CURLING'S IMPACT ON STRUCTURAL RESPONSES OF JOINTED CONCRETE PAVEMENTS

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ABSTRACT

Backcalculation of layer moduli of jointed concrete pavements (JCP) normally uses the slab-on-grade model, which assumes that the concrete slab is flat and in full contact with the subgrade. The shape of a concrete slab, however, is changing due to either seasonal or daily variations of temperature and moisture gradients. This invalidates the commonly used assumption. Falling weight deflectometer (FWD) data collected at various times of a day exhibit significant variations and so do the subsequently backcalculated layer moduli using these data. This paper presents a case study that quantitatively characterizes the amount of change in the daily deflections and backcalculated layer moduli for data collected for JCP sections under the seasonal monitoring program (SMP) of the long-term pavement performance (LTPP) study. This paper also provides a method that accounts for slab curling during the backcalculation process using a finite element model. Pavement engineers shall understand the variations associated with the deflection data and backcalculated moduli for JCP pavements while using the data for pavement rehabilitation/reconstruction design as the material moduli are essential in the structural evaluation process.

INTRODUCTION

Pavement layer moduli backcalculation using Falling Weight Deflectometer (FWD) data is widely used among the pavement engineering community to evaluate the existing Jointed Concrete Pavements (JCP) and the backcalculated layer moduli provide valuable information for highway engineers when they perform rehabilitation and reconstruction designs. It is thus of great importance that the selected backcalculation algorithm is based on a sound engineering model to simulate the actual pavement structure performance so that the representative layer moduli are backcalculated for rehabilitation and reconstruction designs.

Pavements of different types respond differently to temperatures changes. The resilient modulus of asphaltic concrete (AC) changes dramatically as the temperature changes while the concrete resilient modulus does not. The concrete slabs, however, curl up or down due to the changing temperature gradient, which changes the contact condition between the concrete slabs and the underlying layer. The slab-on-grade model is often used for JCPs to backcalculate layer moduli, which assumes that the concrete slabs are lying flat and in full contact with the underlying layer. This assumption, however, is not always valid due to the slab curling.

This paper quantitatively summarizes the amount of change in the daily deflections and backcalculated layer moduli for data collected for JCP sections under the seasonal monitoring program (SMP) of the long-term pavement performance (LTPP) study. Even though these JCP sections are intended for studying the performance of highway concrete slabs, which are typically smaller dimensionally wise, the procedures to analyze the FWD data for highway concrete slabs are essential the same as those for the airport concrete slabs. Therefore, this summary provides equally important factual information to airport pavement engineers to better understand the variations associated with the deflection data and backcalculated moduli for JCP pavements.

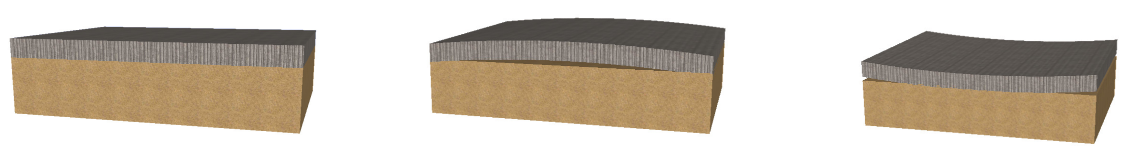
BACKGROUND

The mission of the LTPP program is to promote increased pavement life through the following:

- Collecting and storing performance data from a large number of in-service highways in the United States and Canada over an extended period to support analysis and product development.
- Analyzing these data to describe how pavements perform and to explain why they perform as they do.
- Translating these insights into knowledge and usable engineering products related to pavement design, construction, rehabilitation, maintenance, preservation, and management.

