Temperature and Curling Measurements on Concrete Pavement

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ABSTRACT

Curling generally results from the temperature differential across the concrete slab thickness. Curling induces stresses in the pavement slab that may contribute to early-age concrete cracking. This study deals with the field measurement of temperature and curling on a newly built jointed plain concrete pavement. The pavement section consisted of a 12-inch concrete slab, 4-inch bound drainable base, and 6-inch lime-treated subgrade. Temperature data was collected at five different depth locations across the thickness of the concrete slab with the digital data loggers embedded in the slabs. Curling was measured on five different days in the summer and fall with a simple setup. The results show that both upward and downward curling increase as the temperature differential increases. The magnitude of curling deflection resulting from a particular positive temperature differential is slightly higher than that resulting from the same negative temperature differential value. The in situ curling can be simulated with a properly built finite element model. Since temperature differential has a significant influence on curling, the effect of curling can be mitigated at an early age of pavement concrete with proper measures, such as enhanced curing.

Key words: concrete—curling—pavement

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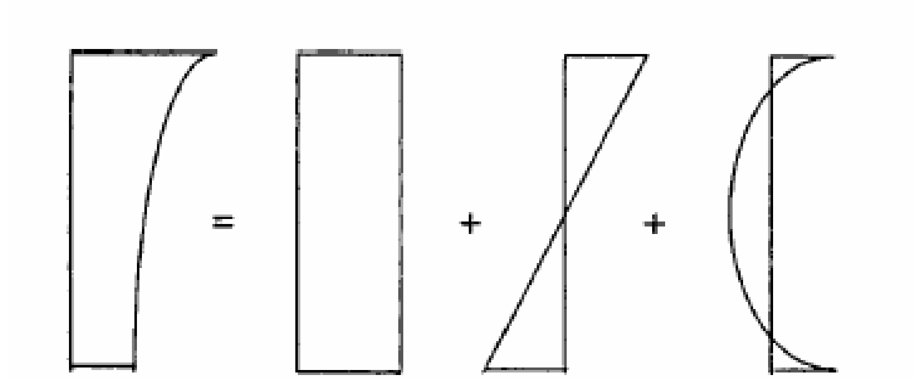
INTRODUCTION

Temperature is an important environmental factor that influences the performance of concrete pavements. Curling, which results from the temperature gradient between the concrete pavement top and bottom surfaces, induces stresses in the pavement, since the pavement is restrained by its weight. The thermally induced stress caused by such interaction may result in early pavement cracking (Tang et al. 1993). Curling also results in a loss of support along the slab edges or at the slab interior. The effect of the loss of support results in higher stresses as the subbase becomes stiffer. This may become critical, particularly within a few hours after slab placement, since concrete at the early stage of hydration may not have sufficient strength to prevent cracking. Temperature increase caused by hydration does not immediately produce thermal stresses because of the process of stress relaxation or creep in the concrete (Emborg 1989). Thermal stresses arise when the temperature drops after its peak value and the concrete has set. The temperature gradient that causes the slab to curl is affected by ambient temperature and solar radiation. Even if cracks do not develop, the temperature gradient can cause curling and permanent set of the concrete slabs in a non-planar fashion, a phenomenon known as as-built curling. The temperature differential between the slab top and bottom surfaces of a concrete pavement is also related to the fatigue damage (Masad et al. 1996). Fatigue damage caused by truck traffic can be 10 times higher for a 1°F/in.-temperature differential compared to that for a zero temperature gradient.

CONCRETE PAVEMENT TEMPERATURE AND CURLING

The concrete pavement temperature's effect on curling has been studied since the 1920s. Westergaard (1926; 1927), in his analysis of concrete pavement curling stresses, assumed the temperature distribution through the thickness of the slab to be linear. In the early 1930s, nonlinear temperature gradients were obtained from the results of the Arlington road tests (Teller and Sutherland 1936). The nonlinearity in the temperature distribution has been proven by experimental data presented by several investigators (Richardson and Armaghani 1987; Armaghani et al. 1987; Thompson et al. 1987; Choubane and Tia 1995). Typically, the nonlinear profile is featured with a relatively rapid change of temperature within the top quarter of the slab thickness, followed by a more gradual change toward the bottom face (Yoder and Witczak 1975). Researchers have also represented temperature profile by a quadratic equation or by a third-order polynomial (Choubane and Tia 1992; Zhang et al. 2003). Following the classical theory of plates, the nonlinear temperature distribution can be divided into three parts based on their respective effects on plate deformation: a) a part with uniform temperature that causes the pavement slab to expand or contract uniformly across its cross section, b) a linear part that causes bending of the pavement slab, and c) a nonlinear part that remains after the linear and uniform temperature parts have been subtracted from the total temperature distribution, as shown in Figure 1 (Choubane and Tia 1992). Some other regression-based and theory-based equations have also been developed to estimate effective temperature differential between pavement top and bottom (Kuo 1998; HIPERPAV 2003).

