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Simulation of early-age Jointed Plain Concrete Pavement deformation under environmental loading using the Finite Element method

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Keywords

critical periods, environmental loadings, finite element models, jointed plain concrete pavements, linear variable differential transducers, Portland cement concretes, slab deformation, temperature and humidity sensor, soil mechanics

Comments

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Simulation of Early-age Jointed Plain Concrete Pavement Deformation under Environmental Loading Using the Finite Element Method

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Abstract

The objective of this study was to quantify the early-age Portland Cement Concrete (PCC) slab deformations due to pure environmental loading at critical periods immediately following construction. A newly constructed Jointed Plain Concrete Pavement (JPCP) section on highway US-30 near Marshall town, Iowa, USA was instrumented to monitor the pavement response to variations in temperature and moisture during the first seven days after construction in the summer of 2005. Temperature and humidity sensors installed within the test sections monitored the variations in temperature and moisture. The PCC slab deformations were measured using the Linear Variable Differential Transducers (LVDTs) installed at corner, edge, and center of the PCC slab. The surface profiles were measured along the diagonal and transverse directions of the slab using an inclinometer-profiler. The measurements revealed the zero-gradient temperature deformation in the form of slab curling due to built-in temperature difference. Two-dimensional (2-D) and three-dimensional (3-D) Finite Element (FE) models were employed to characterize the zero-gradient temperature deformation. Comparisons between the field-measured and the FE-computed slab deformations are presented in this paper.

INTRODUCTION

The early-age deformations of PCC slab due to pure environmental loading (i.e., without traffic loading) have been noticeable recently (Siddique & Hossain 2005, Rao et al. 2001). It is believed that this early-age slab deformation could result in the loss of pavement smoothness (Siddique & Hossain 2005) and the tensile stress induced by these deformations could result in early-age cracking (Lim & Tayabiji 2005). Even though the deformation of slab due to environmental loading has long been recognized as curling and warping primarily due to temperature and moisture variations, many other factors such as the curing condition, influence of climatic conditions on paving, and the creep of slab (Janssen 1987, Rao et al. 2001, Rao & Roesler 2005) may also be involved. Especially, the complicated interactions of many such factors result in "locked-in" curvature such that the slab shape at zero temperature gradient does not remain flat or plain (Byrum 2000). Many researchers have reported that these built-in slab curvatures are associated with the temperature differences between the top and bottom of the slab (Armaghani et al. 1986, Byrum 2000, Rao et al. 2001, Beckemeyer et al. 2002, Yu et al. 2004, Rao & Roesler 2005). However, the temperature differences reported were different for different slab thicknesses, climatic conditions, and methods of slab deformation measurement.

In spite of many research efforts, the early-age PCC pavement behavior under environmental loading has not been fully understood. Thus, developing analytical solutions for these behaviors has been extremely difficult. The primary objective of this study is to quantify the pave-

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ment deformations due to pure environmental loading at critical periods immediately following pavement construction. For this study, a newly constructed JPCP section on highway US-30 near Marshalltown, Iowa was instrumented to monitor the pavement response to variations in temperature and moisture during the first seven days after construction. A series of laboratory tests were undertaken to characterize the properties of paving material in the field. The methodology and the results of the FE analysis based on the field data collected from the instrumented pavement are discussed in this paper. Comparisons between the field measured and the FE computed slab deformations are presented.

AP OF FE METHOD TO ANALYSIS OF RIGID PAVEMENT RESPONSE

The application of FE Method (FEM) to analyze rigid pavement response to mechanical and environmental loading has significantly increased over the past decade (Hammons & Ioannides 1997). The ability of FEM to solve a broad class of boundary value problems provide a better understanding of the critical aspects of pavements response, such as joint load transfer (Armaghani et al. 1986, Ioannides & Korovesis 1990, 1992, Davids 2001), pavement response under dynamic loads (Chatti et al. 1994, Vepa & George 1997) and environmental load (Ioannides & Salsili-Murua 1989, Beckemeyer et al. 2002, Rao & Roesler 2005) that couldn't have been captured with other analytical solutions.

This advantage of FEM has enabled many researchers to apply FE-based methodology for rigid pavement analysis either by using ready-made software for rigid pavements (Tabatabaie & Barrenberg 1978, Chou 1981, Tayabji & Colley 1986, Tia et al. 1987, Huang 1993, Davids et al. 1998), or by using the commercially available general purpose FE software (Kuo et al. 1995, Massad & Taha 1996, Kim & Hjelmstad 2003, Mahboub et al. 2004, Siddique & Hossain 2005). Most ready-made FE programs, customized for rigid pavement modeling and analysis, such as ISLAB 2000, JSLAB, KENSLABS, and FEACONS III use two dimensional (2D) plate elements, while the commercial FE software such as ABAQUS and ANSYS, and the EverFE 2.24 choose three-dimensional continuum elements for modeling the slab behavior. The major advantages of using ready-made FE software are that they are readily available, require only modest computer resources, and have user-friendly interfaces that can be easily accessed by the pavement designer. However, the commercial 3-D FE softwares have the advantage of the ability to more realistically model the pavement structure compared to the ready-made 2-D FE programs. The disadvantages of using the commercial 3-D FE software for rigid pavement modeling are that very few models have been validated and the various features of the software cannot be readily understood by the pavement designer in general.

