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Development of Thin Bonded Concrete Overlay of Asphalt Design Method: Evaluation of Existing Mechanistic-Empirical Design Methods

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Development of Thin Bonded Concrete Overlay of Asphalt Design Method: Evaluation of Existing Mechanistic-Empirical Design Methods

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Partnered Pavement Research Center (PPRC) Strategic Plan Element Number 4.67: Development of Thin Bonded Concrete Overlay on Asphalt Design Method (DRISI Task 3198)

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15. SUPPLEMENTAL NOTES

16. ABSTRACT

The California Department of Transportation (Caltrans) is interested in advancing the technology needed to implement thin bonded concrete overlay of asphalt (BCOA) on its road network. Recent accelerated pavement tests showed that thin BCOA exhibited promising results for structural performance and constructability in California's dry environment when made with the high early-strength concrete mixes typically used by Caltrans. However, to continue moving forward, Caltrans needs to adopt a thin BCOA design method since the current Caltrans Highway Design Manual does not consider this type of pavement. In order to help Caltrans decide how to adopt a thin BCOA design method, this technical memorandum includes an evaluation of two existing mechanistic-empirical methods: BCOA-ME, developed by the University of Pittsburgh, and MEPDG, as implemented in Pavement ME Design versions 2.3 (2016) and later. The evaluation includes a sensitivity analysis that considered the most important factors in thin BCOA performance. The evaluation results show that the BCOA-ME and MEPDG methods are both based on sound mechanistic-empirical principles, but that they currently have technical and practical limitations that render them difficult to use for thin BCOA design in California. Based on the analysis presented in this technical memorandum, it is recommended that additional model development be performed to produce a design method that is more suitable for thin BCOA for the Caltrans road network. If Caltrans chooses this option, it is recommended that the new design method incorporate some models already used in BCOA-ME and MEPDG. Regardless of whether Caltrans decides to adopt an existing design method without changes or to further develop models to produce a more suitable method, the selected method will still need to be calibrated for California-specific materials and construction practices, in particular, the use of high early-strength materials; traffic; and climate conditions, with a focus on the prolonged drying that occurs throughout the state.

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This technical memorandum is expected to help Caltrans make a decision regarding a thin BCOA design method to be used on the Caltrans road network; more specifically, it is intended to help Caltrans decide whether to adopt either the BCOA-ME or MEPDG method without changes or to develop additional modeling to produce a design method that specifically covers California conditions.

8. RELATED DOCUMENTS
None

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DISCLAIMER

PROJECT OBJECTIVES

The goal of Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) Project 4.67, "Development of Thin Bonded Concrete Overlay on Asphalt Design Method," is to propose a mechanistic-empirical (ME) design method applicable to thin BCOA for the Caltrans road network and to develop recommendations and guidelines for use of the proposed method. The proposed method may be a new one developed as part of project 4.67 or modification of an existing procedure. In either case, field calibration/recalibration will be required to improve the reliability of BCOA performance prediction for Caltrans road network traffic, materials, pavement structures, and weather conditions. The project includes these tasks:

1. Analysis of Pros and Cons of the Different ME Design Options
2. Caltrans will decide if the project goes forward based on the results of Task 1.
3. Build Experimental Database for Calibration of the Procedure
4. Define Mechanistic-Empirical Framework
5. Calibration of the Design Method
6. Validation (Sensitivity Analysis) of the Design Method
7. Tool Finalization

The objective of the work presented in this technical memorandum is to help Caltrans decide whether to adopt the BCOA-ME or MEPDG thin BCOA design method as they are except for calibration, or to develop a new design method, completing the work of Task 1. To inform that decision, this memo includes the following:

- A summary of the current BCOA-ME and MEPDG design methods (Chapter 2)
- A summary of the main factors expected to impact thin BCOA performance in California (Chapter 3)
- Elaboration on how those main impact factors are addressed in the current ME design methods (BCOA-ME and MEPDG), including a sensitivity analysis (Chapter 4)
- Discussion of the current ME design methods' advantages and limitations (Chapter 5)
- A recommendation for how to move forward

LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ACPA	American Concrete Pavement Association
AASHTO	American Association of State Highway and Transportation Officials
BCOA	Bonded concrete overlay of asphalt
CSA	Calcium sulfoaluminate
CTE	Coefficient of thermal expansion
ELTG	Equivalent linear temperature gradient
EELTG	Effective equivalent linear temperature gradient
EICM	Enhanced Integrated Climatic Model
FD	Fatigue damage
FEM	Finite element method
HD	High Desert
HDM	Highway Design Manual
HMA	Hot mix asphalt
HVS	Heavy Vehicle Simulator
IRI	International Roughness Index
JPCP	Jointed plain concrete pavement
LTE	Load transfer efficiency
ME	Mechanistic-empirical
MEPDG	Mechanistic-Empirical Pavement Design Guide
MR	Modulus of rupture
PCC	Portland cement concrete
PPRC	Partnered Pavement Research Center
RSC	Rapid strength concrete
SC	South Coast
SJPCP	Short jointed plain concrete pavement
UCPRC	University of California Pavement Research Center

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)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		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)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		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

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (Revised March 2003).

1 INTRODUCTION

Thin bonded concrete overlay of asphalt (BCOA), formerly known as thin whitetopping, is a pavement rehabilitation alternative that consists of placement of a concrete overlay 4 to 7 inches thick (0.3 to approximately 0.6 ft) on an existing asphalt-surfaced pavement (flexible, composite, or semi-rigid). This rehabilitation technique has been used frequently on highways and conventional roads in several US states as well as in other countries, although its use has been very limited in California *(1)*.

The California Department of Transportation (Caltrans) is interested in implementing thin bonded concrete overlay of asphalt (BCOA) on its road network since recent accelerated pavement testing in Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) project 4.58B, showed that thin BCOA exhibited promising results for good structural performance and constructability in California's environment when made with the high early-strength concrete mixes typically used by Caltrans *(2)*. However, to continue moving forward, Caltrans needs to adopt a BCOA design method.

Several mechanistic-empirical (ME) design methods already developed can be used for thin BCOA designs:

1. The Colorado Thin Whitetopping Design method *(3)* developed in 2004
2. The BCOA Thickness Designer of the American Concrete Pavement Association (ACPA) *(4),* which was developed in 2008
3. The BCOA-ME design method developed at the University of Pittsburgh in 2013 *(5)*
4. The Mechanistic-Empirical Pavement Design Guide (MEPDG), as implemented in *Pavement ME Design,* versions 2.3 (2016) and later *(6)*

BCOA-ME and MEPDG are the most widely accepted of these design methods.

The current *Caltrans Highway Design Manual* does not consider thin BCOA, and Caltrans does not currently require or recommend any specific method or tool for designing this type of pavement. Caltrans's current interest in developing thin BCOA for California, coupled with the need for a recommended design method and tool, led to PPRC SPE 4.67, "Development of Bonded Concrete Overlay on Asphalt Design Method." This project's primary goal is to develop and implement a mechanistic-empirical method for designing thin BCOA adapted for the Caltrans road network *(7)*. Two general options were considered to achieve the goals of SPE 4.67:

- Option 1: Adopt either the BCOA-ME or the MEPDG design method without changes other than recalibration or validation for Caltrans road network conditions.
- Option 2: Adapt existing models and develop additional models as needed for a California BCOA design method as part of project 4.67. This updated method would be calibrated for Caltrans road network conditions.

1.1 Project Objective

The objective of the work presented in this technical memorandum is to help Caltrans decide whether to adopt the BCOA-ME or MEPDG thin BCOA design method or to develop an updated design method. To inform that decision, this memo includes the following:

- A summary of the current BCOA-ME and MEPDG design methods (Chapter 2)
- A summary of the main factors expected to impact thin BCOA performance in California (Chapter 3)
- Elaboration on how those main impact factors are addressed in the current ME design methods (BCOA-ME and MEPDG), including a sensitivity analysis (Chapter 4)
- Discussion of the current ME design methods' advantages and limitations (Chapter 5)
- A recommendation for how to move forward

1.2 Scope

The evaluation presented in this memorandum focuses on thin BCOA with half-lane-width slabs in dry California climates. Typical half-lane-width slabs are 5 to 7 ft wide and are arranged with their longitudinal joints either between lanes or halfway between the left and right vehicle wheelpaths (Figure 1.1). Because truck wheelpaths lie at the middle of the half-lane-width slabs, cracking typically occurs longitudinally, at roughly the middle of the slab. This cracking is due to tensile stresses that occur at the slab bottom under traffic loading *(8)*. The typical transverse joint spacing of half-lane-width slabs is also 5 to 7 feet.

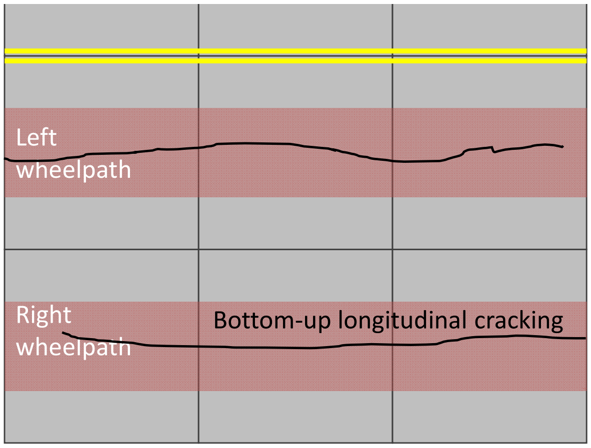


Figure 1.1: Layout and typical cracking pattern of half-lane-width slabs.

Thin BCOA with full-lane-width slabs (e.g., 12×12 ft) have been and continue to be built in some US states, including Iowa and Minnesota. Other states, such as Colorado, abandoned full-lane-width slabs. Based on results from Caltrans/UCPRC research project 4.58B, use of full-lane-width slabs is not recommended for California conditions. As stated in the 4.58B summary report *(2)*, "the increase in slab size from 6×6 to 12×12 resulted in three negative effects: 1) much worse transverse joint load transfer efficiency (LTE) performance, 2) much larger corner deflections, and 3) much larger concrete tensile strains under traffic loading."

