FHWA Research and Technology Evaluation

Precast Concrete Pavement

Final Report
October 2018

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Foreword

The Federal Highway Administration's (FHWA's) Research and Technology Program furthers the FHWA Office of Research, Development, and Technology's (RD&T's) goal of ensuring transparency, accessibility, and responsiveness of RD&T for all stakeholders.

This report examines how the benefits and costs associated with precast concrete pavement (PCP) as well as FHWA's investment in PCP technology and deployments have affected the development and expanded use of the practice over the last 10 to 15 years.

This report should be of interest to engineers, practitioners, researchers, and decisionmakers involved with the research, design, performance, and deployment of concrete pavement technology.

Hari Kalla, P.E.
Associate Administrator, Office of Research,
Development, and Technology

Notice

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<tr><td colspan="4">16. Abstract
This evaluation assesses the outcomes of the Federal Highway Administration’s (FHWA’s) investment in precast concrete pavement (PCP). The evaluation team determined the benefits and costs of individual PCP projects and, where possible, extrapolated findings from the data based on overall themes. Additionally, the evaluation team determined the outcomes and impacts of FHWA research, demonstrations, workshops, and related activities and developed recommendations to facilitate the continued adoption of the technology. FHWA’s efforts were found to be largely successful and contributory to the development and adoption of PCP. FHWA has overseen initial research and prototypes and has helped the use of PCP technology become routine in some States. PCP is an effective and efficient way to conduct roadway maintenance, repairs, and reconstruction. Benefits significantly exceed costs in high-volume areas or unique roadway sections that would lead to significant detours if closed for long periods of time. PCP also allows for innovative maintenance practices and cost savings, such as the reuse of concrete panels for temporary repairs.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*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)

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List of Abbreviations and Acronyms

Abbreviation	Definition
AASHTO	American Association of State Highway and Transportation Officials
ALDOT	Alabama Department of Transportation
CIP	cast-in-place
Caltrans	California Department of Transportation
ConnDOT	Connecticut Department of Transportation
DDOT	District of Columbia Department of Transportation
ETG	Expert Task Group
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
HDOT	Hawaii Department of Transportation
IAP	Implementation Assistance Program
ICCP	International Conference on Concrete Pavements
INDOT	Indiana Department of Transportation
KDOT	Kansas Department of Transportation
LaDOTD	Louisiana Department of Transportation & Development
NJDOT	New Jersey Department of Transportation
NYSDOT	New York State Department of Transportation
PCP	precast concrete pavement
PennDOT	Pennsylvania Department of Transportation
R&T	Research and Technology
SHRP2	second Strategic Highway Research Program
TIG	Technology Implementation Group
TxDOT	Texas Department of Transportation
UDOT	Utah Department of Transportation
VDOT	Virginia Department of Transportation
WisDOT	Wisconsin Department of Transportation

Executive Summary

Purpose of the Evaluation

The purpose of the precast concrete pavement (PCP) evaluation was to better understand the usage of PCP as a developing technology. This evaluation was designed to determine the benefits and costs of individual PCP projects and to enable, when possible, the evaluation team to extrapolate findings based on overall themes related to the technology. The evaluation team sought to determine the outcomes and impacts of Federal Highway Administration (FHWA) research, demonstrations, workshops, and related activities. These activities were evaluated in terms of how they contributed to the state of the practice and promoted the use of PCP technology.

Program Description

Multiple FHWA-led research efforts, demonstrations, technical briefings, and technology refinements relating to PCP have occurred over the last 10 to 15 years. Significant to this evaluation, PCP was incorporated as a project (Project R05) within the second Strategic Highway Research Program (SHRP2).(2) SHRP2 Project R05 is a part of the renewal focus area, which focused on "enabling faster, minimally disruptive, and longer-lasting improvements."(3) SHRP2 Project R05 was a primary focus of this evaluation.

Methodology

The evaluation approach consisted of three main areas: short-term outcomes, medium- and long-term outcomes, and impacts. The key hypotheses were based on usage and implementation of PCP technology as well as the impacts on travel time and construction. These impacts included timelines for road closures and detours as well as overall project timelines. Additionally, FHWA played an important role in formulating components of the hypotheses. The evaluation team sought not only to determine the usage and outcomes of PCP technology, but also to isolate what role FHWA has played in spurring usage and adoption.

Three primary data sources were used to evaluate PCP technology. First, the evaluation team reviewed publicly available information, including FHWA materials, outreach, and reports. Second, the evaluation team attended presentations at the 94th and 95th Transportation Research Board Annual Meetings, the 11th International Conference on Concrete Pavements, and privately at FHWA's Turner-Fairbank Highway Research Center. Finally, the evaluation team interviewed routine users of PCP technology and a subset of grant recipients of SHRP2 Rounds 3 and 6 Implementation Assistance Program. In addition to these formal interviews with State transportation department users of PCP, the evaluation team held numerous informal conversations with FHWA staff, FHWA contractors, and other stakeholders.

Findings

In terms of PCP uptake, the evaluation team found that PCP is used in an array of settings. FHWA contributed to this diffusion and technological development through FHWA and SHRP2 publications, funding, and programming.

The evaluation team found that, despite cast-in-place (CIP) concrete being less costly to install than PCP, higher lifetime maintenance costs for CIP concrete led to higher overall project costs. Similarly, the durability of PCP makes it more cost effective compared to other rapid-repair alternatives, such as high-early-strength concrete. However, additional upfront training costs exist as contractors and inspectors are still relatively unaware of the specifics of designing and installing PCP panels compared to established alternatives.

In terms of benefits, the evaluation team found both installation- and travel-time savings exist when using PCP compared to traditional CIP concrete. PCP is comparable to other rapid-repair alternatives, such as high-early-strength concrete; however, while PCP is comparable to CIP concrete in terms of longevity and performance, it is far superior to high-early-strength concrete in this regard. Additionally, PCP provides options for innovative maintenance techniques, such as reusing and recycling pavement slabs.

Recommendations

Based on the evaluation findings described within this report, the evaluation team developed several recommendations for FHWA and potential State adopters. Based on the success of FHWA efforts to this point and the continued adoption and implementation of PCP across numerous States, these recommendations emphasize particularly successful practices that are already in use.

The evaluation team recommends that FHWA, in its effort to continue promoting PCP through the Resource Center, continues to champion the technology and document institutional knowledge without endorsing particular systems. Additionally, the evaluation team recommends that potential State adopters and users of PCP develop and maintain their own institutional knowledge while considering the applicability of PCP and conducting test trials for new users or when attempting innovative techniques.

Conclusion

Overall, the evaluation team found FHWA's efforts to be largely successful and contributory to the development and adoption of PCP. FHWA oversaw initial research and prototypes and helped use of the technology to become routine in some States. With its continued efforts, FHWA has facilitated adoption and initial use in other States. Using PCP is an effective and efficient way to conduct roadway maintenance, repairs, and reconstruction. Benefits significantly exceed costs in high-volume areas or unique roadway sections that would lead to significant detours if closed for long periods of time.

1. Introduction

1.1 Evaluation Purpose

The Federal Highway Administration (FHWA) has initiated an effort to evaluate the Research and Technology (R&T) Development Program. Leaders of governmental transportation R&T programs need to be able to effectively communicate the impacts of their programs. The R&T Evaluation Program helps FHWA assess how effectively it is meeting its goals and objectives and provides useful data to inform future project selections.

In its initial year, the R&T Evaluation Program worked with nine FHWA offices to identify projects for evaluation. The FHWA Office of Infrastructure in conjunction with the second Strategic Highway Research Program (SHRP2) identified precast concrete pavement (PCP) research efforts as a project to evaluate. The evaluation assessed the benefits and costs of using PCP, using deployments of this technology as case studies. The assessment also addressed FHWA's efforts related to conducting PCP research and analysis as well as supporting the adoption of PCP technology by State and local agencies.

The purpose of the PCP evaluation was to better understand the outcomes of this developing technology. While existing research suggests that clear time savings and advantages exist in using PCP, these advantages have not been fully understood or quantified. Additionally, while cost information is known, it is unknown to what extent the advantages of PCP exceed the costs, if at all, compared to existing alternatives. As a result, this evaluation was designed to determine the benefits and costs of individual PCP projects and, when possible, the evaluation team extrapolated overall themes related to the technology in general.

