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Development of Improved Guidelines and Designs for Thin Whitetopping: Literature Review

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Partnered Pavement Research Center (PPRC) Strategic Plan Element (SPE) 4.58B:
Evaluate Early Age and Premature Cracking for PaveM and LCCA (whitetopping);
Project Task 2878

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Abstract:

Thin whitetopping, also known as thin bonded concrete overlay on asphalt (BCOA), is a rehabilitation alternative consisting of a 0.33 to 0.58 ft (100 to 175 mm) thick portland cement concrete (PCC) overlay of an existing flexible or composite pavement. It has been frequently used in different U.S. states and in other countries in the Americas, Europe, and Asia. This technical memorandum constitutes the literature review for Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) Project 4.58B, whose primary goal is to develop recommendations and guidance on the use of thin BCOA as a rehabilitation alternative in California. Different state-of-practice documents as well as specific technical papers and reports have been analyzed. This analysis shows that even though thin BCOA is a mature technology, further development and improvement will help to optimize its design as a rehabilitation alternative for California. The analysis shows that some critical elements do not seem to have been adequately explored to date. Performance of the interface between PCC and asphalt is one of these elements. Other critical elements are the characterization of the asphalt base, the interaction between asphalt and PCC distresses, and the mechanics of thin BCOA faulting. The application of internal-curing concrete technology, the use of fibers, and the optimization of Caltrans PCC mixtures for thin BCOA rehabilitation projects are also considered to warrant further research. Furthermore, little experience exists concerning the use of new asphalt mixtures before BCOA overlays, and no reference was found where rubberized mixtures had been used. Thin BCOA has been used as an alternative for the rehabilitation of asphalt pavements that were not highly deteriorated, which has limited the number of rehabilitation projects where the technique could be applied.

Keywords:

Rigid pavement, bonded concrete overlay on asphalt, thin whitetopping, rubberized asphalt, PCC-asphalt interface, pavement rehabilitation, mechanistic-empirical design

Proposals for implementation:

This technical memorandum is a state-of-practice report that identifies critical elements in the design of thin bonded concrete overlays on asphalt that warrant further research. Research will be conducted within the framework of Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) Project 4.58B, "Development of Improved Guidelines and Designs for Thin Whitetopping."

Related Documents:

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PROJECT OBJECTIVES/GOALS

Thin whitetopping, also known as bonded concrete overlay on asphalt (BCOA), is a rehabilitation alternative consisting of a 0.33 to 0.58 ft (100 to 175 mm) thick portland cement concrete overlay on an existing flexible or composite pavement. It has been frequently used in different U.S. states and in other countries in the Americas, Europe, and Asia. This technical memorandum constitutes the literature review for Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) Project 4.58B, whose primary goal is to develop recommendations and guidance on the use of thin BCOA as a rehabilitation alternative in California. This project is a continuation of SPE 4.58, "Evaluate Early Age and Premature Cracking for PaveM and LCCA." Project 4.58B will be accomplished through nine tasks:

- Task 1: Literature Review
- Task 2: Development of Concrete Mix Designs for Thin BCOA in California
- Task 3: Development of Mix Designs for Rubberized Asphalt for Use as a Base for Thin BCOA
- Task 4: Improved Modeling of Thin BCOA for Cracking and Development of Recommended Designs in California
- Task 5: Modeling of Thin BCOA for Faulting and Development of Recommended Designs
- Task 6: Evaluation and Performance Estimates of Improved Designs Using the Heavy Vehicle Simulator and Mechanistic-Empirical Analysis
- Task 7: Development of Preliminary Maintenance and Rehabilitation Strategies, Cost Estimates, and Life-Cycle Assessment Inventory Framework
- Task 8: Evaluation of Improved Designs on Mainline Highway at MnROAD
- Task 9: Final Recommendations, Report, and Guidelines

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ACPA	American Concrete Pavement Association
BCOA	Bonded concrete overlay on asphalt
BCOA-ME	Bonded Concrete Overlays on Asphalt—Mechanistic-Empirical
Colorado DOT	Colorado Department of Transportation
EELTG	Effective equivalent linear temperature gradient
ESAL	Equivalent single axle loads
FHWA	Federal Highway Administration
FRC	Fiber-reinforced concrete
HMA	Hot mix asphalt
HVS	Heavy Vehicle Simulator
ICC	Internal-curing concrete
LCCA	Life-cycle cost assessment
LTE	Load transfer efficiency
MEPDG	Mechanistic-Empirical Design Guide
M-E	Mechanistic-Empirical
MnDOT	Minnesota Department of Transportation
MnROAD	Minnesota Road Research Facility
NCHRP	National Cooperative Highway Research Program
PCC	Portland cement concrete
PPRC	Partnered Pavement Research Center
SR	Stress ratio
TRB	Transportation Research Board
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 whitetopping, also known as thin bonded concrete overlay on asphalt (BCOA), is a rehabilitation alternative consisting of a 0.33 to 0.58 ft (100 to 175 mm) thick portland cement concrete (PCC) overlay of an existing flexible or composite pavement. It has been used on highways and conventional roads in several U.S. states, including Minnesota, Colorado, Iowa, Missouri, Kansas, Mississippi, Washington, Ohio, and Kentucky, as well as in other countries, including Canada, Mexico, Brazil, Belgium, Austria, Japan, and France *(1)*. In the past, this technology has been known as "thin whitetopping." Currently, the term "bonded concrete overlay on asphalt" is preferred because it more accurately reflects the overlay's mechanical behavior and differentiates it from unbonded concrete overlays.

Thin BCOA differs from unbonded PCC overlay, which is also in current use, in two significant ways. First, thin BCOA overlays use a PCC thickness below the range of the unbonded PCC overlays, which are typically at least 0.67 ft thick (200 mm). Second, and more importantly, thin BCOA technology has a considerably different structural conception than unbonded PCC overlay. Specifically, in unbonded overlays, the asphalt base is primarily intended to serve as a flexible, nonerodible support for the PCC slabs. In the bonded structural conception, the base stiffness (typically accounted for in terms of k, the classical modulus of subgrade reaction) reduces PCC tensile stresses under traffic- and environment-related loads and also provides limited resistance to expansion and contraction by permitting shear creep while remaining bonded. In the conception of thin BCOA technology, the asphalt base makes a greater contribution to the structure's strength by bonding with the PCC slabs to form a composite slab where both layers work together to resist bending. All other characteristics being equal, this new conception results in a much stronger pavement structure than if the slabs were to act alone, in the same way that two independent beams cannot stand as much load as a single beam of double thickness. Critically, this new structure relies on the bond between the PCC and asphalt and constitutes the main factor leading the conception, design, construction, and maintenance and rehabilitation of this type of pavement.

BCOA technology has been steadily improving since the mid-1990s, and several documents exist that constitute a state-of-the-practice reference. NCHRP Synthesis 338, from 2004, is focused on thin and ultrathin BCOA *(1)*. The thin BCOA thickness range is defined in this report as 0.33 to 0.67 ft (100 to 200 mm). A synthesis of practice is also available from the Minnesota Department of Transportation (MnDOT), dated 2005 *(2)*. Minnesota has been a pioneer in thin and ultrathin BCOA technology since its first thin BCOA rehabilitation in 1982. Numerous successful projects in Minnesota show that thin BCOA can be an important alternative even for highway-volume roads, provided that they are properly designed and built *(2)*. According to MnDOT, the thickness range of thin BCOA is 0.33 to 0.5 ft (100 to 150 mm). A more recent state-of-the-practice document is the *Guide to Concrete Overlays* of the American Concrete Pavement Association (ACPA), developed by the National Concrete Pavement Technology Center at Iowa State University. This document deals with all types of PCC overlays, including thin and ultrathin BCOA, and its third edition is from 2014 *(3)*.

One of the most comprehensive studies of BCOA to date was developed under the FHWA pooled-fund study TPF-5(165): "Development of Design Guide for Thin and Ultrathin Concrete Overlays of Existing Asphalt Pavements" *(4)*. This study was led by MnDOT and resulted in the mechanistic-empirical design method BCOA-ME, "Bonded Concrete Overlays on Asphalt Mechanistic-Empirical" *(5)*, developed by Prof. Julie Vandenbossche of the University of Pittsburgh. Other design methods that have been used for thin BCOA were developed by the Colorado DOT *(6)* and by the ACPA *(7)*. The former is applicable to PCC thicknesses of 0.33 to 0.5 ft (100 to 150 mm), i.e., thin BCOA. The latter was initially conceived for a thickness range of 0.17 to 0.33 ft (50 to 100 mm), i.e., ultrathin BCOA, although its scope was recently expanded up to 0.5 ft (150 mm). Agreement exists on the division of PCC thickness between ultrathin and thin BCOA occurring at 0.33 ft (100 mm). The upper limit of thin BCOA does not seem to be that clear. Once the slab is about 0.55 ft (165 mm) thick, it no longer engages the HMA layer in a substantial way and the PCC section just acts as a concrete pavement on top of an asphalt base. For this reason most of the procedures for bonded overlays suggest evaluating the structure as both a bonded overlay as well as a conventional pavement when the overlay thickness is around 0.55 ft (165 mm).

