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Effect of Concrete Strength and Stiffness Characterization on Predictions of Mechanistic–Empirical Performance for Rigid Pavements

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Abstract

The hierarchical approach for specifying design inputs is a key feature of the new "Mechanistic–Empirical Pavement Design Guide" (MEPDG). The three levels of design input for the strength and stiffness characterization of portland cement concrete (PCC) range from a Level 1 laboratory measurement of modulus of elasticity and modulus of rupture at 7, 14, 28, and 90 days to a Level 3 estimation of the 28-day unconfined compressive strength. This paper evaluates the effect of design input level for PCC strength and stiffness properties on MEPDG performance predictions for jointed plain concrete pavements (JPCPs). The effects of the different PCC stiffness and strength design input levels on predicted faulting, transverse cracking, and international roughness index (IRI) are evaluated for eight PCC mixtures in several JPCP design scenarios. Faulting was found to be insensitive to the MEPDG PCC input level, transverse cracking was extremely sensitive, and IRI was only moderately sensitive. In particular, the results showed that the Level 3 input combination of a measured 28-day modulus of rupture and a measured 28-day modulus of elasticity yielded predicted distresses that were consistently in closest agreement with predictions that used Level 1 inputs. Reliable and accurate 28-day modulus of rupture and modulus of elasticity values can therefore be used as less-expensive and more-practical alternatives to full Level 1 stiffness and strength characterization in JPCP analysis and design. When full Level 1 characterization is performed, high-quality testing is mandatory for avoiding small anomalies in measured values that can cause physically unrealistic predictions by the MEPDG of stiffness and strength gains over time.

Keywords

International Roughness Index, Mechanistic-Empirical Pavement Design Guide, Jointed plain concrete pavements

Disciplines

Civil and Environmental Engineering | Construction Engineering and Management

Comments

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The interim edition of the *Mechanistic–Empirical Pavement Design Guide* (MEPDG) represents a paradigm shift for the analysis and performance prediction of new and rehabilitated pavement structures (*1, 2*). In comparison with the previous empirical AASHTO design guides (*3*) derived largely from the AASHO Road Test in the late 1950s (*4*), the MEPDG is based upon mechanistic–empirical design principles that directly predict pavement structural distresses and roughness over the pavement's life.

Another distinctive feature of the MEPDG is that it uses an explicit hierarchical approach for specifying the design inputs. This hierarchical approach gives the designer flexibility in selecting design inputs on the bases of relative importance, size, cost, and available resources of the project. Design inputs can be specified at one of three levels: Level 1 for the highest accuracy, with direct measurement of inputs through laboratory or field tests; Level 2 for intermediate accuracy, with estimation of inputs through correlations with index and other properties; and Level 3 for the lowest accuracy, with inputs set at typical default values. The models and procedures for prediction of pavement performance are the same for all input levels.

Unsurprisingly, the increased analysis and design sophistication of the MEPDG requires substantially more design inputs than did the older AASHTO design guides. The primary stiffness and strength inputs for portland cement concrete (PCC) in jointed plain concrete pavement (JPCP) systems are the modulus of elasticity (E_c) and the modulus of rupture (MOR). Level 1 of the MEPDG requires direct measurements of these PCC properties at various ages to predict stiffness and strength gains over time. The required stiffness and strength values at Level 2 are estimated from unconfined compressive strength (f'_c) results at various ages and at Level 3 from a single-point measurement of the concrete MOR or compressive strength and optionally the corresponding E_c at 28 days. With these inputs, the MEPDG estimates stiffness and strength gains over time, critical elements in analysis of incremental damage and modeling of performance prediction.

Although numerous sensitivity analyses have been conducted to relate MEPDG JPCP performance predictions to variations in input parameter values (*5–9*), few if any have evaluated the effect of the different levels for PCC stiffness and strength design inputs on JPCP performance predictions. The present study was conducted to fill that gap. The primary objective of this study is to answer the fundamental question, "Do all the MEPDG alternatives for PCC stiffness and strength design inputs yield comparable predictions of JPCP performance?" If the answer to that question is no, then there is a clear follow-up question: "When Level 1 design inputs are not available, which other PCC stiffness and strength design inputs provide the most comparable and reliable JPCP performance predictions?" These questions are addressed in this paper by (*a*) reviewing the MEPDG input characterization procedure for the PCC materials, (*b*) comparing predicted faulting, transverse cracking, and international roughness

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index (IRI) from the different PCC strength and stiffness design input levels for eight PCC mixes and multiple pavement sections, and (*c*) evaluating the influence of each PCC strength and stiffness input on JPCP performance predictions.

MEPDG INPUT CHARACTERIZATION FOR PCC MATERIALS

The stiffness and strength of new PCC used in new construction, reconstruction, and PCC overlays increase significantly over time because of its continuing hydration and aging. These relationships of stiffness and strength versus time are critical to the computed structural response and predicted performance of the pavement. The approaches followed by the MEPDG for characterizing this PCC stiffness and strength behavior at each design input level are as follows:

- Level 1. The required MEPDG inputs are the laboratory-measured values of E_c (ASTM C469) and MOR (AASHTO T97) at 7, 14, 28, and 90 days and the estimated ratio of 20-year to 28-day values. These measured E_c and MOR values are used to calibrate the respective stiffness and strength gain relationships:

$$\text{modratio} = \alpha_1 + \alpha_2 \log_{10}(\text{age}) + \alpha_3 \left[\log_{10}(\text{age})\right]^2 \tag{1}$$

$$\text{strratio} = \beta_1 + \beta_2 \log_{10}(\text{age}) + \beta_3 \left[\log_{10}(\text{age})\right]^2 \tag{2}$$

where

modratio = ratio of measured E_c at a given age to measured E_c at 28 days,
strratio = ratio of measured MOR at a given age to measured MOR at 28 days,
age = age in years,
α_1, α_2, α_3 = regression constants, and
β_1, β_2, β_3 = regression constants.

- Level 2. The required inputs are the laboratory measured values of f'_c (AASHTO T22) at 7, 14, 28, and 90 days and the estimated ratio of 20-year to 28-day values. Corresponding values of E_c and MOR are estimated from f'_c by use of the standard empirical relationships (*1*):

$$E_c = 33\rho^{3/2}\sqrt{f'_c} \cong 57{,}000\sqrt{f'_c} \tag{3}$$

$$\text{MOR} = 9.5\sqrt{f'_c} \tag{4}$$

where ρ is the unit weight (lb/ft^3).