The evaluation team sought to determine the outcomes and impacts of FHWA research, demonstrations, workshops, and related activities. These activities were evaluated in terms of how they contributed to the state of the practice and promoted the use of PCP technology. Determining how States and other stakeholders have received and utilized PCP information and their plans for using PCP moving forward was critical.

Answering these questions will determine the degree to which PCP technology meets the objectives of FHWA's Research & Technology Agenda.(4) Specifically, PCP can be applied to infrastructure objectives 3, 4, and 5:(5)

- Objective 3: Improve the ability of transportation agencies to deliver projects that meet expectations for timeliness, quality, and cost.
- Objective 4: Reduce user delay attributable to infrastructure system performance, maintenance, rehabilitation, and construction.
- Objective 5: Improve highway condition and performance through increased use of design, materials, construction, and maintenance innovations.

Using PCP is an innovative design and construction technique that facilitates improved maintenance. PCP technology also facilitates timely, high-quality projects that can be implemented in high-traffic areas with limited disruption. By enabling roadway sections to open the morning after an evening of reconstruction, PCP allows agencies to manage projects that meet expectations and reduce impacts on users, unlike projects that do not use PCP. Thus, PCP technology is ideal for reducing user delay in high-traffic areas where it is difficult to detour.

Given these underlying objectives, the evaluation team developed an analytical framework based on the evaluation areas described in table 1.

Table 1. Summary of evaluation framework.

Evaluation Area	Description
Technology diffusion and research	Evaluation of the current state of PCP technology in relation to projects and research conducted. Includes determination of the impact and usefulness of PCP-related FHWA activities and research from a State agency perspective.
Costs of PCP	Evaluation of the cost of PCP compared to a conventional concrete alternative or baseline. Construction and installation costs for PCP potentially greater than costs for conventional concrete alternatives; overall societal costs and costs determined using lifecycle cost analysis lower than alternatives.
Benefits of PCP	Evaluation of PCP benefits compared to a conventional concrete alternative or baseline. Benefits include construction-time and travel-time savings.

1.2 Program Background

Timeline

PCP installation is an innovative practice of using prefabricated concrete panels for pavement and roadway maintenance and rehabilitation. This practice is often utilized in high traffic–volume areas and in variable or moderately inclement weather due to the construction-time and overall travel-time savings that it provides. Significant to this evaluation, PCP was incorporated as a SHRP2 project (Project R05). SHRP2 Project R05 was within the renewal focus area, which concentrated on "enabling faster, minimally disruptive, and longer-lasting improvements."(4) Other focus areas under SHRP2 included safety, reliability, and capacity. SHRP2 Project R05 is a primary focus of this evaluation.

The progression of PCP in the United States, with the exception of some projects that occurred earlier, is as follows:

- Mid-1990s: FHWA-led research efforts began, including development of feasibility studies.
- Early 2000s: Highway and airport agencies began using PCP technology, and additional FHWA-led research was conducted.

- Mid-2000s: The American Association of State Highway and Transportation Officials (AASHTO) Technology Implementation Group (TIG) promoted PCP, and FHWA supported PCP demonstrations under the FHWA Highways for LIFE Program.[1]
- Late 2000s: SHRP2 Project R05 work began, and FHWA technical briefs were produced.
- Early 2010s: A SHRP2 Project R05 final report was published, and the implementation program under the project began.
- Mid-2010s: SHRP2 Project R05 awarded Lead Adopter and User Incentive grants to States through the Implementation Assistance Program (IAP) (Rounds 3 and 6).

As demonstrated by this timeline, multiple FHWA-led research efforts, demonstrations, technical briefings, and technology refinements have occurred over the last 10 to 15 years.

Based on this work, PCP technology has reached the maturity point when the technology will soon be transferred from FHWA headquarters to the FHWA Resource Center. The FHWA Resource Center provides, "technical assistance, training, technology deployment, and interagency cooperation" by deploying Resource Center staff nationwide to conduct webinars and workshops.(5) With the transfer, the Resource Center will become responsible for PCP outreach and will be the primary source of information and experience for States looking to undertake a PCP project. The technical assistance provided will include answering questions, sharing best practices, introducing new innovations, and engaging with States on a one-to-one basis through meetings, training sessions, and publication development. All activities will help promote the continued use and development of PCP technology.

Project Details

SHRP2 Project R05 began by investigating 16 PCP projects and determined that, while pavement systems are still evolving, "well-designed and well-constructed PCP systems can provide high-quality, long-term service and are often a good choice for rapid repair and rehabilitation of existing pavements."(2) Major deliverables from this first phase of SHRP2 Project R05 were a set of guidelines for selection, design, fabrication, and installation of PCP systems as well as the development of model specifications.

Along with the final report, FHWA and its contractor developed a marketing plan for implementing SHRP2 Project R05. The SHRP2 Project R05 implementation plan focused on technical support, education, outreach, and research. The plan indicated that technical support would be provided to a limited number of new PCP users with the goal of mitigating any perceived implementation risks. Highway agencies that have received technical support are Alabama, California, Connecticut, Delaware, the District of Columbia, Florida, Hawaii, Indiana, Kansas, Louisiana, New Mexico, Pennsylvania, Texas, Virginia, Washington State, and Wisconsin.

Education and outreach focused on increasing awareness of PCP technologies, dispelling misunderstandings, and providing training to highway agencies and the PCP contractor community. FHWA's contractor developed training modules to support the needs of highway agencies, targeting

[1]The Highways for LIFE Program sought demonstrations that were long lasting, innovative, fast to construct, efficient, and safe.

key design, materials, and construction personnel as well as administrators and chief engineers. Contractor-community education focused on addressing the role of the contractor in PCP applications. Over the course of SHRP2 Project R05, education and training outreach included the following:

- Twenty-three workshops for highway agencies.
- One industry workshop.
- Three webinars.
- Four Expert Task Group (ETG) meetings.
- One PCP open house.

Finally, the SHRP2 Project R05 implementation plan sought to continuously improve PCP technology through research and development. Efforts included reaching out to other agencies, organizations, and academia to encourage project-level data collection. Eighteen briefings with these other entities have occurred thus far.

SHRP2 Project R05 also awarded grants through Rounds 3 and 6 of the IAP. This evaluation focused on the PCP-related projects and activities funded by the IAP awards, projects recently undertaken by routine users of PCP technology, and FHWA activities that promoted PCP. This evaluation was conducted in two phases.

Phase 1

SHRP2 Project R05 was included in Rounds 3 and 6 of the IAP. Under Round 3, four State agencies received awards of $300,000 each to include PCP technology in a construction or rehabilitation project. Awardees were the following:

- Hawaii Department of Transportation (HDOT).
- Kansas Department of Transportation (KDOT).
- Texas Department of Transportation (TxDOT).
- Wisconsin Department of Transportation (WisDOT).

The goal of these demonstrations was to show the variability and usability of PCP technology. For phase 1 of the evaluation, the evaluation team evaluated the projects undertaken by these agencies as well as projects undertaken by various routine users of PCP technology. These users utilize PCP regularly, have not received IAP awards, and include the following State transportation departments:

- California Department of Transportation (Caltrans).
- New Jersey Department of Transportation (NJDOT).
- New York State Department of Transportation (NYSDOT).
- Utah Department of Transportation (UDOT).

The evaluation team interviewed a subset of these agencies as part of the evaluation and utilized publicly available information for the remaining projects. A full list of interviewees can be found in section 3.3.

Phase 2

Most recently, the evaluation team assessed projects awarded under Round 6 of the IAP. These included Lead Adopter awards of $300,000 each to the following transportation departments:

- Alabama Department of Transportation (ALDOT).
- Florida Department of Transportation (FDOT).

- Louisiana Department of Transportation & Development (LaDOTD).
- Pennsylvania Department of Transportation (PennDOT).