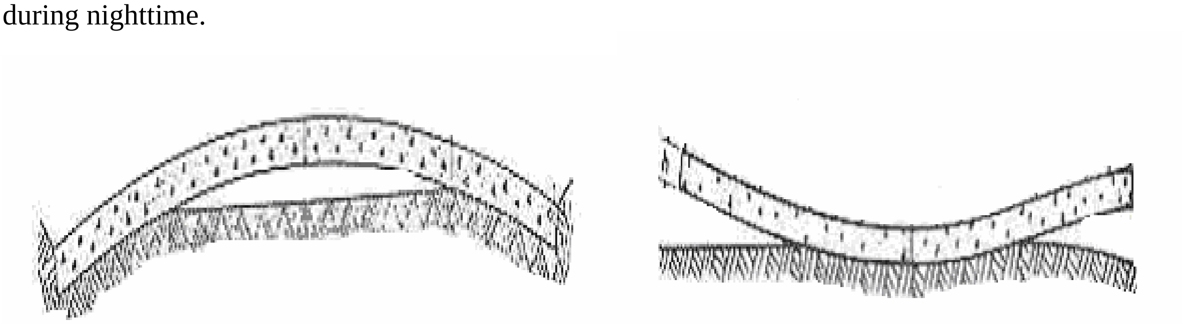
The implications of nonlinear temperature distribution across the concrete pavement slab have been studied by Choubane and Tia (1992) and Zhang et al. (2003). Choubane and Tia showed that the assumption of a linear temperature profile could lead to errors of 30% or more in the computed peak warping stresses (Choubane and Tia 1992). In their study, Zhang et al. (2003) reported that assuming a linear temperature distribution overestimated tensile stresses during certain periods of the day, while underestimated them during other periods. Differences between the peak tensile stresses of the linear and nonlinear analyses reached as high as 75%.



Nonlinear temperature distribution | Component causing axial expansion or contraction | Linear component causing bending | Nonlinear component

Figure 1. Temperature distribution across the concrete slab

As mentioned earlier, the temperature gradient may result in as-built curling. Studies have shown that pavement slabs are not necessarily flat at a zero temperature gradient, i.e. these slabs are built with significant curling already in them. The factors that cause built-in curling in jointed plain concrete pavement (JPCP) slabs include temperature gradient at the time of concrete hardening and differential shrinkage (Beckemeyer 2002). The differential shrinkage causes pavement slabs to curl upward, as shown in Figure 2. Because pavements are typically constructed during the daytime, the temperature gradients during construction also tend to cause upward curling. Yu et al. (1998) have shown that on average, the magnitude of built-in curling is about 1°F/in. for the pavements in wet-freeze climates. The combination of built-in curling and actual temperature gradients can cause significant upward curling of the slabs during nighttime.



(a) Downward curling **(b) Upward curling**

Figure 2. Curling of concrete slab due to temperature gradient

TEMPERATURE AND CURLING MEASUREMENTS

Test Section

The test section for temperature and curling measurements was a JPCP section on Interstate 70, constructed in the summer of 2003. The section has 16.4-ft joint spacing with 1.5-inch–diameter dowels.

The pavement cross section consists of a 12-inch concrete slab, 4-inch portland cement-treated subbase (known as bound drainable base, BDB) and 6-inch lime-treated subgrade. The concrete mixture was composed of 40% coarse and 60% fine aggregates with a water-cement ratio of 0.45. The entrained air was 5.8%. Average 28-day core compressive strength and 3-day modulus of rupture were 5,220 psi and 575 psi, respectively. The section was cured with a curing compound.

Temperature Measurement

Temperature data was collected by a digital data logger iButton® (iButton 2003). iButton® is a computer chip enclosed in a 0.63-inch stainless steel can. Because of this unique and durable stainless steel can, up-to-date information can be obtained readily. The steel button can be mounted anywhere because it is rugged enough to withstand harsh environments, indoors or outdoors. Information from the iButton® can be retrieved with a computer at any time intervals. They are also very cheap and easy to install.