Thin BCOA can be regarded as a mature technology although several issues still remain to be solved. Probably the most critical one is the role and performance of the PCC–asphalt interface. Studies *(1)* through *(7)* all agreed on the critical importance of bonding, and this conclusion is supported by the modeling and experimental results reported in References *(5)*, *(6)*, *(8)*, and *(9)*. However, the importance attributed to the bonding condition contrasts with the fact that very little research has been conducted to understand bonding mechanics and performance, not only for thin BCOA, but for conventional rigid pavements in general. For example, the well-known AASHTO Mechanistic-Empirical Pavement Design Guide *(10, 11)* only considers two conditions for PCC-base bonding: full bonded or full unbonded. The transition from the full bonded condition to the full unbonded condition must be an input to the calculations in the MEPDG since no damage model is available for the PCC–asphalt interface. This means that the user has to introduce an estimate of the number of years before complete debonding instantaneously takes place. Fortunately, a major NCHRP study was launched in order to understand and model the interaction between PCC slabs and bases, and not only asphalt bases but any type of base. This study, led by Prof. Lev Khazanovich, is being conducted at the University of Minnesota, and it is expected to be finished in the second half of 2015 *(13)*.

Another critical phenomenon that seems to have been oversimplified by the BCOA studies to date is asphalt base mechanics. In almost all cases, the asphalt base is regarded as a linear elastic material with constant stiffness (no temperature variation), and modulus values that are mostly estimated rather than measured. Only one approach, BCOA-ME *(5),* was found where seasonal temperature variation was accounted for. Interaction between the distress mechanisms of asphalt and PCC is another phenomenon that has been oversimplified by all BCOA design approaches, although all studies agree on its importance. In fact, References *(1)* through *(7)* indicate that certain asphalt distresses should be addressed before the portland cement concrete is placed in order to slow reflection through the overlay. Additionally, distress mechanisms explicitly considered by the different BCOA design methodologies are related only to PCC cracking (corner, transverse, or longitudinal), while to date a faulting model is unavailable. Transverse joint faulting is known to be one of the primary factors that influences ride quality because of its great impact on longitudinal unevenness *(10)*. Faulting mechanisms in thin BCOA could be very different from the classic build-up of eroded materials under the approaching slab that, together with loss of support under the leaving slab, causes faulting at conventional rigid pavement joints. Consequently, it is clear that an effort is necessary in order to understand and model thin BCOA faulting.

Finally, differences among U.S. states exist regarding the design features of thin BCOA, such as slab dimensions, shoulder types, the need for asphalt milling before placing the overlay, etc. These differences are reported in this technical memorandum. An effort will also be devoted, within the framework of Project 4.58B, to understanding the implications of these differences and to determining which alternatives would better suit California-specific traffic, materials, environmental conditions, existing pavements, and transportation policy.

1.1 Background to the Study

The California Department of Transportation (Caltrans) is interested in developing thin BCOA as a potential rehabilitation alternative for asphalt and composite pavements. Thin BCOA designs may include use of fiber-reinforced concrete, use of tied longitudinal joints between slabs, placement of dowels at transverse joints, and different slab dimensions. Caltrans is also interested in investigating the use of rubberized asphalt concrete bases beneath thin BCOA. This interest led Caltrans to launch Project 4.58B, whose primary goal is to develop recommendations and guidance on the use of thin BCOA as a rehabilitation alternative in California based on the adoption of and improvements to the technology developed in other states. Project 4.58B is a continuation of Strategic Plan Element 4.58: “Evaluate Early Age and Premature Cracking for PaveM and LCCA.” This technical memorandum constitutes the literature review for Project 4.58B.

Project 4.58B is based on three activities expected to build upon current thin BCOA knowledge: laboratory testing, modeling, and full-scale testing by means of the Heavy Vehicle Simulator (HVS). The possibility of real load testing at the MnROAD facility mainline is also considered, although this would depend on funding availability. Project 4.58B has been structured in nine tasks to be accomplished according to the timeline shown in Figure 1.1.

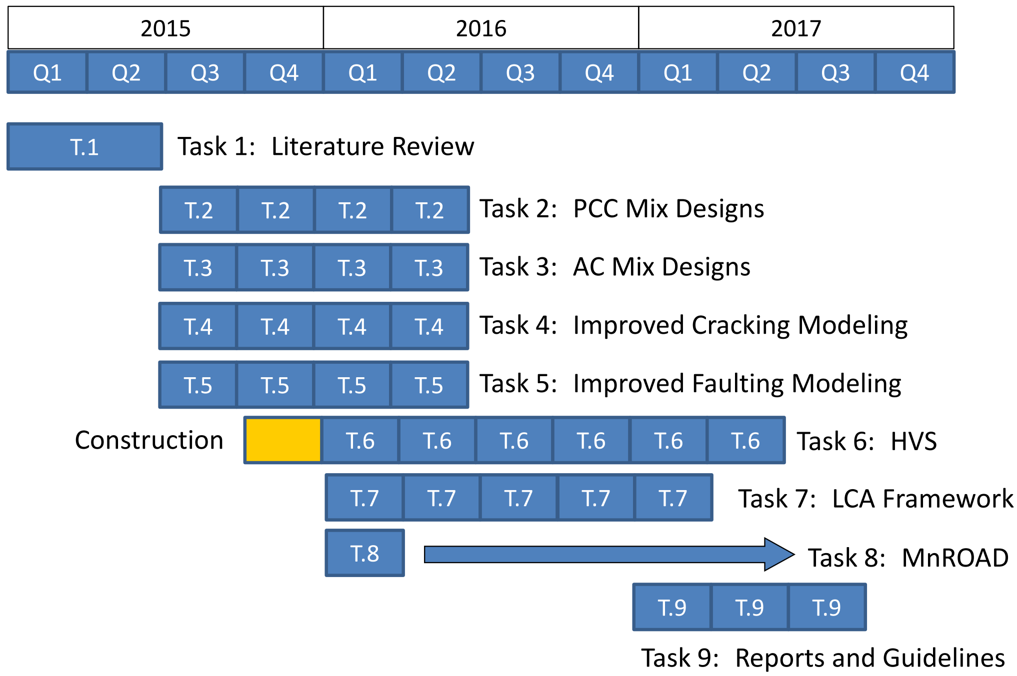

Figure 1.1: Project timeline.

Preliminary review of BCOA studies and state-of-practice documents, as well as inputs from national experts on BCOA from Caltrans, the University of Pittsburgh, the University of Minnesota, and MnDOT, indicate that further development and improvement will help to optimize thin BCOA design as a rehabilitation alternative for California. Different issues were identified in a preliminary scoping document for Project 4.58B *(14)* so that its goals could be based on the answers to a series of questions. The literature review presented in this document reflects the preliminary consideration given to these questions.

1. What traffic design criteria should be used?
2. What is the contribution of layer bonding to the extension of overlay life?
    - ✓ How can layer bonding be improved?
    - ✓ How well will thin BCOA work on existing rubberized asphalt surfaces?
    - ✓ How well will thin BCOA work on new rubberized asphalt surfaces?
3. How are shoulders designed and constructed?
4. What is the cost-effectiveness of thin BCOA?

5. What are optimal strategies for the maintenance and rehabilitation of thin BCOA?
6. Should Caltrans concrete mix designs for new concrete pavement be optimized for thin BCOA?
7. What is the contribution of structural fibers in extending overlay life?
   - ✓ For cracking?
   - ✓ For faulting?
   - ✓ Can the use of fibers be improved?
8. Should wider slabs be considered in truck lanes?
9. What are the mechanisms of joint faulting?
   - ✓ Should dowels be used?
   - ✓ Do fibers play a role?
   - ✓ How can performance be improved?
10. What is the mechanism of cracking in the underlying asphalt layer and how does it affect thin BCOA performance?
    - ✓ What are optimized slab lengths?
    - ✓ What is the role of debonding and asphalt deterioration?
    - ✓ What is the role of shrinkage and temperature gradients?
    - ✓ How can performance be improved?
11. Which asphalt-treated base is typically used for thin BCOA?

