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Finite element modeling of environmental effects on rigid pavement deformation

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Keywords

curling and warping, finite element analysis (FEA), jointed plain concrete pavements (JPCP), rigid pavement analysis and design, sensitivity analyses

Disciplines

Civil and Environmental Engineering | Construction Engineering and Management

Comments

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Finite Element Modelling of Environmental Effects on Rigid Pavement Deformation

SUNGHWAN KIM, HALIL CEYLAN, and KASTHURIRANGAN GOPALAKRISHNAN

Abstract

In this study, Finite Element (FE)-based primary response models are employed for investigating the early-age deformation characteristics of Jointed Plain Concrete Pavements (JPCP) under environmental effects. The FE-based ISLAB (two-and-one -half-dimensional) and EverFE (three-dimensional) software were used to conduct the response analysis. Sensitivity analyses of input parameters used in ISLAB and EverFE were conducted based on field and laboratory test data collected from instrumented pavements on highway US-34 near Burlington, Iowa. Based on the combination of input parameters and equivalent temperatures established from preliminary studies, FE analyses were performed and compared with the field measurements. Comparisons between field measured and computed deformations showed that both FE programs could produce reasonably accurate estimates of actual slab deformations due to environmental effects using the equivalent temperature difference concept.

Keywords**:** Jointed Plain Concrete Pavements; Curling and Warping; Sensitivity Analyses; Rigid Pavement Analysis and Design; Finite Element Analysis.

1 Introduction

Studies focusing on deformation characteristics of early-age JPCP subjected to pure environmental effects have drawn significant interest amongst concrete pavement researchers (Rao, et al., 2001; Siddique and Hossain, 2005; Ceylan et al., 2007). It is believed that the early-age deformation of Portland Cement Concrete (PCC) slabs could result in the loss of pavement smoothness (Siddique and Hossain, 2005; Kim et al, 2008) and the tensile stresses induced by these deformations could result in early-age cracking (Lim and Tayabji, 2005). However, the complex nature of the curling and warping phenomenon arising from interactions of multiple environmental factors has resulted in difficulties in predicting the JPCP deformation characteristics under environmental effects.

In the Mechanistic-Empirical Pavement Design Guide (MEPDG) developed under the National Cooperative Highway Research Program (NCHRP) 1-37A project, FE-based structural analysis models using a neural networks-based approach were employed for rigid pavement analysis and design (NCHRP, 2004). The application of FE modeling techniques in recent times has significantly improved our understanding and the way rigid pavement behavior is characterized in special situations where it is difficult to conduct laboratory and field testing (Armaghani, et al., 1986; Ioannides and Salsili-Murua, 1989; Ioannides and Korovesis, 1990; Ioannides and Korovesis, 1992; Chatti et al., 1994; Hammons and Ioannides, 1997; Vepa and George, 1997; Davids, 2001; Beckemeyer et al., 2002; Rao and Roesler, 2005).

This study focuses on evaluation of two FE-based primary response models, namely ISLAB 2000 (Khazanovich et al, 2000) and EverFE 2.24 (Davids, 2006), for characterizing the deformation of early-age JPCP under environmental effects. These models were selected primarily because they posses some special advantages over other FE programs. The ISLAB 2000 2.5-D FE program was used as the main structural model for generating rigid pavement responses in the new MEPDG under the NCHRP 1-37A project (2004), and EverFE 2.24 is the only 3-D FE program specifically designed for modeling and analyzing rigid pavements (Davids, 2003).

The numerical models used in both the FE programs for computing slab deformation under environmental effects are briefly discussed in this paper. Sensitivity analyses of input parameters used in ISLAB 2000 and EverFE 2.24 were carried out based on field and laboratory test data collected from instrumented pavements on highway US-34 near Burlington, Iowa. Field-measured and the FE-computed slab deformations are also discussed and compared in this paper. The primary objective of this study is to evaluate the ability of FE programs for modeling the deformation of early age JPCP under environmental effects.

2 Existing rigid pavement FE programs used in modeling environmental effects

The temperature and moisture variations across the depth of rigid pavements result in pavement deformation referred to as curling and warping. Other factors contributing to curling and warping include the permanent built-in negative or positive curling that occurs during the concrete hardening, the permanent warping due to differential shrinkage, and the weight of the slab contributing to the creep of the slab (Yu et al, 1998; Yu et al., 2004). Therefore, the deformation caused by each of these factors must be taken into consideration. Although analytical (Westergaard, 1927) or numerical solutions have been used in the past to predict the rigid pavement responses, such as stress, strain or deflection under environmental effects without conducting laboratory or field experiments, these methods have their own limitations and have not been successfully used in fully characterizing the environmental effects.

2.1 ISLAB 2000

ISLAB 2000 is a 2.5-D FE program for the analysis of rigid pavements developed by Applied Research Associates (ARA), Inc. with support from the Michigan Department of Transportation and the Minnesota Department of Transportation (Khazanovich et al, 2000). The ISLAB 2000 is the most recent version of an evolving ILLI-SLAB program

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developed in 1977 at the University of Illinois at Urbana-Champaign, and is the primary structural model for generating pavement responses in the MEDPG software (NCHRP, 2004). During the improvement and extension of ILLI-SLAB over the years, curling analysis was incorporated in 1989 by Korovesis (1990).

To calculate the deflection due to temperature, a thin plate element (Kirchhoff plate element) having three deflection components at each node (i.e., a vertical deflection in z-direction, a rotation [Θ_x] about the x-axis, and a rotation [Θ_y] about the y-axis) is used for a concrete slab on Winkler foundation or dense liquid foundation. The equilibrium matrix equation of element assemblage shown in equation 1 is formulated using the principle of virtual work and is used to calculate the stress, strain and deflection incorporating the element boundary condition (Korovesis, 1990). Temperature effect is considered through the load vector in equation 1. The stress–strain–temperature relation shown in equation 2 is used to derive this load vector due to temperature.

$$P = KU \tag{1}$$

Where, P = load vector $=P_B+P_S-P_I+P_C$; P_B = load vector due to element body forces; P_S = load vector due to element surface forces; P_I = load vector due to element initial stresses; P_c = concentrated loads; K = structure stiffness matrix; and U = deflection vector.

$$\sigma_t = \alpha_t \Delta T E = \varepsilon_t E \tag{2}$$

Where, σ_t = stress due to temperature; and ε_t = strain due to temperature = $\alpha_t \Delta T$.

Since the load vector in equation 1 includes the self–weight of the layer and the temperature distribution, the calculated deformation shown in figure 1.a. is more realistic than an analytical solution but still does not include the deflection due to the moisture changes and the permanent curling and warping.

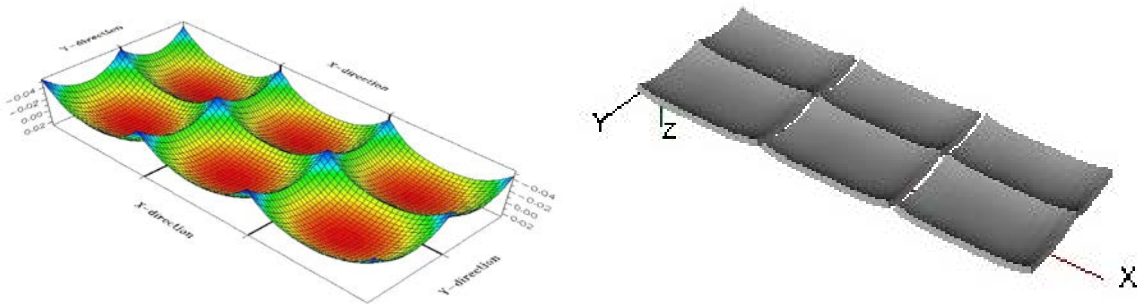
2.2 EverFE 2.24

EverFE is a 3-D FE analysis tool for simulating the response of JPCP to traffic loads and temperature effects. The original software, EverFE 1.02, was developed at the University of Washington and has been continuously upgraded. The most recent version, EverFE 2.24, was used in this study. EverFE 2.24 is in the public domain and can easily be obtained (Davids, 2006).

