ACPT

TechBrief

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Continuously Reinforced Concrete Pavement: Design Using the AASHTO Pavement ME Design Program

INTRODUCTION TO MECHANISTIC–EMPIRICAL DESIGN OF CRCP

With the completion of the mechanistic–empirical pavement design guide (AASHTO 2008) and the recent availability of the AASHTO-Ware® Pavement ME Design software (http://www.darwinme.org/MEDesign/Index.html), design of continuously reinforced concrete pavement (CRCP) has undergone significant changes. The primary purpose of this TechBrief, based on a more comprehensive Technical Summary (Roesler and Hiller 2013), is to provide engineers with the basic mechanistic–empirical design background and criteria utilized in the new ME Design software for CRCP. This document describes the main CRCP design inputs and identifies the most sensitive design inputs and features. Also, examples are included to demonstrate the use of the new software for the design of both new CRCP and CRCP overlays.

ME Design incorporates the pavement structure layers, materials, local climate, and traffic into the design process. In addition to the selection of slab thickness, ME Design includes selection of steel content and depth, concrete material constituents, support layers and properties, edge support, and construction methods and season. A state-of-the-art mechanistic–empirical design of CRCP is incorporated into the software based on many years of research conducted under NCHRP 1-37 (AASHTO 2008) and current knowledge and practices. The fundamental CRCP performance criteria incorporated in the ME Design software are development of punchouts and roughness (International Roughness Index (IRI)). Factors that have been reported to affect the punchout criterion are loss of foundation and edge support, excessive crack width and spacing, slab thickness, and high temperatures during construction.

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AASHTO PAVEMENT ME DESIGN GUIDE PRINCIPLES

With the ME Design guide, the engineer can assess how the various inputs and features selected for a particular project affect the final CRCP design. There are approximately 150 potential inputs for CRCP design, but changes to all these inputs are not necessary each time a design is performed, as many default values can be left unchanged. Based on recent studies, the following inputs are considered important for optimizing the CRCP design: slab thickness, base type, soil type, steel content, bar depth, bar size, shoulder type, local climate, construction month, concrete strength, concrete elastic and thermal properties, lane width, traffic, and reliability level considered.

The steps in the structural design process are summarized below:

1. Identify required inputs and select the desired design features.
2. Run the software. The program will predict the mean crack spacing and the age-dependent crack width. Crack spacing between 3 and 6 ft (0.9 to 1.8 m) and crack width less than 0.02 inch (0.5 mm) have resulted in successful CRCP performance.
3. The critical tensile stresses for punchout development located at the top of the slab between the wheel paths are then computed. The slab tensile stresses are calculated at various time periods to account for the interaction between the loading, changes in crack load transfer efficiency (LTE), foundation support and erosion, and slab temperature profile.
4. Incremental concrete fatigue damage is then calculated at the critical stress location for each month in the design life. The cumulative fatigue damage is related to the number of expected punchouts through a field-calibrated performance model (ARA 2003; AASHTO 2008).
5. Next, based on the limits set for the allowable number of punchouts at the end of the design life (typically between 10 and 20 per mile (6–13/km)) at a given level of reliability, the current design is accepted or further optimized by changing some of the design inputs.
6. In the final step, CRCP smoothness at any time increment is determined based on the calculated punchouts, initial CRCP roughness (IRI), and site factors such as pavement age, soil type, and climate. For most CRCP designs, the threshold value for IRI roughness failure is about 172 inch/mi (2.7 m/km) (ARA 2003; ARA 2001).
7. The program can be rerun with modified inputs until an appropriate slab thickness is found that does not exceed the user-defined CRCP performance criteria. The optimized CRCP design is the one that meets both the punchout and the smoothness criteria at the lowest life-cycle cost, which must be determined separately by the user.

AASHTO PAVEMENT ME DESIGN USER INPUTS

The ME Design program uses a hierarchical approach (Levels 1 through 3) to define the level of preciseness that the user has available for input parameters as follows:

1. Level 1 indicates very specific testing or data gathering.
2. Level 2 indicates the use of less specific input characterization.
3. Level 3 indicates the use of global (regional) default values.

This hierarchical approach is only available for certain inputs in the design of CRCP, such as traffic or material characterization. Design of a CRCP project normally includes inputs from all three levels. Regardless of the level of inputs entered into the program, the calculation process to predict CRCP performance is the same.