1.2 Project Scope

As noted in Section 1.1, thin BCOA is defined in this study as a 0.33 to 0.58 ft (100 to 175 mm) thickness PCC overlay of an existing flexible or composite pavement. As noted, Caltrans may consider the use of fiber-reinforced concrete, tied longitudinal joints between slabs, placement of dowels at transverse joints, and different slab dimensions. Different alternatives for improving PCC and asphalt bonding, including milling, will be also explored in this research project. Caltrans is also considering the use of rubberized asphalt concrete bases beneath thin BCOA overlays, from either new or existing mixtures. The use of an asphalt overlay before placing PCC could improve thin BCOA performance and widen the range of applications of this rehabilitation alternative.

Further development of ultrathin BCOA (a PCC overlay less than 0.33 ft [100 mm]) is not an objective of this research project, although experiences with ultrathin BCOA are included in this literature review since they are related to thin BCOA performance, especially regarding bonding between the PCC and asphalt base. These ultrathin concrete overlays require closely spaced joints, maximum 4 ft, (1.2 m) and are likely to be impractical for rehabilitating medium- and high-traffic volume roadways. Unbonded PCC overlays, typically over 0.67 ft

(200 mm), are not considered in this study. Performance of overlays with thickness over 0.58 ft (175 mm) might be extrapolated as soon as bonding is considered in the design, although, at such thicknesses a section begins to work as a conventional concrete pavement on top of an asphalt base rather than as a *bonded* concrete overlay on asphalt.

Both medium and high traffic levels will be considered. For these traffic levels, the higher initial cost of thin BCOA alternatives compared to conventional asphalt overlays may be balanced by reduced future maintenance and rehabilitation costs. For low traffic, the higher initial cost of thin BCOA alternatives may be difficult to balance.

1.3 Approach to the Literature Review

One of the three main activities of Project 4.58B is modeling, as stated above. For this reason, consideration of the different BCOA design methodologies is included in Chapter 2. Modeling is directly or indirectly related to each of the questions formulated above. The three most recognized BCOA design approaches are analyzed in Chapter 2.

This literature review has been focused on the eleven questions stated above (Section 1.1) since the answers to these questions are regarded as a starting point for achieving the goals of Project 4.58B. Each question is considered separately in Chapter 3.

This literature review started with the main reference documents listed by Caltrans, the University of Pittsburgh, University of Minnesota, and Minnesota DOT BCOA experts, who were consulted within the framework of this research project. Most of these documents are included within the first ten references listed in Chapter 5. The UCPRC conducted a separate search using the University of California (UC) library system to find journal articles, the Transportation Research Board (TRB) publications index to search for papers in the Transportation Research Record and Annual Meeting Compendiums, the NCHRP Projects database, and Google Scholar™ and other internet search engines to identify papers, reports, and articles not located in the reference documents, or the UC and TRB searches. Research conducted in the United States as well as internationally was reviewed. Reference lists in sourced publications were also checked to identify any other potentially relevant publications that were missed in the earlier searches.

2. EXISTING BCOA DESIGN METHODOLOGIES

In the past, two design methodologies were commonly used to design BCOA overlays. The first one was developed by Colorado Department of Transportation in 1998 *(8)* and updated in 2004 *(6)*. The second methodology was sponsored by the American Concrete Pavement Association *(7)* in 1998, and to date it has been updated several times *(15)*. A more recent thin and ultrathin BCOA design method *(5)* was developed by the University of Pittsburgh in 2014 within the framework of FHWA pooled-fund study TPF-5(165).

It should be noted that the AASHTO Mechanistic-Empirical Pavement Design Guide *(10, 11)*, one of the most widely known pavement design methodologies, cannot be used for thin BCOA design. The minimum PCC thickness used in the calibration of this guide was 0.63 ft (175 mm), and the minimum slab size is 12 ft (3.7 m), both of which exceed the upper limits of thin BCOA designs.

2.1 Thickness Design of Bonded Whitetopping Pavement in the State of Colorado

The Colorado Department of Transportation design method, which is applicable to thin BCOA rehabilitations, is based on mechanistic-empirical principles. It is based in particular on experimental data gathered from four thin BCOA sections that were instrumented with sensors in order to measure the strains that developed at various locations in the PCC overlay under traffic loads and with changing temperature gradients *(6, 8)*. Single and tandem axle loads applied statically at different locations in the slabs were used for this experimental study. The critical response, the maximum strain values measured, occurred at the bottom of the PCC overlay at the middle of the longitudinal edge, where tensile stresses are known to result in transverse cracking. As expected, the maximum strain values were measured at this location when the wheels moved close to the longitudinal edge or right alongside it. These values were even higher than those measured at the slab corners. The effects of temperature gradients across the overlay were evaluated by measuring pavement structural response at different times during the day, with positive (daytime) and negative (nighttime) gradients. This way, the effect of temperature gradients on the structural response could be evaluated, as well as the structural response for zero gradient. PCC thicknesses between 0.33 and 0.58 ft (100 to 175 mm) and slab lengths between 4 and 12 ft (1.2 and 3.7 m) were evaluated in this experimental study.

A finite element model (Illislab) was used to estimate strain at the critical location under the single and tandem axles, and the theoretical responses were compared to measured strains. This comparison indicated that predicted strains were much smaller than measured values, and this was attributed to the fact that full bonding between the PCC and base layers was assumed in the finite element analysis. This discrepancy was in fact regarded as evidence of partial bonding between the PCC and the asphalt base. Measured strains exceeded theoretical estimations by 54 percent and 35 percent, respectively, for the evaluations conducted for the original design guide (1998) and the 2004 revision. A final increase in the theoretical strains of 51 percent for use in the design was adopted in the 2004 revised guide, which is related to a 95 percent confidence level. It should be remarked that the discrepancy between the model predictions and the measured responses could have been attributed to other potential causes. In fact, the discrepancies could be also related to the static axle loads. Asphalt mixture stiffness is known to diminish as speed decreases, so the stiffness under the static axle loads could have been much smaller than assumed in the finite element model. Unfortunately, neither the 1998 report nor the 2004 revision indicate the approach for estimating asphalt base stiffness.

The stresses due to a loss of support from the slabs due to curling under temperature gradients were also estimated in the experimental study, as explained above. Strains under the static axle loads were measured for changing temperature gradients. By doing this, the change in strain (which determines stress) could be related to temperature gradient. A very simple equation was calibrated: $\Delta\sigma(\%) = 3.85 \cdot \Delta T$, where ΔT is temperature gradient across the slab in °F per inch and $\Delta\sigma(\%)$ is the percent increase of stress versus the zero gradient condition. Nonetheless, it should be noted that this increase in stress does not account for the stresses directly generated as a consequence of curling and warping due to the temperature and moisture differentials across the slab thickness. Curling and warping create tensile stresses even if no load is applied, apart from loss of support. However, only the loss of support is considered in the approach proposed by this design methodology. A design effective ΔT is an input to the calculations that the user must provide. ΔT is a constant temperature difference that is combined with traffic loads in order to determine PCC damage. No indication is provided in the guide as to how this parameter should be estimated.

Closed-form solutions were developed on the basis of a structural response database generated by the Illislab software. These equations allow the estimation of slab edge stresses under 20 kip single and 40 kip tandem axle loads. Stresses for other load levels can be estimated in linear proportion, according to the design methodology. It should be remarked that only edge stresses are considered in this design procedure, which means that only transverse cracking is predicted. A correction factor is also proposed in this guide to account for tied shoulders or tied adjacent slabs, which are known to significantly reduce tensile stresses when traffic loads move close to the slab longitudinal edge. In particular, stress under free edges is considered to increase 87 percent over the tied-shoulder condition according to this design methodology.

This methodology also includes a closed-form solution to estimate strain at the bottom of the asphalt layer under traffic loads (single and tandem axles). Maximum strain is assumed to take place at the middle of the slab, under the transverse joints. The approach determines the fatigue life of the asphalt mixture by using the well-known

Asphalt Institute fatigue model *(16),* and considers that a percentage of this fatigue life has already been consumed before BCOA rehabilitation; an estimate of this percentage is to be provided by the designer. As a result of this calculation, a BCOA rehabilitation may fail in the asphalt base before reaching PCC fatigue.

