# Continuous Reinforced Concrete Pavement:

# Design Using the AASHTOWare Pavement

# ME Design Procedure

PUBLICATION NO. FHWA-HIF-13-025 APRIL 2013

U.S.Department of Transportation
**Federal Highway Administration**
**Office of Asset Management,**
**Pavement, and Construction**
**1200 New Jersey Avenue, SE**
**Washington, DC 20590**

**Technical Report Documentation Page**

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| FHWA-HIF-13-025 | | |

| 4. Title and Subtitle | 5. Report Date |
|---|---|
| Continuously Reinforced Concrete Pavement:<br>Design Using the AASHTOWare Pavement ME<br>Design Procedure | April 2013 |
| | 6. Performing Organization Code |
| 7. Author(s) | 8. Performing Organization Report No. |
| Jeffery Roesler, Ph.D., P.E., and Jacob E. Hiller, Ph.D. | |
| 9. Performing Organization Name and Address | 10. Work Unit No. (TRAIS) |
| Concrete Reinforcing Steel Institute<br>933 North Plum Grove Road<br>Schaumburg, IL 60173-4758 | 11. Contract or Grant No.<br>DTFH61-07-H00033 |
| 12. Sponsoring Agency Name and Address | 13. Type of Report and Period Covered |
| Federal Highway Administration<br>Office of Asset Management, Pavement, and Construction<br>1200 New Jersey Avenue, SE<br>Washington DC 20590 | Technical Summary,<br>July 2012–March 2013 |
| | 14. Sponsoring Agency Code<br>HIPT (HIAP-20) |

15. Supplementary Notes

Samuel S. Tyson, P.E., Concrete Pavement Engineer, Agreement Officer's Technical Representative; E-mail: sam.tyson@dot.gov; Phone: 202-366-1326.

16. Abstract

With the completion of the *Mechanistic–Empirical Pavement Design Guide* (MEPDG) and the recent designation of the MEPDG software as "AASHTOWare® Pavement ME Design," the standard for CRCP design has undergone significant changes from the 1993 AASHTO Pavement Design Guide. CRCP performance problems observed in the past, such as material durability, base erosion, steel placement and content, and construction methods have been addressed, and the improved pavement design procedure reflects modern construction practices, pavement layer materials, specifications, and best concrete pavement engineering practices.

The primary purpose of this technical summary is to provide engineers with the basic mechanistic–empirical design background and criteria utilized in the AASHTO Pavement ME Design software for CRCP. Secondly, this technical summary describes the key CRCP design inputs to assist the pavement engineer through the CRCP design process with the AASHTO Pavement ME Design software, including identifying the most sensitive design inputs and features. Finally, example problems are included in this document to demonstrate the robustness of the new design software for both new CRCP and CRCP overlays in different climatic zones. It is expected that as the mechanistic–empirical design procedure for CRCP continues to evolve, refinements in the failure mechanisms and data inputs likely will be made, providing even greater reliability in the design process.

| 17. Key Words | 18. Distribution Statement |
|---|---|
| AASHTO Pavement ME Design, continuously reinforced concrete pavement, concrete pavement design, mechanistic-empirical pavement design | No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 34 | |

**Form DOT F 1700.7** (8-72) Reproduction of completed page authorized

| SI* (MODERN METRIC) CONVERSION FACTORS | | | | |
|---|---|---|---|---|
| **APPROXIMATE CONVERSIONS TO SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oF$ | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | $^oC$ |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |
| **APPROXIMATE CONVERSIONS FROM SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oC$ | Celsius | 1.8C+32 | Fahrenheit | $^oF$ |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

## TABLE OF CONTENTS

## LIST OF FIGURES



## LIST OF TABLES

# Continuously Reinforced Concrete Pavement: Design Using the AASHTOWare Pavement ME Design Procedure

## Technical Summary

## INTRODUCTION TO MECHANISTIC–EMPIRICAL DESIGN OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENT

With the completion of the *Mechanistic–Empirical Pavement Design Guide* (MEPDG; AASHTO 2008) and recent designation of the software as "AASHTOWare® Pavement ME Design" (http://www.darwinme.org/MEDesign/Index.html), the standard for design of continuously reinforced concrete pavement (CRCP) has undergone significant changes from that presented in the 1993 AASHTO Pavement Design Guide. CRCP performance problems observed in the past, such as material durability (LaCoursiere et al. 1978; Gharaibeh et al. 1999), base erosion (LaCoursiere et al. 1978; Zollinger and Barenberg 1990), steel placement and content (LaCoursiere et al. 1978; Dhamrait et al. 1977), and construction methods (Rasmussen et al. 2009), have been resolved, and thus this improved design procedure reflects modern construction practices, pavement layer materials, specifications, and best concrete pavement engineering practices. Almost all CRCPs have provided road users with performance levels exceeding their original design assumptions, as was summarized in a recent publication (Plei and Tayabji 2012).

The primary purpose of this technical summary is to provide engineers with the basic mechanistic-empirical (ME) design background and criteria utilized in the AASHTOWare Pavement ME Design software (hereinafter Pavement ME Design) for CRCP. Secondly, to assist the pavement engineer with the CRCP design process using the AASHTO Pavement ME Design software, this technical summary describes the main CRCP design inputs and identifies the most sensitive design inputs and features. Finally, example problems are included to demonstrate the robustness of the new design software for both new CRCP and CRCP overlays in different climatic zones.

### ME Design Background

The design of CRCP has evolved over the years from empirical design procedures based on field observations and performance results from field test sections (Burke and Dhamrait 1968; McCullough et al. 1975; Tayabji et al. 1995; Gharaibeh and Darter 2003; Zollinger et al. 1999; Tayabji et al. 1998a, 1998b; Smith et al. 1998; Kohler and Roesler 2006). These field observations combined with engineering principles have been used in an ME framework to explain past performance as well as to design CRCP to meet future objectives. AASHTOWare Pavement ME Design incorporates the pavement structure layers, materials, local climate, and traffic into the final design process. In addition to slab thickness, the software allows selection of steel content and depth, concrete material constituents, support layers and properties, edge support, and construction methods and season.

The need to understand and utilize the AASHTOWare Pavement ME Design process is driven by a combination of factors that includes continual increases in truck traffic, a desire for longer life pavements, changes in construction materials, a focus on pavement sustainability and maintenance, and the need for a reliable design procedure for new CRCP and CRCP overlays. Clearly, an ME design method for CRCP is essential for providing solutions for design problems to be encountered over the next few decades. A state-of-the-art ME design of CRCP is incorporated into the AASHTOWare Pavement ME Design software based on many years of research conducted under National Cooperative Highway Research Program (NCHRP) project 1-37 (ARA 2003; AASHTO 2008; Rao and Darter 2013) and current knowledge and practices. The fundamental CRCP performance criteria are development of punchouts and roughness (International Roughness Index (IRI)). Factors having been shown to affect these design criteria are loss of foundation and edge support (Dhamrait and Schwartz 1978; Zollinger and Barenberg 1990; Jung et al. 2010), excessive crack width and spacing (LaCoursiere et al. 1978), slab thickness, and high temperatures during construction (Schindler and McCullough 2002).

When designed and built correctly, CRCPs offer long life, exceptional smoothness, and minimal maintenance (Gharaibeh et al. 1999; Gharaibeh and Darter 2003; FHWA 2012). Additionally, CRCPs have a high end-of-life salvage value, i.e., they easily accommodate either an unbonded concrete overlay or an asphalt overlay.

### CRCP Main Design Inputs

With the AASHTO Pavement ME Design guide, the engineer has significant control on 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 completed as many default values can be left unchanged. Recently, many research efforts have focused on evaluating the sensitivity of MEPDG input parameters for jointed plain concrete pavements (e.g., Hall and Beam 2005; Kannekanti and Harvey 2006), but only a few have looked into the sensitivity of the CRCP design to changes in the input parameters (Freeman et al. 2005; Won 2009; Bordelon et al. 2009; Schwartz et al. 2011; Vandenbossche et al. 2012; Ley et al. 2013). Based on these studies, the following inputs are recommended to be reviewed and possibly changed by the CRCP design engineer: slab thickness; base type; soil type; steel content, depth, and bar size; shoulder type; climate location; construction month; concrete strength; concrete elastic and thermal properties; lane width; traffic; and reliability.

## AASHTO PAVEMENT ME DESIGN GUIDE PRINCIPLES

The AASHTO Pavement ME Design guide has been developed to represent the state of the art in rigid pavement stress calculations, fatigue damage analysis, and performance prediction. A basic overview of the AASHTO Pavement ME Design Guide’s internal process is given next to assist the pavement engineer in understanding how input changes may affect the CRCP design.

The first step in the design process is gathering the required inputs and selecting the desired design features. Once these are completed, the program first predicts the mean crack spacing that eventually will develop as a result of the steel restraint, concrete properties, base friction, and local climate condition. An age-dependent prediction of crack width is subsequently calculated from the crack spacing, steel and concrete properties, base friction, and temperature conditions. The crack spacing and width prediction are critical components of the design process since research and performance studies have shown generally that crack spacing between 3 and 6 ft (0.9 and 1.8 m) and crack width less than 0.02 inch (0.5 mm) have resulted in successful CRCP performance. Once the predicted crack spacing and width are established, the process of modeling the development of a classic punchout can begin.

Figure 1 schematically shows the key factors that contribute to classic punchouts in CRCP, which are directly linked to repeated traffic loading (fatigue). The critical tensile stresses for punchout development are located at the top of the slab between the wheels. 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. Incremental concrete fatigue damage is then calculated at the critical stress location for each month in the design life. Next, the cumulative fatigue damage is related to the number of expected punchouts through a field-calibrated performance model (ARA 2003; AASHTO 2008). In the final structural design of CRCP, the pavement engineer limits the allowable number of punchouts at the end of the design life to an acceptable level (typically between 10 and 20 per mile (6 to 13 per kilometer)) at a given level of reliability. Lastly, 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 trigger value for IRI roughness failure is 172 inch/mi (2.7 m/km). A detailed description of the aforementioned algorithms and performance prediction models can be found in *Mechanistic-Empirical Pavement Design Guide, Interim Edition: A Manual of Practice* (AASHTO 2008) and Appendices LL and PP of the NCRHP 1-37 project (ARA 2003, 2001).

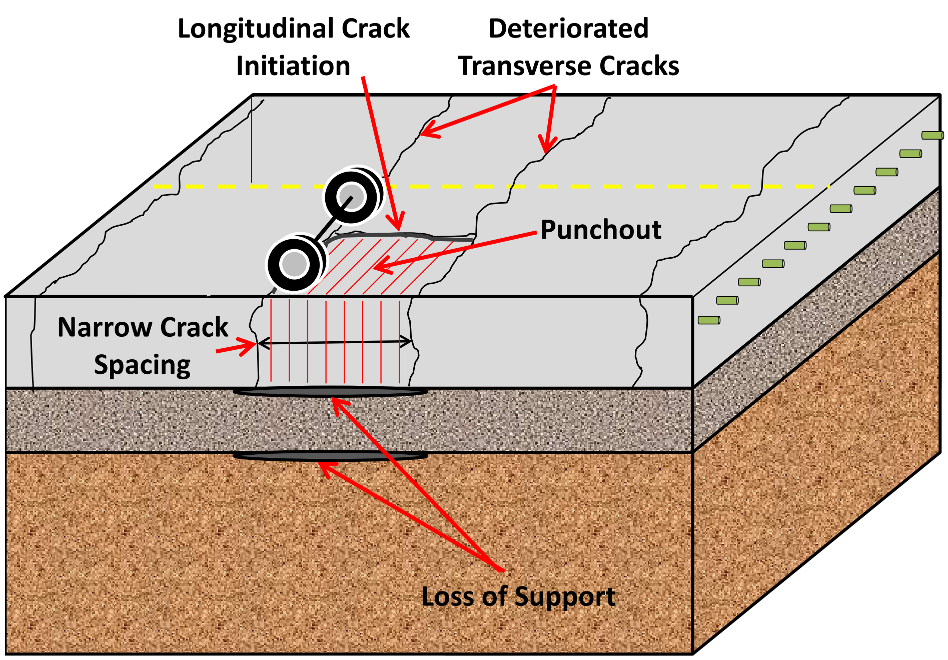


**Figure 1. Schematic of CRCP punchout mechanism.**

## AASHTOWARE PAVEMENT ME DESIGN USER INPUTS

The Pavement ME Design program utilizes the user-defined inputs to conduct a CRCP mechanistic analysis to predict the expected incremental distress levels based on a national calibration. As the Pavement ME Design program represents a fundamental change in design philosophies in CRCP design, it requires much greater knowledge of design parameters affecting design including layer materials, climate, and traffic characterization. For users new to the program, the following section outlines a basic overview of the program's format and design parameters. Figure 2 shows the main input screen of the Pavement ME Design program. General input categories are viewed in the left of the screen while specific input parameters are viewed and entered in the middle of the screen.