PAVEMENT TYPE SELECTION AND PORTLAND CEMENT CONCRETE MATERIAL PROPERTIES

For CRCP design, the user should select the appropriate "Design Type" (such as new pavement or overlay). The program will automatically select a portland cement concrete (PCC) surface layer with default properties. The PCC thickness and material properties can be modified to be project-specific. The mixture design parameters include the following:

1. Concrete thermal properties.
2. Concrete water-to-cementitious materials ratio (w/cm).
3. Cementitious content.
4. Concrete strength.
5. Concrete modulus of elasticity.

Concrete properties such as the PCC set temperature and the ultimate shrinkage from the concrete mixture can either be calculated internally by the software from the mixture design parameters or be entered directly by the user if values are known. Other sensitive input factors such as the concrete surface shortwave absorptivity and permanent curl/warp effective temperature difference should only be changed if users have site-specific input information verified and understand that such a change may require a recalibration of the punchout model.

SELECTING SUPPORT LAYERS FOR DESIGN

The user must select the various layers to be represented in the pavement cross section along with the individual layer input parameters. Beneath the PCC layer in a CRCP structure, the user may add up to six different layer types: PCC, flexible (asphalt concrete), sandwiched granular, nonstabilized base, subgrade, or bedrock. Within each of these six general layer categories, several material options exist. Each of these specific layer options has default material property values that can be modified by the user if more accurate information exists for a given project. The ME Design software graphically displays the selected pavement section to confirm the user's choices.

SELECTING REINFORCEMENT AND OTHER PAVEMENT PARAMETERS

The user must specify several other critical design input parameters in one of the design input menus. In this menu, the user specifies the following reinforcement properties: percentage of steel in the cross section, bar diameter, and steel cover depth.

The user must also specify the shoulder type, base/slab friction level, and whether the crack spacing will be predicted using the program's algorithm or will be inputted directly.

TRAFFIC

One significant improvement in the ME Design approach is that the traffic is no longer characterized in terms of an equivalent single-axle load (ESAL). Instead, axle load spectra information is utilized in the fatigue analysis by defining the traffic in terms of the Federal Highway Administration's (FHWA) vehicle class distributions, hourly and monthly distributions, axle type configurations, and other traffic factors. The axle load spectra input requires defining the expected axle load distribution for single, tandem, tridem, and quad axles for a given month in addition to the FHWA vehicle classification type. To characterize the volume, the total amount of truck traffic is input as average annual daily truck traffic (AADTT) including the expected lane and directional distribution factor for the facility. Additionally, the ME Design program also allows for site-specific lateral wander characteristics to be directly considered.

CLIMATE

A key improvement to the CRCP design process is accounting for site-specific climate. The ME Design program models account for daily and seasonal variations in temperature and moisture profiles in the CRCP and soil layer, respectively, through site-specific factors such as percent sunshine, air temperature, precipitation, wind, and water table depth. There are several hundred weather stations across North America from which the user can select the nearest one to the project site or create a "virtual weather station" by allowing the program to interpolate nearby weather station data to the user's specific project site.

CRCP FAILURE ANALYSIS AND DESIGN THICKNESS OPTIMIZATION

For CRCP, the software predicts two performance parameters that can be used for assessing the validity of the CRCP design at a given level of reliability:

1. IRI magnitude.
2. Number of CRCP punchouts per mile.

Three CRCP characteristics directly affect the performance prediction of punchouts and IRI: crack spacing, crack width, and crack LTE. To achieve and maintain good performance, crack spacing should generally be within 3 to 6 ft (0.9 to 1.8 m), crack width should remain less than 0.02 inches (0.5 mm), and crack LTE should be greater than 80 to 90 percent. The user can specify the initial IRI level, which is related to an agency's construction smoothness specification, as well as the terminal IRI level and the number of punchouts that define failure for a given project. The ME Design program also utilizes a design reliability level to account for uncertainty in the inputs, model predictions, as-constructed pavement materials, and construction process. The IRI and punchout thresholds as well as the reliability level selected are related to the roadway's functional classification.