The estimated values of E_c and MOR are then used with Equations 1 and 2 to calibrate the respective relationship in stiffness and strength gain. The constants in the empirical Equations 3 and 4 represent average values across mixes, and the scatter of the data around these empirical mean trends is quite high (*10*).

- Level 3. The MEPDG provides four options for specifying Level 3 PCC stiffness and strength design inputs:
  - – 28-day MOR,
  - – 28-day f'_c,
  - – 28-day MOR and corresponding 28-day E_c, and
  - – 28-day f'_c and corresponding 28-day E_c.

For the first two options, the corresponding 28-day E_c is estimated by using the empirical Equations 3 and 4; Equation 4 is also used to estimate the 28-day MOR in the second and fourth options. A default aging relationship is used to estimate E_c and MOR at other times:

$$\text{ratio} = 1.0 + 12 * \log_{10}(\text{age}/0.0767)0.01566 * \left[\log_{10}(\text{age}/0.0767)\right]^2 \tag{5}$$

where ratio is the ratio of either E_c or MOR at a given age to its respective 28-day value.

Supplementary procedures are required for characterizing the properties of existing PCC materials in rehabilitation designs. For existing PCC slabs, the E_c and MOR values must be adjusted for the damage caused to the pavement by traffic loads and environmental effects, and the gains in E_c and MOR over time are not considered. The characterization of existing PCC slabs is outside the scope of the present study.

Many other design inputs are required for PCC materials. These inputs include mix properties (unit weight, Poisson's ratio, cement type, cementitious material content, water–cement ratio, aggregate type, curing method), thermal properties (thermal conductivity, heat capacity, surface shortwave absorptivity, coefficient of thermal expansion, PCC zero-stress temperature), and shrinkage properties (ultimate shrinkage at 40% relative humidity, reversible shrinkage, time to develop 50% of ultimate shrinkage). These are not considered in this study, and the MEPDG Level 3 default inputs are used as appropriate.

PCC MIX PROPERTIES

PCC material characterization data were compiled for a total of eight mixtures. Data for the first five mixtures were taken from the Missouri Department of Transportation (DOT) local calibration study (*11*), and the remaining three were obtained from a study of in-service JPCP sites reported by Ceylan et al. (*12*). Table 1 provides a summary of the mix compositions. All mixes used conventional Type I cement.

The measured Level 1 stiffness and strength values for all eight mixes are summarized in Table 2. The 3-day stiffness and strength shown in the table were measured but are not used in the MEPDG. Figure 1 depicts the growth over time of f'_c, the normalized E_c $(E_c/57{,}600)^2$, and the normalized MOR $(\text{MOR}/9.5)^2$. Equation 3 with $\rho = 145$ lb/ft^3 and Equation 4 are the motivation for these normalizations of E_c and MOR; for a mixture exactly following the empirical relationships in Equations 3 and 4, all three curves should be coincident. Among the noteworthy observations from the trends in Figure 1 are the following:

- The f'_c consistently exhibits the smoothest gains in time. Most of the mixes have 28-day f'_c on the order of 5,000 psi, reasonable for paving concrete. The exceptions to this are Mixes 6 and 7, which exhibit significantly greater 28-day f'_c values approaching 7,000 psi.
- Several of the time trends for normalized MOR and normalized E_c exhibit local anomalies (e.g., Mixes 2, 4, 6, and 7). The anomalies in 28-day MOR, 28-day E_c, or both in Mixes 4 and 6 are especially problematic because these values are key Level 3 inputs. In Mix 6, it is impossible to tell whether the 7-day MOR is disproportionately high or the 14- and 28-day values are disproportionately low. These anomalies are most likely attributable to the real-world vagaries of laboratory measurement and can only be addressed through meticulous

TABLE 1 Description of Study Mixtures

Mix	State	Location	Cement Content (lb/yd^3)	Fly Ash Content (lb/yd^3)	Total Cementitious Materials Content (lb/yd^3)	Fly Ash (%)	Water-to-Cement Ratio
1	Mo.	US-412 in Dunklin County	445	111	556	20	0.41
2	Mo.	I-435 in Jackson County	510	90	600	15	0.43
3	Mo.	MO-367 in St. Louis County	441	110	551	20	0.39
4	Mo.	US-63 in Randolph County	432	108	540	20	0.39
5	Mo.	I-35 in Clinton County	517	91	608	15	0.38
6	Iowa	US-34 in Burlington	443	111	554	20	0.40
7	Iowa	US-30 in Marshalltown	448	112	560	20	0.40
8	Wis.	US-151 in Platteville	395	170	565	30	0.36

NOTE: 1 $lb/yd^3 = 0.593\ kg/m^3$.

TABLE 2 Measured Strength and Stiffness Values for All Mixes

Mix	Sample Age (days)	Compressive Strength (psi)	Modulus of Rupture[a] (psi)	Modulus of Elasticity (psi)
1	3	2,934	414	4,090,658
	7	3,537	498	4,479,212
	14	3,768	587	4,707,686
	28	4,348	619	5,042,242
	90	4,904	656	5,224,673
2	3	3,472	564	3,729,516
	7	3,936	634	3,972,549
	14	4,474	652	4,161,557
	28	4,857	718	4,266,237
	90	5,606	788	4,632,843
3	3	3,756	587	3,835,707
	7	4,472	595	4,291,245
	14	4,848	640	4,271,614
	28	5,082	655	4,452,082
	90	5,875	725	4,974,852
4	3	3,884	540	4,049,615
	7	4,382	583	4,239,712
	14	4,810	637	4,347,735
	28	5,120	744	4,958,388
	90	5,970	699	4,785,520
5	3	3,243	566	3,348,184
	7	3,847	654	3,767,819[b]
	14	4,502	739	4,101,783
	28	4,886	772	4,320,960
	90	5,643	897	4,635,612
6	3	3,224	462	3,503,971
	7	4,952	622	4,479,009
	14	6,111	583	4,573,864
	28	6,690	563	4,621,292
	90	7,846	804	5,080,550
7	3	4,770	656	4,449,651
	7	5,303	533	4,363,452
	14	6,159	588	4,803,838
	28	6,587	616	5,024,031
	90	7,183	603	4,879,745
8	3	3,116	586	3,016,613
	7	4,059	672	3,160,825
	14	4,396	690	4,121,029
	28	4,565	699	4,601,131
	90	5,786	720	4,667,153

NOTE: 1 psi = 6.9 kPa.