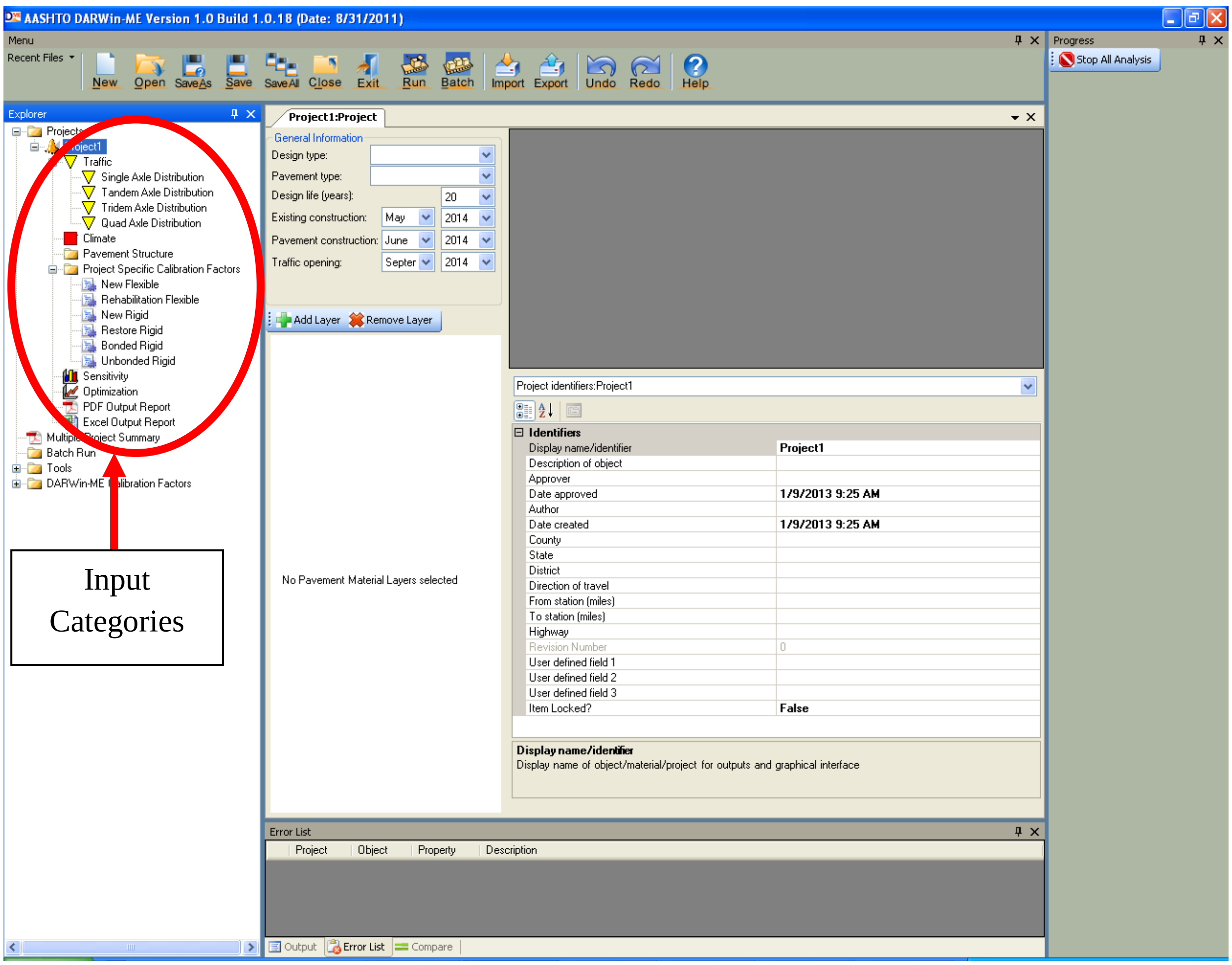


**Figure 2. Initial input screen for Pavement ME Design software.**

The Pavement 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. Level 1 indicates very specific testing or data gathering, while Levels 2 and 3 indicate the use of less-specific input characterization and use of default values, respectively. 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 would normally include inputs from all three levels. Regardless of the level of inputs entered into the Pavement ME Design program, the calculation process to predict CRCP performance is unchanged.

### Pavement Type Selection and Portland Cement Concrete Material Properties

For CRCP design, the user should select the appropriate “Design Type” (such as new pavement, overlay, restoration, or rehabilitation) and “Pavement Type” (JPCP, CRCP, or flexible) for the project, as shown in figure 3. When “continuously reinforced concrete pavement” is selected for the pavement type, the program will automatically select a portland cement concrete (PCC) surface layer with default properties as shown in figure 3. Graphically, the program will also show the concrete layer under a wheel load near the middle of the program screen. From this menu, the PCC thickness and material properties can be modified to be project-specific. The mixture design parameters include concrete thermal properties, water-to-cementitious materials ratio, cementitious content, strength, and elastic modulus. PCC material properties such as the PCC set temperature and the ultimate shrinkage from the concrete mixture can either be calculated internally from the mixture design parameters or entered directly by the user if values are known.

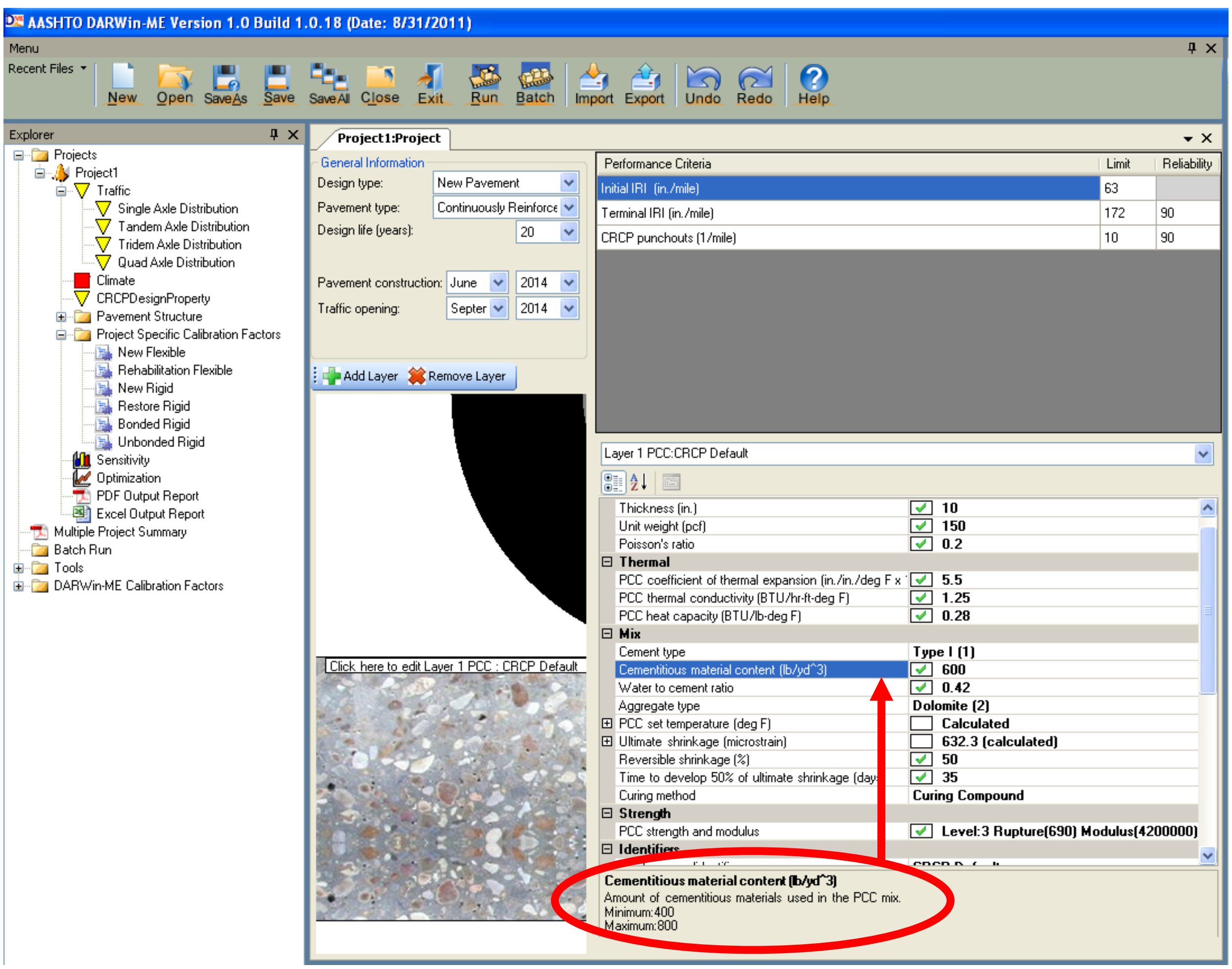


**Figure 3. Pavement type selection, CRCP performance criteria, and PCC material properties in the AASHTO Pavement ME Design program.**

While inputs to the Pavement ME Design program are substantial and new to many users, the program has been designed to give users help in selecting values. As shown in figure 3 for the input "cementitious material content," when the user clicks on the variable name, the variable will be highlighted and typical ranges will be highlighted at the bottom of the program screen (see red oval and arrow in figure 3). The program will allow values beyond these typical ranges for many variables when possible, but will give the user a warning to alert an out-of-range input.

For more specific guidance in running this program, the user should use the extensive Help menu developed for the Pavement ME Design software.

**Selecting Support Layers for Design**

Before the mechanistic analysis is begun, the user must select the various layers to be represented in the pavement cross section along with the individual layer input parameters. Using the "Add Layer" button near the center of the screen (see figure 3), the user can build the proposed pavement structure to be analyzed. Beneath the PCC layer in a CRCP structure, the user may add six different general layer types including PCC, flexible (asphalt concrete (AC)), sandwiched granular, nonstabilized base, subgrade, or bedrock. Within each of these six general layer categories, several material options exist, as shown in the example in figure 4. 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. Guidance is provided on the selection of material values using typical ranges for a chosen layer and material type. When the user has built the trial section to be analyzed, the Pavement ME Design software graphically displays the pavement section to confirm the user's choices.

**CRCP Design Properties**

After the proposed CRCP cross section has been input with accompanying material properties, the user must specify several critical design input parameters to the "CRCP Design Property" category in the software's input categories (on the left in figure 3). In the CRCP Design Property menu, shown in figure 5, the user specifies the reinforcement properties through the percentage of steel in cross section, bar diameter, and steel cover depth. Other sensitive input factors such as the PCC 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 re-calibration of the punchout model. 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 directly input by the user.

