

Effect of PCC Material Properties on MEPDG Jointed Plain Concrete Pavement (JPCP) Performance Prediction

Halil Ceylan¹, Sunghwan Kim², Charles W. Schwartz³, Rui Li⁴,
and Kasthurirangan Gopalakrishnan⁵

Abstract

This paper focuses on comprehensive sensitivity analyses of various rigid pavement scenarios. Jointed Plain Concrete Pavement (JPCP) sections designed for three traffic levels in each of five climate zones are evaluated in the sensitivity analyses. One-at-a-time (OAT) local sensitivity analysis was implemented using a design limit normalized sensitivity index (NSI) to provide both quantitative and qualitative sensitivity information. All portland cement concrete (PCC) material properties examined showed sensitivity to at least one rigid pavement performance measure. The highest ranked sensitive inputs for JPCP analysis include the PCC strength and stiffness properties and the curling and warping related properties. The findings of this study can provide some practical guidance in PCC material property selection for rigid pavement practitioners in using MEPDG.

Introduction

The properties of the portland cement concrete (PCC) in a rigid pavement section are intuitively expected to have a significant influence on pavement performance. In recognition of this, the Mechanistic-Empirical Pavement Design Guide (MEPDG) requires comprehensive PCC material properties compared to any other rigid pavement design procedure.

The PCC material properties required in MEPDG consist of thermal, mix, and mechanical properties:

- PCC Thermal Properties
 - unit weight, Poisson ratio, Coefficient of Thermal Expansion (CTE), heat capacity, and thermal conductivity
- PCC Mix Properties
 - mix design properties and shrinkage related properties
- PCC Mechanical Properties
 - modulus of elasticity (E), modulus of rupture (MOR), compressive strength (f_c'), or split tensile strength (TS)

The modulus of elasticity (E) is required as a stiffness property for critical concrete pavement response computations. The additional mechanical property inputs in MEPDG for rigid pavement are modulus of rupture (MOR), compressive strength (f_c'), and split tensile strength as strength properties for distress predictions. The MEPDG also uses an explicit hierarchical approach for the designer flexibility to select design inputs based on the relative importance, size, cost, and available resources of the project. There is an obvious need for practical guidance in PCC material property selection for rigid pavement practitioners.

¹ **Corresponding Author**, Ph.D., Associate Professor, Iowa State University, Ames, IA 50011, USA, Email: hceylan@iastate.edu; ² Ph.D., P.E., Post-Doctoral Research Associate, Iowa State University, Ames, IA 50011, USA, Email: sunghwan@iastate.edu; ³ Ph.D., P.E., Professor, University of Maryland, College Park, MD 20742, USA, Email: schwartz@umd.edu; ⁴ Graduate Research Assistant, University of Maryland, College Park, MD 20742, USA, Email: lirui@umd.edu; ⁵ Ph.D., Research Assistant Professor, Iowa State University, Ames, IA 50011, USA, Email: rangan@iastate.edu

MEPDG sensitivity studies began appearing in the literature immediately after the initial release of the MEPDG in 2004. Early sensitivity studies for rigid pavements include work by Rao et al. (2004), Selezneva et al. (2004), Khazanovich et al. (2004), Hall and Beam (2005), Kannekanti and Harvey (2006), Darter et al. (2006), and Khanum et al. (2006). All of the studies mentioned above were conducted using versions of the MEPDG software prior to Version 1.0 release in 2007. However, some MEPDG design input sensitivities changed significantly from one version to the next owing to software error corrections, model recalibrations, and other implemented changes.

The rigid pavement sensitivity studies conducted after the Version 1.0 release include work by Tanesi et al. (2007), Buch et al. (2008), Kapmann (2008), McCracken et al. (2009), Oh and Fernando (2008), Puertas (2008), Tran et al. (2008), Guclu et al. (2009), Hall (2009), Hiller and Roesler (2009), Moon (2009), Oman (2010), Johanneck and Khazanovich (2010), and Hall et al. (2010). Some concerns of past studies include (1) varying of only a small subset of inputs in local conditions, (2) primitive sensitivity analysis approaches without quantitative interpretation – e.g., answering that “if input x goes up by $n\%$, out y goes down by $m\%$,” and (3) not using version 1.1 which forms the main framework of new AASHTO pavement design procedure called as DARWin-ME™. To resolve these concerns, the NCHRP 1-47 project “Sensitivity Evaluation of MEPDG Performance Prediction” was initiated and recently completed.

As part of NCHRP 1-47 project, this study focused on comprehensive sensitivity analyses of various Jointed Plain Concrete Pavement (JPCP) scenarios. The JPCP sections designed for three traffic levels in each of five climate zones are evaluated in the sensitivity analyses. The procedure and the results of sensitivity analyses are discussed in this paper highlighting the significant properties among the required PCC material properties for running MEPDG.

Sensitivity Analysis

Sensitivity analysis (SA) is the apportionment of output variability from a model to its various inputs. Sensitivity analysis draws upon many of the same concepts as the design of experiments. Design of experiments theory provides a framework for selecting the combinations of factor values that will provide the most information on the input-output relationships in the presence of variation (Box and Draper 1987, Box et al. 1978).

The classical approach is factorial design. For example, consider a model having k inputs. In order to evaluate the effect of each input on the model output, each input is varied over l levels—e.g., minimum, average, and maximum values for $l=3$. A full factorial experimental design then evaluates the model for all combinations of inputs and levels—i.e., l^k combinations. The full factorial experiment permits assessment of the main effect of each variable (i.e., the average effect of that variable over all conditions of other factors) as well as interactions. The principal disadvantage of full factorial experimental designs is that the l^k number of combinations quickly becomes very large as the number of inputs, k increases. Unfortunately, most models, including the MEPDG, have large sets of input parameters and are computationally expensive to evaluate. Reducing the number of combinations is the motivation for various partial or fractional factorial design techniques (e.g., blocking, aliasing, etc.).

