Interpreting the effects of curled/warped pavements on the analysis of FWD data

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ABSTRACT: Falling Weight Deflectometer (FWD) test results of concrete pavements are influenced by the presence of temperature and moisture gradients in the pavement. Performing FWD testing at times when pavement support varies due to the presence of temperature and/or moisture gradients results in the measurement of nonrepresentative deflections and can lead to improper evaluations of material properties and pavement conditions. A study was performed to quantify the effects of curling and warping on FWD-based evaluations of concrete pavements. Deflection, strain, temperature, moisture and surface profile data were collected from the concrete pavement test sections at the Minnesota Road Research Facility (Mn/ROAD). The field data was used to determine the effect of gradients on FWD data. The measured slab response was compared to analytical results generated using the pavement finite element analysis program ISLAB2000.

KEY WORDS: Curling, slab profile, gradients, FWD, curvature.

1. INTRODUCTION

The scope of this research effort included both field measurements and finite element analysis to to quantify the effects of curling and warping on FWD-based evaluations of concrete pavements. Deflection, strain, temperature, moisture and surface profile data were collected from the concrete pavement test sections at the Minnesota Road Research Facility (Mn/ROAD). The field data was used to determine the effect of gradients on FWD data. The measured slab response was compared to analytical results generated using the pavement finite element analysis program ISLAB2000.

2. Mn/ROAD RESEARCH FACILITY

Mn/ROAD is a densely-instrumented pavement test facility constructed adjacent to I-94 approximately 65 km (40 miles) northwest of Minneapolis, Minnesota. This study includes data collected from the nine test cells that constitute concrete test sections, representing different combinations of slab thicknesses, joint spacings, restraint conditions, and subbase types. All test sections have asphalt shoulders. The test sections contain temperature, moisture and static strain sensors that were used to determine the response of the pavement to vehicle loads and/or environmental effects.

Initially all test cells were constructed with dowels and tie bars; therefore, slab curling and warping could only be quantified under restrained slab conditions. While there are many concrete pavements built with load transfer devices, there are still pavements constructed which do not include them. The objective of this project involves quantifying the amount of curling and warping displayed by all concrete pavement slabs. Therefore, it was desirable to measure curling and warping deflections for slabs restrained by load transfer devices, as well as those not restrained. The dowel and tie bars were cored at the joint from one slab representing each pavement design in September 1995. Dowel bars were only cut on slabs in the passing lane to minimize the structural damage that results from the loss of load transfer across the joints. The released slabs allow comparisons of curling/warping characteristics between restrained and unrestrained slabs under otherwise identical conditions.

The field data included in the study were collected during September 1995, April 1996 and October 1996. Data was collected at the Mn/ROAD research facility on three different occasions in an attempt to quantify seasonal effects. Each test period required 24-hour data collection to capture daily effects by collecting data for each test cell under zero, negative and positive gradient conditions. A description of the research facility, design parameters of each test section and the data collection techniques is provided below in table 1. The gradations of the base materials referred to in table 1 are provided in table 2.

3. QUANTIFYING NON-LINEAR TEMPERATURE GRADIENTS

The pavement temperature and moisture gradient present while the profile measurements were performed must first be determined to develop curvature prediction models. Frequently the temperature distribution is characterized as a gradient be dividing the difference between the temperature at the top and the bottom of the pavement by the distance between the two temperature measurements. A linear gradient must be present for this method to accurately characterize the temperature distribution in the pavement. It is common knowledge nonlinear gradients also develop. It has been suggested that a parameter referred to as the “temperature moment” can be used to describe the combined effects of both uniform temperature changes and linear and nonlinear gradients (Janssen and Snyder, 2000). Figure 1 presents a graphical description of how to calculate temperature moment. Proving that the temperature moment is capable of uniquely

Table 1: Summary of concrete test cell design features at Mn/ROAD.