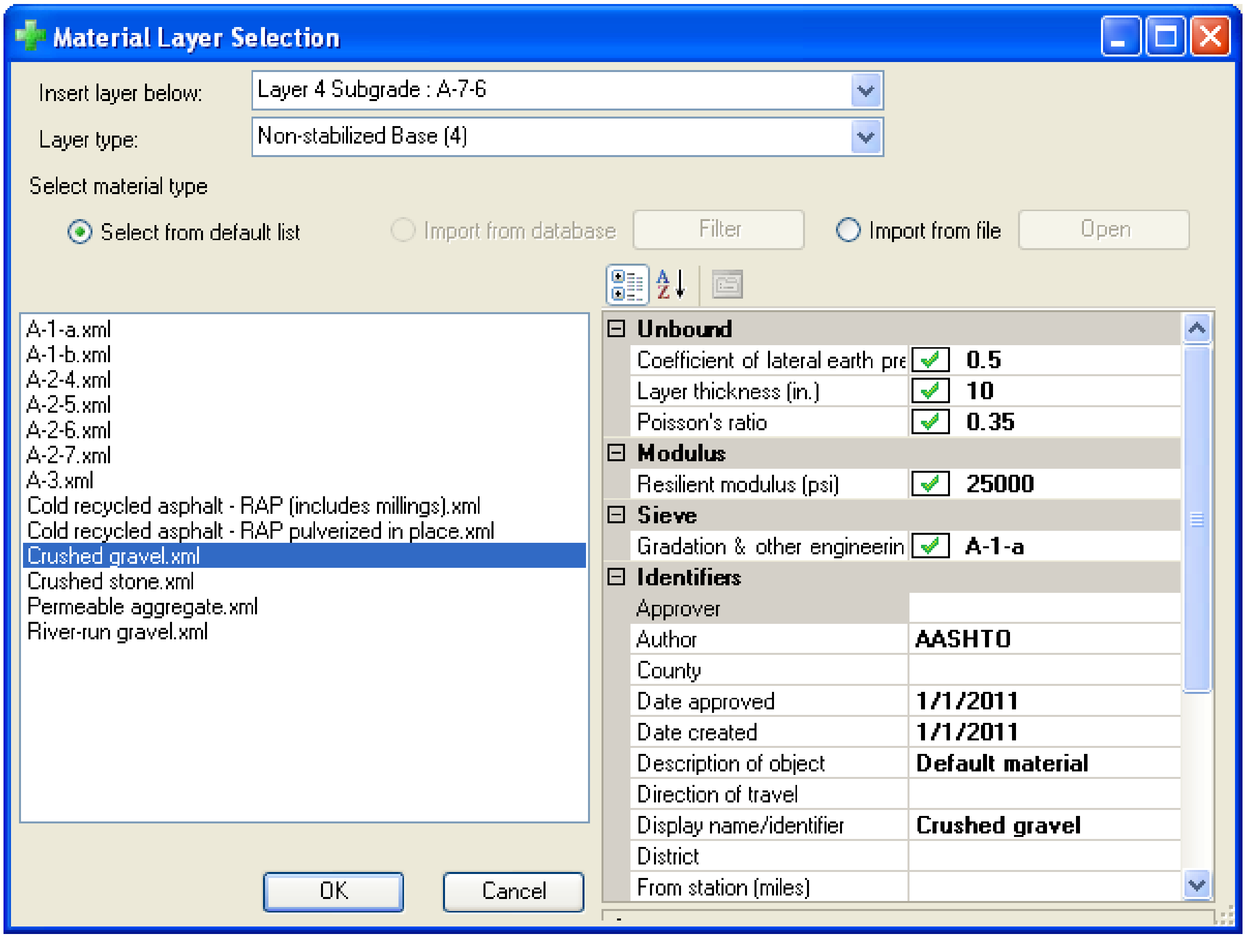


**Figure 4. Selecting support layer types and properties in AASHTO Pavement ME Design.**

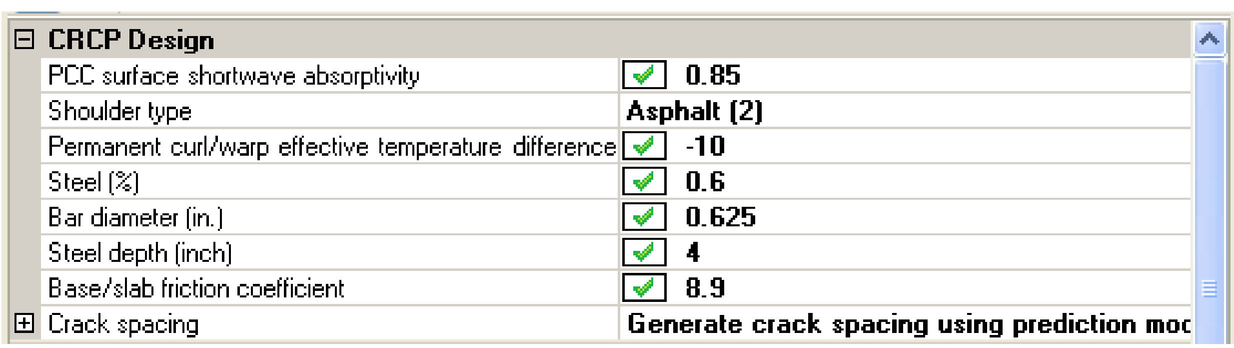


**Figure 5. Input menu for CRCP reinforcement properties, base/slab friction, permanent curl, shoulder type, and short-wave absorptivity.**

## Traffic

One significant change in the MEPDG approach relative to the 1993 AASHTO Pavement Design Guide is that traffic is no longer characterized in terms of an equivalent single-axle load (ESAL). Instead, load spectra information, as shown in figure 6, is utilized in the fatigue analysis by defining the FHWA vehicle class distributions, hourly and monthly distributions, axle type configurations, and other traffic factors. In addition to the FHWA vehicle classification type, the axle load spectra input also requires defining the expected axle load distribution for single, tandem, tridem, and quad axles for a given month, as displayed in figure 7. Much of the load spectra data is quantified by automatic vehicle classification (AVC) systems at weigh-in-motion or weigh stations as described in the FHWA *Traffic Monitoring Guide* (FHWA 1995). These data can also be uploaded from standard AVC outputs from weigh-in-motion systems. 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, this program also allows for site-specific lateral wander characteristics to be directly considered.

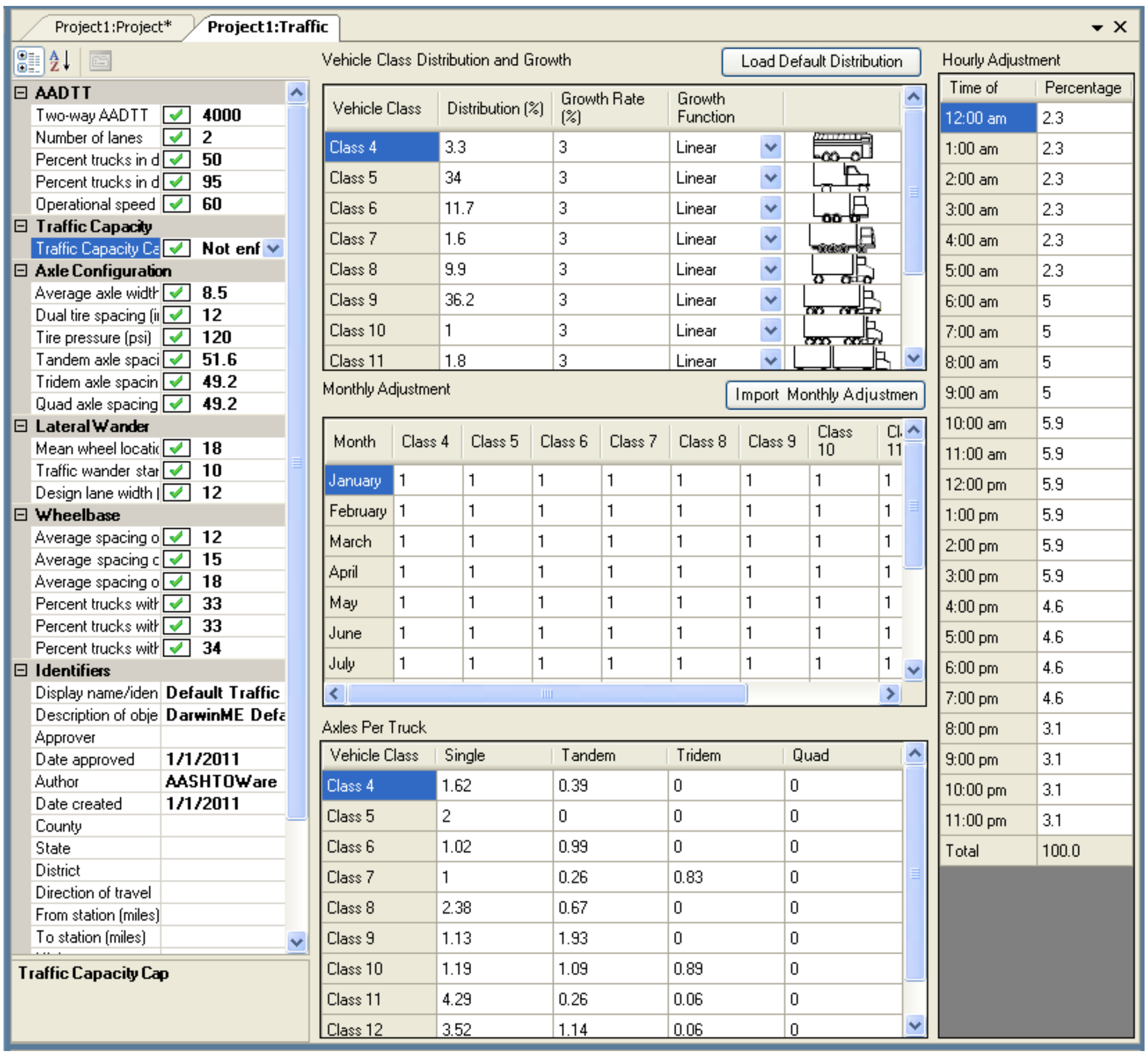


**Figure 6. Traffic input parameters screen.**

Project1:Single

| Month | Class | Total | 3000 | 4000 | 5000 | 6000 | 7000 | 8000 | 9000 | 10000 | 11000 | 12000 | 13000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| January | 4 | 100 | 1.8 | 0.96 | 2.91 | 3.99 | 6.8 | 11.47 | 11.3 | 10.97 | 9.88 | 8.54 | 7.33 |
| January | 5 | 100 | 10.05 | 13.21 | 16.42 | 10.61 | 9.22 | 8.27 | 7.12 | 5.85 | 4.53 | 3.46 | 2.56 |
| January | 6 | 100 | 2.47 | 1.78 | 3.45 | 3.95 | 6.7 | 8.45 | 11.85 | 13.57 | 12.13 | 9.48 | 6.83 |
| January | 7 | 100 | 2.14 | 0.55 | 2.42 | 2.7 | 3.21 | 5.81 | 5.26 | 7.39 | 6.85 | 7.42 | 8.99 |
| January | 8 | 100 | 11.65 | 5.37 | 7.84 | 6.99 | 7.99 | 9.63 | 9.93 | 8.51 | 6.47 | 5.19 | 3.99 |
| January | 9 | 100 | 1.74 | 1.37 | 2.84 | 3.53 | 4.93 | 8.43 | 13.67 | 17.68 | 16.71 | 11.57 | 6.09 |
| January | 10 | 100 | 3.64 | 1.24 | 2.36 | 3.38 | 5.18 | 8.35 | 13.85 | 17.35 | 16.21 | 10.27 | 6.52 |
| January | 11 | 100 | 3.55 | 2.91 | 5.19 | 5.27 | 6.32 | 6.98 | 8.08 | 9.68 | 8.55 | 7.29 | 7.16 |
| January | 12 | 100 | 6.68 | 2.29 | 4.87 | 5.86 | 5.97 | 8.86 | 9.58 | 9.94 | 8.59 | 7.11 | 5.87 |
| January | 13 | 100 | 8.88 | 2.67 | 3.81 | 5.23 | 6.03 | 8.1 | 8.35 | 10.69 | 10.69 | 11.11 | 7.32 |
| February | 4 | 100 | 1.8 | 0.96 | 2.91 | 3.99 | 6.8 | 11.47 | 11.31 | 10.97 | 9.88 | 8.54 | 7.32 |
| February | 5 | 100 | 10.03 | 13.21 | 16.41 | 10.61 | 9.24 | 8.27 | 7.12 | 5.85 | 4.54 | 3.46 | 2.56 |
| February | 6 | 100 | 2.47 | 1.78 | 3.45 | 3.95 | 6.7 | 8.45 | 11.87 | 13.57 | 12.13 | 9.47 | 6.82 |
| February | 7 | 100 | 2.14 | 0.55 | 2.42 | 2.7 | 3.21 | 5.81 | 5.26 | 7.38 | 6.85 | 7.41 | 8.99 |
| February | 8 | 100 | 11.65 | 5.36 | 7.83 | 6.99 | 7.99 | 9.64 | 9.93 | 8.51 | 6.47 | 5.19 | 3.99 |
| February | 9 | 100 | 1.74 | 1.37 | 2.84 | 3.53 | 4.93 | 8.43 | 13.68 | 17.68 | 16.71 | 11.56 | 6.09 |
| February | 10 | 100 | 3.64 | 1.24 | 2.36 | 3.38 | 5.18 | 8.34 | 13.85 | 17.35 | 16.21 | 10.28 | 6.52 |
| February | 11 | 100 | 3.55 | 2.91 | 5.19 | 5.27 | 6.33 | 6.98 | 8.08 | 9.68 | 8.55 | 7.28 | 7.16 |
| February | 12 | 100 | 6.68 | 2.29 | 4.88 | 5.87 | 5.98 | 8.86 | 9.58 | 9.95 | 8.61 | 7.09 | 5.86 |
| February | 13 | 100 | 8.88 | 2.67 | 3.81 | 5.23 | 6.04 | 8.1 | 8.35 | 10.69 | 10.69 | 11.11 | 7.31 |
| March | 4 | 100 | 1.8 | 0.96 | 2.91 | 3.99 | 6.81 | 11.45 | 11.31 | 10.97 | 9.88 | 8.54 | 7.33 |
| March | 5 | 100 | 10.04 | 13.21 | 16.41 | 10.59 | 9.23 | 8.28 | 7.13 | 5.86 | 4.53 | 3.46 | 2.56 |
| March | 6 | 100 | 2.47 | 1.78 | 3.45 | 3.95 | 6.7 | 8.44 | 11.87 | 13.57 | 12.14 | 9.47 | 6.82 |
| March | 7 | 100 | 2.14 | 0.55 | 2.42 | 2.7 | 3.21 | 5.81 | 5.26 | 7.38 | 6.85 | 7.43 | 8.99 |
| March | 8 | 100 | 11.64 | 5.36 | 7.83 | 6.99 | 7.99 | 9.64 | 9.94 | 8.52 | 6.47 | 5.19 | 3.99 |
| March | 9 | 100 | 1.74 | 1.37 | 2.84 | 3.53 | 4.93 | 8.43 | 13.66 | 17.68 | 16.71 | 11.58 | 6.09 |
| March | 10 | 100 | 3.64 | 1.24 | 2.36 | 3.38 | 5.18 | 8.34 | 13.86 | 17.35 | 16.21 | 10.27 | 6.52 |
| March | 11 | 100 | 3.55 | 2.91 | 5.19 | 5.27 | 6.32 | 6.97 | 8.08 | 9.68 | 8.55 | 7.29 | 7.17 |
| March | 12 | 100 | 6.68 | 2.29 | 4.87 | 5.86 | 5.97 | 8.86 | 9.59 | 9.96 | 8.59 | 7.09 | 5.86 |
| March | 13 | 100 | 8.88 | 2.67 | 3.81 | 5.23 | 6.03 | 8.1 | 8.36 | 10.69 | 10.69 | 11.11 | 7.31 |
| April | 4 | 100 | 1.8 | 0.96 | 2.91 | 3.99 | 6.8 | 11.47 | 11.28 | 10.99 | 9.88 | 8.55 | 7.32 |

