A SIMPLIFIED APPROACH FOR PREDICTING EARLY-AGE CONCRETE PAVEMENT DEFORMATION

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Abstract. Studies on deformation characteristics of early-age Jointed Plain Concrete Pavements (JPCP) due to environmental effects have drawn significant interest over the years. However, the complex nature of the problem arising from interacting environmental factors has resulted in difficulties in predicting the JPCP deformation characteristics. This study introduces a simplified approach for predicting the early-age deformation of JPCP due to environmental factors using an equivalent temperature difference concept. 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. Based on the collected field data, the total equivalent linear temperature difference (ΔT_{teltd}) corresponding to the actual deformation was quantified using Finite Element (FE) based approach, namely ISLAB 2000. The FE-based calculations were compared with the field measured slab deformation properties. Better predictions were obtained when employing a simplified equivalent temperature difference (ΔT_{teltd}) concept for FE based primary response model.

Keywords: concrete, JPCP, curling, warping, finite element analysis, equivalent temperature difference, pavement analysis and design.

1. Introduction

Research on the early-age deformation of Portland Cement Concrete (PCC) slab due to pure environmental effects (i.e., without traffic loading) has drawn significant interest recently (Siddique and Hossain 2005; Rao *et al.* 2001). It is believed that the early-age slab deformation could result in the loss of pavement smoothness (Siddique and Hossain 2005) and the tensile stress induced by these deformations could result in early-age cracking (Lim and Tayabji 2005). Even though the deformation of slab due to environmental effects 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 and Roesler 2005; Rufino and Roesler 2006) may also be involved. Especially, the complex interactions of different factors involved results in "locked-in" curvature such that the slab shape at zero-temperature gradient is not flat (Byrum 2001). This permanent deformation makes the prediction of PCC deformation due to environmental effects difficult.

The Finite Element Method (FEM) is believed to provide analytical solution for predicting the PCC deformation resulting from environmental effects because FEM can solve a broad class of boundary value problems (Hammons and Ioannides 1997). And, the FE programs, specifically developed for rigid pavement analysis such as ISLAB 2000 (Khazanovich *et al.* 2000) and EverFE 2.24 (Davids 2003, 2006), include the analysis of pavement response due to temperature changes as well. However, the actual temperature distributions should be adjusted in these programs to provide prediction of deformation due to moisture variations and permanent deformation which can be obvious during early age of the PCC (Rao *et al.* 2001). For this purpose, researchers have recently attempted to convert the all of environmental effects into an "equivalent temperature difference" (Rao *et al.* 2001; Yu and Khazanovich 2001; Jeong and Zollinger 2004; Yu *et al.* 2004; Rao and Roesler 2005).

This study focuses on predicting the early-age deformation of JPCP due to environmental loads using the simplified equivalent temperature difference (ΔT_{teltd}) concept with Finite Element (FE) based primary response model, namely ISLAB 2000. ISLAB 2000 was primarily selected because ISLAB 2000 was used as the main structural model for generating pavement responses in the new Mechanistic-Empirical Pavement Design Guide (MEPDG) under the National Cooperative Highway Research Program (NCHRP) 1–37A project (NCHRP 2004) in US.

For this study, a newly constructed JPCP section on highway US–30 near Marshalltown, Iowa was instrumen-

ted to monitor the pavement response to variations in temperature and moisture during first seven days after construction. Based on collected field data, the equivalent temperature difference corresponding to actual deformation due to environmental effects were quantified with FE based approach. The procedures and the results of FE model, based on the collected data and the quantified equivalent temperature differences, are discussed. Comparisons between the field measured and the FE-computed slab deformations are presented in this paper.