[a] Estimated as 1.5 times the split cylinder tensile strength (*13*).

[b] Missing data; interpolated through regression analysis from other Mix 5 E_c values.

testing technique (e.g., consistent sample preparation, increased number of replicates).

- Although some of the mixes satisfy the empirical relationships in Equations 3 and 4 quite well (i.e., have reasonably coincident trends, as in Mixes 2, 3, and 8), others do not. Mix 1 has disproportionately high E_c values; Mix 5 has disproportionately high MOR values; and Mixes 6 and 7 have disproportionately low MOR values, particularly at intermediate-to-long ages.

The coefficient of thermal expansion (CTE) was also measured, in accordance with AASHTO TP-60, for all mixtures. The measured CTE values for Mixes 1 through 5 were lower than national averages and require further confirmation before use (*11*); consequently the Level 3 default values for CTE were used for these mixes. The average measured CTE values for Mixes 6 through 8 were, respectively, $6.25 \times 10^{-6}\ \epsilon/^\circ F$ ($1.12 \times 10^{-5}\ \epsilon/^\circ C$), $5.35 \times 10^{-6}\ \epsilon/^\circ F$ ($9.63 \times 10^{-6}\ \epsilon/^\circ C$), and $5.79 \times 10^{-6}\ \epsilon/^\circ F$ ($1.04 \times 10^{-5}\ \epsilon/^\circ C$). These are all within the range of the MEPDG Level 3 defaults.

ANALYSIS SCENARIOS

The PCC material characterization data for Mixes 1 through 5 were compiled as part of a comprehensive MEPDG local calibration for the Missouri DOT (*11*). Although these mixtures originated in specific projects (Table 1), the traffic and pavement structural details for these projects are unknown. Consequently, Mixes 1 through 5 were analyzed for the baseline conditions of the sensitivity analysis conducted as part of the local calibration study. These baseline conditions consisted of a 10-in. (250-mm) JPCP slab on a 4-in. (100-mm) dense aggregate base over a silty sand gravel (AASHTO Class A-2-4) subgrade. The slabs had a 15-ft (4.8-m) transverse joint spacing with tied PCC shoulders. The two-way annual average daily truck traffic (AADTT) was 16,300, with a 50% directional distribution, a 95% lane distribution factor, a linear growth rate of 1.64%, and a vehicle distribution having 74% Class 9 trucks (Principal Arterials, Truck Traffic Classification 1). Construction was assumed to be completed in October, with its being opened to traffic in November and having a 20-year initial design life. The climate was based on conditions in Camden County in central Missouri. The ratios of 20-year to 28-day E_c and MOR were both set at 1.2, consistent with recommendations by Wood (*14*). All other inputs were taken as the Level 3 default values.

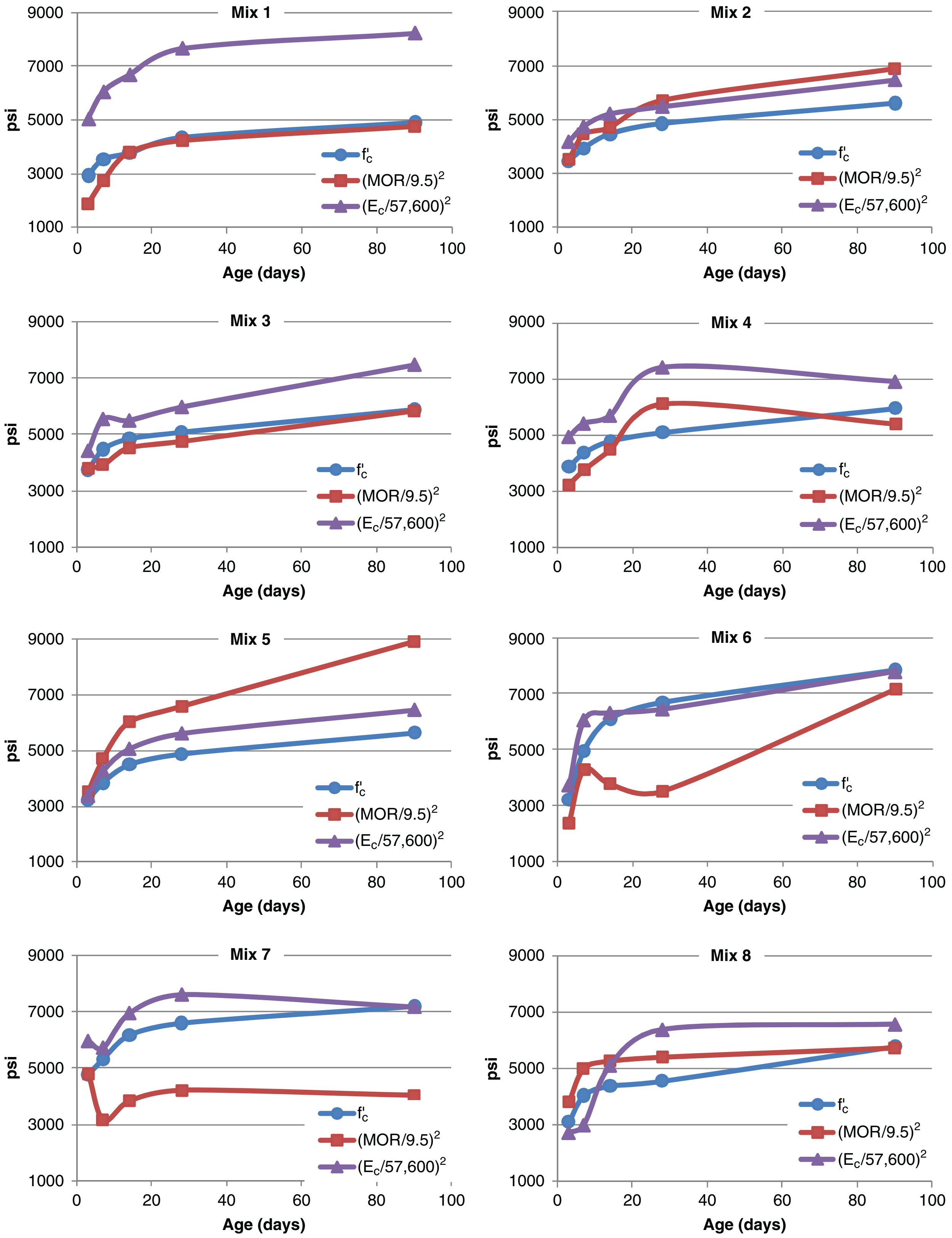


FIGURE 1 Normalized strength and stiffness gains with time for Mixes 1 through 8.