Only two of the design methods mentioned earlier consider longitudinal cracking of half-lane-width slabs: BCOA-ME and MEPDG. The ACPA method focuses on corner cracking, which is critical for ultrathin BCOA with its very short slabs (e.g., 4×4). The Colorado Department of Transportation method focuses on transverse cracking, which is critical for thin BCOA with full-lane-width slabs. Consequently, only the BCOA-ME and MEPDG methods are considered as candidates for implementation in California.

1.3 Design Method versus Design Tool

Conceptually, a design method is quite different than a design tool. A design method includes a collection of models and procedures that can be used to estimate pavement performance. A design tool is the way the design method is implemented, that is, the design tool is the instrument used to conduct the design. The MEPDG method's design tool is the *Pavement ME Design* software (referred to in this technical memorandum as Pavement ME) and the design tool used in the BCOA-ME method is a web-based application. The same distinctions will apply to the Caltrans thin BCOA design method, regardless of whether Caltrans adopts Option 1 (an existing design method) or Option 2 (an updated design method). Table 1.1 shows combinations for the design method and the design tool options being looked into.

Table 1.1: Examples of Design Method and Design Tool Options for Caltrans

Option	Design Method	Design (Implementation) Tool
Option 1	MEPDG, with local calibration factors	Catalog
Option 1	MEPDG, with local calibration factors	Pavement ME
Option 1	BCOA-ME, with local calibration factors	Catalog
Option 2	New method, to be developed in SPE 4.67	Catalog
Option 2	New method, to be developed in SPE 4.67	Web-based application
Option 2	New method, to be developed in SPE 4.67	Catalog (for less experienced users) and a web-based application

2 EXISTING METHODS FOR THIN BCOA DESIGN: A SUMMARY

2.1 BCOA-ME

As with any mechanistic-empirical design method, BCOA-ME includes a mechanistic component and an empirical component. Both are described below.

2.1.1 Mechanistic Component of BCOA-ME

The mechanistic component of the BCOA-ME method consists of determining the tensile stresses under a 18 kip standard axle and an effective thermal gradient, respectively *(5)*. For half-lane-width slabs, the BCOA-ME method determines the stress due to a standard axle by using Equation [1], which was developed using a structural response database generated with the finite element method (FEM) software *Abaqus*. This stress (σ_{18})—the tensile stress at the bottom of the slabs at the transverse joints in the transverse direction— is supposed to result in bottom-up longitudinal cracking of the slabs. The FEM calculations used to develop the equation assumed a continuous asphalt base and full bonding between the base and the PCC. For the thermal-related stress, BCOA-ME adopted Equation [2], which was developed as part of the Colorado design procedure.

$$\sigma_{18}(\text{psi}) = \frac{e^{\frac{91.3668 + 0.0512\,H_{\text{HMA}}^2 + 8.6096\,H_{\text{PCC}} - \log(\text{NA})\,[27.4911 + 7.7478\,H_{\text{PCC}} + 7.7478\log(k\,E_{\text{HMA}})]}{15}}}{1.14} + 10 \qquad [1]$$

where H_{HMA} and H_{PCC} are HMA and PCC thickness, respectively, in inches; NA is depth of neutral axis in inches; k is *modulus of subgrade reaction* in psi/in.; and E_{HMA} is HMA stiffness in psi.

$$\sigma_T(\text{psi}) = 3.85\,\Delta T\,\sigma_{18} \qquad [2]$$

where ΔT is the *effective equivalent linear temperature gradient* (EELTG) in °F/in.

BCOA-ME determines the asphalt base stiffness (for use in Equation [1]) and the *effective equivalent linear temperature gradient,* EELTG (for use in Equation [2]), by employing two sets of equations that were developed using the *Enhanced Integrated Climatic Model (EICM)* as well as mechanic-empirical principles (the *EICM* is the climate model implemented in Pavement ME). In developing the two sets of equations, *EICM* was used to predict hourly temperature profiles in the slab and asphalt base of a number of BCOA sections at a large number of US locations. Then the two sets of equations were developed, as summarized below. Further details are available in the BCOA-ME theory manual *(5).*

According to the BCOA-ME, an asphalt mixture's stiffness changes depending on the BCOA section's characteristics and on which climate zone (defined by the annual mean daily average air temperature) it is in. In the development of BCOA-ME, a predefined dense-graded aggregate gradation was adopted for the asphalt mixture, and the type of binder was predetermined following recommendations from the software *LTTPBind3.1 (9).* Then the mixture stiffness was estimated by using the Witczak dynamic modulus predictive equation *(10)*, which is also implemented in Pavement ME. The modulus was reduced to account for damage present in the asphalt mixture: 5 and 12 percent reductions, respectively, for asphalt pavements with zero to 8 and 8 to 20 percent of the wheelpaths with fatigue cracking. Finally, the set of equations were calibrated. The equations allow determination of the effective asphalt base stiffness, for use in Equation [1], as a function of pavement location, slab thickness, and asphalt base thickness.

EELTG is the temperature gradient that, when applied to the slabs, results in the same fatigue damage as the actual temperature gradient distribution over the design life of the overlay. In developing the set of EELTG prediction equations, the hourly slab temperature profiles were first used to determine the hourly equivalent linear temperature gradients (ELTG), then these hourly ELTGs were used with mechanistic-empirical principles to determine the effective values (EELTG), and these effective values were finally used to calibrate the set of EELTG prediction equations. The equations allow the determination of the EELTG, for use in Equation [2], as a function of pavement location, slab thickness, asphalt base thickness, and concrete flexural strength.

It should be noted that, for a particular thin BCOA section, BCOA-ME adopts constant, effective, values for asphalt base stiffness and EELTG. The effective values are representative of the overlay's design life.

2.1.2 Empirical Component of BCOA-ME

The empirical part of BCOA-ME consists of the determination of the design stress—by combining the traffic and thermal-related stresses following Equation [3]—and the determination of the number of load repetitions to failure (N_f)—by using the Riley PCC fatigue model, Equation [4]. (The Riley fatigue model *[11]* was originally developed for the ACPA design method.)

$$\sigma_{\mathrm{Design}} = F_{\mathrm{Stress}}\,\sigma_{18} + \sigma_{\mathrm{T}} \qquad [3]$$

where F_{Stress} is a field calibration factor

$$\log(N_f) = \left[\frac{-SR^{-10.24}\log(R)}{0.0112}\right]^{0.217} \qquad [4]$$

where SR is the stress ratio (PCC design tensile stress divided by flexural strength), and R is reliability expressed as a decimal (>0 and <1).

An important difference between BCOA-ME and its predecessors (ACPA and Colorado) is that it has been field calibrated. The calibration was based on the performance of 11 thin BCOA sections with half-lane-width slabs: three in Minnesota, two in Illinois, and six in Colorado. The calibration sections included transverse joint spacings from 5 to 6 ft, PCC thicknesses from 3 to 6 in., and HMA thicknesses from 3 to 10 in. The field calibration factor, F_{Stress}, was assumed to depend on HMA thickness, PCC thickness, and flexural strength (Equation [5]).

$$\mathrm{F_{Stress}} = [1.70815412 - 0.03953861\,\min(4\text{ in.}, \mathrm{H_{PCC}}) + 0.03623689\,\mathrm{H_{HMA}} - 0.01942344\,\mathrm{H_{HMA}^2} + 0.00091517\,\mathrm{H_{HMA}^3}]\left(\frac{\mathrm{MR}}{650}\right)^{0.35} \quad [5]$$

where $\mathrm{H_{HMA}}$ and $\mathrm{H_{PCC}}$ are HMA and PCC thickness, respectively, in inches, and MR is PCC flexural strength in psi.

A summary of BCOA-ME's design features is included in Table 2.1.

The BCOA-ME method is implemented using the web-based tool available at *www.engineering.pitt.edu/ Vandenbossche/BCOA-ME/.* The tool's output is the calculated slab design thickness.

2.2 MEPDG

The preliminary research conducted for this project found only one source that documented the MEPDG thin BCOA design procedure: the training webinar that accompanied the release of *PavementME,* version 2.3 *(12).* This webinar included some general information about the design procedure but lacked the detail needed to fully support the analysis presented in this memorandum. Therefore, some reverse-engineering analysis was conducted as part of this study to complement the information in the webinar. The information presented below is based on both the webinar and the reverse-engineering analysis.

2.2.1 Mechanistic Component of MEPDG

The mechanistic component of MEPDG thin BCOA design consists of determining the tensile stresses under traffic loading while considering thermal gradients. MEPDG calculations are based on a full traffic-loading spectrum rather than on an 18 kip standard axle. Tensile stresses are determined using a neural network structural model that was calibrated using a database generated with the FEM software *ISlab2000 (13).* The stress predicted by the neural network model is the tensile stress at the bottom of the slabs at the transverse joints in the transverse direction, which is supposed to result in bottom-up longitudinal cracking of the half-lane-width slabs. Full bonding between the PCC and asphalt base was assumed in those FEM calculations, based on the BCOA-ME assumption. Jointed asphalt base was also assumed. The MEPDG uses the *EICM* to determine PCC temperature gradients and HMA temperatures. The latter are used to determine HMA stiffness, based on the dynamic modulus master curve, while the PCC temperature gradients are used with traffic loading to determine PCC tensile stresses.

2.2.2 Empirical Component of MEPDG

The empirical component of MEPDG thin BCOA design consists of determining the cumulative fatigue damage (FD) throughout the section's design life—as shown in Equation [6]—and determining the percentage of cracked slabs by using the transfer function shown in Equation [7]. Equation [6] represents the application of Miner's law to the different loading scenarios the thin BCOA will undergo throughout its design life. The different loading scenarios are represented by the sub-indexes i, j, k, l, m, and n, which refer to age, month, axle type, axle load, temperature gradient, and wheelpath offset, respectively. The allowable number of load repetitions is determined by using the fatigue law shown in Equation [8], which was calibrated based on standard jointed plain concrete pavement (JPCP) cracking performance.

$$\mathrm{FD} = \sum \frac{\mathrm{n}_{\mathrm{i,j,k,l,m,n}}}{\mathrm{N}_{\mathrm{i,j,k,l,m,n}}} \qquad [6]$$

where $n_{i,j,k,l,m,n}$ is the number of load applications under certain loading conditions, and $N_{i,j,k,l,m,n}$ is the allowable number of load repetitions under the same conditions.

$$\mathrm{Cr} = \frac{1}{1 + \mathrm{C4}\ \mathrm{FD}^{\mathrm{C5}}} \qquad [7]$$

where C4 and C5 are field calibration coefficients: C4 = 0.40 and C5 = -2.21.

$$\log\left(\mathrm{N}_{\mathrm{i,j,k,l,m,n}}\right) = 2.0 \left(\frac{\mathrm{MR}_{\mathrm{i}}}{\sigma_{\mathrm{i,j,k,l,m,n}}}\right)^{1.22} \qquad [8]$$

where $\sigma_{i,j,k,l,m,n}$ is tensile stress under the loading conditions represented by i, j, k, l, m, and n, and MR_i is PCC flexural strength at age i.