2. Equivalent Temperature Difference Concept

The temperature and moisture variations across the depth of rigid pavements result in pavement deformation. In addition, a higher unrecoverable drying shrinkage of concrete near the top of the slab and a positive temperature gradient during the concrete hardening can cause permanent displacement at zero-temperature gradient (Yu *et al.* 2004). There is also the weight of the slab contributing to the creep of the slab. Therefore, the displacement caused by each of these factors must be taken into consideration. The total environmental effect resulting in PCC slab deformation is represented as a temperature difference between top and bottom of slab – the total equivalent linear temperature difference (TELTD), ΔT_{teltd} (Yu *et al.* 2004; Rao and Roesler 2005):

$$\Delta T_{teltd} = \Delta T_{transient} + \Delta T_{permanent}, \qquad (1)$$

where: ΔT_{teltd} – total equivalent linear temperature difference; $\Delta T_{transient}$ – transient component of total equivalent linear temperature difference; and $\Delta T_{permanent}$ – permanent component of total equivalent linear temperature difference, called as permanent curling and warping effective temperature difference in MEPDG. Fig. 1 presents a schematic of TELTD concept.

As seen in Fig. 1, the transient component caused by daily or seasonal weather condition change can result in slab deflection variation while the permanent component caused by the combination of several environmental effects induce the deflection of slab at zero-temperature and zero-moisture gradient. The transient component of ΔT_{teltd} is the sum of the temperature difference between top and bottom of slab equivalent to (producing similar response to) actual temperature gradient ($\Delta T_{trans-temp-diff}$) and moisture gradient ($\Delta T_{trans-mois-diff}$). The permanent component of ΔT_{teltd} consists of (1) built-in temperature difference between top and bottom of slab during the time of PCC construction or hardening ($\Delta T_{perm-temp-diff}$), (2) temperature difference between top and bottom of slab equivalent to (producing similar response to) irreversible differential dry shrinkage component between top and bottom of slab ($\Delta T_{perm-mois-diff}$), and (3) temperature difference between top and bottom of a slab equivalent to (producing similar response to) creep behavior of slab ($\Delta T_{perm-creep}$).

Although the total environmental effect resulting in slab displacements could be theoretically decomposed, the concept of an equivalent temperature difference to combine all the active effects has more often been used by researchers (Rao *et al.* 2001; Jeong and Zollinger 2004; Rao and Roesler 2005) since the environmental effects are highly correlated with each other and some effects such as non–uniform moisture distribution are difficult to quantify in terms of temperature difference. Hiller and Roesler (2005) summarized ΔT_{teltd} values reported by previous researchers.

3. Test Sections and Data Collection

A newly constructed 267 m (10.5 in) thickness JPCP section on a 152 to 260 mm (6 to 10 in) open-graded granular base on US–30 near Marshalltown, Iowa was selected for this study. 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
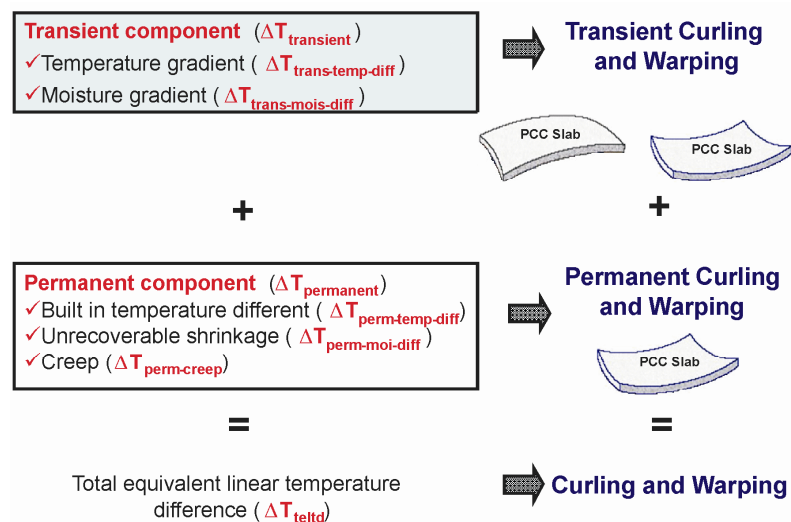

Fig. 1. The concept of total equivalent linear temperature difference (TELTD, ΔT_{teltd})

was approximately 4.3 m (14 ft) in width. Tie-bars of 914 mm (36 in) length and 12.7 mm (0.5 in) diameter were inserted approximately every 762 mm (30 in) across the longitudinal joints. Dowel bars of 457 mm (18 in) length and 38 mm (1.5 in) diameter were inserted approximately every 305 mm (12 in) across the transverse joints. A bituminous shoulder was added about 2 months after construction. 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 days after construction. During the field evaluation periods, the weather was clear and sunny.