Figure 3 shows the layout of iButton® placement for the study. The assembly was installed near the right wheel path, which is about three feet away from the edge of the driving lane. Temperature data was collected at five different depths along the slab thickness: the top surface; three inches, six inches, and nine inches below the top surface; and the bottom surface. Data was collected at 10-minute intervals. The advantage of using five buttons is that they capture the actual temperature distribution across the slab thickness.

Figure 3. Digital data logger placement

Figure 4 presents a typical hourly pavement temperature distribution curve. It is apparent from the figure that the temperature distribution along the thickness of the slab is nonlinear. The nonlinearities of temperature distribution along pavement thickness for the bottom half of the slab are not as pronounced as they are for the top half. For the bottom half, the distribution is almost linear. For the top half, the distribution for the hours of positive temperature differential (i.e., the temperature of the top surface is higher than that of the bottom) is steeper than that for the hours of negative temperature differentials (i.e., the temperature of the bottom is higher than that of the top). The hourly temperature variation at the bottom of the slab is not much: the difference between maximum and minimum temperature is about 7°F for this particular case. However, this difference is more pronounced for the top surface (about 32°F).

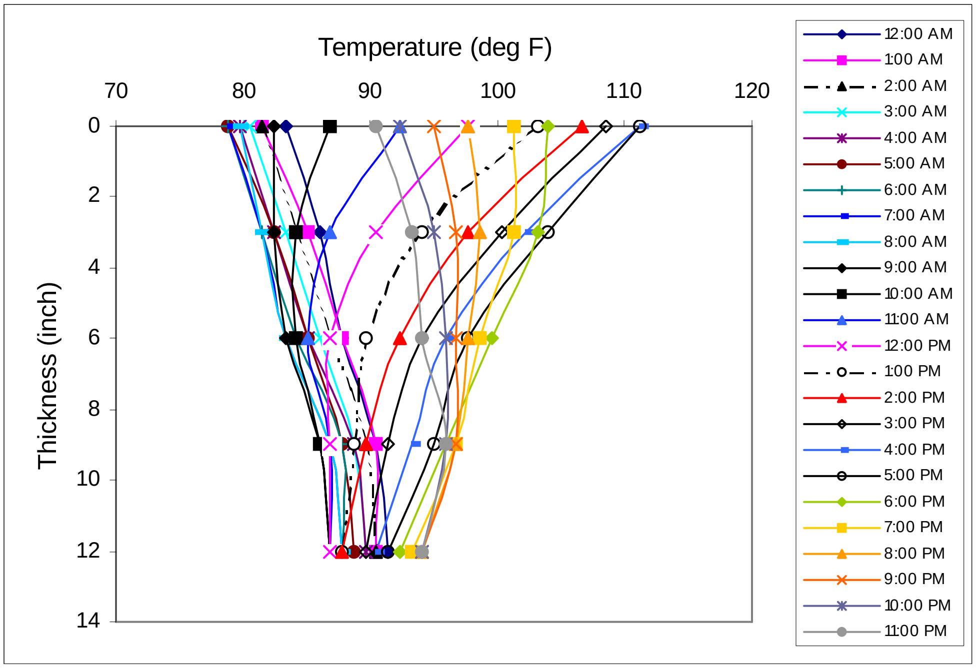


Figure 4. Typical temperature variation across the slab thickness

Curling Measurement

Curling on the section was measured by a simple setup, shown in Figure 5. It consists of an extensometer, which is mounted at the center of a lightweight aluminum frame. The length of the frame is approximately 16.4 ft, which represents the length of the concrete slab. The frame is positioned on steel pins attached to the bottom of the frame. These pins ensure correct and repeatable positioning and serve to form a reference level. The pavement surface moves vertically with time because of the temperature differential between the pavement top and bottom surfaces. The extensometer, which is in contact with the top surface of the pavement, moves with the vertical movement of the concrete slab, thus measuring both upward and downward movements. This measurement represents the curling or mid-slab deflection of the pavement slab with respect to the reference plane established by the pin.

Curling was measured at different locations of the Maple Hill section: the left and right wheel paths, and the center of the slab. These locations were selected randomly and were located on both driving and passing lanes. Data was collected on five different days: August 7, September 2, September 25, October 19, and November 6 of 2003. The first set of data was taken approximately one week after construction. Other measurements were done at approximately three-week intervals. In Kansas, during the summer when the first measurement was done, the ambient temperature was very high. On the other hand, during November when the last set of measurements was made, the weather was cooler, and the ambient temperature, as well as the pavement temperature, was relatively low compared to that of the summer. For a particular day, hourly curling measurements were taken throughout the day. No nighttime measurements were done.