Considering the advantages and disadvantages of different FE programs, ISLAB 2000 and EverFE 2.24 were chosen as the representative 2-D and 3-D FE programs, respectively, for studying the early-age JPCP behavior under environmental loading. These two programs have evolved from earlier versions with validation using field data (Tabatabaie & Barrenberg 1978, Davids & Mahoney 1999, Khazanovich et al. 2000, Davids et al. 2003) and can simulate field observed response very well (Wang et al. 2006). In addition, these two FE programs have some special advantages over other FE programs. ISLAB 2000 was used as the main structural model for generating pavement responses in the new Mechanistic-Empirical Pavement Design Guide (MEPDG) under National Cooperative Highway Research Program (NCHRP) 1-37 A project (2004). EverFE 2.24 is the only 3-D FE program among the ready-made FE programs specifically designed for modeling and analyzing rigid pavements.

TEST SECTION AND DATA COLLECTION

The test section selected for this study consists of a 267-mm (10.5-in.) thick JPCP slab constructed on highway US-30 near Marshalltown, Iowa. The pavement was constructed on open-graded granular base. The transverse joint spacing was approximately 6 m (20 ft). The passing lane was approximately 3.7 m (12 ft) in width, and the travel lane was approximately 4.3 m (14 ft) in width. A Hot Mix Asphalt (HMA) shoulder was added approximately 2 months after initial construction. Tie-bars, 914-mm (36-in.) long and 12.7-mm (0.5-in.) diameter were inserted approximately every 762 mm (30 in.) across the longitudinal joints. Dowel bars, 457 mm (18 in.) long and 38 mm (1.5 in.) diameter, were inserted approximately every 305 mm (12 in.) across the transverse joints.

The travel lane constructed at 3:30 PM Central Standard Time (CST) on July 13, 2005 (7/13/05) was selected for data collection. The data collection involved conducting material tests in the laboratory on field samples and monitoring of responses using in-situ instrumentation.

To obtain the fundamental physical properties of the paving material, a series of laboratory tests at various ages of PCC were conducted in Iowa State PCC mobile laboratory (parked in the test section) and Iowa State PCC laboratory. The split tensile test (ASTM C 496), the compressive strength test (ASTM C 39), the elastic modulus test (ASTM C 469), and test for determining the coefficient of thermal expansion (AASHTO TP 60) were performed on PCC samples obtained during construction.

Temperature sensors, relative humidity sensors, and LVDTs were instrumented in this section to observe the effects of environmental loading on slab behavior during the early age period (7 days after construction). Surface profiles were measured using a SurPRO 2000® rolling inclinometer profiler (manufactured by International Cybernetics Corporation) along the diagonal and transverse directions of the slab. The selected locations and their corresponding field testing activities are illustrated in Figure 1. Iowa State PCC mobile laboratory parked in the test section monitored and recorded the weather condition information such as the ambient temperature, ambient relative humidity, wind direction, and rainfall during seven day after construction. During the field evaluation periods, the weather was clear and sunny.

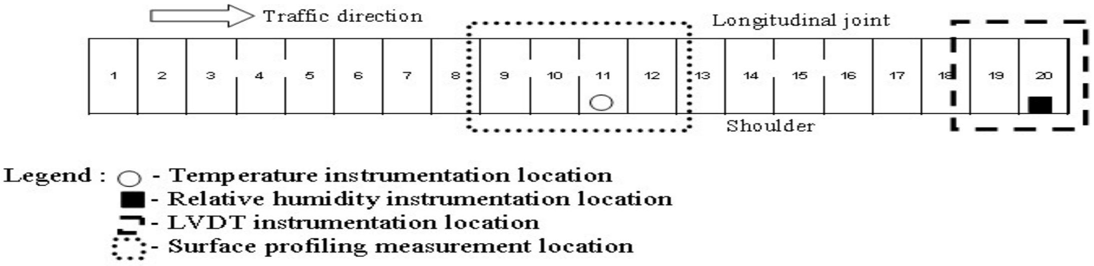

Figure 1. The location of field testing activities in test section.

The slab deformations were influenced not only by temperature differences but also by moisture differences between the top and the bottom of the PCC slab. Temperature and humidity sensors installed within the test sections detected the temperature and moisture variations, respectively. Slab temperature and moisture data were collected at five–minute intervals throughout the field evaluation periods. Temperature instrumentation consisted of seven Thermochron I-buttons® attached to a stake at different depths below surface and placed 0.9-m (3-ft) from the pavement edge before the paving started. Six Thermochron I-buttons® measured the slab temperature and one Thermochron I-button® measured the subgarde temperature. Humidity instrumentation consisted of four Hygrochron I-Buttons® inserted into small PVC pipes which were placed side by side at different depths from the pavement surface to measure the humidity variations in the slab.

The variations in temperature and moisture differences with time are plotted in Figure 2. In general, temperature differences are positive during daytime and early night time and negative during late night time and early morning. In contrast, moisture differences presented as "RH Diff" in Figure 2 show the reverse trend. Especially during day 0 and day 1 of paving, moisture differences are negative for most part, i.e., higher moisture at the bottom of the slab compared to the top. This indicates higher drying shrinkage of concrete near the top of the slab causing the slab corner to warp upward during the day 0 and day 1 of paving.

