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Sensitivity analysis of rigid pavement systems using the mechanistic-empirical design guide software

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Abstract
Initiatives are underway to implement the new mechanistic-empirical pavement design guide (MEPDG) in Iowa. This paper focuses on the sensitivity study of jointed plain concrete pavements (JPCP) and continuously reinforced concrete pavements (CRCP) in Iowa using the MEPDG software. In this comprehensive study, the effect of MEPDG input parameters on the rigid pavement performance is evaluated using the different versions of the MEPDG software (0.7, 0.9, and 1.0) available to date. Representative JPCP and CRCP sections in Iowa were selected for analysis. Based on the sensitivity plots obtained from the MEPDG runs, the design input parameters were categorized as being most sensitive, moderately sensitive, or least sensitive in terms of their relative effect on distresses. In this study, the curl/warp effective temperature difference, the PCC coefficient of thermal expansion, and PCC thermal conductivity had the greatest impact on the JPCP and CRCP distresses. Compared to the original version of MEPDG software (Version 0.7), the updated versions (Versions 0.9 and 1.0) are more sensitive to inputs, which shows the evolution of engineering reasonableness.

Keywords
Iowa, pavement design, rehabilitation, rigid pavements, sensitivity analysis

Disciplines
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Sensitivity analysis of rigid pavement systems using the mechanistic-empirical design guide software

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Abstract: Initiatives are underway to implement the new Mechanistic-Empirical Pavement Design Guide (MEPDG) in Iowa. This paper focuses on the sensitivity study of Jointed Plain Concrete Pavements (JPCP) and Continuously Reinforced Concrete Pavements (CRCP) in Iowa using the MEPDG software. In this comprehensive study, the effect of MEPDG input parameters on the rigid pavement performance is evaluated using the different versions of the MEPDG software (0.7, 0.9 and 1.0) up to date. A representative JPCP section and a representative CRCP section in Iowa were selected for analysis. Based on the sensitivity plots obtained from the MEPDG runs, the design input parameters were categorized as being most sensitive, moderately sensitive, or least sensitive, in terms of their relative effect on distresses. In this study, the curl/warp effective temperature difference, the PCC coefficient of thermal expansion, and PCC thermal conductivity had the greatest impact on the JPCP and CRCP distresses. Compared to original version of MEPDG software (0.7), the updated versions (0.9 and 1.0) are more sensitivity to inputs which shows the evolution of engineering reasonableness.

Key Words: Pavement design and rehabilitation, Mechanistic-Empirical Design Guide, Sensitivity Analysis, Rigid Pavement Systems

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Introduction

The American Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures (1993) is currently used by most State highway agencies to design new and rehabilitated highway pavements. There are various versions of the AASHTO design guide (1972, 1986, and 1993), but they are all empirically based on performance equations developed using the 1950's AASHO Road Test (AASHO 1962) data. Although the various editions of the AASHTO design guide have served well for several decades, many have questioned their continued use for the analysis and design of new and rehabilitated pavements as material specifications, traffic volumes and weights, tire types and pressures have changed significantly since the time of 1950's AASHO Road Test (AASHO 1962).

In recognition of the limitations of the current AASHTO Guide, the AASHTO Joint Task Force on Pavements (JTFP) initiated an effort to develop an improved pavement design procedure based on Mechanistic-Empirical (M-E) principles. The product of this effort is the newly released Mechanistic-Empirical Pavement Design Guide (MEPDG) based on the National Cooperative Highway Research Program (NCHRP) Study 1-37A (NCHRP 2004). After the release of the original MEPDG software (Version 0.7) in July, 2004, the MEPDG software has been updated under NCHRP project 1-40 D (2006) from original version to version 1.0. with recalibration of distress prediction model based on the most up-to-date database. Especially, the MEPDG version 1.0 released in 2007 would become an interim AASHTO pavement design procedure after the permission of the AASHTO Joint Technical Committee (JTC). A detailed discussion of differences amongst the different MEPDG software versions can be found in NCHRP project report 1-40D (2006).

The MEPDG does not provide a design thickness at the end of pavement analysis; instead, it provides the pavement performance throughout its design life. Therefore, the MEPDG is a performance prediction tool more than an analysis tool. The design thickness can be predicted by modifying design inputs and obtaining the best performance with an iterative procedure.

It is expected that the Iowa Department of Transportation (DOT) will benefit by implementing the MEPDG in Iowa (Ceylan et al. 2006). The MEPDG method will reduce the degree of uncertainty in the design process and allow the Iowa DOT to specifically design pavement to minimize or mitigate the predominant distress types that occur in Iowa. It will help ensure that major rehabilitation activity occurs closer to the actual design life by providing better performance predictions. Material-related research questions can be answered through the use of the MEPDG which provides tools for evaluating the variations in materials on pavement performance. The MEPDG can also serve as a powerful forensic tool for analyzing the condition of existing pavements and pinpointing deficiencies in the past designs.

However, prior to the development of any implementation plan, 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. Several rigid pavement sensitivity studies have recently been reported by researchers from different states (Selezneva, et al. 2004; Khazanovich, et al. 2004; Kannekanti and Harvey 2006; Khanum, et al. 2006). However, most of these studies were conducted using the older versions of MEPDG software before the recent MEPDG version 1.0 was released in 2007. Note that the MEPDG version 1.0 would become an interim AASHTO pavement design procedure. NCHRP project 1-40 D (2006) recommended further sensitivity analyses using the newly released MEPDG version and therefore the current study is very relevant for researchers, practitioners and highway agencies. 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.

It is also important to note that the national Long Term Pavement Performance (LTPP) database used to develop the MEPDG calibrated distress models did not include test sections from Iowa. It may be necessary, therefore, to validate the MEPDG performance predictions using the available LTPP and Iowa DOT Pavement Management Information System (PMIS) data and further calibrate the models locally so that they may be used for pavement design and rehabilitation in Iowa. In support of the MEPDG implementation initiatives, sensitivity studies was undertaken to estimate the relative effects of design inputs on rigid pavement performance predictions, to check the reasonableness of model predictions and to identify those inputs which have the most effect on desired performance of rigid pavement systems in Iowa.

Objective

The main objective of this paper is to evaluate and compare the relative sensitivity of input parameters needed for the design of Jointed Plain Concrete Pavements (JPCP) and Continuously Reinforced Concrete Pavements (CRCP) in Iowa using the different versions of MEPDG software (Version 0.7, 0.9 and 1.0) up to date.

