

EFFECTS OF TEMPERATURE AND MOISTURE ON THE RESPONSE OF JOINTED CONCRETE PAVEMENTS

Chetana Rao
Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
205 North Mathews
Urbana, IL 61801
E-mail: crao@uiuc.edu

Dr. Ernest J. Barenberg
Professor, Emeritus
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
205 North Mathews
Urbana, IL 61801
E-mail: ejbm@uiuc.edu

Mark B. Snyder
Executive Director
Concrete Paving Association of Minnesota
6300 Shingle Creek Parkway, Suite 325
Brooklyn Center, MN 55430
Email: mbsnyder@cpamn.com

and

Sarah Schmidt
Sarah Schmidt, Design Engineer
Mark Thomas & Co.
90 Archer Street, San Jose, CA 95112
Email: sschmidt@sj.mthomas.com

ABSTRACT

This paper includes a study of curling and warping in jointed Portland Cement Concrete (PCC) pavements based on the temperature and moisture conditions at the time of paving and immediately following construction. Field data collected from fully instrumented sections at two locations, Phoenix, Arizona and Mankato, Minnesota, were used in this study. These sections were paved at nighttime and daytime respectively. Temperature data were collected through the slab thickness at different times of the day and profile measurements were recorded along the longitudinal edge, transverse edge and the diagonal of the slab. As the data at Mankato were

collected for three days immediately following construction and later at the end of 15 days, 40 days and two years, this section provided data suitable for the study of early age and longterm behavior of PCC slabs. On the other hand, the test sections at Arizona with data collected at 3 days and 40 days provided a comparison of the effects of slab length and restraint conditions on the curling and warping of PCC slabs. Material properties determined from lab tests were used in modeling using the Finite Element Method (FEM) program, ISLAB2000. Based on theoretical analysis, an “equivalent temperature gradient” was determined at different ages to account for the combined effects of built-in curl, shrinkage and creep. It was observed that paving during daytime induced high negative gradients that further increased as the pavement underwent drying shrinkage and creep. At the end of two years, as a result of creep in concrete, the pavement appeared to relax its upward curling and warping. Furthermore, the equivalent temperature gradient increased with larger slab length and decreased with the presence of load transfer mechanisms. Finally, it was concluded that in addition to actual temperature gradients, the effects of not only built-in curl but also shrinkage and creep have to be considered in pavement analysis and design.

CURLING AND WARPING

Temperature differentials between the top and bottom of PCC slabs result in slab curling. A higher temperature at the top of the slab, typically seen during daytime, results in a positive temperature gradient and causes the corners of the slab to curl downwards. Similarly, a higher temperature at the bottom of the slab results in a negative temperature gradient and causes the corners of the slab to curl upwards. Change in volume due to non-uniform shrinkage through the slab thickness also impacts slab deformations. A higher shrinkage at the top of the slab causes the slab corners to warp upwards relative to the mid panel. Temperature gradient reversals occur daily whereas moisture gradients are considered to be more seasonal. In the presence of restraining effects from slab weight, friction with the underlying base layer, and joint load transfer mechanisms, significant stresses are induced in the slab that can sometimes equal or exceed load-induced stresses.

In addition, the temperature conditions at the time of paving influence the extent of locked in or ‘built-in’ gradient at the time of concrete set. The built-in gradient is the temperature gradient required in the pavement to maintain a flat-slab condition. Therefore, if an initial upward curl is built in, a positive temperature gradient will have to first compensate for the built-in curl prior to allowing the slab to curl downwards. The amount of built-in curl is dependent on factors such as the temperature gradient at the time of set, differential shrinkage of the concrete, the relative humidity of the region, wind speeds etc., which all make curling difficult to estimate. Further, creep deformations over time, and creep in combination with concrete drying tend to reverse the deformations built into the pavement at the time of setting. Effects of these unknown built-in gradients, shrinkage and creep have only complicated modeling and predicting the responses of PCC slabs.

Westergaard provided closed form solutions for corner, edge, and interior loading conditions based on a slab-on-elastic foundation analysis (Westergaard, 1926). This work was later extended (Westergaard, 1927 and Bradbury, 1938) to account for positive and negative temperature gradients in the analysis. Superposition of stresses due to load and temperature was recommended for positive temperature gradients but the stresses due to a negative temperature gradient were not subtracted from load-induced stresses. This approach resulted in more conservative solutions. However, over the years, sophisticated finite element tools were developed for analysis of pavement systems with two or more layers and allowed separation between these layers (Korovesis, 1990 and Khazanovich, 1994). These tools were hence also very suitable for temperature analysis. As first suggested by Thomlinson (Thomlinson, 1940) the temperature gradient existing through the thickness of the slab was found to be nonlinear in nature. Compared to a linear temperature gradient, a non-linear gradient causes higher tensile stresses at the top of the slab during nighttime curled up conditions. Analysis with non-linear temperature gradient was subsequently incorporated in the FEM program, ILSL2 (Khazanovich, 1994 and Ioannides et al., 1998). ILSL2 was eventually modified to model several support and load transfer conditions and is now called ISLAB2000 (Khazanovich et al., 2000).