As shown in Fig. 2, two test sections in the JPCP travel lane, one representative of afternoon (3:30 PM CST) construction and the other corresponding to late morning (11:00 AM CST) construction conditions construction, were selected for data collections in this study.

Thermochron I-Buttons® were placed throughout the depth of the pavement on each section and Hygrochron I-Buttons® were installed at various depths on test section 1 during construction to observe the temperature and moisture effect on the slab behavior during early age (7 day after construction). Slab temperature and moisture data were collected at five–minute intervals throughout the field evaluation periods.
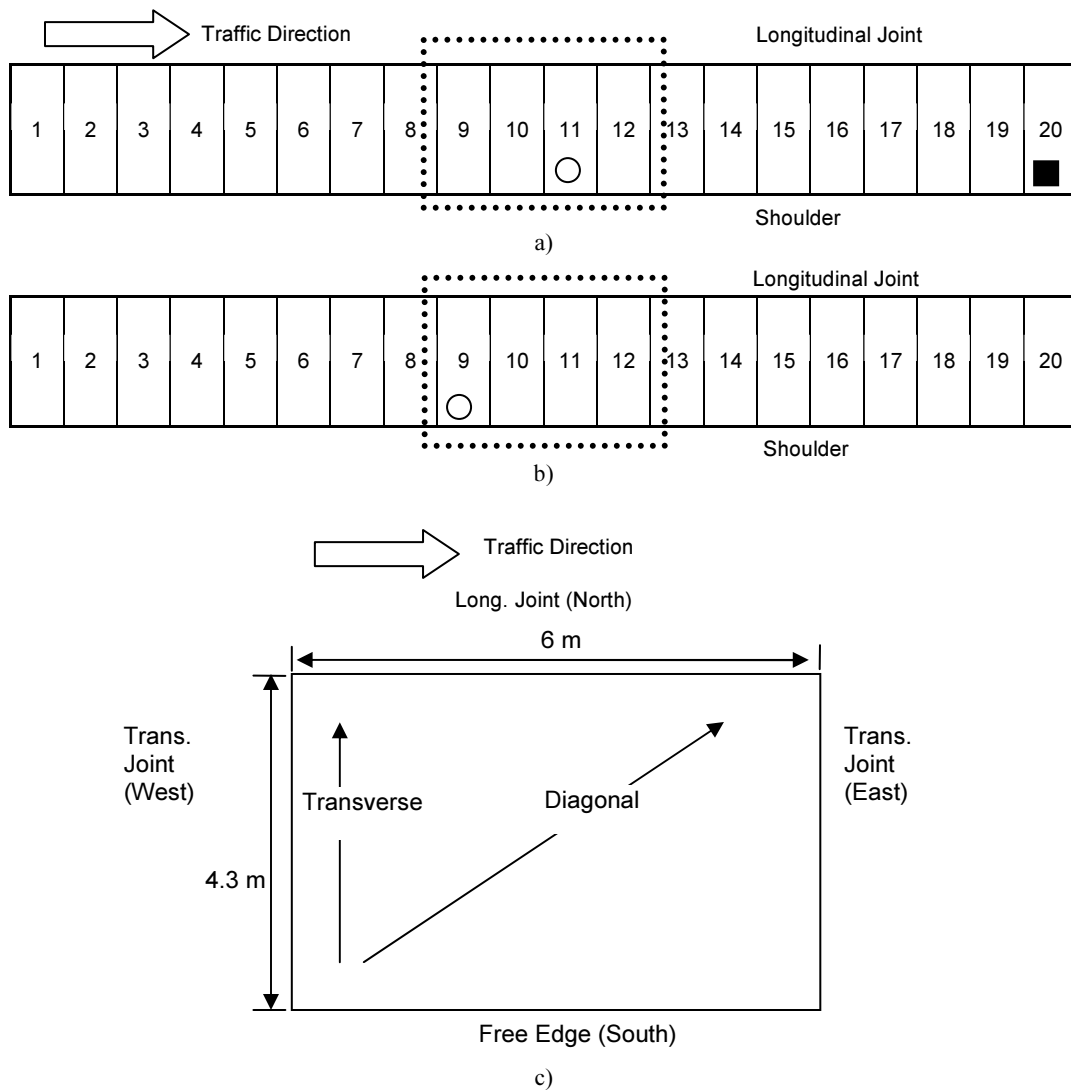
Fig. 2. Instrumentation layout in JPCP test sections: a) test section 1 – paving during afternoon hours (7/13/05, 3:30 PM CST); b) test section 2 – paving during late morning hours (7/14/05, 11:00 PM CST); c) profiling pattern