The MEPDG thin BCOA design procedure was calibrated based on the cracking performance of 30 thin BCOA sections with half-lane-width slabs in Minnesota, Illinois, and Colorado. The calibration sections included transverse joint spacings from 5 to 6 ft, PCC thicknesses from 4 to 6 in., and HMA thicknesses from 3 to 8 in.

MEPDG design reliability is based on the standard deviation of the cracking prediction model error. This standard deviation can be estimated with Equation [8], which is an output of the field calibration of the design procedure. Once the standard error (SE_{Cr}) is determined, the cracking at any reliability level can be estimated by multiplying SE_{Cr} by the corresponding z-value (cumulative standard normal distribution corresponding to R).

$$\mathrm{SE}_{\mathrm{Cr}} = 3.5522\ \mathrm{Cr}^{0.4315} + 0.5 \qquad [9]$$

where Cr is predicted cracking at 50% reliability (Equation [7])

MEPDG thin BCOA design is implemented in the Pavement ME software, version 2.3 and later. The Pavement ME software refers to thin BCOA to as short jointed plain concrete pavement (SJPCP).

Pavement ME's output is not the slab design thickness. Rather, slab thickness is a Pavement ME input. Instead, the program's output is the expected evolution of slab longitudinal cracking, at 50 percent and R reliability levels, throughout section's design life. In practice, the designer reruns the software until a slab thickness and other design variables (slab dimensions, asphalt thickness, etc.) that satisfy the required traffic and reliability are found.

Table 2.1: Summary of BCOA-ME and MEPDG Design Methods

Design Feature	BCOA-ME	MEPDG
Overall approach	Non-incremental	Incremental non-recursive
Climate	Sets of equations that were developed based on *EICM* and mechanistic-empirical principles	Hourly temperature and moisture determined with the *EICM*
Traffic	ESALs	Traffic loading spectrum
Stress calculation	Load-related stress: equation based on *Abaqus* FEM software results; Thermal-related stress: Colorado thin BCOA equation	Neural network based on *ISLAB2000* software results
Cracking calculation	Riley fatigue equation (predicts cracking based on stress ratio and reliability)	Two-step approach: 1) calculate cumulative damage using Miner's law, and 2) relate damage to cracking by using a field-calibrated transfer function
Reliability	Included in Riley fatigue equation	Based on standard error of the estimation
Field calibration	11 sections in Minnesota, Illinois, and Colorado	30 sections in Minnesota, Illinois, and Colorado
Range of slab dimensions	6×6 and 7×7 3–6.5 in. PCC thickness	5×5, 6×6, 7×7, and 8×8 4–8 in. PCC thickness
Software output	Slab thickness	Prediction of cracking throughout section's design life
Implementation	Web-based application	Pavement ME computer software

3 IMPORTANT FACTORS FOR THIN BCOA PERFORMANCE IN CALIFORNIA

The goal of the recently completed PPRC SPE 4.58B research project was to develop recommendations and guidance on the use of thin BCOA as a rehabilitation alternative in California. As part of that project, 11 full-scale thin BCOA sections were tested with the Heavy Vehicle Simulator (HVS). The HVS testing revealed that three design factors had a large impact on the performance of this type of pavement *(14):*

- *Asphalt base thickness.* This factor was found to have a considerable impact on the load transfer efficiency (LTE) performance of the transverse joints. During HVS testing of sections with a thin (2.5 in.) asphalt base LTE dropped considerably, but it remained stable during tests on sections with a thick (over 4 in.) asphalt base. The asphalt base thickness also had a considerable impact on the strains measured at the bottom of the concrete slabs under the HVS traffic, as expected.
- *Asphalt base condition.* Under HVS traffic, one of the sections with asphalt fatigue cracking and a deteriorated concrete-asphalt interface showed worse LTE performance and larger strains at the slab bottom than the sections where the asphalt base was in fair condition.
- *Slab size.* This factor was found to have a considerable impact on the LTE of the transverse joints, as expected. It was also found that the 12×12 ft slabs presented concrete-asphalt debonding along their perimeter. The 8×8 ft slabs also presented concrete-asphalt debonding and poor LTE, although less than the 12×12 ft slabs.

The research conducted in project 4.58B also revealed other design factors with important roles in thin BCOA performance, although secondary to the three factors noted above.

- *Asphalt mix type.* The use of new rubberized asphalt base (RHMA-G) resulted in improved LTE performance, compared to old HMA. The improved LTE performance was attributed to the rubberized mix's greater fatigue resistance.
- *Widened slab.* Widening the slabs (into the shoulder) resulted in a considerable reduction of the traffic-related strains at the edges of the slabs and a consequent reduction of transverse cracking risk. Conversely, widening the slabs increased the risk of top-down longitudinal cracking.
- *Concrete curing procedure.* This factor was evaluated based on the performance of six full-scale thin BCOA sections whose structural response to ambient environment was monitored for 15 months. One of the sections, treated with a shrinkage-reducing admixture spray, presented much smaller drying shrinkage than the sections where the concrete was cured with curing compound. The relevance of the curing procedure is particularly applicable to dry and warm weather conditions in California.

The research conducted in project 4.58B also revealed that thermal and drying shrinkage deformations have a large impact on the LTE of transverse joints and slab deflection under HVS traffic. Based on that finding, the coefficient of thermal expansion (CTE) and drying shrinkage of concrete are regarded as important properties that impact thin BCOA performance.

The concrete types considered in the research were 4-hour opening time concrete made with Type III portland cement or with calcium sulfoaluminate (CSA) cement, and 10-hour opening time concrete made with Type I/II portland cement. Other than the effects of CTE and drying shrinkage, the concrete type selected did not produce any remarkable effects on the sections' performance under HVS traffic. This outcome is explained by the fact that cracking only occurred on one of the sections—and this was during an extended HVS test conducted on that section only. Consequently, no comparative analysis could be conducted. In the field, the concrete's mechanical properties are expected to impact its cracking fatigue life. Long-term durability, which is strongly related to the properties of concrete, was not evaluated in project 4.58B.

Slab thickness was another design factor evaluated in project 4.58B and it too produced no remarkable effects on the sections' performance under HVS traffic. The study found that this was due to the sound concrete-asphalt bonding in the sections where the effect of slab thickness was evaluated. In the field, however, long-term concrete-asphalt bonding is not guaranteed. Once debonding (full or partial) takes place, the additional slab thickness results in lower tensile stresses at the bottom of the slabs under traffic loading, extending cracking fatigue life.

It is also believed that climate conditions and the bearing capacity of a pavement's foundation (subbase/subgrade) affect thin BCOA performance, although these factors were not evaluated in project 4.58B.

Table 3.1 summarizes some of the factors described above that each design procedure considers. The summary is based on a review of BCOA-ME and Pavement ME documentation and input variables.

Table 3.1: Important Design Factors to Consider in BCOA-ME and Pavement ME

Design Factor	BCOA-ME	Pavement ME
Asphalt base thickness	Yes	Yes
Asphalt base condition	Yes	No
Slab size	Yes	Yes
Type of asphalt mix	No	No
Widened slab	No	No
Concrete curing procedure	No	Yes
Concrete type and properties	No	Yes
Slab thickness	Yes	Yes
Concrete-asphalt debonding	No	No
Climate	Yes	Yes
Foundation (subbase/subgrade)	Yes	Yes

4 SENSITIVITY ANALYSIS OF EXISTING TOOLS FOR DESIGNING THIN BCOA

A sensitivity analysis was performed as part of this project to compare the designs generated using the BCOA-ME and Pavement ME tools. The purpose of the sensitivity analysis was to determine whether the tools produce similar results for typical California situations, and to evaluate whether the results seem reasonable based on the findings of the 4.58B project and experiences in other states found in the literature.

4.1 Reference Section and Sensitivity Analysis Approach

Except for slab thickness differences, the reference section was the same for both design tools and consisted of a PCC overlay with 6×6 slabs (6 ft long, 6 ft wide) on a flexible pavement, as shown in Figure 4.1. The asphalt base was assumed to be in fair condition, with 15 percent fatigue cracking. The design traffic in the design lane was equivalent to 4 million ESALs over a 20 year design life. The 20 year design life is the minimum period specified by Caltrans for roadway rehabilitation projects. The reference section's slab thickness was determined independently with each design tool.

In the slab thickness design, the selected failure criterion was 15 percent slab cracking. This percentage is higher than the 10 percent that *Caltrans Highway Design Manual* (HDM) Chapter 622 specifies for standard JPCP but it is still below the 25 and 20 percent failure criteria that the BCOA-ME and ACPA design methods recommend, respectively. The adopted design reliability was 85 percent, which is lower than the 90 percent assumed in the development of the current HDM JPCP design catalog. The 85 percent reliability value aligns with the assumption that the rehabilitation is to be conducted on a secondary state highway. The failure criterion was unrelated to transverse joint faulting and IRI since neither the BCOA-ME nor the MEPDG methods model thin BCOA faulting.

Reference Section

- 6×6 thin BCOA in Sacramento
- Two-lane road, one lane per direction
- HMA layer is 8 in. thick, 6 in. after milling (2 in. milling), and has 15% fatigue cracking
- Design traffic is equivalent to 4 million ESALs
- Slab design thickness is either 4 in. (based on BCOA-ME) or 6 in. (based on Pavement ME)
- Asphalt shoulder

Reference Calculation

- Design life: 20 years
- Failure criterion: 15% cracked slabs
- Reliability: 85%

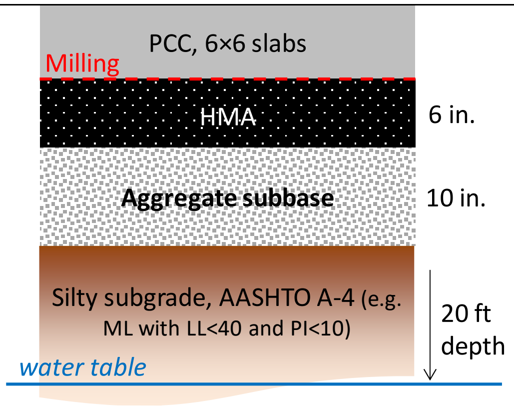


Figure 4.1: Thin BCOA reference section and reference design.