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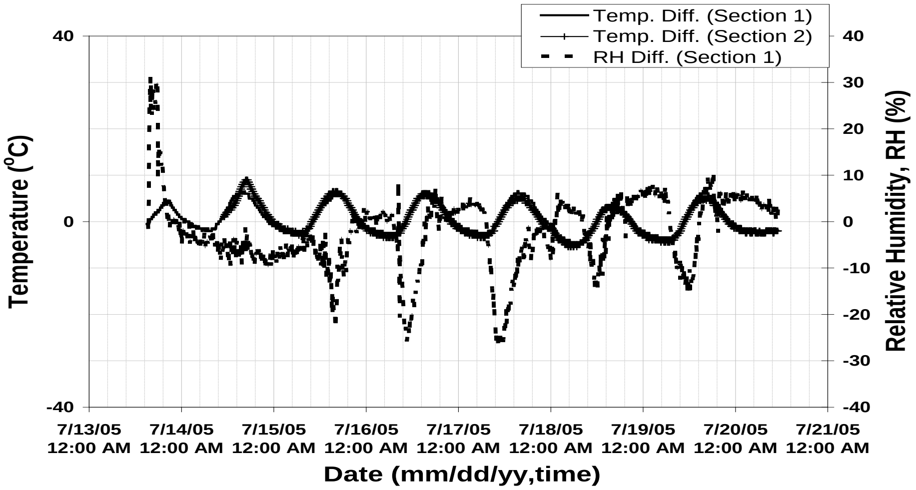

Figure 2. Pavement temperature and moisture difference between the top and the bottom of slab with time.

Even though LVDTs were installed on two slabs (slab 19 and slab 20), the slab 19 was selected as the representative slab to study the pavement vertical movements because the LVDTs on slab 20 were not installed in some positions (the center of slab and the mid-slab edge near shoulder) due to data logger limitations. LVDTs were installed in special locations on slab 19 as shown in Figure 3 to capture the vertical movements of the slab. All the sensors were placed only after the concrete hardened (1 day after paving). LVDTs were held by a bracket fastened to the steel rod which was inserted in subgrade and was placed on a smooth glass on the pavement surface. The LVDTs were connected to data loggers, which collected data at 10-minute intervals throughout the field evaluation periods.

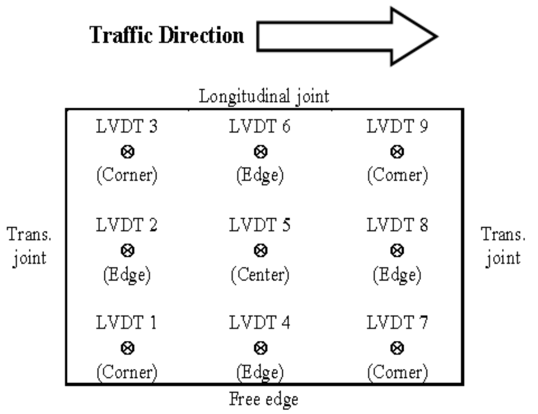

Figure 3. LVDT instrumentation layout.

A rolling inclinometer profiler was used for surface profile measurements at different times (morning and the afternoon) for both test sections. A rolling inclinometer profiler can measure the true unfiltered elevation profile of pavement surface (ICC. 2006). Many researchers have used the inclinometer measurements to quantify slab curvature (Rao et al. 2001, Vandenbossche & Snyder 2005). In this study, the rolling inclinometer profiler followed transverse and diagonal traces for four individual slabs in test section to capture the slab curvature in different measuring times. Each profiling segment was measured independently.

The surface profile measurements using rolling inclinometer profiler were analyzed to confirm the trend in vertical movements observed using the LVDTs. The raw data of surface profile measurements include not only slab deformation pattern referred to as slab curvature profile, but also the built-in construction slope and the surface irregularities. Currently, there does not seem to be a standard method to identify the slab curvature due to curling and warping from the raw surface profiling data. However, several indirect procedures have been proposed to detect the slab curvature profile from the raw surface profiling data (Byrum 2000, Sixbey et al. 2001, Vandenbossche 2003, Siddique et al. 2003). Among them, the procedures suggested by Sixbey et al. (2001) and Vandenbossche (2003) were used in this study. The diagonal slab curvature profile in test section constructed using this procedure is displayed in Figure 4 for illustration.

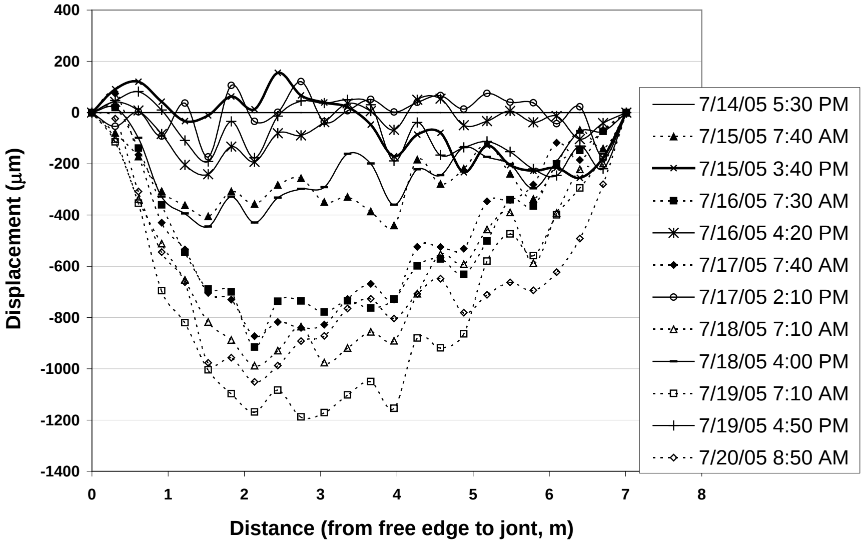

Figure 4. A diagonal slab curvature profile.