Surface profiling was conducted with a rolling profiler (SurPRO 2000®) following diagonal and transverse directions on four individual slabs in each test section at different times (morning and the afternoon) representing negative/positive pavement temperature difference conditions to study the slab deformation behavior. 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 pattern called as "slab curvature profile". Each profiling segment was measured independently. Details of the instrumentation and data acquisition procedure of each section are available in Kim (2006).

4. Field Data Results

Slab temperature, moisture and surface profile measurements were taken over a seven-day period after construction on these test sections. The results from these test sections provide an excellent source of information for understanding the early age slab displacement behavior under environmental loading. The results are summarized in the following sections.

4.1. Temperature and Moisture

Temperature differences were calculated by subtracting the temperature sensor reading at the bottom of slab from the reading of sensor closest to the top of the pavement surface. Moisture differences were computed by subtracting the moisture sensor reading at the middle of slab from the moisture sensor reading closest moisture sensor to the slab surface. The variations in temperature and moisture differences with time are plotted in Fig. 3. 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 in Fig. 3 show the reverse trend. Especially during day 0 to day 2 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 day 0 to day 2 of paving.
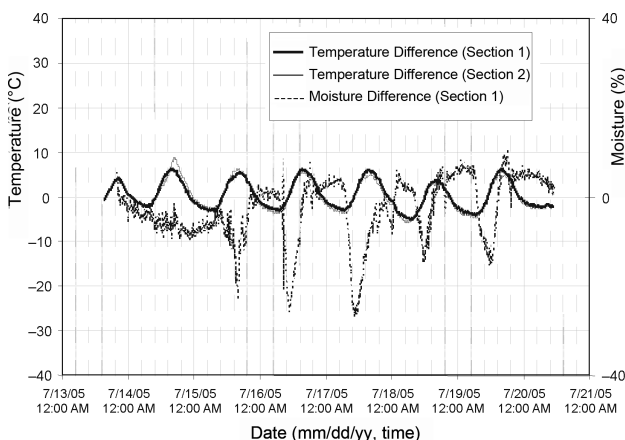
4.2. Profile Measurement Response from Environmental Effects

The typical diagonal direction slab curvature profile in this study is displayed in Fig. 4 for illustration. A negative temperature or moisture difference result in upward movement of the slab (upward slab curling or warping) while a positive temperature or moisture difference result in downward movement of the slab (downward slab curling or warping). However, the slab curvature profile measured in test sections clearly showed upward curling for the morning measurements corresponding to negative temperature difference and almost flat shape for the afternoon measurements corresponding to positive temperature difference.

This phenomenon may be related to a certain positive temperature gradient which results in flat slab condition. A positive temperature gradient occurred due to daytime construction and heat of hydration. This positive temperature gradient could result in upward movement of the slab. Due to rapid drying of moisture in the exposed slab surface, there might have been drying shrinkage of concrete near the slab top and a higher saturated condition at the slab bottom. This drying shrinkage of concrete could result in downward movement of the slab. These behaviors in combination with slower moisture movement through slab depth compared to temperature led to a flat-slab condition at positive temperature gradient. This phenomenon has been commonly observed in previous research studies focusing on the early age behavior of PCC (Yu *et al.* 1998; Rao *et al.* 2001; Rao and Roesler 2005; Vandenbossche *et al.* 2006). In addition, the concrete is still plastic immediately after construction and hence it is quite difficult to support the whole weight just by the slab corners (Byrum 2001). Therefore, when a zero-temperature gradient occurs, the slab tends to curl upwards (Yu *et al.* 1998; Rao *et al.* 2001; Rao and Roesler 2005; Vandenbossche *et al.* 2006).

