



DESIGN OF RIGID PAVEMENTS IN IOWA USING THE MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE

Halil Ceylan¹, Brian Coree², Kasthurirangan Gopalakrishnan³

¹ Dept of Civil, Construction and Environmental Engineering,
482B Town Engineering Building, Iowa State University, Ames, IA 50011-3232, USA
E-mails: ¹hceylan@iastate.edu; ²bcoree@iastate.edu; ³rangan@iastate.edu

Abstract. The Iowa Dept of Transportation (DOT) currently utilizes the empirically-based *American Association of State Highway and Transportation Officials* (AASHTO) pavement design procedures originally derived from the 1960 *Road Test* data. It is clear that these empirical procedures are no longer applicable to current conditions in Iowa. With the release of the new Mechanistic-Empirical Pavement Design Guide (MEPDG) in the USA, there is a big shift in pavement analysis and design and many state highway agencies undertake initiatives to implement the MEPDG. In order to effectively and efficiently transition to the MEPDG and accelerate its adoption, the Iowa DOT needs a detailed implementation and training strategy. In support of the MEPDG implementation initiatives, sensitivity studies were conducted using the MEPDG software to identify design inputs pertaining to both rigid pavements and flexible pavements that are of particular sensitivity in Iowa. This paper is the first of the two companion papers discussing the need for implementing the MEPDG in Iowa, benefits of implementing the MEPDG in Iowa, and the results of rigid pavement input parameter sensitivity analysis. The results of flexible pavement design inputs sensitivity analysis and implementation recommendations are presented in the second paper.

Keywords: M-E Pavement Design Guide (MEPDG), Portland Cement Concrete (PCC), faulting, cracking, sensitivity analysis.

1. Introduction

With the release of the new Mechanistic-Empirical (M-E) Pavement Design Guide (MEPDG) by 2004 *National Cooperative Highway Research Program* (NCHRP) “*Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*” Project 1-37A in the USA, pavement design has taken a leap forward. The MEPDG provides the user with an integrated set of models (climate + traffic + materials), which by a set of empirical models projects future performance (cracking, rutting, faulting, etc.).

The edition currently available for evaluation (as of Dec 2007) will change and a provisional design guide is yet to be released. Some areas of change are known even now, while others have yet to be identified and may only come to light, as they are identified during the general implementation.

In order to effectively and efficiently transition to the MEPDG, state Dept of Transportations (DOTs) needs a detailed implementation and training strategy. In addition, pavement design input parameters must be determined locally based on their effects on pavement performance.

It is suspected that it will take most states in the USA approx 3 years just to prepare to implement the MEPDG

in its current form. Initiatives and strategies for implementing the MEPDG in Indiana (Nantung *et al.* 2005) and Texas (Uzan *et al.* 2005) were published recently. This paper discusses the development of a strategic plan for implementing the MEPDG in Iowa.

2. Objectives

The objectives of this paper:

- discuss the need for implementing the MEPDG in Iowa;
- discuss the benefits of implementing the MEPDG in Iowa;
- conduct sensitivity analyses to determine pavement design input parameters which have a significant effect on pavement distresses for rigid pavements in Iowa.

3. Need for implementing the M-E Pavement Design Guide in Iowa

The current *American Association of State Highway and Transportation Officials’* (AASHTO) *Design Guide* is based

on methods that have evolved from the AASHTO Road Test (1958–1961) (Carey, Irick 1962). Through a number of editions from the initial publication in 1962, the Interim Guide in 1972 and other later editions, i.e. AASHTO 1986 and AASHTO 1993, minor changes and improvements have been published (Carvalho, Schwartz 2006). Nonetheless, these later modifications have not significantly altered the original methods, which are based on empirical regression techniques relating simple material characterizations, traffic characterization and measures of performance. Since the time of AASHTO 1962 Road Test in 1960s, the following changes can be noted related to traffic, materials, and climatic conditions:

- the AASHTO 1962 Road Test traffic varied; drivers were moving at about 56 km/h; cross-ply truck tires were used with an average inflation pressure of 600 kPa. By the end of the experiment, a total of approx 1.1 mln Equivalent Single Axle Loads (ESALs) had been recorded;
 - according 2004 Iowa DOT “Automatic Traffic Recorder Monthly Report” and 2005 Iowa DOT “Traffic Book: Volume of Traffic the Primary Road System” modern highway traffic generally moves at 80 km/h to 113 km/h, using radial tires with inflation pressures typically in the range of 689 kPa to 827 kPa, with cumulative design (20 years) traffic repetitions (in Iowa) up to 100 mln ESALs;
- the AASHTO 1962 Road Test environment was specific to Ottawa, Illinois;
 - the environment in Iowa is not dissimilar to that of Ottawa, Illinois, but not identical either – especially over a typical design period of 20 years compared to the 18 months of the AASHTO 1962 Road Test;
- the subgrade was a low-plasticity clay (CL) with an average California Bearing Ratio (CBR) of 3.5.
 - Iowa subgrade soils cover a wide range of materials from clays, silts, sandy gravels, loess and calcareous outcropping;
- pavement materials in flexible pavement were characterized using “layer coefficients”, which have no physical meaning since they are simply regression coefficients,
 - layer coefficients have no physical meaning and relate only to the materials used at the AASHTO 1962 Road Test. Material specifications have evolved and changed significantly in the intervening 45 years, as have the requirements of quality assurance and control.

From these observations, it is clear that the current AASHTO pavement design procedures are no longer applicable to conditions in Iowa in the early 21st century.

The MEPDG relies on actual traffic operating at appropriate speeds and tire pressures using mathematical (not empirical) models to analyze the stress states within the pavement structures under appropriate local environmental conditions, which can change over the span of the design life of the pavement. The stress states at each time

interval are used to evaluate and accumulate specific distress types using (mostly) calibrated distress models.

Even if the current AASHTO method could accurately predict the life of a pavement to yield a terminal serviceability of 2.5 after 20 years, there is no way to predict the development of the components of serviceability (rutting, cracking and patching, and roughness) over the design life.

4. Benefits of implementing the M-E Pavement Design Guide in Iowa

The major benefits of adopting the MEPDG are long-term. While it is possible that immediate benefits may be seen in terms of thinner pavements, or pavements with different component properties, it is more likely that the benefits will be identified in the long term. These benefits will accrue in a number of areas:

- *More appropriate designs.* Due to the inherently empirical nature of the current design methods, pavements are inherently over-designed for strength. Other performance measures, such as thermal cracking and faulting, are not addressed. The MEPDG method has the potential to significantly reduce the degree of uncertainty in the design process, and provide more realistic designs that are appropriate to the type of performance expected. The MEPDG approach will allow the Iowa DOT to specifically design pavement to minimize or mitigate the predominant distress types that occur in Iowa.
- *Better performance predictions.* For the design life of pavements, the predicted occurrence of distresses will be much closer to the actual occurrence. Combined with realistic criteria for design levels of distress, this will lead to significantly less maintenance and rehabilitation activities. Currently, although pavements are designed for 20 years, it is common that major rehabilitation may be required as early as 12 years into the design life. The MEPDG will help ensure that this type of major rehabilitation activity occurs closer to the actual design life, i.e. 20 years. A saving of even 1% in maintenance and rehabilitation frequencies (which is considered conservative: estimates vary from 1% to 15%) will lead to significant savings in the long term. Iowa spends approx US \$400 mln annually in maintenance and rehabilitation; therefore, a 1% savings represents a potential annual savings of approx US \$4 mln.
- *Better materials-related research.* Since the MEPDG method is based on actual material properties, what if-type research will enable the Iowa DOT to examine the effects of specification change on ultimate performance. It is likely that over the next 5 years or so, such questions as “should richer or leaner hot mix asphalt base mixtures be promoted?” will arise. This type of question can be answered through the use of the MEPDG, reducing the need to conduct extensive, lengthy, and costly

field trials. Many other materials-related questions can be addressed in this manner.

- *Powerful forensic tool.* The MEPDG software has an interesting and powerful capability as a forensic tool. By analyzing failed pavement using the actual materials properties, climate, traffic, etc., the Iowa DOT will be capable of identifying the components or factors responsible for the failure.