The analysis scenarios for Mixes 6 through 8 were based on their respective actual projects (Table 1). The US-34 project near Burlington, Iowa (Mix 6), was constructed in June 2005 and was a JPCP slab 11 in. (280 mm) thick on a 6-in. (150-mm) open-graded granular base. The transverse joint spacing is approximately 15 ft (4.8 m). The design lane was approximately 14 ft (4.2 m) wide and included a 2-ft (0.6-m) lane widening. An open-graded granular shoulder was added after construction. The value of two-way AADTT obtained from the state traffic map was 1,300. The US-30 project near Marshalltown, Iowa (Mix 7), was constructed in July 2005 and was a JPCP slab 10 in. (250 mm) thick on a 6- to 10-in. (150- to 250-mm) open-graded granular base. The pavement geometry and joint information were the same as for the US-34 site. The value of two-way AADTT was 950. The US-151 project near Platteville, Wisconsin (Mix 8), was constructed in 2004 as a JPCP slab 9.5 in (240 mm) thick on a 6-in. (152-mm) open-graded granular base. The transverse joint spacing was approximately 15 ft (4.6 m). The design lane was approximately 14 ft (4.2 m), which included a 2-ft (0.6-m) widened lane. The two-way AADTT was 1,700. A 25-year design life was used for all three of these projects. The design climate for each project was obtained from the closest weather station available in the MEPDG database. The ratios of 20-year to 28-day E_c and MOR were set at 1.2 for all projects, consistent with recommendations by Wood (*14*). All other inputs were taken as the Level 3 default values.

RESULTS OF PREDICTIONS

The public domain Version 1.100 of the MEPDG software was used in this study. The analyses focused on the predicted faulting, transverse cracking, and IRI results at the end of the project's design life. These are summarized in Figure 2 for the analyses that used the Level 1 PCC stiffness and strength inputs. Wide ranges of distresses were predicted for the various scenarios. Faulting ranged from extremely small values in the lightly trafficked Mixes 6 through 8 to values approaching the default design limit in the more heavily trafficked Mixes 1 through 5. Final IRI similarly ranged from quite small values in Mixes 6 through 8 to moderate-to-substantial values in Mixes 1 through 5. Slab cracking exhibited the widest variation, with more than 80% cracked slabs predicted for some mixes (Mix 1) and much smaller percentages predicted for others (Mixes 4 and 8). The 10-in.-thick slabs for Mixes 2 and 5 in particular produced zero cracking when their respective Level 1 inputs were used. Because zero slab cracking is not useful for comparison of the different input levels, these scenarios were reanalyzed with 9- and 8-in. JPCP thicknesses, respectively, being used; the slab cracking (but not faulting and IRI) results shown in Figure 2 are for these thinner slab assumptions.

One focus of this study was the effect of PCC stiffness and strength design input level on predicted JPCP distress. Consistent with anecdotal evidence in previous studies (*15*), input level had an effect, and it was particularly large for slab cracking, as shown in Figure 3. For example, predicted slab cracking for Mix 1 ranged from 5% when the Level 3 input of 28-day f'_c was used to 81% when the full Level 1 characterization was used. Predicted cracking for Mix 7 increased from 0 to 6% for Level 2 versus Level 1 inputs, while predicted cracking for Mix 2 decreased from 46% to 4% for Level 2 versus Level 1. A fundamental explanation is clearly required for these large and inconsistent discrepancies in predicted cracking at different design input levels for design input levels for material properties.

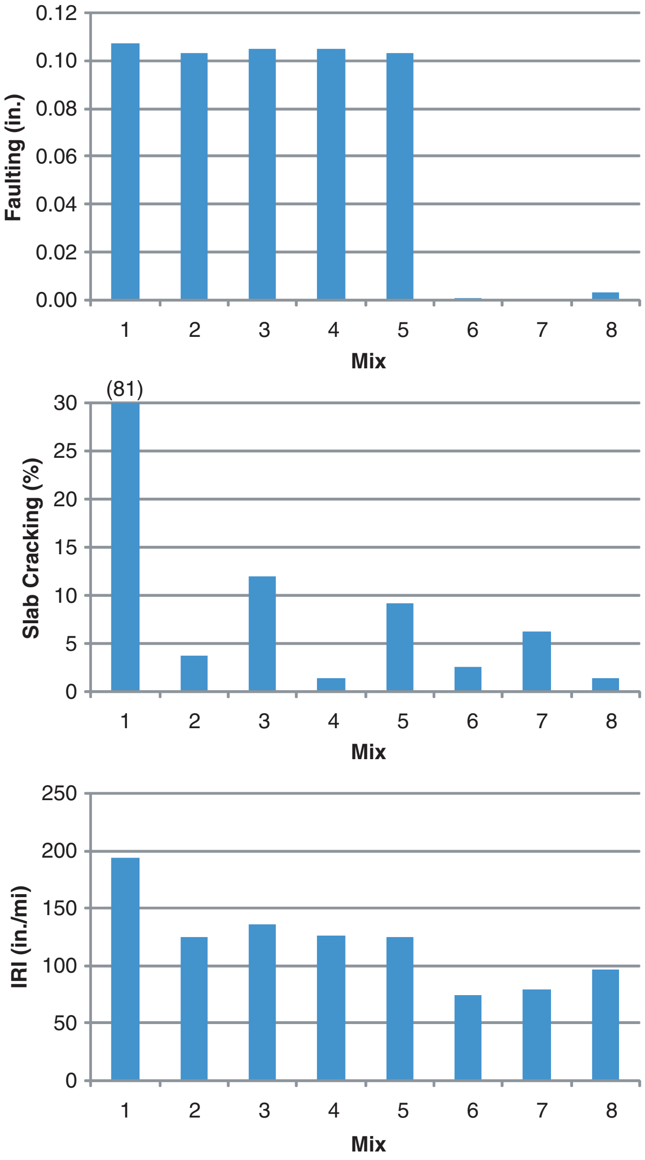


FIGURE 2 Predicted distresses from use of Level 1 inputs (1 in. = 25.4 mm; 1 in./mi = 0.0158 m/km).