Therefore, the observed slab curvature profiles clearly demonstrate that the early-age JPCP slab curling behavior can not only account for temperature variations but also other environmental effects such as moisture and temperature conditions during PCC hardening.
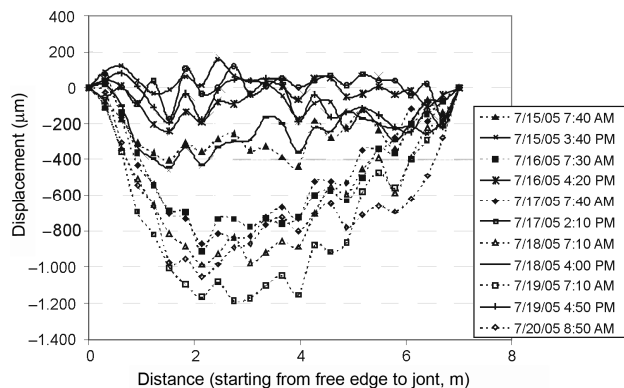
Fig. 3. Pavement temperature and moisture difference between the top and the bottom of slab with time

Fig. 4. Typical diagonal direction slab curvature profile (test section 1)

5. FE Model for Slab Deformation

FE modeling of ISLAB 2000 was conducted to understand the early age deformation behavior of concrete pavement systems under environmental loads in more detail. ISLAB 2000 can simulate the slab deformations due to temperature changes but cannot directly simulate the slab deformations due to moisture variation and permanent deformation at zero-temperature difference which can be quite obvious during the early age. Therefore, an actual temperature gradient should be adjusted to a total equivalent linear temperature difference, ΔT_{teltd}, to entirely reflect the deflection of the slabs due to environmental effects (Rao *et al.* 2001).

5.1. FE Modeling of Instrumented Pavements

A six-slab system (3 panels in each lane), as shown in Fig. 5, were used and middle slab in the travel lane was selected for representing field measurements. The actual geometric proportions and the collected material properties from the test sections are used for modeling. Those material input parameters which were required in FE simulations, but could not be collected, were assigned typical values for Iowa conditions. Table 1 summarizes the values of material input parameters used in this modeling.
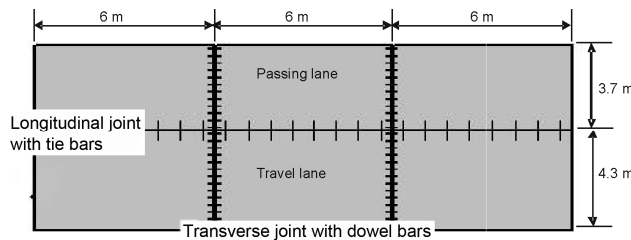
Fig. 5. PCC slab systems layout used in FE simulation

Table 1. Material input parameters

Material	Property	Value
PCC	Modulus of elasticity (MPa)	30,500
	Unit weight (kg/m³)[a]	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)[a]	200,000
	Poisson's ratio[a]	0.3
Tie bar	Diameter (mm)	13
	Length (mm)	914
	Spacing (mm)	762
	Modulus of elasticity (MPa)[a]	200,000
	Poisson's ratio[a]	0.3
Subgrade	Modulus of subgrade reaction (kN/m³)[a]	62,400 (230 pci)