In an effort to better understand the actual behavior of the slab under environmental conditions, several field studies have been undertaken. Many tests (Poblete et al., 1988; Yu et al., 1988 and Boyle 2000) have shown evidence of built-in curl conditions, i.e. permanent upward curling, from deflection measurements. In the tests conducted in Chile (Poblete et al. 1988), it was observed that positive temperature gradients only reduced, but did not eliminate or reverse, the upward curling of the slab corners. Increased tensile stresses at the top of the pavement due to curling resulted in cracking starting from the surface and extending downwards. From test sections in Colorado and Florida (Yu et al. and Armaghani, 1987) it was determined that positive temperature differentials of -5 C (-9 F) and -11.1 C (-19.8 F) were preexisting in the 228 mm (9 inch) and 292 mm (11.5 inch) thick slabs respectively. In a study on moisture gradients in concrete pavements (Janssen 1987), shrinkage was predominantly found to exist only up to a shallow depth and the stresses exceeded the tensile strength of concrete only in the top $\frac{3}{4}$ " of the slab. A study in Munich, Germany, (Eisenmann et al., 1990) showed that the warping due to shrinkage was higher with smaller slab thickness due to a larger gradient. In addition, the stresses developed from early age shrinkage have been found to be very critical their effects cannot be ignored (Altoubat, 2000) in the longterm performance. However, over time, the upward curling of the corners with respect to the slab interior was reduced due to creep effects (Schmidt, 2000). Experimental work has shown that tensile creep can substantially relax shrinkage stresses by nearly 50% (Altoubat, 2000). It is important to recognize that early life of concrete are characterized by a complex interaction of internal drying, external drying and thermal effects. In light of these findings, the assumption of a flat slab condition for pavement analysis and design obviously poses some inadequacies. Although daily temperature variations can be included in the design process, it will also be necessary to incorporate the built-in curl, shrinkage and creep effects as the slab support conditions change with temperature gradients.

FIELD DATA

Data from two test locations at Mankato, Minnesota and Phoenix Arizona were included in this study. At both locations, thermocouples were placed at four different locations in the slab, the interior, corner, transverse and longitudinal edge. Temperature gradients could be estimated using the temperature data collected along the depth of the slab at each measurement period. Profile data were collected along the longitudinal edges, transverse edges and a diagonal of each slab. These measurements were done using a Dipstick Autoread Profiler. The profile was essentially the surface elevation recorded using the Dipstick and was only relative to the point from where the measurement traverse began. Therefore, for analysis purposes, all profiles were zeroed to the elevation of the slab interior so that relative curl-up or curl-down could be estimated.

The instrumentation also included vibrating wire gages for strains, psychrometers for moisture measurements, and gage studs for joint width measurements; but data from these sensors shall not be discussed in this paper as the focus is mainly on the findings drawn from the profile measurements.

ANALYSIS OF MANKATO TEST SECTION DATA

The Mankato test section was a three-panel cell on the passing lane of southbound Highway 14. This fully instrumented section had 4.6 m (15 feet) long, 4.0 m (13 feet) wide, and 216 mm (8.5 inch) thick slabs. PCC was placed over a 102 mm (4 inch) thick open graded base layer on top of a 76 mm (3 inch) thick dense graded base material. The joints were undoweled and untied. The silty-loam subgrade with a high water table and edge drains had an R-value of 12. Data at this test site were collected at regular intervals for a period of 3 days immediately following construction so that temperature and shrinkage effects on the early age setting of concrete slabs could be studied. The pavement was built on August 1, 1997 at 7:30 AM Central Standard Time (CST) and data collection was started soon after. In order to characterize the longterm effects, data were then collected at 15 days (approximately two weeks), 40 days (approximately 6 weeks) and 2 years after placement. For the longterm study, data were collected only during the critical hours of maximum, minimum and zero temperature gradients as per Long Term Pavement Performance (LTPP) protocols. At the end of 2 years, data were collected for a period of 5 days at regular intervals of approximately 2 hours. Concrete cores were tested at the University of Minnesota at different ages to determine concrete modulus of elasticity and coefficient of thermal expansion.

For modeling purposes material strength properties determined from lab testing were used. A modulus value of 17.3 GPa (2.5×10^6 psi), 27.5 GPa (4.0×10^6 psi), and 34.5 GPa (5.0×10^6 psi) was used for concrete at 3 days, 15 days and 40 days respectively. A longterm modulus value of 34.5 GPa (5.0×10^6 psi) was used for analysis of the 2-year data. The coefficient of thermal expansion, ' α ', from lab tests of companion specimens cast in the field, was determined to be 8.84×10^{-6} /deg C (4.49×10^{-6} /deg F). For the subgrade in this location, a k-value of 32.5 Kpa/mm

(120 psi/in) was assumed and the base was modeled as a 178 mm (7 inch) layer with a modulus of 20.6 Mpa (30,000 psi).

Figure 1 shows the variation of field temperature at the top and bottom of the PCC slab during the first 3 days of concrete curing. The peak temperatures at the top of the slab occur at 3:00 PM and 5:00 AM, similar to the air temperatures in this region. The temperature gradient at hours of peak temperatures is minimal on day1. This is indicative of the presence of the concrete's heat of hydration, which causes a uniform temperature distribution through the slab thickness. The gradient is found to increase as the concrete continues to harden. Instead, on day1, the gradient is largest between 1:00 PM and 2:00 PM, and the minimum is between 2:00 and 4:00 AM. Temperature profiles at hours of maximum and minimum gradients are plotted in Figure 2. The distribution is nonlinear at all ages, and more pronounced at the top of the slab during the daytime profiles.