5. Sensitivity analysis – rigid pavement design inputs

Prior to the development of any implementation strategy, it is important to conduct a sensitivity analysis to determine the sensitivity of different input design parameters in the design process, which can differ from state to state depending on local conditions. Such a sensitivity study may be helpful in developing local calibration recommendations as well as aid designers in focusing on those design inputs having the most effect on desired pavement performance. For instance, a recent sensitivity study conducted on the *Jointed Plain Concrete Pavement* (JPCP) model in the MEPDG revealed that of the 29 inputs associated with the Portland Cement Concrete (PCC) slab only (except for edge support, a drainage path length input and an erodibility input), 11 input parameters were seen to effect cracking and 7 to effect faulting significantly (Hall, Beam 2005; Kannekanti, Harvey 2006).

In support of the initiatives for implementing the MEPDG in Iowa, a study was undertaken to estimate the sensitivity of performance models used in the MEPDG (version 0.7) to various design inputs for 2 rigid pavement sections (JPCP) selected from the Iowa DOT's *Pavement Management Information System* (PMIS), also part of the *Long Term Pavement Performance* (LTPP) program (Guc-lu, Ceylan 2005). A history of pavement deflection testing, material testing, traffic, and other related data pertaining to these 2 sections, named PCC-1 and PCC-2, is available in the LTPP database.

5.1. Design input parameters

Two typical PCC pavement sections in Iowa, referred to as PCC-1 and PCC-2, were selected. PCC-1, located on US-218 near Johnson County, Iowa, was constructed in 1983. This section of US-218 is located in the wet-freeze environmental region. The pavement is a 24 cm thick JPCP with 4.5 m joints. The slab rests on 10 cm granular subbase course. The subgrade is an AASHTO A-7-6 material (clay).

PCC-2, located on US-20 near Hamilton County, Iowa, was constructed in 1968. The test section was west-bound in the North Central LTPP SHRP (Strategic Highway Research program) region, and designated between 241 km and 247 km of US-20. This section of US-20 is also located in the wet, hard freeze-thaw environmental region of the US. The pavement is a 25 cm thick JPCP with 4.5 m joints. The slab rests on 10 cm granular subbase course. The subgrade layer is an A-6 (7) to A-6 (10) (silt-clay materials) glacial till soil.

Table 1. Rigid pavement (JPCP) design inputs (base case values)

Input parameter	Value
Design life in years	25
Pavement construction month	May/2003
Traffic open month	Oct/2003
Initial IRI in m/km	1
Terminal IRI in m/km	2.68 (limit)
Transverse cracking in % slabs cracked	15 (limit)
Mean joint faulting in cm	0.4 (limit)
Initial 2-way average annual daily track traffic (AADTT) in vpd	6000
Number of lanes in design direction	2
% of trucks in design direction	50
% of trucks in design lane	90
Operational speed in km/h	97
Mean wheel location in cm	46
Traffic wander standard deviation in cm	25
Design lane width in m	3.65
Average axle spacing: tandem, tridem, quad axle in m	3.65, 4.6, 5.5
% of trucks	33, 33, 34
Permanent curl/warp effective temperature difference in °C	-23
Joint spacing in m	4.6
Dowel diameter in cm	2.5
Dowel spacing in cm	30.5
Base type	Granular
Erodibility index	Erosion Resistant (3)
Base/slab friction coefficient	0.85
PCC-base interface	Bonded
Loss of bond age in months	60
Surface shortwave absorptivity	0.85
Infiltration	minor (10%)
Drainage path length in m	3.65
Pavement cross slope in %	2
Layer thickness in cm	25
Unit weight in kN/m ³	24
Poisson's ratio	0.2
Coefficient of thermal expansion in (per °C)	9.9×10^{-6}
Thermal conductivity in calories/sec×cm×C°	0.00413
Heat capacity in calorie/g × °C	0.28
Water/cement ratio	0.42
PCC zero-stress temperature in °C	derived
Ultimate shrinkage at 40% R.H. (micro strain)	derived
Reversible shrinkage in % of ultimate shrinkage	50
Time to develop 50% of ultimate shrinkage in days	35
Curing method	curing compound
Input level	level 3
28 day PCC modulus of rupture in kPa	4750