Also included were User Incentive awards of $75,000 each to the following transportation departments:

- Connecticut Department of Transportation (ConnDOT).
- District of Columbia Department of Transportation (DDOT).
- Indiana Department of Transportation (INDOT).
- LaDOTD.
- PennDOT.
- Virginia Department of Transportation (VDOT).

Under this phase, the evaluation team interviewed a subset of Lead Adopter and User Incentive awardees. A full list of interviewees can be found in section 3.3.

1.3 Report Structure

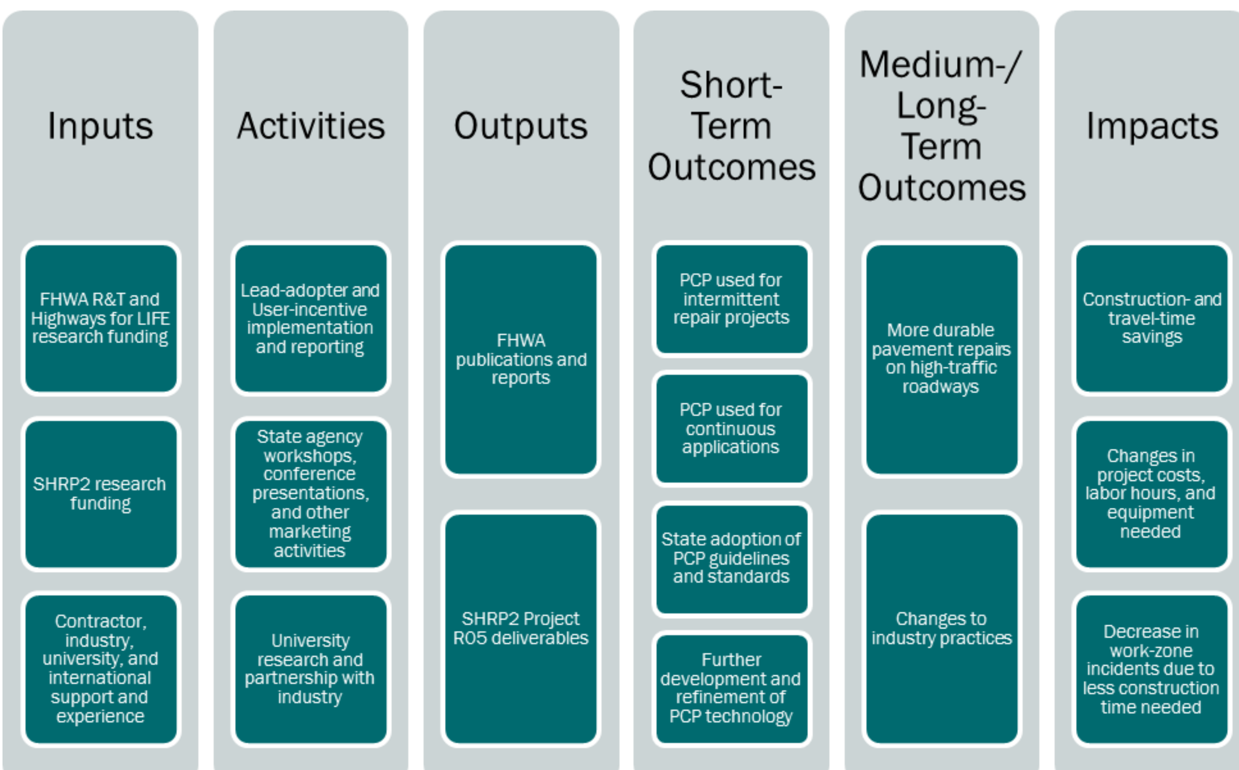
The next chapter of this report, Evaluation Design, describes the evaluation methodology and key hypotheses and provides a logic model for the PCP research effort. Evaluation Design is followed by the chapter Evaluation Findings, which delves into the findings and results of this evaluation, and then by the chapter Recommendations, which offers recommendations for FHWA based on the results of this evaluation. The chapter entitled Conclusions summarizes the report's findings and recommendations.

2. Evaluation Design

This chapter describes the logic model that formed the basis of the evaluation. The logic model was converted into an evaluation approach consisting of key hypotheses and performance measures. Based on these hypotheses and performance measures, the evaluation team determined three evaluation areas and a set of secondary hypotheses in which to frame the evaluation. These secondary hypotheses are explored and directly addressed in section 2.4.

2.1 Logic Model

A logic model is a logical series of statements that links program components (inputs, activities, outputs, outcomes, and impacts) in a chain of causality. It describes the relationship between program resources, planned activities, and expected results. It is not intended to be a comprehensive or linear description of all program processes and activities, but rather to clearly show how program stakeholders expect program activities to affect change. The logic model helps explain the theories of change that drive the design of a program and provides hypotheses (i.e., if this is done, then that will happen) that can be tested in an evaluation. Figure 1 represents the PCP logic model.



Source: FHWA.

Figure 1. Illustration. PCP logic model.

The primary inputs and activities of the PCP research program consist of conducting research related to PCP and funding outreach and implementation with State agencies through SHRP2. These activities have led to PCP projects, research reports, and guidance for future implementations. Using these outputs as a reference, the evaluation team tested the outcomes and impacts of PCP, most notably, in terms of adoption, benefits relating to durable repairs and travel-time savings, and costs relating to installation and maintenance. A particular emphasis, evident through the progression of the logic model, is on the role FHWA played in generating outputs that have diffused the technology. An overview of the evaluation team's approach follows.

2.2 Evaluation Approach and Key Performance Measures

Overview

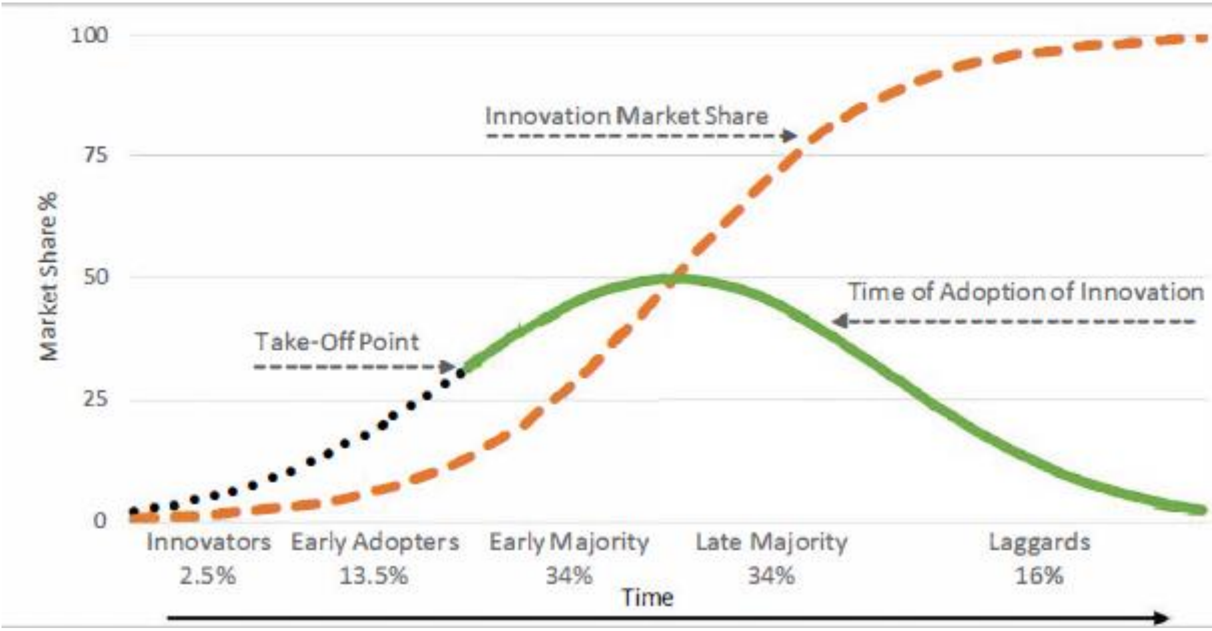
As table 2 describes, the evaluation approach consisted of three main areas. Following the logic model, those areas are short-term outcomes, medium- and long-term outcomes, and impacts. The key hypotheses are based on usage and implementation of PCP technology as well as its impacts on travel time and construction. These impacts include timelines for road closures and detours as well as overall project timelines. An important component of the hypotheses is the role played by FHWA. The evaluation team sought not only to determine the usage and outcomes of PCP technology, but also to isolate what role FHWA played in spurring initial usage and adoption.