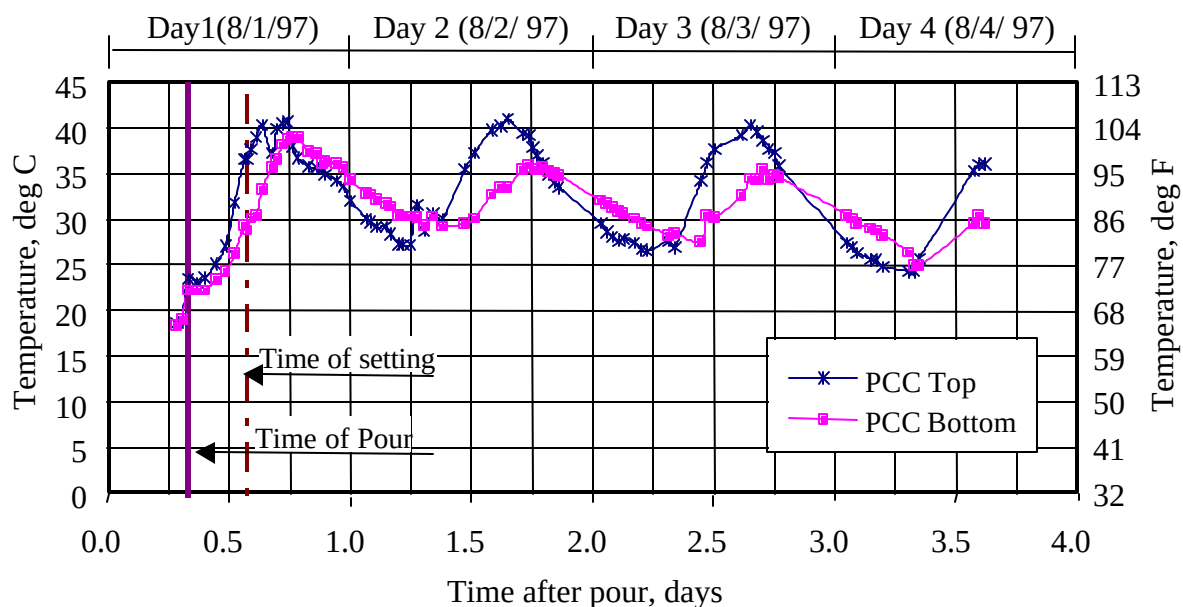


Figure 1. Temperature Variation during the First 3 days after pour

Profile Measurements: The slab was cast at 7:30 AM CST, and hence the concrete was expected to set a few hours later during high air temperatures. In order to enable comparison across different measured profiles (longitudinal edge, transverse edge and diagonal), all profiles were zeroed to the elevation of the slab interior. From the diagonal surface profile data collected soon after paving, the flattest condition was determined and all subsequent profiles were tared with respect to the profile at this time to eliminate geometric and surface irregularity components in the measured data. The flat-slab condition was established from the first profile measurement recorded when the concrete had set hard enough to withstand the weight of the Dipstick Autoread Profiler and the weight of the operator. It is difficult to estimate the exact time of setting but it was assumed that this condition was reasonably indicative of concrete hardening.

Built-in Curl: Based on this assumption, it was determined that the slab hardened, and maintained a flat-slab condition, six and one half hours after pouring, at 13:34 hours on August 1, 1997. The measured temperature differential, ΔT , in the slab at this hour was +7.3C (13.1F) between gages placed at 13mm (1/2 inch) from the top and bottom surfaces within the PCC slab. This is equivalent to a temperature differential of +9.6C (17.3F) across the entire depth of the slab. Therefore, $\Delta T = +9.6C$ can be quantified as the 0.45C/cm (2.03 F/in) built-in temperature gradient required to keep the slab in a flat condition. So, under conditions of zero temperature gradient, the slab will maintain an upward curl equivalent to a curl resulting from a temperature differential of -9.6C.

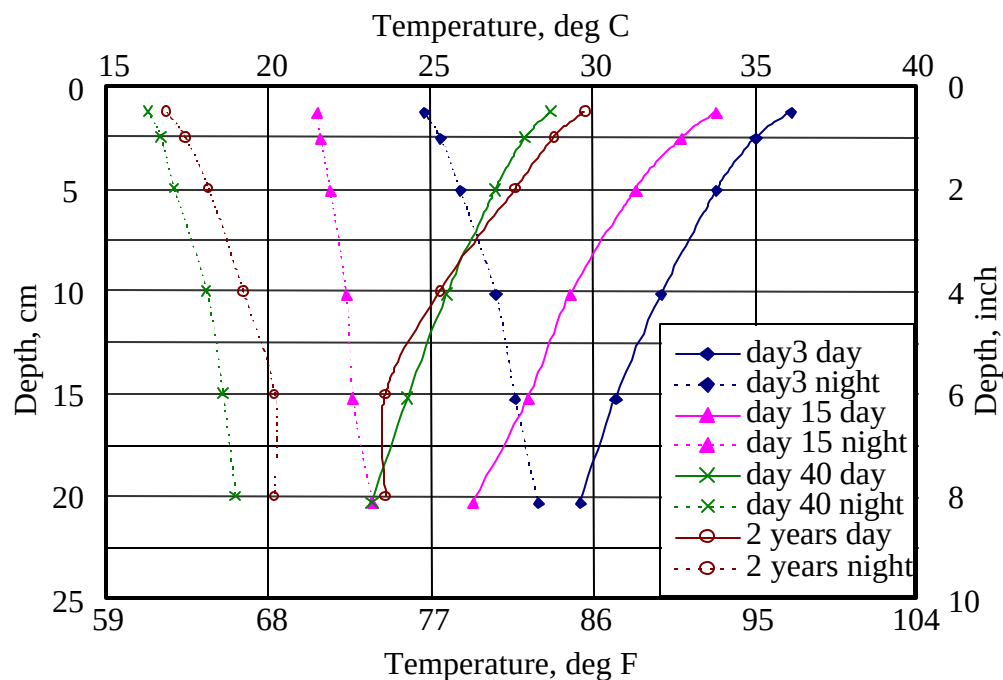


Figure 2. Measured Temperature Distribution through PCC Thickness at Peak Gradients

Effects of Shrinkage and Creep: Over the life of a pavement, moisture conditions typically vary seasonally. However, the loss of moisture due to plastic shrinkage can cause significant warping in early age concrete, which is still in the process of strength development. In combination with warping, creep effects tend to counter the slab deformations due to shrinkage. The diagonal, transverse and longitudinal profile data provided an insight into these aspects of the slab behavior. Figure 3 shows the curl measured at the corner, longitudinal edge and the transverse edge of the slab with respect to its center over the first 3 days after paving. The curl, which is non-existent at the time the concrete is poured, is seen to cycle with the daily reversals in temperature gradient. With increasing temperature gradient, the magnitude of the curl is seen to reduce and vice versa as expected. However, as the concrete sets, the slab curling is seen to increase although the temperature gradients have approximately the same value over the 3 days.