It is acknowledged that the MEPDG is a complicated engineering simulation with many inputs and multiple outputs. Correlations among inputs are present when a change in one input tends to cause change in another input (e.g., PCC modulus of rupture and modulus of elasticity as related to unconfined compressive strength). Thus, interactions among inputs are manifested when simultaneous changes in two independent inputs cause changes in outputs that are greater than the sum of the individual effects (e.g., interactions between climate and subgrade support degradation due to excessive moisture). The sensitivity analysis approach used in this study is thus limited in capturing such interaction effects. More formalized and powerful approaches for global sensitivity analysis are available and will be applied in future research for including input correlations or detecting input interactions.

Description of research

To study the effect of various design inputs used in the MEPDG on the predicted pavement distresses or performance measures (faulting, cracking, and smoothness for JPCP; and punchouts and smoothness for CRCP), sensitivity analyses were carried out.

It is suspected that the new MEPDG requires over 100 inputs to model traffic, environmental, materials, and pavement performance to provide estimates of pavement distress over the design life of the pavement (Hall and Beam 2005). Many designers may lack specific knowledge of the data required and therefore a sensitivity study which identifies those inputs which have the most effect on desired performance will be very useful.

The initial study focused on identifying the sensitivity of input parameters needed for designing JPCP in Iowa using the MEPDG version 0.7 (Guclu 2005). Two JPCP sections, also part of the LTPP program (LTPP 2005), were selected from the Iowa DOT's PMIS for performing sensitivity analysis. These two sections are denoted as PCC-1 and PCC-2, respectively. A history of pavement deflection tests, material tests, traffic, and other related data pertaining to PCC-1 and PCC-2 are available in the LTPP database and they were used to establish default or baseline values for MEPDG design input parameters. For unknown parameters needed to run the MEPDG software, the nationally calibrated default values were used.

For simplicity, sensitivity analyses were conducted on a standard representative pavement section formed from PCC-1 and PCC-2. Several hundred sensitivity runs were conducted using the different versions of MEPDG software and plots were obtained. Based on the visual inspection of the sensitivity graphs, the input parameters were categorized from most sensitive to least sensitive, in terms of their effect on performance.

In the second phase of the study, sensitivity analyses were conducted on a representative CRCP section to identify the sensitivity of input parameters needed for designing CRCP in Iowa using the MEPDG. It is noted that CRCP is not widely used in Iowa. For the CRCP, the same traffic and material input values as JPCP were used. This was done for consistency and for comparing the JPCP and CRCP results.

Data collection

PCC-1, located on US-218 near Johnson County, Iowa, was constructed in 1983. The test section is in the northbound direction, and is designated between 86.03 and 90.08 miles of US-218 (Iowa DOT 2003). This section of US-218 is located in the wet-freeze environmental region. This area has a freezing index of 466.88, and receives 930.58 mm of rainfall annually. The latitude and longitude are 41.57 and 91.55 degrees, respectively.

The PCC-1 pavement section is a 24-cm (9.6-in) thick JPCP with 4.5-m (15-ft) joints. The slab rests on 10-cm (4-in) Class A sub-base course. The subgrade is an AASHTO A-7-6 material. From the project files, the modulus of subgrade reaction (k) for this section is 16 KN/m^3 (100 pcf), and the modulus of rupture value from 3rd point loading is noted as 3,700 kPa (535 psi). The traffic records from the Iowa DOT indicate that, in 1983, the pavement carried a two-way Average Daily Traffic (ADT) of 2,500 vehicles per day, including heavy trucks. In 2002, traffic was estimated to be 3,590 vehicles per day, including 540 vehicles of truck traffic.

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 Strategic Highway Research Program (SHRP) region, and is designated between 149.5 and 153.47 miles of US-20 (Iowa DOT 2003). This section of US-20 is also located in the wet-freeze environmental region. This area has a freezing index of 763.69, and receives 861.74 mm of rainfall annually. The latitude and longitude are given as 42.46 and 93.59 degrees, respectively.

The pavement is a 25-cm (10-inch) thick JPCP with 4.5-m (15-ft) joints. The slab rests on 10-cm (4-in.) granular sub-base course. The subgrade layer was an A-6 (7) to A-6 (10) glacial till soil. The modulus of subgrade reaction, k, for this section is recorded as 24 KN/m^3 (150 pcf) in the project files. The traffic records indicate that in 1968, the pavement carried a two-way ADT of 3,160 vehicles per day, including heavy trucks. In 2002, it was 5,610 vehicles per day, including 840 vehicles of truck traffic (Iowa DOT 2005).

The input information gathered from the LTPP database and Iowa DOT PMIS for PCC-1 and PCC-2 respectively were used to predict the International Roughness Index (IRI) for both the sections using the MEPDG. For unknown parameters, the nationally calibrated default values used in the MEPDG were assigned. The IRI values predicted by the MEPDG were compared with those reported in the Iowa DOT PMIS. Interestingly, the MEPDG predicted IRI values were almost twice as much as the values recorded in the PMIS. This is due to the nature of the IRI model included in the MEPDG. The predictions of IRI model used in the MEPDG are linked to the predictions of other distresses such as cracking and faulting projected from the calibrated distress models from national LTPP database. The coefficients of IRI model are also determined from LTPP database. However, as mentioned previously, the national Long Term Pavement Performance (LTPP) database used to develop the MEPDG calibrated distress models and the coefficients of IRI model did not include test sections from Iowa. This indicates the need for local calibration of the performance prediction models considering Iowa conditions.

It was also found that the available cracking data in Iowa DOT PMIS have different units then those used in the MPEDG. Therefore, the MEPDG units need to be correlated to the actual field data in the Iowa DOT PMIS for local calibration of the performance prediction models in Iowa.

Sensitivity analyses

As mentioned earlier, a standard pavement section representative of Iowa type pavements was formed from PCC-1 and PCC-2 for conducting the sensitivity analysis. The cross-sectional details of pavement structure used in this study are shown in Fig. 1. A total of 28 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 for the JPCP representative section. A total of 15 inputs were evaluated for the CRCP representative pavement section.

