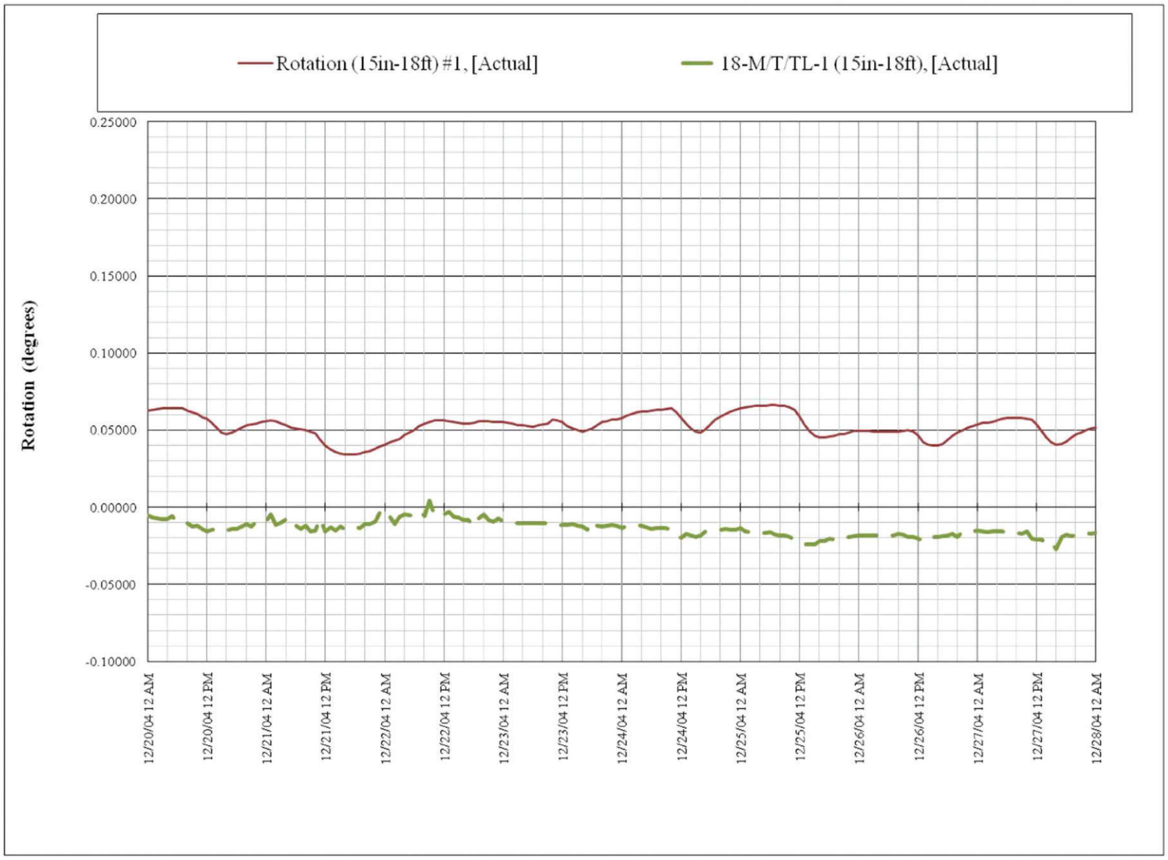


Figure 4.55 Tilting of Slab B on longitudinal left corner, typical winter

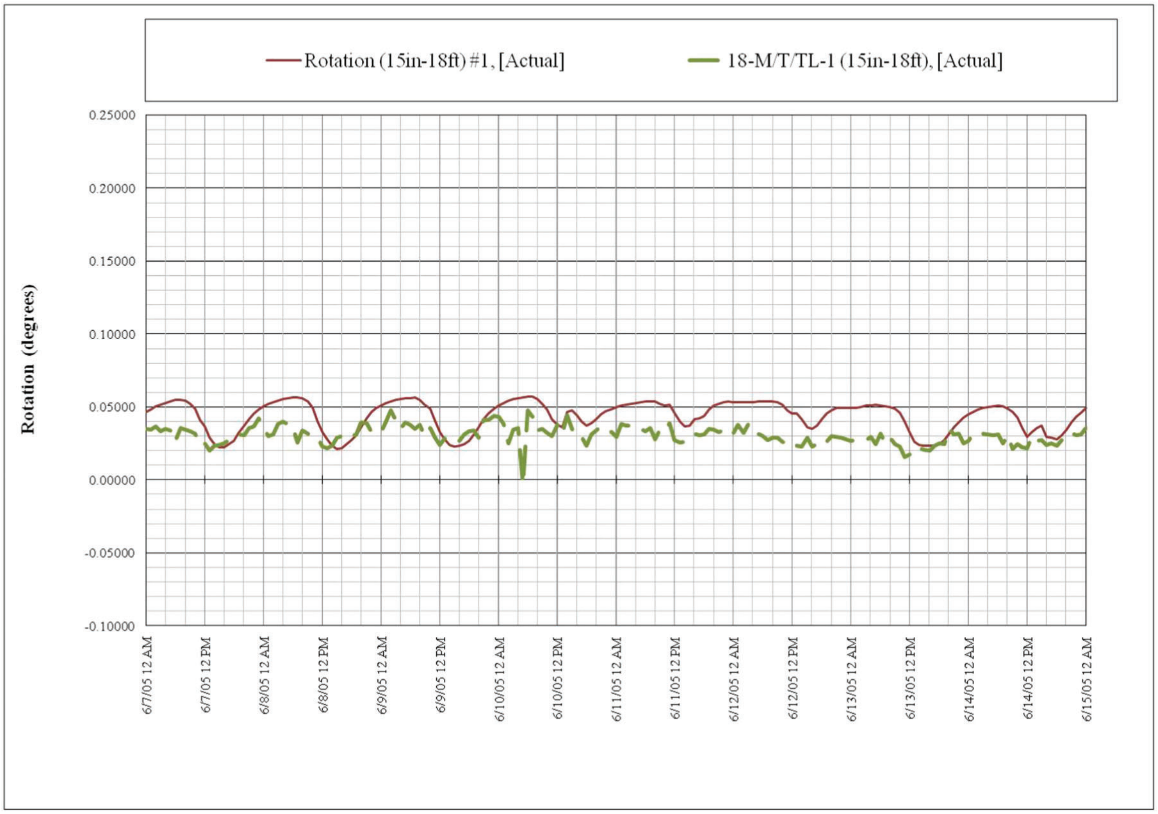


Figure 4.56 Tilting of Slab B on longitudinal left corner, typical summer

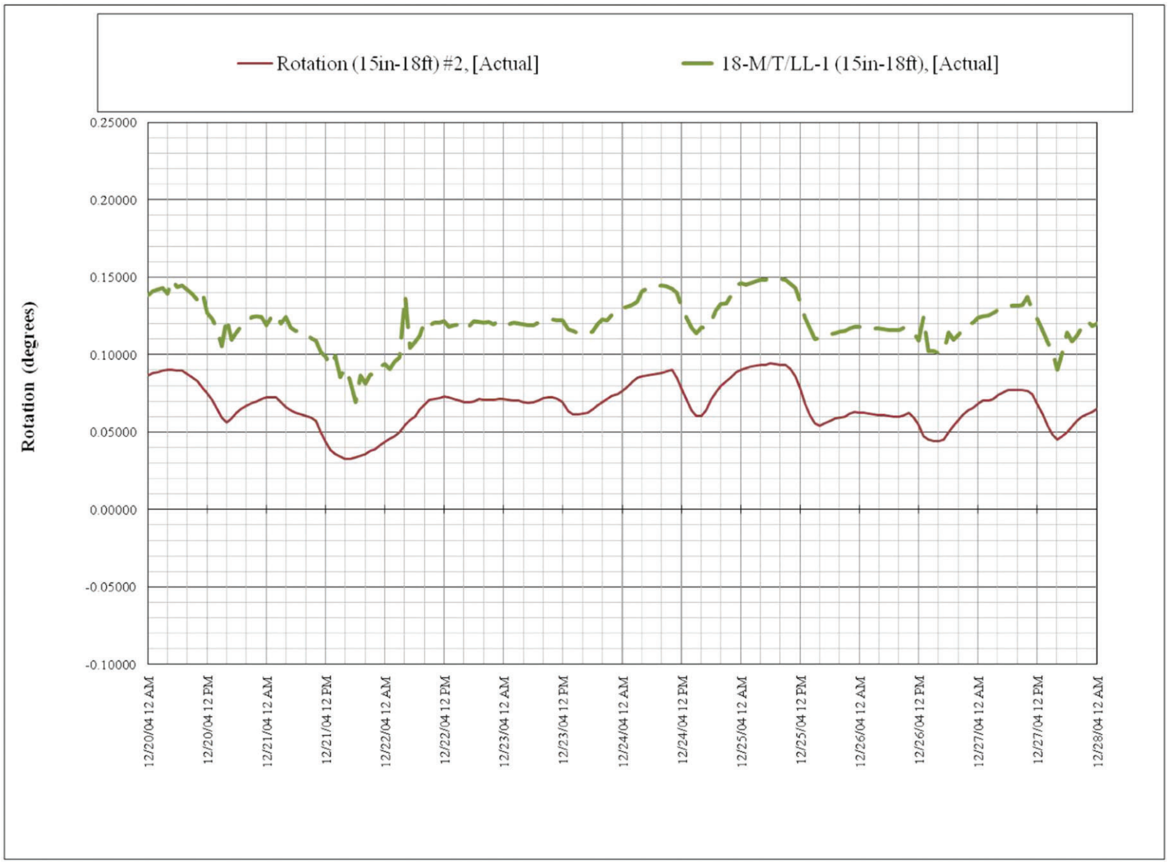


Figure 4.57 Tilting of Slab B on transverse left corner, typical winter