Table 2. Evaluation approach.

Evaluation Component	Key Hypotheses	Key Performance Measures
Short-term outcomes	PCP technology is being used in a broad range of project types. FHWA/SHRP2 activities contributed to the state of the practice.	• Determine usage of PCP technology. • Determine full range of FHWA activities and the impact they had on States.
Medium-/long-term outcomes	PCP technology leads to more durable pavement repairs and changes to industry practices. FHWA/SHRP2 activities encouraged adoption of PCP technologies.	• Compare PCP-project maintenance required against a baseline. • Analyze industry practices.
Impacts	PCP technology leads to implementation- and travel-time savings compared to conventional rapid hardening–material projects (baseline).	• Compare PCP-project timelines, crew size, and maintenance required compared to a baseline. • Compare itemized PCP-project costs to conventional ready-mixed concrete projects.

As described in section 1.2, PCP technology has been utilized for a number of years. It is a relatively mature technology that is being adopted in multiple ways and implemented in many States and countries for roadway repair and reconstruction. Additionally, a number of installation methods have been designed and utilized by both public and private entities. As noted in the timeline in section 1.2, beginning in 2005, AASHTO featured PCP as a Focus Technology within its Innovation Initiative.(6) The full list of Focus Technologies, including information for Precast Concrete Paving Slabs can be found on AASHTO's website under the Design section.(7)

Figure 2 is an adaptation of a figure generated by the State Government of Victoria, Australia, and shows the standard theory for the adoption of innovation over time. The x-axis represents time but does not have an exact range; the range for this x-axis is better explained as a starting point in time to a later point in time. The time range is flexible for all innovations. Based on the progression of PCP, the evaluation team views PCP as within the early-majority stage as many States have adopted or shown interest in the technology.



Source: Adapted from State Government of Victoria, Australia.

Note: The stages shown above the x axis apply only to the line labeled "Time of Adoption of Innovation."

Figure 2. Line graph. Adoption of innovation over time.[8]

Once the approximate level of adoption of PCP was established, the evaluation team sought to determine the role that FHWA research and outreach played in advancing PCP through the innovators stage.

In addition to technological diffusion and adoption based on usage and implementation, the key hypotheses incorporated the principles of benefit–cost analysis by comparing the outcomes of PCP usage to a baseline of possible alternatives. These alternatives include traditional ready-mixed concrete as well as high-early-strength concrete. While data for a full benefit–cost analysis were unavailable, the evaluation team made illustrative comparisons using a benefit–cost analytical framework. The comparisons were completed for various known demonstrations and implementations of PCP. The specific benefits and costs assessed are described in more detail in the next chapter. The key hypotheses detailed in table 2 were utilized to address the evaluation areas outlined in table 1.

Primary and Secondary Hypotheses and Key Measures of Effectiveness

Table 3 describes the full set of secondary hypotheses for each evaluation area as well as the measures of effectiveness used to evaluate the hypotheses. The findings of the evaluation are presented by hypothesis in chapter 4.

Table 3. Hypotheses and measures of effectiveness by evaluation area.

Evaluation Area	Secondary Hypothesis	Measure of Effectiveness
Technology diffusion and research	PCP technology is being used for a broad range of applications in a variety of settings.	Determine usage of PCP technology (intersections, road sections, highway sections, bridges, etc.).
Technology diffusion and research	FHWA activities (research, demonstrations, workshops, etc.) contributed to PCP-technology development and usage.	Determine contribution FHWA research had on State decisionmaking regarding PCP usage.
Technology diffusion and research	States are aware of and utilize SHRP2 PCP guidelines and technical standards.	Determine level of awareness and usage of guidelines and technical standards.
Costs of PCP	PCP-procurement and -construction costs are greater than those for conventional ready-mixed concrete projects.	On average, costs for materials, equipment, training, installation, and crews are greater for PCP projects compared to conventional ready-mixed concrete projects.
Costs of PCP	Overall PCP-project costs, including maintenance costs over time, are less than those for conventional ready-mixed concrete projects.	On average, costs associated with maintenance, labor time, and travel time are less for PCP projects compared to conventional ready-mixed concrete projects.
Costs of PCP	Use of PCP presents additional installation challenges compared to conventional ready-mixed concrete projects.	On average, PCP projects lead to other disadvantages or challenges compared to conventional ready-mixed concrete projects.
Benefits of PCP	Use of PCP leads to pavement installation-time savings (based on ability to install in varying weather conditions or at night) compared to conventional ready-mixed concrete projects.	On average, installation time for PCP projects was less than for conventional ready-mixed concrete projects.
Benefits of PCP	Use of PCP leads to overall travel-time savings (based on no field cure time) compared to conventional ready-mixed concrete projects.	On average, travel time for PCP projects (measured in delays or detours) was less than for conventional ready-mixed concrete projects.
Benefits of PCP	Use of PCP leads to increased durability and longer service life compared to conventional ready-mixed concrete projects.	On average, PCP projects require less maintenance compared to conventional ready-mixed concrete projects.
Benefits of PCP	Use of PCP leads to other advantages, including innovative approaches, compared to conventional ready-mixed concrete projects.	On average, PCP projects lead to other advantages or unique benefits compared to conventional ready-mixed concrete projects.

Adoption of PCP and the role played by FHWA were determined by assessing the usage of PCP and stakeholder awareness of FHWA activities and research. Costs were determined based on road closures as well as overall costs for pavement installation, which were calculated by price per square yard of pavement. Benefits were similarly determined based on travel-time impacts and durability of PCP compared to alternatives.

3. Evaluation Methodology

Three primary data sources were used to evaluate PCP technology. First, the evaluation team reviewed publicly available information, including FHWA materials, outreach, and reports. This review included a compilation of known PCP projects to determine a baseline of PCP usage. Second, the evaluation team attended presentations at the 94th and 95th Transportation Research Board Annual Meetings, the 11th International Conference on Concrete Pavements (ICCP), and internally at FHWA's Turner-Fairbank Highway Research Center. Last, the evaluation team interviewed routine users of PCP technology and a subset of SHRP2 Rounds 3 and 6 IAP recipients. In addition to these formal interviews with State transportation department users of PCP, numerous informal conversations were held with FHWA staff, FHWA contractors, and other stakeholders. The subsections of this chapter expand upon these three data sources and the hypotheses addressed. Chapter 4 then describes the findings associated with each hypothesis.

3.1 PCP Documentation

The evaluation team assessed all FHWA and State-level materials and reports related to PCP as well as publicly available information from other sources. This literature included documentation and promotional materials from private companies relating to their PCP work and from industry groups. FHWA materials consisted of technical briefs and reports, notes and minutes from ETG meetings, and guidelines and standards produced through SHRP2 Project R05. State-level materials were primarily project specific. Additional research regarding private entities and industry provided further background regarding the state and size of the PCP industry.

The evaluation team began by reviewing the guidance document completed through SHRP2 Project R05.(1) This document provided background on current PCP technical standards and practices. The team also reviewed the SHRP2 Project R05 ETG-meeting minutes to understand the current challenges experienced by States and previous projects and technical briefs prepared by FHWA for context.(9–13) Additionally, the evaluation team relied heavily on technical reports that summarized the completed IAP-awarded projects.(1,14–18)

The literature was primarily used to assess the diffusion of PCP technology and to gain an understanding of the FHWA materials used by stakeholders. Where possible, anecdotal information regarding the benefits and costs of PCP was extracted to inform and supplement the findings of the evaluation.

3.2 Conference and Presentations

As noted in the introduction to chapter 3, the evaluation team attended several conferences with the intent of determining both the level of interest in PCP technology from the transportation industry and the benefits and costs associated with PCP compared to other available alternatives. All conferences included broad presentations and discussions covering the technology itself, such as the various design and installation methods, as well as specific project demonstrations or implementations. These conferences indicated that transportation stakeholders were still learning about PCP and considering whether or not they had a desire to implement the technology. This aspect of the presentations provided information regarding the technological diffusion of PCP.