Test Section	Cell	Slab Thickness mm (in)	Joint Spacing m (ft)	Lane Widths, Inside/Outside m (ft)	Dowel Diameter mm (in)	Base Type, Thickness, mm (in)	Edge Drains	Comments
5-Year	5	190 (7.5)	6.1 (20)	4.0/4.3 (13/14)	25 (1)	cl4sp, 75 (3) over cl3sp (68)	No	
5-Year	6	190 (7.5)	4.6 (15)	4.0/4.3 (13/14)	25 (1)	cl4sp, 125 (5)	No	
5-Year	7	190 (7.5)	6.1 (20)	4.0/4.3 (13/14)	25 (1)	PASB 100 (4) over cl4sp, 75 (3)	Yes	
5-Year	8	190 (7.5)	4.6 (15)	4.0/4.0/4.3 (13/13/14)	25 (1)	PASB 100 (4) over cl4sp, 75	Yes	3 lanes, transverse steel
5-Year	9	190 (7.5)	4.6 (15)	4.0/4.0/4.3 (13/13/14)	25 (1)	PASB, 100 (4) over cl4sp, 75 (3)	Yes	3 lanes, no transverse steel
10-Year	10	240 (9.5)	6.1 (20)	3.7/3.7 (12/12)	32 (1.25)	PASB, 100 (4) over cl4sp, (75)	Yes	
10-Year	11	240 (9.5)	7.3 (24)	3.7/3.7 (12/12)	32 (1.25)	cl5sp, 125 (5)	No	
10-Year	12	240 (9.5)	4.6 (15)	3.7/3.7 (12/12)	32 (1.25)	cl5sp, 125 (5)	Yes	
10-Year	13	240 (9.5)	6.1 (20)	3.7/3.7 (12/12)	32 (1.25)	cl5sp, 125 (5)	No	

Table 2: Aggregate gradations (percent passing) for Mn/ROAD base materials.

	Base Material			
Sieve Size	cl3sp	Cl4sp	cl5sp	PASB
37.5-mm-(1-1/2-in)	--	100	--	--
31.5-mm (1-1/4-in)	--	--	--	100
25-mm (1-in)	--	95-100	100	95-100
19-mm (¾-in)	--	90-100	90-100	85-98
12.5-mm (½-in)	100	--	--	--
9.5-mm (3/8-in)	95-100	80-95	70-85	50-80
4.75-mm (No. 4)	85-100	70-85	55-70	20-50
2-mm (No. 10)	65-90	55-70	35-55	0-20
850-µm (No. 20)	--	--	--	0-8
425-µm (No. 40)	30-50	15-30	15-30	0-5
75-µm (No. 200)	8-15	5-10	3-8	0-3

1 in = 25.4 mm

Special crushing requirements (sp):

cl3sp and cl4sp: crushed/fractured particles are not allowed

cl5sp: 10-15 percent crushed/fractured particles are required.

Permeable asphalt stabilized base (PASB)

***Temperature Moment* = $\Sigma(A_i \times r_i)/D$**

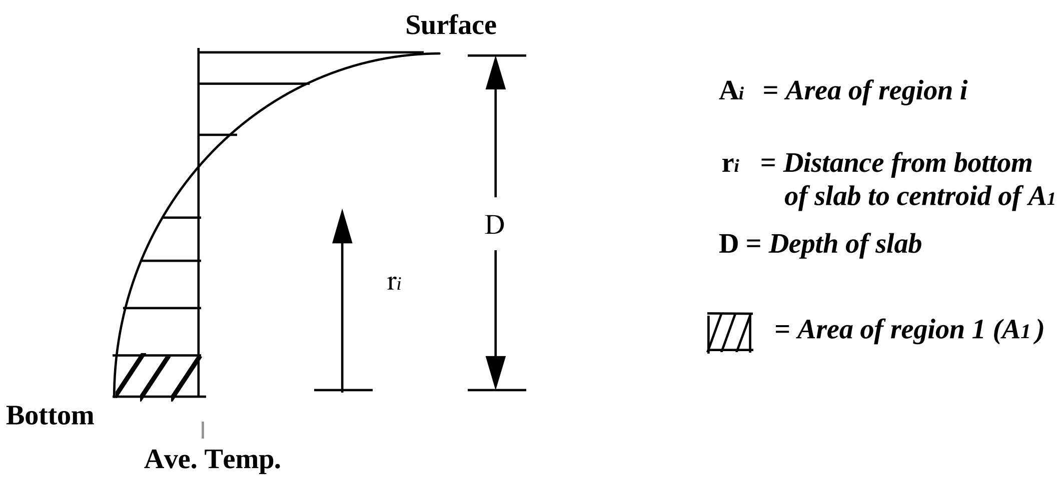

Figure 1: Graphical description of how to calculate temperature moment.