Local SA provides an economical approach for identifying the subset of inputs that have the largest impact on the outputs. Only the sensitivities around the reference input values for the baseline cases are evaluated—i.e., the evaluation is only for very

small regions of the overall solution space. This provides only a “local” as opposed to a “global” sensitivity evaluation. The drawback of most standard local SA is that it tends to provide only qualitative sensitivity information—e.g., a ranking of input parameters in terms of their importance. However, these methods can be used to reduce the search space for subsequent quantitative sensitivity analysis.

One-at-time (OAT) methods are the most common type of local SA. In standard OAT applications, one or more baseline scenarios are exercised by varying each input independently. The number of model evaluations required by OAT techniques is on the order of k (rather than the l^k combinations required for a full factorial experimental design).

This study employed OAT local SA to provide an essential triage of MEPDG inputs to reduce the set of variables that need be considered in the much more computationally intensive global SA. To overcome the main drawback of most standard local SA providing only qualitative sensitivity information (a ranking of input), a normalized sensitivity index (NSI) was employed to provide both quantitative and qualitative sensitivity information. Note that quantitative sensitivity information here is the physical interpretation of sensitive analysis results. The NSI used in this study is “design limit” normalized sensitivity index S_{jk}^{DL} :

$$NSI = S_{jk}^{DL} = \frac{\Delta Y_j}{\Delta X_k} \frac{X_k}{DL_j} \quad (1)$$

in which X_k is the baseline value of design input k , ΔX_k is the change in design input k about the baseline, ΔY_j is the change in predicted distress j corresponding to ΔX_k , and DL_j is the design limit for distress j .

The NSI always uses the design limit as the normalizing factor for the predicted distress. NSI can be interpreted as the percentage change in predicted distress relative to the design limit caused by a given percentage change in the design input. For example, consider faulting of JPCP as the predicted distress with a design limit of 0.12 inches. An NSI of -0.19 for the sensitivity of faulting to 28-day PCC MOR implies that a 10% increases in 28-day PCC MOR will decrease faulting by $NSI \times \Delta X_k = 1.9\%$ of its design limit DL_j --i.e., it will decrease faulting by $0.10 \times 0.19 \times 0.12 = 0.00228$ inches.

Sensitivity Analysis Inputs

Global inputs. There are two sets of global inputs used in all OAT analyses: climate conditions and traffic levels. Five climate zones utilized for base case are hot-dry, hot-wet, temperate, cold-dry and cold-wet.

Table 1 summarizes the specific locations and the weather station used to generate the climate files for each of the five climate zones.

The three traffic levels used in all OAT analyses are summarized in Table 2. The baselines of Average Annual Daily Truck Traffic (AADTT) values are designed to fall within the low (<5,000), medium (5,000-10,000), and high (>15,000) truck volume categories in the FHWA *FAF Freight Traffic Analysis Report* (Alam et al. 2007). To put these traffic volumes into a more familiar context, the approximate numbers of Equivalent single axle loads (ESALs) are also included in Table 2. The AADTT ranges for varying AADTT values in each of traffic categories are listed in Table 2.

Table 1. Climate categories for base cases

Climate Category	Location	Weather Station
Hot-Wet	Orlando, FL	ORLANDO INTERNATIONAL ARPT
Hot-Dry	Phoenix, AZ	PHOENIX SKY HARBOR INTL AP
Cold-Wet	Portland, ME	PORTLAND INTL JETPORT ARPT
Cold-Dry	International Falls, MN	FALLS INTERNATIONAL ARPT
Temperate	Los Angeles, CA	LOS ANGELES INTL AIRPORT

Table 2. Traffic ranges for base cases

Traffic Category	Baseline Inputs		AADTT Range
	AADTT¹	Est. ESALs²	
Low	1,000	5M	500-5,000
Medium	7,500	25M	5,000-10,000
High	25,000	75M	20,000-30,000

¹Based on MEPDG Interstate Highway TTC4 Level 3 default vehicle distribution.

²Based on 25 year design life.

The five climate zones and three traffic levels give a total of 15 base cases for the sensitivity analyses. The combinations and abbreviations for each are as follows:

- CDL Cold-Dry-Low-Traffic
- CDM Cold-Dry-Medium-Traffic
- CDH Cold-Dry-High-Traffic
- CWL Cold-Wet-Low-Traffic
- CWM Cold-Wet-Medium-Traffic
- CWH Cold-Wet-High-Traffic
- TL Temperate-Low-Traffic
- TM Temperate-Medium-Traffic
- TH Temperate-High-Traffic
- HDL Hot-Dry-Low-Traffic
- HDM Hot-Dry-Medium-Traffic
- HDH Hot-Dry-High-Traffic
- HWL Hot-Wet-Low-Traffic
- HWM Hot-Wet-Medium-Traffic
- HWH Hot-Wet-High-Traffic

Special consideration of PCC stiffness and strength properties. The MEPDG needs PCC stiffness and strength design inputs at all three input levels. Level 1 of the MEDPG requires measured values of PCC E and MOR at various ages to characterize stiffness and strength gains over time. The required stiffness and strength values at Level 2 are estimated from f_c' results at various ages. Corresponding values of E and MOR are estimated from f_c' using standard empirical relations (Mallela et al. 2001). The required stiffness and strength values at Level 3 are estimated from a single point measurement of MOR (or f_c') and optionally the corresponding measured E at 28 days. The four options for specifying level 3 PCC stiffness and strength design inputs are (1) the 28-day MOR only; (2) the 28-day f_c' only; (3) the 28-day MOR and the corresponding 28-day E; and (4) the 28-day f_c' and the corresponding 28-day E. Using these inputs, the MEPDG estimates stiffness and strength gains over time.