Project-specific presentations, including a dedicated workshop at the 11th ICCP, included technical details of project implementations as well as the resulting outcomes and impacts, which the evaluation team extrapolated into benefits and costs.[19,20,21]

3.3 Formal Interviews

For this evaluation, the team conducted interviews in two phases. The team identified prospective agencies to interview through their routine use of PCP or chose them due to their receiving a SHRP2 Project R05 IAP award. With the exception of ConnDOT, which completed its interview via email at the interviewee's request, the team conducted interviews by phone; participants included evaluation team members and a representative from FHWA. Interviewees were provided with a list of questions in advance. Table 4 shows the list of agencies interviewed during each phase.

Table 4. Interviewees.

Interviewee	Evaluation Phase	Role
ALDOT	Phases 1 and 2	SHRP2 Round 6 IAP Lead Adopter awardee.
Caltrans	Phase 1	Routine user of PCP technology.
ConnDOT	Phase 2	SHRP2 Round 6 IAP User Incentive awardee.
DDOT	Phase 2	SHRP2 Round 6 IAP User Incentive awardee.
INDOT	Phase 2	SHRP2 Round 6 IAP User Incentive awardee.
KDOT	Phase 1	SHRP2 Round 3 IAP Lead Adopter awardee.
LaDOTD	Phases 1 and 2	SHRP2 Round 6 IAP Lead Adopter and User Incentive awardee.
NJDOT	Phase 1	Routine user of PCP technology.
NYSDOT	Phase 1	Routine user of PCP technology.
PennDOT	Phases 1 and 2	SHRP2 Round 6 IAP Lead Adopter and User Incentive awardee.
TxDOT	Phase 1	SHRP2 Round 3 IAP Lead Adopter awardee.
UDOT	Phase 1	Routine user of PCP technology.
VDOT	Phase 2	SHRP2 Round 6 IAP User Incentive awardee.

Phase 1 interviews were wide ranging in that they covered all relevant hypotheses and included several types of interviewees. Interviewees included routine users of PCP and Round 3 IAP awardees and a select number of IAP Round 6 awardees. The team asked interviewees to describe the assistance FHWA provided, including what was most and least helpful. The interviewees also described specific projects and implementations of PCP and the outcomes and impacts of those projects from a benefit–cost perspective. For the IAP awardees, this discussion focused on the IAP Lead Adopter–awarded projects, rather than the User Incentive–awarded projects, in cases when States received both awards.

For phase 2, followup interviews were held with ALDOT, LaDOTD, and PennDOT regarding the status of their Lead Adopter projects, and additional interviews were held with the remaining Round 6 IAP awardees regarding their User Incentive awards. Interviews provided insight into the activities undertaken and activities the State transportation departments plan to undertake using the User Incentive award. Interviewees described how their States first became aware of SHRP2 funding. For State transportation departments with completed (or nearly completed) projects, the team asked interviewees to discuss potential updates to the contractor-selection process or specifications.

The following are lists of sample questions asked of interviewees for each evaluation phase.

The following list includes a sample of questions for phase 1:

- When did your agency start using PCP?
- For projects where PCP was selected, what alternative construction methods were considered?
- Did you (or your agency) work with FHWA and/or access FHWA documents about PCP prior to implementation?
- For each PCP project, what was the cost per square yard? What was the total project cost?
- For each PCP project, how long did it take to install the PCP panels and how long was the detour set up for?

The following list includes a sample of questions for phase 2:

- How did you first become aware of SHRP2 funding for PCP?
- What activities have you undertaken regarding PCP as part of the User Incentive award?
- Which FHWA resources, if any, were used in the completion [or planning] of this/these project(s)/activities?
- Based on your experience and future plans, do you expect to make any systemic changes in how PCP projects are implemented?
- Have you made any updates to contractor selection or specifications? [Will you make any updates to contractor selection or specifications?]

4. Evaluation Findings

This chapter is divided into the three evaluation areas examined by the evaluation team. Each section contains an overview, which assesses the evaluation area at a high level. Within each section, there is also an indepth discussion of findings. These specific findings address the evaluation team's key hypotheses. Findings are supported by evidence collected through the evaluation methods described in chapter 3.

4.1 Technology Diffusion and Research

As described in section 2.2, several hypotheses related to the research, development, and usage of PCP technology were explored. These hypotheses consisted of evaluating the impact of FHWA and SHRP2 activities on the implementation of PCP and the development of PCP technology. Based on this analysis, and as described in this chapter, the evaluation team found that FHWA and SHRP2 publications, funding, and programming contributed to the development and use of PCP technology in an array of settings.

Hypothesis: PCP technology is being used for a broad range of applications in a variety of settings.

A review of current PCP deployments showed that 27 States have completed projects and several other States are planning to install PCP or exploring the use of the technology. (See references 1, 10, 14–18, and 22–36.) Table 5 lists each State by PCP activity level.

Table 5. State PCP activities.

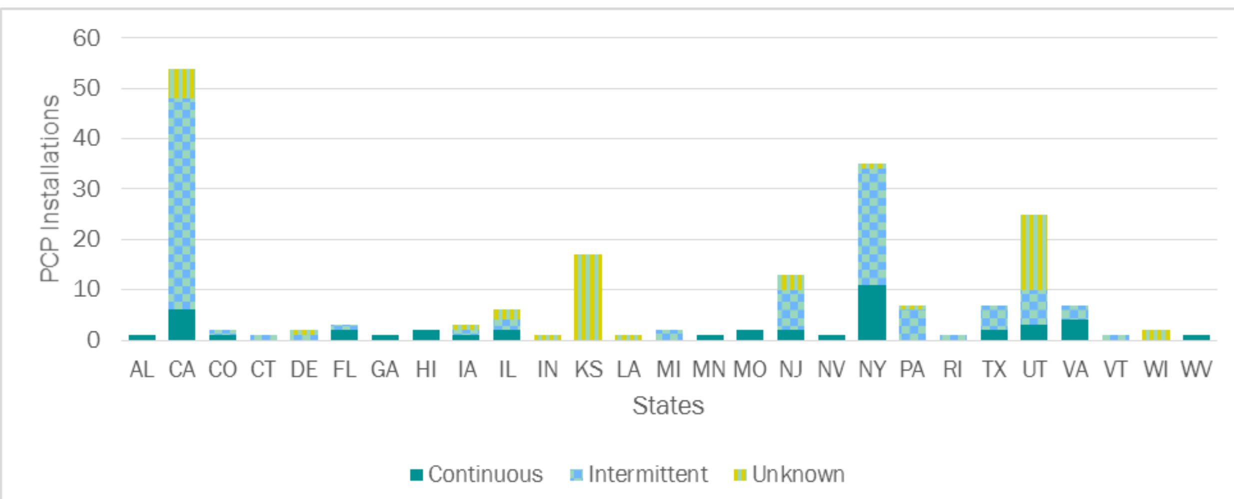
Previous Demonstrations	Agencies Using PCP	New Agencies Implementing PCP	New Agencies Planning PCP Use	Evaluating PCP Use
Missouri	California	Alabama	New Mexico	Arkansas
Virginia	Colorado	Connecticut	West Virginia	District of Columbia
	Delaware	Florida		South Carolina
	Georgia	Hawaii		
	Illinois	Indiana		
	Iowa	Kansas		
	Michigan	Louisiana		
	Minnesota	Wisconsin		
	Nevada			
	New Jersey			
	New York			
	Pennsylvania			
	Rhode Island			
	Texas			
	Utah			
	Vermont			
	West Virginia			

Of the completed projects and demonstrations, intermittent repairs or replacements of continuous sections of highways and other high-traffic roadways were most common. Repairs of busy intersections without accessible alternative traffic routes were also common. At least 10 projects involved installation along a bridge approach. Innovative uses of PCP included a bus pad at a busy transit terminal and a trial project replacing sections of airport runway.(19)

During interviews, States mentioned novel uses for precast-concrete panels. For example, ALDOT noted its use of single panels for emergency repairs in high-use areas. Similarly, INDOT expressed interest in using PCP panels for repairs. INDOT noted that, while it has contractors who can pave with traditional methods at the same speed they can pave PCP, these contractors cannot do the same for intermittent patching. Thus, INDOT indicated a desire to devise two systems that its maintenance team can use: one for intermittent patching and one for long patching. Additionally, PennDOT noted the possibility of using panels with an overlay of asphalt for consistency with Philadelphia's municipal pavement standards. Because the technology is expensive, PennDOT representatives are not sure that applying an overlay (in this case, asphalt) makes sense, but they indicated interest in exploring the technique.