EverFE uses five elements for simulating JPCP systems: 20-noded quadratic element having three deflection components at each node are used for the slab, elastic base, and sub-base layer; 8-noded planar quadratic elements model the dense liquid foundation below the bottom-most elastic layer; 16-noded quadratic interface elements implement both aggregate interlock joint and shear transfer at the slab-base interface; and 3-noded embedded flexural elements coupled with conventional 2-noded shear beams are used to model the dowel bars and tie bars (Davids, 2003). The subgrade models available in

EverFE are dense liquid foundations with and without supporting vertical tension (Davids, 2003). Similar to ISLAB 2000, the equilibrium matrix equation of element assemblage is formulated and is used to compute the stresses, strains and deflections incorporating boundary condition of element. The formulation of structural stiffness, K, is required to solve the equilibrium equation. However, 3D models of rigid pavement systems need combinations of large memory and computational requirements if using the direct matrix factorization for K. To circumvent this problem, EverFE employs multi-grid methods to solve the equilibrium equation, which are some of the most efficient iterative techniques available (Davids et al, 1998; Davids and Turkiyyah, 1999).

Like ISLAB 2000, the temperature changes are converted to equivalent element strains via the slab coefficient, and these strains are numerically integrated over the elements to generate equivalent nodal forces (Davids et al, 2003). The computed deflections from EverFE 2.24 can be provided in the form of 3-D deformed shapes, as shown in figure 1.b., or in terms of numerical values, depending on the user's choice. Like ISLAB 2000, EverFE 2.24 also has limitations with respect to environmental effect analysis, i.e., it cannot directly calculate deflections due to the moisture change and the permanent curling and warping.



(a) (b)

Figure 1. Deformed slab shape generated from ISLAB 2000 and EverFE2.24 due to temperature differences: (a) ISLAB 2000; (b) EverFE 2.24.

3 Sensitivity of FE-based input parameters to slab deformations under environmental effects

The MEPDG developed under the NCHRP 1-37A employs FE-based models to compute pavement primary responses for predicting rigid pavement performance. Although ISLAB 2000 and EverFE 2.24 have limitations in calculating slab deformations under environmental effects, it is important to evaluate these programs and compare field measurements and predicted responses as a first step in calibrating the models to improve the accuracy of prediction. To do this, it is desirable that the input parameters used in the simulations be as close as possible to the actual situation. However, it is not necessary to collect all input parameters in the field or from lab testing and use them to model actual behavior. Sensitivity analyses can be performed to identify the critical input parameters

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that have the most effect on curling analysis. Based on the results of sensitivity analyses, realistic combinations of input parameters can be established to model the actual field behavior.

A total of eight key inputs related to material properties and climate were selected for sensitivity analyses using both ISLAB 2000 and EverFE 2.24. The concrete pavement was modeled as a six-slab system (3 panels in each lane) over a dense liquid foundation. Based on typical rigid pavement geometry used for highway pavements in Iowa (IDOT, 2005), each slab was modeled. The passing lane was 3.7 m in width, and the travel lane was 4.3 m in width. The transverse joint spacing and thickness of each slab were 6 m and 267 mm.

It is important to note that EverFE 2.24 employs either tension or tensionless supporting dense liquid foundation below the bottom-most elastic layer (Davids et al, 2003). The tensionless supporting foundation accounts for the subgrade with compression. The tension supporting foundation accounts for the subgrade with compression and tension. The EverFE 2.24 assumes the tension supporting foundation by default while the ISLAB 2000 automatically assumes tensionless supporting foundation when the curling analysis is performed to provide more realistic solutions. The dense liquid foundations used in sensitivity analysis of this study employed tensionless supporting foundation for ISLAB 2000. In the case of EverFE 2.24, both tensionless and tension supporting foundation were employed.

When any one input parameter was varied over the typical range of values, the values of the other input parameters were held constant at standard values during the sensitivity analyses. Table 1 summarizes the input parameters and ranges used in this study. These ranges have been selected based on the information reported in the literature related to curling and warping studies.

Table 1. Summary of input parameters

Parameter	Standard value	Ranges of value
Unit weight (kgm^{-3})	2,400	2,240, 2,400, 2,560
Poisson's ratio	0.2	0.1,0.2,0.3
Coefficient of Thermal Expansion (CTE, ε $^{o}C^{-1}$)	9.6×10^{-6}	6.3×10^{-6}, 9.6×10^{-6}, 13.5×10^{-6}, 17.1×10^{-6}
Elastic modulus (MPa)	30,483	13,790, 30,483, 41,370
Load Transfer Efficiency (LTE, %)	90	0.1, 50, 90
Modulus of subgrade reaction (k, kPa mm^{-1})	62.4	8.1, 35.3, 62.4, 89.6
FE Mesh size (mm × mm)	254 × 178	152 × 152, 254 × 178, 305 × 305
Temp difference between top and bottom of slab (°C)	1. 8.5 °C: positive temp. diff. 2. -6.6°C: negative temp. diff.	-13.3 °C to 13.3 °C with increments of 2.2 °C

Analytical results were used to quantify the slab deformation and shape for each combination of inputs. The total amount of deformation was quantified using the relative corner-to-center (R_c) deflection in the defined direction on surface of modeled concrete pavements. The R_c values could easily be calculated by subtracting the elevation of center in the defined direction from that of corner in the same direction. The centers of defined directions could be varied, i.e., the centers in transverse, longitudinal and diagonal directions correspond to mid transverse joint, mid longitudinal joint and slab centre, respectively.

The mid-line slabs in the traveling lane were selected in this study. This is because the middle slabs among three- panels in each lane (i.e., 6–slab assembly) were connected to the other slabs through transverse joints, which represents realistic slab condition in JPCP. The diagonal direction Rc values for the modeled concrete pavement are summarized in tables 2 and 3.

Based on the observation of absolute difference (ABD) of R_c between two adjacent input values in one parameter, the calculated R_c are significantly influenced by several input parameters including the coefficient thermal expansion (CTE), temperature difference between top and bottom of slab, elastic modulus and modulus of subgarde reaction. This finding is quite reasonable considering those parameters composing the equilibrium matrix equation of element assemblage of these two FE programs (See equations 1 and 2). Especially, small changes in CTE and temperature difference between top and bottom of slab resulted in relatively large difference of R_c.

The differences in deflections calculated using the two FE programs were also investigated. The deflections of EverFE 2.24 with tensionless foundation were nearly similar to those of ISLAB 2000 with tensionless foundation within about 7 % of average difference. Wang et al. (2006) reported that small differences could be found even when the basic theory underlying the FE programs is the same. They explained that small differences observed actually lie in the details of each program related to program coding issues such as nonlinearity, approximation, treatment of elements at interfaces and discontinuities, rounding off of numbers, etc.

However, the deflections of EverFE 2.24 with tension foundation were about 30% less than those of ISLAB 2000 with tensionless foundation. The magnitude of differences between the two programs increased as the estimated deflections increased in general. These results indicate that a good agreement of curling analysis between the two programs could be obtained with the same foundation model (tensionless foundation).