The SMP within the LTPP study intends to understand effects of environmental conditions (e.g., temperature and precipitation) on pavement behaviors. For the LTPP sections under the SMP study, FWD tests at the same locations were performed at different times of a day. The deflection basins at different testing times from the same testing locations changed significantly, and so did the layer moduli based on those deflection basins using the conventional backcalculation method. The concrete modulus is unlikely to change due to the normal daily temperature variation. It is the contact condition change between the slab and the underlying layer due to temperature gradient variation that causes the change in the deflection basin. Therefore, the contact condition needs to be accounted for when backcalculating layer moduli, as described by Ceylan [1].

The typical contact conditions are illustrated in Figure 1. Typically, a concrete slab is flat early in the morning or late in the evening when the temperature gradient is relatively uniform, is curled downward during daytime when the surface concrete temperature is greater than that of the bottom, and is curled upward during nighttime when the surface concrete temperature is less than that of the bottom. It should be noted that the apparent shape of the slab at any time is resulted from the combined effects of built-in curling, concrete shrinkage induced warping, temperature gradient, and perimeter constraining conditions at that time. Even though the causes are different, the combined can all be modeled using an equivalent resultant temperature gradient.



(a) Flat slab (typically early in the morning or late in the evening)

(b) Slab curled downward (typically during daytime)

(c) Slab curled upward (typically during nighttime)

Figure 1. Slab and subgrade contact scenarios.

The curling behavior of concrete slabs is well recognized in the pavement engineering community. The Federal Aviation Administration's (FAA) Advisory Circular (AC) 150/5370-11B [2] does caution that slab curling may affect FWD data analysis, but the AC only discusses its effect on void analyses. There is still lack of documentations and guidelines on slab curling's impact on the structural responses of JCP pavements.

SIGNIFICANCE

The backcalculated layer moduli are directly used to evaluate the existing pavement and to reconstruction designs and rehabilitation designs. Variations in backcalculated moduli for the same pavement under different ambient conditions can produce substantially different results in evaluation, reconstruction designs, and rehabilitation designs. It is thus of great importance to obtain values that represent the true material properties.

The following example shows how much variation of backcalculated moduli occurred due to daily temperature fluctuation. Figure 2 and Figure 3 are excerpted from Khazanovich's Report [3] and show the backcalculated subgrade reaction moduli and the concrete resilient moduli, respectively, from the FWD tests performed at different times of the same day for Test Section 133019, one section located in Georgia. As shown in Figure 2, the daily variation in backcalculated subgrade reaction modulus can be very significant. The lowest subgrade moduli are from the testing at 2:10 PM, which are only one-third of the subgrade moduli from the 7:30 AM testing. Even though the variation in PCC moduli between different testing times in a day is less significant, the highest backcalculated PCC moduli are still about 50% more than that of the lowest backcalculated PCC moduli, as shown in Figure 3. The report further stated: "Almost all sections showed dependence of backcalculated parameters on the time of the testing."

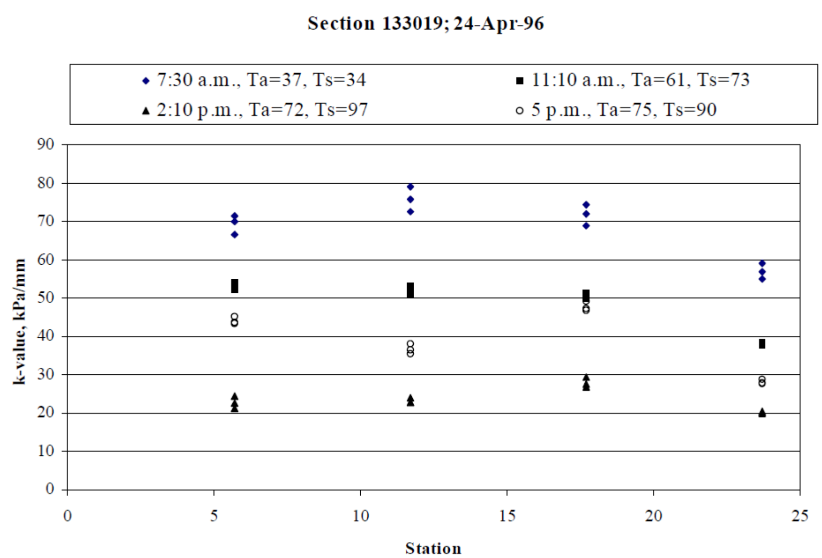


Figure 2. Daily variation in backcalculated subgrade reaction modulus [3].