The outputs of the program can be opened in Microsoft® Excel® or in Acrobat® Reader® to view the predicted distress levels in the CRCP, as shown in figure 1. The output displays the IRI and punchout rates over time for both 50-percent reliability (mean prediction) and at the specified reliability level (e.g., 90 percent in this case). If the predicted IRI and punchout extent at the specified reliability level exceed the user-specified limits at the end of the design life, the user needs to adjust the input parameters and reanalyze the CRCP section until an acceptable section is determined.

AASHTO PAVEMENT ME DESIGN INPUT SENSITIVITY

Based on the findings of a number of research studies, the most sensitive design inputs have been found to be slab thickness, climate, shoulder type, concrete strength, base properties (base type/erodibility/friction), steel content and depth, and construction month. Other sensitive variables include construction month, surface absorptivity, coefficient of thermal expansion (CTE), and built-in curling.

The ME Design program was used in the example that follows to demonstrate the sensitivity of the CRCP design to changes in key input parameters such as PCC thickness, concrete CTE, steel percentage, depth to steel, shoulder type, base type, and construction month. The impact of climate was also demonstrated to show how the ME Design program incorporates the effect of site-specific weather patterns on the CRCP predicted distresses. For these analyses, the input assumptions listed below represent the standard case, which meet the IRI (172 inch/mi (2.7 m/km) and punchout (10/mi (6/km)) criteria set at 90-percent reliability. For traffic and material

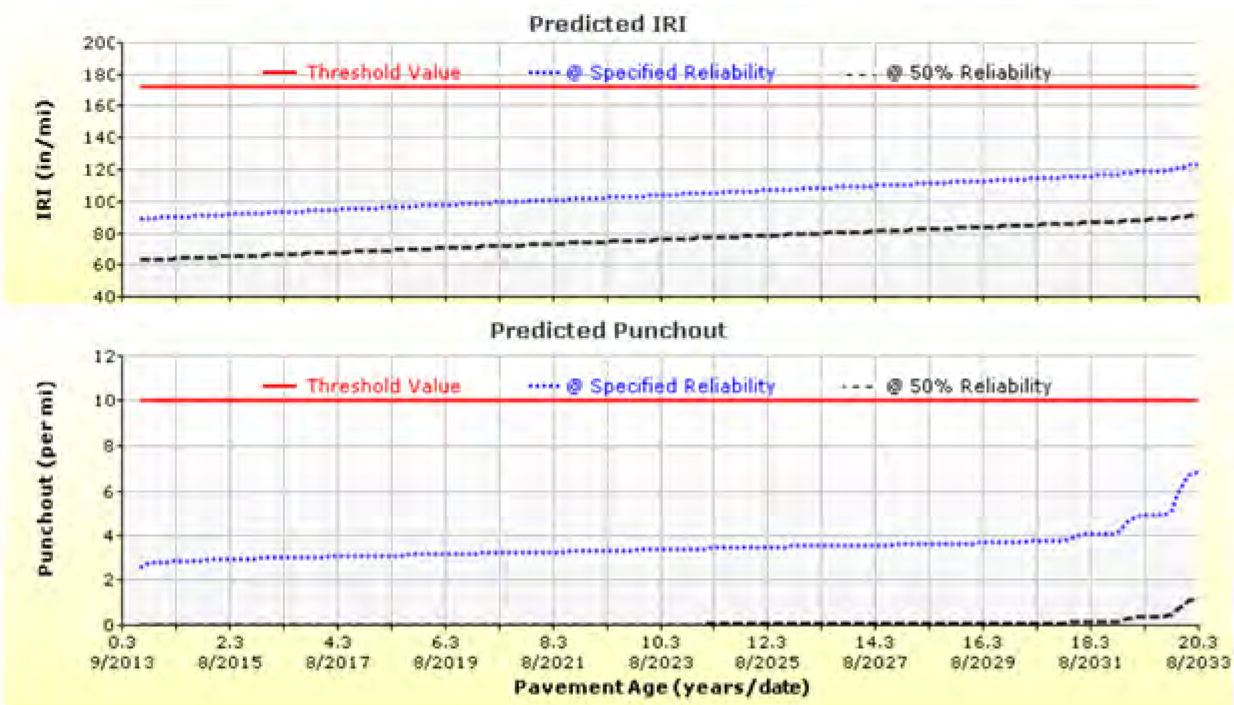

FIGURE 1. Example of IRI and punchout predictions for 50-percent and specified reliability over time.

property inputs in the ME Design, Level 3 default values were used except where noted.

