IMPLEMENTATION OF COMPOSITE PAVEMENT SYSTEMS

Final Report

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Notice

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16. Abstract

In 2014, the Federal Highway Administration (FHWA), working in collaboration with the American Association of State Highway and Transportation Officials (AASHTO), selected the SHRP2 Project R21 for funding under the SHRP2 Implementation Assistance Program (IAP). The IAP is designed to help highway and transportation agencies implement and deploy technologies and solutions developed under the SHRP2 program. To accomplish this, the FHWA administered a series of activities aimed at fostering the implementation of composite pavement systems:

- Provision of technical assistance and support to State Highway Agencies (SHAs) in the planning, design, and construction of new composite pavement systems.
- Development of a workshop on the design and construction of new composite pavement systems and delivery of the workshop to SHAs.
- Sponsorship of a multi-state showcase event promoting new composite pavement systems and featuring a visit to a nearby project.
- Conduct of a multi-state peer exchange providing a forum for SHAs to share their knowledge of and experience with new composite pavement systems.
- Provision of technical outreach through technical presentations on new composite pavement systems at national conferences and events.

This report documents the various implementation activities that were performed and captures some of the critical lessons learned that can be used by SHAs as they move forward with adopting composite pavement systems.

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Unclassified	Unclassified	68	None.

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	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)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION

Background

The Strategic Highway Research Program 2 (SHRP2) R21 project, *Composite Pavement Systems*, examined the history, usage, materials, modeling, and behavior of composite pavement structures and developed detailed design and construction guidelines (Rao et al. 2013a; Rao et al. 2013b). These composite pavement systems are considered to include one of two types of designs:

1. HMA over PCC: A hot-mix asphalt (HMA) surface placed on a new portland cement concrete (PCC) pavement in new construction.
2. PCC over PCC: A top lift of concrete placed on a lower lift of concrete in a wet-on-wet process to create a monolithic structure.

Each of these structures is designed and constructed as composite systems at the time of their initial construction, which differentiates them from the majority of the composite pavements in service today that are the result of periodically applied maintenance and rehabilitation activities (e.g., HMA overlays placed on existing PCC pavements). With the ability to incorporate optimized mixtures in each paving layer, these designs offer sustainable, cost-effective solutions for a range of applications while providing long life and excellent surface characteristics. More details on the characteristics of each composite pavement type are provided below.

HMA/PCC Composite Pavements

HMA/PCC pavements are one type of composite pavement that includes a new asphalt pavement surface placed on a new concrete pavement. The asphalt pavement can employ a variety of materials and design options, including dense and porous hot-mix asphalt, stone matrix asphalt (SMA), polymer-modified asphalt (PMA), and asphalt rubber friction course (ARFC), among others. In general, the wearing course typically consists of a relatively thin, high-quality asphalt concrete that can include one or more asphalt concrete layers with or without special considerations to mitigate the potential for reflection cracking from the underlying concrete layer. The concrete layer typically consists of either a jointed plain concrete pavement (JPCP) or a continuously reinforced concrete pavement (CRCP). The underlying concrete pavement provides the load-carrying capacity for the composite pavement system whereas the asphalt layer is designed to meet the required functional characteristics (smoothness, friction, noise levels) for the roadway. Figure 1 provides a schematic of a new HMA/PCC composite pavement system.

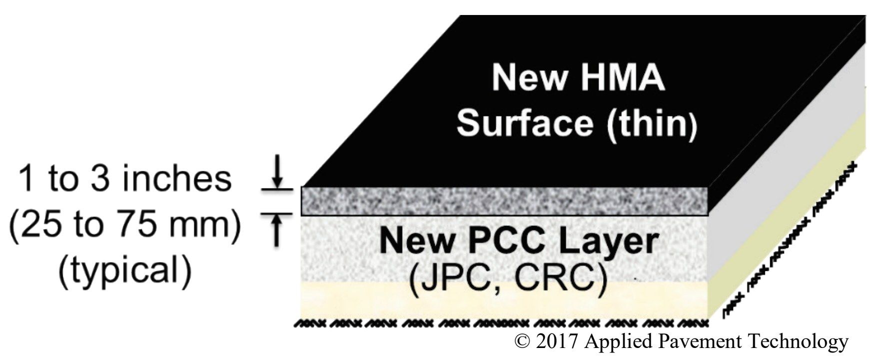

Figure 1. New HMA/PCC composite pavement system.

Two-Lift Concrete Pavements

Two-lift concrete pavements use two separate lifts of concrete that are placed in a wet-on-wet process to produce a monolithic structure (see figure 2). Although not new, two-lift concrete pavements are an innovative approach to optimizing the characteristics of each layer and, hence, the overall pavement structure. For example, the upper lift may consist of abrasion-resistant and more durable materials optimized for surface characteristics such as noise and texture, while the lower lift may employ recycled or marginal aggregate materials and possibly higher quantities of supplementary cementitious materials (SCMs), such as fly ash or slag cement. The construction operation is set up in such a way that the typical time lag between the placement of the top and bottom lifts is between 30 and 90 minutes to ensure that adequate bond develops between the two lifts.

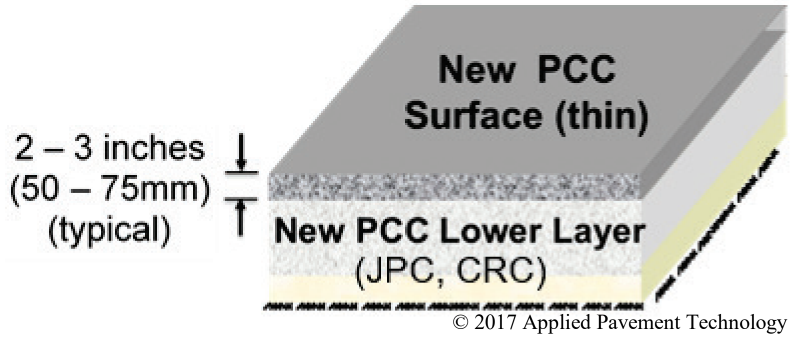

Figure 2. Two-lift concrete pavement.

Implementation of Composite Pavement System Technologies

In 2014, the Federal Highway Administration (FHWA), working in collaboration with the American Association of State Highway and Transportation Officials (AASHTO), selected the SHRP2 Project R21 for funding under the SHRP2 Implementation Assistance Program (IAP). The IAP is designed to help highway and transportation agencies implement and deploy technologies and solutions developed under the SHRP2 program. To accomplish this, the FHWA administered a series of activities aimed at fostering the implementation of composite pavement systems:

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- Conduct of a multi-state peer exchange providing a forum for SHAs to share their knowledge of and experience with new composite pavement systems.
- Provision of technical outreach through technical presentations on new composite pavement systems at national conferences and events.

These activities were performed over a 4-year period and yielded additional insight on different aspects of composite pavement systems, from their general applicability and selection to their improved design, construction, and performance. This report, therefore, documents the various implementation activities that were performed and captures some of the critical lessons learned that can be used by SHAs as they move forward with composite pavement systems.

Report Organization

This report consists of five chapters, including this introductory chapter. Brief descriptions of the chapters are provided below:

- **Chapter 2: Summary of Project Implementation Activities.** This chapter provides a brief summary of the implementation activities that were performed under the project, which ranged from the provision of technical assistance to the delivery of presentations, workshops, and peer exchange and showcase events.
- **Chapter 3: Selection of Composite Pavement Systems.** This chapter presents some general guidance on the selection of composite pavement systems, including the overarching project characteristics and features that best lend themselves to a composite pavement systems solution.
- **Chapter 4: Design and Construction of Composite Pavement Systems.** Chapter 4 extracts key information learned from the outreach activities described in chapter 2 and provides additional guidance on the design and construction of composite pavement systems that can be used to supplement the original SHRP2 Project R21 guidelines.
- **Chapter 5: Concluding Remarks.** This chapter provides a brief recap to the report and describes the future use and implementation of composite pavement systems, including the current gaps and research needs.
- **Appendix A: Implementation Assistance Program Composite Pavement Field Projects.** This appendix provides a brief summary of the characteristics of the four field projects constructed under the FHWA Implementation Assistance Program.

CHAPTER 2. SUMMARY OF PROJECT IMPLEMENTATION ACTIVITIES

Introduction

Under this project, the FHWA engaged in a multi-pronged outreach and deployment effort to help promote and implement the use of composite pavement systems. The implementation effort was targeted to SHAs but offered varied levels of effort and involvement. A summary of the overall implementation activities performed under the project is provided in this chapter.

Implementation Assistance Program Composite Pavement Field Projects

Four highway agencies applied for and were granted funding to support the construction of composite pavement projects (see figure 3 and Appendix A):

- Tennessee Department of Transportation (TDOT): PCC/PCC project on the shoulder of a portion of I-65 in Nashville. Distinguishing features: polish-resistant limestone aggregate in top layer, polish-susceptible limestone aggregate in bottom layer. Additional details are provided by Smith et al. (2015).
- California Department of Transportation (Caltrans): PCC/PCC project on a section of I-210 near Burbank. Distinguishing features: two separate segments with different aggregates in the lower lift, one with recycled concrete aggregate (RCA) and one with conventional aggregate (no RCA). Additional details are provided by Ram et al. (2019).
- Texas Department of Transportation (TxDOT): PCC/PCC project on a frontage road parallel to U.S. 59 near Beasley (south of Houston). Distinguishing features: CRCP with steel placed in lower lift, aggregate in lower lift has coefficient of thermal expansion (CTE) > 5.5 x 10^{-6} inch/inch/ºF (9.9 x 10^{-6} mm/mm/ºC). Additional details are available from Snyder, Smith, and Naranjo (2019).
- Virginia Department of Transportation (VDOT): HMA/PCC project on a section of U.S. 60 near Richmond. Distinguishing features: underlying PCC is CRCP, surface course is SMA. Additional details are available from Espinoza-Luque, Smith, and Hossain (2019).

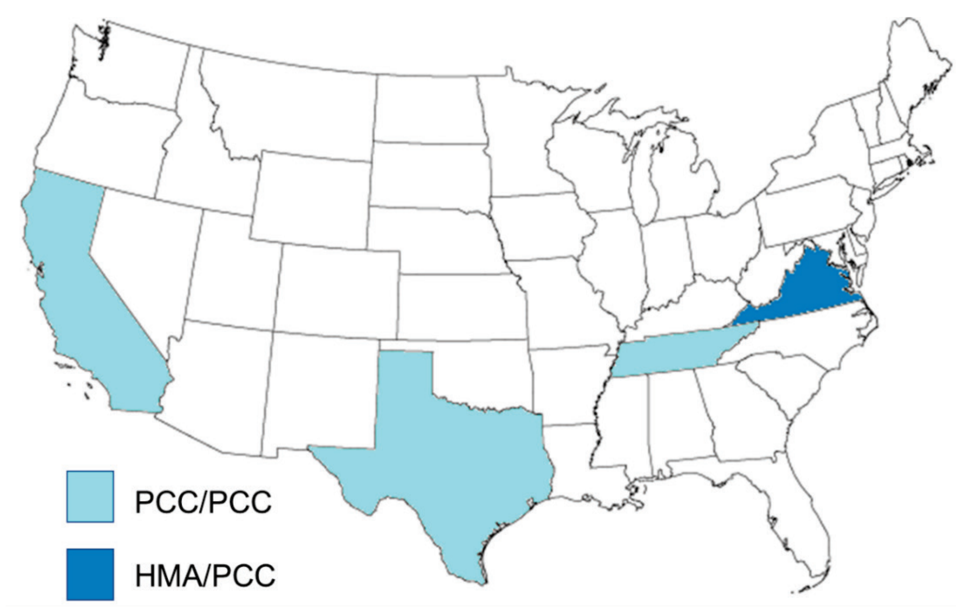


Figure 3. States with composite pavement field projects.

The FHWA provided technical assistance and support in the design of these projects, and project team representatives also visited the project sites during construction to observe the paving operations. Detailed summary reports documenting the construction of each composite pavement project were developed and are available from FHWA (Smith et al. 2015; Ram et al. 2019; Espinoza-Luque, Smith, and Hossain 2019; Snyder, Smith, and Naranjo 2019).

Workshops

Using the guidelines from the original SHRP2 R21 project, a 1-day workshop on the design and construction of composite pavement systems was developed. Targeted to managers, engineers, contractors, and technicians, the overall learning objectives of the workshop were to:

- Describe the concepts and benefits of new composite pavement systems.
- Identify conditions when new composite pavement systems are appropriate.
- List the design components for new composite pavement systems.
- Describe the process for constructing new composite pavement systems.

A generic agenda for the workshop is shown in table 1, but each workshop was tailored to the interests and preferences of the host highway agency. The workshop used a series of PowerPoint slides that followed a parallel format in the layout and presentation of the materials as they pertained to HMA/PCC and PCC/PCC systems.

Table 1. Generic agenda for composite pavements workshop.

TIME	TOPIC
8–8:30 AM	Welcome, Introductions, SHRP2 Project R21 Overview
8:30–9:45 AM	Module 1, Lesson A: Introduction to Composite Pavements
9:45–10:00 AM	Break
10:00–11:00 AM	Module 1, Lesson B: Design Guidelines—HMA/PCC Systems
11:00–12 Noon	Module 1, Lesson C: Design Guidelines—PCC/PCC Systems
12:00–1:00 PM	Lunch
1:00–2:30 PM	Module 2, Lesson A: Construction Guidelines—HMA/PCC Systems
2:30–2:45 PM	Break
2:45–4:00 PM	Module 2, Lesson B: Construction Guidelines—PCC/PCC Systems
4:00–4:15 PM	Closing Remarks/Adjourn

The workshop was delivered nine times over the contracting period to a total of more than 250 participants. A team of three instructors were available to deliver the workshops, with a two-person team for each individual workshop selected based on the specific topics and interests raised by the hosting agency. The workshops were well-received and garnered positive ratings from the participants. Table 2 summarizes the presentation details for the workshops, while figure 4 illustrates the SHAs that hosted the events.

Table 2. Summary of workshops delivered on composite pavement systems.

Date	Agency	Location	Topic(s)	Length	# of Participants
July 15, 2015	New Mexico DOT	Albuquerque, NM	HMA/PCC PCC/PCC	1 day	16
November 17, 2015	Texas DOT	Houston, TX	PCC/PCC	½ day	24
February 16, 2016	Virginia DOT	Charlottesville, VA	HMA/PCC	½ day	45
February 24, 2016	California DOT	Los Angeles, CA	PCC/PCC	½ day	26
February 25, 2016	California DOT	Sacramento, CA	PCC/PCC	½ day	23
March 22, 2017	Delaware DOT	Dover, DE	PCC/PCC	½ day	30
May 24, 2017	Florida DOT	Gainesville, FL	HMA/PCC PCC/PCC	1 day	25
December 14, 2017	Pennsylvania DOT	Montoursville, PA	HMA/PCC	½ day	33
March 20, 2018	Pennsylvania DOT	King of Prussia, PA	HMA/PCC PCC/PCC	1 day	31

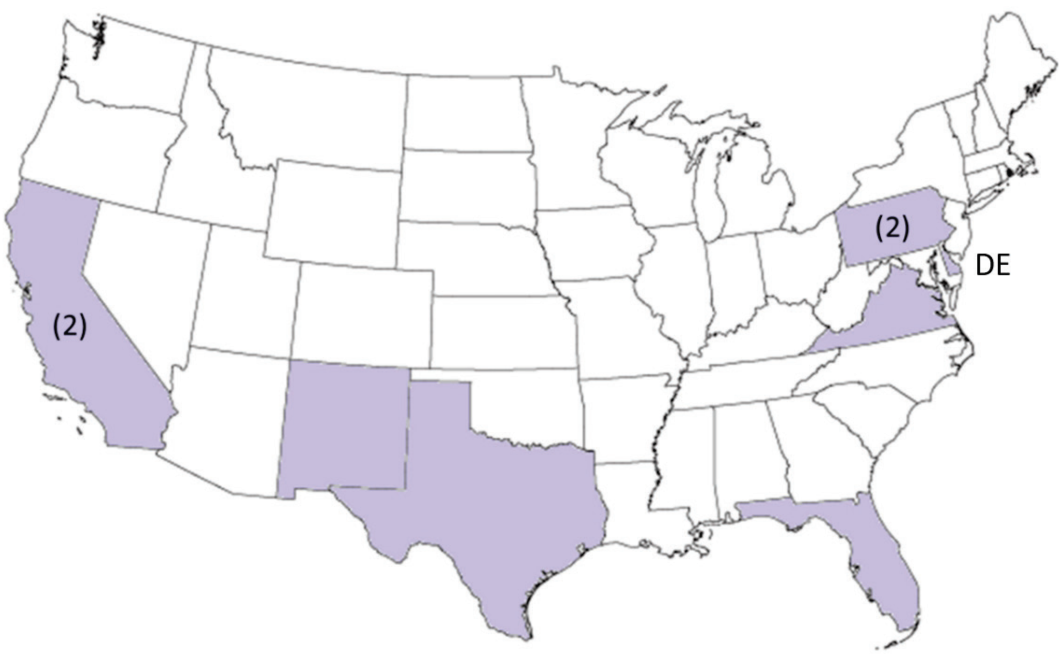


Figure 4. States hosting composite pavement workshops.