FINITE ELEMENT MODELING

FE models based on the actual geometric proportions and material properties from the test sections (shown in Tables 1-2) were studied. The concrete pavement was modeled as a slab-on-grade system. The slab was represented as a one-layer model consisting of combinations of elements with a mesh fineness of 250-mm x 175-mm (10-in x 7-in) in both ISLAB 2000 and EverFE 2.24. The base and subgrade were modeled as unbounded dense liquid foundation having a k-value of 62.4 kPa /mm (230 psi/in.). Even though the slab temperature profiles with depth have long been characterized as non-linear distributions, the observed temperature profile in this study showed nearly a linear temperature distribution. Additionally, it has been reported that the non-linear component of the slab temperature distribution doesn't influence the deflections very much (Yu et al. 2004). Therefore, a linear temperature distribution was used in the FE modeling to investigate slab deflections in this study. Although this assumption is not strictly valid, it makes the design conservative and simple (Silfwerbrand et al. 2004). A linear temperature distribution was assumed in this study based on the readings from the top and bottom temperature sensors.

FE analyses were conducted on the maximum positive and negative temperature difference distributions with slab depth. FE analyses were also performed on the positive and the negative temperature difference distributions on days when the pavement profile data were collected.

Table 1. Geometric properties for the test section.

Layer	Lane	No. of slab	Width (m) of a slab	Length (m) of a slab	Depth (mm)
Concrete	Passing	3	3.6	6	267
	Traveling	3	4.3	6	267

Table 2. Material properties for the test section.

Material	Property	Value
Concrete	Modulus of elasticity (MPa)	30,483
	Unit weight (kg/m3)	2,400
	Poisson's ratio	0.2
	Coefficient of thermal expansion (ε/ °C)	9.63×10^{-6}
Dowel Bar	Diameter (mm)	38
	Length (mm)	457
	Spacing (mm)	305
	Modulus of elasticity (MPa)	20 x 10 4
	Poisson's ratio	0.3
Tie Bar	Diameter (mm)	13
	Length (mm)	914
	Spacing (mm)	762
	Modulus of elasticity (MPa)	20 x 10 4
	Poisson's ratio	0.3
Subgrade	Modulus of subgrade reaction (kPa/mm)	62.4

FEM ANALYSIS RESULTS

Preliminary analyses of the pavement systems using the ISLAB 2000 and EverFE 2.24 FE software with appropriate material property inputs and linear temperature distributions indicated that the FEM results couldn't generate the effect of built-in upward deformation measured using the LVDTs and profiling in the field. For instance, the field-measured slab shape at maximum positive temperature difference in seven days was almost flat while the FEM-generated slab shape showed curling-down at the same temperature difference. This may be because of the zero-temperature deformation due to differential shrinkage or a positive thermal gradient during initial curing of the concrete (Yu et al. 1998, Byrum 2000, Rao et al. 2001, Rao & Roesler 2005). Note that ISLAB 2000 and EverFE 2.24 can't simulate drying shrinkage behavior in terms of moisture variations. If the pavement temperature difference reaches certain amount of positive value after the initial curing of concrete, these zero temperature deformations are removed such that the slab tends to flatten. Thus, the zero temperature deformation could be the deformation corresponding to the negative value of the temperature difference on flat slab condition defined as the effective built in temperature difference.

Based on the LVDT measurements in Figure 5 which showed the deformation of the slab was not sensitive at positive temperature difference condition, 8.5°C (15.3°F), the maximum positive temperature difference during the evaluation periods, was assumed as the positive temperature difference to maintain a flat-slab condition (for a 267mm thick slab) in this study. This positive temperature difference is similar in magnitude to those reported by other researchers in the past. Armaghani et al. (1986) reported a value of 5°C (9°F) for a 230mm (9-in.) thick slab in Florida. Beckermeyer et al. (2002) observed values of 8.8°C (16°F) and 6.7°C (12°F) for a 330mm (13-in.) thick slab on an open-graded granular base and an asphalt treated permeable base, respectively, in Pennsylvania. For a 432 mm (17-in) thick slab in the Denver International Airport (DIA), Rufino et al. (2006) estimated approximately values of those between 5.6°C (10°F) and 8.3°C (15°F).

The zero temperature gradient deformations associated with the effective built-in temperature differences (-8.5°C) could be estimated using ISLAB 2000 and EverFE 2.24. The slab deformations measured using the LVDTs were calibrated with the estimated zero temperature deformation to obtain the actual slab deformation. This calibrated slab measurement (the actual slab deformation) could be associated with an equivalent temperature difference, which is the sum of the measured temperature difference and the effective built in temperature difference. The equivalent temperatures differences, at the maximum positive and negative temperature difference and the positive and negative temperature under which pavement profile data were collected are listed in Table 3.