Example: 20-Year Analysis Period for a High-Volume Highway in Chicago, Illinois

- AADTT = 20,000 (high truck traffic):
  - Approximately 103 million ESALs for assumed load spectra/vehicle class distribution.
- CRCP cross section:
  - 11.25-inch (286-mm) PCC layer.
  - 4-inch (102-mm) asphalt-treated base layer.
  - 8-inch (203-mm) lime-stabilized soil layer.
  - A-7-6 subgrade with resilient modulus of 13,000 lbf/in^2 (89.63 MPa).
- Asphalt shoulder.
- PCC modulus of rupture (28-day) = 650 lbf/in^2 (4,482 kPa).
- Concrete CTE = 5.5 x 10^{-6}/°F (9.9x10^{-6}/°C).
- PCC w/cm = 0.42.
- Base/slab friction coefficient = 7.50.
- Construction month = June.
- Reinforcing steel content = 0.7 percent of cross-sectional area at 3.5-inch (89-mm) depth.

The sensitivity analysis results for this example are summarized below.

PCC Thickness Variation

One of the most sensitive parameters affecting CRCP performance is slab thickness. The impact of slab thickness on punchout development and smoothness is shown in figure 2. For this analysis, at the end of the design life, the punchout rate was kept below the threshold of 10/mi (6.2/km) and the IRI rate below the threshold of 172 inch/mi (2.7 m/km) to be acceptable. Due to the sensitivity of tensile bending stresses to thickness changes, small increases in thickness (from 11.25 inches to 11.5 inches (from 286 mm to 292 mm)) can reduce the number of punchouts significantly (from 8.4 to 4.4 per mile (from 5.2 to 2.8/km)).

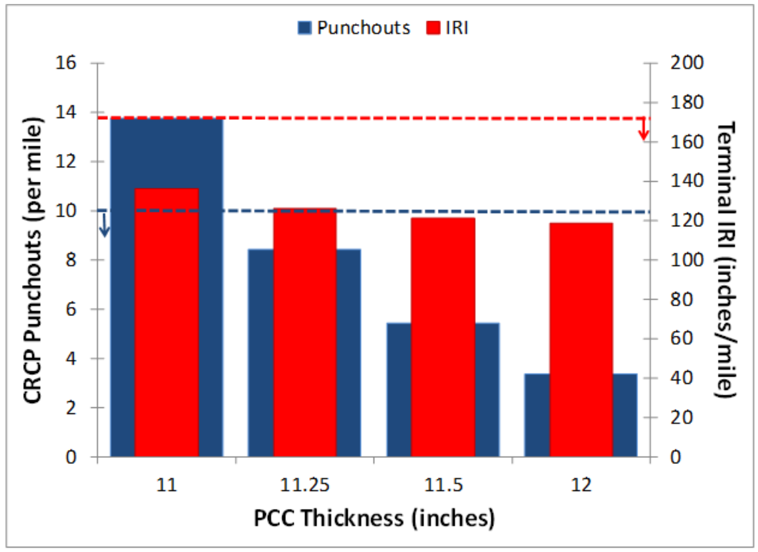

FIGURE 2. Impact of slab thickness on IRI and punchouts.

Reinforcing Steel

The impact of steel reinforcement is shown in figure 3. For this analysis, a reduction in steel content from 0.7 percent to 0.6 percent results in a significant increase in punchouts, from 8.4 to more than 32 per mile (from 5.2 to 20/km), resulting in an inadequately designed CRCP section. The figure also indicates how an increase in the amount of steel decreases the spacing between the cracks, leading to tighter cracks widths and more sustained load transfer between slabs. Since the IRI is related to the number of punchouts, the decrease in IRI is directly related to the reduction in punchouts with increase in steel content.

Another option for designers of CRCP that may be more cost effective than additional steel content is to modify the location of the steel within the PCC. As shown in figure 4, there is a significant increase in punchouts and terminal IRI with an increased depth of steel from the slab surface. Reinforcing steel at 0.7-percent content placed at the PCC slab mid-depth (5.5 inch (140 mm)) resulted in a 150-percent increase in predicted punchouts.