The sizes of PCP projects varied greatly. Some small repair and experimental projects used only a few panels, while projects along longer sections of highway required hundreds of panels. The mean installation size among projects with accurate data was 23,660 square feet. Panel dimensions varied by project and State, though panel depth of 8 to 8¾ inches was most common.

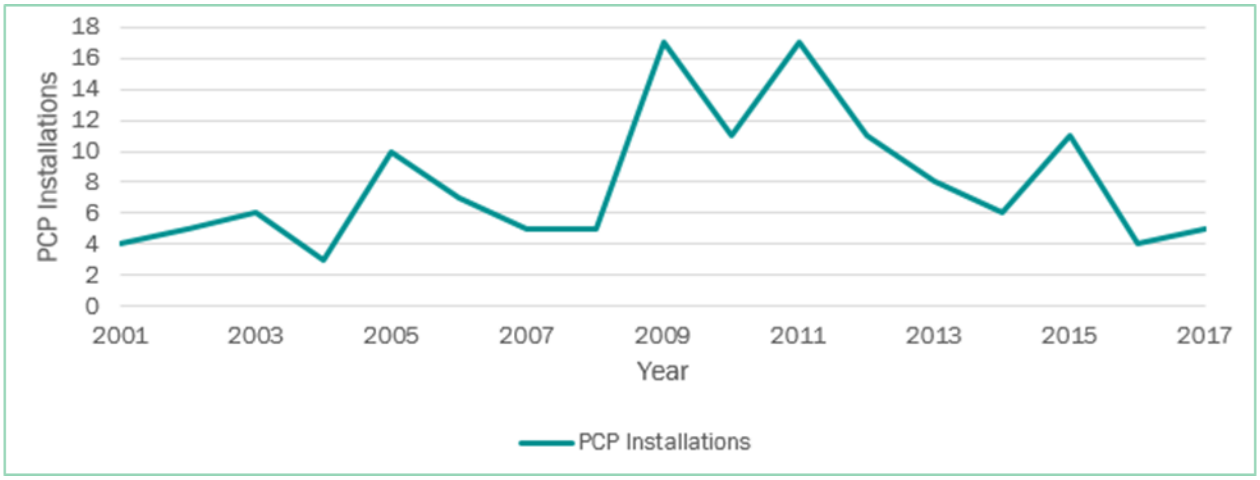
State-level use varied significantly, with slightly more than half of all State transportation departments reporting completed installations of PCP, as can be seen in figure 3. Routine-user States (California, New Jersey, New York, and Utah) made up a large portion of total PCP installations nationally. However, several State transportation departments provided reports and feedback to FHWA regarding their trial projects and may not have identified PCP as the technology used in subsequent projects, which may have led to underreporting PCP implementation in this evaluation report.



Source: FHWA.

Figure 3. Bar chart. PCP-installation type by State.

As shown in figure 4, an initial high point in PCP installations corresponded with FHWA's Highways for LIFE and AASHTO's TIG efforts to promote its use in the mid-2000s. PCP usage then peaked overall in the late 2000s and early 2010s, corresponding with SHRP2 Project R05 activity. Since the peak in the early 2010s, PCP installations have declined somewhat. This decline could be the result of a decreased emphasis on PCP usage in State transportation department and FHWA publications or of States using PCP but reporting and promoting successful projects less. In particular, single-panel emergency repairs that were not part of a larger project are unlikely to be captured by this evaluation report.



Source: FHWA.

Figure 4. Line graph. PCP installations by year.[1]

Finding: PCP technology is in broad use for continuous and intermittent repairs in a variety of settings.

Boosted by FHWA, AASHTO, and SHRP2, PCP installations have been used for a wide variety of installation types (urban and rural, highways, arterials, intersections, and bridge approaches) in a variety of project sizes that include both intermittent and continuous repairs.

Hypothesis: FHWA activities (research, demonstrations, workshops, outreach, etc.) contributed to PCP-technology development and usage.

FHWA has been involved in the promotion and development of PCP applications for nearly 2 decades. Prior to SHRP2, FHWA primarily worked with State transportation departments to fully or partially fund demonstration projects. Starting with a project produced with the University of Texas and TxDOT in 2000, FHWA began funding and monitoring a series of demonstration projects with a variety of partners, recording best practices and performance. More recently, FHWA efforts have focused on the SHRP2 Project R05 implementation plan, discussed in chapter 2. Based on the

[1]Of the 184 total PCP installations determined from publicly available sources and interviews, 28.8 percent (or 53) had unclear dates with no year recorded and were, therefore, excluded from this graph.

implementation plan, FHWA has produced reports on PCP technology and has provided individual technical assistance to interested States looking to implement PCP. FHWA has also conducted workshops and four ETG meetings, bringing together representatives from State transportation departments, industry, and academia with knowledge and interest in PCP technology. A by-product of FHWA's outreach efforts is the fact that the 2017 ETG meeting had a record attendance of 68 participants—a 209-percent increase over the 2016 meeting (22 participants)—including a large number of first-time attendees.[9,10] These attendance numbers suggest that FHWA's marketing efforts and overall outreach strategy have been successful. Under the logic that someone at the agency is interested and could serve as a PCP champion in his or her State, FHWA has also marketed to agencies that have applied for PCP funding but not received an award.

Precast concrete is not a new technology. The innovations required for PCP include techniques for installation and application, and the use of PCP involves a steep learning curve for interested States and municipalities. By publishing reports that detail the techniques used in and performance of demonstration projects in various applications and settings, FHWA provided interested States with some guidance on how to move forward with the technology.

During phase 1 and 2 interviews, State transportation departments frequently identified FHWA involvement as beneficial to the design, specification, and construction phases of projects. States often mentioned FHWA's contractor as being a valuable resource for developing and modifying specifications as well as providing more general one-on-one support for State transportation department representatives as the project progressed through the construction phase.

Of States interviewed, only one reported not making use of FHWA materials in its first installation of PCP. NYSDOT worked solely with private precast companies in developing and applying the early installations that occurred in 2000, either prior or concurrent to early FHWA publications. Every other routine user reported reviewing FHWA publications and participating in FHWA programming.

UDOT coordinated with FHWA on a scanning tour of installations elsewhere in the country and participated in a Highways for LIFE demonstration project. In interviews, a representative from UDOT specifically noted the usefulness of the initial FHWA and AASHTO TIG reports in preparing early PCP projects. UDOT has continued involvement through participation in the SHRP2 Project R05 ETG.

Caltrans reported using FHWA assistance in the form of publications and websites as well as personal email communication and contacts at technical events prior to its first installation in 2004. Since then, Caltrans has participated in workshops, technical groups, and other programs for PCP users. Representatives from Caltrans specifically noted the SHRP2 Project R05 ETG as a helpful resource to discuss PCP issues and find solutions to implementation problems.

Similarly, NJDOT started using PCP technology following research produced by FHWA. NJDOT has participated in FHWA workshops, webinars, and briefings to help inform its staff and others about the uses and effectiveness of PCP. NJDOT specifically noted that FHWA has "powered things forward" for PCP.[2]

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[2]NJDOT Engineer, phone interview conducted by Greg Bucci (evaluation team), Joe Condon (evaluation team), and Sam Tyson (FHWA), June 2016.

ALDOT specifically mentioned this one-on-one FHWA support as an important component of project success. While ALDOT mentioned using a variety of FHWA resources, it indicated that the one-on-one support provided by FHWA staff and contractors was the most helpful in decreasing the severity of the PCP-installation learning curve for ALDOT. Participants reported that site visits and the personal attention of FHWA's contractor gave those working on the project confidence that the project was progressing as it should. Specifically, when difficulties arose, the people working on the project had an experienced resource to help mitigate those challenges.