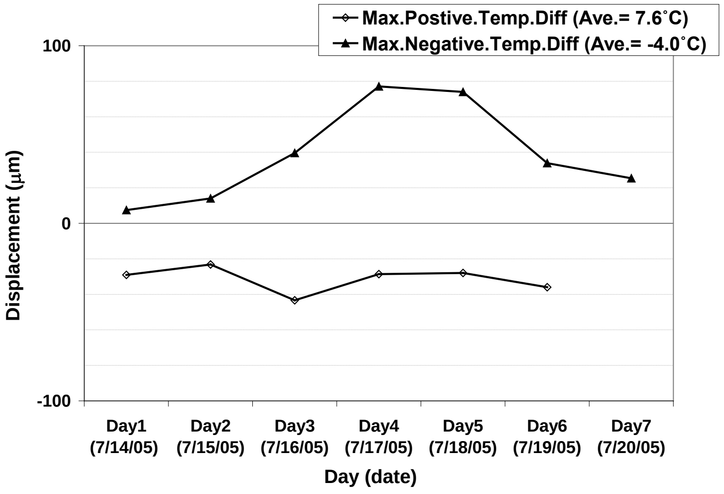

Figure 5. Vertical displacement of slab at maximum temperature difference.

Table 3. The equivalent temperature differences in a day during field evaluation.

Concrete age	Measured temperature difference				Equivalent temperature difference			
	Max. positive temp. diff.	Max. negative temp. diff.	Positive temp. diff. at profile measurement	Negative temp. diff. at profile measurement	Max. positive temp. diff.	Max. negative temp. diff.	Positive temp. diff. at profile measurement	Negative temp. diff. at profile measurement
	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
Day 1	7.8	-1.3	N/A	N/A	-0.7	-9.8	N/A	N/A
Day 2	7.8	-3.9	7.2	-3.5	-0.7	-12.4	-1.3	-12.0
Day 3	8.5	-3.9	8.1	-3.3	0.0	-12.4	-0.4	-11.8
Day 4	8.5	-3.9	7.2	-2.8	0.0	-12.4	-1.3	-11.3
Day 5	5.3	-6.6	4.6	-5.9	-3.2	-15.1	-3.9	-14.4
Day 6	7.8	-5.3	7.9	-4.6	-0.7	-13.8	-0.6	-13.1
Day 7	N/A*	-3.3	N/A*	-1.9	N/A*	-11.8	N/A*	-10.5

*N/A – not available.

LVDT displacement measurements versus FEM results

The predicted slab deflection at the equivalent temperature differences of the maximum positive and negative temperature differences were calculated by ISLAB 2000 and EverFE 2.4. Comparisons were made between LVDT measured slab displacements and FE-predicted values along the directions shown in Figure 6. Due to space constraints, comparisons at the maximum negative and positive temperature difference during the field evaluation periods are presented in Figures 7-8, respectively for only Direction 4.

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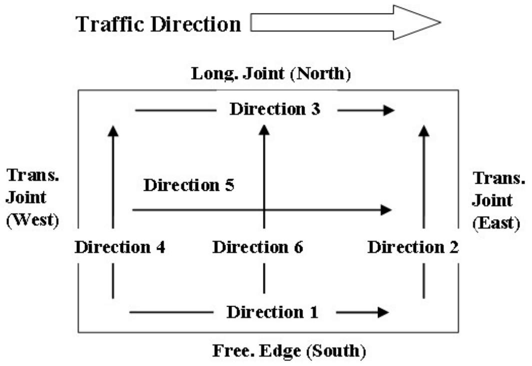

Figure 6. The directions in slab used in the comparisons between LVDTs measured slab displacements and predicted slab displacements.

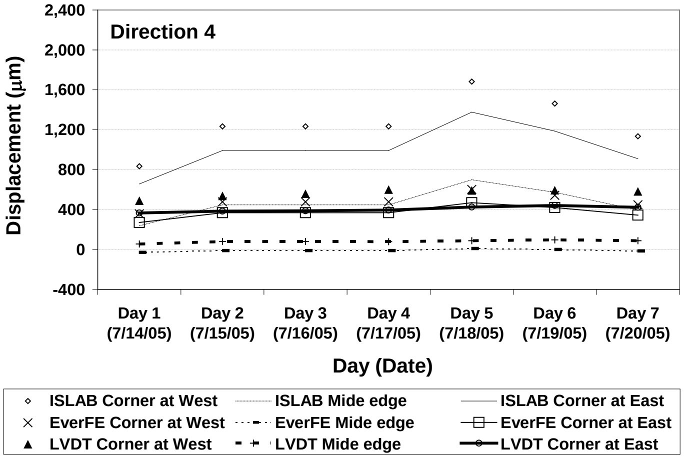

Figure 7. Comparison between measured and predicted slab deflections at maximum negative temperature difference in a day during 7 days after paving.

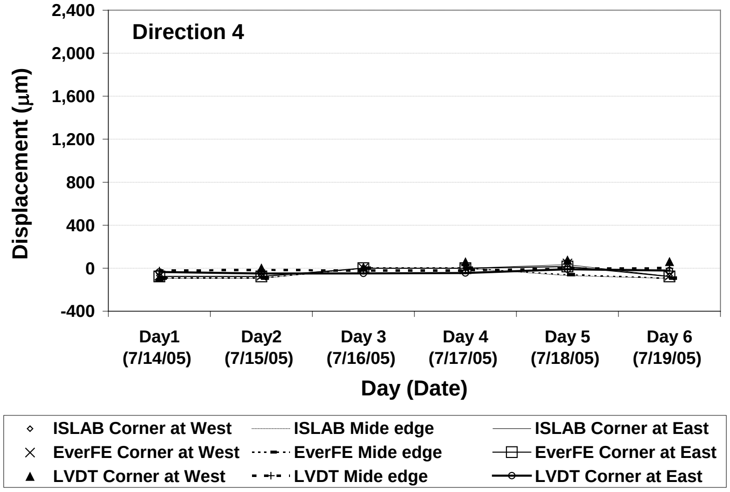

Figure 8. Comparison between measured and predicted slab deflections at maximum positive temperature difference in a day during 6 days after paving.