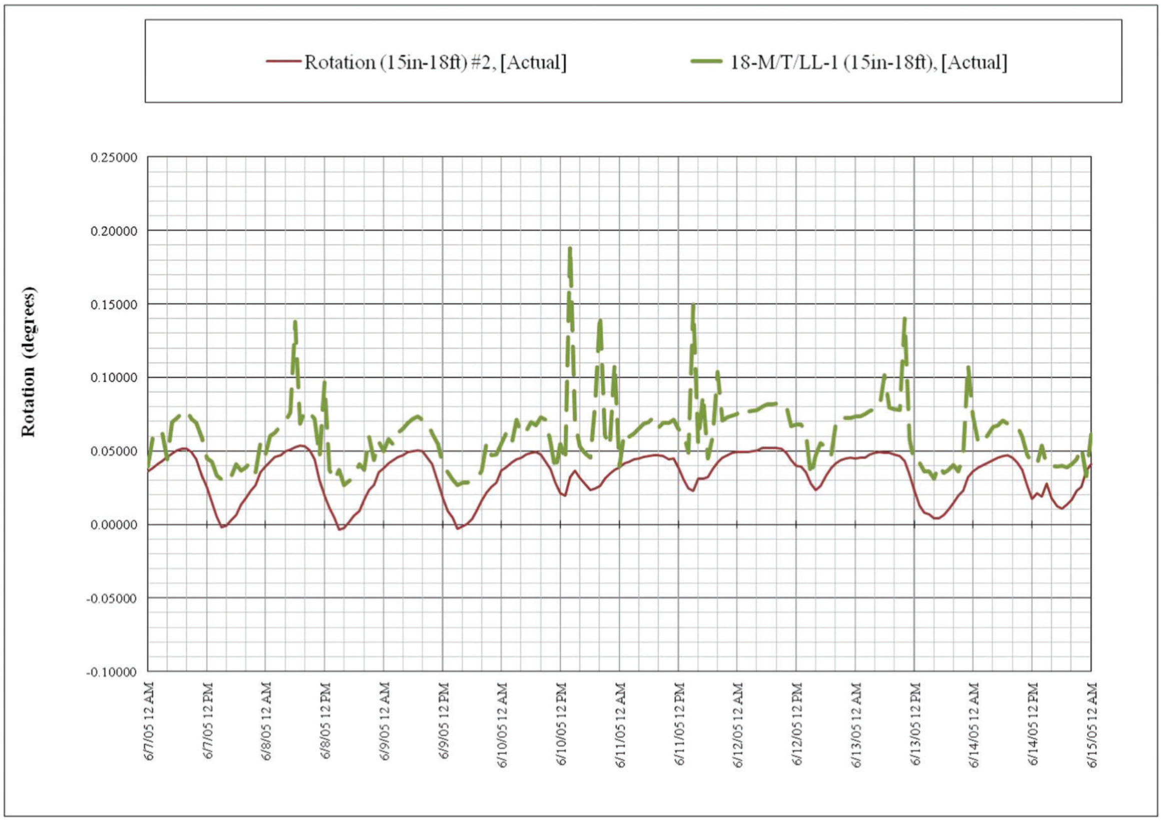


Figure 4.58 Tilting of Slab B on transverse left corner, typical summer

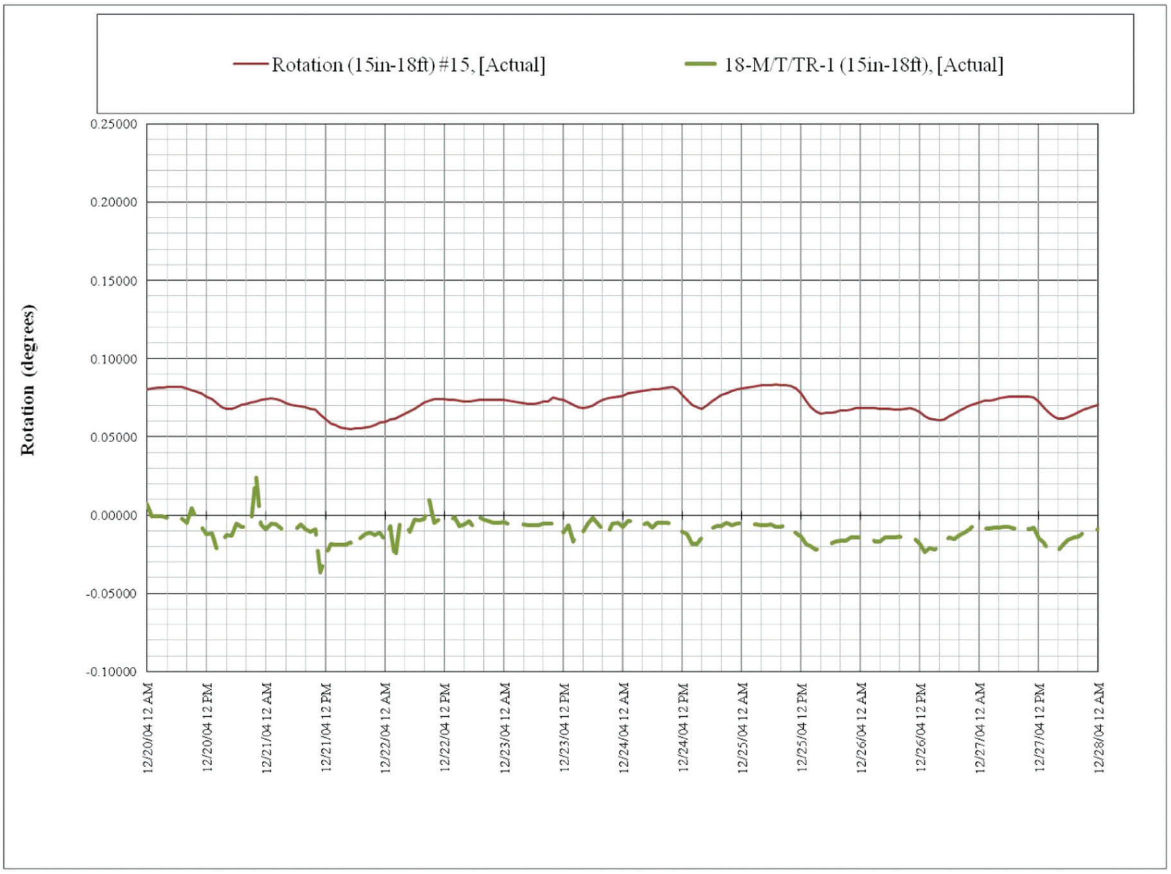


Figure 4.59 Tilting of Slab B on longitudinal right corner, typical winter

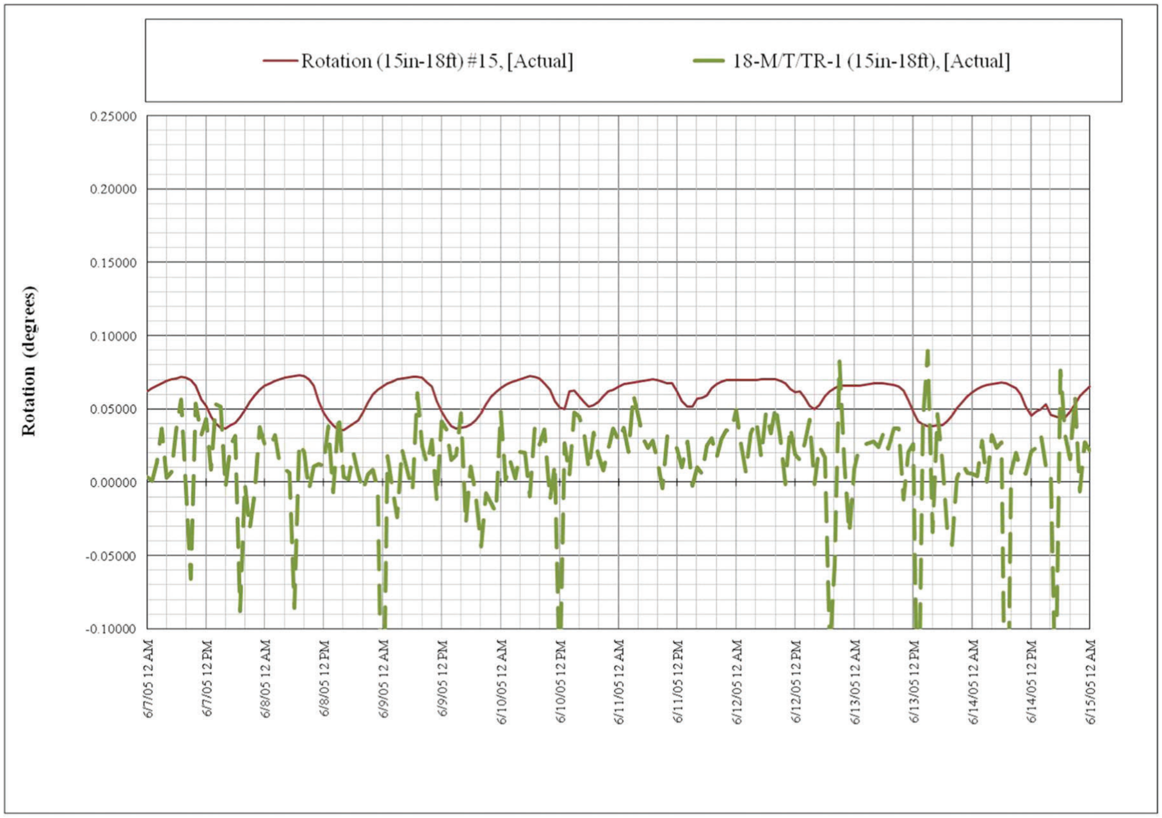


Figure 4.60 Tilting of Slab B on longitudinal right corner, typical summer

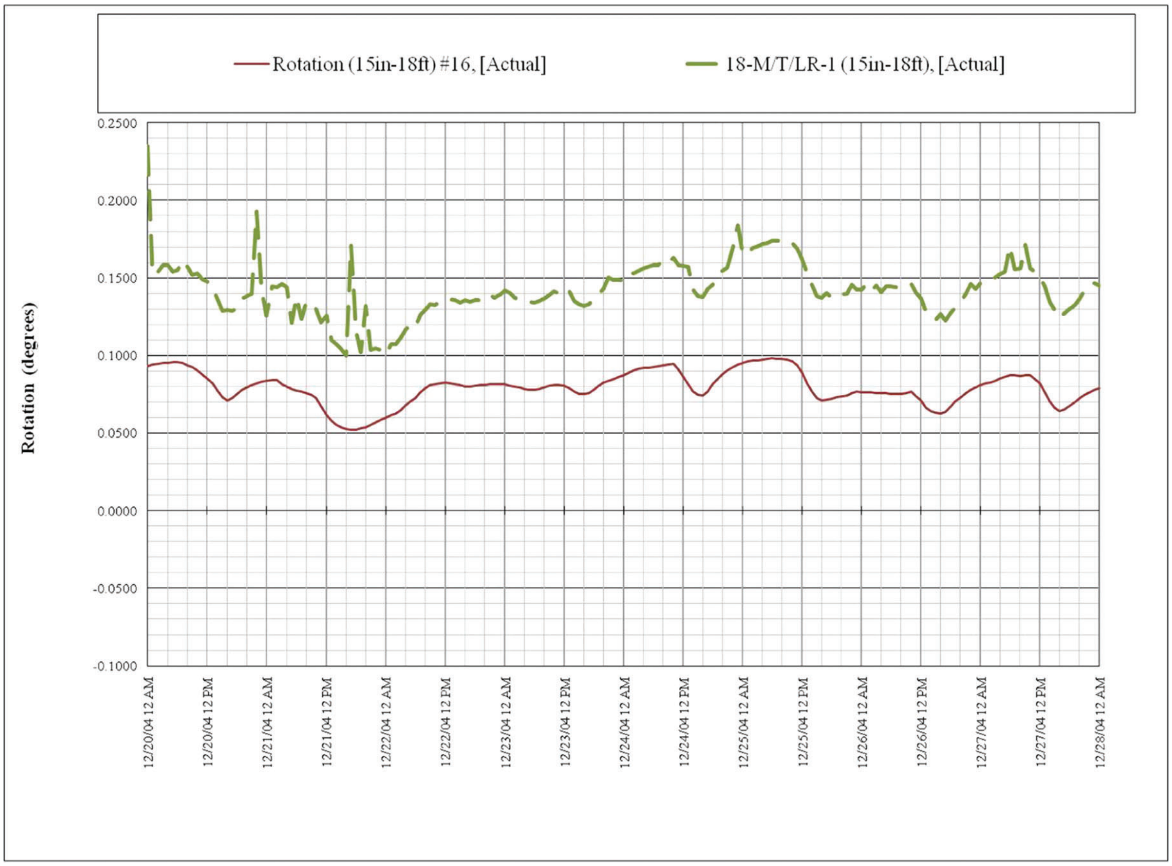