A total of six design input options (Level 1, Level 2, and the four Level 3 alternatives) are available in the MEPDG for PCC stiffness and strength. This leads to two questions for the sensitive analyses. The first is “Do all of the MEPDG alternatives for PCC stiffness and strength design inputs yield comparable predictions of rigid pavement performance?” If the answer to this question is “no,” then the follow-on question is: “When Level 1 design inputs are not available, which other PCC stiffness and strength design inputs provide the most comparable and reliable rigid pavement performance predictions?”

To answer these questions, the effect of JPCP design input level (PCC strength and stiffness properties) on MEPDG performance predictions were evaluated (Schwartz et al. 2011). All MEPDG PCC input levels provided comparable predictions for faulting and to a lesser extent for IRI but different predictions for transverse slab cracking. Figure 1 presents the ranges and averages for the normalized slab cracking predictions for all input levels. The predicted slab cracking predictions were normalized by their respective Level 1 results. It is clear that the Level 3 inputs of measured 28-day MOR and E agree best with the Level 1 results in terms of having the smallest range and a mean value closest to 1. Based on these results, Level 3 inputs of measured 28-day MOR and E were utilized in all OAT analyses.

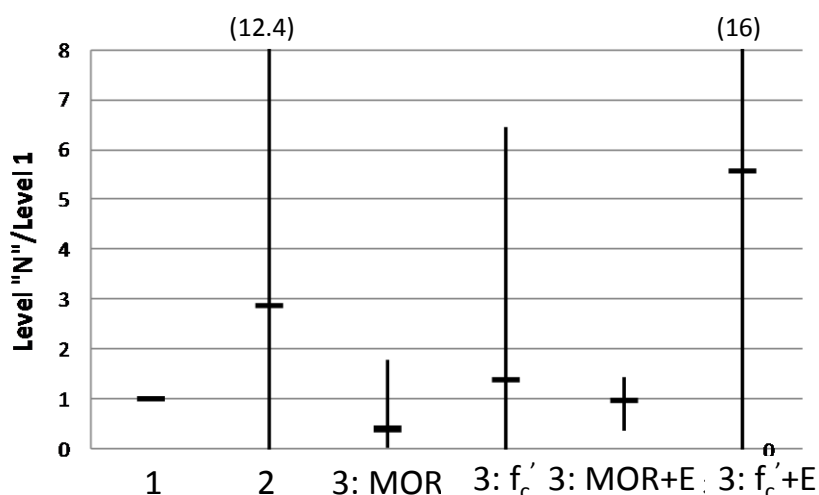


Figure 1. Ranges and mean values for normalized slab cracking predictions at each PCC design input level (Schwartz et al. 2011)

Analysis inputs for new JPCP. The OAT analyses of new JPCP encompassed a total of 15 base cases consisting of five climate zones and three traffic levels. Table 3 presents project-specific parameters that were fixed for all JPCP analyses.

Table 3. Fixed design inputs for new JPCP cases

Input Parameter	Value
Design Life	25 years
AADTT Category	Principal Arterials – Interstate and Defense Route
Truck Traffic Classification (TTC)	4
Number of Lanes in Design Direction	2 for low traffic/ 3 for medium and high traffic
Truck Direction Factor	50
Truck Lane Factor	75 for low traffic /55 for medium traffic /50 for high traffic
Default Growth Rate	No Growth
First Layer Material Type	Portland Cement Concrete
Second Layer Material Type	Granular Base
Subgrade Material Type	Soil

Table 4 summarizes the design inputs that are related to traffic levels. Higher traffic levels require correspondingly thicker PCC and base layers. The baseline value, reduced value (“-value”), and increased value (“+value”) for the PCC and granular base layers are listed under each traffic level category.

The remaining design inputs varied in the OAT sensitivity analyses are summarized in Table 5. These inputs correspond to the “Highly Sensitive” and “Sensitive” design inputs as identified from previous studies (Hall and Beam 2005, Kannekanti and Harvey 2006, Guclu et al. 2009). The baseline value, reduced value (“-value”), and increased value (“+value”) are listed for each design input. Absolute terms and multiplicative factors were utilized to describe the decreases/increases from the baseline values. The edge support inputs in MEPDG JPCP analyses are specified as one of three options: no support, tied PCC, and widened slab. The “no support condition” represented as a 5% LTE and 12-ft slab width was selected as the base condition. The distress predictions under the no support condition were compared to those for two other LTE values (50% and 80%) for the tied PCC option or two slab widths (13ft and 14ft) for the widened slab option.

Table 4. Design inputs related to traffic levels in new JPCP cases

Traffic Level Input Parameter	Low Traffic			Medium Traffic			High Traffic		
	Baseline	-	+	Baseline	-	+	Baseline	-	+
Nominal AADTT	1,000	500	5,000	7,500	5,000	10,000	25,000	20,000	30,000
Design Lane AADTT	375	188	1,875	2,063	1,375	2,750	6,250	5,000	7,500
PCC Thick.,	8	6	10	10	8	12	12	10	14

inch									
Base Thick., inch	4	2	6	6	3	9	8	5	12

Table 5. Input parameters and variations in new JPCP cases

Input Parameter	Baseline Value ¹	- value	+ value
Construction Month	July 2006	March 2006	October 2006
Design Lane Width	12	11	N/A ²
Joint Spacing	15	10	20
Dowel Diameter	1.2	1.0	1.5
Edge Support – LTE	5 (no support)	5	50, 80
Edge Support – Widened Slab	12 (no support)	12	13, 14
Erodibility Index	3	1	5
Surface Shortwave Absorption (SSA)	0.85	0.80	0.98
PCC Unit Weight	150	140	160
PCC Poisson's Ratio	0.15	0.10	0.20
PCC Coef. of Thermal Expansion (CTE)	5.56	2	10
PCC Thermal Conductivity	1.25	0.5	2
Cement Content	500	400	700
Water/Cement Ratio (W/C)	0.4	0.3	0.7
PCC Modulus of Rupture at 28 days (28-day MOR)	620	× 0.8 (496)	× 1.2 (744)
PCC Elastic Modulus at 28 days (28-day E)	3,956,571	× 0.8 (3,165,257)	× 1.2 (4,747,885)
Base Resilient Modulus (M _r)	25,000	15,000	40,000
Subgrade Resilient Modulus(M _r)	15,000	10,000	20,000
Ground Water Depth (GWD)	10	2	18

¹All values are in same units as MEPDG inputs.²N/A is not available.