$$Equiv.LinearGrad. = \frac{12(TMo)}{h^3} \qquad \text{Equation 1}$$

TMo = Temperature moment

h = Slab thickness

representing a non-linear temperature profile in the slab to reduce the parameters required to characterize the temperature profile to one. The temperature moment can then be converted to an equivalent linear temperature gradient using equation 1 (Janssen and Snyder, 2000). A positive gradient will result in a negative temperature moment and a negative gradient creates a positive temperature moment.

4. FWD DATA ANALYSIS

FWD data collected out at Mn/ROAD was used to determine how gradients affect FWD data analysis. The first parameter investigated was joint performance as indicated by the load transfer efficiency [(δ_{unload} /δ_{loaded})x 100 percent]measured across the joint. The results of this analysis showed load transfer efficiencies measured for doweled slabs are not affected by temperature moments (or gradients), regardless of the dowel size (25-, 32-, and 38-mm [1-, 1.25-, and 1.5-in] dowels were considered). This even held true for the doweled slab with a low load transfer efficiency. Figure 2 is an example of the data analyzed for one test section. All load transfer efficiency FWD testing was performed when the joints were not locked. A more thorough analysis of all of the test sections is provided in Vandenbossche, 2003.

A sensitivity analysis was performed to determine if the backcalculated k-value was affected by temperature gradients in the slab when the deflection data was measured. The results of this analysis are summarized in figures 3 and 4. Figures 3 and 4 indicate backcalcuated k-values are influenced by temperature gradients for thin [191-mm (7.5-in)] slabs but not thick slabs [241-mm (9.5-in)] because the deflections measured on thicker slabs are less sensitive to changes in support conditions.

The next step was to determine if estimating the size of a void under the corner of the slab is affected by the presence of a gradient in the slab. The void size parameter was estimated using the Variable Corner Deflection Analysis Procedure developed by Crovetti and Darter. See 1993 AASHTO Design Guide. Plotting temperature moment against the void size parameter (See figure 5.) shows the estimated void size parmater is a function of the temperature moment (gradient) in the slab at the time of testing. The void parameter increases with an increase in temperature moment (increasing upward curvature). Data collected from of the test cells also indicated voids to be present when the joints were locked when the slabs had negative gradients. Based on these results, the loss of support under the slab can be identified even when the joints are locked. Methodology for interpreting FWD deflection data for the detection of voids has been provided in Vandenbossche, 2003 along with a more detailed analysis of all of the void size parameter data analyzed.

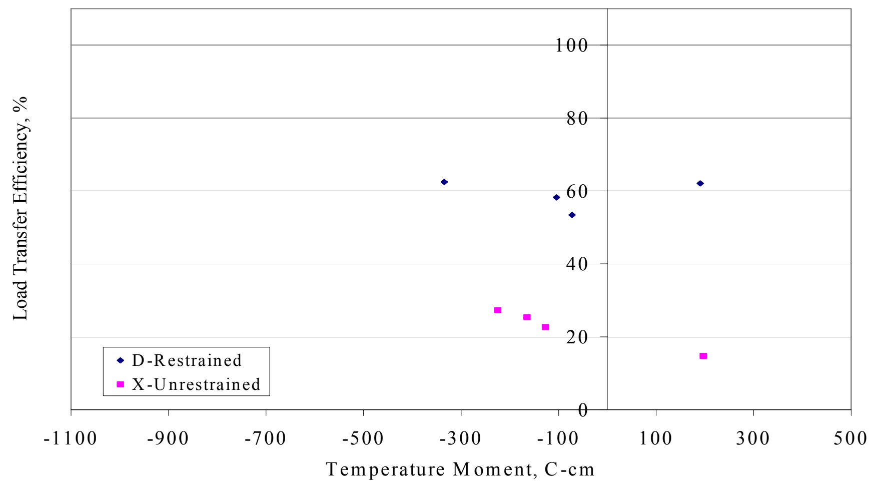

Figure 2: LTE data collected for Cell 7 in Oct. 1996.