**Figure 7. Expected single-axle load distribution (percentage) for a given month and FHWA vehicle classification.**

## Climate

A key improvement to the CRCP design process is accounting for site-specific climate. The Pavement ME Design program models account for daily and seasonal fluctuations 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 the user can create a "virtual weather station" by allowing the program to interpolate nearby weather data to the user's specific project site. Figure 8 shows the selection of an existing weather station in Oklahoma City. The locations are separated by State/Province, which must be chosen first before specific sites will be listed for selection.

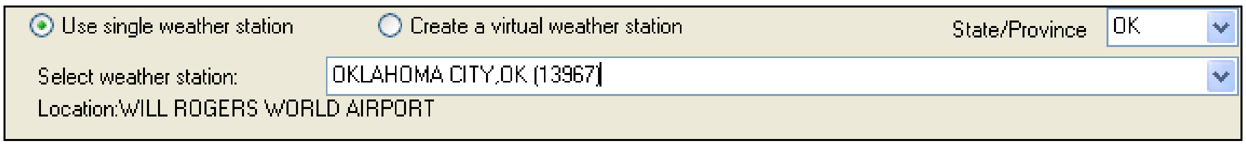


**Figure 8. Climate selection using existing weather station data.**

## CRCP Failure Analysis and Design Thickness Optimization

For CRCP, the software predicts only two performance criteria that can be used for assessing the validity of the CRCP design at a given level of reliability: IRI and the number of CRCP punchouts per mile. Three other mean quantities that directly affect the performance prediction of punchouts and IRI are calculated based on the inputs: crack spacing, crack width, and crack LTE. Recommended levels of crack spacing, crack width, and load transfer are provided in the *Manual of Practice* (AASHTO 2008). 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. As shown in figure 9, the user can specify the initial IRI, which is related to an agency's construction smoothness specification, as well as the terminal IRI level and punchouts defined as failure for a given project. The Pavement 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. Once the traffic, pavement cross section, material properties, and climate inputs have been entered, the program can be run to either predict the number of punchouts and smoothness at the end of the design life or until an appropriate thickness is found to the nearest 0.25 inches (6.4 mm) that does not exceed the user-defined CRCP performance criteria.

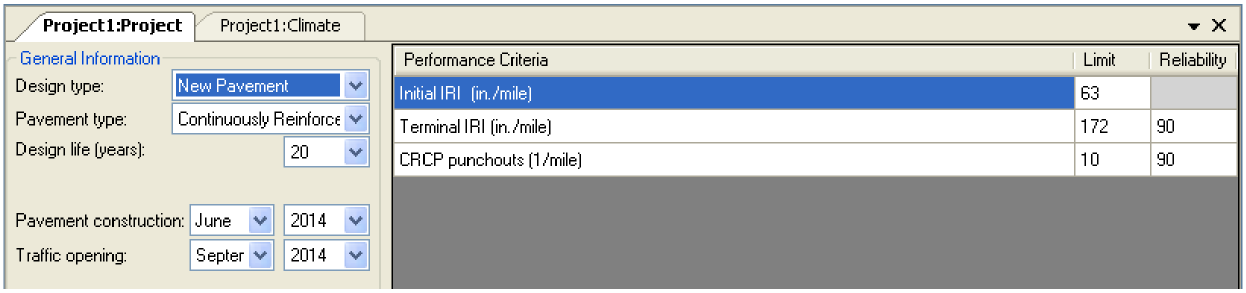


**Figure 9. CRCP performance criteria and design reliability input screen.**

The outputs of the program can be opened in Microsoft® Excel® or in Acrobat® Reader® to review the inputs and view the predicted distress levels in the CRCP, as shown in figure 10. The output displays the IRI and punchouts 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 punchouts at the specified reliability level exceed the user-specified limits at the end of the design life, the user needs to intelligently adjust the input parameters and re-analyze the CRCP section.

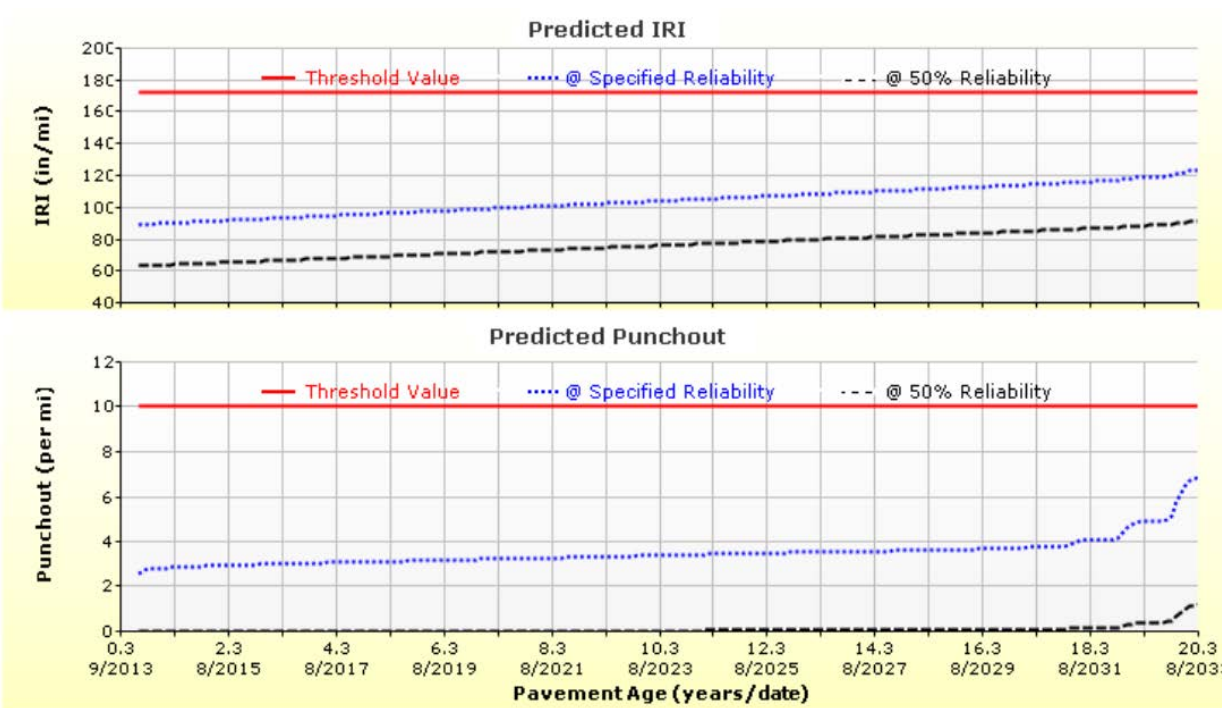


**Figure 10. Example of IRI and punchout predictions for 50-percent and specified reliability over time.**

## AASHTO PAVEMENT ME DESIGN INPUT SENSITIVITY

There have been a few valuable research studies on the sensitivity of the CRCP design to input variable changes (Freeman et al. 2005; Bordelon et al. 2009; Won 2009; Schwartz et al. 2011; Vandenbossche et al. 2012; Ley et al. 2013). 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 AASHTO Pavement ME Design program is used in the subsequent design examples 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 is also demonstrated to show how the Pavement ME Design program captures the effect of site-specific weather patterns on the CRCP's predicted distresses. For these analyses, the input assumptions listed below represent the standard case, which pass the IRI (172 inch/mi (2.7 m/km)) and punchout (10/mi (6.2/km)) criteria set at 90-percent reliability. For traffic and material property inputs in the Pavement ME Design, level 3 default values are 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 (9.9 x 10$^{-6}$/°C).
- PCC water-to-cementitious materials ratio = 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) cover depth.

### PCC Thickness

One of the most sensitive parameters to the CRCP performance is slab thickness, as shown in figure 11, with predicted CRCP punchouts in blue and IRI in red. For this example, the punchouts at the end of the design life must be below a threshold of 10/mi (6.2/km) (blue dotted line) and the IRI below the threshold of 172 inch/mi (2.7 m/km) (red dotted line) to pass. Due to the sensitivity of tensile bending stresses to thickness changes, small increases in thickness (from 11.25 to 11.5 inches (from 286 to 292 mm)) can reduce the number of punchouts significantly (8.4/mi to 4.4/mi (5.3/km to 2.8/km)), respectively). While slab thickness is a sensitive input, it is important to note that the Pavement ME Design program is much more than a “thickness design” approach. Changes in layer material properties, steel design, or other sensitive input parameters may be more cost effective in producing an acceptably performing CRCP. For comparison, the AASHTO 1993 thickness design would require a 14-inch (356-mm) concrete layer to handle this level of traffic at the specified reliability level, demonstrating the clear benefit of a mechanistic–empirical CRCP procedure.