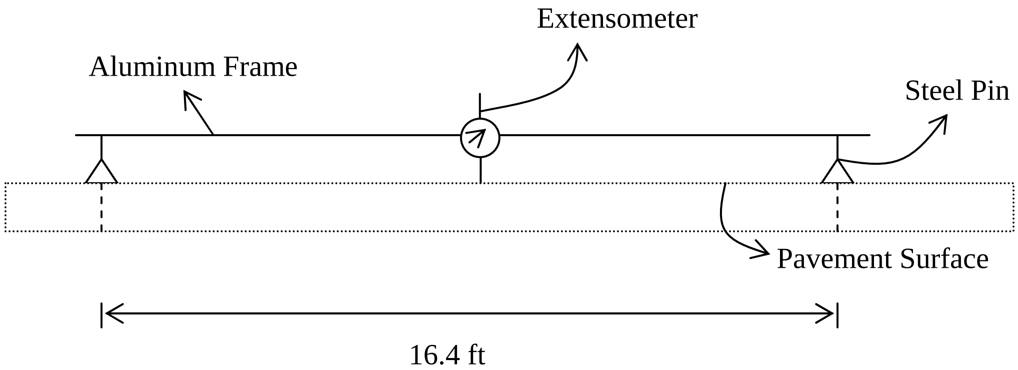
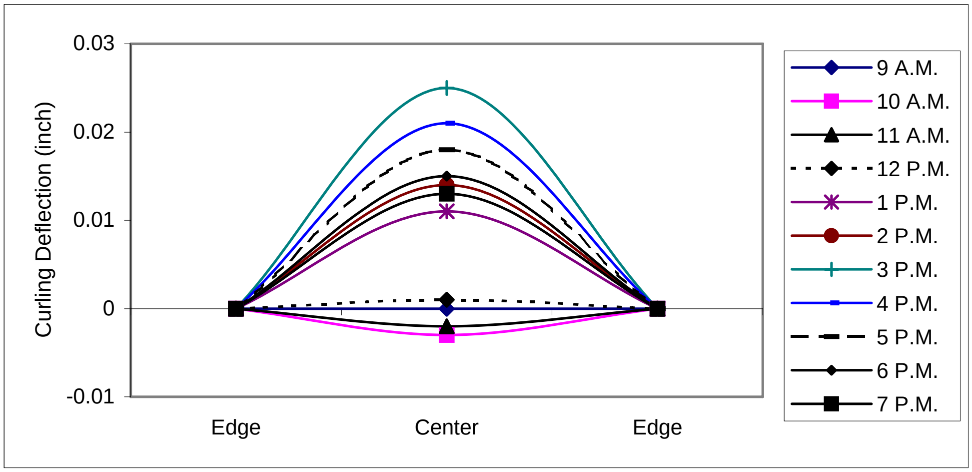