As shown in Figure 4.1, BCOA-ME and Pavement ME yielded very different slab design thicknesses. BCOA-ME generated a 4.0 in. slab while Pavement ME yielded in a 5.7 in. slab (rounded up to 6 in.). One reason for this significant difference is the different asphalt damage levels assumed in the two design procedures. This topic is elaborated on in Section 4.3.8, Asphalt Base Condition.

In the sensitivity analysis, identical changes were made to the two reference designs' input variables, and the changes to the predicted percent cracking were examined.

4.2 Sensitivity Analysis Factorial

Selection of the design factors for the sensitivity analysis was based on the conclusions presented in Chapter 3. Those factors are presented in Table 4.1. The table includes each design's reference value (under the heading "Reference Section") and two alternative values adopted in the sensitivity analysis.

4.3 Results of Sensitivity Analysis for BCOA-ME and Pavement ME

The BCOA-ME sensitivity analysis results are presented in Figure 4.2 and Figure 4.4, which correspond to longitudinal cracking predictions at 50 and 85 percent reliability, respectively. The Pavement ME sensitivity analysis results with those same respective reliability levels are presented in Figure 4.3 and Figure 4.5. The sensitivity analysis focused on the percentage of cracked slabs each model predicted at the end of the design life. This variable is an output of Pavement ME but not of the BCOA-ME web implementation tool, which has instead a design thickness output. For this reason, reverse-engineering was required to determine the percentage of cracked slabs predicted by BCOA-ME at the end of the design life (trial and error would have been another option).

The two design procedures' sensitivity analysis results are discussed below.

Table 4.1: Factorial Design of the Sensitivity Analysis

Design Factors	Reference Section	Sensitivity Analysis	
		Level 1	**Level 2**
Climate zone	Inland Valley (IV)	South Coast (SC)	High Desert (HD)
	City of Sacramento (asphalt PG 64-10)	City of San Diego (asphalt PG 64-10)	City of Alturas (asphalt PG 64-28)
Traffic level (design lane)	4 million ESALs	2 million ESALs	8 million ESALs
	Pavement ME Truck Traffic Classification group 15, initial two-way AADTT 850, 3% linear growth rate	Pavement ME Truck Traffic Classification group 15, initial two-way AADTT 425, 3% linear growth rate	Pavement ME Truck Traffic Classification group 15, initial two-way AADTT 1700, 3% linear growth rate
PCC MR (28 days)	650 psi	600 psi	750 psi
	Concrete stiffness is 4.15 million psi (ACI formulas)	Concrete stiffness is 3.83 million psi (ACI formulas)	Concrete stiffness is 4.79 million psi (ACI formulas)
PCC type	Normal strength concrete (NSC)	Sulfate resistant concrete(SRC)	Rapid-strength concrete (RSC)
	600 lb/cy of Type I portland cement, 0.42 water/cement ratio	600 lb/cy of Type II portland cement, 0.42 water/cement ratio	700 lb/cy of Type III portland cement, 0.33 water/cement ratio
PCC CTE	5.5 με/°F	4 με/°F	6.5 με/°F
	Adopted for calculation of current HDM catalog	Limestone aggregates	Sandstone aggregates
Slab thickness	Design thickness	-0.5 in.	+0.5 in.
	Pavement ME: 6 in. BCOA-ME: 4 in.	0.5 in. below design thickness	0.5 in. over design thickness
Asphalt thickness	6 in.	5 in.	7 in.
	After milling	After milling	After milling
Asphalt condition	Fair (Marginal)	Poor (Inadequate)	Good (Adequate)
	15% fatigue cracking	25% fatigue cracking	No fatigue cracking
Slab size	6×6	5×5	7×7
Shoulder type	Asphalt shoulder	Tied PCC shoulder	Widened slab
Transverse joint LTE*	Default	-10%	+10%
	Pavement ME: 80% BCOA-ME: 90%	10% below default LTE	10% above default LTE
Foundation	Fair	Weak	Strong
	10 in. aggregate subbase; subgrade soil A-4; water table depth: 20 ft; equivalent k: 240 psi/in	10 in. aggregate subbase; subgrade soil A-5 (silty); water table depth: 10 ft; equivalent k: 160 psi/in.	10 in. aggregate subbase; subgrade soil A-3 (sand); water table depth: 30 ft; equivalent k: 460 psi/in.

*The LTE of the transverse joints is not a design factor, but a performance variable. In this regard, LTE is not different from cracking: the two are variables the design procedure should predict. Nonetheless, BCOA-ME and the Pavement ME either pre-assume LTE or require that LTE is input by the user. For this reason, LTE is included in the table.

4.3.1 Climate Zone

Weather conditions in each climate zone are expected to impact thin BCOA performance in a number of ways, although BCOA-ME only accounts for the impact on asphalt base temperature (stiffness) and PCC temperature gradients, and Pavement ME does something similar. As shown in Figure 4.2 through Figure 4.5, both design procedures show sensitivity to the climate zone, although the resulting effects from BCOA-ME are much larger and go in the opposite direction than the effects resulting from Pavement ME.

It is unclear why the effects of climate zone differ so much between the BOCA ME and Pavement ME procedures, particularly because they follow similar approaches to account for these effects and are both based on a temperature that *EICM* determines. The fact that Pavement ME results show less cracking in the High Desert (HD) zone than in the other two zones does not seem reasonable.

Based on the HDM JPCP design catalog, design slab thicknesses for a pavement with a traffic index between 10.5 and 11 (approximately 4 million ESALs), no shoulder support, and an asphalt base are 10.8 in. for the Inland Valley (IV), 9.6 in. for the South Coast (SC), and 11.4 in., and High Desert (HD) climate zones. This means that for an equal slab thickness, slab cracking should be lowest in the SC and the highest in the HD, an outcome that does not agree with BCOA-ME and Pavement ME. It should be noted that the HDM catalog is not applicable to thin BCOA, which may explain the observed differences.

Further analysis would be required to determine which design procedure would yield the more realistic consideration of the effects of climate zone in California.

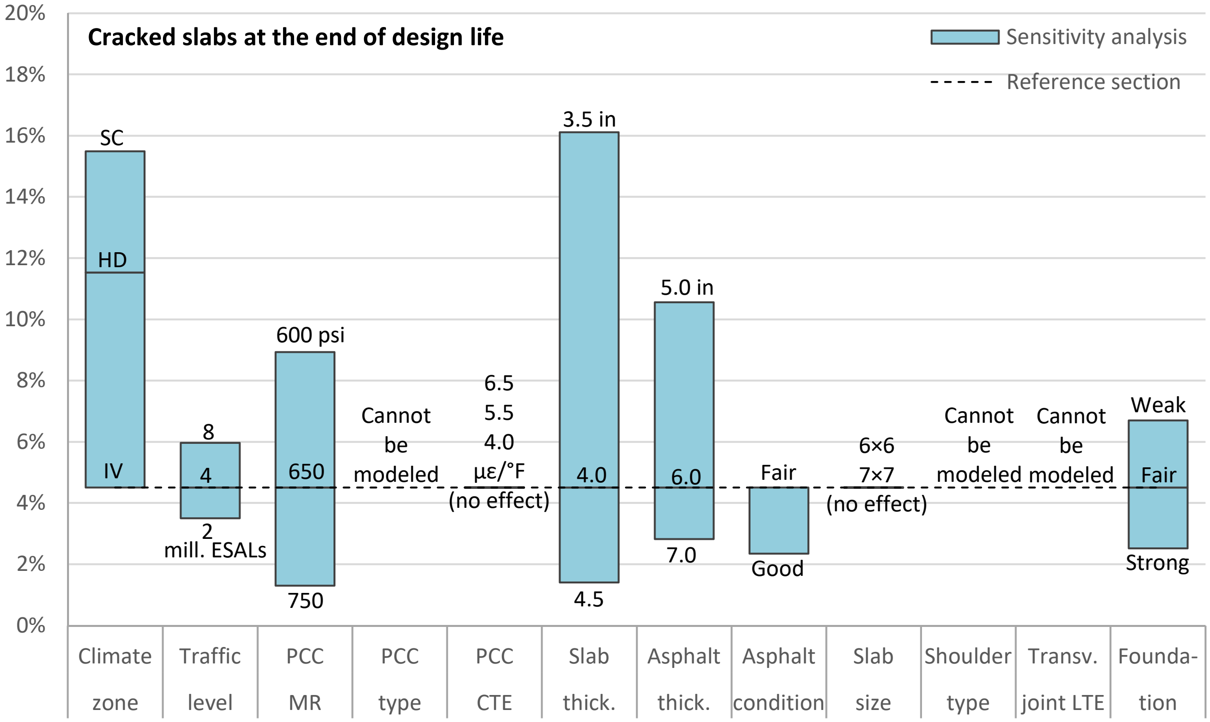


Figure 4.2: BCOA-ME sensitivity analysis at 50 percent reliability.