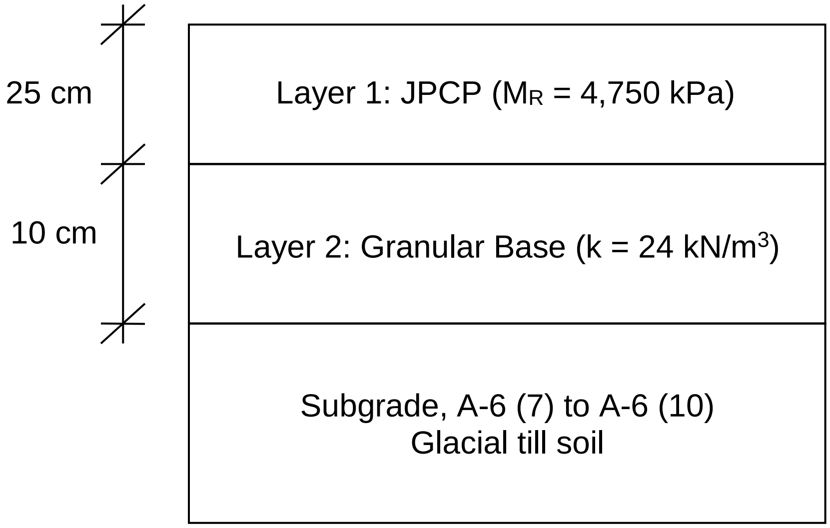

Fig. 1. JPCP pavement structure considered in this study

Each evaluated input was varied within its recommended range to study its effect on predicted performance (faulting, transverse cracking and IRI for JPCP; and punchouts and IRI for CRCP) while assigning base case values to all other input parameters. A detailed summary of the design inputs for the reference case or the base case is presented in Table 1 for JPCP. Note that similar inputs were used for CRCP sensitivity analyses and therefore the table is not repeated for the CRCP section. As far as possible, the values and factor levels for input variables used in the sensitivity analyses were chosen to represent the practices adopted by the Iowa Department of Transportation in consultation with the Iowa DOT personnel.

Table 1. MEPDG design inputs (reference/base case values)

Input Parameter	Value
Design life (years)	25
Initial IRI – m/km (in/ mi)	1 (63)
Terminal IRI – m/km (in / mi)	2.68 (170) (limit)
Transverse cracking (% slabs cracked)	15 (limit)
Mean joint faulting – cm (in)	0.4 (0.15) (limit)
Initial two-way AADTT	6,000
Number of lanes in design direction	2
Percent of trucks in design direction	50
Percent of trucks in design lane	90
Operational speed (mph)	60
Mean wheel location – cm (in)	46 (18)
Traffic wander standard deviation – cm (in)	25 (10)
Design lane width – m (ft)	3.65 (12)
Average axle spacing – m (ft)	3.65, 4.6, 5.5 (12, 15, 18)
Percent of trucks (%)	33, 33, 34
Permanent curl/warp effective temperature difference (°F)	-10
Joint spacing – m (ft)	4.6 (15)
Dowel diameter – cm (in)	2.5 (1)
Dowel spacing – cm (in)	30.5 (12)
Base type	Granular
Erodibility index	Erosion Resistant (3)
Base/slab friction coefficient	0.85
PCC-Base Interface	Bonded
Loss of bond age (months)	60
Surface shortwave absorptivity	0.85
*Infiltration	Minor (10%)
*Drainage path length – m (ft)	3.65 (12)
*Pavement cross slope (%)	2
Layer thickness – cm (in)	25 (10)
Unit weight – kN/m^3 (pcf)	24 (150)
Poisson's ratio	0.2
Coefficient of thermal expansion (per F° x 10- 6)	5.5
Thermal conductivity (BTU/hr-ft-F°)	1.25
Heat capacity (BTU/lb-F°)	0.28
Water/cement ratio	0.42
Reversible shrinkage (% of ultimate shrinkage)	50
Time to develop 50% of ultimate shrinkage (days)	35
Curing method	Curing Compound
28-day PCC modulus of rupture – kPa (psi)	4,750 (690)

* Drainage parameters were not included in version 0.9 and 1.0.

A new feature in the MEPDG, which is not present in the existing versions of the AASHTO Design Guide, is the hierarchical approach to design inputs. Depending on the desired level of accuracy of input parameter, three levels of input are provided from Level 1 (highest level of accuracy) to Level 3 (lowest level of accuracy). Level 1 inputs require lot of lab and

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field testing and consume more resources, while Level 3 inputs are default values or typical averages for the project location and materials used. Depending on the criticality of the project and the available resources, the designer has the flexibility to choose any one of the input levels for the design as well as use a mix of levels. However, it should be recognized that irrespective of the input design level, the computational algorithm used to predict distress and smoothness remains the same (NCHRP 2004).

Several hundred sensitivity runs were conducted using the MEPDG software version 0.7, 0.9 and 1.0, and plots of pavement distresses were obtained over the design life. All runs were performed with a reliability level of 50% and a design life of 25 years.

Discussion of results

Several hundreds of graphs were produced by the MEPDG software during the sensitivity analyses. Due to space constraints, it is difficult to present a full discussion of all the investigated input parameters in this paper. For this reason, a summary of the results of MEPDG software runs is presented.

The sensitivities of MEPDG performance measures (faulting, cracking, and IRI for JPCP; and punchouts and IRI for CRCP) to design inputs were investigated by varying one input parameter per trial run.

The next step is to objectively quantify the effect of each investigated input parameter on performance based on the MEPDG results. However, this is a very difficult task since currently there is no common yardstick or established criteria to compare the sensitivity of different performance measures to inputs based on objective quantitative measures. Therefore, at this point, it may only be possible to make qualitative inferences related to the significance of differences in predicted damage resulting from changing a given input variable based on subjective, visual inspection of the sensitivity plots. A similar approach is recommended in the MEPDG design guide documentation for sensitivity analysis with regard to local calibration (NCHRP 2004).

In this study, the sensitivity plots were visually examined and each evaluated input parameter was categorized into one of the three groups: Very sensitive (↑↑ or ↓↓), Sensitive (↑or ↓), or Not sensitive (↔). Also, the trend (increasing or decreasing) in each predicted performance measure with respect to changes in input parameters was examined. This was done because a designer may want to know, for example, whether an increase in joint spacing leads to increase or decrease in cracking in addition to the knowledge that cracking is sensitive to changes in joint spacing.

It is noted that subjective criteria, based on engineering judgment and past experience, were used in determining the degree of sensitivity of each evaluated input parameter with respect to a specific performance measure. Several factors such as the recommended distress criteria, rate of change in output with changes in input, relative scale of the "Y" axis (the damage axis) as well as the "X" axis (the input variable axis) were taken into account in determining the qualitative effect of each evaluated input parameter on performance.

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

- Directly under the control of the designer (e.g., layer thickness)

- May be changed, but will require committee action (e.g., specification 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.