DISCUSSION OF RESULTS

To help in understanding of the influence of PCC stiffness and strength input level on predicted performance, the predicted faulting, slab cracking, and IRI at the various input levels for each mix were normalized by the respective distress values predicted through the use of the Level 1 inputs for each case. In other words, the predictions using Level 1 inputs were the benchmarks against which all other predictions were compared. The real gold standard, of course, was actual field performance. However, well-characterized sites having high-quality Level 1 material characterization and consistent performance monitoring over 10 or 20 years simply do not exist.

The predicted distresses after normalization by their respective Level 1 results are summarized in Figure 4. Several important observations can be drawn from this figure:

- Predicted faulting was essentially independent of the input level for PCC stiffness and strength. This finding is sensible: the faulting

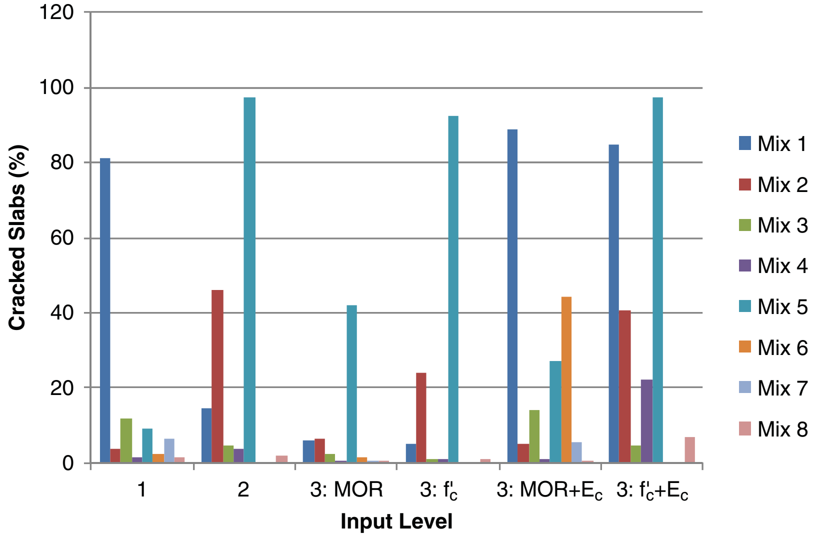


FIGURE 3 Effect of PCC stiffness and strength input level on predicted slab cracking.

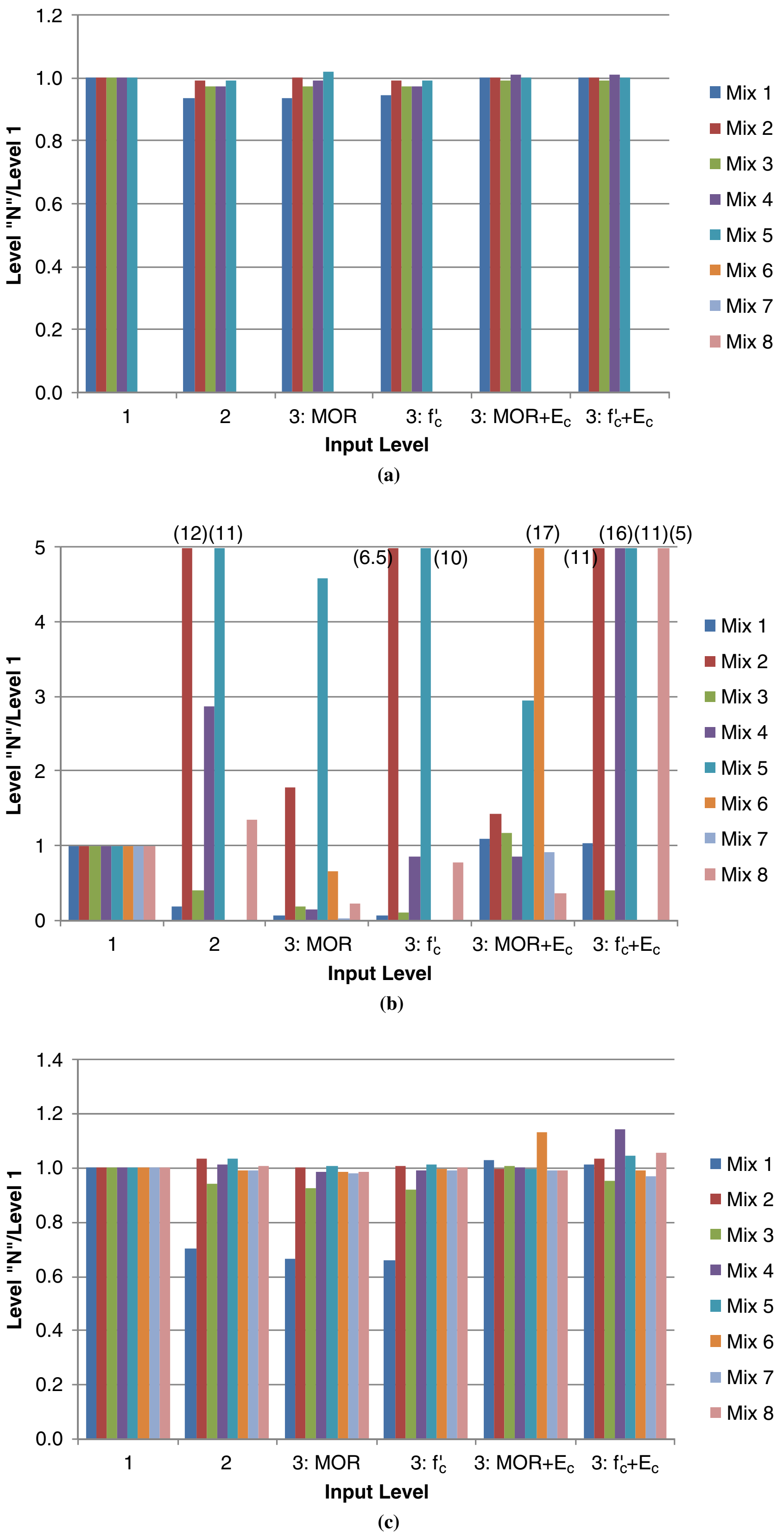
distress model is primarily a function of the base erodibility, subgrade deformation and other subgrade properties, climate variables, and slab corner deflection caused by temperature curling and moisture warping. Only the last factor depends on PCC stiffness, and none of the factors depend on PCC strength. (Normalized faulting for Mixes 6 through 8 is omitted from Figure 4. The magnitudes of predicted faulting were too small for adequate calculation precision.)