Figure 4.61 Tilting of Slab B on transverse right corner, typical winter

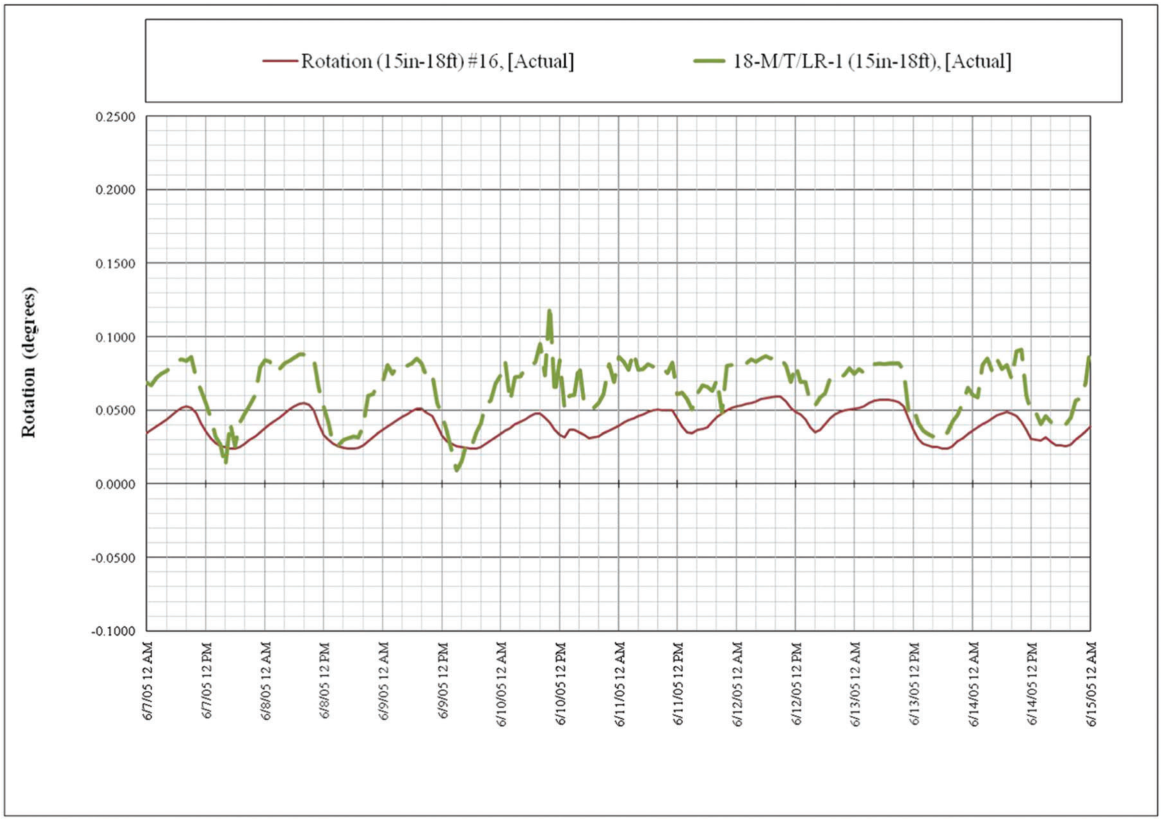


Figure 4.62 Tilting of Slab B on transverse right corner, typical summer

CHAPTER 5 CONCLUSIONS AND IMPLEMENTATION

The study of concrete pavement behavior in response to surrounding climate conditions is extremely complicated. Not only does concrete pavement respond differently to temperature and moisture, but concrete itself experiences shrinkage and creep throughout its life, starting just after construction. The response parameters of shrinkage and creep in concrete slabs are difficult to dissociate from the total responses of a concrete to temperature and moisture.

Equipment is also a significant issue in conducting an experiment to measure the responses of concrete to climate. In 2005, although the measurement technology was already advanced, the sensors and equipment were not up to the challenge of the field environment. Current advancements in measurement technology, especially sensors and data acquisition systems, will make recording more accurate measurements in the field easier and more achievable. In turn, this will help determine the responses of concrete pavement to the environment.

Previous studies that incorporated only deflection of the slabs to a reference position cannot describe the total responses of concrete to temperature and moisture. Rather, they are only an indication of the existence of curling in slabs, whether curling up or curling down. For this reason, the study of responses of concrete to the environment should examine more than just deflection of the slabs.

In this experimental study, several important conclusions were drawn from temperature analysis, stress-strain analysis, and tiltmeter data analysis. The following are the most important conclusions drawn from this study.