Table 2. Summary of sensitivity analyses results for JPCP

JPCP Design Inputs	Performance Models		
	Faulting	Cracking	Smoothness
Curl/warp effective temperature difference ↑	↓↓	↓↓	↓↓
Joint spacing ↑	↑ (↔*)	↑↑	↑
Sealant type	↔	↔	↔
Dowel diameter ↑	↓(↔*)	↔	↓(↔*)
Dowel spacing ↑	↔	↔	↔
Edge support ↑	↓(↔*)	↔(↑*)	↓(↔*)
PCC-base interface ↑	↔	↔	↔
Erodibility index ↑	↑(↔*)	↔	↑(↔*)
PCC layer thickness ↑	↔	↓↓	↓
Unit weight ↑	↓(↔*)	↑	↔
Poisson's ratio ↑	↑(↔*)	↑	↑
Coefficient of thermal expansion ↑	↑↑(↑*)	↑↑	↑ (↑↑*)
Thermal conductivity ↑	↓	↓↓	↓ (↓↓*)
Heat capacity ↑	↔	↔	↔
Cement type	↔	↔	↔
Cement content ↑	↑	↔	↑
Water/cement ratio ↑	↑	↔	↑
Aggregate type	↔	↔	↔
PCC set (zero stress) temperature ↑	↑(↔*)	↔	↔
Ultimate shrinkage at 40% R.H. ↑	↑(↔*)	↔	↔
Reversible shrinkage ↑	↔	↔	↔
Time to develop 50% of ultimate shrinkage ↑	↔	↔	↔
Curing method	↔	↔	↔
28-day PCC modulus of rupture ↑	↔	↓↓	↓
28-day PCC compressive strength ↑	↔	↓↓	↓
*Infiltration of surface water*** ↑	↔	↔	↔
Drainage path length** ↑	↔	↔	↔
Pavement cross slope** ↑	↔	↔	↔

Note: ↑↑ **or** ↓↓ - very sensitive to changes in input value (direction of arrow indicates trend)
↑ **or** ↓ - sensitive to changes in input value (direction of arrow indicates trend)
↔ - insensitive to changes in input value (direction of arrow indicates trend)
Bold – designer can control directly
Italic – designer may change, but needs to get permission of a specific committee or the agency
Bold, italic – designer may not change, but must know
* The results of version 0.7
** Drainage parameters were not included in version 0.9 and 0.1

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JPCP

Selected results illustrating different sensitivity ratings or performance trends using different MEPDG versions are shown in Figs. 2, 3 and 4, respectively.

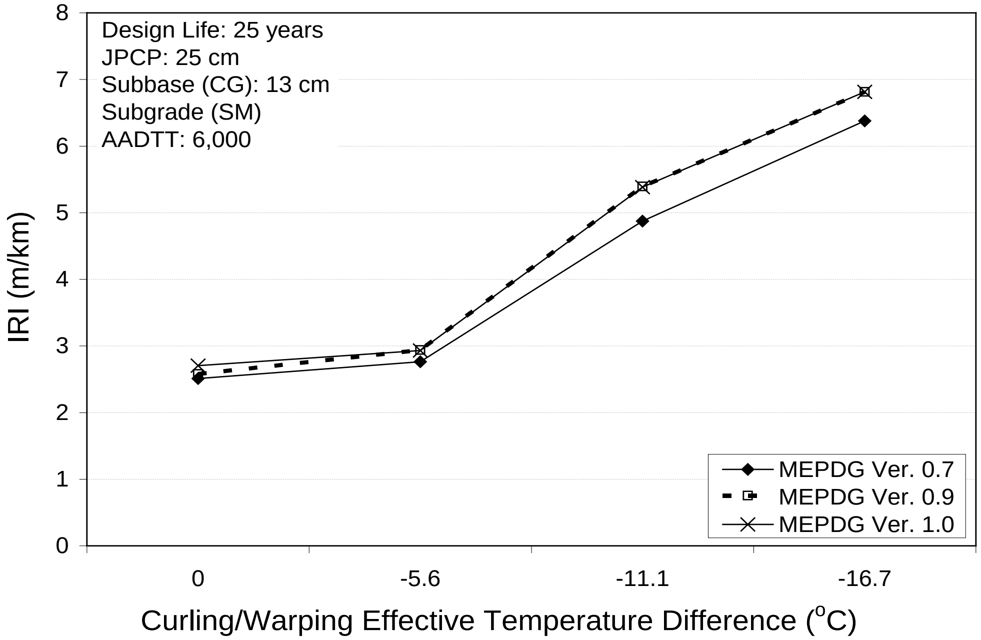

Fig. 2. Effect of curl/warp effective temperature difference on JPCP smoothness (IRI) using different versions of MEPDG software: example of "very sensitive" input

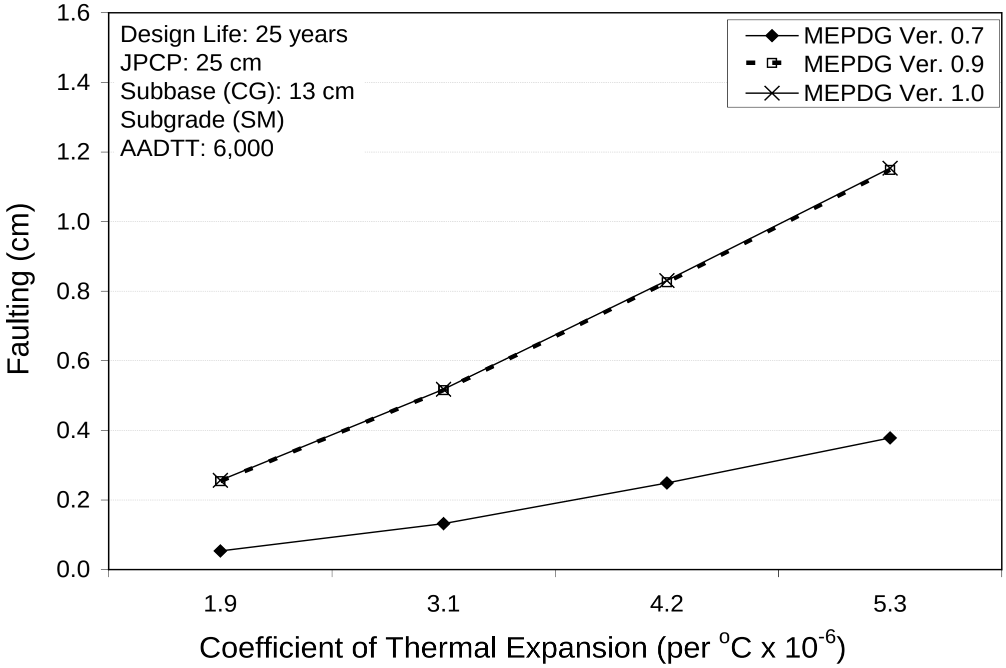

Fig. 3. Effect of PCC coefficient of thermal expansion on JPCP faulting: example of "sensitive" input (MEPDG 0.7) and "very sensitive" input (MEPDG 0.9 and MEPDG 1.0)