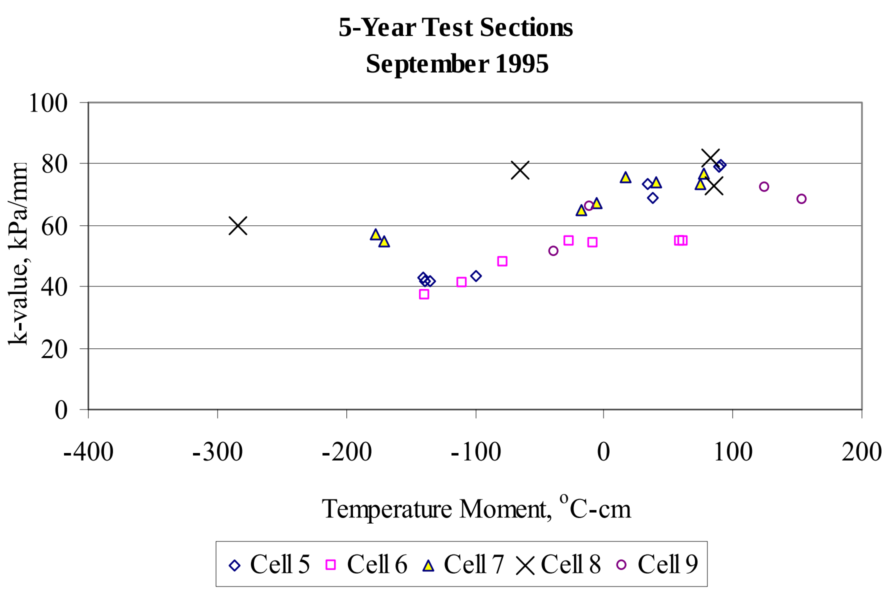

Figure 3: Relationship between temperature moment and k-values for thinner slabs.

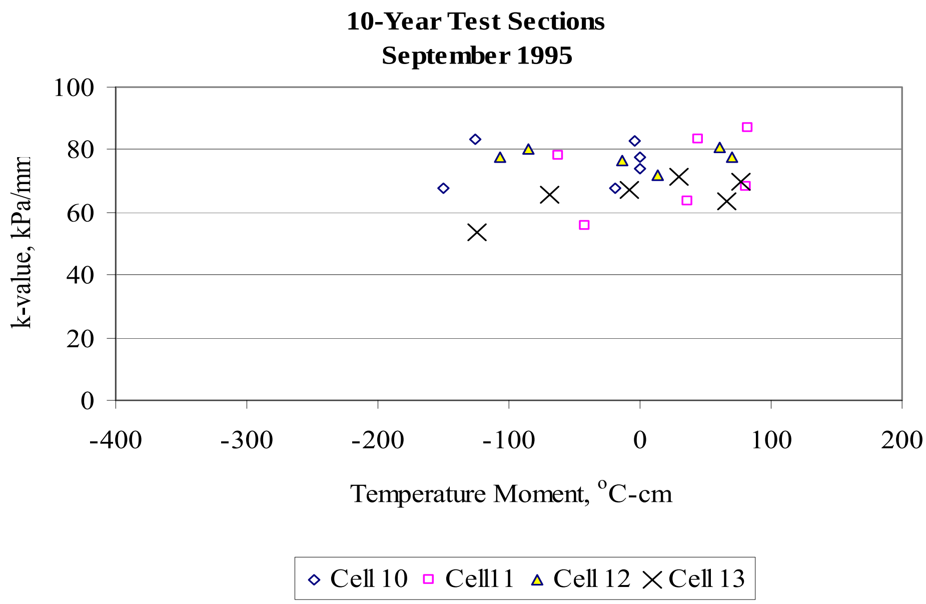

Figure 4: Relationship between temperature moment and k-values for thicker slabs.