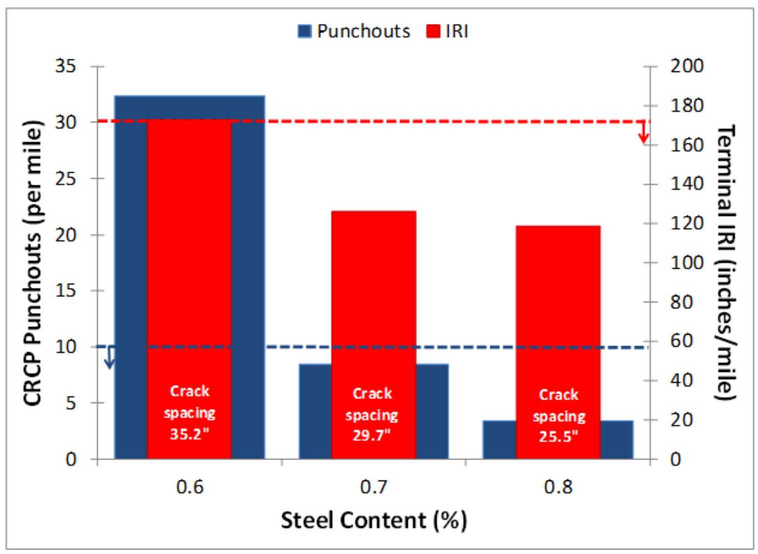

FIGURE 3. Impact of steel content on crack spacing, IRI, and punchouts.

Concrete Coefficient of Thermal Expansion

The PCC CTE is a parameter with a significant effect on the performance of CRCP in the ME Design program. The concrete CTE is highly influenced by the coarse aggregate type and its associated thermal expansion/contraction rates, shown in table 1. The concrete CTE can be measured with the recently adopted AASHTO T336 procedure (2009).

Figure 5 shows how changing the coarse aggregate type having an average CTE value (5.5×10^{-6}/°F (9.9×10^{-6}/°C)) to one having a

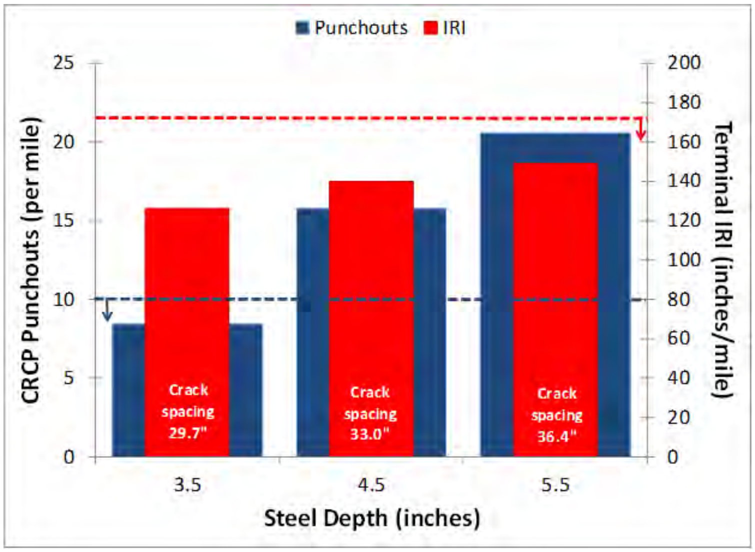

FIGURE 4. Impact of steel depth on crack spacing, IRI, and punchouts.

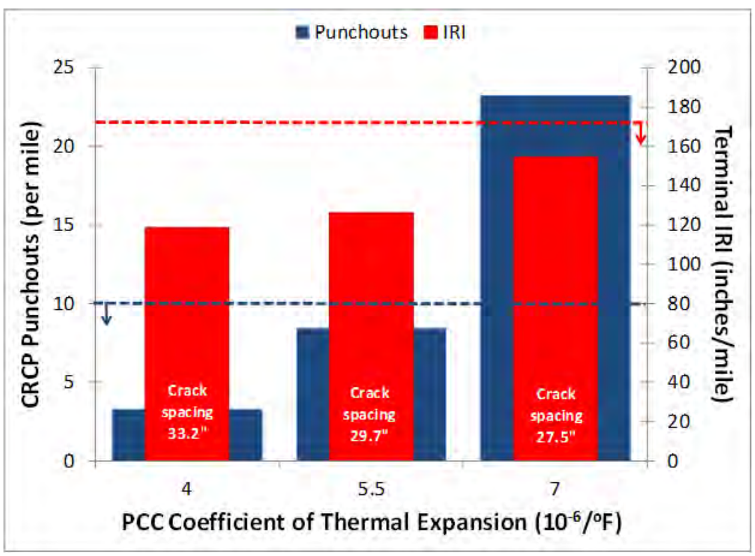

FIGURE 5. Impact of CTE on crack spacing, IRI, and punchouts.