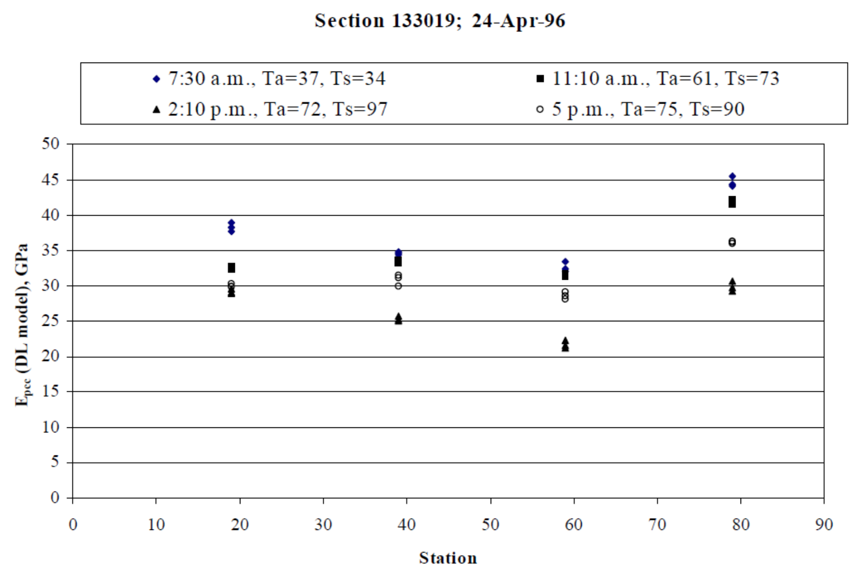


Figure 3. Daily variation in backcalculated concrete resilient modulus [3].

To show how much the variation in moduli can affect the evaluation, the backcalculated moduli at 7:30 AM and 2:10 PM at the first station, as shown in Table 1, were used in an example evaluation.

Table 1.
Approximate Backcalculated Layer Moduli.

Time	Concrete resilient modulus	Subgrade reaction modulus
7:30 AM	5,800 ksi (40 GPa)	258 psi/in. (70 kPa/mm)
2:10 PM	4,351 ksi (30 GPa)	74 psi/in. (20 kPa/mm)

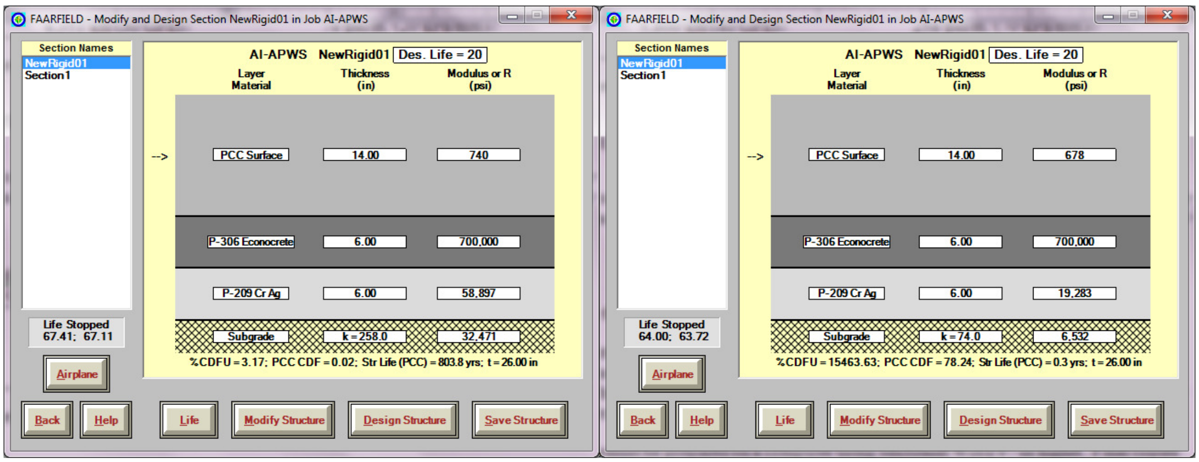
The concrete modulus of rupture was estimated based on the equation below:

$$M_r = 43.5 \times E_{pcc}/10^6 + 488.5$$

Where M_r is concrete modulus of rupture in psi and E_{pcc} is concrete resilient modulus in psi. The estitmated concrete moduli of rupture are 740 psi and 678 psi, respectively, at 7:30AM and 2:10 PM. The airplane traffic mix that comes with the New Rigid section in the “samples” in FAARFIELD was used in this example, as shown in Table2. Figure 4 shows the remaining life estimates based on the backcalculated moduli at different time of testing. The remaining life is 803.8 years based on the backcalculated moduli at 7:30 AM while it is only 0.3 year based on the values at 2:10 PM.

Table 2.
Airplane mix data.

Airplane	Gross weight, lb	Annual departure	% Annual growth
DC10-10	458,000	2,263	0
B747-200B	833,000	832	0
B777-200ER	634,500	425	0



(a) Estimate for testing at 7:30 AM (b) Estimate for testing at 2:10 PM

Figure 4. Remaining life estimates.

Extremely contradicting evaluation results were obtained for those two cases where only the time of testing was different. This indicates the conventional model produces significant variation in backcalculated moduli and thereafter the evaluation results based on those values.

BACKCALCULATION WITH SLAB CURLING CONSIDERED

Ideally a sound model should correctly take into account necessary factors. The conventional model primarily takes into account the pavement layer thicknesses and layer moduli. As the slab curling has significant effect on the FWD deflections, it is thus necessary to incorporate a factor into the backcalculation model to account for this effect.

For a basin test, the FWD load plate is typically placed at the slab center, as shown in Figure 5. Symmetries in both longitudinal and transverse directions with respect to the slab center can be applied. As a result, only a quarter of the slab is used in the model to improve the model efficiency. The load plate is modeled as a square print with the same size of the circular load plate. Similarly, only a quarter of the load is used in the model. The approximate tandem weight of an LTPP FWD trailer is 3.4 kips. Figure 6 illustrates the FEM model using ILSL2 [4,5,6].