Comparison of FE-predicted slab displacement with the field-measured values at maximum negative temperature difference conditions show that the displacements predicted by EverFE 2.24 agree reasonably well with the measured values. The ISLAB 2000 predicted deflections tend to overestimate the slab deformations. However, at maximum positive temperature difference conditions, the FE-predicted displacements (using both ISLAB 2000 and EverFE 2.24) are very similar to field-measured values. It is also observed that the slab maintained almost a flat shape during maximum positive temperature difference conditions.

It is not very surprising to note that the exact curl could not be accurately predicted, especially at maximum negative temperature difference conditions. Note that a constant value of effective built-in temperature difference, the reversible displacement resulting from moisture variation in a day was assumed as constant in the FE modeling of slab displacement. This is a valid assumption since it is believed that reversible displacement resulting from moisture variation in slab has more influence on seasonal weather variation rather than on daily weather variation (Yu et al. 2004). Thus, the error associated with approximating a variable effective built-in temperature difference with a constant value might have produced some error in the predicted results.

Slab curvature profiling measurements versus FEM results

Comparisons between the field-measured slab curvature profiles and the FE-computed slab curvature profiles were undertaken to verify the results from the previous comparisons between the LVDT measured and FE-predicted slab deflections. Note that a rolling inclinometer profiler was used for measuring the slab curvature profiles. The LVDT displacement measurements calibrated during the pavement profiling were also included in these comparisons. The slab curvature profiles at equivalent temperature differences during pavement profiling were computed by ISLAB 2000 and EverFE 2.24 along each direction shown in Figure 9. All measured profiles were zeroed with respect to the center elevation in each direction. This is because the measured slab curvature profiles were normalized at the center in each measured direction to remove the construction slope and surface irregularity components.

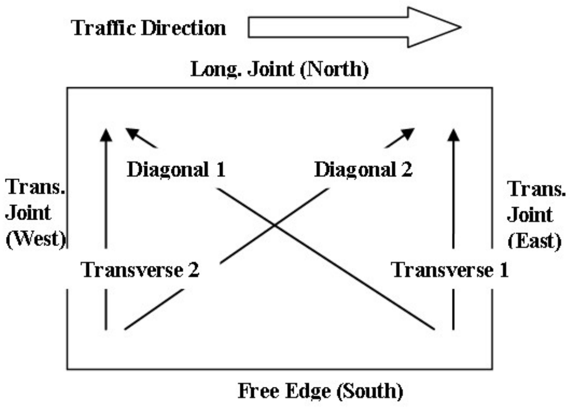

Figure 9. The directions of slab profiling measured.

Forty-four field profiling measurements and the corresponding FE-predicted profiles were obtained during the field evaluation periods. The measured and predicted slab curvature profiles for diagonal 1 direction are presented in Figure 9. The measured and predicted slab curvature profiles at the equivalent temperature difference 5 days after paving are presented in Figures 10-11 for the sake of illustration.

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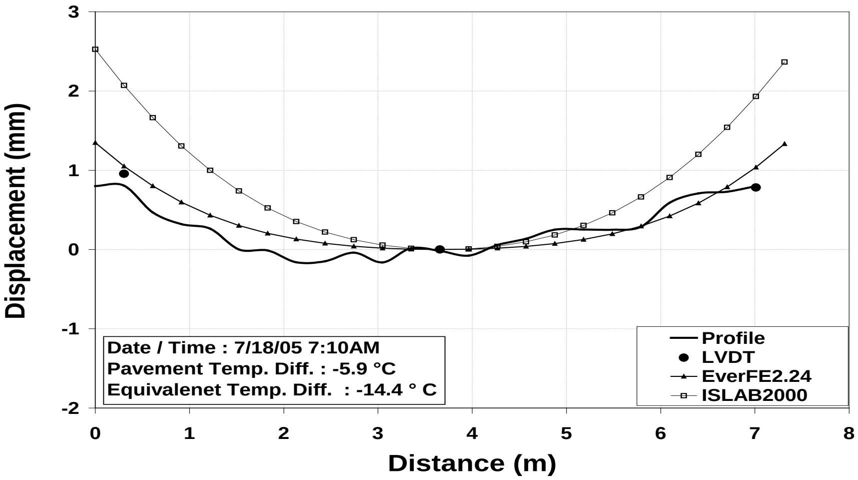

Figure 10. The comparison between measured and predicted slab curvature profiles at negative temperature difference condition (Note: All elevations are relative to the center in measured direction).

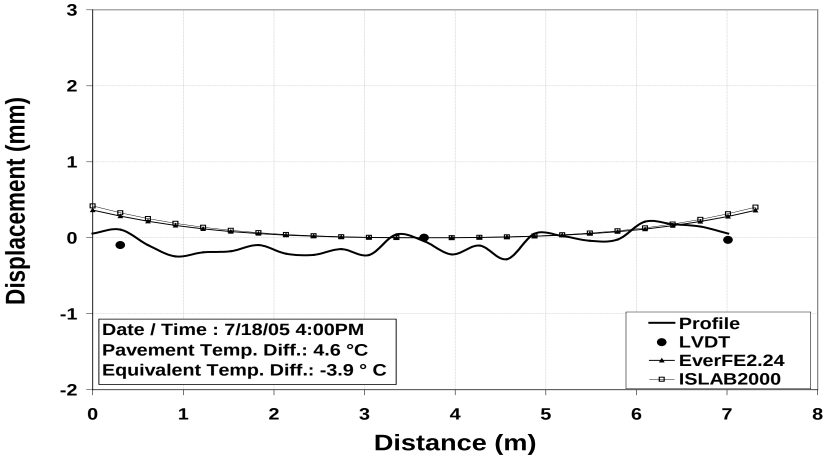

Figure 11. The comparison between measured and predicted slab curvature profiles at positive temperature difference (Note: All elevations are relative to the center in measured direction).