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Table 2. Sensitivity of relative corner deflections (R_c) to input parameters in ISLAB 2000 and EverFE 2.24 at positive temperature difference condition

Input parameter	Input value	R_c, μM			ABD of R_c in input values[a], μM			Difference of R_c[b], %	
		ISLAB[c]	EverFE[d]	EverFE[e]	ISLAB[c]	EverFE[d]	EverFE[e]	ISLAB[c] & EverFE[d]	ISLAB[c] & EverFE[e]
Unit weight, kgm^{-3}	2,240	-1,035	-975	-792	0	0	0	6.2	30.8
	2,400	-1,007	-954	-792	28	21	0	5.6	27.2
	2,560	-983	-933	-792	25	20	0	5.3	24.1
Poisson's ratio	0.1	-954	-898	-758	0	0	0	6.3	25.9
	0.2	-1,008	-954	-792	53	56	33	5.7	27.3
	0.3	-1,066	-1,012	-830	58	58	38	5.3	28.4
CTE, × 10^{-6} ε $^{o}C^{-1}$	6.3	-564	-518	-518	0	0	0	8.9	8.9
	9.63	-1,008	-954	-792	444	436	274	5.7	27.3
	13.5	-1,599	-1,474	-1,110	591	520	318	8.5	44.0
	17.1	-2,193	-1,975	-1,406	594	502	296	11.0	55.9
Elastic modulus, MPa	13,790	-540	-504	-504	0	0	0	7.2	7.2
	30,483	-1,007	-954	-792	467	450	288	5.6	27.2
	41,370	-1,189	-1,128	-921	182	175	129	5.4	29.1
LTE, %	0.1	-1,018	-957	-794	0	0	0	6.4	28.2
	50	-1,012	-952	-791	6	4	4	6.2	27.9
	90	-1,008	-954	-786	4	1	5	5.7	28.3
k, $kPamm^{-1}$	8.1	-1,660	-1,614	-1,614	0	0	0	2.8	2.8
	35.3	-1,149	-1,032	-1,032	510	583	583	11.4	11.4
	62.4	-1,007	-954	-792	142	78	240	5.6	27.2
	89.6	-932	-856	-653	75	98	138	8.9	42.6
Mesh size, mm × mm	152 × 152	-1,007	-956	-793	0	0	0	5.3	27.0
	254 × 178	-1,007	-954	-792	0	2	1	5.6	27.2
	305 × 305	-1,006	-951	-791	1	3	1	5.8	27.2
Temp. diff., ^{o}C	2.2	-211	-207	-207	0	0	0	2.3	2.3
	4.4	-427	-414	-414	215	207	207	3.1	3.1
	6.7	-721	-621	-621	294	207	207	16.1	16.1
	8.9	-1,072	-1,012	-828	351	391	207	6.0	29.5
	11.1	-1,455	-1,279	-1,035	383	267	207	13.7	40.5
	13.3	-1,861	-1,699	-1,242	406	420	207	9.5	49.8

[a] Absolute difference (ABD) of R_c between two adjacent input values in one parameter,

[b] % Difference of R_c in FE programs = $\left(\frac{Rc\ of\ ISLAB2000 - Rc\ of\ EverFE2.24}{Rc\ of\ EverFE2.24}\right)\times 100$,

[c] ISLAB 2000 with tensionless foundation, [d] EverFE2.24 with tensionless foundation, [e] EverFE2.24 with tension foundation.

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Table 3. Sensitivity of relative corner deflections (R_c) to input parameters in ISLAB 2000 and EverFE 2.24 at negative temperature difference condition

Input parameter	Input value	R_c, μM			ABD of R_c in input values[a], μM			Difference of R_c[b], %	
		ISLAB[c]	EverFE[d]	EverFE[e]	ISLAB[c]	EverFE[d]	EverFE[e]	ISLAB[c] & EverFE[d]	ISLAB[c] & EverFE[e]
Unit weight ,kgm^{-3}	2,240	851	806	611	0	0	0	5.5	39.2
	2,400	828	790	611	23	17	0	4.8	35.4
	2,560	807	776	611	21	14	0	4.0	31.9
Poisson's ratio	0.1	790	734	585	0	0	0	7.6	34.9
	0.2	828	790	611	38	56	26	4.9	35.5
	0.3	870	856	641	42	66	30	1.7	35.7
CTE, × 10^{-6} ε °C^{-1}	6.3	466	400	400	0	0	0	16.4	16.4
	9.63	828	790	611	363	390	211	4.9	35.5
	13.5	1,326	1,213	857	498	423	246	9.3	54.7
	17.1	1,838	1,629	1,085	512	416	228	12.8	69.4
Elastic modulus, MPa	13,790	486	470	390	0	0	0	3.2	24.7
	30,483	828	790	611	342	319	222	4.8	35.4
	41,370	970	922	711	143	132	100	5.2	36.5
LTE, %	0.1	843	796	613	0	0	0	5.9	37.5
	50	830	788	611	14	9	3	5.3	35.9
	90	828	790	607	1	2	4	4.9	36.5
k, kPamm^{-1}	8.1	1,276	1,247	1,247	0	0	0	2.4	2.4
	35.3	923	797	797	353	450	450	15.9	15.9
	62.4	828	790	611	95	7	185	4.9	35.5
	89.6	778	721	504	50	69	107	7.9	54.3
Mesh size, mm × mm	152 × 152	829	791	612	1	0	0	4.7	35.4
	254 × 178	828	790	611	1	2	1	4.9	35.5
	305 × 305	825	788	611	3	2	1	4.7	35.0
Temp. diff., °C	-2.2	212	208	208	0	0	0	2.0	2.0
	-4.4	488	415	415	276	207	207	17.7	17.7
	-6.7	847	807	621	359	392	206	5.0	36.5
	-8.9	1,266	1,091	829	419	284	208	16.1	52.7
	-11.1	1,724	1,536	1,036	459	446	207	12.3	66.5
	-13.3	2,208	1,923	1,243	484	387	207	14.8	77.7

[a] Absolute difference (ABD) of R_c between two adjacent input values in one parameter,

[b] % Difference of R_c in FE programs $= \left(\frac{Rc\ of\ ISLAB2000 - Rc\ of\ EverFE2.24}{Rc\ of\ EverFE2.24}\right)\times 100$,

[c] ISLAB 2000 with tensionless foundation, [d] EverFE2.24 with tensionless foundation, [e] EverFE2.24 with tension foundation.

4.1 Test pavement description

A newly constructed JPCP section on well-graded granular base on US-34 near Burlington, Iowa was selected for this study. The transverse joint spacing was approximately 6 m. The passing lane was approximately 3.7 m in width, and the travel lane was approximately 4.3 m in width. Tie-bars of 914 mm length and 12.7 mm diameter were inserted approximately every 762 mm across the longitudinal joints. Dowel bars of 457 mm length and 38 mm diameter were inserted approximately every 305 mm across the transverse joints. The powder type curing compounds were sprayed on slabs during early cure period, but no protection against wind was employed in the test sections.

Two test sections in the JPCP travel lane, one corresponding to afternoon (June 7, 2005, 5:30 PM CST) construction conditions and the other representative of late morning (June 8, 2005, 10:45 AM CST) construction, were selected for field data collection.

Thermochron I-Buttons® were placed throughout the depth of the pavement in each section during construction to observe the temperature effect on the slab behavior during early age (7 day after construction). As illustrated in figure 2, surface profiling was conducted using a rolling profiler (SurPRO 2000®) over diagonal and transverse directions on four individual slabs in each test section at different times (the morning and the afternoon) representing negative/positive pavement temperature difference conditions, especially, to study the slab deformation behavior.