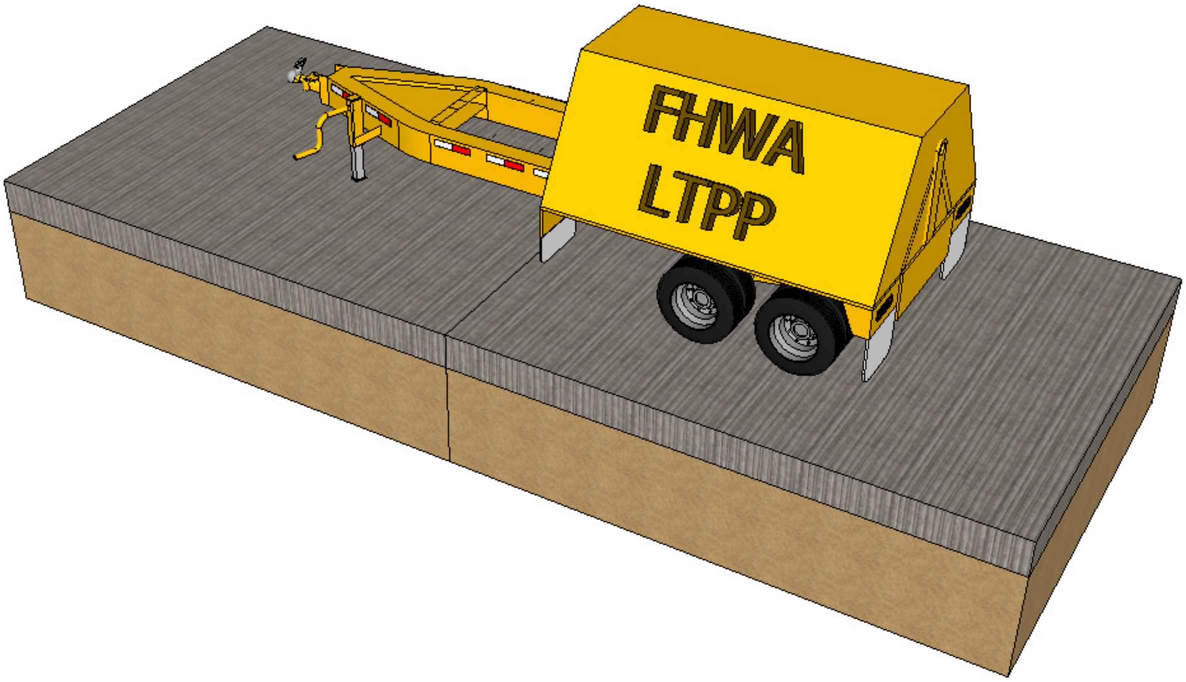


Figure 5. Placement of an FWD trailer.

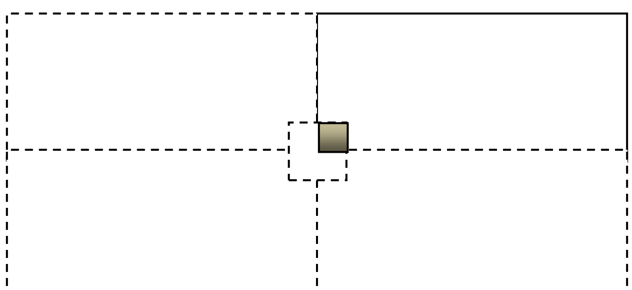


Figure 6. FEM Model of a quarter of a slab.

It is important to note that the FWD deflections measure the difference of the slab surface profiles before and after applying the FWD load. Before applying the FWD load, the slab has deflected due to the self-weight, resultant temperature gradient (built-in temperature gradient, moisture gradient, daily temperature gradient), and trailer tandem weight. In order to model the FWD deflections, two separate FEM runs have to be performed: one with combined loads of concrete self-weight, resultant temperature gradient, and trailer tandem, and the other with all previous loads plus the FWD load. The differential deflections between those two runs are the FWD deflections. Figure 7 shows an example to determine the FWD induced deflections using FEM.