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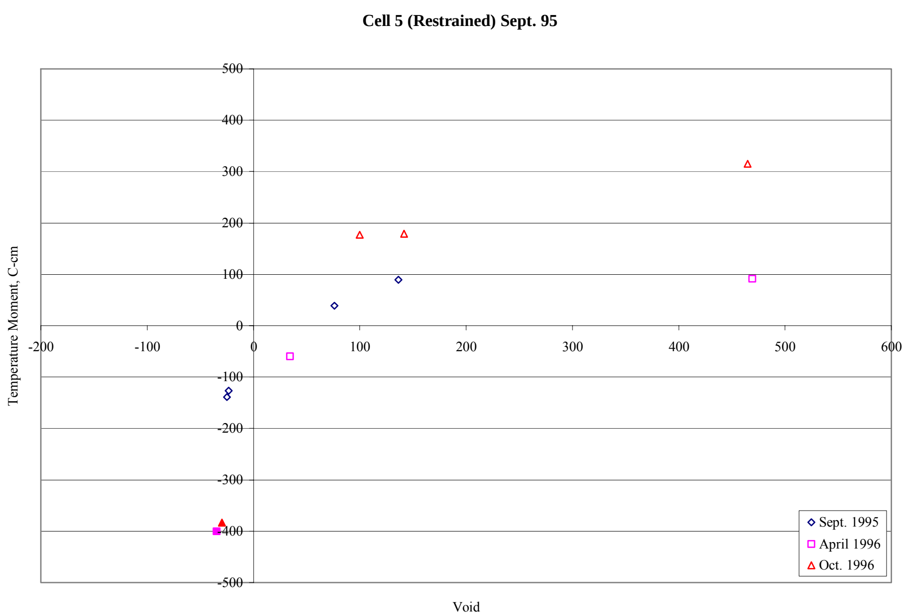

Figure 5: Void analysis for restrained slab in Cell 5.

5. COMPARISON BETWEEN MEASURED SLAB PROFILES AND FINITE ELEMENT DATA

The profile data collected at Mn/ROAD was used to evaluate the ability of the finite element program ISLAB2000 to predict pavement response. A finite element model was constructed for each slab included in the study. A finite element analysis was performed representing the joint load transfer and temperature profiles present at the time the slab profiles were measured. The modulus of subgrade reaction was calculated for each test cell for the FWD measurements made when the zero deformation gradient, or a gradient close to the zero deformation gradient, was present. These support values were then used in the finite element models. A finite element analysis was performed for the restrained and unrestrained slabs from which profile data was collected. Models representing the temperature profile conditions under which profile data was collected were developed for both a positive and negative temperature moment for each data collection period. Comparisons were made between measured and predicted diagonal profiles for both a restrained and unrestrained (when available) slab in each test section.

The comparisons made between the FEM and measured slab profiles consisted of two components; 1. the length of the unsupported portion of the slab profile and 2. the shape of the slab profile. See figure 6.a. The profile estimated using FEM does not always sink into the base to the same degree as the measured slab for large positive temperature moments. This results in a shift upward of the whole FEM profile from the measured profile. See figure 6.b. This would indicate the stiffness of the base (estimated as the backcalculated k-value) used in the FEM model has been overestimated. The FEM models using the same base stiffness for the same cell and data collection period but for a different gradient produce FEM profiles that accurately represent the measured profiles indicating the assumed base stiffness is correct. This shift in the FEM profile from the measured profile only occurred when a large negative temperature moment is present and is always upward resulting in a larger portion of the FEM slab being unsupported compared to the support conditions of the measured slab shape. All temperature moments were less than -163 °C cm (-45 °F in) for slab approximately 190 mm (7.5 in) thick and less than -609 °C cm (-165 °F in) for slabs approximately 240 mm (9.5 in) thick. Only 12 percent of the FEM profiles were shifted upward from the measured slab profile. The shift in the profile was always less than 500 microns (20 mils).

A quantitative comparison was made between the shape of the FEM and measured diagonal profiles by calculating the curvature for each profile. The FEM curvature was plotted against the measured curvature for each slab. Table 3 was developed to provide a summary of thee graphs. A graph of the curvatures calculated and measured for all of the restrained cells and all of the unrestrained cells are provided in figures 7 and 8, respectively. .