From even a cursory examination of the comparison charts such as Figures 10-11, it is observed that the FE-predicted slab curvature profiles agree well with the measured slab curvature profiles and the measured LVDTs displacements. However, it is necessary to quantify these observations to enable more detailed comparisons.

If the slab behavior could be characterized in terms of total amount of deflection and the slab shape, then the total amount of deflection could be quantified using the relative deflection of corner to center in the measured direction (Rc) and the slab shape could be quantified by the curvature of slab profile (k).

The relative deflection of corner to center (Rc) in the defined direction could easily be calculated by subtracting the elevation of center in the defined direction from that of corner in same direction. The curvature of slab profile (k) was calculated using a methodology similar to that proposed by Vandenbossche (2005). A second-order polynomial curve was fit to slab profile for each of field-measured and FE-predicted profile and then the curvature was calculated using Equations 1 and 2 shown below:

$$k = \frac{\frac{d^2y}{dx^2}}{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{\frac{3}{2}}} \tag{1}$$

$$y = Ax^2 + Bx + C \tag{2}$$

where k = Curvature; y = Measured displacement; x = Location along the profile traverse; and A,B, and C = Coefficients

The calculated relative deflection of corner (Rc) and the calculated curvature of shape (k) in diagonal and transverse directions were all averaged. The quantitative comparisons between the measured profiles and the FEM profiles are presented in Figures 12-15. In these figures, a positive value indicates the upward movement of the slab and a negative value indicates the down ward movement of the slab.

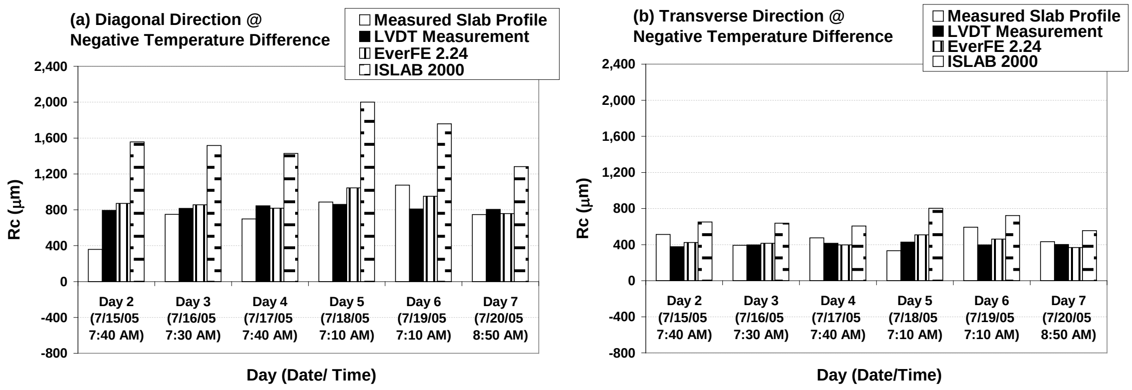

Figure 12. The comparison of the relative corner deflection (Rc) between measured and predicted slab profiles in negative temperature difference conditions.

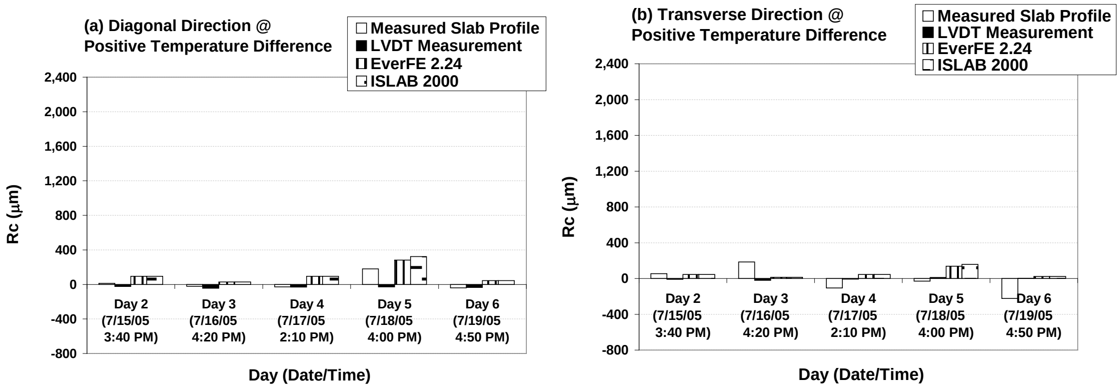

Figure 13. The comparison of the relative corner deflection (Rc) between measured and predicted slab curvature profiles in positive temperature difference conditions.