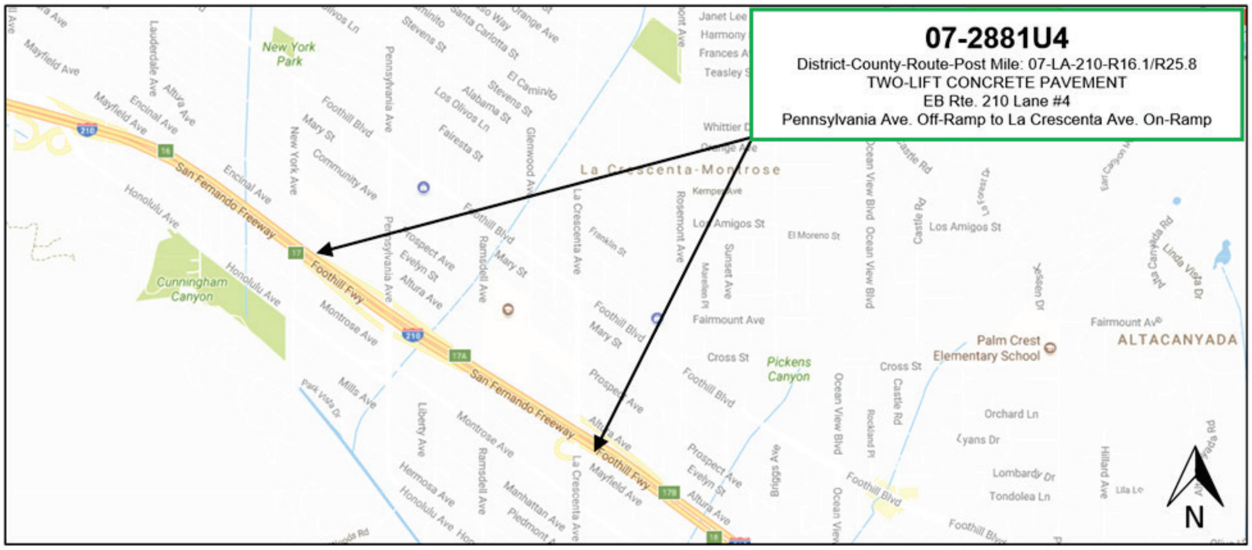
Showcase

The FHWA, in conjunction with the California Department of Transportation, sponsored a showcase on composite pavement systems on January 31, 2017 in Burbank, CA. The purpose of the showcase was to highlight innovations in the design and construction of composite pavement systems, and included a site visit to a nearby paving project. The showcase attracted nearly 70 attendees with representation from highway agencies, academia, contractors, consultants, and industry.

The showcase featured a strong technical program in which several highway agencies shared their knowledge of and experience with composite pavement systems (see agenda in table 3). This was followed by a visit to a nearby two-lift paving project located in the eastbound lanes of I-210 (see figure 5). Figures 6 through 8 provide some selected photos from the I-210 paving project. Copies of the presentations from the showcase (in pdf layout) may be downloaded at: https://goo.gl/azWAtR. The showcase event is fully documented in a report by Ram and Smith (2017).

Table 3. Agenda for showcase event (Ram and Smith 2017).

Time	Topic
7 AM	Registration
8 AM	Welcome | *Kurt Smith, APTech* FHWA Remarks | *Steve Cooper, FHWA* Caltrans Welcome | *Caltrans DOT Administrator*
8:20 AM	SHRP2 Project R21 Research on Two-Lift Concrete Pavement | *Derek Tompkins, University of Minnesota*
8:45 AM	Two-Lift Concrete Pavement on I-65 in Nashville | *Jamie Waller, TNDOT*
9:15 AM	IL Tollway Experience with Two-Lift Concrete Paving | *Steve Gillen, Illinois Tollway*
9:45 AM	Texas DOT Two-Lift Paving Project | *Andy Naranjo, Texas DOT*
10:05 AM	BREAK
10:20 AM	Virginia DOT Composite Paving Project | *Shabbir Hossain, Virginia DOT*
10:40 AM	Caltrans I-210 Project: Description and Objectives | *Mehdi Parvini, Caltrans*
11 AM	Caltrans I-210 Project: Materials and Design | *Caltrans Project Manager*
11:25 AM	Caltrans I-210 Project: Planning, Logistics, Challenges | *George Butorovich, Flatiron Construction*
11:50 AM	Caltrans I-210 Project: FHWA Mobile Concrete Trailer Data Collection | *Jagan Gudimettla, FHWA*
12:15 PM	Field Trip Overview and Logistics
12:30 PM	Grab boxed lunches / Board buses at hotel
1 PM	Arrive at Site
3 PM	Depart Project Site
3:30 PM	Return to hotel / adjourn



Map data ©2017 Google (see Acknowledgments page)

Figure 5. Location of I-210 two-lift paving project.

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Figure 6. Concrete mixture for the bottom lift of the I-210 project.

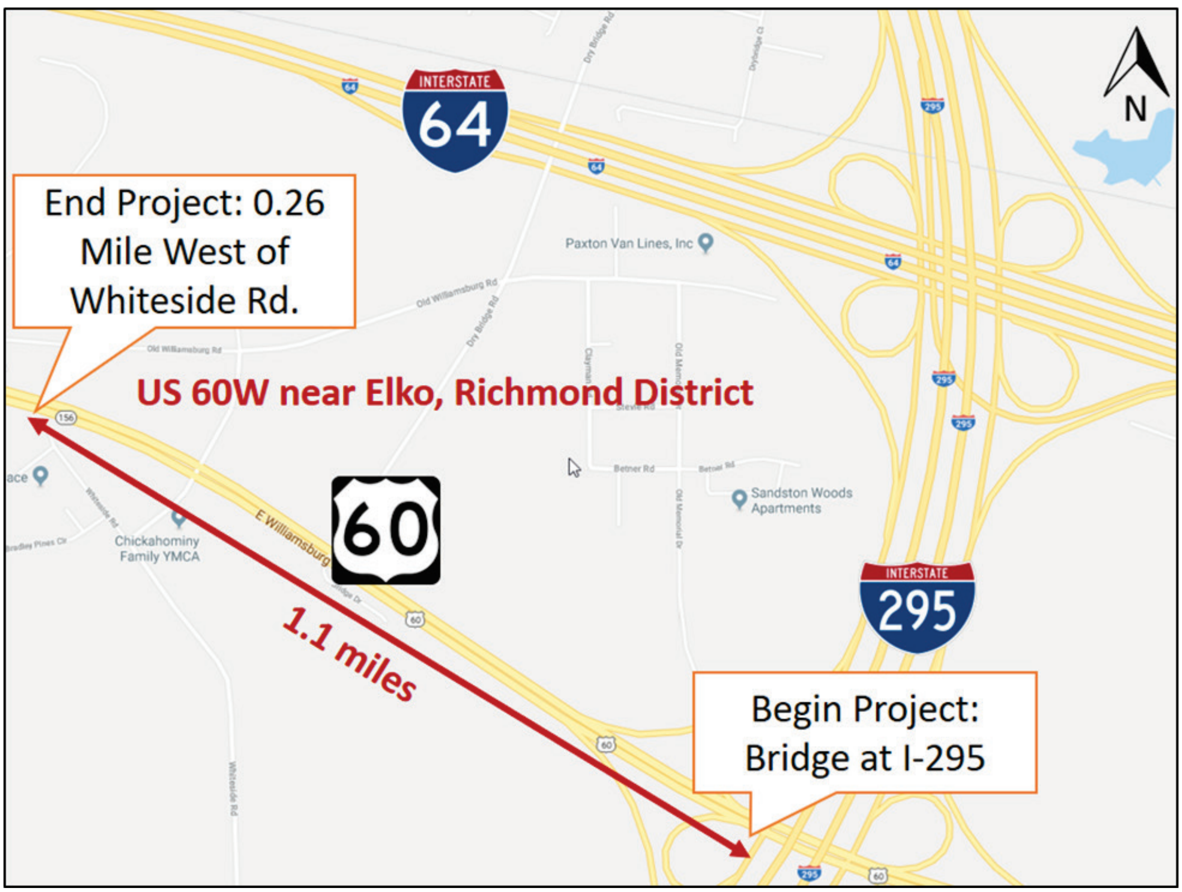
Figure 7. Concrete mixture for the top lift of the I-210 project.

Figure 8. Showcase attendees visit the two-lift concrete pavement project on I-210.

Peer Exchange

In conjunction with the Virginia Department of Transportation, the FHWA sponsored a peer exchange on composite pavement systems in Richmond, VA on December 5-6, 2017. The peer exchange provided a forum for highway agencies to not only share their experiences with composite pavement systems but also to discuss critical topics related to composite pavement systems such as project selection criteria, implementation issues, and research needs. The peer exchange attracted nearly 50 attendees with representation from highway agencies, academia, contractors, consultants, and industry.

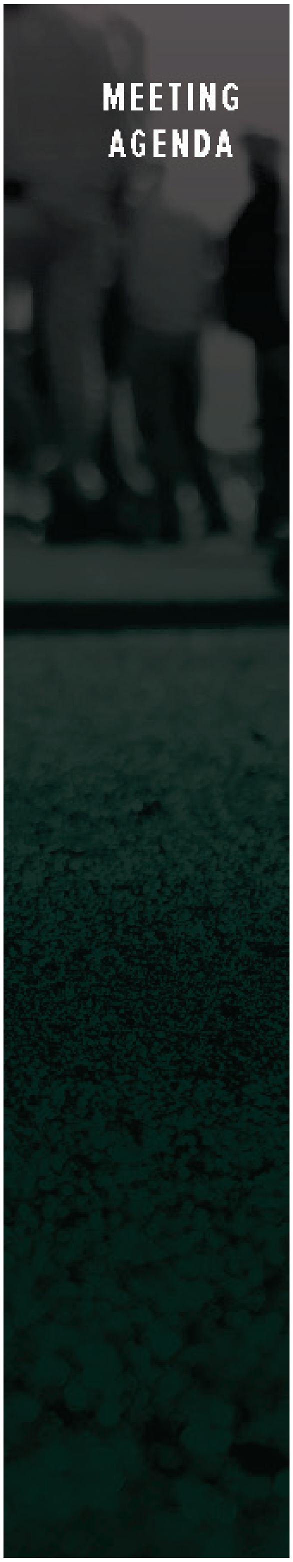
The first part of the peer exchange focused on HMA/PCC composite systems, including background information on the original R21 research work and an overview of the experiences of several DOTs (see agenda in table 4). This was followed by a visit to the IAP-funded HMA/PCC composite pavement project that had been recently constructed by VDOT on U.S. 60 (see figure 9), as well as visits to several nearby HMA/PCC composite pavement projects (overlays) constructed by VDOT (see figure 10). Figures 11 to 14 show selected photos of the U.S. 60 project site.



Map data ©2017 Google (see Acknowledgments page)

Figure 9. U.S. 60 HMA/PCC composite pavement project site location.

Table 4. Agenda for peer exchange event (Ram and Smith 2018).



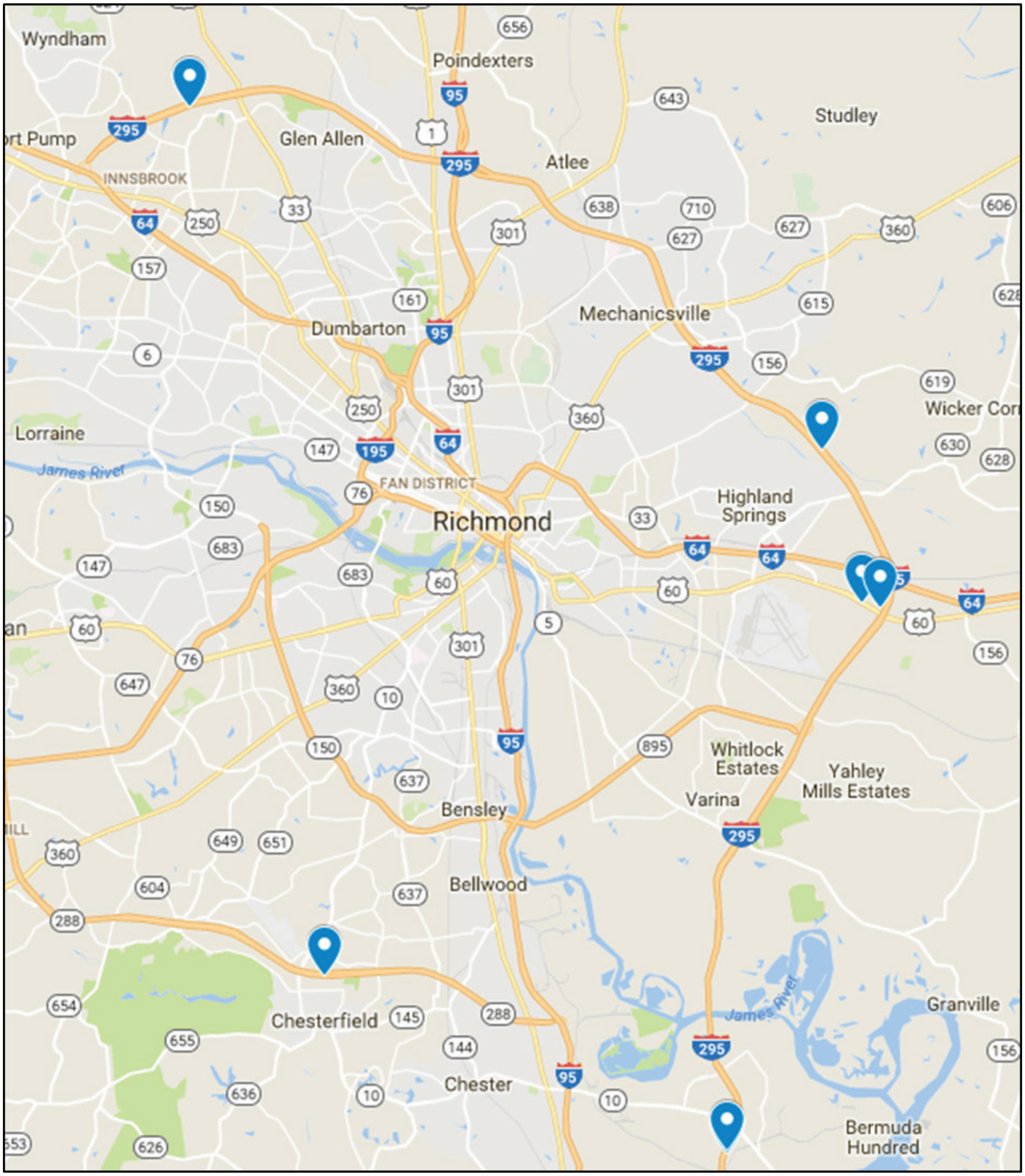
TUESDAY, DECEMBER 5

Time	Topic
8:30 AM	Welcome | *Kurt Smith, APTech* FHWA Remarks | *Steve Cooper, FHWA* VDOT Welcome | *Rob Cary, VDOT*
8:40 AM	**New Composite HMA/PCC Pavements** • Overview of SHRP2 Project R21 | *James Signore, NCE* • Illinois Tollway Experience | *Daniel Gancarz, ARA* • Arizona DOT Experience | *Paul Burch, ADOT*
10:00 AM	*Break*
10:15 AM	**Virginia Composite Pavement Projects** • Virginia Experience with Composite Pavements | *Kevin McGhee, VDOT* • U.S. 60 Project Overview | *Shabbir Hossain, VDOT* • Design of U.S. 60 Project | *Affan Habib, VDOT* • Construction of U.S. 60 Project | *Tommy Schinkel, VDOT*
11:45 AM	Virginia Composite Pavement Project – Site Briefing | *VDOT*
NOON	*Lunch (provided)*
12:30 PM	Board Bus/Visit to Project Site*
5:00 PM	Return to Hotel/Adjourn for the Day

**Please bring your own Class III safety vests and hard hats for the site visit.*

WEDNESDAY, DECEMBER 6

Time	Topic
8:30 AM	Review of Day One/Opening Remarks for Day Two | *Kurt Smith, APTech; Steve Cooper, FHWA*
8:40 AM	**Facilitated Discussion** Selecting Projects for Composite Pavements | *Kurt Smith, APTech*
10:00 AM	*Break*
10:15 AM	**Facilitated Discussion** Implementation of Composite Pavements | *Kurt Smith, APTech; Kevin Wright, VDOT*
11:30 AM	Final Discussion | *Kurt Smith, APTech; Steve Cooper, FHWA*
11:45 AM	Adjourn



Map data ©2017 Google

Figure 10. Approximate location of additional HMA/PCC overlay project sites visited in peer exchange.

Figure 11. Overview of the U.S. 60 project site (Ram and Smith 2018).

Figure 12. Peer exchange attendees on the U.S. 60 project site (Ram and Smith 2018).