Also, at a zero temperature differential, the pavement still experiences an upward curling, which can be attributed to the built-in temperature gradient. Further, the curl experienced at the corner during a zero temperature gradient increases as the concrete hardens. This indicates that the slab is accumulating an upward curl as the concrete hardens. It is also to be noted that the entire slab edges are being lifted upwards because the curl measured at the longitudinal and transverse edges have a positive value. The edge curling also increases with time. This additional curling can be attributed to differential shrinkage in the slab in combination with drying creep.

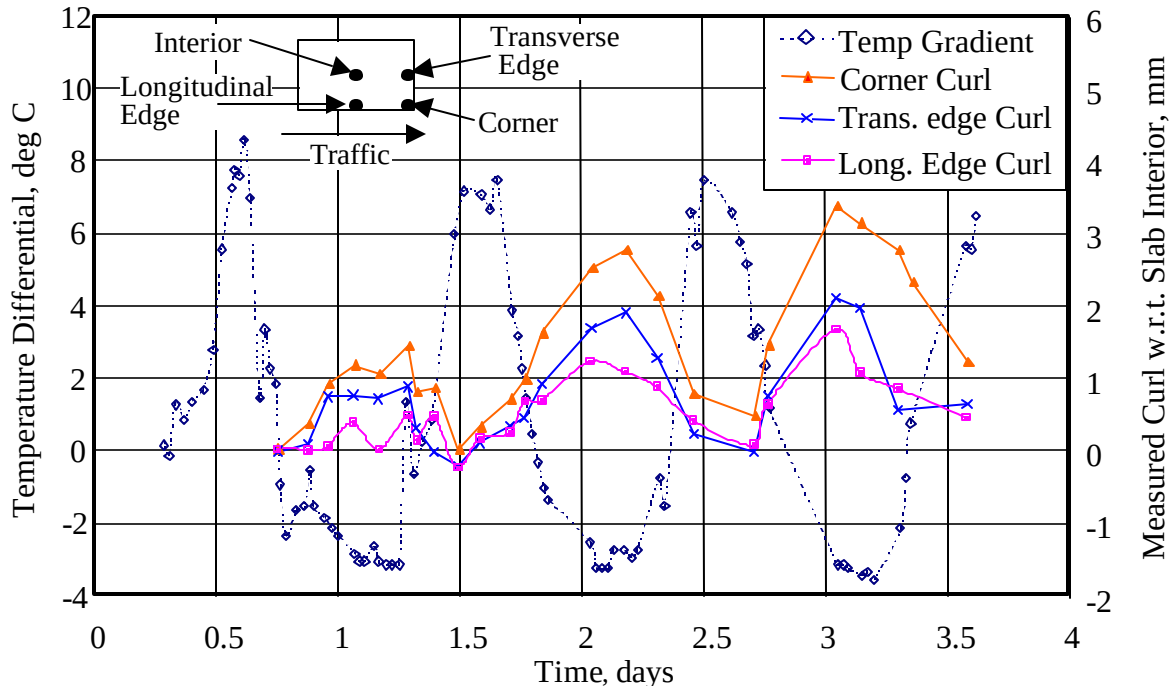


Figure 3. Curl Recorded at Mankato during the First 3 days after Paving
(Note: All elevations are relative to the slab center)

The daytime and nighttime diagonal profiles at critical temperature gradients are shown in Figures 4 and 5 respectively. The presence of a predominant upward curling is obvious as even daytime profiles show proof of a lift-up of the slab corner with respect to the center. The prevalence of dictating negative gradient conditions was also apparent from both the longitudinal and transverse profiles (figures not shown in this paper).

Modeling Considerations and Equivalent Gradient: A preliminary analysis of the pavement system using the Finite Element Method (FEM) program ISLAB2000 with material inputs from lab testing and nonlinear temperature distributions (from Figure 2), indicated that the resulting curl was heavily underpredicted. As discussed in the previous sections, it can be speculated that concrete shrinkage and creep can cause the apparent increase in upward curling. Further, the presence of an open graded base material could cause the slab center to deflect downwards. Although it is difficult to appropriately quantify each of these effects individually in the given

case, the concept of an equivalent temperature gradient to combine all the active effects was incorporated. This parameter was conceptualized to account for the effects of built-in gradients, shrinkage and creep at different ages. Therefore based on a linear temperature gradient analysis, the equivalent temperature gradient that (in addition to the existing temperature gradient) caused the measured curl conditions was determined. Curl measured from the diagonal profile was chosen for this purpose because it spans the longest segment along the slab and the relative elevations of the corner and the slab interior can be compared. The nighttime profiles give a better estimate of the equivalent gradients because not only are the effective gradients negative, but also because in modeling positive daytime temperature gradients, slab bearing on the base might not be realistically modeled given the “estimated” values for base properties. Table 1 lists the equivalent gradients computed from the diagonal profiles based on this procedure.