Reference to this paper should be made as follows: Kim, S., Ceylan, H., and Gopalakrishnan, K. (2007). "*Simulation of Early-Age Jointed Plain Concrete Pavement Deformation under Environmental Loading Using the Finite Element Method*," International Conference on Advanced Characterization of Pavement and Soil Engineering Materials, Athens, Greece, June 20-22, 2007..

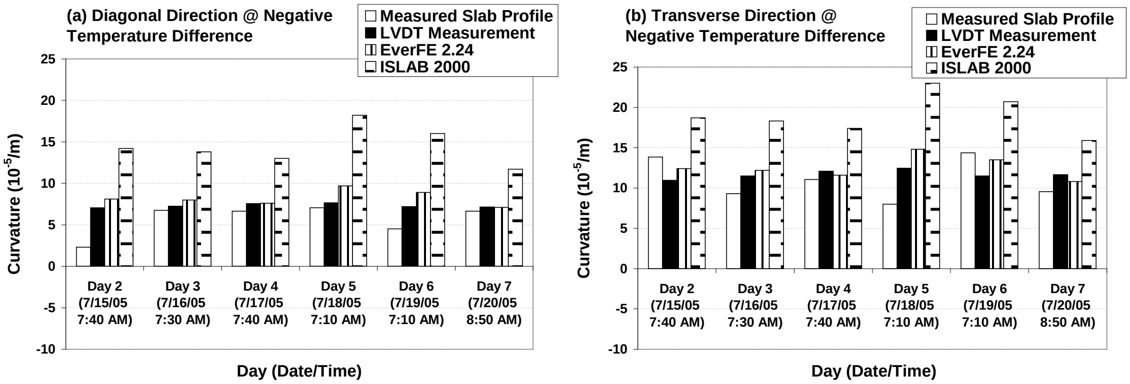

Figure 14. The comparison of curvature (k) between measured and predicted slab curvature profiles in negative temperature difference conditions.

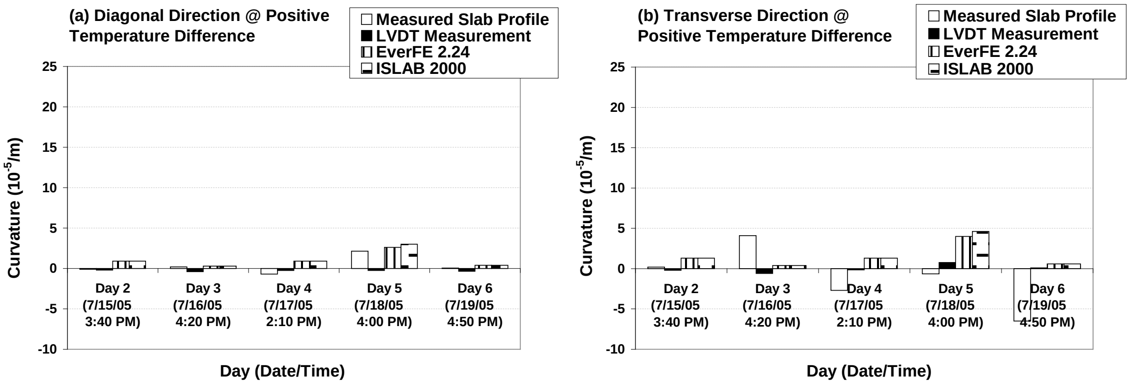

Figure 15. The comparison of curvature (k) between measured and predicted slab curvature profiles in positive temperature difference conditions.

From these observations, it is clearly noted that the measured slab curvature profiles show upward curl at negative temperature differences and maintain almost a flat shape at positive temperature differences, similar to the trends obtained using LVDT deflections. It is also observed that both FE models could reproduce these observed trends of the measured slab curvature, and the 3-D FE model, EverFE 2.24, provided better estimations of the curvature and the relative corner deflection with the slab profile and LVDT deflection measurement compared to ISLAB 2000 (2-D FE software).

CONCLUSIONS

This study investigated the early-age deformations in PCC pavement due to environmental loading. A newly constructed JPCP on US30 near Marshalltown, Iowa was instrumented to monitor the pavement response to temperature and moisture variations during the first seven days after the construction in the summer of 2005. The slab deformations could be detected using the colleted data from installed LVDTs and surface profile measurements. FE analyses were conducted using the 2-D ISLAB 2000 and 3-D EverFE 2.24 rigid pavement structural models. Comparisons between the measured and computed deformations were made. Based on the observations of the measured data and the results of the comparison, the followings conclusions were drawn;

- The zero-temperature deformation could be observed from both the LVDT and profile measurements. The temperature difference corresponding to this zero-temperature deformation was -8.5 ^{o}C (-15.3^{o}F) for the 267-mm (10.5-in.) thick slab considered in this study.

Reference to this paper should be made as follows: Kim, S., Ceylan, H., and Gopalakrishnan, K. (2007). "*Simulation of Early-Age Jointed Plain Concrete Pavement Deformation under Environmental Loading Using the Finite Element Method*," International Conference on Advanced Characterization of Pavement and Soil Engineering Materials, Athens, Greece, June 20-22, 2007..

- The measured slab deformation under negative temperature difference condition showed the upward curl clearly. However, under positive temperature difference condition, the shape of slab did not show downward curl. This behavior was successfully simulated through FEM using equivalent temperature difference concept considering zero-temperature deformation.
- The 3-D FE model, EverFE 2.24, provided better estimations of slab deformation properties in terms of relative deflection of corner (Rc) and curvature(k) compared to ISLAB 2000 (2-D FE software).

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