Figure 13. Close-up of stone matrix asphalt (SMA) surface (Ram and Smith 2018).

Figure 14. Close-up overview of SMA surface (Ram and Smith 2018).

The second day of the meeting included two facilitated discussions, one focusing on project selection criteria for composite pavements and one focusing on implementation issues related to composite pavements. Key points and issues raised during this facilitated discussion are incorporated into chapters 3, 4, and 5 of this report. Copies of the presentations from the peer exchange (in pdf layout) may be downloaded at: https://goo.gl/uUij1j. The peer exchange event is fully documented in a report by Ram and Smith (2018).

Technical Outreach

As part of the R21 implementation project, the FHWA contributed to technical outreach by participating in several national and regional workshops and conferences. This provided a platform for sharing technical information on the design and construction of composite pavement systems as well as a mechanism for promoting interest in the technology from highway agencies. A summary of the technical outreach presentations furnished under the program is provided in table 5.

Table 5. Summary of technical outreach activities.

Date	Event	Location	Presentation Title
February 19, 2015	Pennsylvania Concrete Conference	Harrisburg, PA	Two-Lift Concrete Pavements
June 8, 2015	ASCE Airfield & Highway Pavement Conference	Miami, FL	New Composite Pavement Systems
November 15, 2016	Nevada Infrastructure Concrete Conference	Reno, NV	Two-Lift Concrete Pavements
November 17, 2016	Nevada Infrastructure Concrete Conference	Las Vegas, NV	Two-Lift Concrete Pavements
March 3, 2017	Virginia Concrete Conference	Richmond, VA	New Composite Pavement Systems
February 20, 2019	Pennsylvania Concrete Conference	Harrisburg, PA	Composite Pavement Technologies

Summary

A number of implementation activities have been performed to help promote and disseminate information on composite pavement systems. These included a series of targeted state workshops to participation in national and regional conferences, and were accentuated with the sponsorship of a 1-day showcase event and a 1½-day peer exchange event in which highway agencies shared knowledge and experience with composite pavement systems and were able to view recently constructed composite pavement structures.

CHAPTER 3. SELECTION OF COMPOSITE PAVEMENT SYSTEMS

Introduction

As described in chapter 1, composite pavement systems offer a number of potential advantages and benefits, which can be broadly classified in terms of the following:

- Sustainability. This includes a number of aspects, from increased use of local and recycled materials (and the associated conservation of resources), reduced transportation and hauling costs (incurred for virgin materials), reduced cement contents, and reduced disposal costs, all of which also provide reductions in important environmental impacts such as emissions and energy usage.
- Economic savings. Reductions in virgin materials and the ability to use recycled products in the lower layers of composite pavements without compromising performance can yield significant life-cycle cost savings in addition to the environmental benefits.
- Extended service life. Composite pavements can be designed for virtually any traffic level and for any service life, providing effective, long-term performance while requiring only occasional surface renewal or texturing.
- Optimized pavement surface. The use of multi-layer, composite pavement systems allows for the optimization of the surface layer properties to meet the specific frictional demands and noise level requirements of a given project.

Even with these benefits, composite pavements may not be appropriate for all paving projects or locations. As part of the peer exchange held in Richmond, Virginia on December 5-6, 2017, a facilitated discussion session explored the topic of selecting projects for new composite pavements. The results of that session are summarized in tables 6 through 8. The following sections discuss some of these considerations for each specific composite pavement type.

Table 6. Agency motivation/construction considerations for HMA/PCC composite pavements (Ram and Smith 2018).

Topic Area	Discussions/Comments
Agency Motivation for Considering HMA/PCC Composite Pavements	• Arizona: Smooth ride, improved structural capacity, reduced noise, and thermal insulation for underlying concrete (which reduces curling and warping stresses) are primary factors. • Virginia: Experience with rehabilitating existing concrete pavements was the primary driver. When concrete is protected from moisture and weather-related distresses, it lasts much longer. Maintaining an asphalt surface is easier. • Illinois Tollway: From a design standpoint, the thermal shielding benefits are definitely a consideration. The ability to use recycled and lower-quality materials in the lower concrete layers improves the overall sustainability of the system.
General Construction Considerations for HMA/PCC Composite Pavements	• HMA/CRCP designs perform better than HMA/JPCP designs due to the reduced potential for reflection cracking. Some agencies have used a saw and seal strategy for controlling the reflection cracking on HMA/JPCP. • The Connecticut DOT has had issues with the precision of sawcuts and consequently no longer uses the saw and seal approach. The precision for the sawcuts may not be much of an issue with shorter joints (such as 15 ft [4.6 m]). With thicker overlays, the joints may not reflect through and the saw and seal may not be the ideal strategy in those cases. • SMA mixtures tend to exhibit better performance when used as the surface layer since load transfer with stone-on-stone contact is better for rutting resistance. • Florida has used open-graded mixtures on concrete pavements to address drainage and splash/spray issues.

Table 7. Agency motivation/construction considerations for PCC/PCC composite pavements (Ram and Smith 2018).

Topic Area	Discussions/Comments
Agency Motivation for Considering PCC/PCC Composite Pavements	• Caltrans: Ability to use recycled materials, reduce landfill usage, and improve overall environmental sustainability. • Tennessee: Availability of quality surface aggregate material was the primary driver. The ability to use local/lower quality materials in the lower pavement layers (in two-lift concrete pavements) is a good application to overcome supply issues related to quality aggregates. Specifications changes are also a big driver, as they tend to strongly influence decisions made on the design option selected. • Illinois Tollway: The primary driver was to improve overall sustainability (cost and environmental) and to make use of recycled materials. There was a projected excess of coarse reclaimed asphalt pavement (RAP), which was used in the lower lifts in two-lift concrete pavements. The replacement rate of virgin coarse aggregate was generally around 20%, but laboratory studies have demonstrated that up to 50% replacement is possible without compromising performance.
General Construction Considerations for PCC/PCC Composite Pavements	• The time lag between the top and bottom lifts should be between 30 and 90 minutes to ensure adequate bonding between both the layers. • Logistical issues (such as using the same concrete plant or two different plants for the top and bottom lifts, using multiple contractors on the job site) should be addressed prior to commencing the construction operations. • Availability of lateral work space is a big issue for two-lift paving due to the need for more equipment on the job site. It may be more suited for rural areas where work space is less of an issue Two-lift paving in urban areas may be a challenge but can be performed (e.g., California I-210 project). • The experience of the contractor will also play a huge role in executing the project in an efficient and effective manner. • There are generally no delamination issues between the top and bottom lifts even with stiffer concrete mixtures. If the time lag between the top and bottom lift exceeds 90 minutes, there may be potential issues. • The position of vibrators will need to be adjusted so that they don't vibrate at the interface between the two lifts. • The Illinois Tollway has used multiple contractors for two-lift paving, and each used a unique approach. Some contractors used belt placers and spreaders while others used pavers. If pavers were not being used, the Tollway required the construction of test sections to ensure that the process was working well and produced a good quality product. • Two-lift paving may be better suited for large projects requiring high productivity levels.

Table 8. Sustainability, performance, and life-cycle cost considerations for new composite pavement systems (Ram and Smith 2018).

Topic Area	Discussions/Comments
Sustainability Considerations	• Sustainability is likely to be the primary driver in the future—the ability to recycle and re-use 100% of the materials so that landfill usage is eliminated. • Re-using local, lower quality materials in the lower layers is both environmentally and economically sustainable. Virgin material usage is reduced, and the detrimental impacts associated with hauling materials is also reduced. • The sustainability benefits achieved will be associated with the size of the project. For smaller projects, composite pavements may not be cost effective.
Performance, Initial and Life-Cycle Costs	• Initial costs for composite pavements are relatively higher when compared to conventional designs. There is little information available on future maintenance cycles and performance models, which makes it difficult to model life-cycle costs. • When lower-quality materials (at higher replacement rates for virgin materials) are used in the lower pavement layer, the initial costs (materials only) for two-lift concrete pavements can potentially be lower when compared to HMA/PCC composite pavements. • In some cases, pavement design decisions are driven by policies which leaves little room for innovation. • Arizona has seen good performance from HMA/PCC composite pavements with the surface layer exhibiting good performance for 17 to 18 years before a resurfacing was required. Traffic repetitions on asphalt rubber friction courses help in alleviating some of the reflection cracking issues as the rubber tends to heal the cracks to some extent. • For high-traffic volume routes, HMA/PCC composite pavements may be preferred over two-lift concrete pavements due to quicker opening time to traffic. • More performance data and experimental projects are required to establish performance models and maintenance cycles to better characterize the performance and life-cycle costs for composite pavements.

Considerations in the Selection of HMA/PCC Composite Pavement Systems

State highway agencies select HMA/PCC pavements for several reasons. These include expected improved structural performance, safety and functional performance, sustainability, and cost and constructability factors. Prior to the SHRP2 R21 project, new HMA/PCC composite pavement systems were not widely considered by SHAs. With an increased focus on sustainability, long-term performance, and rapid renewal, new HMA/PCC composite pavements are now seen as a viable design alternative for many applications.

Structural Performance

HMA/PCC composite pavements offer outstanding structural performance capabilities. First, the lower PCC layer can be designed for an extended fatigue life, such as 40 years or more, resulting in a concrete slab that will remain structurally sound for decades. But the thin HMA surface also protects the concrete from climatic effects, such as moisture intrusion and large temperature differentials; this serves to reduce moisture-related distress and critical curling stresses, leading to improved (and extended) performance. Thus, the underlying concrete pavement should remain relatively distress free and will not require major rehabilitation over its design life.

With regards to the climatic protection provided by the HMA layer, studies by the Minnesota DOT (Mn/DOT) and the University of California Pavement Research Center (UCPRC) under the original R21 study and by the Virginia Transportation Research Center (VTRC) under the R21 implementation project demonstrated that the HMA layer dramatically reduces the temperature differentials between the top and bottom of the PCC slab (Rao et al. 2013a; Espinoza-Luque, Smith, and Hossain 2019). At the same time, the HMA also increases overall slab temperatures, and thereby reduces joint widths and helps increase joint load transfer.

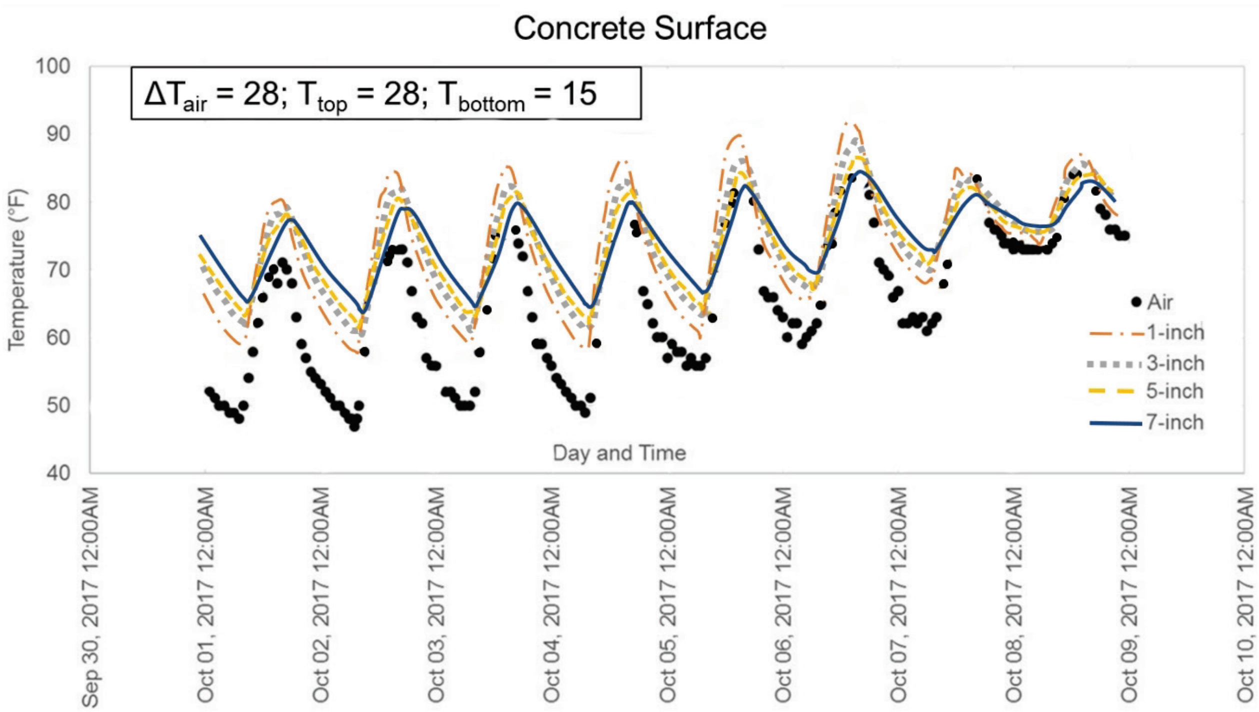
Figure 15 shows the air and slab temperatures versus depth and time for the Virginia DOT HMA/PCC composite pavement on U.S. 60 (Hossain 2017). Prior to the asphalt placement (top graph), the top of the concrete slab (1 inch [25 mm] below the concrete surface) experienced a temperature swing of up to 28 °F (16 °C) while the bottom of the slab (7 inches [178 mm] below the concrete surface) experienced a temperature swing of up to 15 °F (8 °C). Following the placement of the HMA surface layer, the top of the concrete slab showed a temperature swing of up to 27 °F (15 °C) but the bottom of the concrete slab only experienced a swing of up to 12 °F (7 °C), indicating the insulation capability of the HMA. This lower temperature gradient significantly reduces slab curling and associated stresses.

Reflection cracking is a critical consideration for HMA layers placed on an underlying concrete pavement, regardless of whether it is all new construction or an overlay. CRCP designs offer a major advantage is this area, as they not only provide strong load-carrying capacity but also significantly reduce (or even eliminate) the development of reflection cracking in the HMA surface due to their short effective slab lengths. Agencies that make use of an underlying JPCP design in an HMA/PCC composite pavement structure must take more proactive measures to control reflection cracking, such as sawing and sealing joints in the HMA surface directly above those in the underlying concrete.

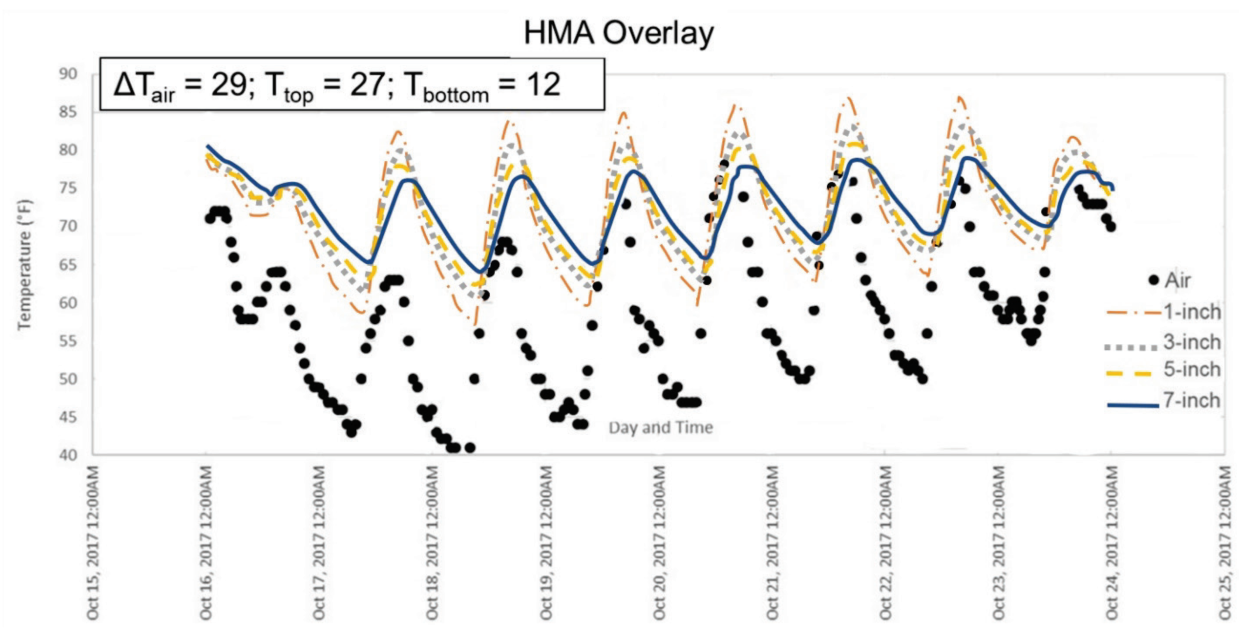
Functional Performance

A new HMA/PCC composite pavement provides the opportunity to instill and maintain effective functional performance. A number of different bituminous products (e.g., dense and porous HMA, SMA, PMA, ARFC) can be used as the asphalt surface layer to meet the project-specific functional performance requirements, such as smoothness, friction, and noise as demonstrated by the following examples:

- After construction, the U.S. 60 project near Richmond exhibited an average international roughness index (IRI) of 58 inches/mile (915 mm/km) in the left lane and 55 inches/mile (868 mm/km) in the right lane. Most of the 0.1-mi (0.16-km) lots in the paving project secured a 10 to 15 percent incentive pavements, with only a few segments receiving a disincentive.
- The Arizona DOT uses a thin 1-inch (25-mm) ARFC over JPCP and CRCP designs to reduce tire-pavement noise levels in urban areas. The entire Phoenix freeway system was surfaced with ARFC beginning in 2003, and many of these were also new JPCP segments. There are also a number of ARFC/JPCP sections constructed on the rural Interstate highways that have been constructed since the early 1990s, and overall this composite design has performed well. Initial smoothness values on these projects was less than 40 inches/mi (631 mm/km) (Burch 2017).
- The Florida DOT uses open-graded HMA mixtures on top of concrete pavements to address drainage and splash/spray issues and to improve safety.



a) Bare CRCP



b) After HMA overlay placement

Figure 15. Temperature differentials in HMA/PCC composite pavement (modified from Hossain 2017).