Funding from FHWA for demonstration projects directly affected the number of installations nationwide, and programming has helped States learn about and develop skills for the implementation of PCP technology.

Finding: FHWA activities provided guidance to States interested in deploying PCP and furthered the development and number of PCP installations.

The initial hypothesis, in this instance, was found to be largely correct. FHWA activities and resources have proven useful to States in promoting usage of PCP and, in turn, have furthered the technological development of PCP implementations.

Hypothesis: States are aware of and use SHRP2 PCP guidelines and technical standards.

SHRP2 produced the R05 final report entitled *Precast Concrete Pavement Technology*.[36] This evaluation investigated 16 installations in a variety of climates and locations to assess the range of applications (both intermittent and continuous). The report assessed the performance of these applications positively and provided guidelines and model specifications to help authorities select projects for PCP and to design and construct successful PCP installations.

As discussed earlier in this section, PCP is a new technology, with limited documentation of best practices. Additionally, a significant portion of the innovation in the PCP realm has been undertaken by private industry, where firms have begun to market proprietary systems to interested agencies and transportation departments. Proprietary systems can be difficult for States and contractors to learn and use; these challenges can slow adoption of otherwise useful or beneficial technologies like PCP. The publication of the R05 final report collected much of the publicly available knowledge on PCP design, fabrication, and installation in one accessible location, and the accompanying marketing and distribution of the report sought to address challenges to PCP adoption.

Every State interviewed reported utilizing the R05 final report extensively in developing and designing PCP installations. Of routine users and Round 3 IAP recipients, five of seven interviewees specifically cited the R05 final report as the most useful resource produced by FHWA thus far. While some noted that the information in R05 was becoming out of date at the time of the interview, it remained the best collection of information on PCP and had helped the development and spread of PCP.

Finding: States have made significant use of PCP SHRP2 materials and activities.

The initial hypothesis was correct in part. In interviews, State transportation departments expressed a strong awareness of SHRP2 materials and commented on their usefulness. While most interviews were conducted with SHRP2-grant recipients, multiple routine users (who began use of PCP before SHRP2) cited R05 as a significant resource for them and noted that SHRP2 implementation activities had furthered their thinking on the subject. For example, UDOT specifically noted its participation in the SHRP2 Project R05 ETG, which provided opportunities to learn from other practitioners and facilitated site visits to observe demonstrations. UDOT and a majority of early PCP users interviewed noted that the SHRP2 documentation was valuable, though UDOT employees noted the technology and knowledge base was continuing to grow, implying new resources were being used or needed. Caltrans noted that the demonstrations and workshops provided through SHRP2 boosted its knowledge base and helped PCP technology be implemented faster than it otherwise would have been.

Finding: States have not yet made significant use of SHRP2 technical specifications but have used FHWA and SHRP2 staff and resources in developing their own generic specifications.

While the SHRP2 Project R05 included a generic specification, few States reported using these specifications in developing standards and procedures of their own. One State noted that the specifications were the least helpful of the resources published and that it would rely on the R05 authors in development of its projects and specifications.

However, in interviews, multiple State transportation departments described developing or starting to develop a generic specification following the publication of the SHRP2 materials. Specifically, most States that received SHPR2 Round 6 IAP User Incentive funding are using that funding to develop their own installation specifications or to update and train staff on existing specifications. However, those States did not specifically mention the use of SHRP2 technical demonstrations as a resource. All interviewees mentioned consulting with FHWA's contractor and other FHWA and SHRP2 resources in their processes.

NJDOT, a routine user of proprietary PCP systems, expressed interest in developing a generic specification in the future. UDOT expressed an interest in improving and expanding its set of specifications following participation in SHRP2 implementation activities, such as the ETG. Currently, UDOT provides guidance and an 18-item checklist to contractors and installers.(11) The DDOT indicated it needed to develop its own specifications due to its use of unique pavement technology on roadways. INDOT indicated it was required to develop specifications stamped by an Indiana Professional Engineer. In addition, approximately half the interviewees indicated they used or had originally developed specifications related to a proprietary PCP system.

4.2 Costs of PCP

As described in section 2.2, several secondary-cost hypotheses were explored. These hypotheses consisted of determining whether the cost of PCP installation and the overall project cost were greater than or less than conventional ready-mixed concrete and other alternative methods of concrete paving. In doing so, the evaluation team also sought to highlight any additional costs that are unique to using PCP. Based on this analysis, and as described further in this section, the evaluation team found that, while less costly to install compared to PCP, the overall project costs for cast-in-place (CIP) concrete are outweighed by increased maintenance costs. Similarly, the durability of PCP makes it more cost effective compared to other rapid-repair alternatives such as high-early-strength concrete. However, additional upfront training costs exist as contractors and inspectors are still less aware of the specifics of designing and installing PCP panels than they are of the conventional alternatives.

Hypothesis: PCP procurement and construction costs are greater than those for conventional ready-mixed concrete projects (baseline).

Initial research suggested that constructing and installing PCP would be more expensive compared to conventional ready-mixed concrete projects. Based on this research and discussions with FHWA staff, it became clear that, as a new technology, using PCP required upfront costs relating to learning how to best use it. Additionally, costs for contractors to prefabricate the concrete slabs offsite and transport the slabs to the construction area were higher than costs would have been if traditional ready-mixed concrete had been used. However, interviewees did not universally confirm this thinking, and other concrete alternatives were described.

Caltrans compared PCP to high-early-strength concrete as those are the two options best suited for short working windows. While the initial cost of installation for high-early-strength concrete was estimated to be roughly half the cost of PCP several years ago, the industry is evolving. Generally, PCP is now viewed as roughly 20 percent more expensive than high-early-strength concrete. However, in Los Angeles specifically, Caltrans District 7 had $250 million worth of active PCP projects in 2016. Based on the increased use of PCP in recent years, the agency now generally views the cost of PCP as two-thirds the cost of high-early-strength concrete in that district. This difference leads to the broader point that specific costs vary based on location and project size. Similarly, Caltrans noted that costs of various PCP-system types vary. Precast, pretensioned concrete pavement is viewed as the most expensive, followed by precast, jointed concrete pavement, followed by individual precast-slab replacement. Depending on project size and the type of PCP used, the comparison to possible alternatives in terms of costs will fluctuate.

NJDOT reported average costs of approximately $525 per square yard for CIP-concrete installation, compared to $625 per square yard for PCP. However, as described in more detail in section 4.3, in New Jersey, the average expected performance of CIP concrete is 8 years, compared to 20 years for PCP. As a result, when including maintenance and repair costs, overall lifecycle costs for CIP concrete exceed PCP costs.

NYSDOT noted that high-early-strength concrete costs between $400 and $500 per cubic yard compared to approximately $2,000 for PCP.[3] While this difference clearly supports the hypothesis, the agency also noted high variability in costs, particularly in New York City, where transporting the slabs and labor costs can be particularly expensive.

UDOT noted that the average unit bid price over the past 5 years for CIP-concrete, intermittent-repair projects has been $119 per square yard and that smaller projects are typically more expensive. A representative sample of five intermittent-repair PCP projects led to an average estimated installation cost of approximately $317 per square yard. In both cases, maintenance costs are not expected for these repairs as the road would be reconstructed prior to additional maintenance.

Similar to Caltrans, UDOT noted variation based on project size (smaller projects tend to be more expensive per square yard as some fixed costs exist) and that rapid-setting concrete, such as high-early-strength concrete, was more expensive for small repairs compared to individual slab replacements. Similar to NJDOT, UDOT pointed out that, while roughly equivalent in cost, CIP concrete was viewed as less durable and reliable than PCP, which impacted decisionmaking.

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[3]NYSDOT reported PCP installations volumetrically (per cubic yard). Other State transportation departments generally reported PCP use and costs by area (per square yard).