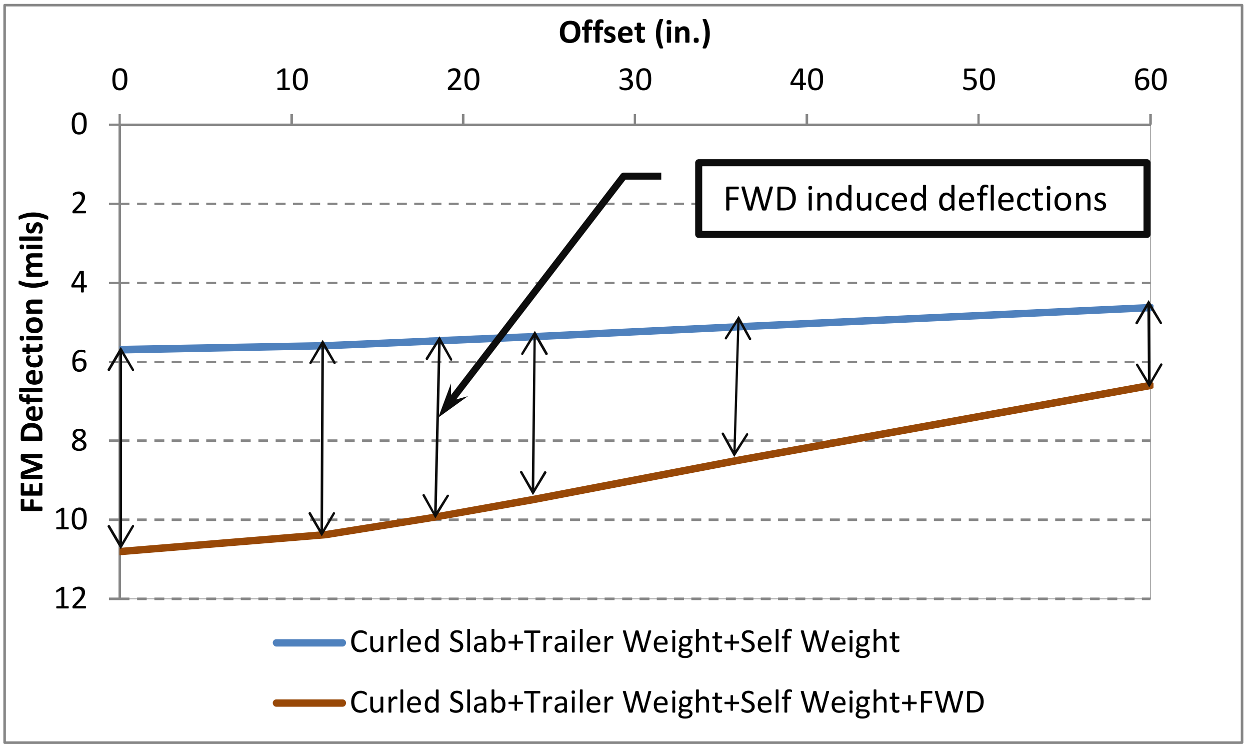


Figure 7. Determination of FWD induced deflections using FEM.

A case study to demonstrate this concept was performed on four sets of deflection basins collected at POINT_LOC -6.4 of LTPP Section 13-3039 on 4/24/1996. There are three load levels available for each set of data and four drops at each load levels.

The slab dimensions are presented in Table 3.

Table 3.
Slab dimensions.

	Measurement
Thickness	9.1 inches
Length	20 ft
Width	12 ft

The coefficient of thermal expansion (CTE) data was obtained from LTPP Table TST_PC03, as shown in Table 4. 8.40E-06 mm/mm/ºC is converted to 4.67 in./in./ºF for use in the finite element model.

Table 4.
CTE values for Section 13-3039.

LOC_NO	SAMPLE_NO	COEF_THERMAL_EXPANSION mm/mm/ºC	TEST_DATE
A1	CP51	8.30E-06	3/28/2011
A2	CP52	8.10E-06	11/8/2006
C10	CP10	8.60E-06	5/8/2002
C3	CP03	8.50E-06	5/22/2002
C4	CP04	7.10E-06	5/18/2004
C6	CP06	9.10E-06	1/20/2011
C9	CP09	8.70E-06	5/9/2002
A1	CP51	8.40E-06	4/7/2011
C6	CP06	8.50E-06	7/31/2012
	Average	8.40E-06	

Temperature gradients in the concrete slabs are available from Table SMP_MRCTEMP_AUTO_HOUR. The following four figures show the temperature gradients at the approximate time of the FWD testing. The temperature gradients only serve for reference purposes. As described earlier, the shape of the concrete slab is resulted from the combined effects of a number of factors. But it is believed that within a day, the temperature gradient variation is the major cause for the change of the deflection basin.