Figure 5. Curling measurement setup

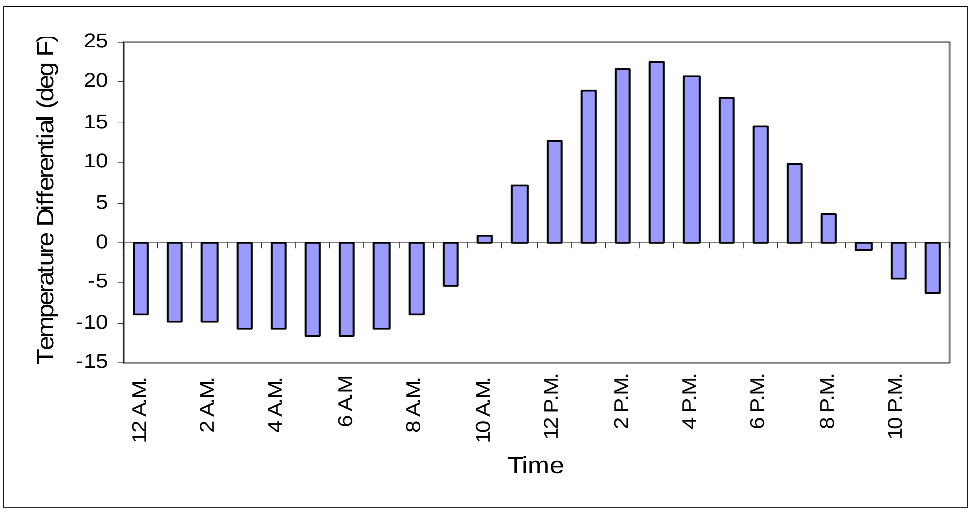
DATA ANALYSIS

Figures 6 (a) and (b) show the measured curling and temperature differentials between the pavement top and bottom on August 7, 2003 for a selected location. On that day, the first measurement was made at 8:00 am and hourly measurements were taken throughout the day. It is to be noted that the curling or mid-slab deflections shown in this figure do not represent the actual curling; rather it is relative to the first measurement. Hence, the actual curling of the pavement may be higher or lower depending on the time of measurement. The figure shows that in the morning, the pavement section was curled upward. At around noon, the opposite scenario (downward curling) was observed. Figure 6 (b) indicates that in 13 out of 24 hours this section experienced negative temperature differentials. The temperature at the top exceeded the temperature of the bottom at around 10 am, and the opposite scenario occurred at 9:00 pm. For the first few hours, upward curling was observed and at around noon; when the pavement first experienced a positive temperature gradient, downward curling was noticed. The maximum downward curling was observed at around 3:00 pm, when the temperature differential was the highest. After this time, downward curling started to decrease. Although nighttime measurements were not taken, it can be assumed that at some point in the evening (at around 9:00 pm in this case), when the bottom temperature exceeded the top temperature, the pavement experienced upward curling again. If there is no difference in moisture content between the pavement top and bottom surfaces, it can be said that the maximum upward curling occurred sometime between 4:00 and 7:00 am. Similar trends were observed at other locations.

Measured curling on other days and temperature differentials between the pavement top and bottom are shown in Table 1. The results show that although the maximum temperature differential on September 2 was higher than that on August 7, measured maximum upward curling was not much higher (0.023 in. compared to 0.025 in.). It happened probably because of the fact that the ambient temperature on September 2 was much lower than that on August 7. The average ambient temperatures on August 7 and September 2 were about 80°F and 69°F, respectively. The last set of measurement was carried out in early November. The maximum upward curling was much lower than previous measurements (about 50% of the first measurement). This is obvious because the maximum positive temperature differential is much lower (about 13°F) compared to other measurements. For the last two measurements, both pavement temperatures and temperature differentials were much lower compared to the other three measurements. During these two measurements, for only about 30% of the time, the pavement experienced a positive temperature gradient, compared to over 45% of the time for other measurements. Since temperature differential has a significant influence on curling, the effect of curling can be mitigated at a early age of the pavement concrete with proper measures, such as enhanced curing.



(a) Measured curling



(b) Temperature differential

Figure 6. Measured curling and temperature differential on August 7, 2003

Table 1. Curling deflection and temperature differential values

Day / Time	August 7		September 2		September 25		October 15		November 6	
	Curling (mils)	Temp. Diff. (°F)	Curling (mils)	Temp. Diff. (°F)	Curling (mils)	Temp. Diff. (°F)	Curling (mils)	Temp. Diff. (°F)	Curling (mils)	Temp. Diff. (°F)
8 am	-	-9.0	-2.008	-9.0	-0.984	-11.7	-	-9.9	-	-8.1
9 am	-0.984	-5.4	-5.000	-5.4	-0.984	-7.2	-2.992	-8.1	-2.008	-8.1
10 am	-2.992	0.9	-0.402	-0.9	-2.008	-2.7	-2.008	-1.8	-2.992	-4.5
11 am	-2.008	7.2	-2.008	2.7	-2.008	2.7	-2.008	4.5	-0.945	0.0
12 pm	0.984	12.6	2.008	9.9	2.008	8.1	2.992	9.9	-0.984	4.5
1 pm	10.984	18.9	7.992	16.2	9.016	11.7	9.016	12.6	2.992	9.0
2 pm	14.016	21.6	12.992	20.7	15.000	14.4	12.992	14.4	7.008	11.7
3 pm	25.000	22.5	22.992	23.4	17.992	15.3	17.008	15.3	14.016	12.6
4 pm	20.984	20.7	20.000	24.3	20.000	14.4	15.984	13.5	12.992	10.8
5 pm	17.992	18.0	15.984	21.6	15.000	11.7	15.984	10.8	10.984	7.2
6 pm	15.000	14.4	12.992	17.1	14.016	7.2	12.008	7.2	9.016	1.8
7 pm	12.992	9.9	12.992	11.7	10.984	2.7	-	3.6	-	-2.7

(negative sign indicates upward curling)