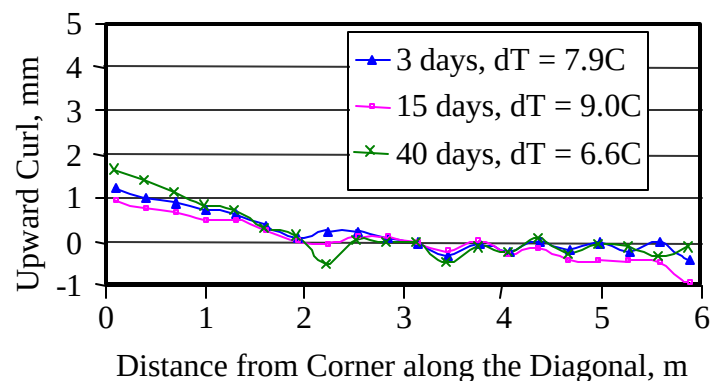


Figure 4. Daytime Diagonal Profiles at Mankato Test Sections
(Note: All elevations are relative to the slab center)

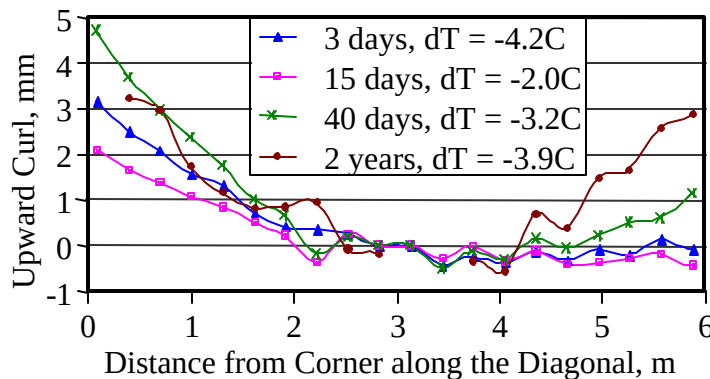


Figure 5. Nighttime Diagonal Profiles at Mankato test sections
(Note: All elevations are relative to the slab center)

From the results presented in Table 1, it appears that the slab has developed a tremendous amount of curling due to plastic shrinkage in the first 3 days after pour. The shrinkage gradient alone is equivalent to a temperature differential of $-22.2\text{ C} - (-7.3\text{ C}) = -14.9\text{ C}$ or -0.69 C/cm (-

3.1 F/in). During the next period between 3 days and 15 days, the dominating effect of drying creep seems to have reduced the equivalent temperature differential to -14.7 deg C. By 40 days, with the concrete gaining more strength and additional shrinkage, the slab corners appear to have curled back upwards. In the longterm, due to creep effects, the equivalent gradient has reduced to -21.9 deg C, which is still a substantial negative gradient acting on the slab. The effects of longterm creep have reduced the effective curl but have not completely eliminated it. The equivalent gradients computed above reflect on the inadequacies of a flat slab analysis in pavement design.

Table 1. Equivalent Temperature Gradients in Diagonal Profiles at Mankato Test Sections

Concrete Age	Measured Slab Temperature Differential degC (degF)	Measured Curl mm (inch)	Equivalent Temperature Gradient degC/cm (degF/in)	Equivalent Temperature Differential degC (degF)
Set time	+7.3 (+13.1)	0.0 (0.000)	-0.4 (-1.7)	-7.3 (13.1)
3 days	-4.2 (-7.5)	3.1 (0.124)	-1.0 (-4.7)	-22.2 (-39.9)
15 days	-2.0 (-3.6)	2.1 (0.083)	-0.7 (-3.1)	-14.7 (-26.4)
40 days	-3.2 (-5.8)	4.7 (0.186)	-1.3 (-5.8)	-27.4 (-49.2)
2years	-3.9 (-7.0)	3.9 (0.153)	-1.0 (-4.6)	-21.9 (-39.4)

Note: The equivalent temperature gradient does not include the measured temperature gradient and purely accounts for the effects of built-in temperature gradient, shrinkage and creep.

It is important to note that the equivalent temperature gradients were computed using the diagonal profile, comparing the elevations at the slab center with respect to the corner at the approach joint. Data differs from one slab to another and from one joint to another. These computed equivalent gradients are hence only an estimate of a typical slab case chosen out of the data analyzed. By merely using longitudinal edge profile data and comparing corner curl values with respect to the midpoint on the longitudinal edge, a set of different, yet closely matching equivalent gradients were determined. The longitudinal profile in Figure 6 shows that relative to the slab center, the longitudinal edge has curled up during the first 40 days (as previously seen in Figure 3), which could also be augmented by the slab center settling into the open graded base. However, at the end of 2 years, although the longitudinal edge profile indicates that the corners still curl upwards, the center of the longitudinal edge has settled into the base layer more than the slab center has. During a condition when the entire slab edge has lifted from the base layer, the weight of the slab could have pushed it downwards resulting in higher settlement of the slab edge.

Critical temperature gradient conditions were modeled incorporating the computed equivalent differentials. The effective temperature distributions are shown in Figure 7 and correspond to the measured distributions shown in Figure 2. Since the equivalent temperature gradients were computed based on the diagonal profile, it is only expected that the predicted diagonal profile will match the actual profile reasonably well. Figure 8, comparing the predicted and measured