The charts in Figure 9 show the FWD deflections vs. the FEM modeled FWD deflections. E_{pcc}, $K_{subgrade}$, and resultant effective temperature gradients were varied to "best fit" those two sets of deflections for all four FWD runs during that day. E_{pcc}, $K_{subgrade}$, were determined to be 4.5 million psi and 250 psi/in., respectively. The resultant temperature gradients are 0, 7, 19, and 15 ºF, respectively, for those four FWD runs during that day.

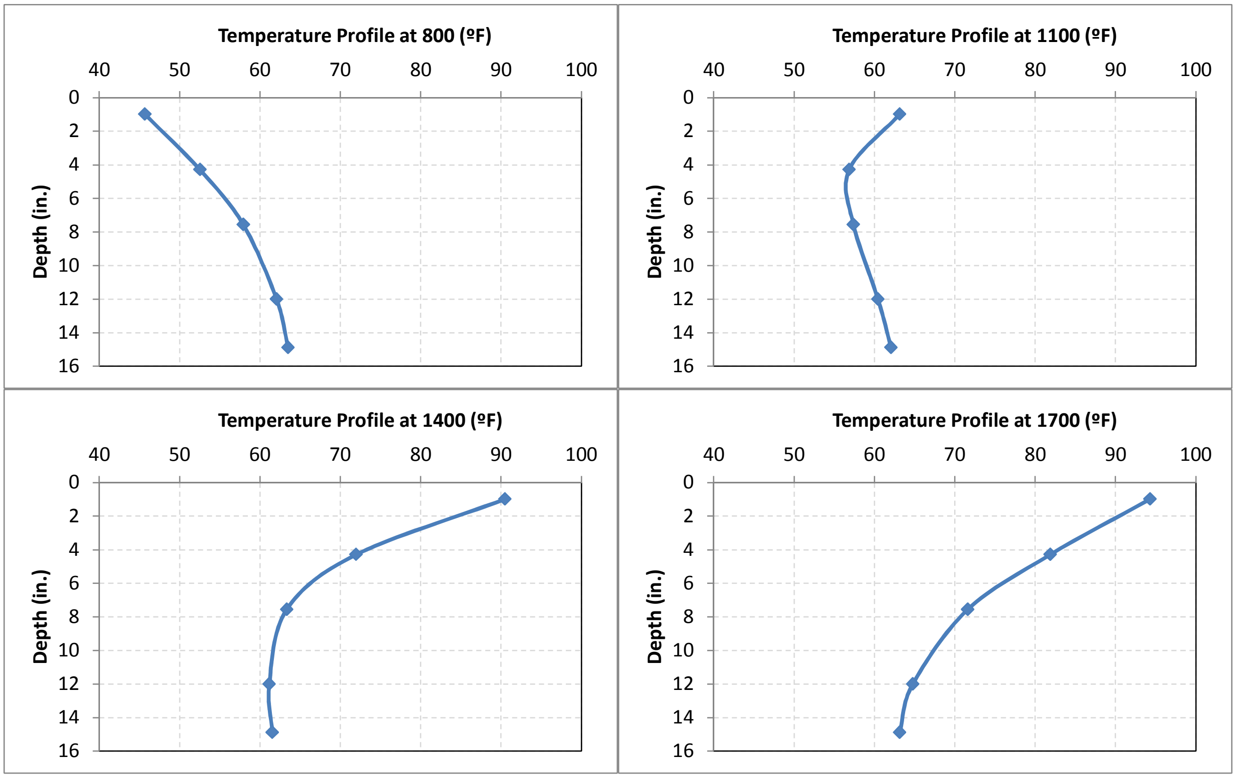


Figure 8. Temperature gradients at different times of the day.