Results and Discussions

New JPCP Base Case Performance Predictions. The 24 design inputs in Table 4 and Table 5 are varied over 3 input levels for 15 base cases (5 climate zones and 3 traffic levels) in the OAT sensitivity analyses. This required a total of 645 MEPDG runs for the JPCP scenarios. The predicted distresses at the 50% reliability level for the new JPCP baseline scenarios are summarized in Table 6. The predictions span a wide range of magnitudes (including values beyond the design limits) for all distresses. When interpreting Table 6, it is important to keep in mind the objectives of the OAT sensitivity analyses: the precise magnitudes of the predicted distresses are not the focus but rather how these predicted distresses vary as each design input is varied about its baseline value.

Table 6. Predicted distress levels for new JPCP baseline scenarios

Traffic	Climate	PCC, inch	Base, inch	Faulting, inch	Trans. Crack, %	IRI, inch/mile
Low	Hot-Wet	8	4	0.008	4.8	72.5
Low	Hot-Dry	8	4	0.009	13.7	80.0
Low	Cold-Wet	8	4	0.018	9.7	105.2
Low	Cold-Dry	8	4	0.009	14.6	142.4
Low	Temperate	8	4	0.005	1.5	68.1
Medium	Hot-Wet	10	6	0.046	2.0	89.9
Medium	Hot-Dry	10	6	0.052	7.2	96.9
Medium	Cold-Wet	10	6	0.089	2.4	134.0
Medium	Cold-Dry	10	6	0.045	5.0	151.1
Medium	Temperate	10	6	0.032	0.4	80.9
High	Hot-Wet	12	8	0.131	0.5	132.8
High	Hot-Dry	12	8	0.156	2.1	147.1
High	Cold-Wet	12	8	0.167	0.6	171.6
High	Cold-Dry	12	8	0.107	1.5	179.0
High	Temperate	12	8	0.102	0.1	117.2
Design Limit				0.120	15	172

A NSI value is calculated for each design input-pavement distress combination for each of the base cases. The NSI values for all distresses of the new JPCP cases are summarized through Figure 2 to Figure 4.

New JPCP Faulting Performance Predictions. Figure 2 present the NSI values for faulting of new JPCP. PCC unit weight, dowel diameter, and edge support with widened slab rank as the three most sensitive design inputs with NSI values ranging from -0.2 to -3.4. The negative sign of the NSI values means that faulting decreases with increases in values of these design inputs. Note that the ranges of NSI values are related to variations of each design input among 15 base cases. The decrease in faulting values using these design inputs is more prominent at higher traffic volumes. The PCC unit weight is a critical factor in the calculation of critical responses in the rigid pavement structural response models employed in MEPDG. An increase in unit weight can decrease curling deflections, which can reduce faulting. The increases in dowel diameter are highly effective for reducing faulting by increasing the transverse joint LTE. The use of a wider slab reduces deflections by keeping the vehicles axles well away from the free edge and corners where they can cause large stresses and strains in the pavement slabs.

The next three most sensitive design inputs are PCC CTE with NSI values varying up to 1.9, joint spacing with NSI values varying up to 1.6, and the PCC slab thickness with NSI values ranging from -1.7 to 0.8 . The positive signs of the NSI

values for these inputs mean that faulting increases with increases in values of these design inputs. A larger PCC CTE can cause higher curling deflections resulting in increased faulting. The decrease in predicted faulting with decreasing joint spacing could be explained by one that the shorter joint spacing results in smaller joint openings which can reduce chance of faulting distress (NCHRP 2004). Although it has been recognized that slab thickness affects slab cracking very significantly and faulting to a lesser extent, it was unexpected that faulting would increase as slab thickness increased in some cases in this analysis. This can be explained by the reduction of dowel shear effectiveness. An increase in PCC thickness leads to a decrease in the ratio of dowel cross-section to PCC cross-section (NCHRP 2004). Thus, an increase in PCC thickness may require a correlated increase in dowel diameter to avoid an increase in faulting. Note that the OAT analysis for PCC thickness varied only PCC thickness design inputs with fixed values of the other design inputs including dowel diameter.

SSA, AADTT, and cement content are the next most sensitive design inputs. Higher cement content and SSA may increase the drying shrinkage at the surface of the PCC slab, which may increase faulting due to increased warping deflection. AADTT agrees with engineering experience.

The other design inputs have less than 0.5 of average NSI values (see Figure 2). The low NSI values for these inputs indicate that they have only minor influence on the faulting predictions for new JPCP.