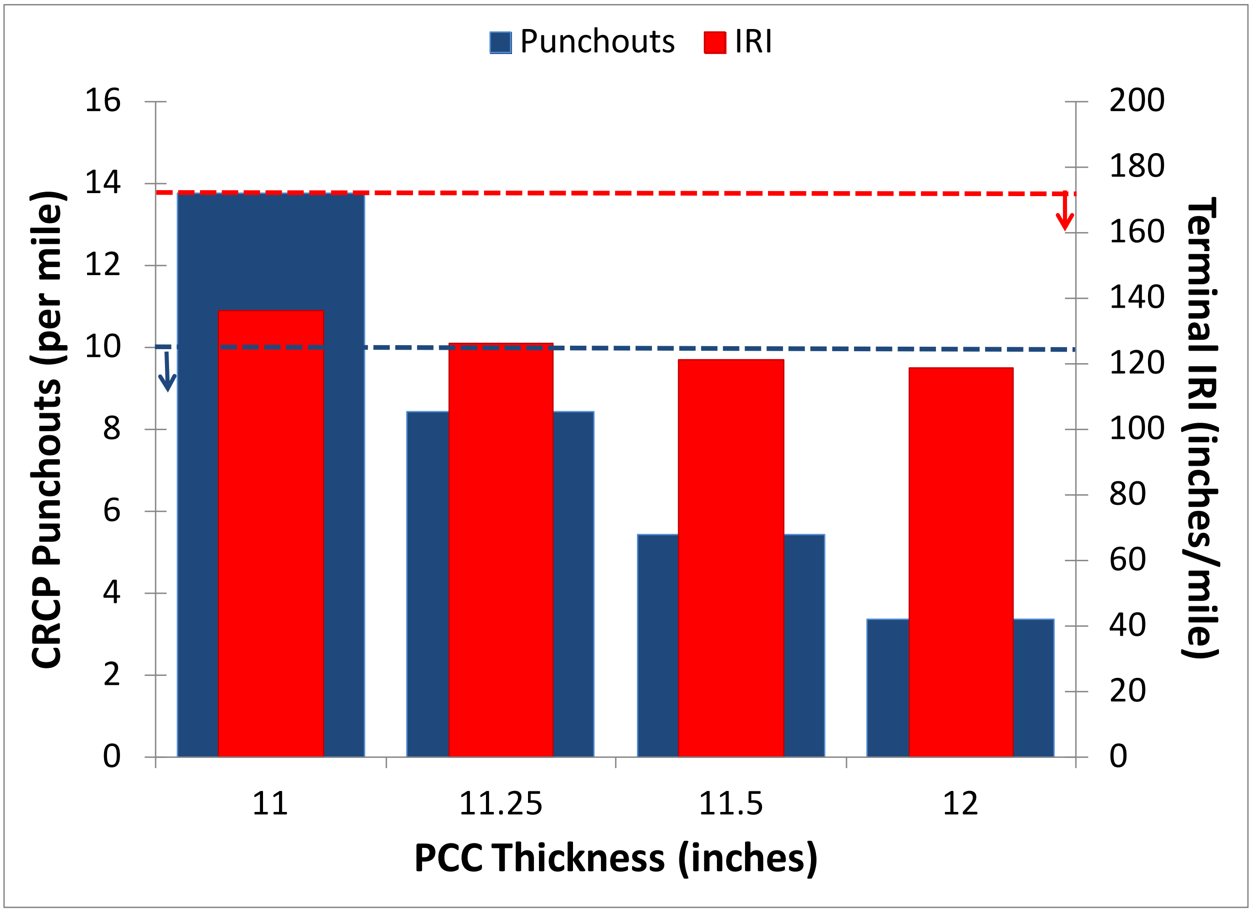


**Figure 11. Impact of PCC thickness changes on predicted CRCP punchouts and terminal IRI.**

## Reinforcing Steel

In the more comprehensive design approach utilized in Pavement ME Design, the impacts of steel reinforcement can be better captured than in the 1993 AASHTO pavement design method. In the example shown in figure 12, a reduction of steel content from 0.7 percent to 0.6 percent results in a significant increase in punchouts, from 8.4/mi (5.3/km) to more than 32/mi (20/km), resulting in an inadequately designed CRCP section. Figure 12 also indicates how an increase in the amount of steel decreases the spacing between the cracks, leading to tighter crack widths and more sustained load transfer between slabs. Since the IRI is related to the number of punchouts, the decrease in IRI in figure 12 is directly related to the reduction in punchouts with increase in steel content. There is a limit to the amount of steel to place in the CRCP since excessive steel content may lead to close crack spacing, resulting in meandering and intersecting cracks.

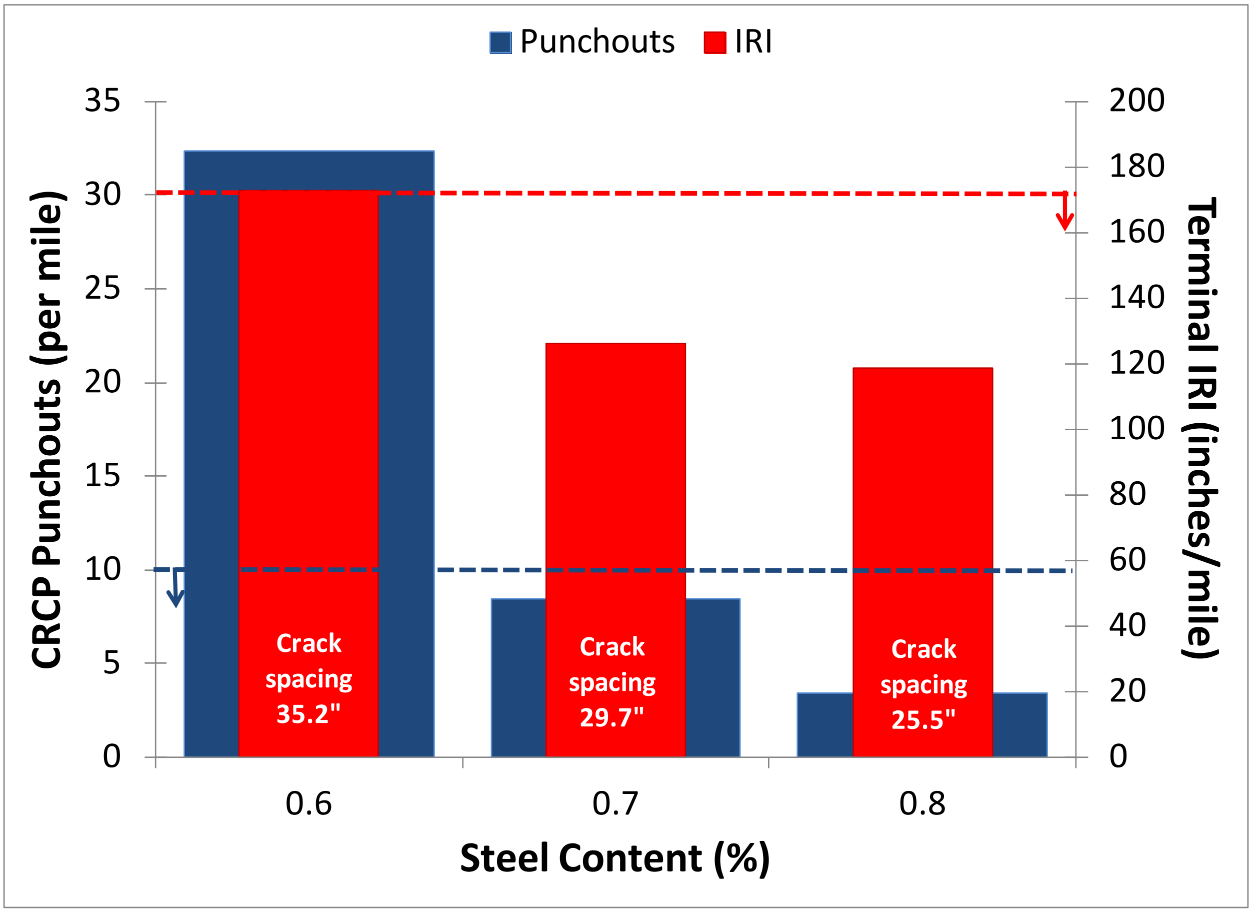


**Figure 12. Impact of reinforcing steel percentage on predicted CRCP punchouts and terminal IRI.**

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. The calibrated models within the Pavement ME Design program have captured the effect of steel depth on the mean CRCP transverse crack spacing, as shown in figure 13, which can lead to better crack LTE and reduced bending stresses in the slab from mechanical and environmental loads. Figure 13 shows 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 inches (140 mm)) resulted in a 150 percent increase in predicted punchouts over steel placed at the 3.5-inch (89-mm) level. This analysis validates the common practice of not placing the steel below the slab mid-depth.

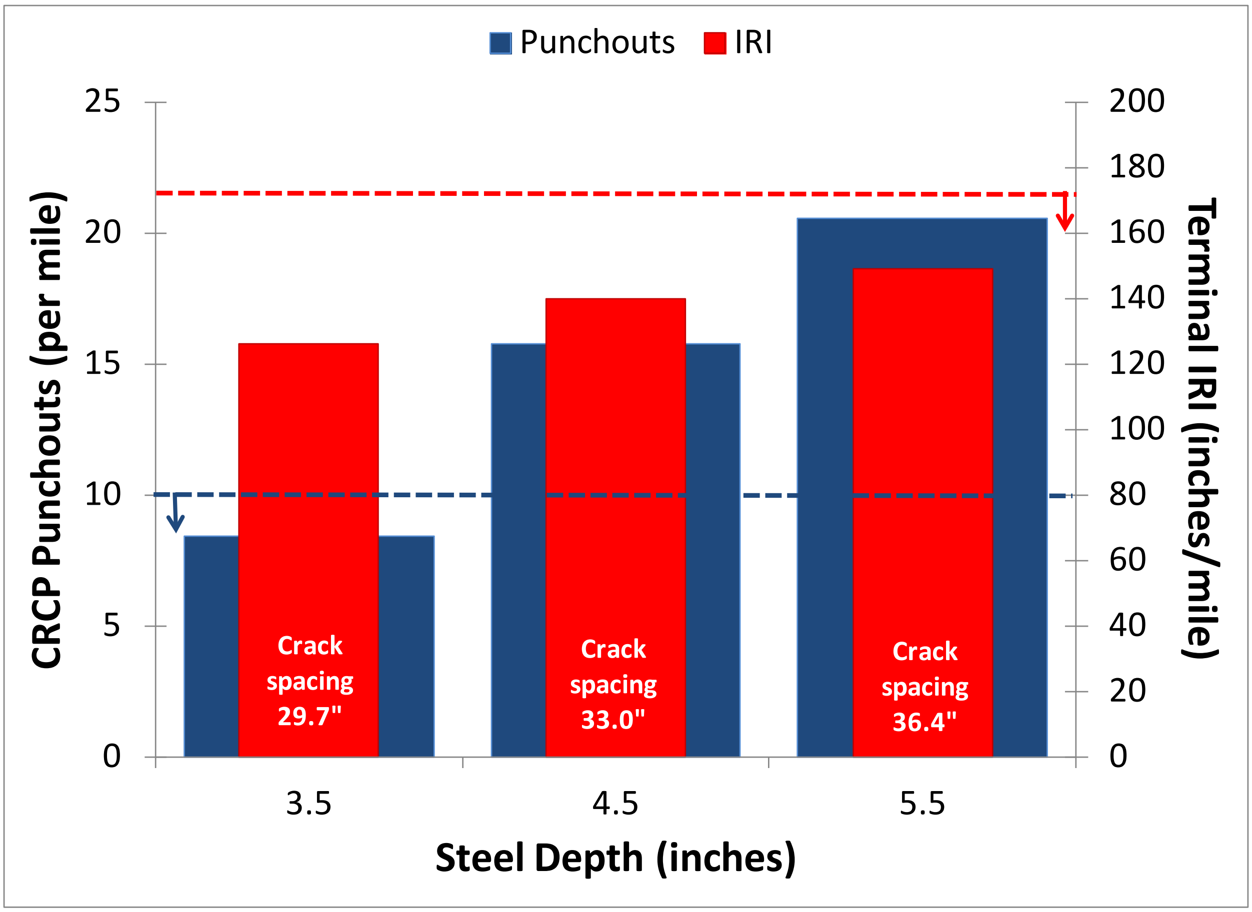


**Figure 13. Impact of depth of reinforcing steel at 0.7 percent on predicted CRCP punchouts and terminal IRI.**

## Concrete Coefficient of Thermal Expansion

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

**Table 1. Typical CTE values for PCC by coarse aggregate type.**
(adapted from Rao et al. 2012, table 25, p. 8)

| **Aggregate Type** | **Average CTE ($\times 10^{-6}$/°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 |

Figure 14 shows how changing the coarse aggregate type, if possible, from a middle CTE value (5.5 x $10^{-6}$/°F (9.9 x $10^{-6}$/°C)) to a 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 tied into the crack-spacing and crack-width prediction models utilized in the Pavement 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. Pavement designers must recognize that the design concrete CTE value needs to be achieved through available aggregate sources. 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 CRCP's predicted performance 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).