[a] assumed value as typical value

5.2. Simplified Equivalent Temperature Difference (ΔT_{teltd})

Using the concept of equivalent temperature difference, the relation between actual measured temperature difference and equivalent temperature difference (ΔT_{teltd}) associated with actual pavement behavior could be established. Similar to the approach used by previous researchers (Rao *et al.* 2001; Yu and Khazanovich 2001; Jeong and Zollinger 2004), equivalent temperature differences of FE program were back-estimated to generate the relative corner deflection to center of the measured slab curvature profiles from diagonal direction. Once the ΔT_{teltd} on given measured temperature difference was estimated, the ΔT_{teltd} values were plotted with measured temperature differences as shown in Fig. 6.
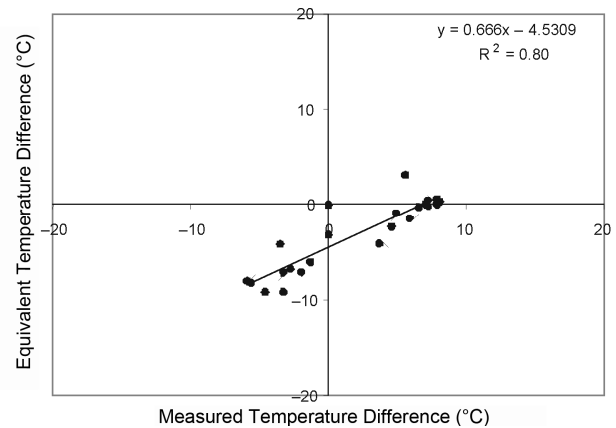
Fig. 6. Equivalent temperature difference versus measured temperature difference

From Fig. 6, the equivalent temperature differences and the measured temperature differences show a linear relation. This linear relation can be also observed in data collected in US–34 near Burlington, Iowa (Ceylan *et al.* 2007). The coefficient of linear regression equation is less than unity. It is possible to relate the coefficient and the independent variable of the linear regression equation to the transient component of equivalent temperature difference ($\Delta T_{transient}$) including temperature ($\Delta T_{trans-temp-diff}$) and moisture gradient ($\Delta T_{trans-mois-diff}$). The value of about 0.6 as coefficient indicates that the effects of the moisture gradient and the nonlinear component of temperature gradient are significant in deformation behavior during early age JPCP, which is in agreement with the results reported by Hayhoe (2004) from the observation of curling behavior at rigid pavement test items of the Federal Aviation Administration's National Airport Pavement Test Facility (NAPTF).

It is also possible to relate the intercept of the regression equation to the permanent component of equivalent temperature difference ($\Delta T_{permanent}$), which is a sum of temperature differences producing similar

response to built-in curling during the time of PCC construction or hardening ($\Delta T_{perm-temp-diff}$), irreversible differential dry shrinkage ($\Delta T_{perm-mois-diff}$), and creep behavior of slab ($\Delta T_{perm-creep}$). Approximately –4.5 °C were obtained as intercepts for the linear regression equations in this study which is similar to –5.6 °C defined as $\Delta T_{permanent}$ in the MEPDG through national calibration results. Based on linear regression equation from Fig. 6, equivalent temperature differences during pavement profile data collection were simply calculated and used as inputs for ISLAB 2000.

5.3. Comparison between Measured and FE-predicted Slab Curvature Profiles

FE-based predicted results were required to quantify the slab curvature profile and characterize the differences between the measured and FE-simulated slab curvature profiles.

If the slab behavior could be characterized in terms of total amount of deflection and the slab shape, the total amount of slab deflection could be quantified using the relative deflection of corner to center in the measured direction (R_c) and the slab shape could be quantified by the curvature of slab profile (k). The relative deflection of corner to center (R_c) in the defined direction could easily be calculated by subtracting the elevation of center in the defined direction from that of corner in the same direction. The curvature of slab profile (k) was calculated using a methodology proposed by Vandenbossche (2003). A second-order polynomial curve represented by Eq. (2) was fit to FE-calculated slab deformation profile and then the curvature was calculated using Eq. (3) as follows:

$$y = Ax^2 + Bx^2 + C \ , \qquad (2)$$

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

where: y – measured displacement; x – location along the profile traverse; A, B, and C – coefficients; and k – curvature.
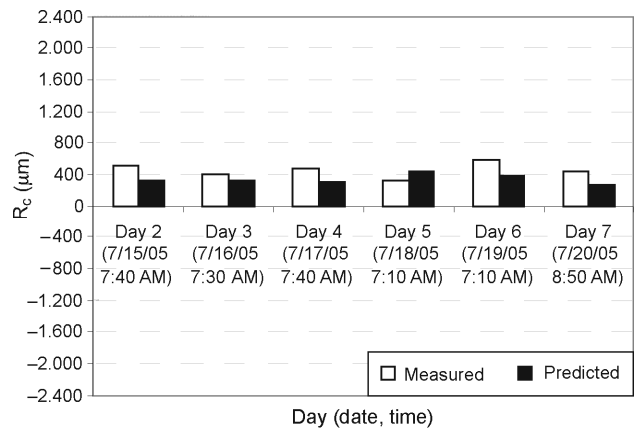
The quantitative comparisons between the measured slab curvature profiles and the FE-computed slab curvature profiles of transverse direction were conducted for both test section and presented in Figs 7 and 8 for test section 1. From a cursory examination of the comparison charts, it can be observed that the FE-predicted slab curvature properties agree well with the measured slab curvature properties such as R_c and k.

To evaluate the statistical accuracy of FE model, a statistical test, paired t-test, was used. The paired t-test 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 hypothe-
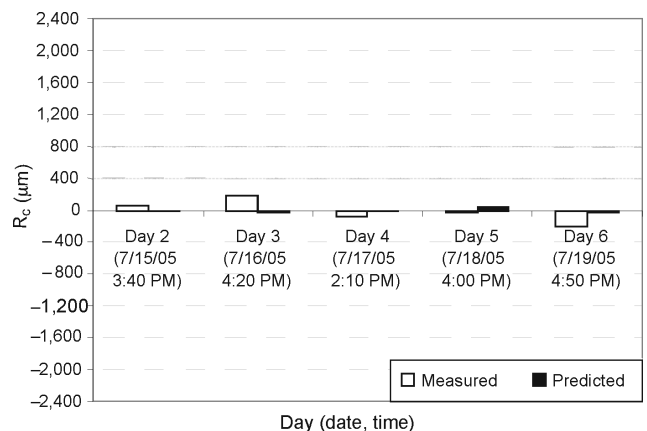
sis of sample equality cannot be rejected if p-value is greater than the selected significant level. Table 2 presents the paired t-test results for R_c and k in terms of p-value. For the significance level (α) of 0.05, the null hypothesis of equality between the measured slab curvature profiles properties and the FE-predicted slab curvature profiles properties cannot be rejected under transverse direction, which indicated that FE models could estimate the slab deformation statistically well at a level of significance of 0.05.

Table 2. Statistical results for properties of slab curvature profiles measured and predicted

Temperature difference condition	Slab curvature profiles properties	Transverse direction	
		p-value	Different?
Positive	R_c	0.34	No
	k	0.08	No
Negative	R_c	0.45	No
	k	0.26	No

a)

b)

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

Fig. 8. Comparisons of curvature (*k*) between measured and FE-predicted slab curvature profiles of transverse direction in test section 1: a) negative temp. diff; b) positive temp. diff
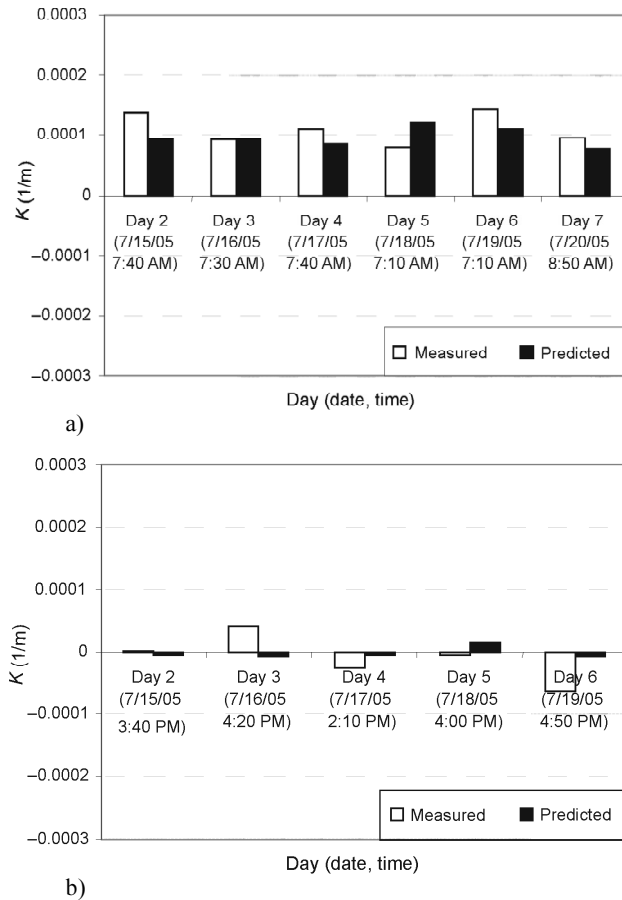
6. Conclusions