FINITE ELEMENT MODELING

Geometry and Element

The finite element (FE) model consists of three layers, as shown in Figure 7. The top layer is the 12-in.–thick concrete slab. The bottom two layers are a 4-in. BDB layer and a 6-in. lime-treated subgrade. The model consists of two lanes (driving and passing) and two shoulders (inside and outside). Each lane is 12 ft wide, whereas the widths of the inside and outside shoulders are 6 ft and 10 ft, respectively. All lanes and shoulders are separated by longitudinal joints with width of 3/8 inches and a depth of a quarter of the slab thickness. Transverse joints in the model are located at 16.4-ft intervals, and the joint dimensions are the same as those of the longitudinal joints. Cracks that developed under the transverse joints were also modeled. Dowel bars were used as load transfer devices. Dowel bars are located at the mid-depth of the slab with a bar diameter of 1.5 inches and length of 18 inches. Dowel bars were placed at 12-in. intervals. Because of the symmetry in the longitudinal (driving) direction, half of two slabs on either side of a transverse joint were used as the model geometry. A 3D 20-node brick element, known as SOLID186 in the ANSYS (ANSYS 2003) library, was used in this study. The element is defined by 20 nodes with three degrees of freedom per node: translations in the nodal x, y, and z directions. The interaction between the concrete and the steel dowel bars is complex, and this interaction was modeled as a contact problem. Rigid-to-flexible type of contact is also available in the ANSYS library. Target element, TARGE170 and contact element, CONTA174 were used in this study to model target and contact surfaces, respectively.

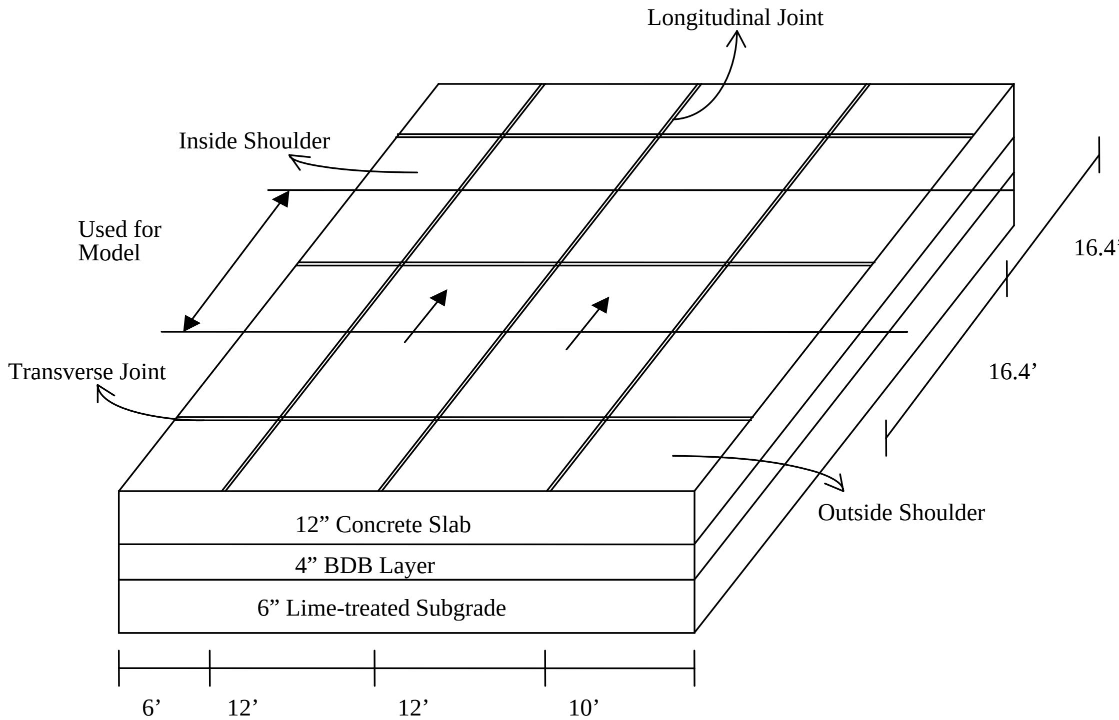


Figure 7. Geometry of the final element model

Material Properties

All layers were modeled as linear elastic. Material properties needed for this FE model include elastic properties, such as the modulus of elasticity and Poisson’s ratio of different layers, density of concrete, etc. Since this study deals with curling caused by temperature, another important material property that was needed is the coefficient of thermal expansion. Modulus of elasticity for the slab, BDB layer, and subgrade layers used in the study were 4.2×10^6 psi, 9.5×10^5 psi, and 40,000 psi, respectively. Poisson ratios for the concrete, BDB, and lime-treated subgrade layers were assumed to be 0.15, 0.15, and 0.20, respectively. The modulus of elasticity and the Poisson ratio for the dowel bars were assumed as 29×10^6 psi and 0.25, respectively. The typical values of 5×10^{-6} in./in./ °F, and 6.5×10^{-6} in./in./°F were used as the coefficients of thermal expansion values of concrete and steel, respectively. Temperature data, collected by iButtons, was applied at the top and bottom of the concrete slab. The thermal loading applied represent a temperature differential of -10°F, -5°F, 5°F, 10°F, 15°F, and 20°F.