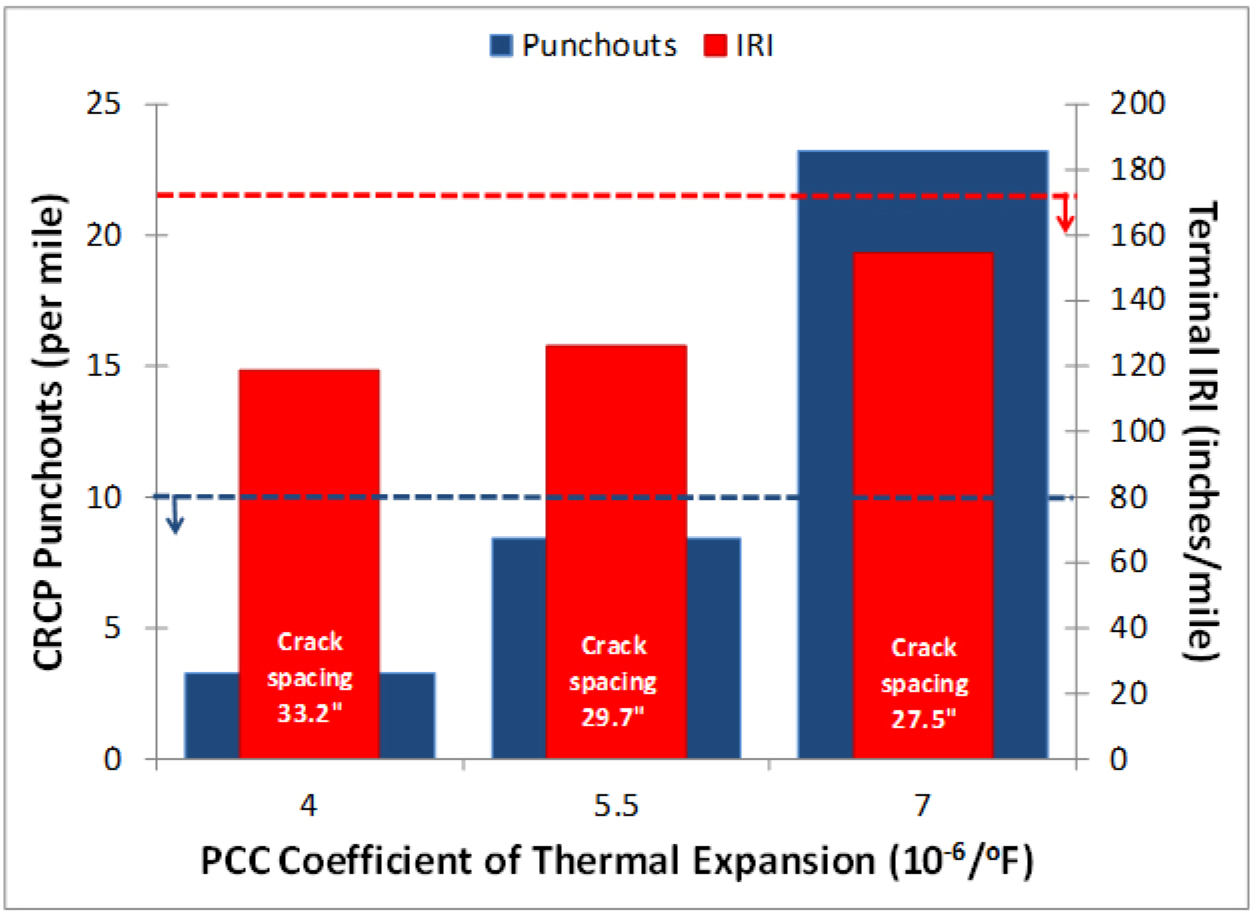


**Figure 14. Impact of PCC CTE on predicted CRCP punchouts and terminal IRI.**

### Shoulder Type and Lane Width

Another design factor that users of the Pavement ME Design program can utilize is the shoulder type. A concrete shoulder, whether monolithically paved or paved separately, can be used to significantly reduce the slab bending stresses and deflections and subsequently punchouts and IRI, as shown in figure 15, relative to an asphalt or gravel shoulder. While the program does not directly consider lane width in its analysis of CRCP, experience in Texas, Oregon, and Illinois has shown that lane widening of up to 13 ft (4 m) tends to promote long-term performance and may be considered for a design.

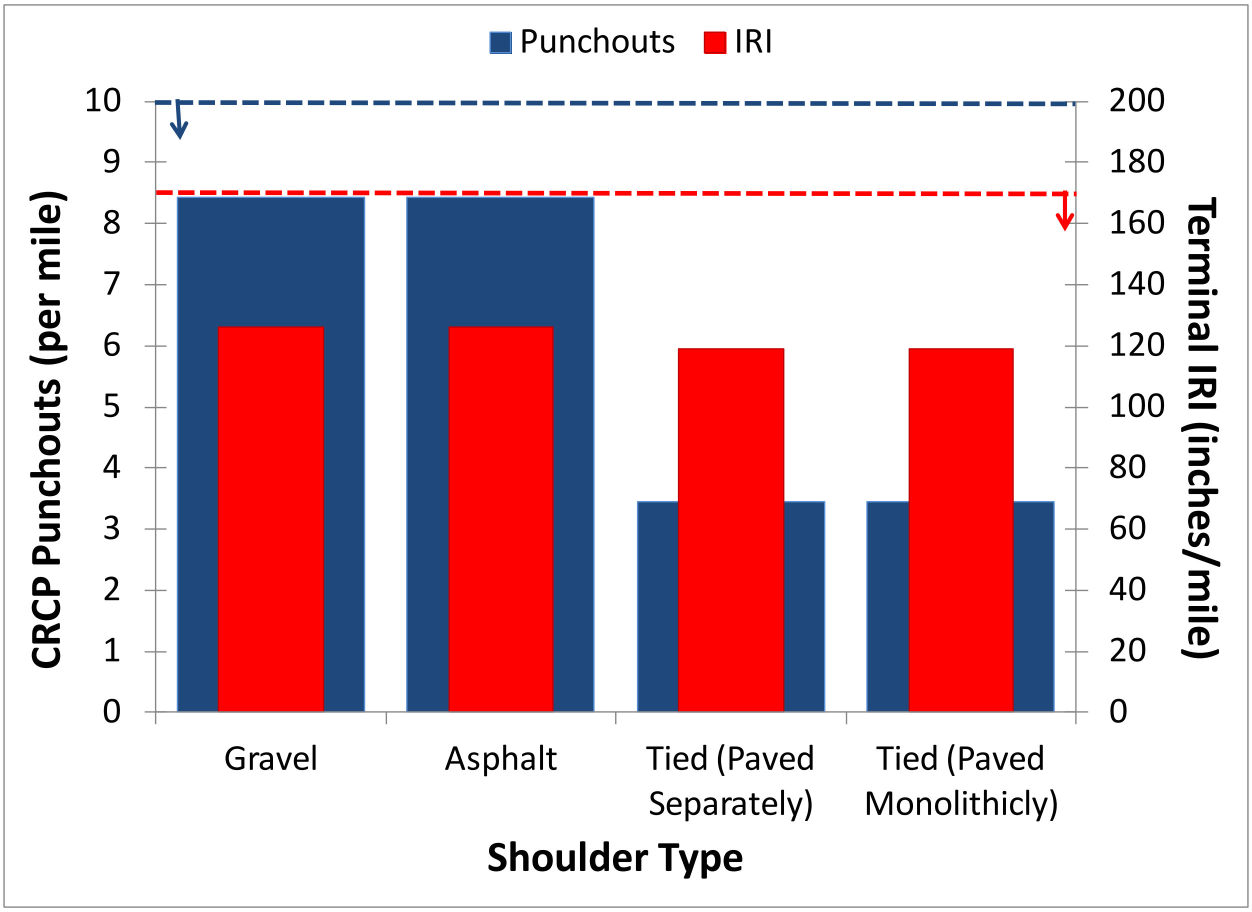


**Figure 15. Impact of shoulder type on predicted CRCP punchouts and terminal IRI.**

**Base Type/Friction**

The base type selected for support in a CRCP is a critical factor impacting projected performance both in the development of cracks and tight crack widths as well as in 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 Pavement 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 recommended ranges in table 2. The base type can have a pronounced impact on the computed crack spacing, crack width, crack LTE, and, ultimately, performance of the CRCP section.

**Table 2. Suggested subbase/base friction values used in Pavement ME Design software.**
(http://www.darwinme.org/MEDesign/Index.html (Help Menu))

| **Subbase/Base Type Friction Coefficient** | **Value (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 – 7.5 – 15 |
| Cement-treated base | 3.5 – 8.9 – 13 |
| Soil cement | 6.0 – 7.9** – 23 |
| Lean cement base (LCB) | 1.0 – 6.6** – 20 |
| Lean cement base not cured** | > 36 (higher than LCB 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.

In addition, the use of a stabilized material as the base type can assist in reducing both the bending stresses in the PCC and the creation of erosion-induced voids, thereby increasing the fatigue life of the CRCP section. Figure 16 shows that stabilized base materials, such as 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 subsequent widths are significantly affected. This reduction in punchouts also leads to a significant improvement in ride quality.

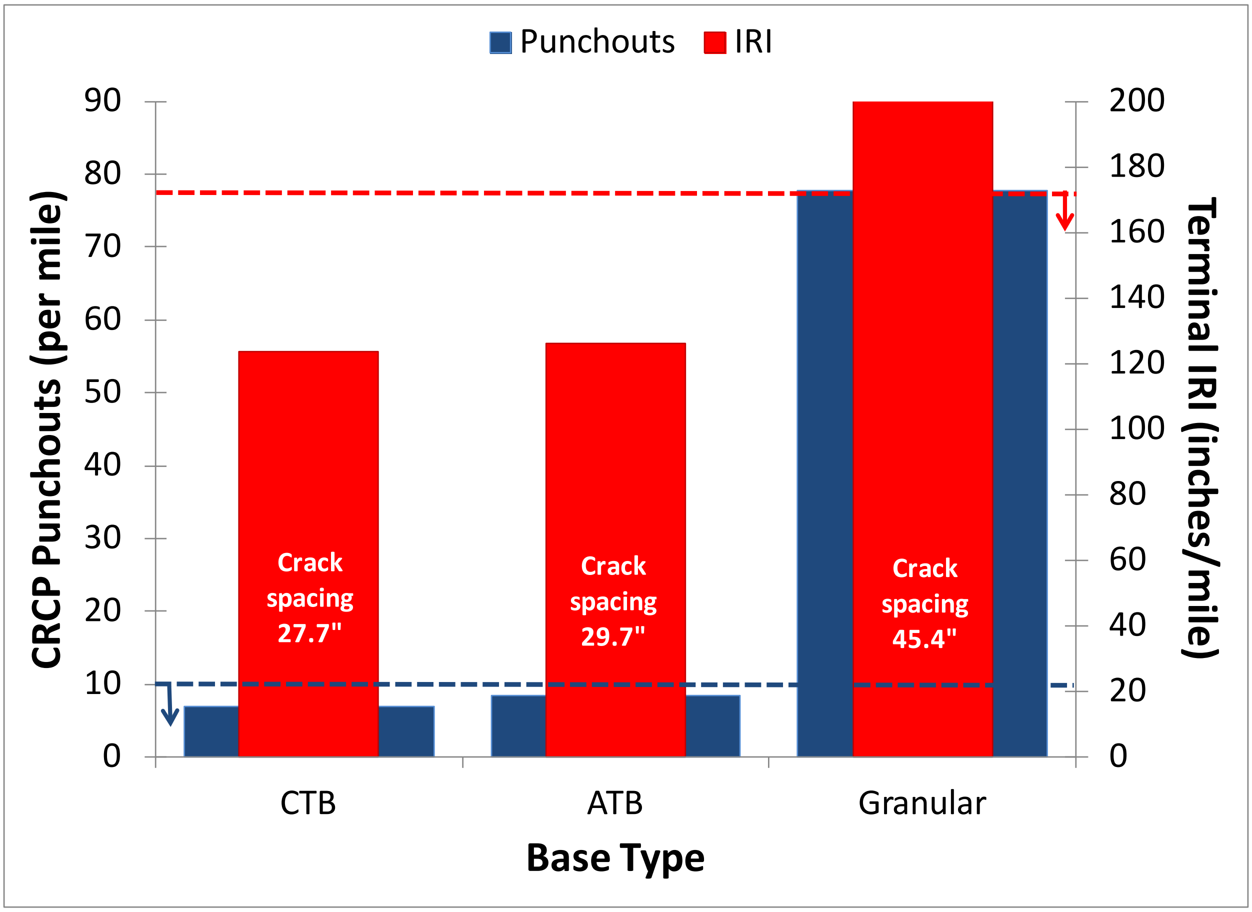


**Figure 16. Impact of base type and associated friction on predicted CRCP punchouts and terminal IRI.**
(CTB = cement-treated base; ATB = asphalt-treated base)

### Construction Month

The construction month has been shown to impact the temperature development at early ages and zero-stress temperature in CRCP (Schindler and McCullough 2002), and thus it is a user input variable in the Pavement ME Design program. The construction temperature affects the concrete set temperature, which subsequently influences the mean CRCP crack spacing and widths. In the example shown in figure 17, the CRCPs constructed in March and October are under cooler temperatures relative to the CRCP constructed in 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 to verify that this design assumption is controlled in the construction process or that a conservative summer month assumption is utilized in the design.