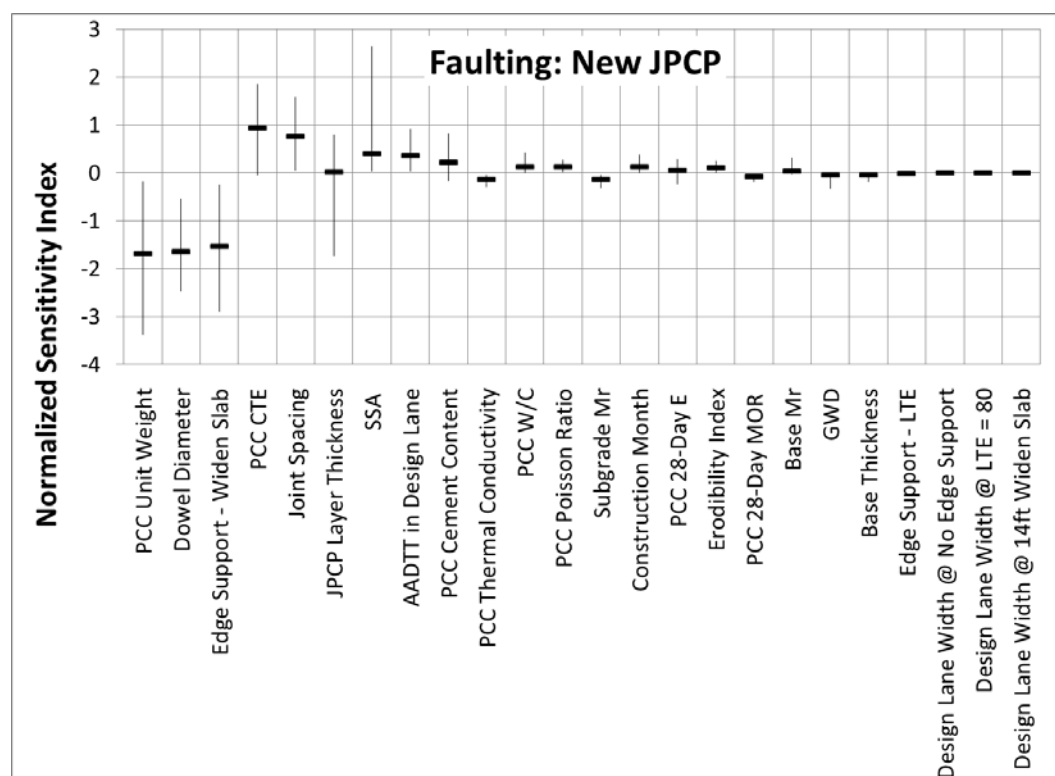


Figure 2 NSI values for faulting in new JPCP

New JPCP Transverse Cracking Performance Predictions. The NSI values for transverse cracking of new JPCP cases are summarized in Figure 3. The most sensitive design inputs in decreasing order are PCC 28-day MOR with NSI values ranging from -9.6 to -16.6, PCC thickness with NSI values ranging from -0.6 to -15, joint spacing with NSI values ranging from 2.5 to 9.9 and PCC 28-days E with NSI

values ranging from 0.4 to 9.8. Reduced transverse cracking with higher PCC strength and increased PCC thickness agrees with engineering experience. Increased transverse cracking with increasing joint spacing also agrees with engineering experience. Increases in PCC E lead to increases in bending stresses that may produce increased transverse cracking. Although in reality PCC MOR also increases with increasing PCC E, this was not reflected in the OAT analyses that by definition vary only one design input at a time.

The next most sensitive design inputs are PCC CTE with NSI values varying up to 4.6, thermal conductivity with NSI values ranging from -1.4 to -5.3, SSA with NSI values varying up to 11, edge support with widened slab with NSI values varying down to -6.6, and design lane width under widened slab condition with NSI values varying down to -7.2. Higher PCC CTE increases curling stresses resulting in increased transverse cracking. Higher thermal conductivity can decrease curling stresses by reducing temperature differences between the top and bottom of PCC slabs, which in turn decreases curling stresses and transverse cracking. As SSA increases, the pavement surface absorbs more heat from solar radiation, which can make PCC slab surface drier. More drying shrinkage at the top of the slab can result in increased transverse cracking due to increased warping stresses. Wider slabs can greatly reduce tensile bending stresses and transverse cracking by keeping the vehicles axles well away from the free edge and corners of the slabs.

Significant but relatively lower sensitive design inputs include PCC unit weight, PCC Poisson's ratio, and AADTT in design lane. PCC unit weight is an important input in the calculation of critical responses in rigid pavement structural response model employed in the MEPDG. An increase in unit weight can increase curling and warping stresses by restraining slabs from expanding and contracting due to temperature and moisture gradients. PCC Poisson's ratio is a required input to the structural response computation models employed in MEPDG. Although its effect on computed pavement responses is not great, the OAT analyses show that higher PCC Poisson's ratio may increase transverse cracking predictions by increasing the influence of lateral stresses. Increased transverse cracking with increasing AADTT agrees with engineering experience.

The other design inputs have average NSI values of less than 0.5 (see Figure 3). The low NSI values of these inputs indicate that they have only minor influence on the transverse cracking of new JPCP.