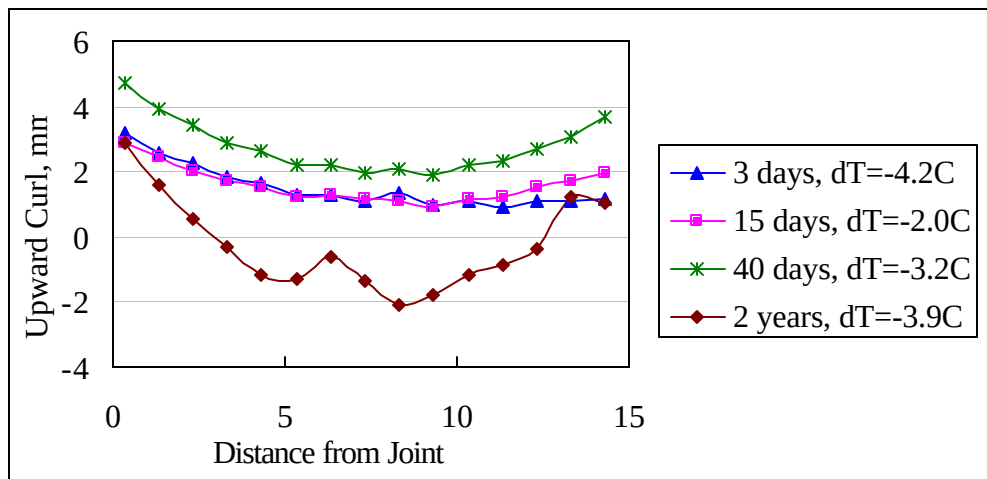


Figure 6. Longitudinal Nighttime Profiles at Mankato Test Sections

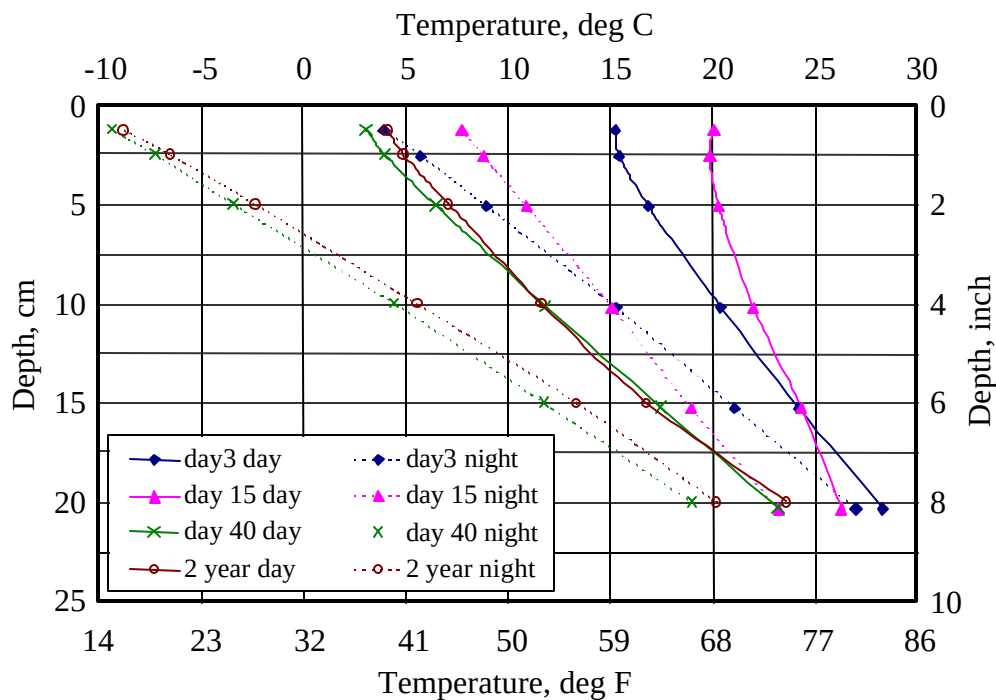


Figure 7. Effective Temperature Profile including Equivalent Temperature Gradient at Mankato

longitudinal profiles, shows that the FEM model estimates the shape of the curve reasonably well. However, the slab edge curls upwards more than predicted during the initial period. The relative deformation of the slab corner between day and night temperature reversals provides a good basis for comparison of various scenarios. The significance of accounting for shrinkage and creep effects, in addition to the built-in curl, in pavement analysis and design was best illustrated from these analyses, a summary of which is in Table 2. In combination with traffic loads, the

fatigue characteristics can be more accurately predicted if the daily stress reversals can be estimated more accurately.