This design methodology considers the structural role of the asphalt base in thin BCOA solutions as a composite slab rather than in terms of an increase in PCC slab support (increase of k parameter). The PCC slabs and the asphalt base are assumed to be working together as a unique composite slab, which considerably increases the structural capacity over that in the first approach (Δk). The composite slab's radius of relative stiffness, ℓe, is computed assuming full bonding.

$$\ell_e = \left(\frac{I_e}{(1 - 0.15^2) \cdot k}\right)^{1/4}$$

Where, ℓ_e is radius of relative stiffness

I_e is moment of inertia of the composite section

$$I_e = \frac{E_C \cdot {h_C}^3}{12} + E_C \cdot h_C \cdot \left(NA - \frac{h_C}{2}\right)^2 + \frac{E_{AC} \cdot {h_{AC}}^3}{12} + E_{AC} \cdot h_{AC} \cdot \left(h_C - NA + \frac{h_{AC}}{2}\right)^2$$

NA is depth neutral axis of the composite section

$$NA = \frac{\frac{E_C \cdot {h_C}^2}{2} + E_{AC} \cdot h_{AC} \cdot \left(h_C - \frac{h_{AC}}{2}\right)}{E_C \cdot h_C + E_{AC} \cdot h_{AC}}$$

Estimation of the number of cycles to failure for the slabs is conducted by using the well-known Portland Cement Association fatigue model *(17),* which was developed using concrete beams, with failure defined as complete beam fracture. This model has been reported to result in very conservative thickness estimates *(21).* The damage caused by single and tandem axles within each load level interval is accumulated according to the Miner hypothesis *(19),* i.e., linear accumulation of damage. No indication is included in the 1998 and 2004 reports as to how tridem axles should be included in the fatigue analysis. The method can be also used in combination with 18 kip equivalent single axle loads (ESALs). It should be noted that AASHTO load equivalency factors depend on PCC thickness, but the minimum thickness considered in the AASHTO procedure is 6 inches (150 mm). For this reason, the Colorado approach includes correction factors to extrapolate AASHTO ESALs calculated for 8 inches (203 mm) to typical thin BCOA thicknesses. A thickness correction factor was also required when using the ESALs approach since it typically resulted in thicker PCC overlays compared to direct consideration of the actual load level distribution of single and tandem axles. Traffic wander is not considered in this design procedure, and neither is the actual wheelpath location with respect to loading location for stress calculation. Stresses are calculated assuming load is close to the midpanel longitudinal edge. Consequently, this method should only be used for panel sizes that exhibit transverse cracking, which are generally slabs that are only full-lane width.

Finally, it should be remarked that this methodology assumes that the old asphalt surface will be milled and thoroughly cleaned prior to concrete placement, which is expected to reduce PCC tensile stresses by 25 percent. New asphalt bases are neither considered nor recommended in this design methodology.

2.2 ACPA Bonded Concrete Overlay of Asphalt Pavements

The American Concrete Pavement Association design method was conceived for ultrathin BCOA rehabilitations, with 0.17 to 0.33 ft (50 to 100 mm) PCC thickness *(15).* Consequently, it is not applicable for the range of thicknesses considered in this study although the mechanistic-empirical principles upon which it is based are considered to be applicable to thin BCOA design.

Experimental data that constitute the basis for this method come from instrumented slabs that were loaded with static 18 kip single and 36 kip tandem axles *(20).* Maximum strain values were measured at slab corners, an approach supported by experimental evidence that shows how corner cracking is the predominant mode of failure for ultrathin BCOA. Finite element estimations of corner strains were much smaller than actual values measured under the axle loads in the full-scale experiment. This discrepancy was attributed to the full bonding assumption behind the finite element analysis, and it was regarded as evidence of partial bonding existing between the PCC and the asphalt base. A factor of 1.36 was subsequently adopted in the design approach to account for partial bonding, i.e., tensile stresses at the slab corner are supposed to increase by 36 percent due to the partial slippage between the PCC and asphalt base layers.

Corner stress under single and tandem axle loads is predicted in this design method by using a closed-form equation. This equation was calibrated on the basis of a structural response database, which contained data from ultrathin BCOA sections with 0.17 ft to 0.33 ft (50 to 100 mm) PCC thicknesses and 2 ft to 4.2 ft slab lengths. As stated above, this method was exclusively conceived for ultrathin BCOA rehabilitations, although the current version expands the thickness upper limit to 0.5 ft (150 mm). This procedure considers only corner cracking, so it should be used only for panel sizes exhibiting this type of distress, which are generally panel sizes below 4.5 ft. The Guide to the Design of Concrete Overlays Using Existing Methodologies, of the National Concrete Pavement Center *(18),* recommends using either the Colorado DOT or BCOA-ME models for thicknesses over 0.33 ft (100 mm), i.e., for thin BCOA.

The Riley PCC fatigue model is used in this guide *(21).* This model uses reliability—in addition to the stress/strength ratio—to predict fatigue life. The guide recommends 80 percent reliability and 20 percent cracked slabs as failure criteria. An effective reliability is used in the Riley fatigue model to consider the percentage of slabs with cracks different from 50 percent at the end of service life. This percentage is an input to the program. Fiber-reinforced concrete can be considered in this procedure, following the approach proposed by Roesler et al. *(15),* which is based on the Residual Strength Ratio determined according to ASTM C1609. In this approach, the modulus of rupture of the reinforced concrete is increased to the residual strength in order to calculate the stress ratio (SR: stress divided by strength). This ratio, SR, is introduced in the fatigue model for calculation of number of loads to failure.

The current version of this design method computes fatigue damage using an 18 kip ESALs concept, although no indication is provided regarding load equivalency factors for determining such small PCC thicknesses. As noted above, AASHTO load equivalency factors are not available for PCC thicknesses below 6 inches. The equations developed for this design method can be also used with traffic load distribution of single and tandem axles to determine the expected fatigue life of BCOA. No wander is considered in the analysis.

The original version of this design method included prediction of strain at the bottom of the asphalt base, beneath the center of transverse joins, which was assumed to be the most critical location. This strain was used with the Asphalt Institute fatigue model *(16)* to estimate asphalt base life. In certain situations, this could determine rehabilitation service life. However, this calculation is not included in the present version of the BCOA design procedure *(22).*

Tensile curling stresses are estimated, as a function of temperature gradient, by using a closed-form solution *(20).* An effective equivalent linear temperature gradient of -1.4°F per inch, occurring 58 percent of the time, was used in the previous version of this guide. This figure is representative of Illinois climatic conditions. This effective gradient was determined using the *Enhanced Integrated Climatic Model* for predicting temperature across PCC slabs and the mechanistic-empirical principles of the guide for determining damage accumulation. The latest version of this procedure, available through the ACPA applications website *(22),* incorporates a more recent development for estimating the effective equivalent linear temperature gradient. This recent development was achieved within the framework of FHWA pooled-fund study TPF-5(165), within which BCOA-ME was developed.

2.3 Bonded Concrete Overlay of Asphalt Pavements—Mechanistic-Empirical

Like the two previous design methods and as its name makes clear, Bonded Concrete Overlay of Asphalt Pavements—Mechanistic-Empirical is based on mechanistic-empirical principles *(23).* There are significant differences between the calibration approaches taken by those models and the BCOA-ME though. In both the Colorado and ACPA procedures, the structural response models were field-calibrated and the fatigue models were uncalibrated. However, the BCOA-ME field-calibration approach is based on performance data from sixteen in-service BCOA sections, which means that the complete procedure is calibrated—including the structural response and fatigue models. In addition, BCOA-ME is applicable to both ultrathin and thin BCOA, for PCC thicknesses between 0.25 and 0.5 ft (75 to 150 mm) and slab lengths between 2 and 12 ft (0.6 and 3.7 m).

This methodology does not predefine the types of distresses the BCOA will undergo. In fact, the critical distress mechanism is assumed to depend on slab size, as is supported by experimental evidence *(24, 25).* For small slabs (≤4.5 ft), corner cracking is selected as the critical distress mechanism; for medium slabs (4.5 to 7 ft), mid-panel longitudinal cracking is supposed to start in the wheelpath at the transverse joints; for large slabs (>7 ft), transverse cracking is supposed to start at the longitudinal edge. A specific closed-form equation is used for each of these three distress modes in order to estimate tensile stresses under traffic loads. In particular, equations developed for the ACPA *(20)* and Colorado DOT *(6)* BCOA procedures were selected for tensile stresses at corners and longitudinal edges, respectively. As noted earlier, the ACPA procedure was focused on ultrathin BCOA, i.e., corner cracking, while the Colorado DOT procedure was focused on transverse cracking. For BCOA-ME *(5),* a new equation was developed for longitudinal cracking. This type of distress had not been predicted before for BCOA, although it is frequently present in midsize slabs *(24, 25).* The procedure adopted for developing this stress prediction equation was very similar to that followed by the two previous design procedures: a database was generated by using a finite element model where full bonding was assumed. Then, an analytical model was formulated and its parameters were determined in a best-fit process. Stress due to temperature curling was estimated as in the ACPA procedure for corner cracking and as in the Colorado DOT procedure for transverse cracking. For longitudinal cracking, the Colorado DOT approach, which is applicable to transverse cracking, was followed. No experimental information was available for the transverse tensile strain at the bottom of the slab in the wheelpath at the transverse joint, which is the source of longitudinal cracking.