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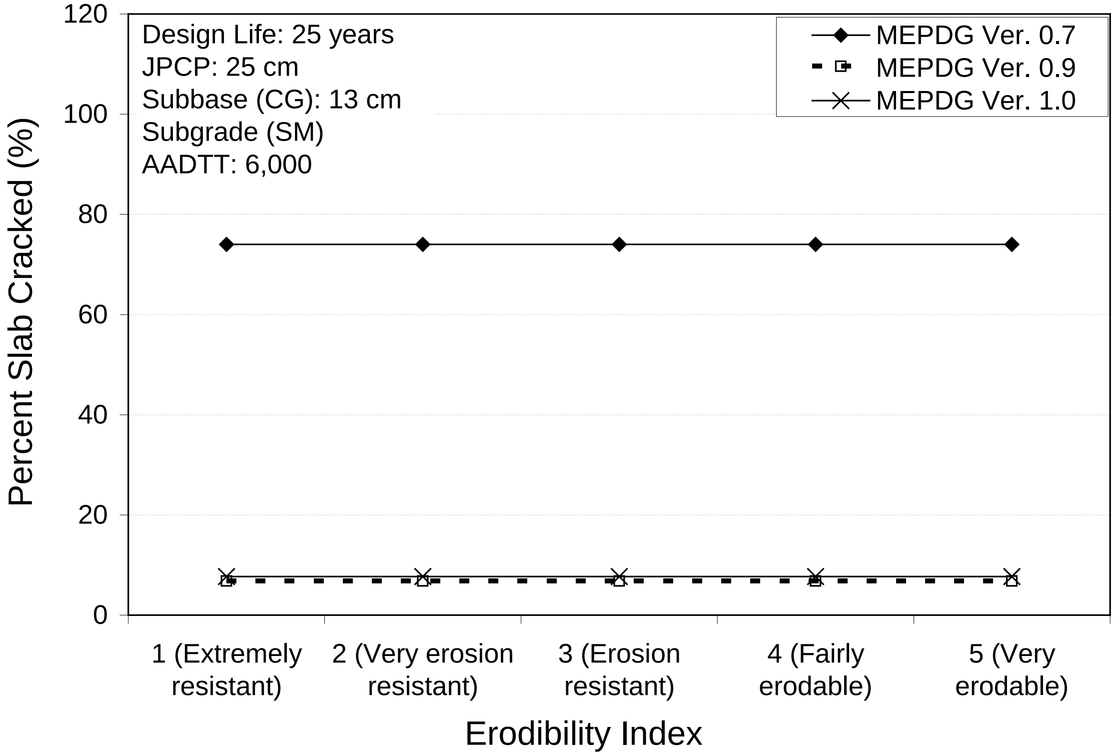

Fig. 4. Effect of erodibilty index on percent slab cracked: example of "insensitive" input

Fig. 2 shows that the predicted JPCP IRI is very sensitive to curl/warp effective temperature difference in all versions of MEPDG. However, as shown in Fig. 3, the predicted JPCP faulting using MEPDG 0.9 and 1.0 is more sensitive to input parameters than using the 0.7 version. Also, the predicted JPCP faulting is higher using MEPDG 0.9 and 1.0 compared to 0.7 version. It is also observed that the predicted JPCP cracking using MEPDG 0.9 and 1.0 is lower than MEPDG 0.7 predictions (see Fig. 4). However, the predicted JPCP cracking is not sensitive to erodibility index. The differences in performance trends among the MEDPG versions might be due to recalibration of distress prediction models based on the most up to database in the newer versions (NCHRP 2006). However, the performance prediction values between MEPDG 0.9 and 1.0 are not significantly different.

A summary of the sensitivity ratings is presented in Table 2 identifying the level of importance associated with each input parameter for JPCP. From Table 2, JPCP transverse cracking was found to be "very sensitive" to curl/warp effective temperature difference, PCC coefficient of thermal expansion, PCC thermal conductivity, PCC thickness, PCC strength properties and joint spacing. Fatigue damage is the main component of the cracking model in the MEPDG. Fatigue damage can be defined by the ratio of the applied number of load applications to the allowable number of load applications. The equation of allowable number of load applications in MEPDG includes the PCC modulus of rupture at age and the applied stress at condition. Since the very sensitive parameters identified in this study are related to the PCC strength and stress, these parameters also influence the predicted cracking in MEPDG.

The "very sensitive" input parameters for faulting were the curl/warp effective temperature difference and PCC coefficient of thermal expansion. Transverse joint faulting is the differential elevation across the joint measured approximately 30 cm (1 ft) from the slab edge, or from the rightmost lane paint stripe for widened slabs (NCHRP 2004). The transverse joint faulting prediction model in MEPDG uses an incremental approach. A faulting increment is determined each month and the faulting during each month is determined as a sum of faulting increments from all previous months during the life of the pavement (NCHRP 2004). The PCC slab corner upward deflection due to curling and warping is a main parameter to determine a faulting increment. Since the curl/warp effective temperature difference and the PCC coefficient of thermal expansion directly influence curling and warping behavior, it is clear that these parameters also influence the predicted faulting in MEPDG.

For smoothness, the curl/warp effective temperature difference, were found to be "very sensitive". In general, the curl/warp effective temperature difference, the PCC coefficient of thermal expansion, and PCC thermal conductivity had the greatest impact on the distresses. Since these input parameters cannot be modified, values having high level of accuracy (Level 1) 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, lab and field test(s) should be carried out to determine the magnitude of these parameters. Otherwise the accuracy of the predicted pavement distresses can differ significantly.

Among the very sensitive and sensitive parameters, the pavement design engineer can only modify PCC layer thickness, doweled transverse joints, and joint spacing. PCC strength properties are also modifiable provided that pavement design specifications are met.

The input parameters showing different sensitivity results (due to differences in MEPDG versions) for JPCP faulting predictions were joint spacing, dowel diameter, edge support, erodibility index, unit weight, poisson's ratio, PCC set (zero stress) temperature, ultimate shrinkage at 40% R.H. and coefficient of thermal expansion. The sensitivity results of JPCP transverse cracking were found to be different only to "edge support" input parameter. In the case of JPCP smoothness perditions, the results are different using different MEPDG versions for several input parameters such as dowel diameter, edge support, erodibility index, PCC coefficient of thermal expansion, and thermal conductivity.