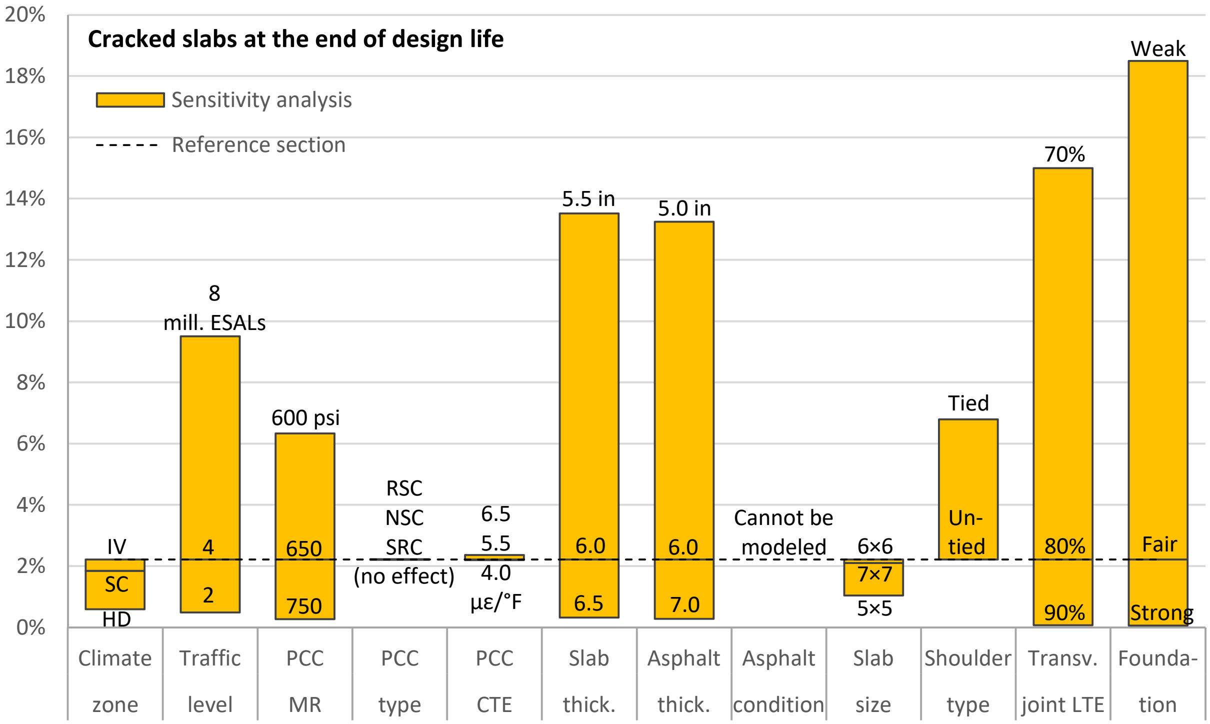


Figure 4.3: Pavement ME sensitivity analysis at 50 percent reliability.

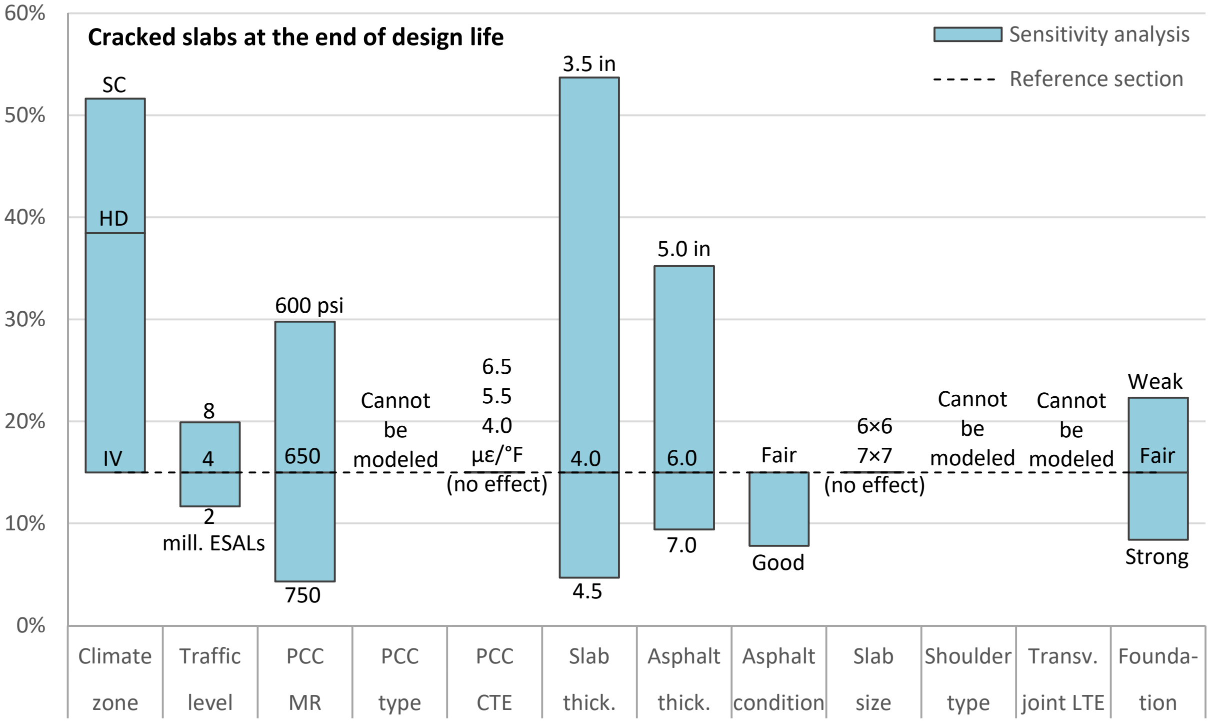


Figure 4.4: BCOA-ME sensitivity analysis at 85 percent reliability.

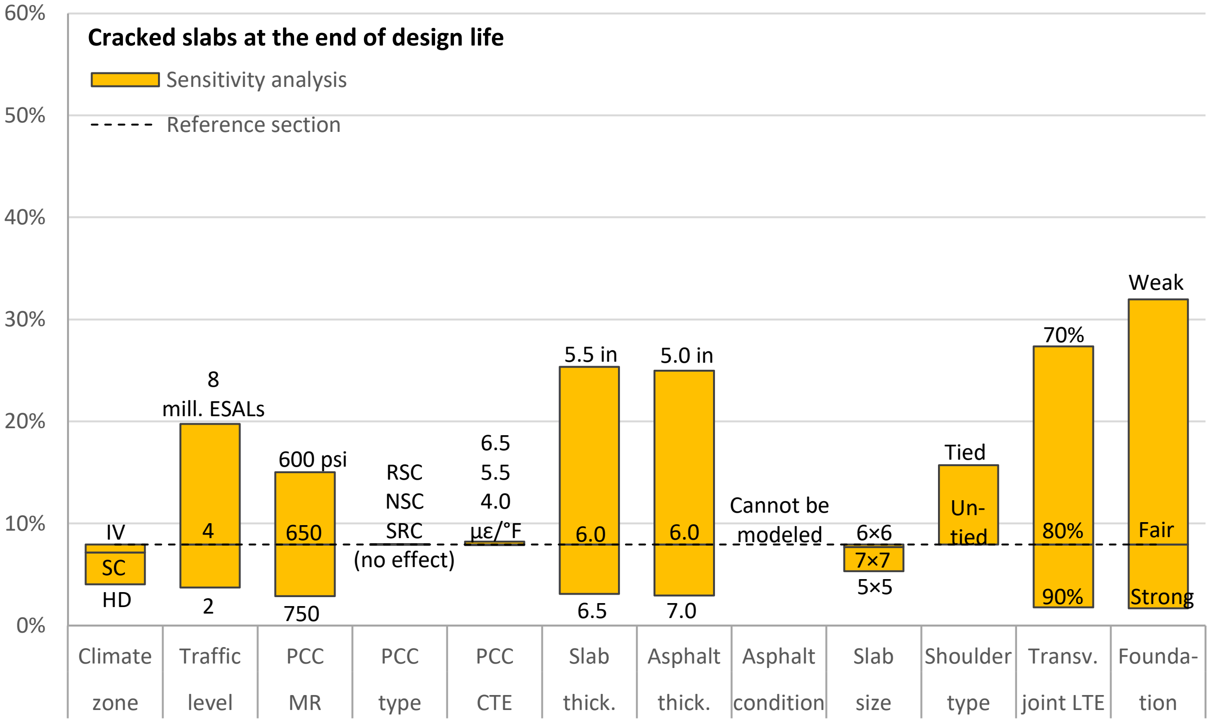


Figure 4.5: Pavement ME sensitivity analysis at 85 percent reliability.

4.3.2 Traffic Level

Traffic level effects were evaluated by either doubling or halving the reference traffic (4 million ESALs). Although the traffic level input to BCOA-ME is number of ESALs, Pavement ME uses truck traffic loading spectrum for this input. Nonetheless, number of ESALs is an output of Pavement ME and it has been used in this sensitivity analysis.

As shown in Figure 4.2 and Figure 4.4, a change in traffic level produces very little change in the cracking predicted by BCOA-ME, which seems to present very little sensitivity to this input. For example: the calculated slab thicknesses of the reference section are 4.00, 4.36, and 4.66 in., respectively, for 4, 40, and 400 million ESALs, the latter being a traffic level far beyond the capacity of any thin BCOA.

As shown in Figure 4.3 and Figure 4.5, the change in traffic level produces a reasonable change in the cracking predicted by Pavement ME at the end of the design life. More specifically, doubling or dividing the design traffic produces an effect comparable to decreasing or increasing the slab thickness by 0.5 in.

4.3.3 PCC Flexural Strength

PCC 28-day flexural strength (MR) in the reference section was 650 psi. As shown in Figure 4.2 through Figure 4.5, a change in flexural strength to either 600 or 750 psi produced a reasonable impact on the cracking predicted by BCOA-ME and Pavement ME at the end of the section's design life.

It should be noted that level 3 inputs were selected for the concrete mechanical properties in Pavement ME; more specifically, 28-day flexural strength was the only input. For this case, Pavement ME uses ACI formulas to first determine concrete compressive strength based on the flexural strength, and then uses that compressive strength result to determine concrete elastic modulus. Then, Pavement ME uses a predefined time function to determine the time evolution of flexural strength and elastic modulus. The predefined time function is based on normal strength concrete and is not applicable to the rapid-strength concrete Caltrans would typically use in thin BCOA rehabilitation projects.

4.3.4 PCC Type

The concrete mix used for the reference section was a normal-strength concrete with 600 lb/cy of Type I portland cement and a 0.42 water/cement ratio. This concrete mix is typically designed to meet the 28 day opening strength requirement. The sensitivity of Pavement ME to the type of concrete was evaluated by considering two other concrete types: 1) a sulfate-resistant concrete that uses Type II portland cement (Type II cement usually generates heat at a slower rate than Type I cement), and 2) a rapid-strength concrete that incorporates 700 lb/cy of Type III portland cement and has a 0.33 water/cement ratio. In practice, the type of concrete and the flexural strength after 28 days are linked. Nonetheless, they were evaluated as two independent variables in this sensitivity analysis. By doing so, the effects of each of the variables could be quantified.