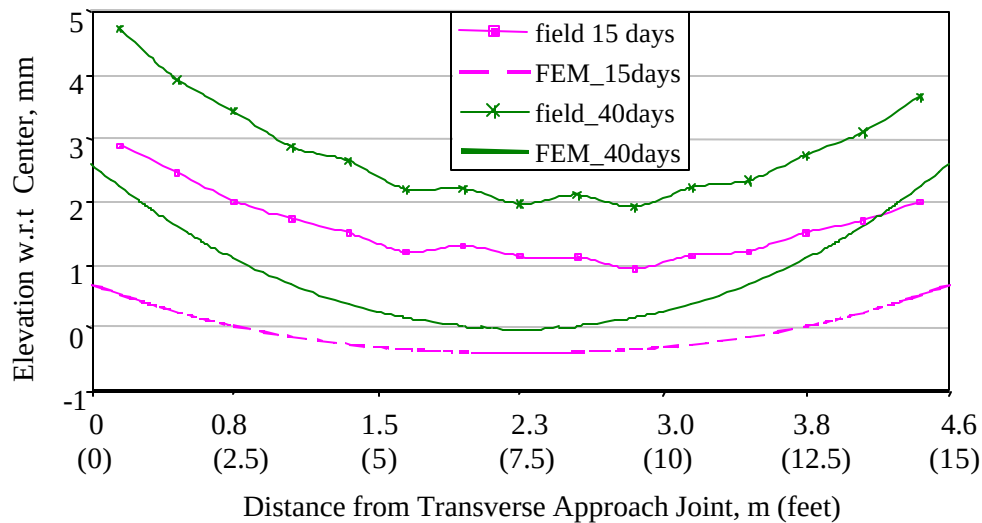


Figure 8. Actual and FEM predicted Longitudinal Profile

Table 2 Summary of Corner Curling

Concrete Age	Curl Condition	ΔT deg C	Curl from FEM Analysis, mm			Curl from Field data mm
			Flat slab	Built-in ΔT	Built-in and equivalent ΔT	
3 days	Nighttime	-4.2	0.26	0.95	2.94	3.15
	Daytime	7.9	-0.48	0.07	1.37	1.24
	Difference		0.74	0.89	1.57	1.91
15 days	Nighttime	-2	0.16	1.00	1.99	2.11
	Daytime	9	-0.70	0.00	0.63	0.92
	Difference		0.87	1.00	1.37	1.19
40 days	Nighttime	-3.2	0.30	1.30	4.62	4.72
	Daytime	6.6	-0.59	0.19	3.02	1.67
	Difference		0.89	1.10	1.61	3.05
2years	Nighttime	-3.9	0.38	1.42	4.77	3.89
	Daytime	7.1	-0.70	0.08	2.82	2.09
	Difference		1.08	1.34	1.95	1.80

(Note: Difference is difference between nighttime curl and daytime curl)

In Table 2, it is not too surprising to observe some inaccuracy in predicting the exact curl, especially during the daytime conditions. The equivalent gradients were determined based on a linear temperature distribution, but when modeled in combination with the daily nonlinear temperature conditions, it can contribute to some of the errors. Also, in comparing daytime field data to the FEM results, it should be noted that the assumed k-value for the subgrade and the material properties for the base layer might not be accurate.

ANALYSIS OF ARIZONA TEST SECTION DATA

The test site at Arizona, located on a section of I-10 south of Phoenix, was constructed on August 21, 1996 and the paving was done between 1:00 AM and 5:00 AM. Data from this location facilitated the study of environmental effects on PCC pavements in an arid climate. This test site had three test cells, identified as AZ1, AZ3 and AZ4, with the following combinations of joint spacing and restrain conditions:

AZ1: Joint spacing of 4.6 m (15 feet), no dowels and no ties

AZ3: Joint spacing of 6.1 m (20 feet), no dowels and no ties

AZ4: Joint spacing of 6.1 m (20 feet) with dowels and ties

These 3.6 m (12 feet) wide slabs were originally designed for 305 mm (12 inch) thickness, but cores removed from the test sections showed that the concrete placed was 349 to 356 mm (13.75 to 14 inch) thick in most cases. The slabs were therefore modeled as 349 mm (13.75 inch) thick slabs for more realistic predictions. The base consisted of a 100 mm (4 inch) dense graded aggregate layer. 38 mm (1.5") epoxy coated dowel bars were placed on 305 mm (12 inch) centers. The dowels were 450 mm (18 inch) long. Data were collected at this site for the first 3 days immediately after construction and after 40 days. Once the heat of hydration had dissipated and the concrete was set, measurements were only made at times of maximum, minimum and zero temperature gradients per LTPP protocols. For modeling purposes, suitable material properties were assumed based on engineering judgement and correlation with field observations.

These test sections provided an opportunity to compare effects of slab length (i.e. AZ1 vs. AZ3) and to compare the effects of slab restraint conditions (i.e. AZ3 vs. AZ4). Figures 9 and 10 show typical nighttime longitudinal profiles at 3 days and 40 days respectively. The profiles in these figures have been recorded at the same hour. As expected, the curling in AZ3 is higher than in AZ1 indicating that longer slabs have a higher curl. In addition, due to larger restraining conditions in AZ4, it curls less than AZ3. The curling at 40 days is in excess of the curling seen in the slabs at 3 days.

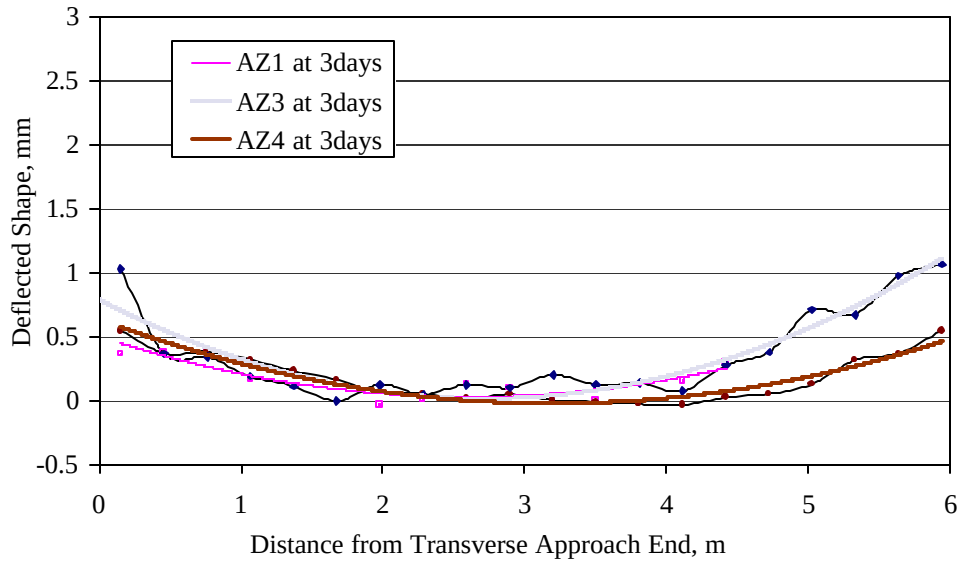


Figure 9. Nighttime Longitudinal Profile in Arizona Test Sections 3 days after Paving