This procedure proposes a mechanistic approach in order to estimate the temperature gradient across PCC slabs. The approach is based on first using the well-known *Enhanced Integrated Climatic Model (26)* to estimate hourly temperature profiles (versus depth) and then using mechanistic-empirical principles to determine the effective equivalent linear temperature gradient (EELTG), which produces the same damage throughout the design life of the overlay. This approach was followed for a large number of locations in the U.S. and for a large number of BCOA sections, representing the scope of the design method *(23).* EELTG was determined for each location and BCOA section. Analytical equations were then fitted to the results, one equation for each distress mechanism. These equations can be used to determine EELTG as a function of a section's characteristics and the geographic location of the road. This approach has been adopted by the ACPA BCOA procedure.

One of the features of BCOA-ME is its consideration of the hourly variation of the stiffness of the asphalt mixture base, which it estimates on a monthly basis. The representative stiffness for each month is calculated using the *Enhanced Integrated Climatic Model* as well as mechanic-empirical principles, in a process similar to the one followed for the estimation of the equivalent linear temperature gradient. According to BCOA-ME, asphalt mixture stiffness changes depending on the climate zone (defined by the annual mean daily average air temperature) and the characteristics of the BCOA section. It should be noted that the representative asphalt modulus is determined in terms of how much damage the PCC overlay undergoes. Accordingly, one set of equations is available for each distress mechanism. A predefined dense-grade aggregate gradation was adopted for the asphalt base mixture, and the type of binder was predetermined following *LTTPBind3.1* software *(27)* recommendations. This way, mixture stiffness can be estimated by using the Witczak dynamic modulus predictive equation *(28)*, including the appropriate level of aging. The final modulus is reduced to take into account damage present in the asphalt mixture: 5 and 12 percent reductions, respectively, for asphalt pavements with 0 to 8 and 8 to 20 percent of the wheelpaths with fatigue cracking.

Traffic in this design approach is based on the 18 kip ESAL concept. In fact, the web-based software, which is available at the ACPA applications website *(22),* includes an ESALs calculator. This calculation is based on the AASHTO guide, although no information is provided in BCOA-ME regarding the extrapolation of load equivalency factors to PCC thickness below six inches. Traffic wander is only considered for predicting longitudinal cracking.

Concerning the contribution of the asphalt base to the structural capacity of the section, this procedure assumes that the PCC slabs and base layer are working together as a composite slab.

This design method uses the fatigue model developed by Riley et al. *(21)* for the ACPA procedure. This means that reliability can be introduced into the design process. It also uses the approach introduced by Roesler et al. *(15)* to consider fiber-reinforced concrete (FRC). In particular, BCOA-ME incorporates an "FRC calculator" that estimates the Residual Strength Ratio as a function of type of fiber and dosage. Finally, it includes a check for the possibility of cracking in the asphalt reflecting through the PCC overlay, based on Vandenbossche's work *(29).* This check determines the existence of the risk of reflective cracking when the flexural stiffness of the PCC slab is less than the flexural stiffness of the asphalt layer, with flexural stiffness being $E \cdot h^3/(12 \cdot (1-\upsilon^2))$.

3. ISSUES TO SOLVE IN ORDER TO ACHIEVE THE GOAL OF PROJECT 4.58B

3.1 What Traffic Design Criteria Should Be Used?

The Colorado Department of Transportation *(8)* design equations were deduced for 20 kip single and 40 kip tandem axles, and other loads levels are determined in linear proportion. No other axle configurations were considered in this method. The same situation applies to the ACPA design procedure, although its reference single and tandem axle levels are 18 kip and 36 kip, respectively.

The New Jersey Department of Transportation approach *(31)* converts all traffic loads to equivalent 18 kip single axle loads for both single and tandem axles. After obtaining the ESALs, a safety factor is applied in order to take into account the overall standard deviation of predictions and the required design reliability.

The Illinois Center for Transportation *(15)* performed separate analyses using load spectra and ESALs, and they concluded that there is no significant difference between the methods. They therefore propose continuing to work with ESALs because of its simplicity.

As shown above, there is a debate concerning which traffic design criteria should be used. The table below is a summary of the approaches followed by several institutions. It should be remarked that all the design procedures calculate ESALs using the AASHTO load equivalency factors (LEF). These factors were developed from the AASHO Road Test results on the basis serviceability drop. This drop was probably related (in the AASHO Road Test) to poor soils and the lack of dowels, and therefore to faulting. But since all the BCOA design procedures are exclusively based on cracking, the applicability of AASHTO LEFs to BCOA design might not be correct. Besides, AASHTO LEFs are provided for a minimum portland cement concrete (PCC) thickness of 0.5 ft (150 mm), which is greater than the PCC thickness in most BCOA rehabilitation projects.

	BCOA-ME	**CDOT**	**NJDOT**	**ACPA**	**ICT**
Method for Traffic Load Characterization	ESALs	Load Spectrum	ESALs	Load Spectrum	ESALs

3.2 What Is the Contribution of Layer Bonding to the Extension of Overlay Life?

Most references agreed on the need for milling of the hot mix asphalt (HMA) surface prior to overlay placement in order to increase surface texture and ensure good bonding between the HMA and PCC. Although the milling process eliminates the majority of surface distresses, there are cases where moderate distresses remain. In these cases, cleaning and patching before the overlay placement are recommended. Some authors did not consider milling on a regular basis as necessary *(31)*. All the references did agree on the need to clean the surface before overlay placement, regardless of whether it had been previously milled. Pressurized air or mechanical brooms can be used to eliminate fine particles that can reduce bonding between the layers.

No reference was found that discussed placement of BCOA on rubberized asphalt surfaces. But information regarding thin BCOA placed on conventional asphalt mixes indicated that the technique works better on previously milled asphalt than on nonmilled surfaces. This is probably related to milling removing soft/distressed asphalt surface. Consequently, it might be expected that the same would apply to rubberized asphalt mixtures. Nonetheless, it is important to conduct investigations and tests to learn more about bonding between the rubberized HMA and PCC overlays since it could differ from that of conventional HMA and PCC.

Strain measurements were collected from slabs instrumented at multiple depths at three locations—namely edge, center, and corner—in an experimental study conducted in Colorado *(30).* An analysis of the data showed that the strains decreased by approximately 25 percent when milling was applied to the existing HMA layer. However, the strains increased by approximately 50 percent when a newly placed HMA layer was milled.

A recent PhD dissertation at the University of Pittsburgh *(32)* has been focused on BCOA PCC–asphalt interface performance. A cohesive zone model was proposed and calibrated on the basis of split-wedge testing. The model was validated with accelerated loading test data. This model acknowledges the complexity of the PCC–asphalt interface by including different critical failure mechanisms: concrete/asphalt matrix debonding, concrete/exposed aggregate debonding, aggregate pull-out, aggregate cracking, and asphalt cracking. Another contribution from this study is the validation of a nondestructive method, based on transient wave analysis, for quantifying the area of debonding between the PCC and the asphalt base.

No further information was found regarding the fundamental mechanics of bonding between asphalt concrete and portland cement concrete slabs. Laboratory tests are needed to better understand the nature of the bonding between these two materials and to analyze other possible procedures to improve it.