The various bituminous products have all generally performed well as the surface layer for HMA/PCC composite pavements, with their selection generally driven by the specific needs of the agency. Dense-graded mixtures are the most commonly used HMA mix type, but agencies may consider the use of PMA mixtures to provide greater resistance to rutting and thermal (reflection) cracking. SMA mixtures provide exceptional rut resistance and structural performance while open-graded friction courses can be used to reduce hydroplaning and splash and spray. Arizona has used wet process asphalt rubber open-graded HMA with good success in friction course applications.

Sustainability

With the availability of high-quality virgin materials diminishing in many areas and with the costs of producing and hauling new materials continuing to increase, many agencies are looking for more sustainable methods in rehabilitating their existing pavements. Using the materials from an existing project in the rehabilitation and reconstruction of a new construction project provides material costs savings, transportation savings, and reduced emissions, and also eliminates or reduces landfill costs, thereby making it more economic and environmentally sustainable. HMA/PCC systems are well-suited for this application by allowing greater amounts of recycled and local materials in the pavement, particularly in the underlying concrete layer.

In addition to materials, HMA/PCC systems also provide additional sustainability benefits, such as:

- Extended service life, which also reduces the overall life-cycle costs (LCC).
- High levels of smoothness, which provides user satisfaction and promotes increased fuel economy.
- Reduced congestion, user delays, and reduced emissions as the result of more rapid periodic surface renewals.

Costs

A primary challenge in the selection of HMA/PCC pavements is the perception that the initial construction costs are high. This is indicated in the recent HMA/PCC project constructed by the Virginia DOT on U.S. 60 near Richmond, the costs of which are shown in table 9 and compared to initial construction costs for alternative full-depth HMA and JPCP designs. The initial construction costs are higher for the HMA/PCC pavement, but because of their long life and the need for only minor periodic surface renewals, the overall LCC of an HMA/PCC pavement are expected to be lower. In performing a life-cycle cost analysis (LCCA), it is important that the analysis period used for the HMA/PCC composite pavements reflect the time over which the highway agency wants the pavement to perform without major structural damage (at the selected level of reliability). Guidelines for conducting an LCCA are available from FHWA (Walls and Smith 1998).

Well-designed SMA, HMA, porous HMA, WMA, and ARFC surface courses are all acceptable toppings to the PCC and can perform for 10 to 15 years or more before requiring replacement or renewal. The underlying PCC pavement can be designed to last for 30, 40, or even 50 or more years without significant structural distress. Still, one item of need for the future evaluation of HMA/PCC projects is improved information on their future maintenance and overall performance, as these can influence the LCCA.

Table 9. Example costs of HMA/PCC pavements compared to other pavement types.

Pavement System	Material	Thickness	Cost $/yd^2
HMA/PCC	SMA 12.5	2 inches (50 mm)	$ 12.21
	HMA SB-12.5D	2 inches (50 mm)	$ 8.24
	CRCP	8 inches (200 mm)	$ 79.81
	Total	-	$ 100.26
Full-Depth HMA	HMA	12 inches (305 mm)	$79.00
Jointed Concrete	JPCP	10 inches (250 mm)	$72.00

Constructability

HMA/PCC pavement systems are readily constructable and make use of conventional paving technologies. One of the critical considerations is the issue of reflection cracking, and appropriate methods must be used to help control that over the life of the pavement. Saw and seal methods are recommended for HMA on JPCP pavements, and proper marking, alignment, and sawcutting practices are crucial to ensure that the procedure is effective.

The HMA can be placed on the underlying PCC after it has achieved adequate strength to support the paving equipment. As with conventional HMA paving, the pavement (or portions of the pavement depending on the paving layout and progress) can be opened to traffic shortly after HMA placement.

For continuity of adjacent lanes, when widening is being designed, it is usually good design practice to continue the widening with similar materials. When the existing pavement is old PCC or old HMA/PCC, then an HMA/PCC composite for the additional lanes has distinct advantages. The main advantage is ease to the driver in maintaining consistency across all lanes. There is also an advantage in connecting the existing and new traffic lanes together so that they will not separate and in providing a similar type of surface without the potential for reflection cracking of the longitudinal joint.

Ease of Maintenance/Rapid Renewal

The HMA surface of the HMA/PCC composite pavement will require periodic removal and replacement every 10 to 15 years or so (depending on traffic and climatic conditions), but this is done primarily for functional issues (e.g., smoothness, friction, noise) and not because of structural deficiencies. A major advantage of this renewal is that it can be done quickly and rapidly with minimal disruption to traffic. Work can be scheduled during off-peak hours to further minimize impacts.

Table 10 presents a summary of the selection and implementation factors involved in the use of HMA/PCC composite pavements.

Table 10. Selection and implementation factors for HMA/PCC composite systems.

Consideration	Item	HMA/PCC Composite Systems
User Benefits	Smoothness	HMA surfaces provide high levels of smoothness. Depending on the thickness, smoothness requirements for the underlying PCC may be relaxed for reduced costs.
	Noise	Certain HMA surfaces (e.g., open-graded HMA) can provide an extremely low noise surface compared to conventional HMA or PCC construction. Sacrificial surface layer can be replaced on a consistent schedule without the likelihood of PCC failures for an extended period.
	Friction	HMA materials can be selected to provide a high level of friction and a wear-resistant surface. This may be particularly important in areas where polishing aggregates is an issue.
Agency Benefits	Cost Savings	The ability to use recycled and lower cost materials will affect overall project first costs, which can result in a lower cost than full depth AC or PCC. Long-term costs for maintenance and rehabilitation are not fully documented at this time, but if built well, distress should be contained to the HMA layer, thereby extending the life (and reducing the costs) of the HMA/PCC system.
	Sustainability	The very long-life PCC support layer using recycled materials and the sacrificial thin HMA layer offers excellent sustainability potential.
	Surface Renewal	Depending on the thickness and material selection, the life of the HMA surface renewal can range from 8 to 20 years. Open-graded layers would be on the lower end of this life expectancy while thicker dense-graded or gap-graded layers would be on the higher end.
Project Characteristics	Project Length/Size	HMA/PCC pavements lend themselves to both large and small projects. However, greater economy of scale is gained in larger projects where increased use of recycled materials can be utilized.
	Project Location (rural/urban)	Given that conventional construction techniques are utilized with HMA/PCC systems, both rural and urban projects are suitable.
	Clearances/ Right-of-Way	The increased section thickness that can sometimes be designed into HMA/PCC may need to be accommodated in certain vertical clearance situations.
	Plant Locations	Agencies will need to have the ability to utilize both HMA and PCC materials. Certain agency districts that do not use one material over the other may be challenged to make HMA/PCC systems viable.
Material Considerations	HMA	Conventional HMA mixes may be readily used in these pavements. Considerations may be made to the use of SMA or open-graded mixes where reflection cracking or noise and friction considerations are particularly important.
	PCC	Conventional PCC mixes may be readily used in these pavements. Recycled materials, RAP, RCA, and otherwise marginal materials are suitable in this layer to help increase their overall sustainability.
Construction Considerations	Plant Operations	HMA and PCC plant operations should not vary from conventional practice.
	Paving Logistics	Aside from typical HMA and PCC paving logistics, it is important to have HMA plant material available for paving within 1 to 2 weeks following PCC paving.
Implementation	Specifications	Sample specifications were developed under the R21 project (Rao et al. 2013a) and can be used as basis for development of agency specifications. Several states have built HMA/PCC pavements and have specifications available for use.
	Demonstrate Feasibility	Pilot projects have been constructed in Virginia and Pennsylvania should an agency be interested in pursuing this technology. Test sections and pilot projects are recommended to ensure that design and construction methods are achievable.

Considerations in the Selection of PCC/PCC Composite Pavement Systems

The agency decision to select a PCC/PCC composite pavement for a given project should consider a number of different factors, including:

- Available materials.
- Maintenance/rehabilitation needs.
- Long-term pavement performance.
- Initial construction and total service life costs.
- Infrastructure and construction demands.

Considering these factors jointly is effectively performing an LCCA that a given agency would conduct in assessing and selecting any paving project. The following sections briefly discuss each of the factors in the selection process.

Available Materials/Sustainability

Many agencies are faced with the need to renew or replace existing HMA or PCC pavements in ways that make use of recycled or marginal materials without sacrificing performance and durability. A primary advantage of PCC/PCC composite pavement systems is that they can accommodate a number of different materials—such as reclaimed asphalt pavement (RAP), RCA, local materials (e.g., polish-susceptible aggregates), and other alternative materials (e.g., industrial by-products or supplementary cementitious materials)—in the lower lift of the pavement system without compromising performance. The use of these materials helps improve sustainability by reducing the need for virgin aggregates, by reducing production and hauling costs, and by reducing the associated energy and emissions.

Maintenance/Rehabilitation Needs

Durable PCC/PCC pavement designs can be used in high traffic and urban areas to limit the need for frequent future repair and rehabilitation activities. These high-volume areas often have significant road user costs associated with lane closures for repairs. Both the structurally sound pavement system (to limit distress) and a quality wearing course (to improve the durability of texture) contribute to extended pavement performance and reduced traffic disruptions. In addition, a high-quality PCC surface can be re-textured rapidly through diamond grinding to restore rideability and surface friction characteristics while minimizing the effects of extended lane closures on road users.

Long-Term Performance

PCC/PCC pavements offer long-term performance that can meet virtually any need, and the performance criteria will vary by project. Many projects will consider conventional criteria such as smoothness, cracking, or faulting, but projects adjoining densely populated regions may also consider issues such as road noise. Projects in wet-freeze climates may also consider material performance measures such as freeze-thaw durability and scaling resistance. Table 11 lists varied performance criteria and how they can be met by selecting PCC/PCC for a given pavement project.

Table 11. Meeting performance needs with PCC/PCC composite pavements.

Performance Need	Relevant PCC/PCC Design Attribute
Smoothness	High-quality upper lift can be adopted to reduce initial IRI and increase the longevity of innovative texturing.
Cracking	Adequate composite structure can be designed to meet specified cracking criterion over design life.
Faulting	Use of adequately sized dowel bars for design traffic levels.
Freeze-thaw durability	Variety of alternative materials can be used in both lifts to outperform conventional concrete in response to freeze-thaw cycles; high quality upper lift can incorporate materials to improve resistance to deicing salt scaling.
Safety	Upper lift that contains durable, polishing-resistant aggregate or innovative texturing can provide higher long-term friction values and lower probabilities of hydroplaning for an extended period as compared to conventional means.
Reduced noise	Upper lift can use high quality, costly materials better suited to innovative textures that reduce road noise.

Cost

The cost of a paving project is determined by factors not limited to those discussed above. Modern considerations of cost frequently refer to LCCA, a "big picture" view that attempts to quantify the complex cost-benefit relationships between pavement cost (e.g., initial, maintenance, and rehabilitation), road network demands, user benefits, environmental effects, and pavement performance. While the original R21 project did not provide specific guidance on LCCA for PCC/PCC, construction projects performed since the completion of R21 have provided more information on some of the issues considered when developing LCCA for PCC/PCC projects.

Perhaps the most important issue in evaluating the suitability of PCC/PCC composite pavement systems is its initial cost relative to conventional paving. The prevailing belief is that PCC/PCC composite pavement systems requiring multiple plants and two placement operations will be more expensive than conventional concrete pavements from a first-cost perspective. However, beginning in 2013, the Illinois State Toll Highway Authority (Illinois Tollway) constructed over 1.3 million yd^2 (1.1 million m^2) of PCC/PCC pavement (Gillen et al. 2013). The average low bid for 11.25-inch (286-mm) PCC/PCC construction on the Illinois Tollway in 2013 and 2014 was \$38.28/yd^2 (\$45.78/m^2), whereas the average low bid during this time for conventional 12-inch (305-mm) single-lift paving was \$56.37/yd^2 (67.42/m^2) (Gillen 2017).

Another important cost issue is related to the discussion of materials. PCC/PCC projects that use recycled, secondary, or otherwise marginal local materials in the base and lower lift PCC provide a means to reduce initial costs and limit adverse environmental impacts. For instance, the use of in-place recycled aggregates may eliminate costs (as well as energy and carbon emissions) associated with extracting, processing, and transporting virgin aggregates from pits or quarries. The use of high-fraction SCMs (such as fly ash or slag cement) in the lower lift not only reduces the amount of cement (thereby saving costs) but also indirectly reduces the carbon load for the project that would otherwise be associated with the formation of clinker.

Infrastructure and Construction Demands

In addition to the factors listed above, agencies should consider construction challenges that are not typically faced in conventional single-lift concrete paving. Both the SHRP2 R21 study and the Illinois Tollway experience highlight the importance of planning for the batching and delivery of the two concrete mixes using more than one batch plant. The experimental full-scale sections constructed during SHRP2 R21 could trace all construction delays to the use of a single batch plant. In this regard, the Illinois Tollway officials explicitly specify that two batch plants are required within a limited haul distance (Gillen 2017). Still, the Tennessee DOT used a single plant for both mixtures in its two-lift project and experienced no issues (Smith et al. 2015).

The construction of PCC/PCC projects also involves more large equipment on site. This includes a slipform paver, either a second slipform paver or a belt spreader, and a belt placer to place the concrete and regular truck traffic to deliver mixes from batch plants. Therefore, potential PCC/PCC projects in urban areas should consider the need for additional lateral clearance and right of way. The PCC/PCC project on I-210 in California was constructed at night and closed down two adjacent lanes to accommodate the paving operation (see figure 16).

Figure 16. Work zone setup for I-210 project in California.

Finally, an important issue in selecting PCC/PCC that summarizes the construction challenges in a general way is the ability of the agency to develop an adequate construction specification. The specification must account for the unusual demands of two-lift paving to provide guidance for potential contractors; unclear specifications can indirectly affect cost, in the sense that contractors may increase their bids in an effort to limit the perceived risks of uncertain terms.

To date, a number of agencies (including the Minnesota, Tennessee, California, and Texas DOTs and the Illinois Tollway have developed two-lift paving specifications. These can serve as a starting point for other agencies faced with modifying their existing specifications to accommodate two-lift construction.

Table 12 presents a summary of the selection and implementation factors involved in the use of PCC/PCC composite pavements.

Table 12. Selection and implementation factors for PCC/PCC composite pavement systems.

Consideration	Item	PCC/PCC Composite Systems
User Benefits	Smoothness	High levels of initial smoothness achievable due to placement of two lifts. Initial smoothness values should hold for a given texture if high-quality materials used in top lift.
	Noise	Top lift allows use of innovative textures to reduce noise.
	Friction	Top lift allows use of innovative textures to meet friction demands.
Agency Benefits	Cost Savings	Achieved through the use of less costly and more readily available local aggregates in lower lift as well as the use of reduced cement contents in lower lift.
	Sustainability	Conservation of resources, increased use of local aggregates, reduced transportation costs, reduced environmental footprint.
	Surface Renewal	Periodic grinding of top-lift surface can be performed to address roughness, friction, and noise issues.
Project Characteristics	Project Length/Size	Larger projects (several miles long) make PCC/PCC more economically and logistically feasible.
	Project Location (rural/urban)	The need for multiple batch plants may limit PCC/PCC to rural or otherwise in accessible locations; these locations would require mobile batch plants. Hauling distances/times from batch plants in urban areas may be an issue under heavy traffic. Urban areas may not have adequate lateral space to accommodate the PCC/PCC paving operations.
	Clearances/Right-of-Way	Construction access and lateral work space may limit PCC/PCC in urban areas.
	Batch Plants	Plant locations must be located nearby and must be easily accessible. Multiple plants required for each mixture.
Material Considerations	Lower Lift	Lower lift can accommodate local and recycled aggregates and other economically beneficial products. Florida DOT illustrated that low cement content is viable. Tennessee DOT used polish-susceptible aggregate in lower lift. California and Mn/ROAD illustrated that high fraction RCA is viable. Illinois Tollway illustrated that high fraction RAP is viable. Texas adopted PCC/PCC to use materials with higher CTE values.
	Top Lift	High-quality materials required for durability and performance.
Construction Considerations	Plant Operations	Plants must produce adequate materials to feed both pavers. Greater amounts of materials required for bottom lift as compared to top lift, and batching and delivery operations must take this into account. Tollway specifications stand out in their willingness to trust contractors to get the job done with different configurations of paving train (provided they successfully pave a test strip).
	Paving Logistics	Provide room for delivery of materials to site. Implement process for directing concrete trucks to the correct paver. Limit time between placement of bottom lift and top lift.
Implementation	Specifications	Development of paving specification is the critical first step in using PCC/PCC systems. Sample specifications are available from Illinois Tollway, MnDOT, Caltrans, TDOT, TxDOT, and others. Key specification items: time between lift placements, dowel location, joint sawing, texturing, QA properties (strength, air) for each lift.
	Demonstrate Feasibility	Test strip or segment recommended so contractor can identify and address paving and logistical issues prior to actual construction.