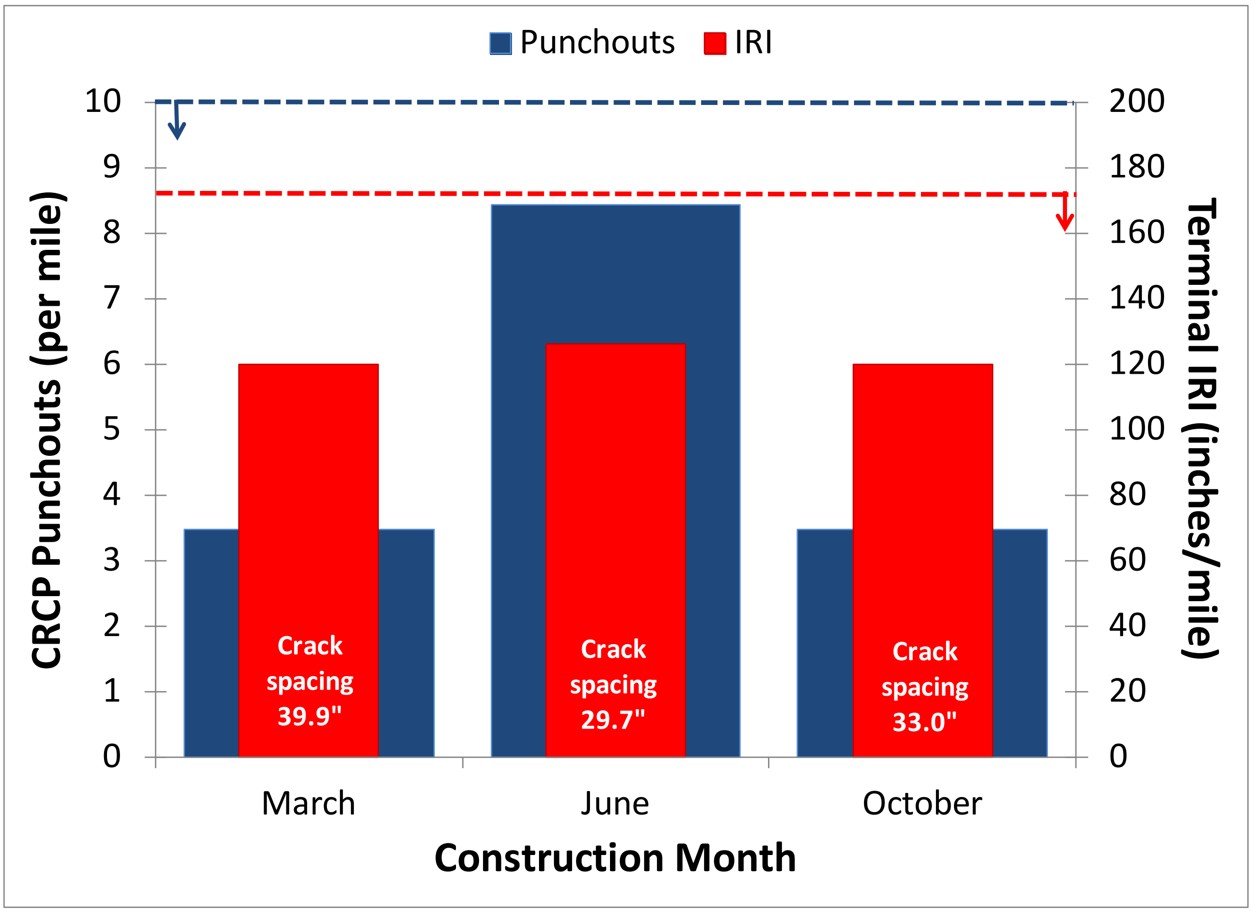


**Figure 17. Impact of construction month on predicted CRCP punchouts and terminal IRI.**

## Climate

It is well-established that local climate conditions can affect the design and performance of CRCP. The AASHTO Pavement ME Design program enables selection of site-specific weather data for a project, which specifically influences the crack spacing, crack width, and punchout prediction models. In this example, the default example in Chicago was changed to include Norfolk (Virginia), Austin (Texas), and Sacramento (California), as shown in figure 18. 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 same CRCP section that passed the punchout threshold for Chicago and Sacramento failed in punchouts in both the Norfolk and Austin climates, while all locations satisfied the IRI criteria at 90-percent reliability. To produce a passing design for the Norfolk and Austin climates, the options include either increasing the CRCP thickness or steel content or adding a tied concrete shoulder.

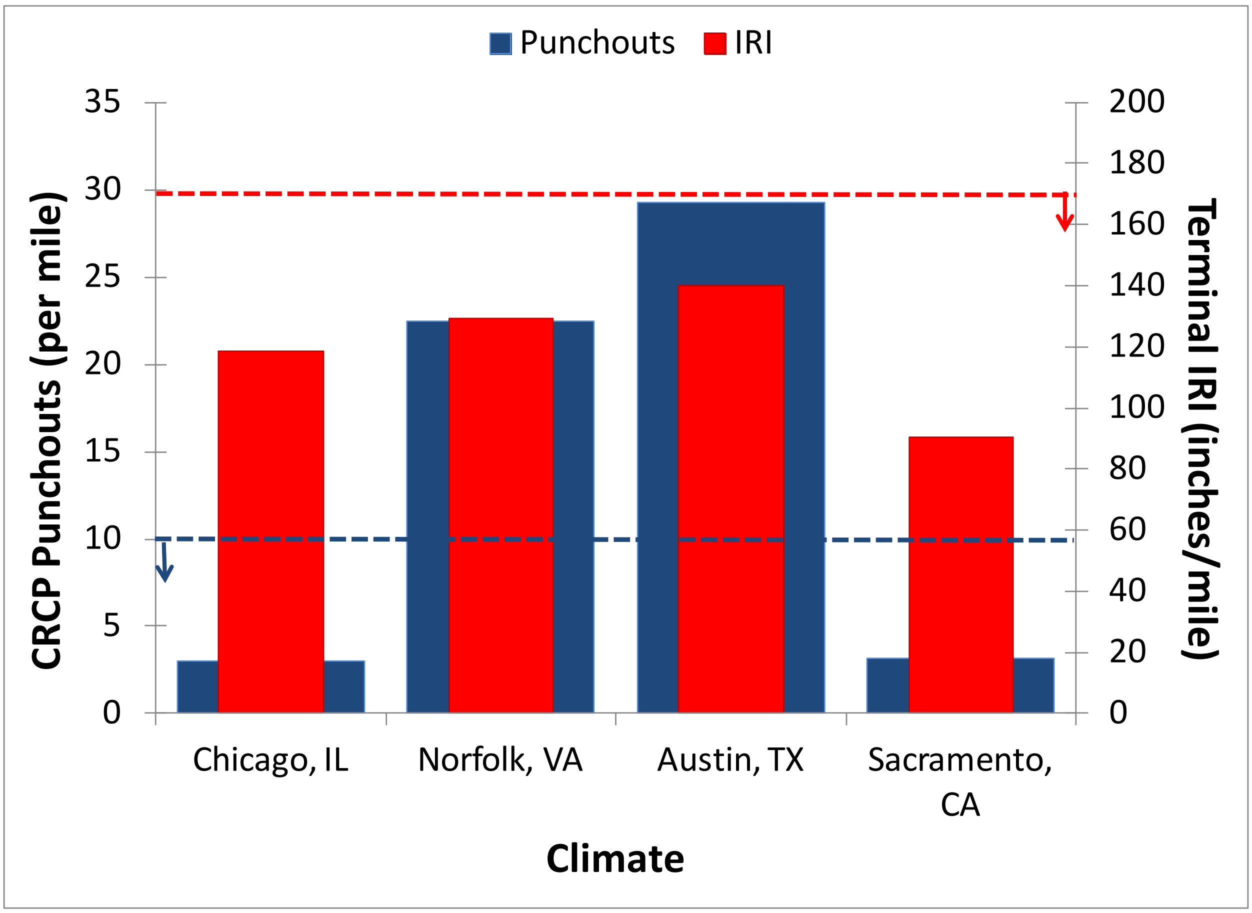


**Figure 18. Impact of climate on predicted CRCP punchouts and terminal IRI.**

## CRCP DESIGN EXAMPLES WITH AASHTO PAVEMENT ME

To demonstrate the Pavement ME Design software, two design examples are illustrated using local site and agency-specific inputs: a new CRCP design for a freeway in Portland, Oregon, and an unbonded CRCP overlay of an existing CRCP in Southern Illinois, both for a 20-year life at 90-percent reliability.

### New CRCP Design Example

For this example, a new CRCP pavement is required on I-84 in Portland, Oregon. The average annual daily traffic for this section is 171,700 vehicles with 6.06 percent of the vehicles being buses and large trucks (AADTT of 10,400). After accounting for lane and directional factors, the total number of trucks in the design lane is 34.2 million over the 20-year design life. Using Oregon DOT traffic data, the observed vehicle class distributions for FHWA Class 4 through Class 13 vehicles were entered into the Pavement ME Design program with the majority of trucks being Class 5 with lower axle loads. The Pavement ME Design default load spectra were utilized for this example.

Other pertinent input parameters for this CRCP design example are listed in table 3. Many of these design parameters, such as steel percentage, base type, etc., are specific to local transportation agencies based on their experience with previous CRCP designs.

Using the Pavement ME Design software, the PCC thickness was optimized to find the thinnest concrete section that met both the punchouts and IRI threshold criteria at 90-percent reliability as shown in figure 19(a). For this particular case, the punchout criterion was the controlling design factor as the IRI level after 20 years of traffic was predicted to be well under the 172-inch/mi (2.7-m/km) limit. With a mechanistic–empirical design method, several of these parameters could be further adjusted, which may produce an even more economical CRCP section with the same intended performance life.

### CRCP Overlay Design Example

While the Pavement ME Design software can design new pavement structures using mechanistic–empirical models, the software can also be used to design major rehabilitation alternatives such as overlays. In this scenario, an existing CRCP on I-57/I-64 near Mount Vernon, Illinois, is evaluated for a CRCP overlay. The existing CRCP slab is 9 inches (229 mm) thick, in fair to poor condition, with a 4-inch (102-mm) granular base resting on an AASHTO A-7-6 subgrade. To reduce the likelihood of reflective cracks and isolate the movement of the existing CRCP, a 2-inch (51-mm) asphalt concrete separation layer is used between the existing and new CRCP layers, producing an unbonded CRCP overlay. With two interstates merging in this section, this is a highly trafficked route with an initial AADTT of 17,391. The total trucks in the design lane were 76.3 million over 20 years. The truck traffic classification 11 is used in this example for the vehicle class distribution, which includes mixed truck traffic with a high percentage of single-trailer trucks, as well as the software's default load spectra. Using other site-specific information for typical Illinois CRCP sections as shown in table 3, the resulting CRCP unbonded overlay design from the Pavement ME Design software is shown in figure 19(b) at 90-percent reliability. Just as with the new CRCP design example, the controlling factor determining the PCC thickness was limiting the frequency of punchouts below the threshold of 10/mi (6.3/km).