As shown in Figure 4.3 and Figure 4.5, the concrete type (i.e., cement type, cement content, and water/cement ratio) produced no effects on the cracking predicted by Pavement ME. This was an unexpected result since Pavement ME uses the mix properties to determine drying shrinkage by using the *RILEM B3* model. The fact that the change in mix properties did not produce any change in the predicted cracking suggests that the Pavement ME thin BCOA design does not consider slab warping due to variable drying shrinkage. The validity of this hypothesis was verified: changing concrete drying shrinkage (input level 1) did not produce any change in the Pavement ME output.

It was also verified that the Pavement ME thin BCOA design tool considers the permanent curl-warp effective temperature difference. Although the output of Pavement ME was sensitive to this parameter, the effects went in the opposite direction of what was expected: a change from -10°F (default value) to 0°F resulted in increased cracking at the end of the design life (approximately twice as much cracking) while a change to -20°F resulted in decreased cracking. It should be noted that the default value for this parameter, -10°F, was backcalculated during the initial development of the MEPDG *(15)*. The backcalculation was based on the cracking performance of standard JPCP and, consequently, the applicability of this value to thin BCOA design is debatable.

The only mechanical properties of concrete that BCOA-ME accounts for are strength and stiffness, so its applicability for modeling different concrete types is limited.

4.3.5 PCC CTE

The concrete CTE in the reference section was 5.5 με/°F, and the effects of CTE were evaluated by changing its value to 4.0 and 6.5 με/°F. These alternate values are typical of portland cement concrete made with limestone and sandstone aggregates, respectively. The typical range of CTE in California, based on UCPRC research and values input by contractors into the Caltrans CTE database, is 3.5 to 7 με/°F.

BCOA-ME output was not sensitive to concrete CTE, as shown in Figure 4.2 and Figure 4.4. This outcome is due to the approach BCOA-ME uses to determine thermal-related stresses in half-lane-width slabs, which is based on Equation [2]. That equation does not consider concrete CTE.

Cracking output from Pavement ME barely changed with changing concrete CTE, as shown in Figure 4.3 and Figure 4.5. This outcome contrasts with the significance that MEPDG 2004 documentation attributes to concrete CTE *(15).*

4.3.6 Slab Thickness

The reference section's slab thickness was 4 in. based on BCOA-ME and 6 in. based on Pavement ME. The sensitivity of the two design procedures to slab thickness was evaluated by respectively increasing and decreasing the thickness by 0.5 in. As shown in Figure 4.2 through Figure 4.5, a change in slab thickness produces a reasonable impact on the cracking predicted by BCOA-ME and Pavement ME at the end of the section's design life.

4.3.7 Asphalt Thickness

The reference section's asphalt thickness was 6 in. The sensitivity of the BCOA-ME and Pavement ME design procedures to asphalt thickness was evaluated by respectively increasing and decreasing the thickness by 1 in. As shown in Figure 4.2 through Figure 4.5, the change in asphalt thickness produced a reasonable impact on the cracking predicted by BCOA-ME and Pavement ME at the end of the section's design life. For Pavement ME, a 1 in. change in asphalt base thickness produced an impact on cracking similar to a 0.5 in. change in slab thickness. For BCOA-ME, the impact of a 1 in. change in asphalt base thickness was smaller than the impact of a 0.5 in. change in slab thickness. This outcome seems reasonable since the original slab thickness was only 4 in.

4.3.8 Asphalt Base Condition

The reference section's asphalt base was assumed to have 15 percent fatigue cracking. In this memorandum, that condition is referred to as "fair." Two other asphalt condition levels were adopted to evaluate the two procedures' sensitivity to asphalt base condition: 1) 25 percent fatigue cracking, which is referred to as "poor," and 2) no fatigue cracking, which is referred to as "good."

It should be noted that, for both BCOA-ME and Pavement ME, the only effect resulting from a change to the asphalt base condition was a change in the layer's stiffness: the worse the condition, the lower the stiffness, and vice versa. Therefore, for the sensitivity analysis presented in this technical memorandum, the term "asphalt condition effect" could be used interchangeably with the term "asphalt stiffness effect."

Asphalt base condition is an input to BCOA-ME, although this method only allows two alternative levels. These two levels are referred to as "adequate" (0 to 8 percent fatigue cracking) and "marginal" (8 to 20 percent fatigue cracking). The latter matches asphalt conditions in the reference section (fair) while the former matches Option 2 of the sensitivity analysis (good). BCOA-ME accounts for asphalt damage following the methodology developed as part of the MEPDG initial calibration *(15).* According to that methodology, asphalt stiffness is first determined for the undamaged condition using the dynamic modulus master curve. Then, the undamaged modulus is corrected for damage. The correction consists of reducing the undamaged modulus by a percentage that depends on asphalt cracking. The adequate (good) and marginal (fair) BCOA-ME asphalt base conditions correspond to, respectively, 5 and 12.5 percent reductions of the undamaged modulus. As shown in Figure 4.2 and Figure 4.4, changing the asphalt condition from marginal to adequate resulted in a reasonable reduction of the fatigue cracking predicted by BCOA-ME.

Pavement ME accounts for the damage of the existing asphalt layers by following the same methodology described above. The percentage of asphalt fatigue cracking is a design input, which Pavement ME uses to determine the asphalt damage. Finally, it uses the damage value to determine the percentage reduction of the modulus of the undamaged asphalt. Pavement ME makes use of this methodology in rehabilitation projects. In particular, the methodology is applicable to a standard JPCP built on an existing asphalt base and to thin BCOA design. In the latter case, it was found that the user cannot change the fatigue cracking value of the existing asphalt base. This means that the user cannot specify asphalt condition in a thin BCOA design. Instead, Pavement ME assumes 65 percent fatigue cracking. This cracking level corresponds to an approximate 50 percent reduction of the undamaged modulus, which may be too conservative for most thin BCOA projects.

The 65 percent asphalt fatigue cracking that Pavement ME assumes is based on the calibration of the thin BCOA design procedure. As explained in Section 2.2, this design procedure was calibrated based on the cracking performance of 30 sections. For each of the 30 sections, asphalt base cracking was used as a fitting parameter, i.e., it was changed to fit actual measured cracking. The resulting asphalt cracking ranged from 50 to 75 percent, with an average value of 65 percent, which was used for every section in the calibration of the cracking model. Finally, 65 percent was set as a constant calibration factor in the software.

4.3.9 Slab Size

The reference section's thin BCOA slabs were assumed to be 6 ft long by 6 ft wide (6×6). Two other slab sizes were adopted in the sensitivity analysis: 5×5 and 7×7. The former could only be modeled with Pavement ME, while the latter could be modeled with both BCOA-ME and Pavement ME.

As shown in Figure 4.2 and Figure 4.4, the change in slab size did not affect the BCOA-ME output. This is because Equation [1], which is used in BCOA-ME to determine concrete tensile stress under the standard axle, does not include slab size as an input variable.

As shown in Figure 4.3 and Figure 4.5, the slab size change had very little impact on the Pavement ME cracking prediction. The fact that predicted cracking was the same for 6×6 and 7×7 slabs does not seem reasonable.

Because the evaluation in this memorandum focuses on thin BCOA with half-lane-width slabs, which are typically 5 to 7 feet long and 5 to 7 feet wide, the sensitivity analysis presented in Figure 4.2 through Figure 4.5 only included 5×5, 6×6, and 7×7 slabs. However, slab design thicknesses were also determined for 12×12 slabs. Based on BCOA-ME, the calculated design thickness for 12×12 slabs was 5.6 in. (it was 4.0 in. for 6×6 slabs). Based on Pavement ME, the calculated design thickness for 12×12 slabs was 7.1 in. (it was 5.7 in. for 6×6 slabs). In short, increasing the slab size from 6×6 to 12×12 required an increase in slab thickness of 1.6 in. based on BCOA-ME and 1.4 in. based on Pavement ME.

In Pavement ME, a thin BCOA with 12×12 slabs is a standard JPCP pavement where the PCC slab and asphalt base remain bonded throughout section's design life. Pavement ME's structural response models and field calibration factors differ between thin BCOA (referred to as *SJPCP* in Pavement ME) and JPCP. One of the differences is that the LTE of the transverse joints is an input to SJPCP design (e.g., 6×6 slabs) while it is an output for a standard JPCP design (e.g., 12×12 slabs). For the particular 12×12 section modeled in this project, the LTE of the transverse joints was approximately 40 percent throughout section's design life. Another difference between SJPCP and JPCP modeling is that the latter includes faulting and IRI. For the particular 12×12 section modeled in this project, because the transverse joints were not doweled, faulting and IRI did not achieve the performance requirements when the slab thickness was 7.1 in. To keep faulting below 0.1 in. and IRI below 170 inches/mile (with both at an 85 percent reliability level), the slab thickness had to be further increased to 8.5 in.

4.3.10 Shoulder Type

The reference section had an asphalt shoulder, and two other shoulder types were introduced in the sensitivity analysis: tied concrete shoulder and widened slab. However, neither design method could consider the full set of alternatives: BCOA-ME cannot model different shoulder types, and Pavement ME can model either an untied shoulder or a tied concrete shoulder but not a widened slab. Pavement ME assumes lane-shoulder LTE is 20 percent when the shoulder is not tied concrete and 40 percent when the shoulder is tied concrete.

As shown in Figure 4.3 and Figure 4.5, Pavement ME predicts more cracking when there is a tied concrete shoulder than when there is not. This outcome seems very unreasonable.

4.3.11 Transverse Joint LTE

The Pavement ME design of the reference section assumed the tool's default LTE value of 80 percent. Two other LTE levels were introduced in the sensitivity analysis: 1) 10 percent below the default value, and 2) 10 percent above the default value. Transverse joint LTE is an input to calculations in Pavement ME but in BCOA-ME it is a fixed value. In BCOA-ME, LTE is driven by the fact that the concrete and asphalt are assumed to be bonded and the asphalt base is assumed to be continuous. Taken together, both hypotheses result in a very large LTE: 90 percent according to Reference *(12)*.