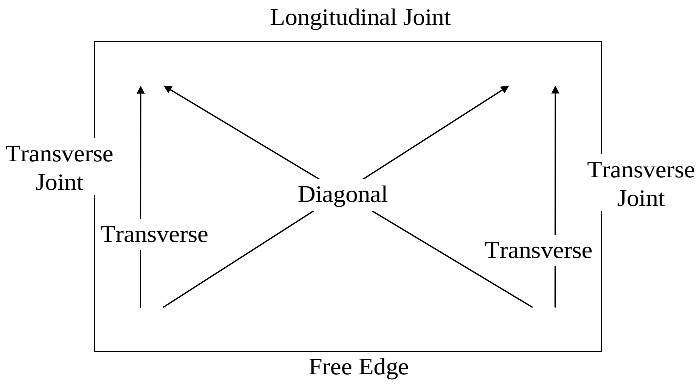

Figure 2. Surface profiling pattern

A rolling profiler can measure true unfiltered elevation profile of the slab surface (ICC, 2006). The raw elevation profile of surface was filtered using a procedure suggested by Sixbey et al. (2001) and Vandenbossche (2003) to obtain slab deformation patterns called "slab curvature profile". A series of laboratory tests were undertaken during the controlled field evaluation periods to provide material input parameter values for FE modeling. A more detailed description of the test sections and test procedures is provided by Kim (2006).

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4.2 Simulation methods

The FE simulations were conducted based on the actual geometric proportions and the collected material properties. Note that the actual geometric proportions in US-34 near Burlington, Iowa are same as the ones used for sensitivity analyses in this study. Uncollected input parameters, which are required in FE simulations but were not collected, were assigned “reasonable values” based on the results of previous sensitivity runs. For instance, it was observed that the slab deformation increased by increasing the modulus of subgrade reaction (k) from 8.1 $kPamm^{-1}$to 35.3 $kPamm^{-1}$, but after 35.3 $kPamm^{-1}$, the slab deformation did not increase much. The k-value, 35.3 $kPamm^{-1}$, is a typical minimum value for Iowa conditions and therefore, 62.4 $kPamm^{-1}$ was assumed as the k-value for the FE simulations.

The values of input parameters used in this simulation are summarized in table 4. A six-slab system (3 panels in each lane), as shown in figure 3, was used and the middle slab in the travel lane was selected representative of field conditions. Since previous sensitivity runs indicated no significant differences in curling analysis results between ISLAB 2000 and EverFE2.24 with same dense liquid foundation (the tensionless supporting foundation), the tensionless supporting liquid foundation for ISLAB 2000 and the tension supporting liquid foundation for EverFE2.24 were selected in comparing the measured slab deformations.

Even though the slab temperature profile with depth has been recognized as a non-linear distribution, the observed temperature profiles under which pavement profile data were collected in this study showed a nearly linear temperature distribution as illustrated in figure 4, so that a temperature difference between the top and bottom of slab was used in this simulation.

Table 4. Values of input parameters used in FE simulation

Geometry properties

Layer	Lane	No. of slabs	Slab width (m)	Slab length (m)	Slab depth (mm)
Concrete	Passing	3	3.7	6	267
	Travel	3	4.3	6	267

Material properties

Material	Property	Value
Concrete	Modulus of elasticity (MPa)	22,000
	Unit weight (kgm^{-3})	2,400
	Poisson's ratio	0.2
	Coefficient of Thermal Expansion (ε °C^{-1})	11.2×10^{-6}
Dowel bar	Diameter (mm)	38
	Length (mm)	457
	Spacing (mm)	305
	Modulus of elasticity (MPa)	200,000
	Poisson's ratio [a]	0.3
Tie bar	Diameter (mm)	13
	Length (mm)	914
	Spacing (mm)	762
	Modulus of elasticity (MPa)	200,000
	Poisson's ratio [a]	0.3
Subgrade	Modulus of subgrade reaction (kPamm^{-1})	62.4

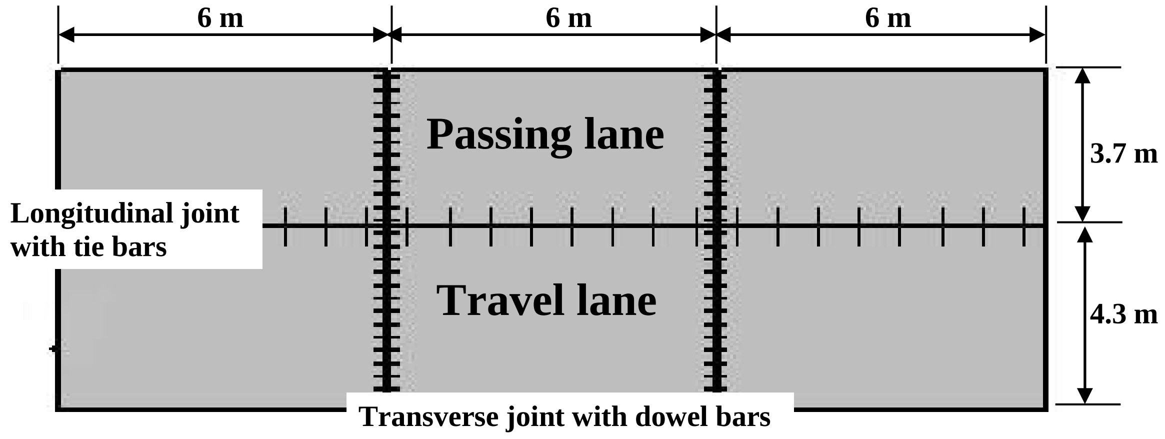


Figure 3. PCC slab system layout used in finite element simulation.

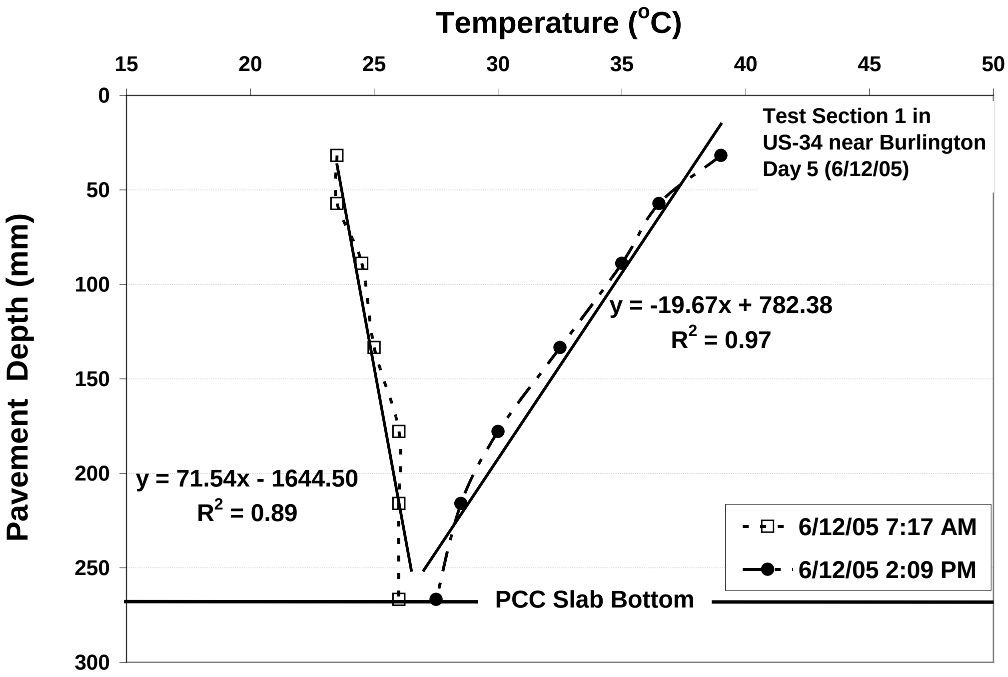


Figure 4. The example of the observed temperature profiles under which pavement profile data were collected.