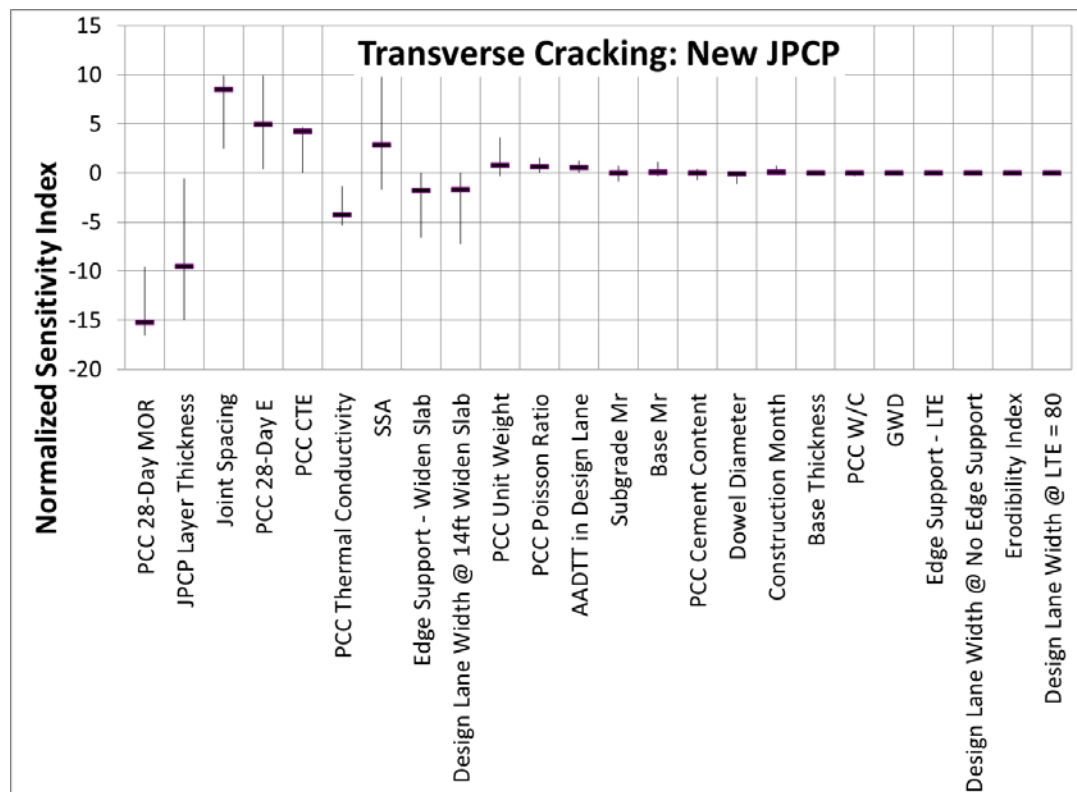


Figure 3 NSI values for transverse cracking in new JPCP

New JPCP IRI Performance Predictions. The NSI values for predicted IRI of the new JPCP cases are summarized in Figure 4. IRI predictions in MEPDG are calculated from regression equations that have as principal inputs the primary distresses (e.g., faulting, transverse cracking) along with a site factor. This means that the highly sensitive design inputs for faulting and/or transverse cracking will also be sensitive design inputs for IRI predictions.

The most sensitive design inputs for IRI predictions include PCC 28-day MOR, PCC thickness, edge support with widened slab, joint spacing, PCC CTE, dowel diameter, and PCC unit weight. Among these, the sensitive design inputs for both faulting and transverse cracking predictions are PCC thickness, edge support with widened slab, joint spacing, PCC CTE, and PCC unit weight. Increased PCC thickness in these OAT analyses resulted in a decrease in predicted faulting and predicted transverse cracking. A widened slab can also improve IRI by reducing faulting and transverse cracking. Higher PCC CTE and increased joint spacing increase predicted IRI by increasing both faulting and transverse cracking predictions. Increased PCC unit weight in these OAT analyses resulted in a decrease in predicted faulting and an increase in predicted transverse cracking. The net effect is that increased PCC unit weight causes a decrease in predicted IRI.

Among the sensitive design inputs for predicted IRI, those that are also sensitive design inputs for predicted transverse cracking alone are PCC 28-day MOR. The sensitive design input for predicted faulting alone is dowel diameter. As stated previously, these design inputs are the most sensitive for individual distress prediction. Thus, it is reasonable that these design inputs are also sensitive for predicted IRI. A higher PCC 28-day MOR can improve IRI by reducing transverse cracking. Increased dowel diameter can also improve IRI by reducing faulting.

The other design inputs have average NSI values of less than 0.5 (see Figure 4). These low NSI values indicate that these inputs have only minor influences on IRI predictions for new JPCP.