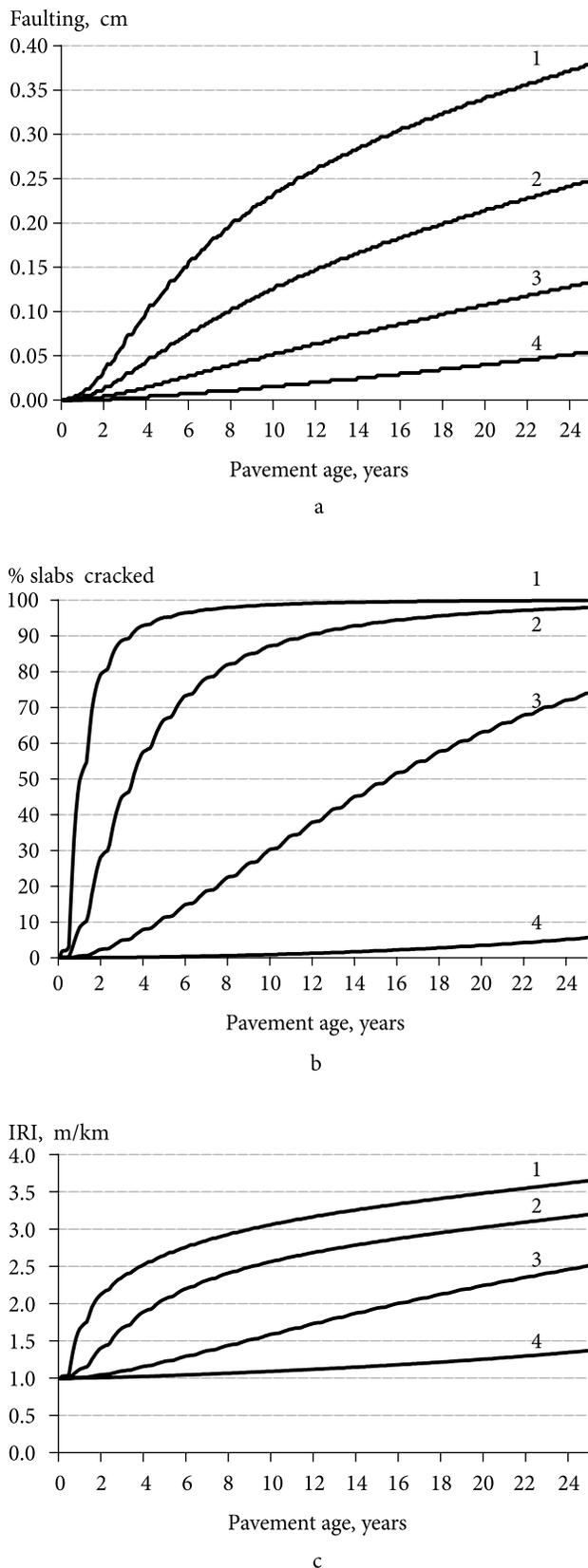


Fig. 1. Effect of PCC coefficient of thermal expansion on JPCP performance: a – faulting, b – cracking, c – roughness (1 – $17.1 \times 10^{-6}/^{\circ}\text{C}$, 2 – $13.5 \times 10^{-6}/^{\circ}\text{C}$, 3 – $9.9 \times 10^{-6}/^{\circ}\text{C}$, 4 – $6.3 \times 10^{-6}/^{\circ}\text{C}$)

Sensitivity analyses were performed on a representative pavement section created from the 2 JPCP sections, PCC-1 and PCC-2. The standard input parameters for the representative Iowa highway pavement section were determined based on the design information for the PCC-1 and PCC-2 as well as by considering Iowa conditions (Table 1).

5.2. Analysis

A total of 30 input parameters related to design features, joint design, base properties, drainage and surface properties, climate, and PCC (general, mix, thermal and strength) properties were evaluated. Each evaluated input was varied within its recommended range to study its effect on predicted performance (faulting, transverse cracking and roughness) while assigning base case values to all other input parameters. For unknown input parameters needed to run the MEPDG software, the nationally calibrated default values were used. The varied values for the climate input were based on weather stations chosen in and around Iowa.