CHAPTER 4. DESIGN AND CONSTRUCTION OF COMPOSITE PAVEMENT SYSTEMS

Introduction

The original SHRP2 R21 project evaluated the performance of composite pavement systems and installed field test sections for monitoring of pavement behavior. Based on those investigations, the study produced guidance on the design and construction of composite pavement systems, the results of which are fully documented in the two-volume technical report (Rao et al. 2013a; Rao et al. 2013b). Those guidelines cover virtually all aspects of the design and construction process, from structural design and materials characterization to foundation preparation and paving.

However, with the continued use and construction of composite pavement systems, including the construction of the four projects as part of the R21 Implementation Assistance Program, some additional elements not explicitly covered in the R21 guidelines were revealed. This chapter highlights some of those additional items along with some of the lessons learned by agencies implementing composite pavement systems.

HMA/PCC Composite Systems

Design of HMA/PCC Composite Systems

One item that is absent for composite pavement systems is an adequate design tool to develop HMA/PCC designs. Although a mechanistic-based version was developed under the original R21 project, it was never implemented or made widely available. Because of that, DOTs improvise by using currently available design methods such as the AASHTO 1986/1993 method (AASHTO 1993). For example, when designing HMA overlays on deteriorated PCC, an effective thickness of the PCC must be selected first based on its condition. In the case of new HMA/PCC, the effective thickness is then the same as the to-be constructed thickness and the overlay process is subsequently followed. Two DOTs (VDOT and PennDOT) utilized the AASHTO 1986/1993 for their designs using this method. The designs were then performed by first selecting an appropriate PCC thickness (D_{eff}), applying an equivalency ("A Factor") to convert PCC thickness to HMA thickness, and then calculating the HMA overlay thickness. While not the intent of this design method, it has been used successfully to develop new HMA/PCC composite designs.

PavementME can be used as evidenced in the first phase of R21, whether for design or verification, and whether the designs were HMA/JPCP or HMA/CRCP. VDOT used PavementME to evaluate their AASHTO 1986/1993 design as a way of providing confidence in the design. ADOT has used Pavement ME as their design tool for HMA/PCC for several years.

There are some philosophical differences in the design of HMA/PCC composite pavements. For example, the Arizona DOT designs very thick JPCP sections and applies thin rubberized asphalt porous friction courses with renewal schedules about every 10 years. Other agencies, such as the Virginia and Pennsylvania DOTs, have used thicker HMA surfaces (some approaching 4 to 5 inches [102 to 125 mm]) over JPCP or CRCP ranging in thickness from 8 to 11 inches (200 to 280 mm), with longer renewal schedules (15 years or more). As a result, the design process often depends on the desired maintenance cycles as much as with maximizing pavement life. Agencies in climates with large temperature swings may be more interested in thicker overlays to help minimize the development of reflection cracking. If noise is an issue, sacrificial noise reducing overlays are an effective (although shorter-lived) strategy for the surface layer.

An example of a successful composite pavement design was performed by VDOT in 2017 as part of the U.S. 60 project near Richmond. This is a four-lane divided roadway with low to moderate traffic volumes (14,000 vpd). VDOT had observed outstanding performance of SMA asphalt surfacings placed on CRCP designs and selected an SMA/CRCP new composite pavement for this project. The AASHTO 1986/1993 design procedure was used for the pavement thickness design by first setting the effective thickness of the new CRCP at 8 inches (200 mm); the thickness of the asphalt overlay was then determined to satisfy a design life of 30 years using the following design parameters (Habib 2017):

- Design life: 30 years
- Number of Lanes: 2
- Lane Distribution Factor: 90 percent
- Directional Distribution: 50 percent
- Design 18k ESALs: 5,306,300
- Initial serviceability: 4.5
- Terminal serviceability: 2.9
- PCC modulus of rupture: 650 lb/in^2 (4.5 MPa)
- PCC elastic modulus: 4,000,000 psi (27.6 GPa)
- Mean effective K-value: 196 lb/in^2/inch (5.43×10^6 kg/m^3)
- Reliability level: 90 percent
- Overall standard deviation: 0.39
- Load transfer coefficient: 2.6
- Drainage coefficient: 1

A mechanistic analysis was also conducted using the AASHTOWare Pavement ME design tool and the analysis showed the following:

- An insignificant amount of predicted punchouts.
- Very small amount of rutting and fatigue cracking in the HMA layer.
- Only a small amount of reflection cracking was predicted, which suggests that the surface course would need to be renewed at some stage in the life cycle.

Based on the analysis, the final design was selected as a 2-inch (50 mm) PG 64E-22 SMA (0.5-inch [13 mm] mix) over an 8-inch (200-mm) CRCP.

As another example, the Arizona DOT developed a composite pavement design for a project on I-10 (Burch 2017). In this case, AASHTOWare Pavement ME was the primary design tool. Some of the specific design parameters include:

- Design life: 20 years
- Number of lanes: 4

- Traffic: 2 million ESALs
- Climate: Desert
- Soil: A-2-4, M_r = 28,000 lb/in^2 (193 MPa)

At a 97 percent level of reliability, the design generated by PavementME design was a 1-inch (25-mm) AR-ACFC over an 11-inch (279-mm) JPCP with 15-ft (4.6-m) joint spacing and 1.5-inch (38-mm) diameter dowels. One item to note is that PavementME designs with AZ calibrated models resulted in JPCP designs 1 to 3 inches (25 to 75 mm) thinner than the AASHTO 1986/1993 designs. After 17 years, this pavement is still performing well.

More detailed information on approaching the structural design of composite pavements is available in the original SHRP2 Project R21 reports (Rao et al. 2013a; Rao et al. 2013b).

Construction of HMA/PCC Composite Systems

Following the successful construction of HMA/PCC pilot projects by several agencies and numerous projects built by the Illinois Tollway, it has been as shown that the construction of HMA/PCC composite pavement does not require any new technologies or equipment that are not already in widespread use. Thus, the key steps in the construction process—consisting of preparing the subgrade and base, placing the PCC, placing the HMA, and addressing jointing issues through saw and seal or alternative means—can be readily and cost effectively performed by virtually any highway paving contractor. Key considerations in each of the steps involved in the construction of HMA/PCC projects are summarized below.

Existing Pavement Removal

The first step in the construction process involves the removal of the existing pavement; depending on the pavement type, this can be achieved through milling or through demolition. Figure 17 shows the concrete broken up on grade by a guillotine breaker on the U.S. 60 project near Richmond (Schinkel 2017).

Figure 17. Broken up CRCP pavement on grade.

Subgrade and Base Preparation

The uniformity of the support conditions beneath an HMA/PCC pavement is critical to the long-term performance of the pavement, just as is in the case of conventional PCC pavements. The same procedures and specifications that are used to prepare the sublayers for conventional PCC construction should be used and specified for the construction of HMA/PCC composite pavements. An agency may choose to incorporate cement- or lime-treatment of the subgrade soils (in accordance with prevailing subgrade conditions and agency practices), and can employ a range of base types including asphalt- or cement-treated base courses, permeable base courses with edge drains, and reclaimed base layers including recycled pavement materials (such as RCA or RAP).

The R21 tour of European composite pavements observed that a high fraction of the base material for new pavements contained in-place reclaimed materials (Tompkins, Khazanovich, and Darter 2010). The R21 tour of European pavements also observed that contractors paid special attention to the moisture levels of the prepared base; for example, a tanker truck liberally sprayed the base layer with water directly in front of the slipform paver to saturate the base layer and minimize the amount of moisture in the PCC lost to the base layer (Tompkins, Khazanovich, and Darter 2010). While this practice is not typical for conventional paving in the U.S., it can be adopted for uncommon conditions (e.g., unusually warm, windy days). If it is employed, precautions should be taken to limit rutting of the saturated base under construction traffic.

In the construction of the HMA/PCC project on U.S. 60, the Virginia DOT noted that no CBR testing was performed since the quality of the soil was generally poor (Schinkel 2017). In some areas of the project that demonstrated pumping, a series of undercuts in the existing soil were made to depths of up to 15 inches (381 mm) and replaced with class 21A aggregate materials over a geogrid. Other parts of the project were stabilized with cement and lime to help provide a strong foundation for the composite pavement (Espinoza-Luque, Smith, and Hossain 2019).

PCC Placement, Texturing, and Curing

The PCC layer can be paved following the same procedures and guidelines as for conventional PCC pavement. The PCC layer is the key structural component of an HMA/PCC composite pavement and as such should meet all specified structural and durability criteria (e.g., compressive and flexural strength, air content, consolidation, material durability, etc.).

For HMA/CRCP construction, the steel reinforcement needs to be securely placed on chairs on top of the base course prior to paving the PCC layer (see figure 18). The spacing of the longitudinal and transverse reinforcement and the depth of the reinforcement should be in accordance with agency specifications.

For HMA/JPC, dowels may be placed in dowel baskets that are securely attached to the base course prior to paving the PCC layer; alternately, dowel bar inserters (DBIs) may be used. In either case, the dowels should be located at the mid-depth of the PCC slab. Dowel bar size and type should be in accordance with typical agency practices for the facility.

Figure 18. Reinforcing steel layout for one lane of Virginia HMA/CRCP composite pavement.

Typical agency QC/QA practices (slump, unit weight, mix temperature, entrained air, etc.) for testing materials and monitoring construction activities for JPCP and CRCP should be followed for the PCC placement. One key difference is that an initial smoothness target for the PCC surface may not be required since it will soon be topped with the HMA surface. However, some control of PCC smoothness is desirable as it can contribute to achieving acceptable levels of smoothness in the HMA surface. For this reason, the Pennsylvania DOT specifies a maximum IRI of 100 inches/mi (1580 mm/km) for the PCC pavement prior to the placement of the HMA surface. Generally, the long- to medium-wavelength roughness in the PCC pavement is the concern, as this may translate to higher initial roughness of the HMA/PCC composite pavement, whereas short wavelength roughness in the PCC surface can be smoothed out by the placement of the HMA layer.

Another difference is that the durability of the surface texture of the PCC is not crucial since it will not be exposed to traffic except for the brief period just prior to the placement of the HMA wearing course. Because of that, lower cost but durable aggregates that may be susceptible to polishing can still be used in the underlying PCC pavement even though they may not be appropriate in conventional designs. Also, durable coarse aggregates, obtained by recycling RCA or RAP, can be incorporated in the PCC mix without significant deleterious effects.

Some form of texturing of the PCC surface (when still plastic) should be done to help promote bonding between the PCC and the HMA surface. The R21 report recommends longitudinal tining or transverse tining as this often means no additional modifications to the construction specifications may be required (Rao et al. 2013a). However, in the Virginia U.S 60 project, the PCC surface was just textured with a burlap drag without any additional tining (see figure 19) and was reported to provide good bonding (Schinkel 2017).

Figure 19. Drag finishing of concrete surface on Virginia HMA/CRCP composite pavement.

Although the PCC surface will be covered with HMA after the PCC hardens, it is still necessary to control moisture loss from the surface of the wet PCC to prevent rapid surface drying and early-age cracking. Typically, agencies will use liquid membrane-forming curing compounds specified under AASHTO M 148 or ASTM C309 to retard the evaporation of moisture from the pavement surface. Some agencies have adopted the use of poly-alpha methylstyrene (PAM) materials for use in pavement curing as these materials display increased moisture retention capabilities.

The PCC thickness used in HMA/PCC composite pavements varies among the DOTs. ADOT, which has built HMA/PCC using AR-ACFC, generally constructs the PCC slabs on the order of 11 to 13 inches (279 to 330 mm) thick (Burch 2017), whereas VDOT recently constructed an 8-inch (200-mm) PCC. However, much of this is still driven by the anticipated traffic that the HMA/PCC pavement will carry, as the VDOT project on U.S. 60 carried much less truck traffic than is typically carried by Arizona pavements.

As an alternative to conventional PCC, and typically for lower volume facilities, the use of roller-compacted concrete as the underlying rigid portion of the HMA/PCC design could be used. The original R21 report cites a number of pavement facilities on local roads and streets that use RCC as the underlying PCC layer in HMA/PCC composite pavement construction (Rao et al. 2013a).

PCC Joint Sawcutting

For HMA/JPC composite pavements, both transverse and longitudinal contraction joints in the PCC should be established in accordance with normal agency practices and specifications for JPCP. Most agencies employ a maximum transverse joint spacing of 15 ft (4.6 m), with joints sawed to one-third of the thickness of the PCC slab. No sealant reservoir is needed.

For HMA/JPC composite pavements, the transverse location of the saw cuts in the PCC should be precisely marked at a location away from the pavement (that will not be covered with the HMA lift), so that the HMA can be later sawed and sealed at the exact same location.

PCC Preparation for HMA Surface

There are several activities that may be performed to the PCC prior to the placement of the HMA surface. First, because of concerns about the concrete curing compound contributing to debonding issues, some agencies work to remove the curing compound from the surface after the concrete has adequately cured (perhaps 7 to 14 days, depending on the specification). This can be accomplished through power washing or by sandblasting and is intended to help promote adhesion of the HMA surface to the PCC layer. Other agencies make no attempt to remove the curing compound, instead relying upon it to decompose with exposure to the environment and construction traffic before the placement of the HMA surface.

Of interest to this discussion is the recognition that there are different types of curing compounds available. ASTM C 309 and AASHTO M 148 classify curing compounds by color (clear or white-pigmented) and by the solids constituent (either Class A or Class B). Class A is a wax resin type that is suitable for use on concrete that will not receive any surface paintings or adhesives, as the wax contained in the material can remain on the surface and hamper future adhesion; consequently, this type of curing material may need to be removed prior to HMA placement. Class B, on the other hand, is a resin type that does not leave a residue on the surface and thus may be more appropriate for use in HMA/PCC construction.

Another activity may include the sealing of the joints in the PCC. For new HMA/PCC construction, ADOT seals the single-cut PCC joints with a rubberized asphalt sealant before placement of the HMA overlay. PennDOT also seals the single-cut PCC joints prior to HMA overlay, but in the Minnesota project the PCC joints were left unsealed (Rao et al. 2013a).

Place the HMA Surface (and Shoulders)

Once the PCC has gained sufficient strength to allow traffic (as specified by agency requirements for opening to traffic), the HMA surface can be placed on the PCC. A tack coat (as specified by agency requirements for asphalt overlays of concrete pavements) should be applied to the surface of the PCC to help promote bonding between the PCC and the HMA layer. The rate of application of the tack coat should be sufficient to cover a large majority of the surface, which may require increasing the normal application rate. If reflection crack treatments such as stress-absorbing membranes, geogrids, or geofabrics are considered, they can be applied at this point; however, they are not necessary if the joints are to be sawed and sealed in the HMA surface.

The HMA layer can be paved following the same procedures and guidelines as for conventional HMA overlays of existing/rehabilitated concrete pavements. The HMA layer is the key functional component of an HMA/PCC composite pavement and as such should meet prevailing job mix criteria (such as asphalt content, aggregate gradation, density, VMA, etc.). Agency QC/QA practices for testing materials and monitoring construction activities for HMA overlays should be followed for the HMA placement of HMA/PCC composite pavements. This includes testing for mix temperature, density, smoothness, and so on. Efforts should focus on the achievement of a high level of smoothness as this will contribute to a smoother pavement over time, all other things being equal.

A range of HMA surfacings can be used. VDOT observed excellent performance of SMA mixtures on PCC pavements in an overlay situation (in terms of greater rutting resistance), which led them to use SMA on their composite pavement project on U.S. 60 (Habib 2017); the placement of the SMA in the driving lane of that project is shown in figure 20. ADOT places AR-ACFC surfaces for reduced noise and reduced splash and spray, and expects about 10 years of service from the surface layer before it is replaced, although some have exhibited 18 or more years of service with good performance (Burch 2017). The Illinois Tollway uses warm-mix asphalt (WMA) exclusively for their HMA/PCC surfacings and has obtained good performance (Gancarz 2017).

Figure 20. Paving of the SMA in the driving lane of the Virginia HMA/CRCP project.