4.3 Equivalent Temperature Difference

Even though ISLAB 2000 and EverFE 2.24 can model slab deformations due to temperature changes, they cannot directly model the slab deformations due to moisture variations and permanent curling and warping, which can be significant for concrete pavement behaviors. Therefore, if FE modeling was conducted using the actual material inputs and the linear / non-linear temperature distribution, the calculated deflection could not estimate the actual deflection due to environmental effects (Rao et al, 2001). However, it has been believed that this limitation of these FE programs could be circumvented if the effects of other environmental effects could be converted to equivalent temperature difference (Korovesis, 1990; Davids, 2003).

Since all of the environmental effects are highly correlated with each other, it is quite difficult to quantify each of these effects in terms of temperature differences. Therefore the concept of combining all of the active effects into an ‘equivalent temperature difference’ has been used by previous researchers (Rao et al., 2001; Yu and Khazanovich, 2001; Jeong and Zollinger, 2004; Rao and Roesler, 2005). Using this concept, the relation between actual measured temperature difference and equivalent temperature difference associated with actual pavement behavior could be established. An equivalent temperature difference was determined to produce each FE calculated deformation that matches measured deformation (measured along the slab diagonal for a given measured temperature

Reference to this paper should be made as follows: Kim, S., Ceylan, H., and Gopalakrishnan, K. (2014). "Finite Element Modelling of Environmental Effects on Rigid Pavement Deformation," Frontiers of Structural and Civil Engineering Journal, Volume 8, Issue 2, pp. 101-114.

difference). Once the equivalent differences were determined for all of the measured temperature differences, they were plotted to develop the linear relations shown in figures 5 and 6.

Based on linear regression equations from figures 5 and 6, equivalent temperature differences calculated from measured pavement profile data were used as inputs for both FE programs. Note that the linear regression equations from figures 5 and 6 are different because of different foundation models used.

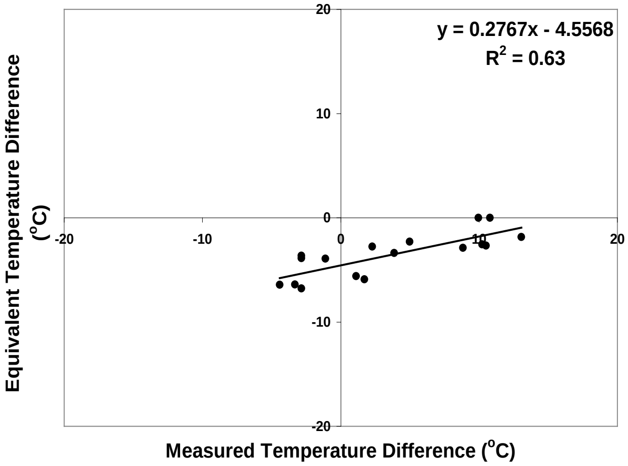


Figure 5. Equivalent temperature difference versus measured temperature difference for ISLAB 2000 with tensionless foundation.

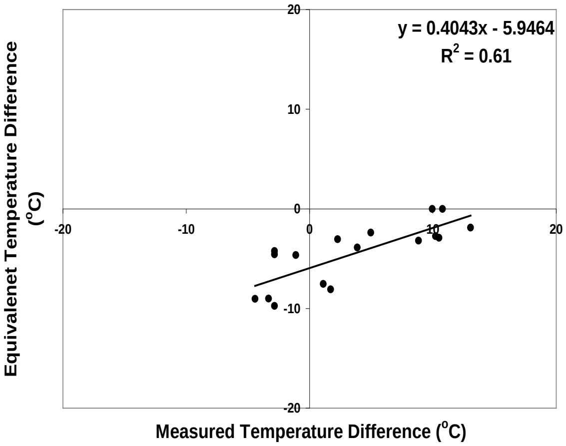
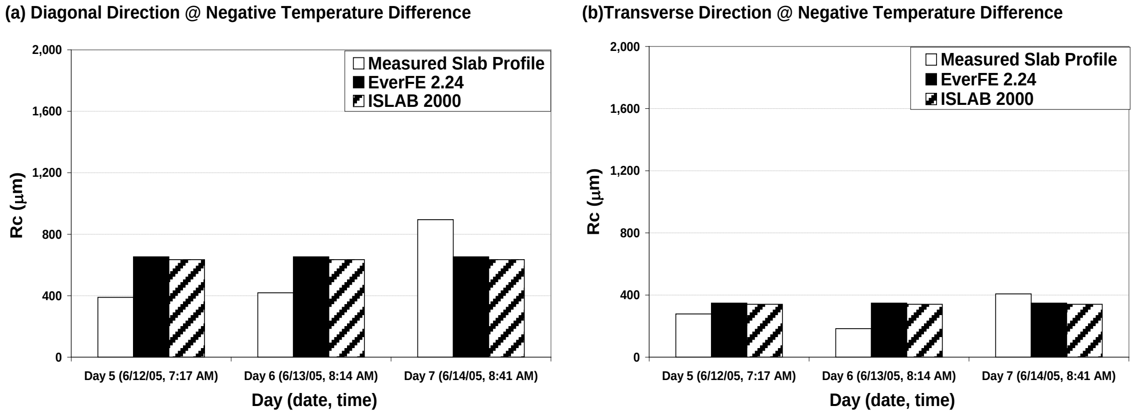


Figure 6. Equivalent temperature difference versus measured temperature difference for EverFE2.24 with tension foundation.

Reference to this paper should be made as follows: Kim, S., Ceylan, H., and Gopalakrishnan, K. (2014). "Finite Element Modelling of Environmental Effects on Rigid Pavement Deformation," Frontiers of Structural and Civil Engineering Journal, Volume 8, Issue 2, pp. 101-114.

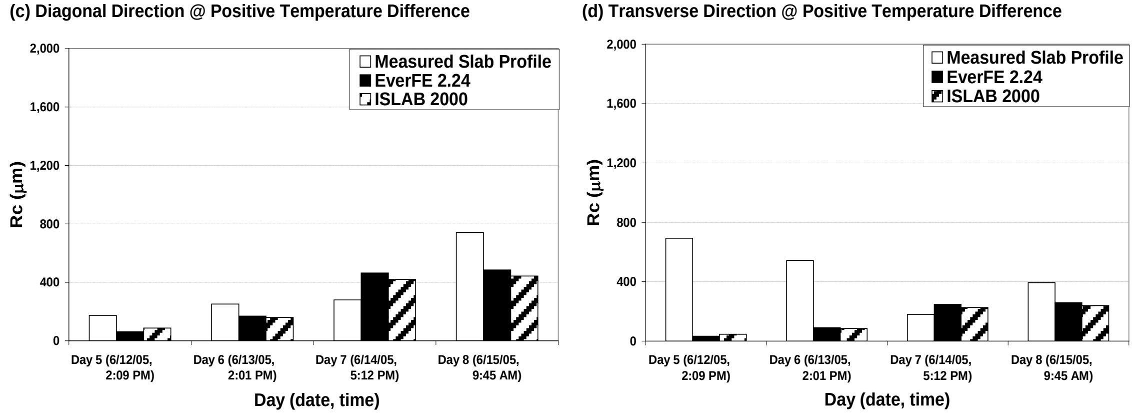
4 Examination of FE models based on field measurements

Comparisons between the field-measured slab curvature profiles and the FE-computed slab curvature profiles in terms of R_c and the curvature of slab profile (k) were undertaken to evaluate the accuracy of the FE-based models. The curvature of slab profile (k) was calculated using a methodology reported by Vandenbossche and Snyder (2005). The quantitative comparisons between the measured profiles and the FE-modeled profiles for test section 1 and test section 2 are presented in figures 7, 8, 9 and 10.