low-expansion coarse aggregate type (CTE = 4 x 10^{-6}/°F (7.2 x 10^{-6}/°C)) can reduce punchouts and maintain a high ride quality on the CRCP. The concrete CTE is incorporated in the models utilized in the ME Design program. As the concrete CTE is lowered for a given crack spacing, the crack width is reduced, thereby leading to increased sustained load transfer across these cracks. Increasing the steel content in the slab can be used as a potential strategy to offset higher concrete CTE without increasing the slab thickness.

Other PCC material properties that affect the predicted performance of CRCP include the concrete surface absorptivity, built-in curling, ultimate shrinkage level, and 28-day modulus of rupture or other material strength properties (depending on hierarchical input level selected).

TABLE 1. Typical Average CTE for Common Aggregate Types (adapted from Rao et al. 2012, table 25, p. 8)

Aggregate Type	Average CTE (x 10^{-6}/°F)
Basalt	4.86
Chert	6.90
Diabase	5.13
Dolomite	5.79
Gabbro	5.28
Granite	5.71
Limestone	5.25
Quartzite	6.18
Andesite	5.33
Sandstone	6.33

Shoulder Type and Lane Width

Another design factor that users of the ME Design program can utilize is the shoulder type. A concrete shoulder, whether monolithically paved or paved separately, can be used to significantly reduce, relative to an asphalt or gravel shoulder, the slab bending stresses and deflections and subsequent punchouts and IRI, as shown in figure 6. While the ME Design software does not directly consider widened lanes in its

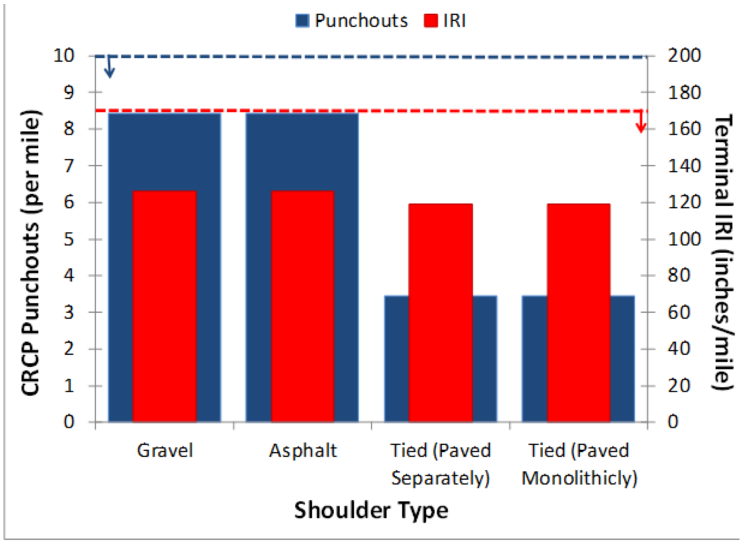

FIGURE 6. Impact of shoulder type on IRI and punchouts.

analysis of CRCP, experience has shown that lane widths up to 13 ft (4 m) have resulted in good long-term performance in Texas, Oregon, and Illinois and may be considered for a design.

Base Type/Friction

The base type selected for support in a CRCP is another important factor impacting projected performance both in the development of cracks and tight crack widths as well as resisting foundation layer erosion from repeated loading. Table 2 shows typical friction coefficients between the PCC and base layers for a range of base types. The ME Design program automatically assigns this friction coefficient depending on the base type selected. Users of the program can alter the friction coefficient with the recommend ranges in the table. The base type can have a pronounced impact on the computed crack spacing, crack width, crack LTE, and, ultimately, performance of the CRCP section.

In addition, the use of a stabilized material as a base can assist in reducing the bending stresses in the PCC and the creation of erosion-induced voids, thereby increasing the fatigue life of the CRCP section. Figure 7 shows that stabilized base materials, such as in a cement-treated base or asphalt-treated base, significantly reduce the projected number of punchouts in comparison to a granular base material, as the resulting crack spacing and widths are significantly affected. This reduction in punchouts also leads to a significant improvement in ride quality.