As shown in Figure 4.3 and Figure 4.5, a 10 percent change in transverse joint LTE resulted in a very large change in the cracking predicted by Pavement ME. This great sensitivity to predicted cracking and uncertainty in LTE prediction, coupled with the fact that LTE is expected to change during a thin BCOA section's design life, represent serious limitations of the Pavement ME design procedure. Something similar also applies to BCOA-ME, where LTE was very high due to the procedure's assumption of both a continuous asphalt base and full PCC-asphalt bonding.

Based on results of the HVS testing conducted in project 4.58B, the LTE values assumed in BCOA-ME and the default value in Pavement ME seem too high.

4.3.12 Foundation

The reference section had a 10 in. thick aggregate subbase on top of a silty soil with low plasticity. The Unified and AASHTO soil classification systems label this soil type ML (silty soil with low liquid limit) and A-4, respectively. The water table was assumed to be 20 ft below the surface. This foundation is referred to as "fair" in this sensitivity analysis. Two other bearing capacity levels were considered in this sensitivity analysis: 1) the same aggregate subbase on top of a silty soil classified as ML and A-5 (e.g., LL=45 and PI=3) with the water table at a depth of 10 ft; and 2) the same aggregate subbase on top of a sandy soil classified as SW (well-graded sand) and A-3 (no plasticity) with the water table at a depth of 30 ft. In this sensitivity analysis, the former is referred to as a "weak" foundation and the latter is referred to as "strong" foundation.

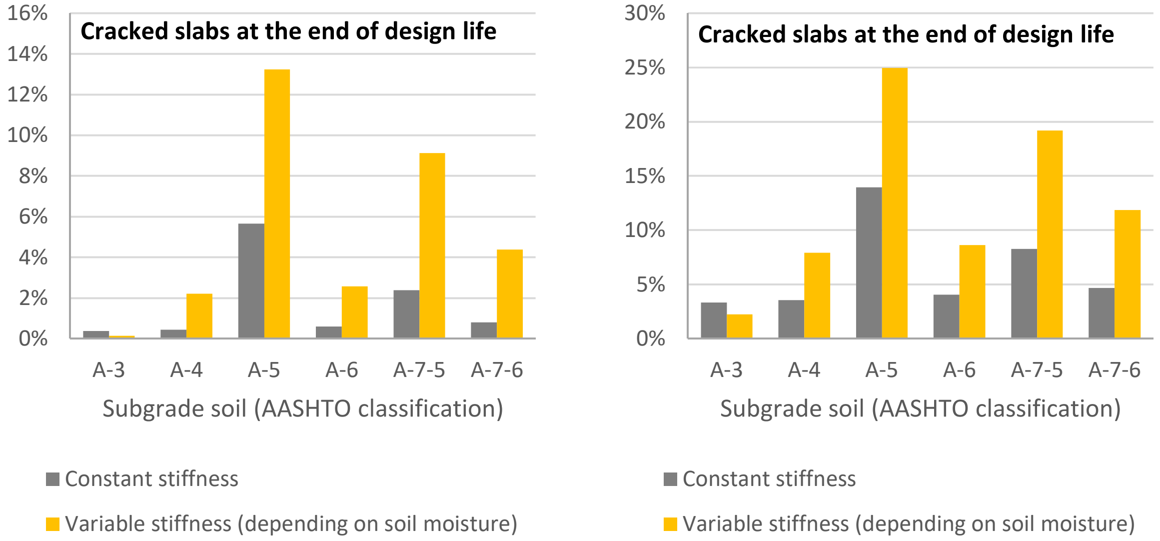
The *equivalent modulus of subgrade reaction*, which represents all layers below the asphalt base, is an input to the BCOA-ME design procedure. No seasonal variation is considered in this procedure. In Pavement ME, the user selects the soil and granular materials types and either defines their elastic modulus or lets the software estimate it. The latter option was followed in all calculations presented in this technical memorandum. The software also allowed the introduction of seasonal variations in the stiffness of these materials. The Pavement ME software reports the *equivalent modulus of subgrade reaction* (combination of the subbase and the subgrade) for each month. The average values that Pavement ME reported for the weak, fair, and strong foundations were 160, 240, and 460 psi/in., respectively. These average values were used in the evaluation of BCOA-ME sensitivity.

As shown in Figure 4.2 through Figure 4.5, the BCOA-ME and Pavement ME cracking predictions reflected the quality of the foundation. Nonetheless, the sensitivity of the BCOA-ME predictions was much less than the sensitivity of the Pavement ME predictions. In BCOA-ME, a change in foundation quality impacted predicted cracking less than a change in slab thickness, asphalt base thickness, concrete flexural strength, or climate zone. Conversely, in Pavement ME, a change in foundation quality impacted predicted cracking more than a change to any other design variable. This outcome is partly related to the fact BCOA-ME assumes a continuous asphalt base, while Pavement ME assumes a jointed asphalt base with the joints aligning with the joints in the concrete. Nonetheless, further analysis would be required to determine which of the two design procedures produced the more realistic consideration of the effects of foundation.

4.3.13 Elaboration on Foundation Effects

The extreme sensitivity to foundation quality that Pavement ME's cracking predictions showed was unexpected. This sensitivity came as a surprise because a sensitivity analysis conducted in developing the current HDM JPCP design catalog showed the opposite result *(16):* in that sensitivity analysis, the quality of the subgrade had very little effect on the cracking predicted by the *MEPDG* (version 0.8, 2007). Despite the fact that the 2007 outcome was applicable to standard JPCP while the outcome presented in this memorandum is applicable to thin BCOA, it is evident that an apparent contradiction exists that deserves further analysis. For this reason, another sensitivity analysis was conducted where the subgrade soil type was changed while the rest of the design inputs were left unchanged. The results of this sensitivity analysis are presented in Figure 4.6. The data in this figure show in greater detail Pavement ME's extreme predicted cracking sensitivity to the type of subgrade soil present with thin BCOA.

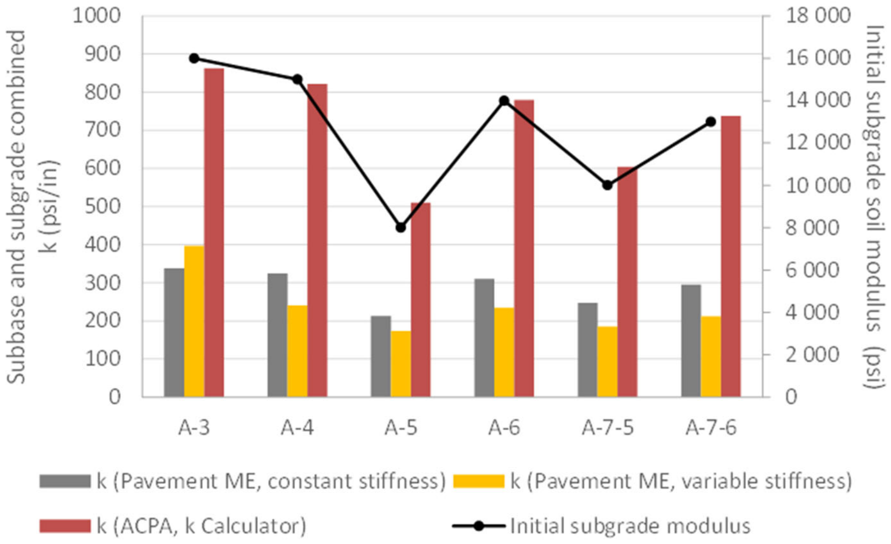
As shown in Figure 4.6, the predicted cracking did not consistently increase as the soil quality increased (A-4, A-5, A-6, etc.), as would have been expected. In fact, the worst result was obtained for the silty soil A-5, and the more plastic clay soil A-7-6 performed better than the less plastic clay soil A-7-5. These outcomes occurred no matter whether Pavement ME was allowed to modify soil stiffness based on predicted soil moisture content or not. In the first case, the initial soil stiffness (which is representative of construction moisture content) was modified based on the moisture content predicted by the *EICM* throughout section's design life. In the second case (constant stiffness), the soil stiffness was assumed to be constant and equal to the initial stiffness. It should be noted that the input to Pavement ME is the initial soil stiffness which, again, is representative of construction moisture content.



50% reliabilty **85% reliability**

Figure 4.6: Pavement ME sensitivity versus the quality of the subgrade soil.

Pavement ME combines all the layers below the asphalt base into a unique foundation characterized by its *modulus of subgrade reaction* (k). The k values that Pavement ME reports for each subgrade soil type are presented in Figure 4.7. As shown in this figure, the silty soil A-5 had the lowest stiffness and the less moisture-susceptible clay soil A-7-5 was softer than the more moisture-susceptible clay soil A-7-6. According to the results shown in Figure 4.7, Pavement ME assumes soils A-5 and A-7-5 have a low bearing capacity. These soils have a relatively high liquid limit and a relatively low plasticity index. Conversely, Pavement ME assumed a relatively high stiffness for soils A-6 and A-7-6. These are plastic soils that might present large volumetric changes due to variations in moisture content.



Note: **Yearly average k values are shown for "Pavement ME, variable stiffness" series.**

Figure 4.7: Stiffness assigned by Pavement ME to different soil types.

It was also observed (in Figure 4.7) that the k values determined by the ACPA k-Value Calculator were much larger than the k values reported by Pavement ME (constant stiffness), despite both sets of calculations being based on exactly the same soil stiffness. This outcome is related—at least in part—to the fact that Pavement ME determines equivalent k values based on the complete pavement structure (including asphalt base and slabs) while the ACPA calculator considers only subbase and subgrade. This consideration biases the k values toward the stiffness of the subbase layer, which is much greater than the stiffness of the subgrade soil.

The ACPA k-Value Calculator is the tool recommended by BCOA-ME web implementation tool.

5 ADVANTAGES AND LIMITATIONS OF EXISTING DESIGN METHODS

As part of its effort to facilitate implementation of thin BCOA in California, Caltrans could start by adopting either the BCOA-ME or MEPDG method. However, before doing so, their advantages and disadvantages would need to be weighed.

For example, it would be advantageous to adopt one of the procedures because both are recognized as having a sound theoretical basis and have been empirically calibrated. Further, adopting one of them would eliminate the need for a research effort to develop new models since both methods include models that have already been formulated. However, the current versions of both procedures also have technical and practical limitations that would make their adoption disadvantageous. Some of these are explained below.