(a) Diagonal Direction @ Negative Temperature Difference

(b)Transverse Direction @ Negative Temperature Difference

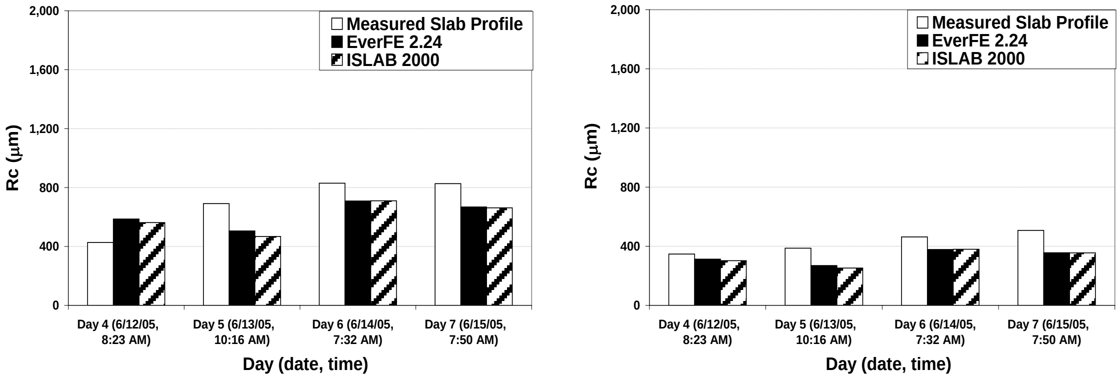


(c) Diagonal Direction @ Positive Temperature Difference

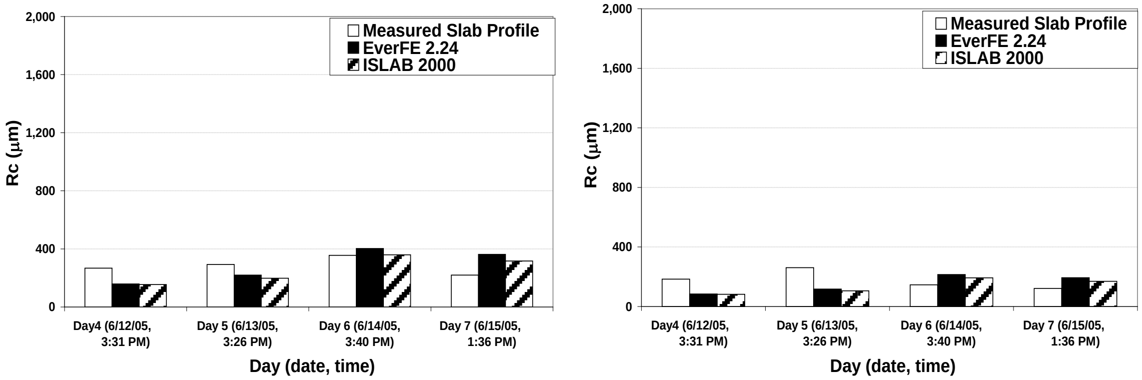
(d) Transverse Direction @ Positive Temperature Difference

Figure 7. Comparison of relative corner deflection (R_c) between measured and FE-predicted slab curvature profiles in test section 1: (a) diagonal direction at negative temp. diff.; (b) transverse direction at negative temp. diff.; (c) diagonal direction at positive. temp. diff.; (d) transverse direction at positive temp. diff.

Reference to this paper should be made as follows: Kim, S., Ceylan, H., and Gopalakrishnan, K. (2014). "Finite Element Modelling of Environmental Effects on Rigid Pavement Deformation," Frontiers of Structural and Civil Engineering Journal, Volume 8, Issue 2, pp. 101-114.


(a) Diagonal Direction @ Negative Temperature Difference

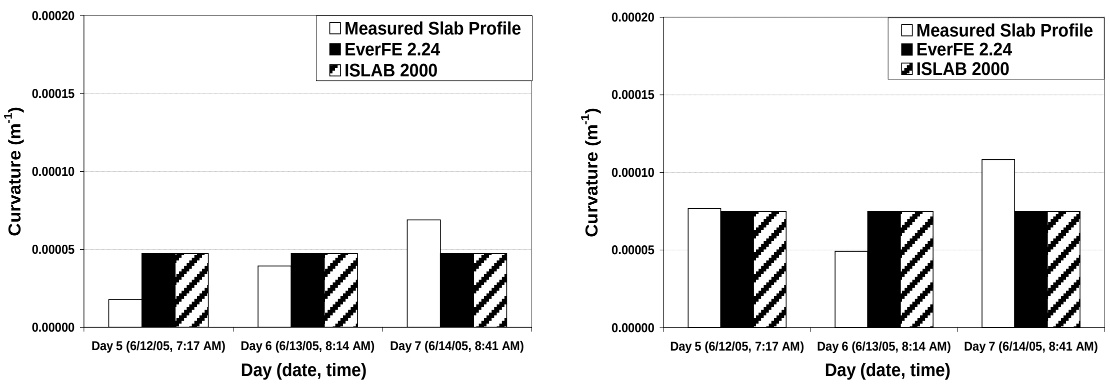
(b) Transverse Direction @ Negative Temperature Difference


(c) Diagonal Direction @ Positive Temperature Difference

(d) Transverse Direction @ Positive Temperature Difference

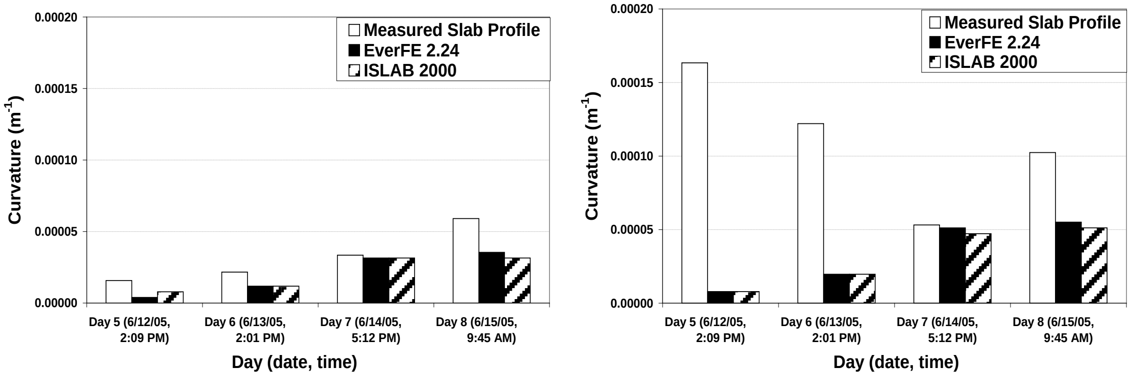
Figure 8. Comparison of relative corner deflection (R_c) between measured and FE-predicted slab curvature profiles in test section 2: (a) diagonal direction at negative temp. diff.; (b) transverse direction at negative temp. diff.; (c) diagonal direction at positive. temp. diff.; (d) transverse direction at positive temp. diff.

Reference to this paper should be made as follows: Kim, S., Ceylan, H., and Gopalakrishnan, K. (2014). “Finite Element Modelling of Environmental Effects on Rigid Pavement Deformation,” Frontiers of Structural and Civil Engineering Journal, Volume 8, Issue 2, pp. 101-114.