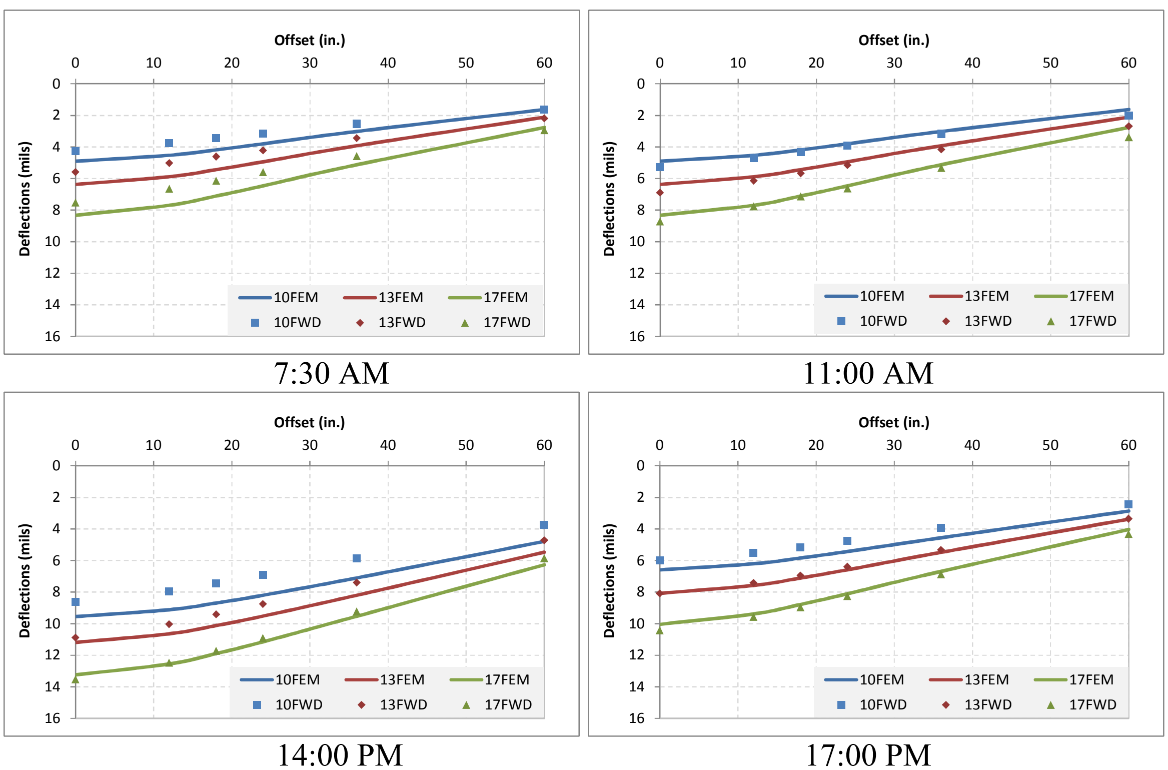


Figure 9. FWD deflections vs. FEM deflections.

It should be noted that the resultant temperature gradients are not the same as the actual measured temperature gradients. The resultant temperature gradient includes built-in curling, warping, daily temperature gradient induced curling, slab perimeter constraint condition, etc. However, the daily temperature gradient variation is the driving force for the FWD deflection response variation within a day. As described earlier, the resultant temperature gradient at each testing time is one of the variables that the backcalculation process is seeking for to best-fit modeled deflections with the FWD deflections.

Based on the conventional method, the time of day when the FWD testing was performed has a significant effect on the backcalculated moduli. By incorporating equivalent temperature gradients in the backcalculation process for JCP pavements, the curling effect is considered in the model so more reasonable layer moduli can be backcalculated.

SUMMARY

Slab curling significantly affects the structural responses due to an FWD load for highway JCP pavements. Airport JCP pavements may exhibit the same behavior, but further investigation is needed as the dimensions for airfield concrete pavements are typically much larger. Backcalculation based on the conventional method computes significantly different layer moduli that lead to contradicting evaluation results. A backcalculation process with a curling factor incorporated is able to inherently characterize the structural response change due to a change in the resultant temperature gradient that is driven by daily temperature gradient variations.

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