TABLE 2. Friction Coefficient Ranges for Typical Subbase and Base Types (http://www.darwinme.org/MEDesign/Index.html (Help Menu))

	Friction Coefficient		
Subbase/Base Type	**Low**	**Mean**	**High**
Fine-grained soil	0.5	1.1	2
Sand**	0.5	0.8	1
Aggregate	0.5	2.5	4.0
Lime-stabilized clay**	3	4.1	5.3
Asphalt-treated base	2.5	8.9	15
Cement-treated base	3.5	8.9	13
Soil cement	6.0	7.9**	23
Lean cement base	1.0	6.6**	20
Lean cement base not cured	>36 (higher than lean cement base cured)		

** Note that these friction coefficients are only used in the prediction of crack spacing for CRCP. The computation of damage for punchout prediction assumes that there is no friction between the CRCP slab and the base course.

Construction Month

The construction month has been shown to impact the temperature development at early ages and the zero-stress temperature in CRCP (Schindler and McCullough 2002). Therefore, it is a user input variable in the ME Design program. The construction temperature affects the concrete set temperature, which subsequently

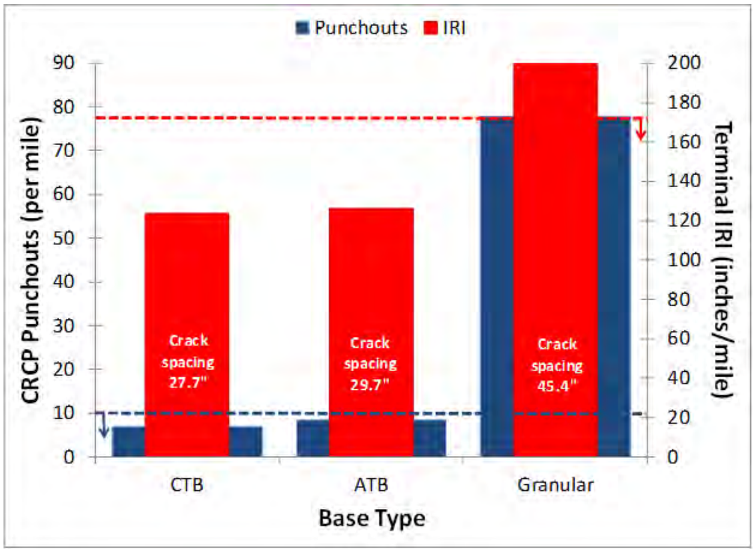

FIGURE 7. Impact of base type on IRI and punchouts.

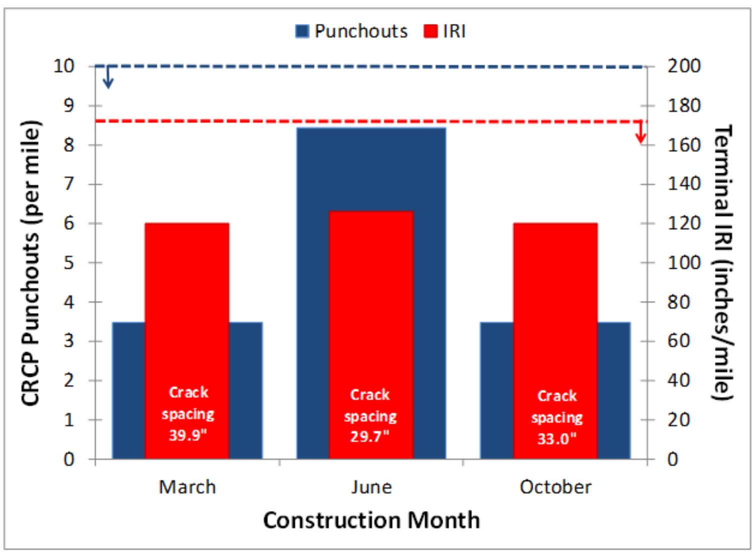

FIGURE 8. Impact of construction month on mean crack spacings, IRI, and punchouts.

influences the mean CRCP crack spacing and widths. In the example shown in the figure, the CRCPs constructed in both March and October are under cooler temperatures relative to June. These cooler months of construction produce smaller crack widths, which promote a high load transfer between adjacent CRCP panels, reducing bending stresses and deflections from axle loads and achieving a lower number of predicted punchouts at the end of the design life. Since the CRCP design is sensitive to this input parameter, the pavement engineer needs either to verify that this design assumption is controlled in the construction process or to utilize a conservative summer month assumption in the design. It should be noted that construction may spread out over several months or several years. Therefore the most critical month should be used in the design.