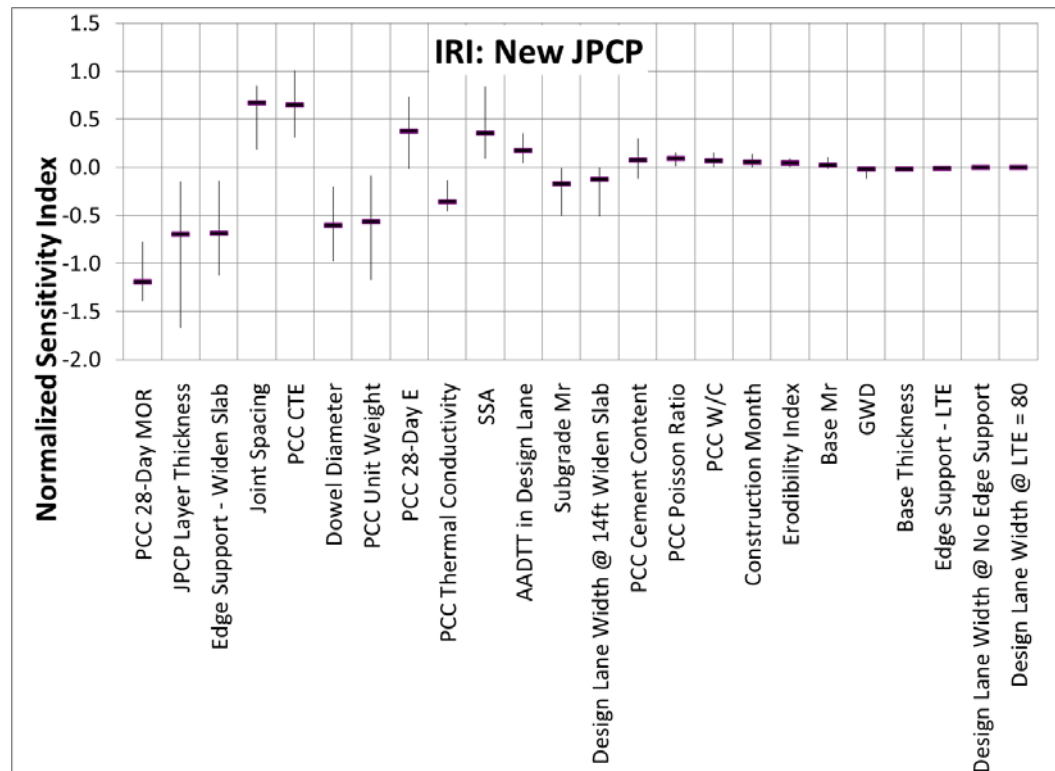


Figure 4 NSI values for IRI in new JPCP

Summary and Conclusions

New Jointed Plain Concrete Pavement (JPCP) sections designed for three traffic levels in five climate zones were evaluated for the sensitivity of predicted distresses to PCC material properties. Sensitivity is characterized by a design limit normalized sensitivity index NSI, which can be interpreted as the percentage change in predicted distress relative to the design limit caused by a given percentage change in the design input. The sensitive level of design inputs over all distresses and base cases for new JPCP considered in this study have been compiled in rank order and summarized in Table 7. For added insight, the design inputs related to PCC material properties are indicated by the shaded cells in Table 7.

All examined PCC material properties had sensitivity for at least one MEPDG rigid pavement performance measure. The PCC flexural strength (MOR) and stiffness (E) were found to be the most sensitive inputs among PCC material properties. Increases in PCC strength results in decreasing performance predictions while increases in PCC stiffness results in increasing performance predictions. In particular, this trend is more obvious for JPCP transverse cracking predictions. A 10% increase in PCC flexural strength decreases transverse cracking by about twice the cracking design limit ($2 \times 15\%$). A 10% increase in PCC stiffness increases transverse cracking by about as much as cracking design limit.

The curling and warping related inputs, including PCC CTE and unit weight, were also among the highest ranked sensitive inputs in JPCP sensitivity analysis. The very high sensitivities for these inputs suggest the need for high quality testing for these properties. The mix design related inputs, including PCC W/C and cement

content, showed sensitivity to JPCP performance predictions. These parameters are used in calculating the PCC zero stress temperature and ultimate shrinkage strain input parameters for the curling and warping stresses and deflections for a given climate. The PCC Poisson's ratio was more sensitive to JPCP transverse cracking predictions than faulting predictions.

The findings in this study were made from OAT local SA to provide an essential triage of MEPDG inputs to reduce the set of variables that need to be considered in the much more computationally intensive global SA. However, they can provide some practical guidance in PCC material property selection for rigid pavement practitioners in using MEPDG/AASHTO DARWin-ME.

Table 7. Ranking of JPCP design inputs by NSI

New JPCP Design Input	Sensitivities				
	Sensitivity Category	Maximum (All Cases)	Faulting	Transverse Cracking	IRI
PCC 28-Day MOR	Hyper Sensitive $ NSI > 5$	-16.55	-0.19	-16.55	-1.39
JPCP Layer Thickness		-15.03	-1.73	-15.03	-1.67
SSA		10.99	2.64	10.99	0.84
Joint Spacing		9.91	1.59	9.91	0.85
PCC 28-Day E		9.87	0.29	9.87	0.73
Design Lane Width @ 14ft Widen Slab		-7.20	0.00	-7.20	-0.51
Edge Support - Widen Slab		-6.60	-2.90	-6.60	-1.12
PCC Thermal Conductivity		-5.33	-0.28	-5.33	-0.45
PCC CTE	Very Sensitive $1 < NSI < 5$	4.63	1.85	4.63	1.01
PCC Unit Weight		3.60	-3.38	3.60	-1.17
Dowel Diameter		-2.46	-2.46	-1.10	-0.98
PCC Poisson Ratio		1.53	0.28	1.53	0.16
AADTT in Design Lane		1.25	0.92	1.25	0.35
Base Mr		1.07	0.31	1.07	0.11
Subgrade Mr	Sensitive $0.1 < NSI < 1$	-0.86	-0.30	-0.86	-0.51
PCC Cement Content		0.83	0.83	-0.71	0.30
Construction Month		0.67	0.38	0.67	0.14
PCC W/C		0.42	0.42	-0.30	0.16
GWD		-0.32	-0.32	-0.11	-0.12
Erodibility Index		0.25	0.25	0.01	0.09
Base Thickness		-0.20	-0.18	-0.20	-0.07
Design Lane Width @ No Edge Support	Nonsensitive $ NSI < 0.1$	-0.08	0.00	-0.08	0.00
Edge Support - LTE		-0.07	-0.02	-0.07	-0.01
Design Lane Width @ LTE = 80		0.00	0.00	0.00	0.00

Note. The shaded cells indicate the design inputs related to PCC materials properties

Acknowledgements

The authors gratefully acknowledge the National Cooperative Highway Research Program (NCHRP) of the Transportation Research Board (TRB) for supporting this study. The authors are also grateful to Dr. Amir N. Hanna and NCHRP 1-47 Project technical panel members for review and providing valuable comments. The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the TRB. This paper does not constitute a standard, specification, or regulation