Saw and Seal the HMA

The sawing and sealing of the HMA surface is the most common method used by DOTs to control reflection cracking for systems using an underlying jointed concrete pavement. The depth of the sawcuts in the HMA surface range from 0.62 inches (16 mm) for the Minnesota DOT and Illinois Tollway to 1 to 1.5 inches (25 to 38 mm) for the Pennsylvania DOT. For relatively thin layers (say, less than 1 to 1.5 inches ([25 to 38 mm]), it was determined that a sawcut depth that extends as deep as the material may be most effective.

The DOTs commonly specify lateral location accuracy of the saw cut to within 0.5 inches (13 mm) of the underlying transverse PCC joints, as precision is crucial to performance. If the sawcut in the HMA surface deviates from the location of the underlying joint, the potential arises for the development of two parallel cracks in the surface, which could quickly spall and deteriorate and lead to reduced performance. To get the proper location, it is common to place secure steel plugs several feet from the slab edge on both sides (beyond the HMA edge) and then snap a chalk line between the plugs to establish exactly where to saw cut a transverse joint. The saw cut can be extended partially into the shoulder or completely into the shoulder if desired. If a tied jointed concrete shoulder exists, the sawcut should extend across the shoulder as well.

Some contractors have been exploring the use of GPS technology as a means of locating the underlying joint.

The Illinois Tollway has had very good performance with saw and seal techniques on HMA/PCC pavements, and point out that the saw and seal strategy is effective at controlling reflection cracking (Gancarz 2017). The lesson learned by the Tollway was how important construction sequencing is in the effectiveness of this operation, and that the sawing and sealing should be performed from edge to edge of the pavement to avoid any random edge cracking. Figure 21 shows two photos from an HMA/PCC project constructed by the Illinois tollway.

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a) b)

Figure 21. Illinois Tollway HMA/PCC project: a) Marking of the HMA above an underlying PCC joint (Gancarz 2017), and b) sawcut HMA surface.

The Connecticut DOT has had issues with the precision of the sawcut and consequently is no longer performing the saw and seal approach (Ram and Smith 2018). The precision for the saw cuts may be less of an issue with shorter joints (such as 15 ft [4.6 m]) or with a thicker HMA surface.

Agency Experience with HMA/PCC Construction

Some example details from recent HMA/PCC composite pavement construction projects are highlighted below.

Illinois Tollway Milwaukee Avenue Interchange

- Two ramps constructed in 2010.
- 2-inch (50-mm) asphalt surface over a 9-inch (229-mm) JPCP.
- Asphalt materials: Warm mix asphalt (WMA) used in surface layer with 10 percent reclaimed asphalt pavement (RAP).
- Concrete materials: Binary cementitious mixture: Type I/II portland cement, 21 percent class C fly ash.

- Aggregates: optimized gradation using three aggregates, 17 percent coarse fractionated reclaimed asphalt pavement (FRAP) used.
- Sawed and sealed HMA surface.

Illinois Tollway Route 47 Interchange

- Six ramps constructed in 2013.
- 2-inch (50-mm) asphalt surface over 9-inch (229-mm) JPCP.
- Asphalt materials: WMA used in surface layer with 10 percent fine FRAP, 16 percent coarse FRAP, and 4 percent recycled asphalt shingles (RAS).
- Concrete materials: Ternary cementitious mixture: Type I/II portland cement, 15 percent class C fly ash, and 10 percent slag cement.
- Aggregates: optimized gradation, 20 percent coarse FRAP.
- Sawed and sealed HMA surface.

VDOT U.S. 60 Composite Pavement Project

- 1.22 mi (1.96 km), 2 lanes, 14,440 ADT, 6 percent trucks (2014).
- 2-inch (50-mm) SMA overlay over an 8-inch (200-mm) CRCP.
- Asphalt materials: 2-inch (50-mm) SMA with 0.5-inch (12.5 mm) NMAS. 10 percent RAP, PG 64-22 with cellulose fiber and Zycotherm warm mix additive.
- Concrete materials: 658 lb/yd^3 (390 kg/m^3) Type II cement and fly ash. CRCP with crack spacing 3 to 8 ft (0.9 to 2.4 m) apart and crack widths between 0.004 and 0.020 inches (0.1 and 0.5 mm).
- Base: cement treated (removed and replaced in some areas, and some base and subgrade stabilization performed in selected areas to address pumping issues).

Summary of Experiences Related to Selected Construction Factors for HMA/PCC Pavements

Table 13 presents a summary of highway agency experiences related to selected construction factors for HMA/PCC pavements.

PCC/PCC Composite Systems

Design of PCC/PCC Systems

Similar to that experienced in the design of HMA/PCC pavement systems, the design of PCC/PCC pavement systems was not adequately accommodated by the two most commonly used pavement design procedures (AASHTO 1986/1993 and AASHTO PavementME). The SHRP2 Project R21 research emphasized the use of the then-AASHTO MEPDG design procedure that had been modified to incorporate composite system concepts, but that procedure was never distributed and hence was never made available for use within the pavement community. However, based on the knowledge of the project team, coupled with interactions with end-users in the series of workshop presentations, fundamental approaches to the design of PCC/PCC pavement systems were developed using both the AASHTO 1986/1993 and AASHTO PavementME procedures. These approaches are presented in the following sections.

Table 13. Summary of experiences related to selected construction factors for HMA/PCC.

Agency/ Resource	PCC Texture	Curing of PCC	PCC Joints	PCC Smoothness Spec	HMA Joints
MN (Mn/Road)	• Burlap & longitudinal tining	• PAM • Do not remove	• Sawed to depth of D/3 (both transverse and longitudinal) • Unsealed • Single Cut (0.12 inches [3 mm])	—	• 0.5 inch (13 mm) wide x 0.62 inch (16 mm) deep (for 3-inch [75 mm] overlay) • 0.5-inch (13 mm) accuracy
Penn DOT	• Burlap & longitudinal tining	• White Pigmented (Type 2) or PAM • Removal required	• Sawed to depth of D/3 (both transverse and longitudinal) • Sealed (but without second cut) • No backer rod	• Yes, Maximum IRI = 100 inches/mi (1580 mm/km)	• 0.5 inch (13 mm) wide x 1 inch (25 mm) deep (for HMA > 1.5 inches [38 mm]) • For overlays > 3.5 inches (89 mm), 0.12-inch (3 mm) wide sawcut to 1.5-inch (38 mm) depth (or D/3) • 1-inch (25 mm) accuracy • Tape bond breaker
Thermally insulated report (Khazanovich et al. 2012)	• Leave untextured or slight texture imparted (but make sure surface is clean)	• No wax based curing regime – try asphalt-based prime coat • Remove with sandblasting	—	—	—
Louisiana	—	—	—	—	• Saw & seal • Longitudinal & transverse joints (for each lift)
Illinois Tollway	—	—	—	—	• 0.5 inch (13 mm) wide x 0.62 in (16 mm) deep (3 inch [75 mm] overlay) • 0.5 inch (13 mm). accuracy • Bond breaker type • Sawed > 48 hrs ahead of HMA
Arizona DOT	• Burlap drag	—	• Sawed to depth of D/3 (both transverse and longitudinal) • Joints sealed	• No	—
Virginia DOT	• Burlap drag	—	• CRCP	—	• CRCP
R21 Report (Rao et al. 2013a)	• Longitudinal or transverse tinging	—	• Sawed to depth of D/3 (both transverse and longitudinal)	• No target values but states that smoothness is desirable	• D/3 • 0.5-inch (13 mm) accuracy

— = Not available or not specified

Design and Performance Criteria

In both AASHTO procedures, design reliability is based on type of facility and overall traffic volumes that it serves, with higher traffic levels warranting higher reliability levels. Interstates, freeways, and divided highways are recommended to have reliability values between 95 and 99 percent, whereas lower volume roads, such as rural roadways and residential streets, are recommended to have reliability values between 75 and 89 percent (AASHTO 1993; AASHTO 2015). These values also appear appropriate for the design of PCC/PCC composite pavements.

The distress criteria imposed on PCC/PCC for design purposes can be identical to those required of conventional single-lift pavements (either serviceability based or distress based). The SHRP2 R21 study prepared criteria for PCC/PCC that are identical to those of single-lift JPCP or CRCP, and also pointed out that designers may wish to consider lower initial smoothness values for composite designs given that improved smoothness levels may be more easily accomplished in these multiple-lift systems (Rao et al. 2013b).

Adopting AASHTO 1986/1993 (or Other Design Methods) for PCC/PCC Design

The AASHTO 1986/1993 design method (or other single-lift design procedures, including agency specific methods) can be used in a simplistic fashion to develop structural PCC/PCC designs. As long as a "wet-on-wet" placement is assumed (meaning that complete bonding is achieved between the two layers to produce a monolithic structure), then a single-lift design procedure can be employed provided that:

1. The top-lift PCC has improved strength and durability over that of the lower-lift PCC.
2. The lower-lift PCC meets agency performance specifications.

With these assumptions, the lower-lift PCC properties can be used to develop a single-lift design, but that design will need to be modified by replacing a top portion of the total slab thickness with an upper-layer concrete mix designed to provide specific qualities (e.g., high friction, low noise). The thickness of that top layer can be selected based on non-structural factors such as constructability, maximum coarse aggregate size, or general economy, and will most commonly be in the range of 3 to 4 inches (75 to 100 mm). This method is most viable if the lower-lift PCC meets the conventional single-lift performance specification in a direct and economical manner; in other words, the method should avoid "over-design" if possible and should attempt to take advantage of PCC/PCC cost and performance benefits that are unique to each layer.

Applying AASHTO Mechanistic-Empirical Pavement Design Methods to PCC/PCC

Using the AASHTO M-E pavement design software, the design of PCC/PCC composite pavement system follows the bonded overlay design process (for either bonded PCC over JPCP or bonded PCC over CRCP). Two M-E procedures are available:

- AASHTO MEPDG version 1.300:R21. One major outcome of the SHRP2 R21 project was the review and modification of the mechanistic-empirical (M-E) models used in the AASHTO M-E rigid pavement design procedure developed under NCHRP 1-37A. The result of these modifications was that the AASHTO M-E procedure—as implemented in MEPDG Version 1.300:R21—could successfully model thin top-lift layers and their contribution to performance, thus impacting thickness design. However, that software was never distributed or made widely available. More details on the modified design software are provided in the SHRP2 R21 final report (Rao et al. 2013b).

- AASHTOWare Pavement M-E Design. The AASHTOWare Pavement M-E design program can be used to design projects with a top-lift thickness of 4 inches (100 mm) or more by using the bonded concrete overlay module within the program. However, the modeling modifications and improvements introduced into the AASHTO M-E procedure during SHRP2 R21 (which are present in MEPDG version 1.300:R21) are not incorporated into the current version of Pavement M-E. Still, the results produced by the program are applicable and can be used to develop competent designs, but cannot accommodate top-lift thicknesses less than 4 inches (100 mm).

Generally speaking, if the structural material properties (concrete strength, elastic modulus) for the lower lift of a two-lift system are less than those of a single-lift system, the required slab thickness of a single-lift JPCP will be slightly less than the total slab thickness of a two-lift PCC/PCC pavement system, all other variables being equal. This was demonstrated in example designs presented in the original SHRP2 R21 research showing that the slab thickness of a single-lift JPCP is slightly less than the total slab thickness of a two-lift PCC/PCC pavement system (Rao et al. 2013b). Although thicker, the PCC/PCC system offers the potential for cost savings in terms of using marginal aggregates and reduced cement contents in the lower lift.

Construction of PCC/PCC Systems

The construction of several pilot pavement projects under the R21 implementation project, as well as projects constructed by the Illinois Tollway and others, has demonstrated that PCC/PCC composite pavement systems can be readily built using existing technologies and equipment. However, at the same time, the demonstration projects and interactions with paving engineers in the workshops and outreach events helped identify a number of overlooked issues for which detailed information was lacking in the original SHRP2 Project R21 guidelines. A summary of some of the critical construction aspects based on agency concerns and experiences are presented in the following sections.

Subgrade and Base Preparation

Preparing the sublayers for PCC/PCC composite pavement is no different from conventional PCC paving. The agency should use the procedures and specifications employed for conventional PCC paving, and may choose to incorporate cement- or lime-treatment of the subgrade soils (in accordance with prevailing subgrade conditions and agency practices), and can employ a range of base types including asphalt- or cement-treated base courses, permeable base courses with edge drains, and reclaimed base layers including recycled pavement materials (such as RCA or RAP). The R21 tour of European composite pavements observed that a high fraction of the base material for new PCC/PCC designs contained in-place reclaimed materials (Tompkins, Khazanovich, and Darter 2010).

The R21 tour of European pavements also observed that contractors paid special attention to the moisture levels of the prepared base (Tompkins, Khazanovich, and Darter 2010). A tanker truck liberally sprayed the base layer with water directly in front of the first paver to saturate the base layer and minimize the amount of moisture that the PCC would lose to the base layer. While this practice is not typical for conventional paving in the U.S., it may be suitable for adoption for severe conditions (e.g., unusually warm, windy days) to preserve the integrity of the lower lift (especially if the lower lift uses a relatively stiff mix). If it is employed, precautions should be taken to limit rutting of the saturated base under construction traffic.

Concrete Materials and Mix Designs

The materials and mix designs used in the design and construction of PCC/PCC composite pavement systems offer a unique opportunity for innovation on the part of the contractor and agency. Depending on the goals and objectives of the project, a range of mix designs can be developed that address sustainability/environmental concerns, provide significant cost savings, and improve long-term performance; these benefits were emphasized by both the R21 experience at Mn/Road (Rao et al. 2013b) and by the Illinois Tollway experience on I-90 (Gillen et al. 2013; Gillen 2017).

The mix design in the top lift of the PCC/PCC composite pavement system can use cementitious blends and contents that yield high performance features such as high-early strengths or improved freeze-thaw durability. The top-lift mix can also incorporate more durable aggregates that withstand polishing and preserve texture.

The lower-lift mix provides an opportunity to improve the overall economy of the project. The lower-lift mix should be designed to act as a structural layer and can utilize features that include lower cement contents, increased SCMs, and the use of local or recycled aggregates.

While the Mn/Road (Rao et al. 2013b) and the Illinois Tollway projects employed lower-lift mixes with conventional total amounts of cementitious products (i.e. cement, slag, and fly ash) (Gillen 2017), the Florida DOT had success using lower total amounts of cementitious content in its two-lift pavements constructed in the late 1970s (Green, Nazef, and Choubane 2011). Strength targets for the lower lift should be mindful of the fact that a lower strength is required for thicker layers.

Experience in Illinois, Minnesota, and California illustrate that recycled materials such as RAP and RCA can be effectively used in the bottom lift of the PCC/PCC composite pavement as an effective means of improving overall sustainability and economy. The Illinois Tollway used fractionated RAP at typical quantities of 15 to 25 percent in its lower-lift mix for I-90 (Gillen 2017), while MnDOT used RCA as 50 percent of the coarse aggregate in the lower-lift mix for I-94 (Rao 2013b). The California project on I-210 evaluated RCA contents of 10 and 15 percent in the bottom lift before finally settling on the use of 15 percent for the demonstration project (Ram et al. 2019).

Dowel Bars

Dowels can be either inserted in the plastic concrete or placed in baskets on grade, in accordance with agency practices. The experience in the U.S. with doweling on PCC/PCC composite pavement systems has been using dowel baskets (see figure 22), although dowel inserters are commonly used for two-lift paving in Europe (Tompkins, Khazanovich, and Darter 2010). The dowel diameter should follow typical agency practices for the thickness of the total composite pavement, as should the selection of the dowel type/coating (e.g., epoxy-coated, stainless steel clad, etc.). Baskets should be sufficiently fastened to the base course to ensure that they are not pushed by the paver. As shown in figure 23, the dowels should be located at the mid-depth of the *total* slab thickness (top lift + bottom lift).

Figure 22. Dowel baskets on grade on two-lift paving projects in Tennessee (left photo) and California (right photo).

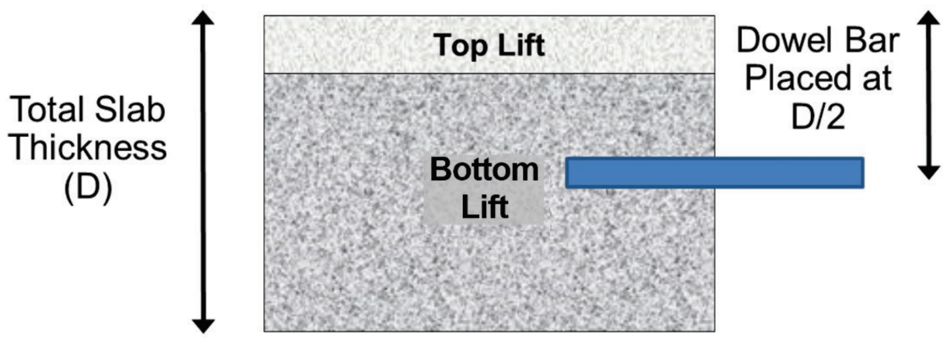

Figure 23. Location of dowel bars in PCC/PCC composite pavement.