- Slab cracking was extremely sensitive to the PCC stiffness and strength input level. This finding is conceptually sensible: the applied slab stresses induced by load and temperature gradients are directly related to E_c, and the slab resistance to these stresses is directly related to MOR. As noted earlier, the different Level 2 and 3 approaches apply different combinations of empirical relationships to determine E_c and MOR over time. These empirical relationships are highly approximate (*10*), and individual mixes may differ substantially from the mean trends. As indicated by the normalized measured property data shown in Figure 1, most of the mixes in this study do not conform very closely to these empirical relationships.
- IRI demonstrated intermediate sensitivity to PCC stiffness and strength input level. Again, this result is conceptually sensible. Predicted IRI is a function of predicted faulting (not sensitive to PCC stiffness and strength input level) and slab cracking (extremely sensitive to input level) in addition to estimated spalling, and site climate and subgrade conditions.

Close examination of the slab cracking results in Figure 4 suggests that the Level 3 option of measured 28-day MOR and E_c tends to agree best with the Level 1 results (i.e., these normalized values have the least dispersion around 1). The two largest outliers to this trend are Mix 6 (normalized slab cracking distress ratio = 17) and Mix 5 (distress ratio = 3). As noted earlier, these two mixes had some anomalies in their measured strength and stiffness values: Mix 6 had anomalously low MOR values, especially at 28 days, while Mix 5 had disproportionately high MOR values. Additional evidence of the atypical predicted behavior of these two mixes appears in Figure 5, which shows the MEPDG-forecast MOR and E_c gains over time based on the Level 1 inputs, that is, the calibrated regression Equations 1 and 2. Figure 5*a* clearly shows that the anomalies in the measured Level 1 input values for Mixes 5 and 6 result in a decrease in predicted MOR with time after a peak value is reached at Year 1 or 2. Figure 5*b* shows a similar decrease in predicted E_c after about 3 years for Mix 8. As Figure 4 shows, Mix 8 (distress ratio = 0.4) is the next largest outlier for normalized slab cracking after Mixes 5 and 6. The clear conclusion is that small anomalies in any of the measured Level 1 stiffness and strength values can result in irrational estimates of strength and stiffness gains with time and, inevitably, errors in predictions of pavement performance.

Figure 6 summarizes the ranges and averages for the normalized slab-cracking predictions for all input levels after the two largest outliers (Mixes 5 and 6) are censored. It is clear that the Level 3 inputs of measured 28-day MOR and E_c agree best with the Level 1 results in having the smallest range and a mean value closest to 1. This information suggests that, as a practical matter, these Level 3 PCC design inputs can be used by the pavement designer as a generally satisfactory alternative to full and careful Level 1 characterization. At the other extreme, predictions using Level 2 inputs or the Level 3 options of 28-day f'_c or 28-day f'_c plus 28-day E_c were clearly the worst in the range in discrepancies in their predicted slab cracking versus predictions when Level 1 inputs were used. This result suggests that characterization of PCC stiffness and strength in relation to f'_c and conversion to the required E_c and MOR values by means of the empirical Equations 3 and 4 are not the best approach for JPCP design.

To emphasize the importance of testing quality for PCC stiffness and strength inputs, a one-at-a-time sensitivity analysis was performed to explore the relative importance of the various Level 1 strength and stiffness inputs. Previous sensitivity studies have explored only the 28-day stiffness and strength inputs (*5, 6, 8, 15*). In the present study, baseline 7-, 14-, 28-, 90-day E_c and MOR data were generated by using average 28-day E_c and MOR values, a typical value of 1.2 for the ratios of 20-year to 28-day stiffness and strength, and the Level 3 aging relationship in Equation 5. Small perturbations were then applied to the baseline value at each age in turn to generate simulated Level 1 input value sets for MEPDG analysis. The sensitivity of predicted output distress Y_j to a change in each Level 1 input

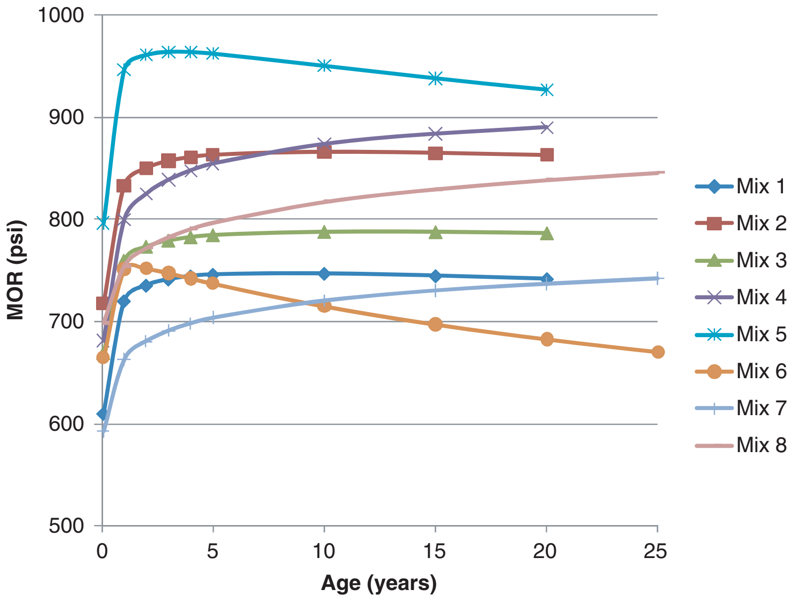


(a)