Climate

It is well established that local climate conditions can affect the design and performance of CRCP. The Pavement ME Design program allows selection of site-specific weather data for a project. For the sensitivity analysis, the default location of Chicago was changed to Norfolk (Virginia), Austin (Texas), and Sacramento (California). The local climate primarily influences the zero-stress temperature during construction, mean crack spacing and width, and temperature profiles in the CRCP throughout the design life. In this case, the CRCP section that passed the punchout threshold for Chicago and Sacramento failed with respect to punchout development in Norfolk and Austin, while all locations satisfied the IRI criteria at 90-percent reliability. Some options for producing a passing design for the Norfolk and Austin climates include increasing slab thickness, increasing steel content, and adding a tied concrete shoulder.

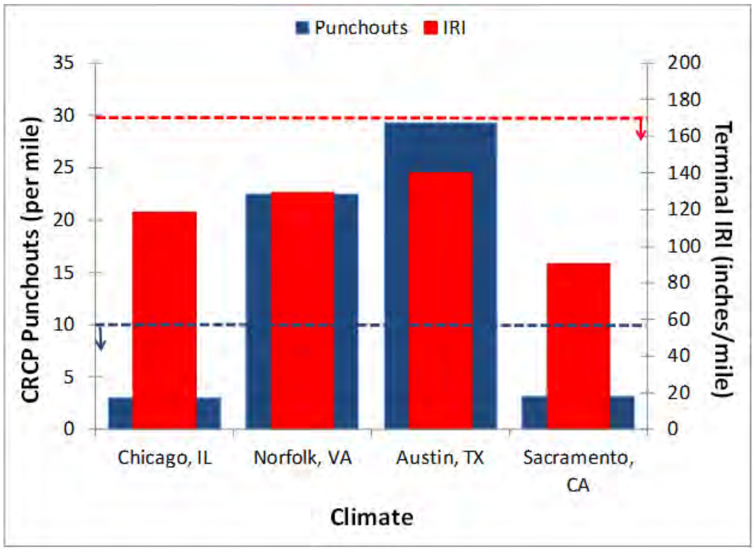

FIGURE 9. Impact of climate on IRI and punchouts.

Refining the ME Design Procedure

As the mechanistic–empirical design procedure for CRCP continues to evolve, refinements in the failure mechanisms and data inputs likely will be made. Such refinements may address current observations and practices from the Texas Department of Transportation (TxDOT), as follows:

- CRCPs in different States may have somewhat different performance than is currently predicted by the ME Design software.
- The effect of steel placement depth needs further validation. TxDOT has experienced excellent performance with longitudinal steel placed at mid-depth.
- Concrete CTE has a significant effect on crack spacing development; however, it is not clear that adjusting slab thickness based on concrete CTE is an effective approach. TxDOT accounts for the CTE effect in the steel design, not the slab thickness design.

SUMMARY

The ME Design program is a significant advancement for the design of economical, long-life CRCP under a variety of climate conditions, traffic loadings, and local materials. This program allows the structural design of new CRCP and unbonded CRCP overlays to be compared with other pavement-type alternatives through a mechanistic–empirical design process. The mechanistic models in the program initially predict the mean crack spacing, crack width, and LTE, which are then used to predict the performance life of the CRCP under repeated loading and climatic effects. The two failure criteria included in the Pavement ME Design program for CRCP are the number of punchouts per mile and IRI. While a large number of variables can be modified in this program, the most sensitive design variables for CRCP have been found to be slab thickness, climate, shoulder type, concrete strength, base type, steel content and position, and construction month. While the ME Design program has been calibrated to empirical observations using a national database, local calibration of these models should be considered once sufficient data are available to improve the CRCP performance prediction models. Using mechanistic models and empirical observations of CRCP behavior, the Pavement ME Design method gives pavement engineers a state-of-the-art, rational approach to designing CRCP in locations across North America.

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