**Table 3. Key input parameters for new CRCP and unbonded CRCP overlay design examples.**

| Key Input Parameter | New CRCP in Portland, Oregon | CRCP Unbonded Overlay in Mount Vernon, Illinois |
|---|---|---|
| PCC 28-day Compressive Strength | 4,000 lbf/in$^2$ | |
| PCC 28-day Modulus of Rupture | | 690 lbf/in$^2$ |
| PCC Coefficient of Thermal Expansion | 4.86 x $10^{-6}$/°F (basalt aggregate) | 5.25 x $10^{-6}$/°F (limestone aggregate) |
| Existing CRCP Thickness | | 9 inches |
| Base Type/Thickness | Asphalt-treated base / 4 inches | Granular / 4 inches |
| Subgrade Type | A-4 | A-7-6 |
| Steel Percentage | 0.60% | 0.70% |
| Depth of Steel | 4 inches | 3.5 inches |
| Lane Width | 12 ft | 12 ft |
| Shoulder Type | Asphalt | Asphalt |
| Initial AADTT | 10,400 | 17,381 |
| Traffic Growth Rate | 3% compound annually | 2.4% compound annually |
| Construction Month | June 2013 | June 2013 |

1 lbf/in$^2$ = 6.89 kPa; 1 °F = 5(F-32)/9 °C; 1 inch = 25.4 mm; 1 ft = 0.305 m.

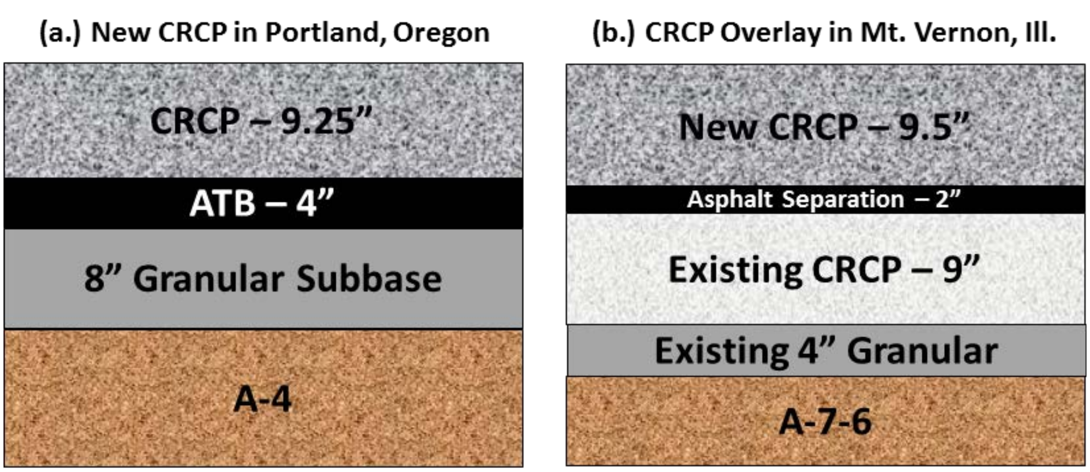


**Figure 19. Example design cross sections for (a) new CRCP in Portland, OR, and (b) CRCP overlay near Mount Vernon, IL.**

## SUMMARY

The AASHTO Pavement 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 an ME 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, strength, base type, steel content and position, and construction month. While the Pavement ME Design program has been calibrated to empirical observations using a national database, local calibration of these models should be considered once sufficient data exist to improve the CRCP performance predictions. Using mechanistic models and empirical observations of CRCP behavior, the AASHTO Pavement ME Design method gives pavement engineers a state-of-the-art, rational approach to designing CRCP in locations across North America.

As the ME 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 TxDOT, as follows:

- CRCPs in different States may have somewhat different performance than currently predicted by the Pavement ME Design software. For example, the effect of construction month on CRCP performance has been reported to be minimal in Texas.
- 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 in the slab thickness design.

## REFERENCES

American Association of State Highway and Transportation Officials (AASHTO). (1993). *Guide for Design of Pavement Structures*. AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO). (2008). *Mechanistic-Empirical Pavement Design Guide, Interim Edition: A Manual of Practice.* AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO). (2009). AASHTO T 336. Standard Test Method for the Coefficient of Thermal Expansion of Hydraulic Cement Concrete. AASHTO, Washington, DC.

Applied Research Associates (ARA). (2001). *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures,* Appendix PP: Smoothness Predictions for Rigid Pavements (NCHRP 1-37A). ARA, Champaign, IL.

Applied Research Associates (ARA). (2003). *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures,* Appendix LL: Punchouts in Continuously Reinforced Concrete Pavements (NCHRP 1-37A). ARA, Champaign, IL.

Bordelon, A., J. R. Roesler, and J. E. Hiller. (2009). *Mechanistic-Empirical Design Concepts for Jointed Plain Concrete Pavements in Illinois, Final Report* (FHWA-ICT-09-052). Illinois Center for Transportation, University of Illinois, Urbana.

Burke, J. E., and J. S. Dhamrait. (1968). A Twenty-Year Report on the Illinois Continuously Reinforced Pavement. *Highway Research Record 239*. Highway Research Board, National Research Council, Washington, DC, pp. 197–211.

Dhamrait, J., F. Jacobsen, and P. Dierstein. (1977). *Construction Experience with CRC Pavements in Illinois* (FHWA-IL-PR-55; Physical Research No. 55). Illinois Department of Transportation, Springfield.

Dhamrait, J., and D. Schwartz. (1978). *Effect of Subbase Type and Subsurface Drainage on Behavior of CRC Pavements* (FHWA-IL-PR-83; Physical Research No. 83). Illinois Department of Transportation, Springfield.

Federal Highway Administration. (FHWA). (1995). *Traffic Monitoring Guide, Third Edition*. (FHWA-PL-95-031). FHWA, Washington, DC.

Freeman, T., J. Uzan, D. Zollinger, and E. S. Park. (2005). *Sensitivity Analysis and Strategic Plan Development for the Implementation of the ME Design Guide in TxDOT Operations* (FHWA/TX-05/0-4714-1). Federal Highway Administration, Washington, DC.

Gharaibeh, N. G., and M. I. Darter. (2003). Probabilistic Analysis of Highway Pavement Life for Illinois. *Transportation Research Record: Journal of the Transportation Research Board, No. 1823,* pp. 111–120.

Gharaibeh, N. G., M. I. Darter, and L. B. Heckel. (1999). Field Performance of Continuously Reinforced Concrete Pavement in Illinois. *Transportation Research Record: Journal of the Transportation Research Board, No. 1684,* pp. 44–50.

Hall, K. D., and S. Beam. (2005). Estimating the Sensitivity of Design Input Variables for Rigid Pavement Analysis with a Mechanistic-Empirical Design Guide. *Transportation Research Record: Journal of the Transportation Research Board, No. 1919,* pp. 65–73.

Jung, Y., D. Zollinger, and A. Wimsatt. (2010). Test Method and Model Development of Subbase Erosion for Concrete Design, *Transportation Research Record: Journal of the Transportation Research Board, No. 2154,* pp. 22–31.

Kannekanti, V., and J. T. Harvey. (2006). Sensitivity Analysis of 2002 Design Guide Distress Prediction Models for Jointed Plain Concrete Pavement. *Transportation Research Record: Journal of the Transportation Research Board, No. 1947*, pp. 91–100.

Kohler, E., and J. Roesler. (2006). *Accelerated Pavement Testing of Extended Life Continuously Reinforced Concrete Pavement Sections, Final Report*. Transportation Engineering Series No. 141, Illinois Cooperative Highway and Transportation Series No. 289. University of Illinois, Urbana.

LaCoursiere, S. A., M. I. Darter, and S. A. Smiley. (1978). *Construction of CRCP Pavement in Illinois*. Technical Report FHWA-IL-UI-172. University of Illinois and Illinois Department of Transportation, Springfield.

Ley, T., A. Hajibabbee, S. Kadam, R. Frazier, M. Aboustait, T. Ebisch, and K. Riding. (2013). *Development and Implementation of a Mechanistic and Empirical Pavement Design Guide (MEPDG) for Rigid Pavements–Phase I, Final Report* (FHWA-OK-12-08). Oklahoma State University, Stillwater.

McCullough, B. F., A. A. Ayyash, W. R. Hudson, and J. P. Randall. (1975). *Design of Continuously Reinforced Concrete Pavements for Highways* (NCHRP 1-15). Center for Highway Research, The University of Texas at Austin.

Plei, M., and S. Tayabji. (2012). Continuously Reinforced Concrete Pavement: Performance and Best Practices (ACPT Tech Brief; FHWA-HIF-12-039). Federal Highway Administration, Washington, DC.

Rao, C., and M. Darter. (2013). Enhancements to the Punchout Prediction Model in the MEPDG Design Procedure. TRB 92nd Annual Meeting Compendium of Papers. Presented at the Transportation Research Board 92nd Annual Meeting, Washington, DC. http://docs.trb.org/prp/13-5249.pdf.

Rao, C., L. Titus-Glover, B. Bhattacharya, and M. I. Darter. (2012). *User's Guide: Estimation of Key PCC, Base, Subbase, and Pavement Engineering Properties from Routine Tests and Physical Characteristics* (Technical Report; FHWA-HRT-12-031). Federal Highway Administration, Washington, DC.

Rasmussen, R. O., R. Rogers, and T. R. Ferragut. (2009). *Continuously Reinforced Concrete Pavement: Design and Construction Guidelines* (FHWA/CRSI Final Report). Federal Highway Administration, Washington, DC.

Schindler, A. K., and B. F. McCullough. (2002). Importance of Concrete Temperature Control During Concrete Pavement Construction in Hot Weather Conditions. *Transportation Research Record: Journal of the Transportation Research Board, No. 1813*, pp. 3–10.

Schwartz, C., S. H. Kim, H. Ceylan, and K. Gopalakrishnan. (2011). *Sensitivity Evaluation of MEPDG Performance Prediction* (NCHRP 1-47). Transportation Research Board of the National Academies, Washington, DC.

Smith, K. D., M. J. Wade, D. G. Peshkin, L. Khazanovich, H. T. Yu, and M. I. Darter. (1998). *Performance of Concrete Pavements, Vol. II: Evaluation of In-service Concrete Pavements* (FHWA-RD-95-110). Federal Highway Administration, Washington, DC.

Tayabji, S. D., P. J. Stephanos, and D. G. Zollinger. (1995). Nationwide Field Investigation of Continuously Reinforced Concrete Pavements. *Transportation Research Record 1482*, pp. 7–18.

Tayabji, S. D., P. J. Stephanos, J. S. Gagnon, and D. G. Zollinger. (1998a). *Performance of Continuously Reinforced Concrete Pavements. Vol. 2—Field Investigations of CRC Pavements* (FHWA-RD-94-179). Federal Highway Administration, Washington, DC.

Tayabji, S. D., D. G. Zollinger, J. R. Vederey, and J. S. Gagnon. (1998b). *Performance of Continuously Reinforced Concrete Pavements. Vol. III—Analysis and Evaluation of Field Test Data* (FHWA-RD-94-180). Federal Highway Administration, Washington, DC.

Vandenbossche, J. M., S. Nassiri, L. C. Ramirez, and J. Sherwood. (2012). Evaluating the Continuously Reinforced Concrete Pavement Performance Models of the Mechanistic-Empirical Pavement Design Guide. *Road Materials and Pavement Design*, Vol. 13, No. 2, pp. 235–248.

Won, M. (2009). *Evaluation of MEPDG with TxDOT Rigid Pavement Database* (FHWA/TX-09/0-5445-3). Center for Transportation Research, The University of Texas at Austin.

Zollinger, D. G., and E. J. Barenberg. (1990). *Continuously Reinforced Pavements: Punchout and Other Distresses and Implications for Design* (FHWA/IL/UI 227; Project IHR–518). Illinois Cooperative Highway Research Program, University of Illinois at Urbana–Champaign.

Zollinger, D. G., N. Buch, D. Xin, and J. Soares. (1999). *Performance of Continuously Reinforced Concrete Pavements. Vol. 6—CRC Pavement Design, Construction, and Performance* (FHWA-RD-97-151). Federal Highway Administration, Washington, DC.