Mesh Generation and Loading

Meshing is an important part of an FE model. Finer meshes produce better results. However, several factors, such as size and complexity of the geometry, use of contact elements, and product restriction of the ANSYS version used in the study, restricted the creation of a very fine mesh. In general, the mesh is coarse, as shown in Figure 8. However, because of discontinuities created by joints in the pavement, areas near the joints were refined to obtain better results. The total number of elements generated for each model was approximately 30,000. As this study deals with curling, temperature was used as the main load. Temperature data was applied at the top and bottom of the concrete slabs. Hence, it was assumed that the temperature distribution across the slab is linear. The bottom of the subgrade layer was assumed to be fixed in all directions. The edges of the base and subgrade layers were fixed in the z-direction

(direction of traffic). The pavement edge was allowed to move in all directions. Both translations and rotations of the dowel bars were restrained in all directions at one side of the joint.

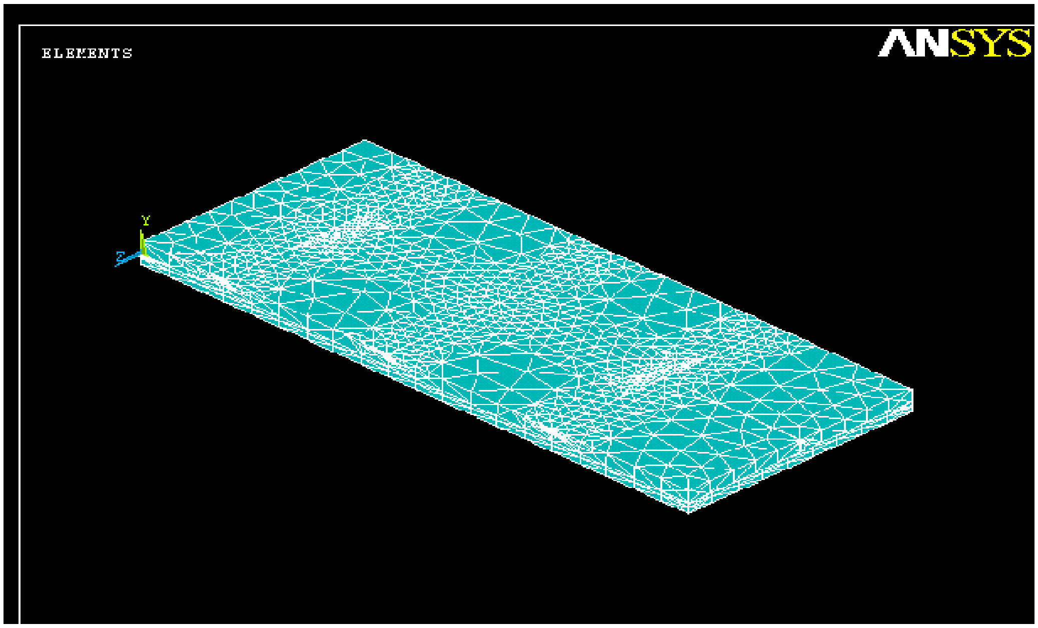


Figure 8. FE Simulation results for measurement section

Figure 9 shows the curled profile of the section for these temperature differentials. As expected, both upward and downward curling deflections increase with an increase in temperature differential. A maximum deflection of 0.012 inches was obtained when the temperature differential was maximum (20°F). However, curling from a temperature differential of 20°F is not twice that amount due to a temperature differential of 10°F, but about 75% higher. Again, the magnitude of curling for the same positive and negative temperature differential was not the same. A positive temperature gradient resulted in a higher magnitude of curling. The magnitudes of upward curling were about 74% and 80% of those of downward curling for temperature differentials of 5°F and 10°F, respectively.