3.3 How Are Shoulders Designed and Constructed?

Shoulders are a very important part of the BCOA rehabilitation method because they decrease the tensile stress up to 15 percent *(33),* and provide lateral support to the structure and erosion protection at the slab edge. There are some designs where the PCC overlay section is wider than the existing bituminous pavement. Where this is the case, competent material, such as compacted crushed aggregate, should be placed. According to experience in Colorado *(34),* the PCC overlay panel should go beyond the actual lane and extend into the shoulder. According to the literature, tied shoulders should be provided if the PCC overlay extends more than two feet into the shoulder *(35).*

Colorado *(34),* Minnesota *(2),* and North Dakota *(36)* recommend the use of PCC shoulders. Minnesota uses a six foot shoulder with the same concrete as the slabs (4,000 psi and slump of 1½ inches, with #3 slab-shoulder tie bars every four feet). North Dakota recommends reduction of the cross-slope of the shoulder from 4:1 to 6:1 for safety, and used the milled asphalt material as the base for the shoulder. Test sections at MnROAD were mill-and-fill type construction, which results in asphalt mix shoulders *(37).*

3.4 What Is the Cost-Effectiveness of Thin BCOA?

Several investigations regarding the cost-effectiveness of the BCOA rehabilitation technique have come to the same conclusion: BCOA rehabilitation is more cost-effective than HMA overlay when the analysis period is longer and takes into consideration not only initial construction costs, but also the maintenance cost for agencies and user delay costs *(33, 1, 3).*

For instance, Purdue University established that a 0.17 ft ultrathin BCOA has a life expectancy of 25 years and becomes cost-effective at only 17 years when compared with a 0.33 ft HMA overlay *(38).* It was also clear that ultrathin BCOA has a longer life span than HMA, and that since ultrathin BCOA would require less rehabilitation in the future, it would further reduce user costs.

Experience from Colorado showed that there is a 1 percent difference in construction cost between thin BCOA and HMA overlays, so both options are considered to be similar when only initial construction cost is analyzed. But the difference between these alternatives was more than 11 percent if rehabilitation costs were taken into consideration: "When user costs are considered, the thin whitetopping [i.e., thin BCOA] becomes a more attractive rehabilitation strategy, owing to its longer service life and low maintenance requirements" *(34).*

A study from Minnesota shows that a 0.5 ft thin BCOA costs 50 percent more than a 0.25 ft HMA overlay, but that it lasts twice as long *(2).* The cost related to user delays can be much higher for an HMA overlay compared to a thin BCOA, which requires less maintenance and fewer rehabilitation activities.

It should be remembered that all of the above cost considerations reflected the relative costs construction and of concrete and asphalt materials at the time of analysis, and that these costs have been highly variable over the past 15 years and will likely remain so. Therefore, some sensitivity analysis to cost fluctuations should be included in any LCCA comparing these strategies.

3.5 What Are Optimal Strategies for the Maintenance and Rehabilitation of Thin BCOA?

Damage to thin BCOA can be divided into long- and short-term distresses *(1)*. Uncontrolled cracking, plastic shrinkage cracking, and joint-edge spalling and raveling are the short-term distresses that have been documented. On the other hand, longitudinal cracking, transverse cracking, corner cracking, and faulting are the most common distresses observed over longer periods of time.

According to the literature and experience from road agencies, the most effective maintenance technique is to maintain the joints in a well-sealed condition. Preventing water from entering underneath layers, especially between the concrete slab and the HMA base, will prevent the composite structure from deterioration due to PCC-asphalt debonding. Debonding seems to accelerate distress evolution *(39)*. Joint sealing can be conducted using hot-liquid asphalt sealant *(40)*. Results have demonstrated up to a 40 percent reduction in cracked slabs when joints are sealed *(41)*.

Experience from Minnesota *(2)* and recommendations from the NCHRP BCOA Synthesis *(1)* provide similar recommendations for designing PCC overlay maintenance and rehabilitation activities. The first step is to determine if the overlay is regarded as ultrathin BCOA, thin BCOA, or unbonded PCC overlay. The second step is to evaluate distresses such as transverse cracking, longitudinal cracking, joint spalling, corner cracking, surface wear, shattered slabs, permanent deformation of support layers, durability, debonding, and faulting. It is important to determine why and how damage is taking place before repairing the rest of the slabs. The third step is to determine possible alternatives for the solution, considering a cost analysis and the time frame needed for each solution. The fourth step is to select the most appropriate process for executing the fieldwork. The last step is to determine an adequate amount of time for the fieldwork and a process for managing traffic while it occurs. The following table summarizes potential distresses and recommended alternatives depending on severity of damage and materials *(1)*.

Distress	Rehabilitation Alternatives
Corner cracking	Crack sealing
	Epoxy injection
	Cross stitching
Mid-panel cracking	Crack sealing
Shattered slab	Slab replacement
Joint spalling	Partial-depth repair
Joint or crack faulting	Slab stabilization
	Load transfer retrofit
	Surface grinding
Surface wear (poor skid resistance)	Surface grinding
Permanent deformation of support layers	Full-depth repair
Corner debonding	Epoxy injection
Panel debonding	Full-depth repair
	Slab replacement

3.6 Should Caltrans Concrete Mix Designs for New Concrete Pavement Be Optimized for Thin BCOA?

Section 90 *(42)* of the Caltrans Standard Specifications provides concrete mix design procedures, issues, and regulations. There is not a unique mix design for pavements but there are minimum requirements such as minimum compressive strength of 3,600 psi, type of cement that should be used (Type II or V), and other parameters for the coarse and fine aggregates, grading, content of water, and additives. Design methodologies from Minnesota and Illinois require a minimum of 4,000 psi in compressive strength (28 days). If flexural strength is used instead of compression, the minimum requirement of Caltrans is 570 psi after 28 days. Other agencies' and methodologies' minimum flexural strengths range from 570 psi to 650 psi.

The Illinois Center for Transportation (ICT) *(15)* evaluated the performance of many PCC mixtures in fracture testing, concrete materials proportion and material selection, composite beam test, and free shrinkage. Those results are good parameters to start with when doing a concrete mix design. Several reports state that regular concrete mix designs could be used *(34)* for thin BCOA. Nominal maximum size of aggregate should not be larger than one-third of the slab thickness *(1)*. Supplementary cementitious materials such as fly-ash and ground-granulated blast furnace slag have been used successfully on thin and ultrathin BCOA projects. Their use is encouraged under hot-weather paving conditions *(43).*

Regarding mix design for thin BCOA, ICT *(15)* analyzed the mix designs of several different projects and agencies. The following chart summarizes the average quantities for projects in Louisville, Kansas, Florida, Tennessee, Colorado, Minnesota (Cells 60/63 Mn/ROAD), and nine projects in Illinois.

	Units	**Average Quantity**
Coarse	lb/cy	1,850 – 1,900
Fine	lb/cy	1,000 – 1,250
Cement	lb/cy	550 – 750
Water	lb/cy	180 – 290
Compressive Strength	psi	3,540 – 4,200
Flexural Strength	psi	650 – 950

Drying shrinkage is a critical phenomenon for thin BCOA performance, due to its high surface-to-volume ratio and reduced PCC thickness *(1, 2, 3).* The depth that can dry out leading to drying shrinkage is around 50 mm, 0.17 ft *(10),* which could mean up to 50 percent of the total thickness of thin BCOA. Drying shrinkage results in joint opening, which reduces load transfer efficiency. It also results in slab-warping that produces additional tensile stresses. In fact, drying shrinkage is a main factor affecting the performance of any rigid pavement. This is the main reason behind the use of the internal-curing concrete (ICC) technology in conventional PCC pavements *(12)*. This technology uses wet light-weight aggregates that provide internal water reservoirs. These internal reservoirs release water on demand for cement paste hydration (internal, autogenous, demand) and drying (external demand), thus reducing the capillary pressures that lead to shrinkage. This technology has resulted in drastic PCC moisture shrinkage reduction in conventional rigid pavements *(12)*. Its application in thin BCOA construction is still to be explored.

3.7 What Is the Contribution of Structural Fibers in Extending Overlay Life?

The literature reviewed generally supports the addition of concrete fiber additives for use with thin BCOA. Fibers increase the strength of concrete considerably and help maintain slab integrity after cracking. According to Vandenbossche *(30),* fiber-reinforced concrete will improve load transfer efficiency across joints and, consequently, will help reduce PCC–asphalt shear stresses and the risk of debonding. Vandenbossche also pointed out that improvement of post-peak performance with fibers is reduced if debonding or reflective cracking take place. Winkelman notes that the use of structural fibers has been widely shown to benefit the flexural capacity of concrete slabs in ultrathin BCOA *(44)*. Some of the references argue that fibers are highly recommended for projects where concrete thickness is less than 0.33 ft (100 mm) and may not be needed when the thickness is higher *(15)*. Fibers have proven efficiency in reducing the rate of crack propagation and increasing flexural strength, which allows an increase in slab dimensions up to 6×6 ft *(39)*.

Currently, beam modulus of rupture and the residual flexural strength ratio are used to determine the effectiveness of each fiber type *(1)*. Fibrillated polypropylene fibers are the most frequently used, at a rate of three pounds per cubic yard *(1)*. In the most frequently used application method, the fibers are blended into the wet concrete mix before it is placed. Nevertheless, some agencies have added the fibers to the dry constituents before preparing the wet mixture.