(a) Diagonal Direction @ Negative Temperature Difference

(b) Transverse Direction @ Negative Temperature Difference



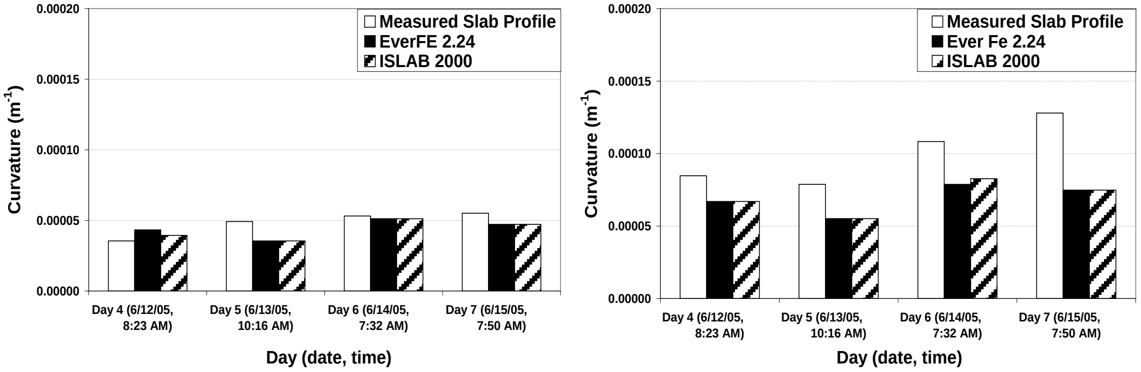
(C) Diagonal Direction @ Positive Temperature Difference

(d) Transverse Direction @ Positive Temperature Difference

Figure 9. Comparison of curvature (*k*) between measured and FE-predicted slab curvature profiles in test section 1: (a) diagonal direction at negative temp. diff.; (b) transverse direction at negative temp. diff.; (c) diagonal direction at positive temp. diff.; (d) transverse direction at positive temp. diff.

(a) Diagonal Direction @ Negative Temperature Difference

(b) Transverse Direction @ Negative Temperature Difference



(c) Diagonal Direction @ Positive Temperature Difference

(d) Transverse Direction @ Positive Temperature Difference

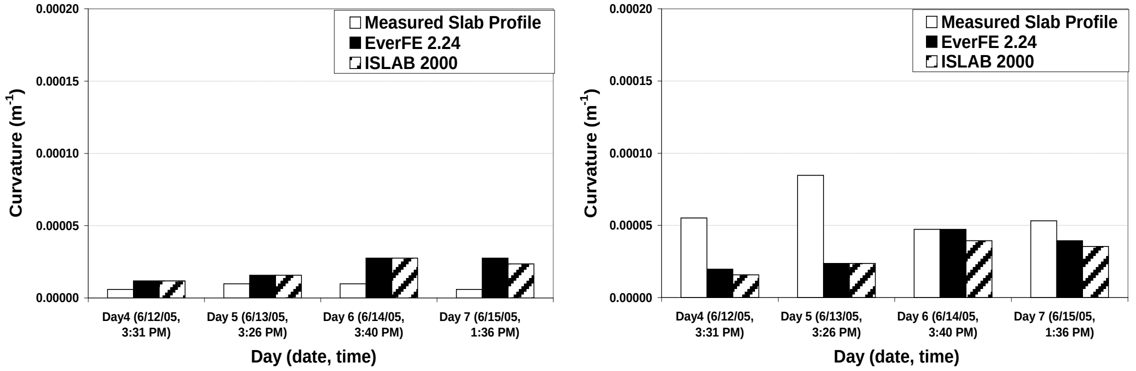


Figure 10. Comparison of curvature (*k*) between measured and FE-predicted slab curvature profiles in test section 2: (a) diagonal direction at negative temp. diff.; (b) transverse direction at negative temp. diff.; (c) diagonal direction at positive temp. diff.; (d) transverse direction at positive temp. diff.

From these figures, it is clearly noted that the measured slab curvature profiles at negative temperature differences show more pronounced upward curl than at positive temperature differences, except for transverse direction measurements on test section 1. The behavior of transverse direction measurement on test section 1 is quite difficult to explain. The deflection due to temperature changes could be confounded by other environmental effects such as moisture loss, especially at early ages under poor curing conditions of JPCP. However, it is believed that temperature change could be a main dominating factor for slab deformation due to environmental effects. At this time, the only plausible explanation for this behavior is that built-in construction slope in the transverse direction could be higher than in the diagonal direction. The built-in construction slopes used to normalize the raw surface profile data were not measured, but estimated from the raw profile data. Therefore, they still influenced the slab curvature profile and the relative corner-to-edge deflection used in transverse slab edge curvature profile may be less obvious than the relative corner-to-center deflection.

An Analysis of Variance (ANOVA) statistical test was conducted to determine whether the measured slab curvature properties (R_c and *k*) were statistically different from the FE-based predictions. ANOVA results can be expressed in terms of a p-value, which represents the weight of evidence for rejecting the null hypothesis (Ott and Longnecker, 2001). The null hypothesis of sample equality cannot be rejected if the p-value is greater than the selected significance level. Table 5 presents the ANOVA results for R_c and *k* in terms of p-value. For the significance level (α) of 0.05, table 5 confirms that the FE-based predictions provide good estimates of slab curvature properties in terms of R_c and *k* under different conditions except the positive temperature transverse direction profiles. Considering the transverse direction measurements on test section 1 as discussed previously, the inaccuracy of FE-predictions for the positive temperature transverse profiles is not unexpected.

Table 5. ANOVA results for R_c and *k* of slab curvature profiles

Temperature Difference Condition	Response	Direction			
		Diagonal		Transverse	
		p-value	Predicted vs Actual: Different ?	p-value	Predicted vs Actual: .Different ?
Positive	R_c	0.67	No	0.00	Yes
	k	0.99	No	0.00	Yes
Negative	R_c	0.91	No	0.70	No
	k	0.99	No	0.18	No

5 Conclusions

This study evaluated two FE-based primary response models, namely ISLAB 2000 and EverFE 2.24, used in characterizing the deformation of early age JPCP under environmental effects. Using typical rigid pavement geometry for Iowa highway pavements, sensitivity analyses were conducted using ISLAB 2000 and EverFE 2.24 for identifying the input parameters that have the most influence on PCC slab deflection due to environmental effects. The procedure and the results of the FE analyses based on established input parameter combinations and equivalent temperature differences were presented. Comparisons between the field-measured and the FE-computed slab deformations due to environmental effects were performed. Based on the results of this study, the following conclusions were drawn:

- A good agreement of curling analysis results between ISLAB 2000 and EverFE 2.24 FE could be obtained when using same dense liquid foundation model (the tensionless supporting foundation).
- An equivalent temperature difference at a certain temperature difference can simply be determined by making the FE calculated deformation match the measured deformation.

- The results from this study showed that the computed slab deformations from both FE programs using equivalent temperature difference have reasonable agreement with the field measured deformations.
- Temperature difference and CTE are the parameters to which slab deformations are most sensitive based on ISLAB 2000 and EverFE 2.24 FE analyses for typical rigid pavement geometry used in Iowa.

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References

Armaghani, J. M., Lybas, J. M., Tia, M., and Ruth, B. E., Concrete pavement joint stiffness evaluation. Transportation Research Record 1099, Transportation Research Board-National Research Council, Washington, D.C., 1986, 22-36.