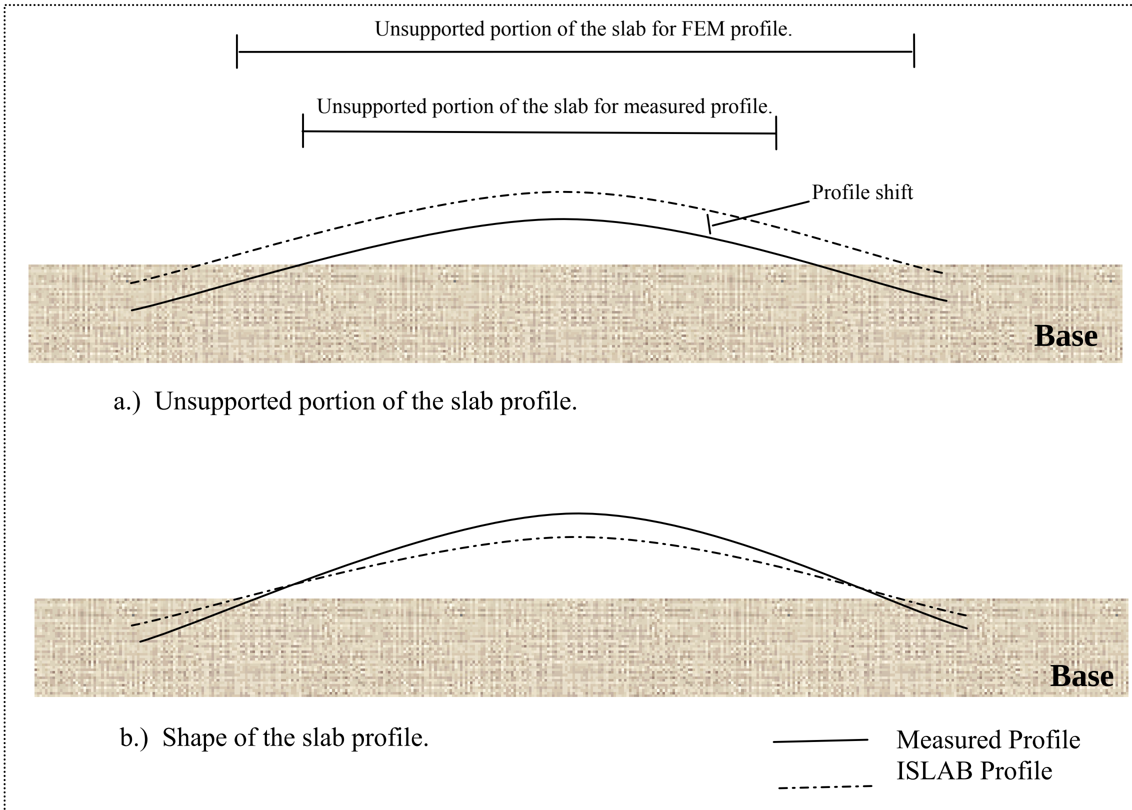

Figure 6: Comparisons between FEM and measured profiles; a) Unsupported portion of the slab profile. b.) Shape of the slab profile.

Curvatures were assumed to be approximately equal when the curvatures calculated using data from the FEM were accurate to +/-20 percent of the curvatures calculated using the measured surface profile data. Curvature was under-estimated by the FEM in 70 percent of the cases, with only a few instances where the FEM over-estimated the measured curvature (16 percent). The FEM predicted higher curvatures than were measured more frequently for the restrained slabs than the unrestrained slab. Seventy-one percent of the curvatures over-estimated by the FEM were negative. This indicates that the FEM is more likely to over-estimate the curvature produce by a positive gradient than the curvature produce by a negative gradient. Based on the results of this study, the FEM is also more likely to estimate higher curvatures than the measured curvature when the curvature is small. Curvature was accurately determined using FEM only 14 percent of the time. Measured curvatures that were accurately predicted using FEM were between -2.5 x 10^{-4} 1/m (-7.6 x 10^{-5} 1/ft) and 2.8 x 10^{-4} 1/m (8.5 x 10^{-5} 1/ft) for the restrained slabs and -3.5 x 10^{-4} 1/m (-10.6 x 10^{-5} 1/ft) and 2.6 x 10^{-4} 1/m (7.9 x 10^{-5} 1/ft) for the unrestrained slab. FEM could not accurately estimate the larger measured curvatures that fell outside of these ranges.