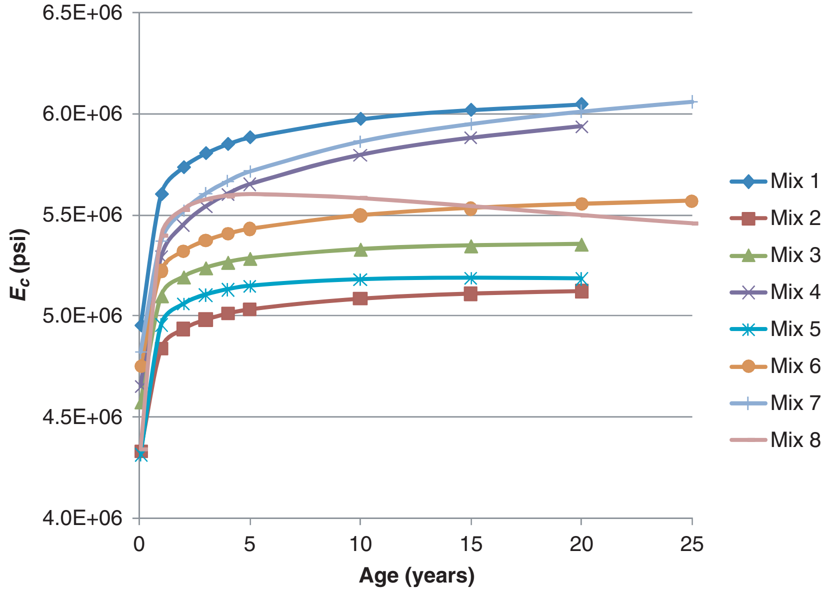
(b)

(c)

FIGURE 4 Normalized predicted distresses: (*a*) faulting, (*b*) slab cracking, and (*c*) IRI.



(a)



(b)

FIGURE 5 MEPDG-predicted stiffness and strength over time on basis of Level 1 design inputs.

parameter X_i was quantified in relation to a normalized sensitivity index S_{ji}:

$$S_{ji} = \frac{\partial Y_j}{\partial X_i} \frac{\overline{X}_i}{\overline{Y}_j} \qquad (6)$$

where $\overline{X}_i$ and $\overline{Y}_j$ are the mean values for each input and output, respectively. Equation 6 essentially quantifies the percentage change in predicted distress Y_j caused by a given percentage change in input parameter X_i. Figure 7 summarizes the computed normalized sensitivity indices of predicted distresses to input E_c and MOR values at different ages. Consistent with previous results, faulting is least sensitive to all the stiffness and strength inputs; slab cracking is the most sensitive; and IRI exhibits intermediate sensitivity. Variations in the 7-day E_c and MOR inputs have comparatively modest influence on any of the predicted distresses compared with the much-larger impacts of the 28-day, 90-day, and 20-year–28-day stiffness and strength values. Measurements at 14 days have almost negligible influence.

CONCLUSIONS AND RECOMMENDATIONS

This study evaluated the effect of PCC design input levels for stiffness and strength on predicted JPCP performance. Faulting, transverse slab cracking, and IRI predictions were compared for Level 1

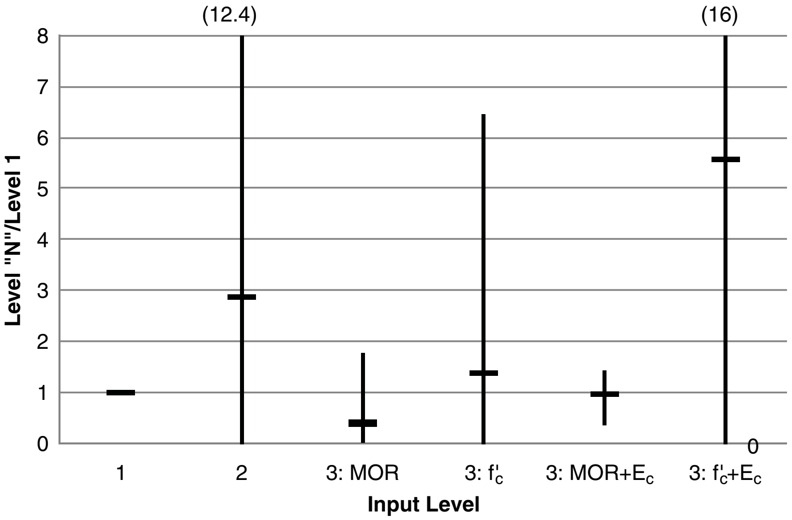
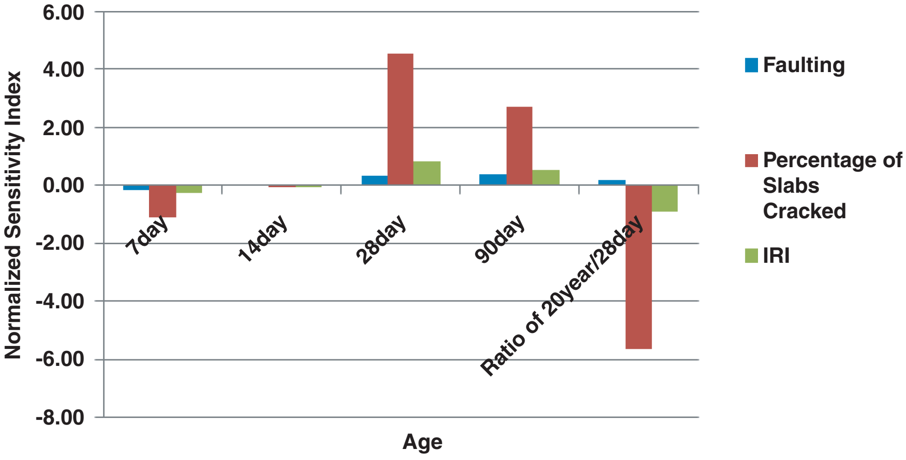
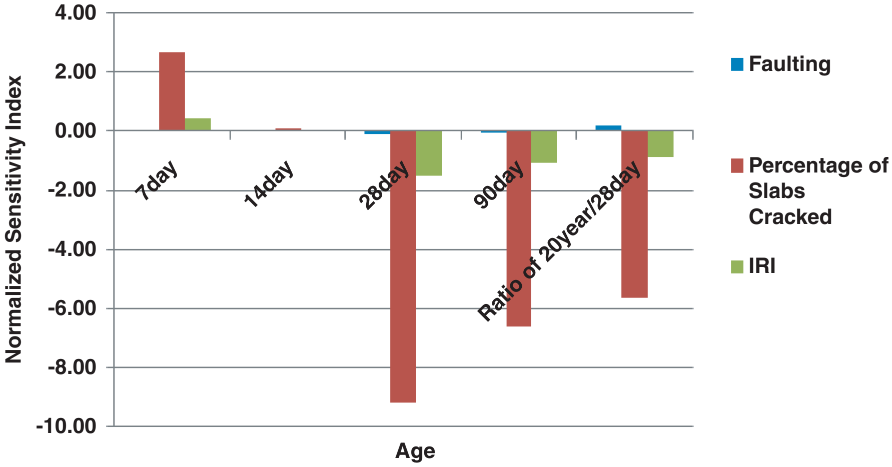


FIGURE 6 Ranges and mean values for normalized slab-cracking predictions at each design input level.