Beckemeyer, C. A., Khazanovich, L., and Yu, H. T., Determining amount of built-in curling in jointed plain concrete pavement: case study of Pennsylvania I-80. Transportation Research Record 1809, Transportation Research Board-National Research Council, Washington, D.C., 2002, 85-92.

Ceylan, H., Kim, S., Gopalakrishnan, K., and Wang, K., Environmental Effects on Deformation and Smoothness Behavior of Early Age Jointed Plain Concrete Pavements. Transportation Research Record: Journal of the Transportation Research Board, No. 2037, 2007, pp. 30–39.

Chatti, K., Lysmer, J., and Monismith, C. L., Dynamic finite element analysis of jointed concrete pavement. Transportation Research Record 1449, Transportation Research Board- National Research Council, Washington, D.C., 1994, 79-90.

Davids, W. G., Turkiyyah, G. M., and Mahoney, J. P., EverFE: rigid pavement three – dimensional finite element analysis tool. Transportation Research Record 1629, Transportation Research Board-National Research Council, Washington, D.C., 1998, 41-49.

Davids, W. G. and Turkiyyah, G. M., Multigrid preconditioner for unstructured nonlinear 3D FE models. Journal of Engineering Mechanics, American Society of Civil Engineering, 1999, **125**(2), 186-196.

Davids, W. G., 3D finite element study on load transfer at doweled joints in flat and curled rigid pavements. The International Journal of Geomechanics, American Society of Civil Engineering, 2001, **1**(3), 309-323.

Davids, W. G., *EverFE theory manual*, University of Maine, Civil Engineering Department, 2003, 1-18.

Davids, W. G., Wang, Z., Turkiyyah, G. M., Mahoney, J. P. and Bush, D., Three-dimensional finite element Analysis of jointed plan concrete pavement with EverFe

2.2. Transportation Research Record 1853, Transportation Research Board-National Research Council, Washington, D.C., 2003, 92-99.

Davids, W. G., EverFE: software for the 3D finite element analysis of jointed plain concrete pavements. Available at http://www.civil.umaine.edu/EverFE (Accessed May, 2006), University of Maine, Civil Engineering Department.

Hammons, M. I. and Ioannides, A. M., *Advanced pavement design: finite element modeling for rigid pavement joints-report I: background investigation*, Technical Report DOT- FAA- AR-95-85, Federal Aviation Administration, U.S. Department of Transportation, Washington, D.C., 1997.

International Cybernetics Corporation (ICC), Rollingprofiler, Available at http://www.internationalcybernetics.com/ rollprofile.htm (accessed May, 2006).

Ioannides, A. M. and Salsili-Murua, R. A., Temperature curling in rigid pavements: an application of dimensional analysis. Transportation Research Record 1227, Transportation Research Board-National Research Council, Washington, D.C., 1989, 1-10.

Ioannides, A. M. and Korovesis, G. T., Aggregate interlock: a pure-shear load transfer mechanism. Transportation Research Record 1286, Transportation Research Board-National Research Council, Washington, D.C., 1990, 14-24.

Ioannides, A. M. and Korovesis, G. T., Analysis and design of doweled slab-on-grade pavement systems. Journal of Transportation Engineering, American Society of Civil Engineering, 1992, **118**(6), 745-768.

Iowa Department of Transportation (IDOT), Standard road plans. Electronic Reference Library, 2005, Available at http://165.206.203.37/Oct_2005/RS/frames.htm (accessed May, 2006).

Jeong, J. H. and Zollinger, D. G., Insights on early age curling and warping behavior from fully instrumented test slab system. CD-ROM, Presented at 83rd Annual Transportation Research Board Meeting, Transportation Research Board, Washington, D.C., 2004.

Khazanovich, L., Yu, H. T., Rao, S., Galasova, K., Shats, E., and Jones, R., *ISLAB 2000-finite element analysis program for rigid and composite pavements: user's guide*, ERES Consultant, Urbana Champaign, Illinois, 2000.

Kim S., Early age behavior of jointed plain concrete pavements subjected to environmental loads. PhD thesis, Iowa State University, Ames, 2006Kim, S., Ceylan, H., and Gopalakrishnan, K. (2008) Smoothness variations of early-age jointed plain concrete pavements. Canadian Journal of Civil Engineering, 2008, **35** (12), 1388-1398.

Korovesis, G. T., Analysis of slab on grade pavement systems subjected to wheel and temperature loadings. PhD thesis, University of Illinois, Urbana Champaign, 1990.

Lim, S. W. and Tayabji, S. D., Analytical technique to mitigate early-age longitudinal cracking in jointed concrete pavements. Proceedings of 8th International Conference on Concrete Pavements, Colorado Springs, Colorado, 2005.

National Cooperative Highway Research Program (NCHRP), *Guide for mechanistic-empirical design of new and rehabilitated pavement structures*, Available one line at:

http://trb.org/mepdg, National Cooperative Highway Research Program 1-37 A, Transportation Research Board, Washington, D.C., 2004.

Ott, L. R. and Longnecker, M., *An introduction to statistical methods and data analysis*, 5th edition, Duxbury, Pacific Grove, CA, 2001.

Rao, C., Barenberg E. J., Snyder, M. B., and Schmidt, S., Effects of temperature and moisture on the response of jointed concrete pavements. Proceedings of 7th International Conference on Concrete Pavements, Orlando, Florida, 2001.

Rao, S. and Roesler, J. R., Characterizing effective built in curling from concrete pavement field measurements. Journal of Transportation Engineering, American Society of Civil Engineering, 2005, **131**(4), 320-327.

Siddique, Z. and Hossain, M., Finite element analysis of PCCP curling and roughness. Proceedings of 8th International Conference on Concrete Pavements, Colorado Springs, Colorado, 2005.

Sixbey, D., Swanlund, M., Gagarin, N., and Mekemson, J. R. Measurement and analysis of slab curvature in JPC pavements using profiling technology. Proceedings of 7th International Conference on Concrete Pavements, Orlando, Florida, 2001.

Vandenbossche, J. M. and Snyder, M. B., Comparison between measured slab profiles of curled pavements and profile generated using the finite element method. Proceedings of 8th International Conference on Concrete Pavements, Colorado Springs, Colorado, 2005.

Vandenbossche, J. M., Interpreting falling weight deflectometer results for curled and warped portland cement concrete pavements. PhD Thesis, University of Minnesota, Minneapolis, Minnesota, 2003.

Vepa, T. S. and George, K. P., Deflection response model for cracked rigid pavements. Journal of Transportation Engineering, American Society of Civil Engineering, 1997, 123 (5), 377-384.

Wang, W., Basheer, I. and Petros, K., Jointed plain concrete pavement models evaluation. CD-ROM, Presented at 85th Annual Transportation Research Board Meeting, Transportation Research Board, Washington, D.C., 2006.

Westergaard, H. M., Analysis of stresses in concrete pavements due to variations of temperature. Proceedings of Highway Research Board 6, National Research Council, Washington, D.C., 1927, 201-215.

Yu, H. T., Khazanovich, L., Darter, M. I., and Ardani, A., Analysis of concrete pavement response to temperature and wheel loads measured from instrumented slab. Transportation Research Record 1639, Transportation Research Board-National Research Council, Washington, D.C., 1998, 94-101.

Yu, H. T. and Khazanovich, L., Effect of construction curling on concrete pavement behavior. Proceedings of 7th International Conference on Concrete Pavements, Orlando, Florida, 2001.

Yu, H. T., Khazanovich, L., and Darter, M. I., 2004, Consideration of JPCP curling and warping in the 2002 design guide. CD-ROM, Presented at 83rd Annual Transportation Research Board Meeting, Transportation Research Board, Washington, D.C., 2004.