CRCP

Selected results to illustrate the differences in performance predictions using different versions of MEPDG software for CRCP analyses are shown in Figs. 5 and 6.

As shown in Fig. 5, the CRCP punchout predictions using MEPDG 0.9 and 1.0 are more sensitivity to unit weight inputs than using 0.7. It is also observed that the punchout predictions using MEPDG 0.9 and 1.0 are, in general, higher than the MEPDG 0.7 predictions (see Figs. 5 and 6.)

The results of CRCP sensitivity analyses are summarized in Table 3. Among the 15 inputs, CRCP punchout was found to be "very sensitive" to percent steel, curl/warp effective temperature difference, PCC coefficient of thermal expansion, PCC thickness, and PCC strength properties. Also, the "very sensitive" input parameters for CRCP smoothness were the percent steel, PCC thickness and PCC Strength properties. Similar to the JPCP cracking prediction model, the CRCP punchout prediction model in MEPDG use fatigue damage as the main component. Therefore, as input parameters identified as very sensitive in this study, the input parameter related to strength and stress can influence the predicted cracking.

Reference to this paper should be made as follows: 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, Vol. 135, No. 8, pp 555-562.

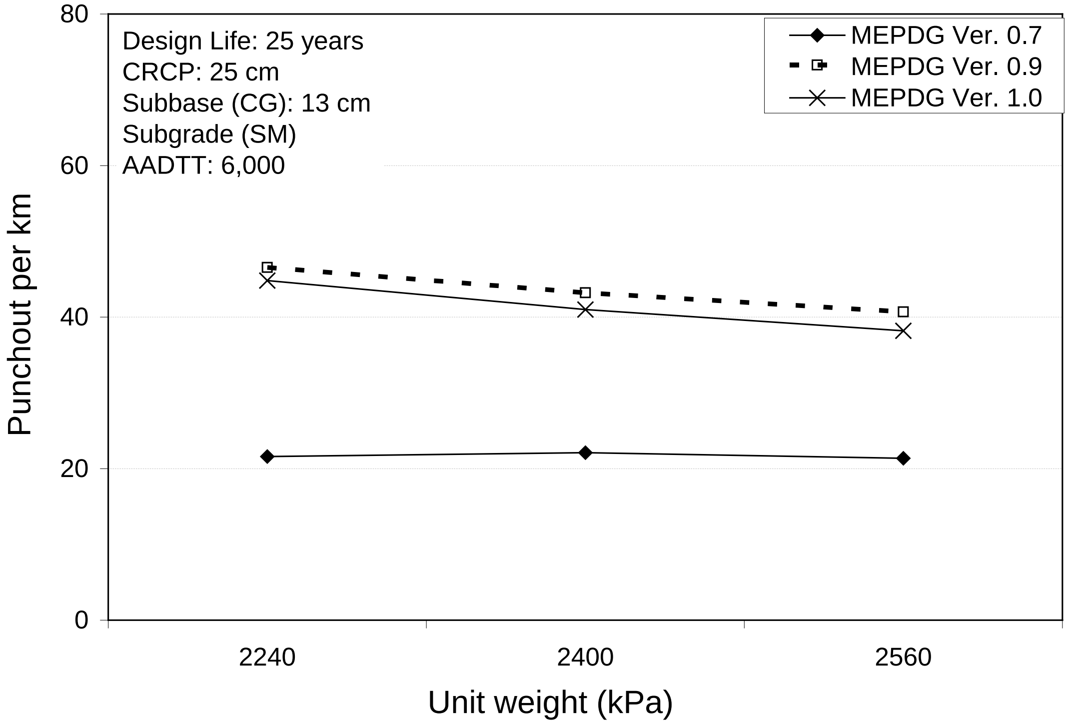

Fig. 5. Effect of PCC unit weight on CRCP punchout

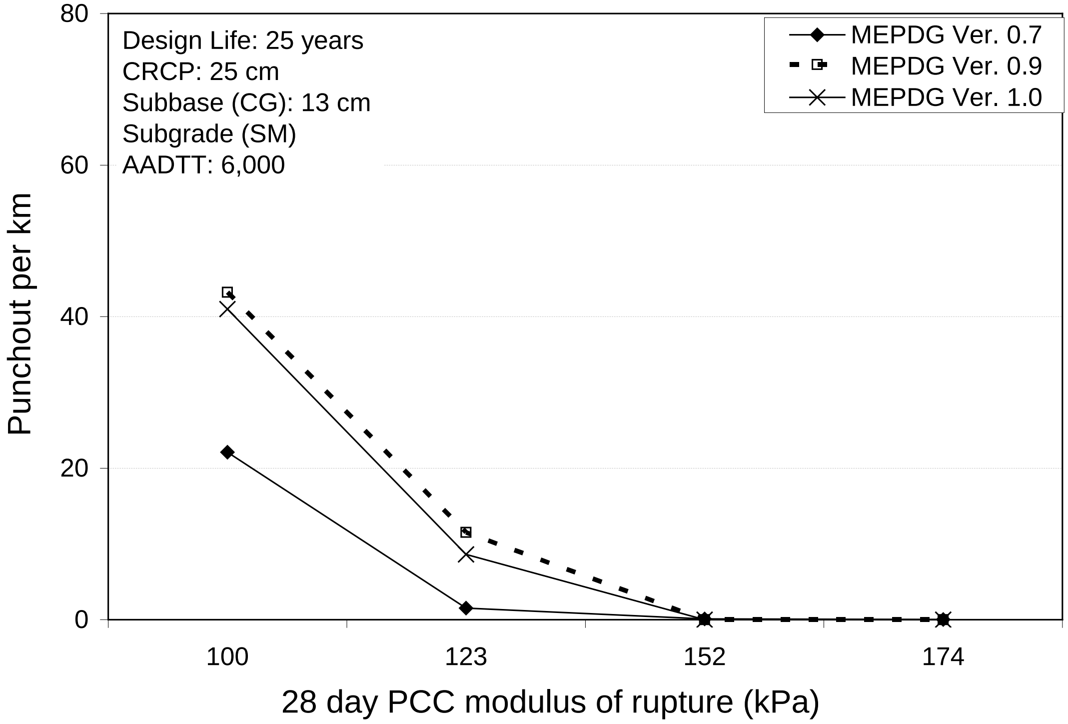

Fig. 6. Effect of 28-day modulus of rupture on CRCP punchout

Table 3. Summary of sensitivity analyses results for CRCP

CRCP Design Inputs	Performance Models	
	Punchout	Smoothness
Curl/warp effective temperature difference ↑	↓↓	↓
Percent Steel ↑	↓↓	↓↓
PCC-base slab friction ↑	↔	↔
Surface shortwave absorptivity ↑	↔	↔
PCC layer thickness ↑	↓↓	↓↓
Unit weight ↑	↓ (↔*)	↔
Poisson's ratio ↑	↓(↔*)	↔
Coefficient of thermal expansion ↑	↑↑	↑
Thermal conductivity ↑	↔	↔
Heat capacity ↑	↔	↔
Aggregate type	↔	↔
28-day PCC modulus of rupture ↑	↓↓	↓↓
Infiltration of surface water** ↑	↔	↔
Drainage path length** ↑	↔	↔
Pavement cross slope** ↑	↔	↔