Apart from a higher resistance to load-related slab cracking (corner, transverse, or longitudinal), the benefit of adding fibers is a higher resistance to reflective cracking, and to thermal, and shrinkage cracks. This higher resistance is based on the higher capability of reinforced concrete to hold “pin” cracks and slow crack propagation *(45)*.

However, the use of fibers can reduce mixture workability, and if fibers are not well distributed their effectiveness is greatly reduced. The effect of fibers on joint-cracking deployment is another critical phenomenon that must be considered since fibers may have a negative effect by reducing the number of working joints.

3.8 Should Wider Slabs Be Considered in Truck Lanes?

Widened slabs are not the focus of any the references analyzed for this literature review. Widened slabs are typically 14 ft wide (4.2 m) and are used with conventional concrete pavements to keep truck loads off of the slab's right edge; this is accomplished by marking the lane edge 2 ft from the slab edge. The widened slab increases stresses caused by temperature and moisture gradients; however, the reduction of stresses under traffic loads is considerable. Studies exist that have been focused on determining the appropriate dimensions of slabs for thin BCOA. Slabs that are 6×6 ft are desirable in order to keep the longitudinal joint far from the wheelpath when thin BCOA is used in truck lanes *(15, 39)*. Widened slabs might make achieving uniform support conditions under the pavement more challenging since existing pavement structures must be widened to establish uniform support conditions under the overlay.

3.9 What Are the Mechanisms of Joint Faulting?

Joint faulting depends on the integrity of the complete structure (HMA+BCOA). Pavements with faulting often also have corner cracking and joint spalling, which are the two most commonly observed distresses according to DOT surveys *(30)*. With BCOA, what starts out as a corner crack frequently changes direction and becomes a longitudinal wheelpath crack.

Faulting in BCOA often appears to be related to transverse cracking of the HMA at the joints, which reduces load transfer efficiency (LTE) at the joint. Cracking in HMA at joints is mostly associated with high shear and potentially with tensile stresses from the slab edge being pushed into the HMA by traffic loads, and also from movement due to a uniform drop in temperature. Faulting progress in BCOA will often follow due to the reduced LTE. FWD tests have shown that LTE is very high as long as cracking has not propagated through the entire HMA thickness *(15)*. There seems to be agreement that HMA bases thinner than 0.1 ft (30 mm) tend to crack easily after the transverse joints cracks have propagated down through the PCC overlay. Loss of LTE can also affect corner cracking and joint spalling. Thin BCOA thicknesses of 0.42 to 0.6 ft (128 to 183 mm) show the best performance in terms of corner cracking *(15)*.

According to experience in Minnesota, small diameter dowels (1 inch) can improve the performance of thin BCOA slabs when they are used under heavy traffic conditions *(39)*. Other agencies have determined that small tie bars across longitudinal joints are helpful in maintaining horizontal and vertical alignment between adjacent lanes.

No records were found relating fibers to joint faulting. All the performance improvements found due to fiber use were related to load, thermal, reflection, and shrinkage cracking.

Faulting performance can be improved by using appropriate slab dimensions, 5×6 ft and 6×6 ft, and joint-sealing treatments *(40)*. Several research studies show that sealing joints will extend the life of thin BCOA *(39)*.

3.10 What Is the Mechanism of Cracking in the Underlying Asphalt Layer and How Does It Affect Thin BCOA Performance?

The literature shows that old HMA works well as the base layer in thin BCOA rehabilitation, and that there are two important asphalt distresses to be considered in the design of the thin BCOA: fatigue cracking and stripping *(39)*. Two factors may contribute to further increasing fatigue cracking in old HMA. First, its age, since old HMA is usually harder than when it was first placed. And second, its thinness, as old HMA has typically been milled several inches in an effort to improve bonding. Combined, these two conditions may create a very thin and brittle layer that may still work well as long as it is bonded to the concrete slab *(15)*. When there is good bonding, the composite structure (HMA+PCC overlay) that exists results in tensile stresses at the bottom of the HMA. Depending on the bonding condition, however, the HMA may also experience tensile strains at the top, which can result in top-down cracking. This possibility should be considered in the analysis of the overlay design life. The Asphalt Institute fatigue model is the one most frequently used for predicting asphalt cracking failure, either bottom-up or top-down, in BCOA sections *(30)*. Researchers agree that this model still needs to be validated for use with BCOA.

Numerous studies have focused on the length of the slabs with thin BCOA. Most agree that the best-designed slabs have a geometry where length is 12 times the thin BCOA thickness and the long/short dimension ratio is not larger than 1.25. Therefore, a thickness of 0.5 ft (150 mm) and lengths of either 6×6 ft or 5×6 ft are the most frequently used and recommended dimensions *(1)*. None of the references addressed the possibility of increasing the length-to-thickness ratio under certain favorable circumstances, like with improved subgrade support, higher concrete flexural strength, or reduced drying shrinkage.

The principal characteristic of thin BCOA structures is the bonded condition between the PCC and the asphalt. When this condition is not achieved during construction, or when it is lost due to traffic and water, the bearing capacity of the overall structure is compromised and many distresses appear rapidly. Debonding at the corners accelerates faulting, and debonding near the edges of the slab accelerates fatigue cracking *(40)*.

Finite element modeling has shown that temperature gradients are generally not as high in thin BCOA as in concrete pavements because they are thinner, although high gradients similar to those in full-depth concrete pavement can exist near the top of a thin BCOA slab. However, induced thermal stresses in a thin BCOA slab can produce cracking since the layers are relatively thin *(40)*. Depending on the design, the location of the calculated critical stresses will vary and, consequently, thermal stresses should be included in the design process. Several thin BCOA projects in the literature were found where temperature differentials went from -1°F/in. up to 5°F/in. *(1).* Among the research documents reviewed, there seems to be agreement on the negligible effect that the underlying asphalt has on the PCC temperature gradient. Thermal contraction of the HMA in winter creates stress concentration at the bottom of the concrete slabs *(2).* Shrinkage is another phenomenon that has to be considered. The maximum slab dimension for adequately avoiding shrinkage cracking seems to be 6×6 ft *(15).* Even though higher cement content leads to greater strength it also induces more drying shrinkage, which can increase cracking. The literature recommends water-to-cement ratios between 0.4 and 0.42 *(1).*

3.11 Which Asphalt-Treated Base Is Typically Used for Thin BCOA?

No references were found where a specific mixture was recommended to be placed before PCC overlay for thin BCOA rehabilitation. The only recommendations that were found were for asphalt mixtures to be used as base for conventional rigid pavements. Some of these references are presented below.

- Texas Procedure Tex-126-E can be used to evaluate the suitability of asphalt materials as base for PCC pavements, asphalt black base materials *(46).*
- Section 287 from Florida is the specification for asphalt-treated permeable bases. Hydrated lime is prescribed as is Superpave PG 67-22 binder. Asphalt content must be 2.0 to 4.0 percent *(47).*
- The University of Texas at El Paso developed a specific procedure, based on Tex-126-E. This procedure establishes a minimum of 85 psi strength in the indirect tensile strength test *(48).*

Only one reference was found where a new asphalt mixture base resulted in bad performance *(6),* and this section had a slab thickness of 0.45 ft (135 mm) with a length of 12 ft, i.e., a length/thickness ratio of 27, which is much higher than the recommended ratio limit of 12 cited previously. The report's authors linked this failure to a lack of support of the PCC overlay due to the permanent deformation of the asphalt mixture. The failure of this section was not related to the strength of the bond between PCC and new asphalt, since this strength was comparable to other sections where the old asphalt had been milled. Some authors indicated that a very soft mixture could be detrimental to BCOA performance *(49),* but that the stiffness of new mixes, placed right before BCOA overlay, can be easily controlled through binder selection and mixture design, especially when overlay protection prevents asphalt from very low temperatures that could induce cracking.

4. CONCLUSIONS

The literature shows that thin BCOA can be treated as a mature technology that has improved considerably over the last decade. This conclusion is supported by the general agreement found about issues pertaining to the design and construction of thin BCOA. For example, reports in the literature agree on thin BCOA's PCC requirements, on the recommended slab thickness-to-length ratios, and on other geometric features. They also agree on the particular importance of achieving good bonding between the PCC overlay and asphalt base.

The mechanical behavior of thin BCOA rehabilitations differs considerably from that of conventional rigid pavements and unbonded PCC overlays with thickness over 0.67 ft (200 mm). The difference comes from the composite action of the PCC overlay and asphalt base. Although this difference in mechanics exists, it has not led to the use of different PCC mixtures for thin BCOA. In fact, almost all of the references agreed that the materials typically used for conventional rigid pavements can also be used with thin BCOA.