Table 3: Summary FEM and measured profile curvatures.

Cell	Slab	FEM Under-estimated Measured Curvature	FEM Over-estimated Measured Curvature	FEM and Measured Curvature Approximately Equal to FEM[1]
5	Restrained	4	1	0
	Unrestrained	5	1	0
6	Restrained	4	1	0
	Unrestrained	4	0	1
7	Restrained	3	2	1
	Unrestrained	3	3	0
8	Restrained	1	1	2
	Unrestrained	3	0	1
9	Restrained	4	0	1
10	Restrained	4	2	0
	Unrestrained	4	0	0
11	Restrained	4	1	0
	Unrestrained	4	1	1
12	Restrained	2	0	0
13	Restrained	5	0	1
	Unrestrained	3	0	3
Summary Statistics	Total	57	13	11
	Percentage	70%	16%	14%

[1]Curvatures were assumed approximately equal if they were within 20 percent of the curvature calculated using the measured profile.

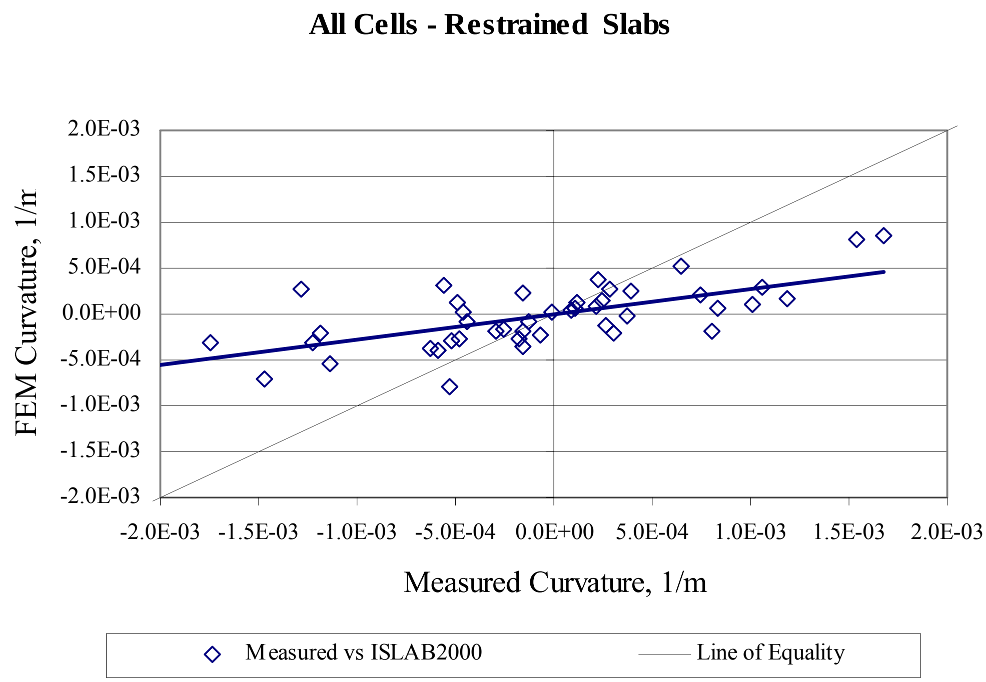

Figure 7: Curvatures of measured and finite element surface profiles for the restrained slabs in all cells.