Note:
↑↑ **or** ↓↓ - very sensitive to changes in input value (direction of arrow indicates trend)
↑ **or** ↓ - sensitive to changes in input value (direction of arrow indicates trend)
↔ - insensitive to changes in input value (direction of arrow indicates trend)
Bold – designer can control directly
Italic – designer may change, but needs to get permission of a specific committee or the agency
Bold, italic – designer may not change, but must know
* The results of version 0.7
** Drainage parameters were not included in version 0.9 and 1.0

Similar to JPCP, the curl/warp effective temperature difference, and the PCC coefficient of thermal expansion had the greatest impact on the CRCP distresses. Since these input parameters cannot be modified, it is recommended that accurate values (Level 1) should be input into the model to achieve reliable performance predictions. Among the very sensitive and sensitive input parameters for CRCP, the pavement design engineer can only modify PCC layer thickness, and percent steel. PCC strength properties are also modifiable provided that pavement design specifications are met.

The MEPDG input parameters that showed different sensitivities using different MEPDG versions were unit weight and poisson's ratio for only CRCP punchout predictions.

Comparison between JPCP and CRCP results

Since very similar design inputs were used in terms of traffic and material properties for both JPCP and CRCP sensitivity analyses, it is possible to directly compare the sensitivity results. In this study, the curl/warp effective temperature difference has been found to have significant effect on both JPCP and CRCP performance. The effect of curl/warp effective temperature difference on JPCP and CRCP smoothness are compared in Fig. 7. Since the rigid pavement designers are interested in PCC design thickness, the effect of PCC thickness on JPCP and CRCP smoothness are compared in Fig. 8. Note that the predictions of IRI model used in the MEPDG are linked to the predictions of other distresses such as cracking and faulting.

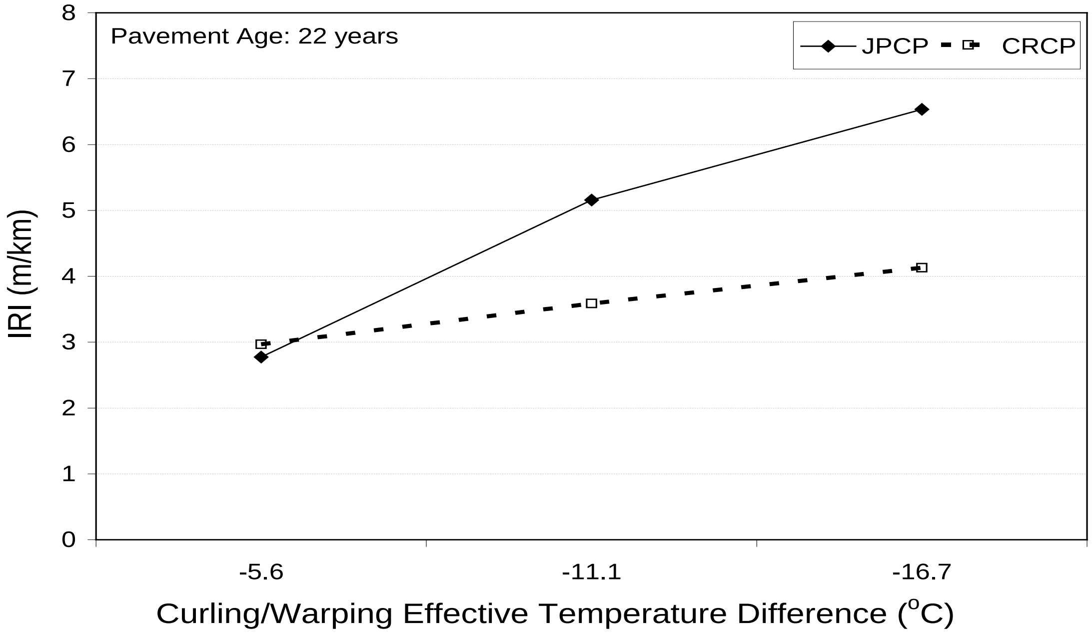

Fig. 7. Comparing the effect of curl/warp effective temperature difference on JPCP and CRCP smoothness