References

- Alam, M., Fekpeet, E., and Majed, M. (2007). *FHWA FAF² Freight Traffic Analysis Report*, < http://ops.fhwa.dot.gov/freight/freight_analysis/faf/faf2_reports/reports7/> (Sept. 19, 2011).
- Box, G.E.P. and Draper, N.R. (1987). *Empirical model-building and response surfaces*, Wiley, NY.
- Box, G.E.P., Hunter, W.G., and Hunter, J.S. (1978). *Statistics for experimenters: an introduction to design, data analysis and model building*, Wiley, NY.
- Buch, N., Chatti, K., Haider, S. W., and Manik, A. (2008). *Evaluation of the 1-37A design process for new and rehabilitated JPCP and HMA pavements*, Research Report RC-1516, Michigan State University, East Lansing, MI.
- Darter, M. I., Khazanovich, L., Witczak, M., and Zapata, C. (2006). *NCHRP research results digest 308: changes to the mechanistic-empirical pavement design guide software through Version 0.900*, Transportation Research Board, National Research Council, Washington, DC.
- Guclu, A., Ceylan, H., Gopalakrishnan, K., and Kim, S. (2009). "Sensitivity analysis of rigid pavement systems using the mechanistic-empirical design guide software," *ASCE Journal of Transportation Engineering*, 135 (8), 555-562.
- Hall, K. D., and Beam, S. (2005). "Estimating the sensitivity of design input variables for rigid pavement analysis with a mechanistic-empirical design guide." *Transportation Research Record* 1919, 65-73.
- Hall, K. D., Xiao, X., and Wang, K. C. P. (2010). "Thickness estimation of existing pavements using nondestructive techniques: matching accuracy to application." *Annual Meeting of Transportation Research Board (DVD)*, National Research Council, Washington, DC.
- Hall, K. T. (2009). "Prediction of spalling and roughness in the mechanistic-empirical pavement design guide." *Proceedings, 9th International Conference on Concrete Pavement (CD-ROM)*, San Francisco, CA, 134-152.
- Hiller, J. E., and Roesler, J. R. (2009). "Comparison of mechanistic-empirical thickness design methods and predicted critical fatigue locations." *Proceedings, 9th International Conference on Concrete Pavement (CD-ROM)*, San Francisco, CA, 171-188.
- Johanneck, L. and Khazanovich, L. (2010). "Comprehensive evaluation of effect of climate in "Mechanistic–Empirical Pavement Design Guide" predictions." *Transportation Research Record* 2170, 45-55.
- Kampmann, R. (2008). *Engineering properties of Florida concrete mixes for implementing the AASHTO recommended mechanistic-empirical rigid pavement design Guide*, M.S. Thesis, Florida State University, FL.

Kannekanti, V., and Harvey, J. (2006). *Sensitivity analysis of 2002 design guide distress prediction models for jointed plain concrete pavement*. UCPRC-DG-2006-01, Pavement Research Center, University of California, Davis and Berkeley.

Khanum, T., Hossain, M., and Schieber, G. (2006). "Influence of traffic inputs on rigid pavement design analysis using the mechanistic-empirical pavement design guide," *Annual Meeting of Transportation Research Board (CD-ROM)*, National Research Council, Washington, DC.

Khazanovich, L., Darter, M. I., and Yu, H. T. (2004). "Mechanistic-empirical model to predict transverse joint faulting." *Transportation Research Record 1896*, 34-45.

Mallela, J., L. Titus-Gover, M.E. Ayers, and T.P. Wilson. (2001). "Characterization of mechanical properties and variability of PCC materials for rigid pavement design." *Proceedings, 7th International Conference on Concrete Pavements (CD-ROM)*, Orlando FL.

McCracken, J. K., Vandenbossche, J. M., and Asbahan, R. E. (2009). "Effect of the MEPDG hierarchical levels on the predicted performance of a jointed plain concrete pavement," *Proceedings, 9th International Conference on Concrete Pavement (CD-ROM)*, San Francisco, CA, 153-170.

Moon, W. (2009). *Evaluation of MEPDG with TxDOT rigid pavement database*, Research Report FHWA/TX-09/0-5445-3, Center for Transportation Research, The University of Texas at Austin, Austin, TX.

NCHRP. (2004). *Guide for Mechanistic-empirical design of new and rehabilitated pavement structures*, Final Report, NCHRP Project 1-37A, Transportation Research Board, National Research Council, Washington, DC.

Oh, J., and Fernando, E. G. (2008). *Development of thickness design tables based on the M-E PDG*, Research Report BDH10-1, Texas Transportation Institute, College Station, TX.

Oman, S. (2010). "MnROAD traffic characterization for the mechanistic-empirical pavement design guide using weigh-in-motion data." *Annual Meeting of Transportation Research Board (DVD)*, National Research Council, Washington, DC.

Puertas, J. J. G. (2008). *Evaluating the JPCP cracking model of the mechanistic-empirical pavement design guide*. M.S. Thesis, University of Pittsburgh, PA.

Rao, C., Selezneva, O., Darter, M. I., Titus-Glover, L., and Khazanovich, L. (2004). "Calibration of mechanistic-empirical performance model for continuously reinforced concrete pavement punch-outs." *Transportation Research Record 1896*, 15-22.

Schwartz, C.W., Li, R., Kim, S., Ceylan, H., and Gopalakrishnan, K. (2011). "Effect of Concrete Strength and Stiffness Characterization on Predictions of Mechanistic-Empirical Performance for Rigid Pavements." *Transportation Research Record: Journal of the Transportation Research Board*, No. 2226, pp. 41-50.

Selezneva, O., Rao, C., Darter, M. I., Zollinger, D., and Khazanovich, L. (2004). "Development of a mechanistic-empirical structural design procedure for continuously reinforced concrete pavements." *Transportation Research Record 1896*, 46—56.

Tanesi, J., Kutay, M. E., Abbas, A. R., and Meininger, R. C. (2007). "Effect of coefficient of thermal expansion test variability on concrete pavement performance as predicted by mechanistic-empirical pavement design guide." *Transportation Research Record 2020*, 40-44.

Tran, N. H., Hall, K. D., and James, M. (2008). "Coefficient of thermal expansion of concrete materials: characterization to support implementation of the mechanistic-empirical pavement design guide." *Transportation Research Record 2087*, 51-56.