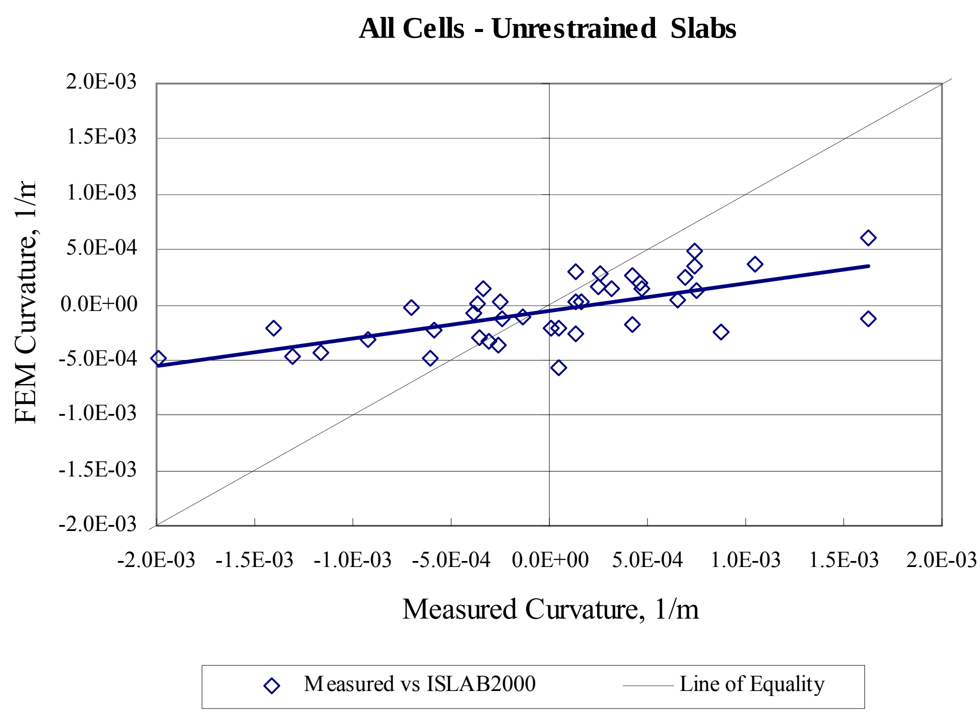

Figure 8: Curvatures of measured and finite element surface profiles for the unrestrained slabs in all cells.

The curvature data was also used to evaluate the ability of the FEM programs to predict curvature for slabs of different thickness, different restraint conditions (dowels and tie bars/no dowels and no tie bars) and different slab support conditions. A summary of the FEM and measured profile curvatures for various pavement design variables is provided in table 4. The curvatures calculated using slab profiles generated using the FEM tend to over-estimate the curvatures calculated using measured profiles more frequently for thinner slabs and granular bases. Curvature was accurately estimated using FEM more frequently for unrestrained slabs than restrained slabs.

The ability of the FEM to accurately estimate curvature appears to be a function of the pavement design and the magnitude of the gradient. The FEM was able to accurately predict curvature for several gradients in all cells but Cells 5, 10 and 12. Curvature was accurately determined using FEM only 14 percent of the time with curvature being under-estimated 70 percent of the time.

Table 4: Summary of FEM and measured profile curvatures for various design variables.

Cell	Slab	FEM Under-estimated Measured Curvature	FEM Over-estimated Measured Curvature	FEM and Measured Curvature Approximately Equal to FEM[1]
All Cells	190 mm slab	67%	20%	13%
	240 mm slab	74%	11%	14%
All Cells	Granular base	63%	23%	14%
	Stabilized base	67%	11%	13%
All Cells	Restrained	70%	18%	11%
	Unrestrained	70%	14%	16%

[1]Curvatures were assumed approximately equal if they were within 20 percent of the curvature calculated using the measured profile.

6. CONCLUSIONS

The presence of a gradient in the slab was not found to affect joint performance as estimated by load transfer efficiency using FWD deflection data. The presence of a gradient did appear to affect the backcalcualted k-value for thinner slabs but not for the thicker slabs. Finally, it was determined the void size parameter estimated using FWD data was highly dependent on the temperature moment (or gradient).

This study also revealed ISLAB2000 provides an accurate estimation of the portion of the slab supported by the base 88 percent of the time for the pavement designs included in this study. ISLAB2000 did under estimate the measured curvature 70 percent of the time. ISLAB2000 provided more accurate estimations of the measured curvature when smaller gradients were present.

REFERENCES

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