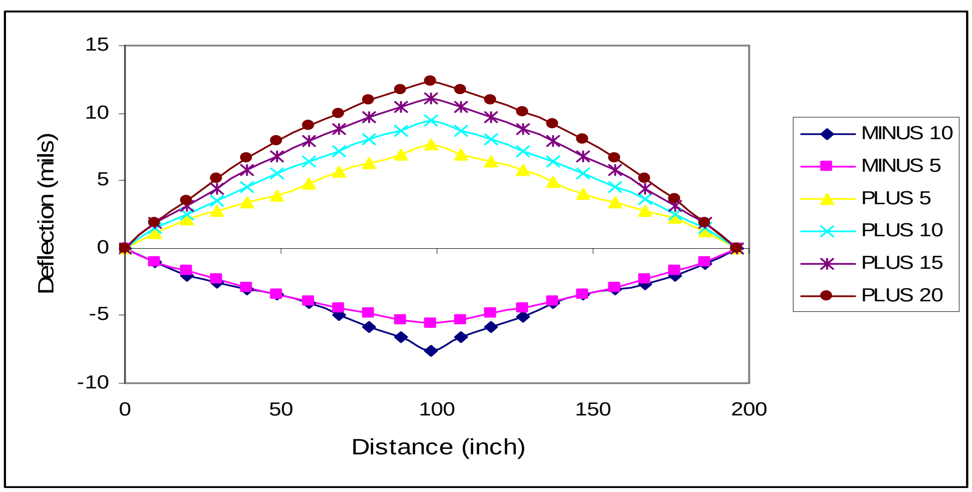


Figure 9. Simulated deflection profiles for different temperature differentials

COMPARISON OF RESULTS

Figure 10 shows the comparison of curling deflection data obtained from the field measurements and the FE simulation. As mentioned earlier, during curling measurement for any given day, it was assumed that the slab was flat during the first measurement. Subsequent measurements were done hourly. Hence, these measurements showed the curling deflection of the section with respect to the first measurement. The relative temperature differential shown in Figure 9 is the difference of temperature between the pavement's top and bottom surfaces for a particular measurement and the first measurement. For example, if the temperatures of the top and bottom surfaces during the first measurement are 84°F and 89°F, respectively, and those at 3 pm are 114°F and 91°F, respectively, then the relative temperature of the top and bottom surfaces are 30°F and 2°F, with a temperature differential of 28°F. Finite element analysis was performed using properties of the curling measurement sections and relative temperatures simulating the actual temperature condition during the curling measurement. Results from both methods show a similar trend, although the actual values are different. Deflections obtained by the FE simulation were lower than those measured in the field. Better agreements were observed for lower temperature differentials. However, the difference increased with an increase in temperature differential.

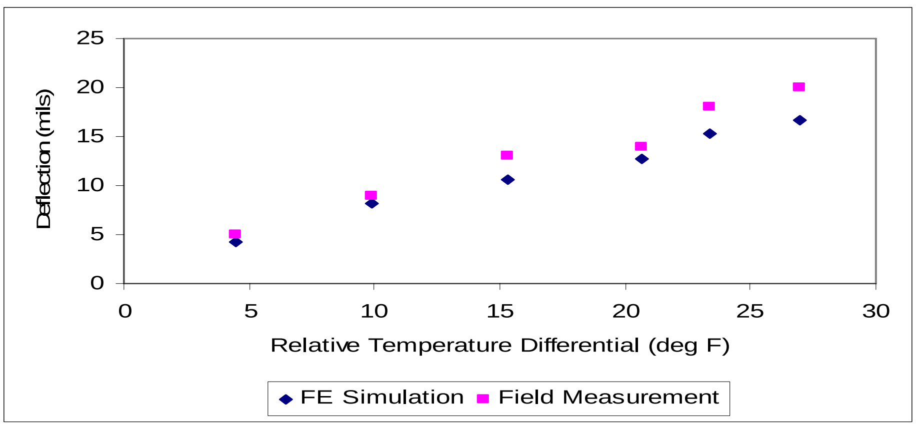


Figure 10. Comparison of results

It is to be noted that beside temperature, a pavement experiences changes in moisture with time. Ambient temperature also has some effect on the response of a pavement. There are also some construction irregularities that result in a pavement profile that is not perfectly plain. These features were not considered during FE model formulation. All or some of these factors might contribute to the differences between the FE simulation and field measurement results.

CONCLUSION

This study presents the results of curling and temperature measurements on a concrete pavement test section in Kansas. The curling was also simulated with a finite element model of the section. The simulated curling deflections were compared with those measured in the field. Based on the study, the following conclusions can be made:

- Higher temperature differentials increase both upward and downward curling. The magnitude of curling deflection resulting from a particular positive temperature differential is slightly higher than that resulting from the same negative temperature differential value. Since temperature differential has a significant influence on curling, the effect of curling can be mitigated at an early age of the pavement concrete with measures such as enhanced curing.
- The curling deflections measured in the field were in close agreement with the deflections obtained by the FE simulation, in most cases.

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