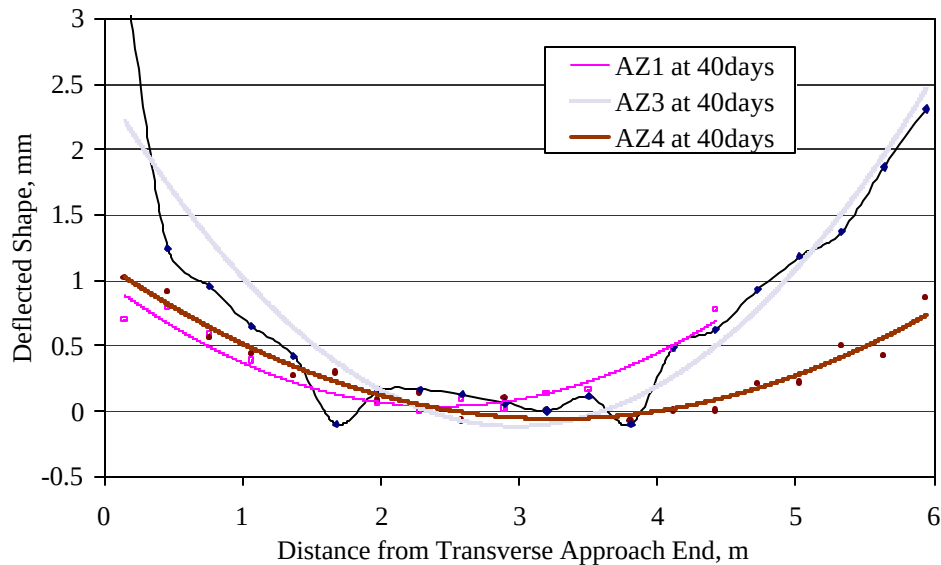


Figure 10. Nighttime Longitudinal Profile in Arizona Test Sections 40 days after Paving

These sections were paved during the night and hence a negative gradient was present in the slab when the concrete set. This implies that in a flat-slab condition the temperature at the top of the pavement is lower than at the bottom. Due to the lack of sufficient early age data, it was not possible to determine the exact time of concrete setting and hence the built-in gradient could not be numerically quantified for these test pavements. It is important to note here that the slab length or restraint conditions do not affect the mechanism inducing built-in curl, which is strictly a function of the temperature gradient in the flat slab at the time of setting. However, profile

data from Arizona, in general, showed reduced trends of shrinkage and creep relative to the Mankato sections. Considering that the Arizona sections were subjected to a more arid environment with low relative humidity, higher humidity at the bottom of the slab due to condensation in the nights, and hence a high shrinkage potential, the sections did not show a substantial upward curl when compared to the Mankato sections. This can be attributed to the positive built-in gradient. Also, since the Arizona slabs had a higher thickness, the resulting shrinkage gradient (degC/cm) would be lower than for the Mankato sections. Equivalent shrinkage and moisture gradients were computed using the same procedure described in the previous section. The longitudinal profiles were used for this exercise in the Arizona sections, as they appeared to be more reliable and consistent than the diagonal profiles. It was seen in the Mankato test sections that the equivalent gradients computed from the longitudinal profiles did not differ significantly from those computed using the diagonal profiles for the 3, 15 and 40-day cases. Since Arizona section data were available only for time periods of 3 days and 40 days after pour, equivalent gradients were only computed for these two periods. The equivalent gradients computed for the three sections in Arizona are summarized below in Table 3. Corresponding data from the Mankato sections are also shown with the intent of providing comparisons.

Table 3. Equivalent Temperature Gradients due to Shrinkage and Creep in the Slab

Section	At 3 days		At 40 days	
	Equivalent Temperature Gradient degC/cm (degF/in)	Equivalent Temperature Differential degC (deg F)	Equivalent Temperature Gradient degC/cm (degF/in)	Equivalent Temperature Differential degC (degF)
AZ1	-0.44 (-1.99)	-15.2 (-27.4)	-0.68 (-3.13)	-23.9 (-43.0)
AZ3	-0.66 (-3.02)	-23.1 (-41.5)	-0.83 (-3.81)	-29.1 (-52.4)
AZ4	-0.34 (-1.55)	-11.8 (-23.1)	-0.57 (-2.62)	-20.0 (-36.0)
Mankato	-1.03 (-4.7)	-22.2 (-39.9)	-1.3 (-5.8)	-27.4 (-49.2)

Note: These equivalent gradients include the effect of built-in gradients

Comparing the AZ1 and Mankato sections, both of which are 4.6 m (15 feet) long, the equivalent gradient that can be attributed to shrinkage and creep, is much larger in the Mankato section. Despite being in a less arid climate, the initial negative built-in gradient and the smaller thickness resulted in higher shrinkage and creep gradients over time in the Mankato sections. For the same built-in gradient conditions as in AZ1 and AZ3, the equivalent gradients were larger by nearly 25% in the longer slab. Since it was not possible to determine the built-in curl component in the equivalent gradients of the Arizona sections, the increase in shrinkage and creep gradients cannot be exactly quantified. Comparing sections AZ3 and AZ4, it can be seen that the equivalent gradient has reduced by 50% and 35% for the 3-day and 40-day periods respectively with the presence of dowels and ties at the joints. However it is worth noting that the reduced equivalent gradients because of the restraining effects would induce stresses in the slab.

CONCLUSIONS

It has long been recognized that PCC pavements develop 'built-in' curling depending upon the climatic conditions at the time of paving. Further, moisture conditions during concrete set can augment the upward curling of the slab. This study has led to conclude that, in addition to built-in gradients, moisture and creep effects need to be considered while modeling. Field data have shown that the equivalent gradient existing in the slab increase with time and implications of considering the combined effects of built-in curl, shrinkage and creep with regard to pavement analysis and design has been presented. The equivalent gradients are shown to increase with slab length and decrease with slab restraint. Most importantly, it was also shown that by controlling the time of paving, slab curling can be considerably alleviated in the longterm and thereby improve fatigue performance of the pavement.

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