5.1. Conclusions from the Temperature Data Analysis

1. The temperature profile in concrete, inch by inch, depends only on seasonal changes in temperature. Unless there is a sudden and drastic change in the air temperature, the temperature profile in concrete pavement is almost constant.
2. The diurnal changes in air temperature influence the temperature profile of a concrete slab only about halfway through the thickness of the concrete pavement. Unless there is a sudden and drastic change in temperature, for example, more than 20 degrees Fahrenheit, the temperature difference between the middle and the bottom portion of the slab is negligible.
3. The temperature profile of concrete's responses for diurnal temperature changes is not a linear profile from bottom to top as was previously assumed. Rather, it is an exponential form with a drastic change toward the surface of the concrete pavement.
4. Drastic changes in temperature in the concrete slab occur mostly during the winter and late spring or early summer seasons. These drastic changes in temperature will determine the maximum and minimum stresses in concrete pavement. This phenomenon is supported by the stress and strain analysis later in this chapter.
5. The temperature differential for calculation of the curling model in the Mechanistic Empirical Pavement Design Guide needs to be adjusted to the more accurate temperature profile from this experiment.

5.2. Conclusions from the Deflection, Stress Analyses, and Rotation of the Slabs

1. Built-in curling did occur as predicted by previous researchers. However, the magnitude of the built-in curling was difficult to predict due to the reference point of the dimensions of the slab and other parameters that influenced the measurements in the slabs.
2. Deflections on the surface of the concrete slabs do not give any indication of the state of stress in the concrete slabs.
3. The state of stress due to temperature curling in the concrete slabs depends significantly on the boundary conditions of the edges of the slabs, the thickness of the slab (self-weight), the moment of inertia of the slabs, and shrinkage and expansion of concrete due to moisture.
4. The maximum and minimum stresses in concrete slabs occurred when there was a drastic, sudden change in the air temperature. Slabs with built-in upward curling tended to have greater maximum stress when the air temperature suddenly changed from warm to cold, especially in the late fall or early winter seasons. Slabs with built-in downward curling tended to have greater minimum stress when the air temperature suddenly changed from cold to hot, especially in the late spring season.
5. Extreme stresses occurred mostly when there was a sudden change in air temperature, resulting in high level of stresses in the slabs. Although diurnal curling occurs, the changes in the values of the concrete diurnal stresses were well under control of the strength of the concrete. Rather, it is extreme changes in air temperature that will generate stresses in excess of the strength of the concrete. Although the occurrence of drastic sudden changes in air temperature is not very common during the year, such stresses can create cracks in concrete slabs.
6. Shorter joint spacing gives an advantage in reducing the stresses in concrete slabs, especially stresses in the longitudinal direction that can influence the occurrence of transverse cracks. Thinner concrete slabs in combination with shorter joint spacing will significantly reduce stresses in slabs.
7. It is impractical to control built-in curling in concrete pavement by attempting to place the fresh concrete in a timely way to avoid the end of the final setting of cement hydration coinciding with the hottest temperature of the day. The more practical concept to reduce built-in curling is to reduce the cement content in the concrete mix as low as possible and/or to include more additives such as fly ash and ground granulated furnace slag in the concrete mix to reduce the temperature of cement hydration. However, the strength should conform to the 28 day strength requirement in the MEPDG design of 700 psi.

5.3. Implementation

1. Propose to the INDOT Pavement Steering Committee that they reduce the thickness of the concrete

pavement as much as possible by maximizing the pavement support layers underneath the concrete pavement layer.

2. Propose to the INDOT Pavement Steering Committee that they adopt shorter joint spacing for concrete pavement in excess of 12 inches in thickness.
3. Propose to the INDOT Portland Cement Concrete Pavement Technical Committee that they support reducing the amount of cement in the concrete mix in order to reduce the temperature of the concrete during the final setting of the cement hydration. However, the concrete strength should be in accordance to the 28 day strength of 700 psi in the INDOT MEPDG requirement.

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