One recurring topic in the thin BCOA construction recommendations pertains to the high surface/volume ratio of thin BCOA applications; it is noted that they require special attention in order to avoid the high drying shrinkage that could cause early cracking or affect long-term performance. How this issue should be balanced with the short construction windows that are typically available in thin BCOA projects is an issue that does not seem to have been thoroughly explored. The use of internal-curing concrete has been shown to drastically reduce moisture shrinkage in conventional rigid pavements. How this reduction improves thin BCOA performance is still to be explored. Another issue that requires further investigation is the use of fiber-reinforced concrete in thin BCOA applications. To date, this type of concrete has been widely used with ultrathin BCOA but it has seen limited use with thin BCOA, possibly due to the higher costs associated with it versus the value of performance improvements. However, available analytical tools such as BCOA-ME can help determine overlay thickness reduction when fibers are employed. The effect of fibers on the faulting mechanism deserves further research; in particular, research is needed to understand how fibers affect load transfer efficiency at joints and joints cracking deployment.

Agreement also exists regarding the heuristic that the slab length should not be much greater than approximately 12 times the thickness, especially for the thinnest slabs. Not exceeding a 1.25 length/width ratio is another consensus item. The maximum slab dimensions and, in particular, whether or not 12 ft wide panels can be used instead of 6 ft wide panels, does not seem clear. The same applies to the suitability of PCC shoulders, tied longitudinal joints, or dowelled transverse joints. The frequently empirical nature of both agreements and disagreements found in the literature contrasts with the criticality of the decisions involved. Modeling could be the key to answering some of these questions, provided that the different phenomena that play a role in these processes can be properly accounted for.

In the past, only asphalt pavements in fair to good condition have been considered as candidates for BCOA rehabilitation. This has limited its field of application, since highly deteriorated pavements constitute an important portion of the rehabilitation projects. A relatively sound and thick asphalt base is regarded by all authors as a primary requirement for thin BCOA, since it is clear that a weak, thin, or distressed asphalt base would make the composite action of a PCC-asphalt slab impossible. It is also clear that cracks in the asphalt base can potentially reflect through the PCC overlay. These facts contrast with the lack of attention that has been paid in the literature to the placement of new asphalt that might limit the risk of reflective cracking and provide additional structural support to thin asphalt bases. Some references suggest that the placement of new asphalt below BCOA should be avoided, but very little evidence was found to support these recommendations. Only one reference was found where a new asphalt base mixture resulted in poor performance, and that section violated the heuristics regarding the slab width-to-thickness ratio. It appears from the literature that further research regarding the PCC–asphalt bonding mechanism would be beneficial; that research should focus on both how to obtain a good bond and how to keep it.

Very little information was found in the literature review concerning PCC–asphalt bonding mechanisms, even though all the authors agreed this is a critical issue for thin BCOA performance. It is clear that the composite action of the PCC and asphalt layers requires this bonding. A number of studies have measured bonding strength by using the Iowa shear test, and a reference value of 100 psi has even been postulated as a desirable strength. However, no experimental study was found from which the mechanical nature of this bonding could be inferred. Questions that should be answered include how to characterize the tensile (vertical) and shear (horizontal) interface strength and stiffness; how these properties change with aging, temperature, and load speed; how they are damaged by traffic and water; how to achieve good bonding; and how to design the pavement so that a good bond is maintained for the longest time possible. The impact of these bond properties on slab mechanics and thin BCOA performance can also be improved. A few experimental references directly attributed the lack of agreement between predicted and measured response to partial bonding, without further investigation. In particular, no consideration was given to the fact that in those experimental studies the loads were applied statically, which could have resulted in a very low asphalt stiffness. These assumptions have been included in BCOA design procedures for more than a decade.

Some analytical tools were found that can be used for mechanistic-empirical design of thin BCOA rehabilitations. The most recent tool, and probably the most powerful, is BCOA-ME, which was developed at the University of Pittsburgh under FHWA pooled-fund project TFP-5(165). This tool integrates stress prediction equations from the Colorado DOT and ACPA design methods (which are applicable to transverse and corner cracking, respectively) with a number of new models for predicting longitudinal cracking, effective equivalent linear temperature gradient, monthly asphalt base modulus, and other useful design features. A faulting model is still not available in this or any other ultrathin or thin BCOA design procedure. BCOA-ME has been calibrated based on the performance of sixteen thin and ultrathin BCOA sections. Traffic is considered in terms of ESALs, which are calculated using AASHTO load equivalency factors. This approach is also implemented in the ACPA and Colorado DOT design methods. Whether AASHTO load equivalency factors can be extrapolated to thin BCOA design is an issue that seems to need further research.

Very little information was found in the literature review concerning faulting in thin BCOA overlays. Nonetheless, available experimental references indicate that the faulting mechanism may be very different from the classic build-up of eroded materials under the approaching slab that, together with loss of support under the leaving slab, cause faulting in conventional rigid pavements. Experimental evidence indicates that asphalt base fatigue resistance and thickness play, together with bonding, a major role. Another variable that current thin BCOA design procedures do not consider is drying shrinkage, even though it is known to result in transverse joints opening and slab permanent and seasonal warping. One reason drying shrinkage is critical for thin BCOA is because of the overlay's high surface/volume ratio. Further, PCC drying shrinkage potential has not been evaluated on a regular basis for thin BCOA applications and may be an important consideration for particularly dry California climate regions. Estimation of stresses related to temperature gradients is mainly conducted empirically in current thin BCOA design procedures, and PCC coefficient of thermal expansion is only accounted for in the corner cracking model. Questions related to slab dimensions and configurations, including shoulders, tie bars, and dowels, will not be properly answered while such important phenomena are not understood and modeled.

To date, very little attention has been paid to characterizing the existing asphalt mixture and the placement of new asphalt layers prior to BCOA. Again, this contrasts with the general agreement that both the distress state and the stiffness of the asphalt base are important factors in determining BCOA performance. In particular, the assumption that asphalt has a constant modulus, i.e., that it is independent of temperature and rate of load application, appears to warrant further research and could result in important changes in design practice. It should be remarked that validated models and procedures already exist for asphalt mixture characterization, so its implementation should be straightforward. The interaction of asphalt distresses with overlay performance is another issue that has been acknowledged and reflected in construction practices, and likely warrants further attention in thin BCOA design. Only one approach was found in the literature where such an interaction was quantified. In particular, reflective cracking potential was related to the ratio of flexural stiffness between PCC overlay and asphalt base.

In closing, it seems clear that even though thin BCOA is already a mature technology, there are a number of important issues that warrant additional research and that are likely to improve thin BCOA technology. The resolution of these issues, as described above and numbered below, constitutes one of the objectives of this research project.

1. PCC mix design
    a. Evaluation of the beneficial effects of internal curing concrete (ICC) for BCOA
    b. Evaluation of the benefits of structural fibers for post-failure performance (laboratory study only)
    c. Balancing the short construction windows with the demanding structural requirements of BCOA through materials type selection and mix design
2. Slab geometry and configuration
    a. Optimization of panel size
    b. Optimization of length-to-width ratio and maximum dimension-to-thickness ratio
    c. Evaluation of the beneficial effects of widened slabs
3. Asphalt base
    a. Optimization of the rubberized hot mix asphalt (RHMA) mix design for BCOA bases where new bases will be placed prior to placement of concrete
    b. Understanding the interaction between asphalt base properties (existing aged hot mix asphalt [HMA] and new RHMA) and BCOA distress mechanisms
    c. Determining the implications of the use of new RHMA bases on BCOA performance
4. PCC−Asphalt interface
    a. Mechanical characterization of the interface
    b. Prediction of interface performance
    c. Evaluation of PCC-asphalt bond in the laboratory
    d. Optimization of techniques to improve PCC-asphalt bonding

5. Mechanistic-empirical design
    a. Development of a comprehensive model that considers the different BCOA design features listed above
    b. Development of a BCOA faulting model
    c. Consideration of concrete shrinkage in BCOA design
    d. Consideration of asphalt base distresses (cracking at joints, moisture damage, permanent deformation under joints contributing to faulting) and granular base/subgrade distresses (permanent deformation under joints contributing to faulting) in BCOA design
    e. Improvements to the current BCOA cracking model (developed by University of Pittsburgh) through better consideration of bonding and asphalt base characteristics
    f. Validation and calibration of all of the above with accelerated pavement testing, data from MnROAD experiments, and field data from California and other states

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