This study characterized the early age JPCP deformation due to environmental effects in terms of equivalent temperature difference by employing a Finite Element (FE) based primary response model, namely ISLAB 2000. Based on field data collected from instrumented JPCP on highway US–30 near Marshalltown, Iowa, the total equivalent linear temperature difference (ΔT_{teltd}) corresponding to actual deformation under environmental loads was quantified. The procedures and the results of the FE analyses based on the collected data and the quantified equivalent temperature differences were presented. Comparisons between the field measured and the FE-computed slab deformations due to environmental effects were reported in this paper. Based on this study, the following conclusions were drawn:

  − Better predictions were obtained when employing a simplified equivalent temperature difference (ΔT_{teltd}) concept for FE based primary response model;

  − A linear relation was observed between the actual measured temperature difference and equivalent temperature difference (ΔT_{teltd}) associated with actual slab displacement under pure environmental effects;

  − The effects of the moisture gradient and the nonlinear component of temperature gradient are significant in deformation behavior during early age JPCP;

  − The coefficient and the independent variable of the linear regression equation could be related to the transient component of equivalent temperature difference ($\Delta T_{transient}$) including temperature ($\Delta T_{trans-temp-diff}$) and moisture gradient ($\Delta T_{trans-mois-diff}$);

  − The intercept of the regression equation could be related to the permanent component of equivalent temperature difference ($\Delta T_{permanent}$), which is a sum of temperature differences producing similar response to built-in curling during the time of PCC construction or hardening ($\Delta T_{perm-temp-diff}$), irreversible differential dry shrinkage ($\Delta T_{perm-mois-diff}$), and creep behavior of slab ($\Delta T_{perm-creep}$).

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SUPAPRASTINTAS METODAS, PROGNOZUOJANTIS ANKSTYVOJO BETONO DANGOS DEFORMACIJAS

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S a n t r a u k a

Pastaraisiais metais ypač domimasi ankstyvojo betono kelio dangos (JPCP) deformacijos charakteristikomis ir poveikio aplinkai tyrimais, tačiau dėl aplinkos veiksnių sąveikos kyla sunkumų prognozuojant JPCP būdingąsias deformacines savybes.

Šiame darbe pateikiamas supaprastintas metodas, kaip galima būtų prognozuoti ankstyvojo betono deformacijas JPCP, kylančias dėl aplinkos veiksnių, vartojant ekvivalentinės temperatūros skirtumo sąvoką. Naujai statomame JPCP US-30 plente prie Maršaltauno Ajovoje buvo sukonstruota bandymų įranga ir stebėta dangų reakcija į temperatūros bei drėgmės pokyčius per pirmąsias septynias dienas po statybų pabaigos. Remiantis gautais rezultatais, visų lygiavertio linijinės temperatūros skirtumų (ΔT_{teltd}), atitinkančių faktinę deformaciją, vertės buvo skaičiuojamos taikant baigtinių elementų (FE) metodą su ISLAB 2000. Apskaičiuotos FE vertės buvo palygintos su natūrinėmis sąlygomis išmatuotomis deformacinėmis savybėmis. Tikslesnė prognozė buvo gauta taikant supaprastintą temperatūrų skirtumo (ΔT_{teltd}) metodiką, grindžiamą pirminiu FE modeliu.

Reikšminiai žodžiai: betonas, JPCP, deformacija, baigtinių elementų metodas, temperatūrų skirtumas, dangos analizė ir projektavimas.

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