Several hundred sensitivity runs were conducted using the MEPDG software (version 0.7) and plots of pavement distresses were obtained over the design life. In addition, sensitivity runs were carried out to study the two-way interaction among input variables and their effect on predicted performance. A deterministic analysis (with a nominal 50% design reliability) was used.

5.3. Results

Several hundreds of graphs were created using the results of MEPDG sensitivity analysis. Selected results illustrating the effect of curl/warp effective temperature differences on predicted performance as well as the interactive effect of joint spacing and PCC thickness on JPCP performance are shown in Figs 1, 2, respectively.

The sensitivity plots were visually examined and each evaluated input parameter was categorized into one of the 5 groups: extremely sensitive (ES), very sensitive (VS), sensitive (S), moderately sensitive (MS), or not sensitive (NS). A summary of the sensitivity ratings is presented in Table 2 identifying the level of importance associated with each design input.

Since not all input factors are under the control of the designer, the parameters were categorized as follows (Note in Table 2) to aid in the better understanding of the sensitivity results:

- directly under the control of the designer (eg. layer thickness);
- may be changed, but will require committee action (eg. Specifications Committee), such as dowel diameter and spacing;
- may not be changed by the designer, but must be known, such as climate, traffic, coefficient of thermal expansion, etc.

In this study, JPCP transverse cracking was found to be ES to curl/warp effective temperature difference, coefficient of thermal expansion, thermal conductivity, PCC

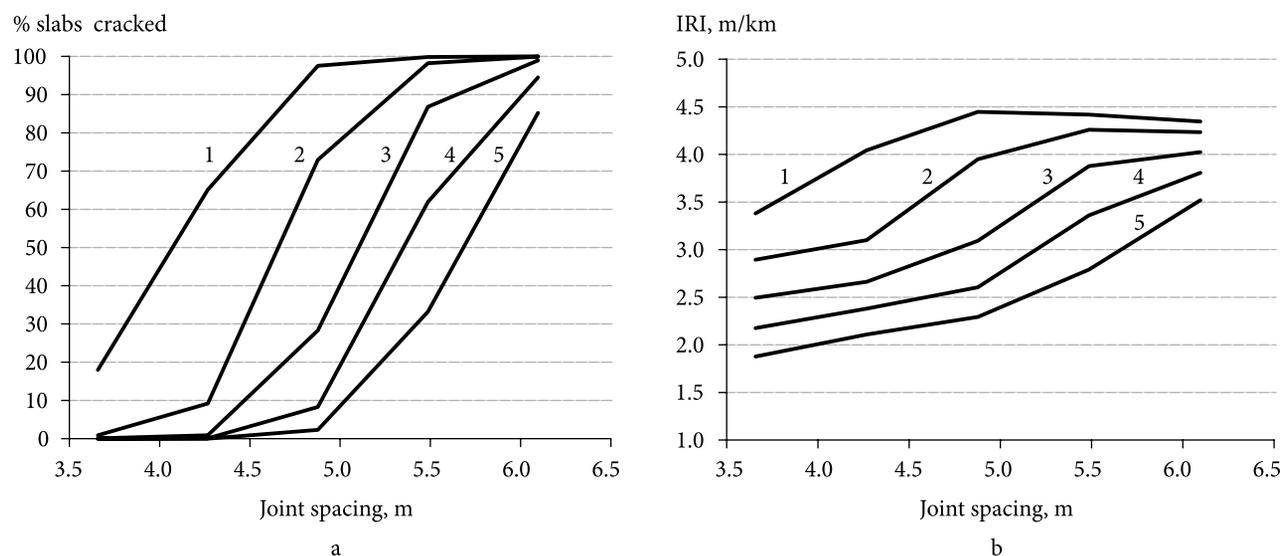


Fig. 2. Interactive effect of joint spacing and PCC thickness, h , on JPCP performance: a – cracking, b – roughness (1 – $h = 20.0$ cm, 2 – $h = 22.5$ cm, 3 – $h = 25.0$ cm, 4 – $h = 27.5$ cm, 5 – $h = 30.0$ cm, design life – 20 years, PCC (JPCP) – 20–30 cm, base (crushed gravel) – 10 cm, $E = 220.5$ MPa, AADTT – 8,000, wet-freeze doweled – $D = 2.5$ cm)