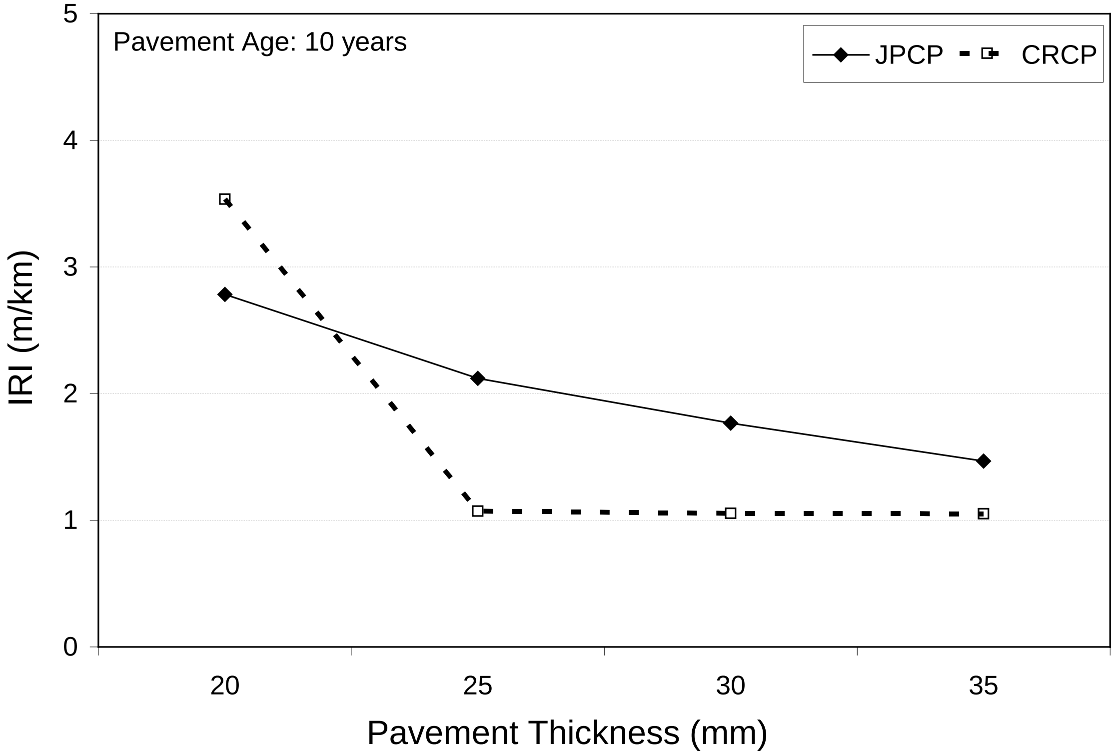

Fig. 8. Comparing the effect of PCC layer thickness on JPCP and CRCP smoothness

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Comparison of MEPDG version 0.7, 0.9 and 1.0

All the analyses were conducted using MEPDG versions 0.7, 0.9 and 1.0. The insensitive drainage parameters on version 0.7, infiltration of surface water, pavement cross slope, and drainage path length, are not found on the user-interface of version 0.9 and 1.0. The JPCP faulting predictions using MEPDG 0.9 and 1.0 are more sensitive to inputs rather than MEPDG 0.7. It is also observed that the JPCP cracking predictions using MEPDG 0.9 and 1.0 are smaller than the MEPDG 0.7 predictions. For CRCP, the punchout predictions using MEPDG 0.9 and 1.0 are higher than those obtained using MEPDG 0.7. These results might be due to recalibration of distress prediction model based on the most up to database in the newer MEPDG versions (NCHRP, 2006). However, the performance predictions between MEPDG 0.9 and 1.0 are not significantly different.

Summary and findings

In support of the Mechanistic-Empirical Pavement Design Guide (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 as well as those factors that are of no particular sensitivity. The results from such sensitivity analyses 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. Findings of this study are summarized as follows:

- The IRI values predicted by the MEPDG software for the actual JPCP sections selected in this study were compared with those reported in the Iowa DOT PMIS. Interestingly, the MEPDG predicted IRI values were almost twice as much as the values recorded in the PMIS, indicating the need for local calibration of the performance prediction models considering Iowa conditions.
- The available field data for cracking in the Iowa DOT Pavement Management Information System (PMIS) are in different units then those used in the MPEDG. Therefore, it is recommended that the units of MPEDG should be correlated to the actual field data in the PMIS as part of the MEPDG implementation in Iowa.
- The curl/warp effective temperature difference and the PCC coefficient of thermal expansion had the greatest impact on the JPCP and CRCP distresses. Since these input parameters cannot be modified, accurate values (Level 1) should be input into the model.
- The influence of "very sensitive" parameters on MEPDG performance predictions is extremely high; therefore, pavement performance outputs can vary significantly depending on the accuracy of these design inputs. 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.
- Among the "very sensitive" parameters, the pavement design engineer can only modify PCC thickness, doweled transverse joints, and joint spacing and also PCC strength properties (provided that pavement design specifications are met) for JPCP pavements and PCC thickness, percent steel and PCC strength properties for CRCP pavements.

- The CRCP pavement structure used in the analyses was intended to have the same design inputs as JPCP so that the performance predictions could be compared between the two types. Comparison of results for pavement smoothness indicated that JPCP is more sensitive to changes in curl/warp effective temperature difference and PCC thickness compared to CRCP.
- The results from sensitivity analyses using different versions indicated that the newer MEPDG versions (0.9 and 1.0) showed higher input sensitivities, especially for JPCP faulting and smoothness predictions. However, the performance predictions between MEPDG 0.9 and 1.0 are not significantly different.

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References

AASHO. 1962. The AASHO road test. Report 5, American Association of State Highway and Transportation Officials, Pavement Research, National Academy of Science, National Research Council, Washington D.C.

AASHTO. 1993. AASHTO guide for design of pavement structures. American Association of State Highway and Transportation Officials, Washington D.C.

Ceylan, H., Gopalakrishnan, K., and Coree, B. 2006. A strategic plan for implementing the mechanistic-empirical pavement design guide in Iowa. CD-ROM Proceedings of the 85th Annual Meeting of the Transportation Research Board, Washington, D.C.

Guclu, A. 2005. Sensitivity analysis of rigid pavement design inputs using mechanistic-empirical pavement design guide, M.S. Thesis, Department of Civil Engineering, Iowa State University, Ames, IA.

Hall, K. D. and Beam, S. R. 2005. Estimation of sensitivity of design input variables for rigid pavement analysis using mechanistic-empirical design guide. Transportation Research Record, **1919**: 65-73.

Iowa Department of Transportation (Iowa DOT). 2003. Test sections by mileposts, Office of Materials, Iowa Department of Transportation, Ames, IA.

Iowa Department of Transportation (Iowa DOT). 2005. Automatic traffic recorder monthly report [on-line]. Office of Transportation Data, Iowa Department of Transportation, Ames, IA, Available from http://www.iowadotmaps.com/atr.html [cited Jan. 1, 2005].

LTPP. 2005. LTPP data pave online release 17 [on-line] . FHWA, U.S. Department of Transportation, Available from http://www.datapave.com/ [cited Jan. 1, 2005].

NCHRP. 2004. Guide for mechanistic-empirical design of new and rehabilitated pavement structures. National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.

Reference to this paper should be made as follows: 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, Vol. 135, No. 8, pp 555-562.

NCHRP. 2006. Changes to the mechanistic-empirical pavement design guide software through version 0.900. Research Results Digest 308, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.

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.

Khazanovich, L., Darter, M., Yu, T. 2004. Mechanistic –empirical model for transverse joint faulting prediction. Transportation Research Record, **1896**: 34-45.

Kannekanti, V. and Harvey, J. 2006. Sensitivity analysis of 2002 design guide JPCP distress prediction models. Transportation Research Record, **1947**: 91-100.

Khanum, T., Hossain, M., and Schieber, G. 2006. Influence of traffic inputs on rigid pavement design analysis using the mechanistic-empirical pavement design guide. CD-ROM Proceedings of the 85th Annual Meeting of the Transportation Research Board, Washington, D.C.