Like any design method, BCOA-ME and MEPDG have technical limitations. Below are some of the ones believed to be relevant for Caltrans design of thin BCOA:

- *Lack of models for a number of relevant performance variables.* The two methods include a cracking model only. They lack models for predicting other relevant performance variables, in particular concrete-asphalt debonding, transverse joint LTE, transverse joint faulting, and longitudinal unevenness (IRI). BCOA-ME is expected to incorporate a faulting model soon and the MEPDG may do the same. Nonetheless, because neither method has included implementation of an LTE model or a debonding model, major limitations remain that hinder their usefulness for thin BCOA design, based on the results of project 4.58B. The full-scale evaluation conducted in that project showed that traffic-related loss of LTE and concrete-asphalt debonding are two of the main distress mechanisms that thin BCOA is expected to present in California *(14).*
- *Lack of consideration of variables that are relevant to thin BCOA cracking.* As explained in Section 4.3, slab size, concrete CTE, concrete drying shrinkage (or curing procedure), type of asphalt base, and type of shoulder cannot be adequately modeled with either of these design procedures. The same applies to the condition of the asphalt base in *MEPDG.*
- *Lack of calibration for California climate conditions.* The two design procedures have been calibrated based on thin BCOA performance in Minnesota, Illinois, and Colorado, but none of those states have the same dry and warm weather conditions that can be expected in most of California (although eastern Colorado is drier than Minnesota and Illinois, which both have considerable summertime humidity and rainfall). It should be noted that Pavement ME allows the user to introduce local calibration factors while the BCOA-ME web implementation tool does not. Another important fact to mention is the existence of NCHRP Project 01-61, "Evaluation of Bonded Concrete Overlays on Asphalt Pavements," one of whose

goals is to gather design and performance data for a number of thin BCOA projects in the US. Data from that project, which are expected to be available in summer 2019, may be used for recalibration of existing design methods or calibration of a new one.

- *Limited consideration of design reliability.* The reliability approach implemented in each of the two design procedures does not consider the variability of design factors within a project. The two reliability approaches are based on the performance of relatively short sections.
- *Lack of applicability to short construction windows.* The two design procedures are conceived and calibrated for normal-strength portland cement concrete. This represents an important limitation because rapid-strength concrete (RSC), including portland cement and other cement types, are likely to be extensively used by Caltrans. For example, the first Caltrans thin BCOA, on SR-113 in Woodland, is being built with a RSC designed to be opened to traffic in 18 hours. Neither BCOA-ME nor MEPDG can model early-age traffic and high early strength mixes.
- *Uncertainty in the models' predictions.* The sensitivity analysis presented in this technical memorandum showed that even with all input variables held equal, the design slab thickness differed considerably between the two methods. The sensitivity analysis also revealed that BCOA-ME and Pavement ME consider climate and subgrade differently.

Adopting either of the two design procedures would also present several practical limitations:

- *Lack of flexibility to design for local conditions.* Caltrans would be unable to adapt the design methods to the construction practices and policies applicable in California.
- *Lack of information about the design procedure.* This limitation is only applicable to the MEPDG. As explained in Section 2.2, very little published information is available about the MEPDG thin BCOA design procedure.
- *Large cost associated with the design.* This limitation is only applicable to the MEPDG. In addition to the cost of maintaining the Pavement ME license, the cost of hand labor (and perhaps testing) associated with the design may be very high.
    - The number of inputs to a thin BCOA design is on the order of 50, excluding traffic and climate inputs and using level 3 for most input variables (level 3 is the least comprehensive input level). Determining all the inputs might require a huge effort. Further, many of those inputs, like those related to concrete mix design, will have no effect on the Pavement ME output.
    - Because of the complexity of the Pavement ME inputs and the way they impact cracking prediction, only personnel with extensive background regarding mechanistic-empirical principles and specific training on Pavement ME would be able to conduct an adequate design process.

6 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The analysis presented in this technical memorandum shows that the BCOA-ME and MEPDG pavement design methods are based on sound mechanistic-empirical principles but that they have technical and practical limitations that currently make them unsuitable for thin BCOA design in California. Specifically, they lack models for a number of BCOA performance variables (concrete-asphalt debonding, transverse joint load transfer efficiency, faulting, and IRI), they cannot consider input variables relevant to thin BCOA cracking (slab size, concrete CTE, concrete drying shrinkage, type of asphalt base, and type of shoulder), they have not been calibrated for California climate conditions, their consideration of design reliability is limited, and they lack applicability to the short construction windows most likely to occur in thin BCOA rehabilitation activity on the Caltrans road network.

As stated in the introduction, the workplan for PPRC SPE 4.67 considered two main options for developing a Caltrans thin BCOA design method: Option 1, adopting either BCOA-ME or MEPDG, and Option 2, adapting existing models and developing additional models as needed for a California BCOA design method as part of project 4.67. This updated method would be calibrated for Caltrans road network conditions. Based on the analysis presented in this technical memorandum, it is believed that Option 2 is the more reliable alternative for designing thin BCOA for the Caltrans road network.

For Option 2, the models already used in the BCOA-ME and MEPDG thin BCOA design methods that are recommended for inclusion in the updated design method for California are:

- *EICM* (the MEPDG climate model) thermal modeling *(Note: EICM* calculations have already been implemented in *CalME,* the Caltrans mechanistic-empirical design method for asphalt pavements, without the need to run *EICM*.)
- The BCOA-ME load-related stress calculation (Equation [1])
- The MEPDG concrete fatigue model (Equations [6] and [8])
- The MEPDG concrete cracking transfer function (Equation [7]), after calibration for local conditions
- The MEPDG truck traffic loading spectrum estimation tool, developed for Caltrans as part of PPRC SPE 5.08
- The faulting model developed by the University of Pittsburgh as part of PPRC SPE 4.58B
- The IRI, load transfer efficiency, and concrete-asphalt debonding models to be developed as part of PPRC SPE 4.67

Regardless of whether Caltrans decides to adopt an existing design method without changes or to create an updated one, the selected method will need to be calibrated for California-specific materials, construction practices, and traffic and climate conditions.

Finally, Caltrans must also decide what type of thin BCOA design implementation tool to use. For example, Caltrans may choose between a catalog (Options 1 and 2), a web-based application (Option 2 only), or the Pavement ME software (Option 1 only), or a combination of a software application and a catalog.

REFERENCES

1. Mateos, A., J. Harvey, J. Paniagua, and F. Paniagua. 2015. Development of Improved Guidelines and Designs for Thin Whitetopping: Literature Review. University of California Pavement Research Center, Technical Memorandum: UCPRC-TM-2015-01.
2. Mateos, A., J. Harvey, F. Paniagua, J. Paniagua, and R. Wu. 2019. Development of Improved Guidelines and Designs for Thin BCOA: Summary, Conclusions, and Recommendations. University of California Pavement Research Center, Summary Report: UCPRC-SR-2018-01.
3. Sheehan, M.J., S.M. Tarr, and S.D. Tayabji. 2004. Instrumentation and Field Testing of Thin Whitetopping Pavement in Colorado and Revision of the Existing Colorado Thin Whitetopping Procedure. Colorado Department of Transportation, Report No. CDOT-DTD-R-2004-12.
4. Roesler, J., A. Bordelon, M. Beyer, and D. Wang. 2008. Design and Concrete Material Requirements for Ultra-Thin Whitetopping. University of Illinois at Urbana-Champaign, Research Report FHWA-ICT-08-016.
5. Li, Z., N. Dufalla, F. Mu, and J.M. Vandenbossche. 2013. Bonded Concrete Overlay of Asphalt Pavements Mechanistic-Empirical Design Guide (BCOA-ME): Theory Manual. University of Pittsburgh, FHWA Pooled Fund Project: TPF-5-165.
6. AASHTO. 2015. *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice.* American Association of State Highway and Transportation Officials.
7. Mateos, A., J. Harvey, R. Wu, J.D. Lea, J. Lea, and J. Paniagua. 2018. Development of Bonded Concrete Overlay on Asphalt Design Method: Work Plan. University of California Pavement Research Center, Workplan: UCPRC-WP-2018-01.01.
8. Li, Z., and J.M. Vandenbossche. 2013. Redefining the Failure Mode for Thin and Ultrathin Whitetopping with 1.8-×1.8-m Joint Spacing. Transportation Research Record: Journal of the Transportation Research Board: Vol. 2368(1): 133–44. *trrjournalonline.trb.org/doi/abs/10.3141/2368-13.* (Accessed January 2019). Available from *journals.sagepub.com/doi/10.3141/2368-13.*
9. Pavement Systems LLC. 2005. *LTTPBind,* version 3.1, Superpave Binder Selection Program. Developed by Pavement Systems LLC for Federal Highway Administration.
10. Andrei, D., M.W. Witczak, and M.W. Mirza. 1999. Development of a Revised Predictive Model for the Dynamic (Complex) Modulus of Asphalt Mixtures. National Cooperative Highway Research Program (NCHRP), Projects 1-37A.
11. Riley, R.C., L. Titus-Glover, J. Mallela, S. Waalkes, and M. Darter. 2005. Incorporation of Probabilistic Concepts into Fatigue Analysis of Ultrathin Whitetopping as Developed for the American Concrete Pavement Association. In *Proceedings of the International Conference on Best Practices for Ultrathin and Thin Whitetoppings,* Denver, CO.

12. AASHTOWare: Pavement ME Design. FY16 Enhancements. Training Webinar. (Internet). 2016. *www.me-design.com/MEDesign/Webinars.html* (Accessed December 2018)
13. Khazanovich L., H.T. Yu, S. Rao, K. Galasova, E. Shats. R. Jones. 2000. *ISLAB2000* – Finite Element Analysis Program for Rigid and Composite Pavements. User's Guide. ERES Consultants Division of Applied Research Associates, Inc., Champaign, IL.
14. Mateos, A., J. Harvey, R. Wu, F. Paniagua, and J. Paniagua. 2019. Development of Improved Guidelines and Designs for Thin Whitetopping: HVS Testing of Full-Scale BCOA Sections. University of California Pavement Research Center, Research Report: UCPRC-RR-2017-06. *(In progress.)*
15. National Cooperative Highway Research Program. 2004. AASHTO Mechanistic-Empirical Design Guide, NCHRP Project 1-37a. Transportation Research Board, Washington, DC.
16. Kannekanti, V., and J. 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: Vol. 1947(1): 91–100.