Table 2. Summary of results of sensitivity analyses for rigid pavements

JPCP design inputs	Performance models		
	Faulting	Cracking	Roughness
Curl/warp effective temperature difference	ES	ES	ES
Joint spacing	NS/MS	ES	S
Sealant type	NS	NS	NS
Dowel diameter	NS/MS	NS	NS/MS
Dowel spacing	NS	NS	NS
Edge support	NS	S	MS
PCC-base interface	NS	NS	NS
Erodibility index	NS	NS	NS
Surface short-wave absorptivity	NS/MS	MS/S	MS/S
Infiltration of surface water	NS	NS	NS
Drainage path length	NS	NS	NS
Pavement cross slope	NS	NS	NS
PCC layer thickness	NS/MS	ES	S
Unit weight	MS	S	NS/MS
Poisson's ratio	MS	S	S
Coefficient of thermal expansion	MS/ S	ES	ES
Thermal conductivity	MS/S	VS/ES	VS
Heat capacity	NS/MS	NS/MS	NS
Cement type	NS/MS	NS	NS
Cement content	MS/S	NS	MS/S
Water/cement ratio	MS/S	NS	MS/S
Aggregate type	NS	NS	NS
PCC set (zero stress) temperature	NS/MS	NS	NS/MS
Ultimate shrinkage at 40% R.H.	MS	NS	MS/NS
Reversible shrinkage	NS	NS	NS
Time to develop 50% of ultimate shrinkage	NS	NS	NS
Curing method	NS/MS	NS	NS
28-day PCC modulus of rupture	MS/NS	ES	S
28-day PCC compressive strength	NS	ES	S
Climatic data from different stations	MS	MS/S	MS

Note: ES – extremely sensitive; VS – very sensitive; S – sensitive; MS – moderately sensitive; NS – not sensitive; **designer can control directly**; *designer may change, but needs to get permission of a specific committee or the agency*; designer may not change, but must know

thickness, PCC strength properties and joint spacing. The ES input parameters for faulting were the curl/warp effective temperature difference and doweled transverse joints (load transfer mechanism, doweled or undoweled, or dowel bar diameter). For smoothness, the curl/warp effective temperature difference, coefficient of thermal expansion, and thermal conductivity were the ES input parameters. Thus, in general, the curl/warp effective temperature difference, the coefficient of thermal expansion, thermal conductivity, layer thickness, joint spacing, etc. had the greatest impact on the distresses (Table 3).

6. Sensitivity analyses – summary

In support of the MEPDG implementation initiatives in Iowa, sensitivity studies were conducted using the MEPDG software to identify those input factors pertaining to rigid pavements that are of particular sensitivity in Iowa. Table 3 lists the input factors which have been identified to be of significant sensitivity for Iowa. Of these, the ES inputs merit early consideration and resolution. In addition to the factors listed in Table 3, there are some other factors that exhibit some degree of sensitivity, such as joint spacing in PCC slabs. However, this factor exhibits ES only for thin slabs; slabs within the normal range of thickness do not exhibit such high sensitivity.

7. Summary of observations

The Iowa DOT is expected to benefit by implementing the MEPDG. The major benefits of adopting the MEP-

DG are long-term. In order to effectively and efficiently transition to the MEPDG, the Iowa DOT needs a detailed implementation and training strategy. In support of the implementation initiatives, sensitivity studies were conducted using the MEPDG to identify design inputs pertaining to rigid pavements that are of particular sensitivity in Iowa as well as those factors that are of no particular sensitivity.

The ES MEPDG input parameters for transverse cracking were found to be curl/warp effective temperature difference (built-in), coefficient of thermal expansion, thermal conductivity, PCC layer thickness, PCC strength properties, and joint spacing.