CRCP Steel Reinforcement Placement

Longitudinal and transverse steel reinforcement should be placed in accordance with the agency specifications with regards to spacing and depth. A minimum cover (typically 3 inches [75 mm]) for the steel is required, and this means that the steel will reside in the lower lift of the pavement. For the two-lift CRCP project in Texas, the steel was placed at mid-depth of the 10-inch (250 mm) composite pavement, and about 2 inches (50 mm) below the top of the lower lift (see figure 24). Figure 25 shows the layout of the reinforcing steel for the outside lane and outside shoulder placed in day 1 of the Texas CRCP project.

Concrete Batching and Delivery

One of the challenges of PCC/PCC for contractors is the need to batch and deliver more than one concrete mix type to the project site in an organized, timely manner. The R21 project at Mn/Road illustrated that batching two mixes at one plant can introduce some complications that could be avoided by using two plants; this experience was among the reasons that the Illinois Tollway PCC/PCC specification and the general practice in Europe requires separate batch plants for the mixes. However, the Tennessee DOT successfully produced both top- and bottom-lift mixtures at a single ready-mix plant for their two-lift paving project without any issues (Smith et al. 2015).

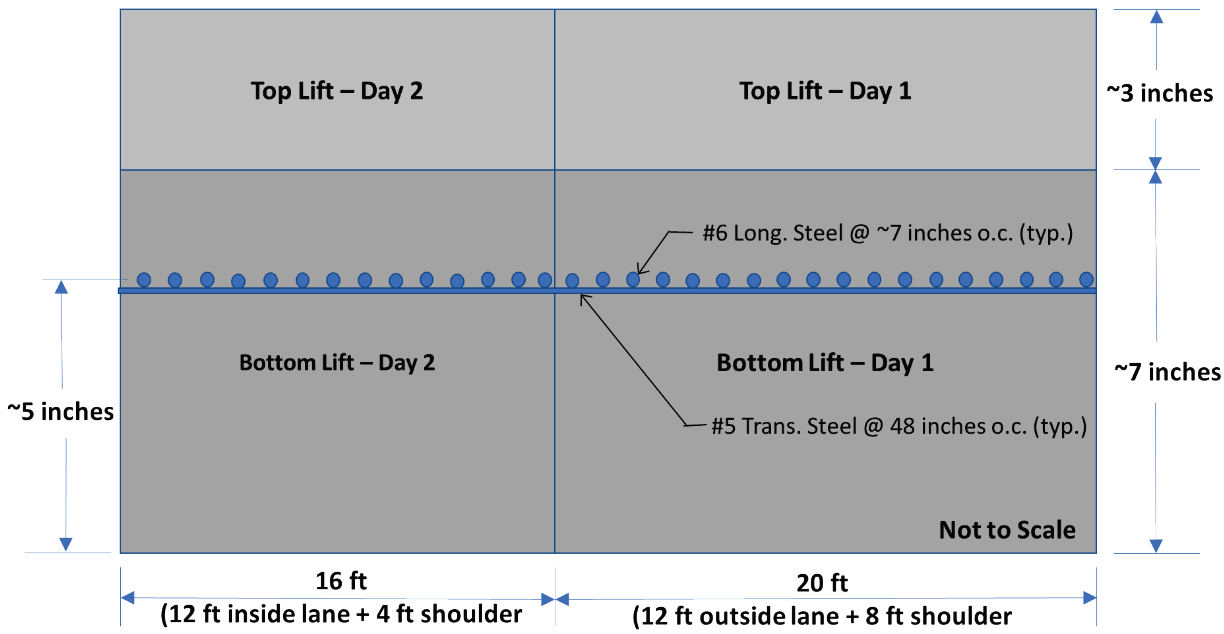

Figure 24. Cross section of two-lift CRCP project in Texas.

Figure 25. Layout of reinforcing steel for outside lane and outside shoulder of Texas PCC/PCC composite pavement.

The delivery of the mixes to the project site should be adequately sized, well organized, and timely. Since the bottom lift makes up a greater volume of concrete than the top lift, the plant production and truck delivery operations should be set up in such a way that greater quantities of the bottom lift are produced in order to keep the first paver (bottom lift paver) sustained. Often, agencies may establish a "truck delivery ratio" of bottom-lift-materials to top-lift-materials (e.g., 4:1, or 4 bottom-lift trucks to 1 top-lift truck) at the beginning of a project as an initial target to help track and monitor deliveries, with the ratio dependent upon the thickness of the individual layers for the project and the capacity of the haul trucks.

In addition to producing adequate quantities, the delivery effort should be organized to make mixes easily identifiable to ensure that they are matched with the correct paver (or spreader). For example, some agencies have used color coding on dump trucks and belt placers to indicate the mix (see figure 26), while others designated certain delivery vehicles for each mix type (e.g., the Tennessee DOT project on I-65 used end-dump trucks for the bottom lift and front-discharging ready-mix trucks for the top lift, see figure 27). The overall goal of the delivery process is to provide clear and effective communication to both the truck drivers and the paving crew.

A final consideration in the delivery of the paving materials is the time between placement of the two lifts. A "wet-on-wet" placement is emphasized in order to promote bonding between the two layers and to minimize the exposure of the lower lift to the elements. Agencies typically specify upper limits of 30 to 90 minutes between the placement of the bottom lift and top lift as a means of helping to ensure that bonding. Significant delays could lead to the bottom lift drying out and not forming a strong bond with the top lift, or may cause concrete to dry in the paver and cause tearing of the surface (see figure 28).

Figure 26. Delivery truck tagged with a red ribbon to indicate bottom-lift material on Texas PCC/PCC composite pavement project.

Figure 27. Tennessee PCC/PCC composite pavement project: bottom-lift material delivered by end-dump truck (left photo) and top-lift material delivered by a front-discharge ready-mix truck (right photo).

Figure 28. Tearing of top-lift concrete surface caused by dried concrete on profile plan.

Paving Operations

The SHRP2 R21 construction observed that the use of two slipform pavers was the standard for achieving wet-on-wet construction in Europe (Tompkins, Khazanovich, and Darter 2010). For the most part, this practice has been followed in North America, although the Illinois Tollway specified that contractors could use any combination of slipform pavers and spreader/placers to construct various configurations of two-lift pavement provided that the contractor satisfactorily completed a test section using the intended methods (Gillen 2017). The need for additional equipment to construct PCC/PCC composite pavements is not so much of a concern but a reminder that PCC/PCC construction is about minimizing costs and maximizing performance features.

The placement of the PCC/PCC pavement begins with the lower lift placed in accordance with the same procedures and guidelines for conventional PCC. The lower lift PCC is a structural layer (not a performance layer in terms of ride quality or surface texture) and therefore should meet relevant structural and durability criteria. The frequency of the vibrators used in the bottom-lift paving are typically set the same as for conventional paving, but the contractor on the Tennessee PCC/PCC project reduced the frequency of the outside vibrators in the bottom lift to 2000 vpm to reduce the potential for segregation (Smith et al. 2015). The vibrators on the paver for the bottom lift should be positioned above the dowel bars or reinforcing steel.

Some agencies also impart a light texture on the surface of the bottom lift using a burlap or turf draft (see figure 29). This helps to promote a mechanical bond between the two paving layers.

Figure 29. Drag texturing of bottom lift on Tennessee PCC/PCC project.

Agency QA/QC practices for materials testing (slump, mix temperature, unit weight, entrained air, compressive strength, flexural strength, etc.) should be performed for each lift following their placement. Figure 30 shows selected field testing activities on the Tennessee PCC/PCC project while figure 31 depicts cylinders and beams being prepared on an Illinois Tollway PCC/PCC project.

a) Unit Weight

b) Slump

c) Air test (left: Super Air Meter, right: standard air meter)

Figure 30. Field testing on Tennessee PCC/PCC project.

Figure 31. Preparing beams and cylinders on Illinois Tollway PCC/PCC project.

The upper lift should be placed as soon as practical after the placement of the bottom lift to help promote bonding between the two layers and to minimize the effects of the environment on the bottom lift. As previously discussed, construction specifications typically require no more than between 30 to 90 minutes between the placement of the two layers. The TxDOT specification requirement specified that the top lift must be placed no more than 60 minutes after the placement of the bottom lift, unless the bottom lift contained a set-retarding chemical admixture (in which case the time would be extended to 90 minutes). In either case, the bottom-lift concrete was required to have sufficient consistency to support the top-lift concrete with only minimal intermingling of the two layers.

In paving the top lift, some agencies require that the vibrators on the paver be raised above the level of the profile pan to avoid intermingling of the two mixtures. The contractor on the Tennessee PCC/PCC project did that and also reduced the frequency of the vibrators used in the top-lift paving to a maximum of 4,000 vpm (Smith et al. 2015).

The SHRP2 R21 construction guidelines (Rao et al. 2013b) recommend that the top lift "crown" or "envelope" the lower lift (see figure 32) to protect the bottom lift and to avoid tearing it with the top-lift paver if it were placed to the same width. A crown of 0.75 inches (19 mm) on either side is recommended (for a total increased paving width of 1.5 inches [38 mm]), but even this could potentially create some issues depending on the size of the coarse aggregate in the top lift and the characteristics of the mix.

It is also important to recognize that the crowning of the lower lift may not be feasible on some projects depending on the specific design details and the overall construction sequencing. For example, this may be an issue if more than two lanes are being paved independently or if paving is being done adjacent to an existing lane or shoulder. Additional discussion on these considerations is described in the next section.

Figure 32. Crowning of bottom lift with top lift material on Tennessee PCC/PCC project.

Tie Bars Across Longitudinal Joints

Tie bars are used across concrete lane-lane or concrete lane-shoulder joints to keep those joints held tightly together and to help maintain aggregate interlock load transfer. Conventional tie bar construction and installation practices should be observed in two-lift paving, but potential tie bar construction issues may arise depending on the construction staging for the particular project. For example, if adjacent two-lift paving lanes are paved separately or if an adjacent tied PCC shoulder is to be placed after the two-lift mainline pavement, the presence of the tie bars along the exposed longitudinal construction joint may present complications when the top lift is placed to crown the bottom lift (see figure 33). This potential issue can be addressed in several different ways, as described below:

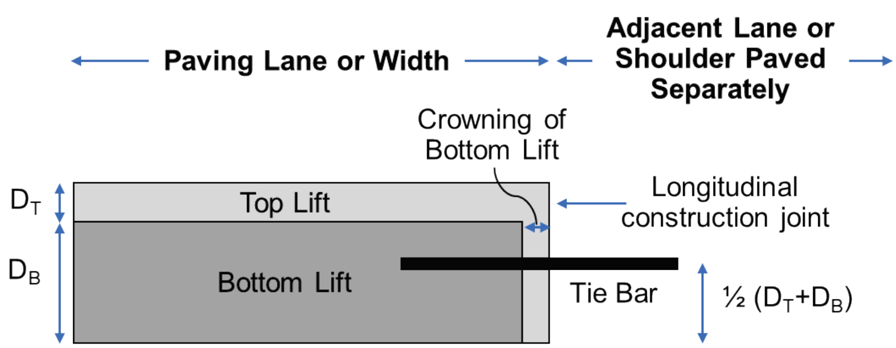

Figure 33. Crowning issue on PCC/PCC pavements with separate paving events.

- Tie bars are inserted in the plastic concrete by the second paver and at the mid-depth of the total pavement thickness, as shown in figure 34.

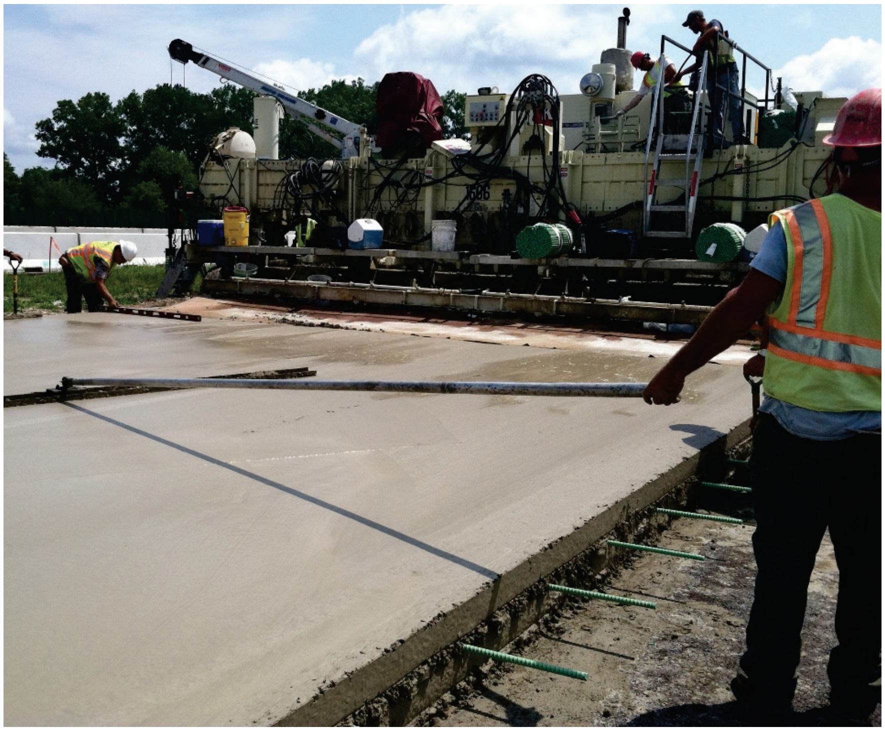

Figure 34. Tie bars inserted into plastic concrete by second paver on Illinois Tollway PCC/PCC composite pavement project (Gancarz 2017).

- A two-piece tie bar system is used that features a mechanical coupler (see figure 35). The coupler is located at the outer edge of the paved concrete and kept exposed during the pavement process so that the second piece of the tie bar can be threaded into the coupler post-construction. While effective, occasionally there were issues with keeping the coupler exposed during the placement of the top lift of concrete that created some finishing issues at the joint face (see figure 36).
- Drill holes in the hardened concrete and anchor tie bars into the slab post construction using epoxy or cementitious anchoring materials.

Figure 35. Threaded coupler used in two-piece tie bar system.

Figure 36. Exposed threaded couplers with accompanying spalling issues in the vertical face of adjacent paving lane.

As with tie bar placement in conventional single-lift construction, the tie bars should be placed parallel to the pavement surface, perpendicular to the longitudinal joint that it is tying, and at the mid-depth of the total composite pavement thickness. It is also recommended that the tie bar should not be placed within 6 inches (150 mm) of the ends of the dowels located in the transverse joints (so at least 15 inches [380 mm] away from transverse doweled joints).

Texturing of Surface Layer

The texturing of the top lift of the PCC/PCC composite pavement follows agency practices for conventional single-lift structures; longitudinal and transverse tining are most common (see figure 37) but some PCC/PCC composite pavement projects (e.g., Minnesota, Kansas) have also experimented with exposed aggregate surfaces (see figure 38). Because many PCC/PCC composite pavements use a high-quality, durable material for the top lift, whatever texturing is imparted is expected to be retained for an extended period of time.

Figure 37. Longitudinal (left, Illinois Tollway) and transverse (right, Tennessee I-65) tining on PCC/PCC composite pavement projects.

Figure 38. Measuring mean texture depth on exposed aggregate surface on Mn/Road PCC/PCC composite pavement.

Curing

After the pavement has been textured, it should be cured in accordance with the agency practices to help promote hydration and control moisture loss. Agencies most commonly use liquid membrane-forming curing compounds specified under AASHTO M 148 or ASTM C309 to retard the evaporation of moisture from the pavement surface. Some agencies have adopted the use of poly-alpha methylstyrene (PAM) materials for use in pavement curing as these materials display increased moisture retention capabilities.

Jointing

The joint spacing used on PCC/PCC pavements should be in accordance with agency standards, and the joint sawcutting should follow established procedures used in conventional PCC paving. As shown in figure 39, the general recommendation is to saw the joints to a depth of either one-third of the total concrete thickness or the thickness of the top lift plus 0.5 inches (13 mm), whichever is greater (Rao et al. 2013b). This is to avoid the potential for the sawcut crack to propagate along PCC/PCC interface instead of directly through slab depth. However, no reported issues of this type of phenomenon have been reported in any of the field installations.

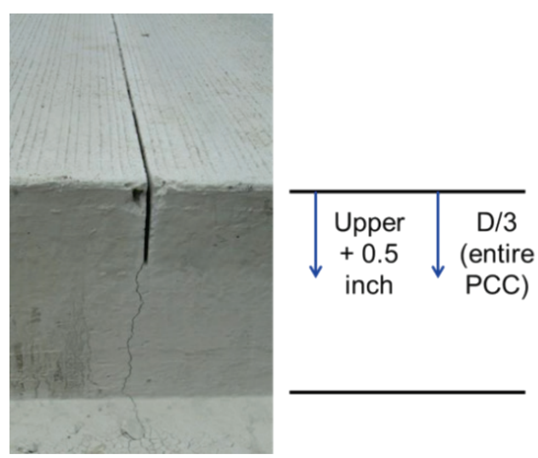

Figure 39. Joint sawing recommendations.

Recent PCC/PCC Composite Pavement Projects

A brief overview of some notable PCC/PCC composite pavement projects are summarized below, including the three PCC/PCC composite projects constructed under the SHRP2 Project R21 implementation effort.