(a)



(b)

FIGURE 7 Normalized sensitivity of predicted distresses to (*a*) E_c and (*b*) MOR values at different ages.

versus Level 2 versus Level 3 (four options) design inputs for eight PCC mixes and several JPCP design scenarios. The different Level 2 and Level 3 approaches for characterizing PCC stiffness and strength applied different combinations of empirical relationships to determine E_c and MOR over time. These empirical relationships were highly approximate at best, and individual mixes did not necessarily conform closely to these relationships.

The conclusions from these analyses of most interest to agencies and design engineers can be summarized by answering the two fundamental questions raised at the beginning:

- "Do all the MEPDG alternatives for PCC stiffness and strength design inputs yield comparable predictions of JPCP performance?" For faulting and to a lesser extent for IRI, the answer to this question is yes. Predictions of transverse slab cracking, in contrast, can vary wildly using Level 1 versus Level 2 versus the four options for Level 3 stiffness and strength inputs.
- "When Level 1 design inputs are not available, which other PCC stiffness and strength design inputs provide the most comparable and reliable JPCP performance predictions?" Predictions based on the Level 3 inputs of measured 28-day MOR and measured 28-day E_c agreed best with the predictions when Level 1 inputs were used. This finding implies that the aging behavior of most mixes reasonably matches the Level 3 default aging built into the MEPDG; this result merits further investigation. From the results of this study, it can be concluded that Level 2 and Level 3 inputs that are based on f'_c and Level 3 inputs that use empirical estimates of 28-day E_c should be avoided. Regardless of whether full Level 1 or the 28-day E_c and MOR values are used, high-quality testing is required to avoid implausible estimates of PCC stiffness and strength gains over time. Such estimates can cause large errors in predicted JPCP distresses.

These conclusions are, as usual, constrained by the finite number of PCC mixes and JPCP design scenarios evaluated. They nonetheless can provide valuable practical guidance to PCC materials engineers and JPCP pavement designers.

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REFERENCES

1. ARA, Inc., ERES Consultants Division. *Guide for Mechanistic–Empirical Design of New and Rehabilitated Pavement Structures.* Final report, NCHRP Project 1-37A. Transportation Research Board of the National Academies, Washington, D.C., 2004. http://www.trb.org/mepdg/guide.htm.
2. *Mechanistic–Empirical Pavement Design Guide: A Manual of Practice.* AASHTO, Washington, D.C., 2008.
3. *Guide for Design of Pavement Structures,* 3rd ed. AASHTO, Washington, D.C., 1993.
4. *Special Report 61: The AASHO Road Test.* Highway Research Board, National Research Council, Washington, D.C., 1962, pp. 291–306.
5. Hall, K. D., and S. Beam. Estimating the Sensitivity of Design Input Variables for Rigid Pavement Analysis with a Mechanistic–Empirical Design Guide. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1919,* Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 65–73.
6. Kannekanti, V., and J. T. Harvey. Sensitivity Analysis of 2002 Design Guide Distress Prediction Models for Jointed Plain Concrete Pavement. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1947,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 91–100.
7. Buch, N., K. Chatti, S. W. Haider, and A. Manik. *Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavements.* RC-1516. Michigan State University, East Lansing, 2008.
8. Guclu, A., C. Ceylan, K. Gopalakrishnan, and S. Kim. Sensitivity Analysis of Rigid Pavement Systems Using the Mechanistic–Empirical Design Guide Software. *Journal of Transportation Engineering,* Vol. 135, No. 8, 2009, pp. 555–562.
9. McCracken, J. K., J. M. Vandenbossche, and R. E. Asbahan. Effect of the MEPDG Hierarchical Levels on the Predicted Performance of a Jointed Plain Concrete Pavement. *Proc., 9th International Conference on Concrete Pavement,* Vol. 1, San Francisco, Calif., Aug. 17–21, 2008, International Society for Concrete Pavements, 2009, pp. 153–170.
10. Mallela, J., L. Titus-Glover, M. E. Ayers, and T. P. Wilson. Characterization of Mechanical Properties and Variability of PCC Materials for Rigid Pavement Design. *Proc., 7th International Conference on Concrete Pavements,* Lake Buena Vista, Fla., International Society for Concrete Pavements, 2001.
11. *Implementing the AASHTO Mechanistic–Empirical Pavement Design Guide in Missouri. Volume I: Study Findings, Conclusions, and Recommendations.* Final report, MODOT Study RI-4-002. Applied Research Associates, Champaign, Ill., 2009.
12. Ceylan, H., S. Kim, D. J. Turner, R. O. Rasmussen, G. K. Chang, J. Grove, and K. Gopalakrishnan. *Impact of Curling, Warping, and Other Early-Age Behavior on Concrete Pavement Smoothness: Early, Frequent, and Detailed (EFD) Study, Phase II.* Final report, FHWA DTFH61-01-X-00042 (Project 16). Center for Transportation Research and Education, Iowa State University, Ames, 2007.
13. Mindess, S., J. F. Young, and D. Darwin. *Concrete,* 2nd ed. Prentice Hall, Inc., Englewood Cliffs, N.J., 2003.
14. Wood, S. L. Evaluation of the Long-Term Properties of Concrete. *Materials Journal,* Vol. 88, No. 6, Nov. 1992, pp. 630–643.
15. Vandenbossche, J. M., F. Mu, and T. R. Burnham. Comparison of Measured vs. Predicted Performance of Jointed Plain Concrete Pavements Using the Mechanistic-Empirical Pavement Design Guide. *International Journal of Pavement Engineering,* Aug. 2010.

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