Since these input parameters cannot be modified, accurate values should be input into the model. The sensitivity of the model to these parameters is extremely high; therefore, pavement performance outputs can vary significantly. Thus, extreme attention should be given to determine input data for these particular parameters. If necessary, material test(s) should be carried out to determine the magnitude of these parameters. Otherwise the accuracy of the predicted pavement distresses differs significantly.

Among the ES and S to VS input design parameters, the pavement design engineer can only modify; PCC layer thickness, properties of the dowel bar system used in transverse joints, and joint spacing. PCC strength properties are also modifiable provided that pavement design specifications are met.

Since the available field data for transverse cracking in Iowa DOT's Pavement Management Information Sys-

Table 3. Input factors of significant sensitivity (rigid pavements)

Rigid pavements (JPCP)	Extremely sensitive (ES)	Sensitive to very sensitive (S/VS)
Cracking	curl/warp effective temperature difference; coefficient of thermal expansion; thermal conductivity; PCC layer thickness; PCC strength properties; joint spacing.	edge support; mean wheel location; unit weight; Poisson's ratio; climate; surface shortwave absorptivity; AADTT.
Faulting	curl/warp effective temperature difference; doweled transverse joints.	AADTT; mean wheel location; unbound layer modulus; cement content; water/cement ratio; coefficient of thermal expansion; thermal conductivity.
Roughness	curl/warp effective temperature difference; coefficient of thermal expansion; thermal conductivity.	doweled transverse joints; AADTT; mean wheel location; joint spacing; PCC layer thickness; PCC strength properties; Poisson's ratio; surface shortwave absorptivity; unbound layer modulus; cement content; water/cement ratio.

tem (PMIS) are in different units than those used in the MPEDG, it is recommended that the units of MPEDG should be correlated to the actual field data.

Acknowledgments

The authors would like to thank the Iowa Highway Research Board for sponsoring this research and the Iowa DOT for their continued interest, help and cooperation. Special thanks to Dr. Michael Heitzman, Bituminous Materials Engineer of the Iowa DOT. Any errors of fact or opinions are those of the authors alone, and the conclusions drawn do not necessarily represent the policies of neither Iowa State University nor the Iowa DOT.

References

- Carey, W. N. Jr.; Irick, P. E. 1962. Relationships of AASHO Road Test pavement performance to design and load factors, *Highway Research Boards Special Report 73*: 198–207.
- Carvalho, R.; Schwartz, C. W. 2006. Comparisons of flexible pavement designs: AASHTO empirical versus NCHRP Project 1-37A mechanistic-empirical, *Transportation Research Record* 1962: 167–174. DOI: 10.3141/1947-16.
- Guclu, A.; Ceylan, H. [on-line] 2005. Sensitivity analysis of rigid pavement systems using the Mechanistic-Empirical Pavement Design Guide [cited 30 Oct, 2008], in *Proc of the 2005 Mid-Continent Transportation Research Symposium*. Aug 18–19, 2005, Ames, Iowa, USA. Available from Internet: <<http://www.ctre.iastate.edu/pubs/midcon2005/GucluRigid.pdf>>.
- Hall, K. D.; Beam, S. R. 2005. Estimating the sensitivity of design input variables for rigid pavement analysis with a Mechanistic-Empirical Design Guide, *Transportation Research Record* 1919: 65–73. DOI: 10.3141/1919-08.
- Kannekanti, V.; Harvey, J. 2006. Sensitivity analysis of 2002 design guide distress prediction models for jointed plain concrete pavement, *Transportation Research Record* 1947: 91–100. DOI: 10.3141/1947-09.
- Nantung, T.; Chehab, G.; Newbolds, S.; Galal, K.; Li, S.; Kim, D. H. 2005. Implementation initiatives of the Mechanistic-Empirical Pavement Design Guides in Indiana, *Transportation Research Record* 1919: 142–151. DOI: 10.3141/1919-15.
- Uzan, J.; Freeman, T.J.; Cleveland, G. S. 2005. Strategic plan of the Texas Department of Transportation for implementing NCHRP 1-37A Pavement Design Guide, *Transportation Research Record* 1919: 152–159. DOI: 10.3141/1919-16.

Received 24 Jan, 2008; accepted 24 Oct, 2008