Kansas Department of Transportation, Interstate 70

The Kansas Department of Transportation constructed a demonstration project of two-lift concrete paving in 2008. In addition to making use of a local limestone aggregate for the bottom lift, the project featured a number of surface textures, including transverse and longitudinal tining, grinding, next generation concrete surface (NGCS), and an exposed aggregate surface (EAS) (Fick 2009). A limited life-cycle assessment (LCA)—which considers the environmental impacts associated with different pavement designs—was performed on the project and indicated that the two-lift design offered a 15 percent reduction in global warming potential and a 20 percent reduction in energy usage when compared to conventional concrete pavements (Hu et al. 2014).

Illinois Tollway, Interstate 90

In 2011, the Illinois Tollway embarked on 15-year, multi-billion dollar program to rehabilitate, reconstruct, and expand its freeway system (Gillen et al. 2013). For a portion of that work on the I-90 Jane Addams Expressway west of Chicago, the Tollway used two-lift construction during the 2013-2014 construction seasons due to the availability of recycled materials and because the rural setting of the project site offered sufficient room for haul roads and equipment maneuverability. The two-lift concrete pavement featured fractionated reclaimed asphalt pavement (FRAP) in the bottom lift of the pavement, enhancing the sustainability of the overall construction process and helping to reduce initial costs. The FRAP was recovered from the existing asphalt pavement and graded, with only the coarse components (greater than No. 4 sieve) used in the bottom lift at typical contents of 15 to 25 percent (Gillen et al. 2013).

Minnesota Department of Transportation, Mn/ROAD Facility

Under the SHRP2 R21 project, the Minnesota Department of Transportation constructed a two-lift concrete pavement in 2010 at the MN/ROAD facility near Albertville, MN (northwest of Minneapolis). The purpose of the project was to demonstrate the feasibility of two-lift concrete pavement systems, and featured two different sections with unique mix designs in the lower lift: one a “low cost” concrete with Class A aggregate and low cement content and one a “recycled” concrete featuring a 50/50 blend of Class A aggregate and RCA (and low cement contents). Both sections included an exposed aggregate surface, but a portion of that surface was diamond ground in the “low cost” section (Rao et al. 2013b).

Tennessee Department of Transportation, Interstate 65

This project was placed in 2014 as part of the reconstruction of I-65 through Nashville and featured the use of a polish-susceptible limestone aggregate in the lower lift. The two-lift component was constructed on the outside shoulder of the project but at the same thickness as the mainline pavement. Based on the results of this project, TDOT noted that the placement of the two-lift composite pavement was a success and determined that it was a viable alternative to the placement of full-depth concrete pavements (Smith et al. 2015).

California Department of Transportation, I-210

This project, located on I-210 northeast of Burbank, investigated two different mixtures in the bottom lift of a 12-inch (305-mm) two-lift composite pavement: a conventional mixture and a mixture containing 15 percent RCA. Constructed in 2017, the project was about 5,100-ft (1,554-m) long and was placed in a 14-ft (4.3-m) wide outside traffic lane during nighttime construction on the heavily-traveled I-210 freeway. The project used RCA derived from the demolition and on-site processing of the existing concrete pavement. Additional details are provided by Ram et al. (2019).

Texas Department of Transportation, Frontage Road Along Southbound U.S. 59

TxDOT constructed a 10-inch (254-mm) two-lift CRCP in 2017 on an 1100-ft (335-m) segment of frontage road along the southbound lanes of U.S. 59 near Beasley, Texas (south of Houston). The project investigated the potential benefits of using concrete with a lower CTE in the top portion of the pavement to reduce thermal stresses and improve pavement performance. The construction specifications called for the lower lift to have a CTE of more than 5.5×10^{-6} inch/inch/°F (9.9×10^{-6} mm/mm/°C) while the concrete in the top lift was specified to have a CTE of less than 5.5×10^{-6} inch/inch/°F (9.9×10^{-6} mm/mm/°C). Additional details are available from Snyder, Smith, and Naranjo (2019).

CHAPTER 5. CONCLUDING REMARKS

Summary

New composite pavements—consisting of either an HMA surface placed on a new PCC pavement or a top lift of PCC placed on a bottom lift of PCC in a wet-on-wet process—offer an intriguing solution to highway agencies in meeting today's economic and environmental constraints. These designs can provide a number of potential advantages and benefits, including:

- Sustainability. This includes a number of aspects, from increased use of local and recycled materials (and the associated conservation of resources), reduced transportation and hauling costs (for virgin materials), reduced cement contents, and reduced disposal costs, all of which also provide reductions in important environmental impacts such as emissions and energy usage.
- Economic savings. Reductions in virgin materials and the ability to use recycled products in the lower layers of composite pavements without compromising performance can yield significant life-cycle cost savings.
- Long service life. Composite pavements can be designed for virtually any traffic level and for any service life, providing effective, long-term performance while requiring only occasional surface renewal or texturing.
- Optimized pavement surface. The use of multi-layer, composite pavement systems allows for the optimization of the surface layer properties to meet the frictional and noise demands of the specific project.

In 2014, the Federal Highway Administration (FHWA), working in collaboration with the American Association of State Highway and Transportation Officials (AASHTO), initiated a project designed to help state highway and other transportation agencies implement and deploy composite pavement systems, and this report documents those efforts. The implementation program included a number of activities, ranging from focused agency workshops, on-site technical assistance, a showcase event, and a peer exchange meeting. In essence, the implementation project worked to disseminate concepts and information from the original R21 research to practicing engineers around the country, generating new and increased interest in the composite pavement technologies and exposing them to greater scrutiny. The result is that additional insight and improved understanding of the challenges and benefits associated with composite pavements was achieved, and these critical lessons learned are highlighted in preceding chapters.

Moving Forward

Composite pavement systems have made great strides in the last several years and they hold the promise of imparting a number of economic, environmental, and societal benefits in future paving projects. To help promote the continued use, development, and evolution of composite pavement systems, general information on implementation efforts and critical research needs are presented in the following sections

Implementation of Composite Systems

The implementation of any technology must address several key elements to help ensure the success of the effort:

1. Goals/objectives. What are the desired end results? For composite pavements, this translates into identifying what role a composite pavement could play for a highway agency and the associated performance benefits that they could provide.
2. Leaders. Who will lead the effort? Having agency personnel who are passionate about the benefits provided by composite pavements can help encourage their early use and adoption. This can be done in conjunction with contractor and industry partners.
3. Execution. How are things moved forward? Working with all stakeholders, the development of a formal implementation plan for composite pavements—from initial pilot projects to integration as a standard practice—can help map out the path forward and identify potential barriers or gaps that need to be addressed.
4. Monitoring. How is the technology working? By monitoring the performance of composite pavement technologies, insights into potential performance capabilities can be determined and any needed design, construction, or specification modifications can be made to help ensure their success and long-term performance.

In consideration of these factors, a facilitated discussion at the SHRP2 Project R21 Peer Exchange held in Richmond, Virginia (see chapter 2) sought guidance from highway agencies in implementing composite pavement technologies. Some of the major implementation recommendations from those discussions are presented in table 14.

Table 14. General implementation recommendations for composite pavement systems.

Recommendation	Implementation Areas (see above list)
Clearly define the benefits of composite pavements, to both the agency and the traveling public, including sustainability, cost, and performance.	1. Goals/objectives.
Develop/test/refine composite pavement paving specifications. A number of sample specifications are available that can be used as a starting point.	1. Goals/objectives. 3. Execution.
Identify a champion within an agency to coordinate the effort and help overcome impediments.	2. Leaders.
Work with industry partners (contractors, material suppliers, etc.) to help identify issues and overcome barriers.	2. Leaders. 3. Execution.
Allocate dedicated funding to implementation of composite pavement systems.	3. Execution.
Share the burden of risk among all stakeholders as a way of encouraging the use of composite pavements.	3. Execution.
Consider the allocation of “seed” money as a way to help encourage the use of composite pavements.	3. Execution
Continue the use of peer-exchange meetings and events to promote the sharing of information on composite pavement technologies.	3. Execution.
Conduct research with university and other partners to address noted gaps that may exist on the design and construction of composite pavements or on the use of suitable materials. Include a section on how the research can be put into practice.	3. Execution. 4. Monitoring.
Perform follow-up studies and evaluation to secure feedback on composite pavements and work to continually improve their design and construction.	4. Monitoring.

In addition, the European experience with composite pavement systems should continue to be monitored. Given the extensive use of both composite pavement systems in a number of European countries (HMA/PCC: Germany, The Netherlands; PCC/PCC: Germany, Austria) under heavy traffic loadings, additional knowledge, insight, and understanding of composite pavement behavior can be gleaned from their experiences and applied to composite pavement practices in the U.S.

Gaps and Research Needs

Despite the growing use of new composite pavement systems and the promising performance obtained to date, several gaps and research needs in the use of the technology remain to be addressed. Some of these items include:

- All composite pavement types.
  - Fully calibrated and verified pavement design tools directly suited to composite pavement systems and based on mechanistic principles.
  - Improved guidance on general applicability of composite pavements (traffic levels, facility type/location, design life, material availability, contractor availability, plant proximity, etc.).
  - Applicability of composite pavement designs outside of new or mainline reconstruction, such as lane additions, truck climbing lanes, and ramps.
  - Guidelines for determining the cut-off point in terms of the economic and environmental advantages of composite pavements; in other words, at what point do the costs and environmental impacts of additional paving crews outweigh the benefits of using local materials with reduced transportation costs (assuming that performance is the same).
  - Improved insight into the maintenance requirements, maintenance/rehabilitation schedules, and performance expectations for composite pavement systems; related to this is the use of life-cycle cost analysis techniques in evaluating their cost effectiveness. Monitoring of recently constructed projects is a first step in looking into these aspects.
  - Ongoing training and outreach events to provide guidance on the design and construction of composite pavements and to promote and demonstrate their use.
- HMA/PCC.
  - Perform additional studies to evaluate the thermal insulation effects of the HMA on the behavior of the underlying concrete. What are the long-term effects on performance?
  - Investigate the need for curing compound removal prior to HMA placement. Does the type of curing compound dictate this need, and what removal methods may be most effective?
  - Evaluate the need to seal the joints in the underlying concrete prior to the placement of the HMA surface.
  - Evaluate the long-term effectiveness of the saw/seal approach in controlling reflection cracking. What future maintenance of those sawed/sealed joints may be needed?

- PCC/PCC.
  - Perform additional studies on the sensitivity of time delays to achieving an adequate bond between the two layers. What environmental and mix design factors may extend or shorten that window and how can they be accounted for in the construction process?
  - Evaluate the potential for using exposed aggregate surfaces on a more routine basis.
  - Develop additional guidance on the mix characteristics of the bottom lift material in terms of cement reductions, SCM content, recycled aggregate content, etc. Are there practical limits on the use of these products?
  - Evaluate the behavior of PCC/PCC composite pavements with different CTE values in the top and bottom lift.

Additional gaps and research needs are expected to emerge with the continued use of these technologies, but these are some of the immediate items that should be addressed to help increase the use and applicability of composite pavement systems.

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APPENDIX A. IMPLEMENTATION ASSISTANCE PROGRAM COMPOSITE PAVEMENT FIELD PROJECTS

I-210, Burbank, California (Ram et al. 2019)

Information Category	Project Details
Project Goal	• Improve environmental sustainability by using recycled concrete aggregate from existing pavement produced on-site
General Project	• Two-lift wet-on-wet composite concrete pavement • Location: I-210 eastbound, lane #4, between the Pennsylvania Avenue Off-Ramp and the La Crescenta Avenue On-Ramp • Length: 5,100 ft (1,554 m)
Pavement Design and Materials	• Design Life: 40 years • 12-inch (305-mm) thick JPCP − Top lift: 3-inch (75 mm) thick conventional portland cement concrete with total cementitious = 565 lb/yd^3 (335 kg/m^3) − Bottom lift: 9-inch (229 mm) thick concrete with total cementitious = 470 lb/yd^3 (279 kg/m^3). Built in two sections, one section with no recycled materials and one section with 15% RCA • Transverse joint spacing: 15 ft (4.6 m) • Dowel bars: 1.5-inch (38-mm) on 12-inch (305 mm) spacings • Base: 4-inch (150 mm) lean concrete
Construction	• Construction Dates: January 30-February 7, 2017 • Two-Way Average Daily Traffic: 55,000 vpd (with 9% trucks) • Weather Conditions: 50-60˚F (10-16˚C), Nighttime paving

I-65, Nashville, Tennessee (Smith et al. 2015)

Information Category	Project Details
Project Goal	• Minimize costs by reducing volume of higher quality aggregates needed for surface course and employ locally available aggregates in the lower-lift
General Project	• Two-lift wet-on-wet composite concrete pavement • Location: Outer shoulder of I-65 Northbound Lanes, just North of East Trinity Lane interchange • Length: 5,000 ft (1,524 m)
Pavement Design and Materials	• Design Life: 40 years • 13-inch (330-mm) thick JPCP shoulder (10-ft wide) − Top lift: 3-inch (75 mm) thick portland cement concrete with 0.75-inch (19 mm) top size limestone surfacing aggregate − Bottom lift: 10-inch (255 mm) thick portland cement concrete with 1.5-inch (38 mm) top size limestone aggregate (non-surface) • Transverse joint spacing: 15 ft (4.6 m) • Dowel bars: 1.5-inch (38-mm) on 12-inch (305 mm) spacings • Base: 4-inch (100 mm) asphalt-treated permeable
Construction	• Construction Dates: October 17-24, 2014 • Two-way Average Daily Traffic: 140,000 vpd • Weather Conditions: 45-68˚F (7-25˚C), sunny, relative humidity 52%

Frontage Road Along SB U.S. 59, Beasley, Texas (Snyder, Smith, and Naranjo 2019)

Information Category	Project Details
Project Goal	• Optimize material usage by employing manufactured sands and aggregates with higher coefficient of thermal expansion in the lower lift
General Project	• Two-lift wet-on-wet composite concrete pavement • Location: Both lanes of a frontage road parallel to U.S. 59 on the north. Section starts at Hamlink Road and proceeds southwest • Length: 1,100 ft (335 m), consisting of two 12-ft (3.6-m) lanes, an 8-ft (2.4-m) outside shoulder, and a 4-ft (1.2-m) inside shoulder
Pavement Design and Materials	• 10-inch (254-mm) thick CRCP – Top lift: 3-inch (75 mm) thick portland cement concrete containing coarse aggregate with coefficient of thermal expansion less than 5.5×10^{-6} inch/inch/˚F (9.9×10^{-6} mm/mm/˚C) – Bottom lift: 7-inch (178-mm) thick portland cement concrete containing coarse aggregate with coefficient of thermal expansion greater than 5.5×10^{-6} inch/inch/˚F (9.9×10^{-6} mm/mm/˚C) • Reinforcement placed at mid-depth of total slab thickness – Longitudinal: #6 bars at 7-inch (178-mm) spacings – Transverse: #5 bars at 48-inch (1219-mm) spacings • Base: 1-inch (25 mm) asphalt bondbreaker over 6-inch (150-mm) cement-treated
Construction	• Construction Dates: April 7, 2017 & April 13, 2017 • Two-way Average Daily Traffic: n/a • Weather Conditions (April 7): Nighttime paving, 65-74˚F (18-23˚C); South wind @ 7-10 mi/hr (11-16 km/hr); relative humidity 37%

U.S. 60, Richmond, Virginia (Espinoza-Luque, Smith, and Hossain 2019)

Information Category	Project Details
Project Goal	• Combine the ease of maintenance of an asphalt pavement along with the increased structural capacity and long-life provided by a CRCP pavement
General Project	• New composite pavement with HMA over CRCP • Location: West side of Richmond on U.S. 60 westbound, approximately 0.26 mi (0.42 km) west of Whiteside Road to I-295 interchange • Length: 1.1 mi (1.8 km)
Pavement Design and Materials	• HMA/PCC Design Life: 30 years • Surface Layer: 2-inch (51-mm) thick PG 64E-22 stone matrix asphalt (0.5-inch [13 mm] mix • Bottom Layer: 8-inch (203-mm) thick CRCP with reinforcement placed at mid-depth – Longitudinal: #5 bars at 6-inch (152-mm) spacings – Transverse: #4 bars at 36-inch (914-mm) spacings • Base: Cement-treated aggregate (some removal/replacement and base/subgrade stabilization to address pumping issues)
Construction	• Construction Dates: July to October 2017 (demolition/foundation repair/all paving) • Two-way Average Daily Traffic: 14,000 vpd (with 6% trucks) • Weather Conditions: —

ACKNOWLEDGMENTS

The original maps on pages 9 and 11 are the copyright property of Google and can be accessed from https://www.google.com/maps/. The map overlays were developed as a result of this research project. The map overlays on page 9 include lines showing the project location with arrows pointing to the beginning and end as well as a text box insert with details on the location. The map overlays on page 11 include lines showing the project location with a line along Highway 60 pointing to the beginning and end as well as text box inserts with details on the location.