KDOT experienced total costs of $6.8 million, with an estimated price per square yard of $355.87 for its SHRP2 Round 3 IAP project on US 73 North in Leavenworth. Given the location of the project, traditional CIP concrete was not feasible; high-early-strength concrete was the only readily available alternative. However, KDOT noted that the cost would have been $581.62 per square yard.

TxDOT experienced total costs of $1.55 million, with an estimated price per square yard of $425 (of which approximately $200 was for the panels themselves) for its SHRP2 Round 3 IAP project at the intersection of State Highway 97 and State Highway 72. Given the location of the project, traditional CIP concrete was not feasible, although that was the only readily available alternative. While the precise cost of asphalt pavement was not known, TxDOT estimated that asphalt would have been slightly less expensive and would have cost a few hundred dollars per square yard. However, given the location of the project, asphalt was not a feasible alternative.

Finding: CIP concrete is generally less expensive than PCP to install; however, installation for high-early-strength concrete is generally more expensive.

While the initial hypothesis was found to be correct, it became clear through research and interviews that traditional CIP concrete, which requires a certain length of time to cure, was not a feasible alternative and does not provide an accurate cost comparison baseline. Most agencies interviewed noted that high-early-strength concrete, which does allow for overnight closures, similar to PCP, is a more accurate comparison. In most cases, high-early-strength concrete was equal to or greater in cost for initial installation, compared to PCP.

Hypothesis: Overall PCP-project costs, including maintenance costs over time, are less than those for conventional ready-mixed concrete projects (baseline).

As described earlier in this section, less detail was provided by interviewees regarding conventional ready-mixed or CIP-concrete solutions. Instead, more information was provided regarding high-early-strength concrete as a viable alternative. Given the particular project types, using PCP led to lower project costs compared to high-early-strength concrete. This finding was particularly evident when considering expected service life and the need for additional maintenance or repairs over time. CIP-concrete repairs were viewed as having higher lifecycle costs compared to PCP in addition to leading to lengthy road closures that, in many cases, are not feasible given the configuration or the traffic volume of the site.

All agencies with which the evaluation team spoke noted that PCP has a longer expected service life than high-early-strength concrete and CIP concrete, leading to notably lower costs for future maintenance and repair. Considering performance and all relevant cost factors, NJDOT viewed PCP as two times more beneficial than CIP concrete. This view is largely based on the fact that the lifecycle costs for PCP are significantly lower compared to high-early-strength concrete and CIP concrete. NJDOT has found that PCP will last for 20 to 50 years compared to 1 to 15 years for CIP-concrete repairs. The agency also noted that PCP has failed in less than 1 percent of cases where it has been installed, leading to increased confidence in the repairs being performed.

UDOT echoed these sentiments, expecting PCP installations to last longer than 15 years and high-early-strength concrete repairs to last 5 to 7 years. It is clear that the reduced maintenance cost associated with PCP makes it cost beneficial from an installation and repair perspective.

Finding: Compared to PCP, initial installation cost savings from CIP concrete and time advantages from using high-early-strength concrete are outweighed by increased maintenance and repair costs.

Based on discussions with interviewees, it was clear that the increased durability and performance of PCP resulted in a reduction in maintenance and repair costs relative to alternatives. PCP alternatives, such as CIP and high-early-strength concrete, had comparable or slightly lower installation costs than PCP. However, the reduction in maintenance and repair costs outweighs the increase in installation costs for PCP relative to these alternatives.

Hypothesis: Use of PCP presents additional installation challenges compared to a conventional ready-mixed concrete project (baseline).

Given that PCP remains a relatively new technology in the United States, many of the implementations, in recent years, have been conducted by agencies using PCP for the first time. This was emphasized by the discussion at the PCP workshop at the 11th ICCP, where attendees primarily asked technical questions relating to specifications and methods. It was evident that the majority of the well-attended session was interested in learning more about undertaking and implementing PCP, rather than refining existing practices.

As a result, based on the limited knowledge of and experience working with PCP, a learning curve exists that can include unexpected costs, particularly on the part of contractors who do not have precasting expertise. This topic was discussed at the 2014 ETG meeting, where participants concluded that this learning curve led to higher risk and costs. As experience increases, it is expected that risk and cost will decrease.(12) Based on this assumption, all 4 of the SHRP2 Round 3 IAP awardees conducted trial installations with a small number of panels (ranging from 4 to 30) before beginning full construction. Additionally, all agencies, including the routine users interviewed, noted that resources were spent determining specifications and refining which methods of PCP to use.

Caltrans noted that PCP does result in higher initial construction costs based, in part, on a higher demand for training. In the agency's experience, most precast-concrete companies do not do pavement finishing that can withstand traffic. As a result, contractors need to invest in different machinery and employee training, which can lead to higher overall project costs.

UDOT noted similar costs associated with learning how to use PCP, stating that PCP requires a higher level of initial design and verification than standard concretes used for intermittent repairs. When designing PCP specifications for an implementation, participants at the 2014 ETG meeting noted a fear of lawsuits and violation of intellectual property as there are a number of proprietary systems already in place.(12) This concern could hinder implementation. Along these lines, when implemented, PCP requires more attention to inspection and workmanship, and a more conscientious and skilled (i.e., trained) workforce. This need was emphasized at the 2017 ETG meeting when participants discussed the fact that some contractors are not regularly inspected, which has led to mistakes and complications.(10)

During the Leavenworth, KS, implementation, panel fabrication began 96 days prior to construction, which lasted approximately 30 days. However, approximately 2 months after the majority of construction at the site was completed, several additional panels had to be fabricated and installed. While some lead time was built in for the panels to reach a certain level of strength prior to installation, experience could lead to a more condensed timeline and potential cost savings.

TxDOT noted that several panels were damaged during handling at the project site, resulting in corner spalls, and several panels were not aligned within the specified tolerances and needed to be redone. This was the result of a problem experienced with the grouting of the base, which was thicker than the workers initially realized. Finally, the placement of panels was made more difficult due to the overhead traffic signals and cables, which interfered with the cranes used to lift and place the panels. While not significant overall, in general, these problems could lead to an increased need for maintenance in the future. Such installation errors, including misplacement of panels, would lead to additional costs and displace some of the advantage of using PCP.

HDOT experienced a shortage of bedding grout as the gap between the panel bottom and base was wider than expected along two of the lanes of the highway installation. Additional grout needed to be shipped from California, which led to a significant delay. In this case, it is unclear how costly the delay was, but generally, delays caused by the learning curve of utilizing PCP can strain operations and be costly depending on resources and the nature of the contracts established by State transportation departments.

WisDOT noted that two inspectors are likely needed to ensure quality work, particularly to verify that grouting reaches minimum strength prior to reopening the roadway to traffic. While it is unclear if these additional inspectors would take the place of inspectors on traditional concrete projects, training inspectors on what to look for represents an additional cost of utilizing PCP.

VDOT noted there is uncertainty regarding the degree to which State transportation departments can minimize costs. It also noted the significant learning curve combined with high upfront costs are a barrier to PCP implementation. VDOT feels this barrier is present as not all transportation departments have the budget to support these costs. These costs are more justifiable when completing multiple projects in a short timeframe. However, VDOT had one installation in 2009, and any future projects would face a similar learning curve—as the interviewee noted, “One experience isn’t enough to create an expert.”[4]

Finding: A learning curve for PCP installation exists compared to CIP and traditional concrete-installation methods, potentially leading to increased costs.

The ETG stresses that every State should not have the same steep learning curve, as States should collaborate and learn from each other, as discussed at the 2015 meeting.(11) However, interviews and conference presentations suggest that a learning curve does exist when working with PCP. The majority of phase 2 interviewees indicated that, while they spoke with other States and attended ETGs, they still felt they experienced a learning curve. Routine users noted that, with experience, refinements were made and specifications were clarified for contractors. It appears that there is no substitute for the experience gained through routine PCP use. This initial learning curve can lead to additional costs from project delays or poorly installed panels that will require maintenance or repair sooner than originally planned.

4.3 Benefits of PCP

As described in section 2.2, several secondary-benefit hypotheses were explored. These hypotheses consisted of exploring the installation- and travel-time savings associated with using PCP as well as highlighting the durability and other unique benefits that PCP provides. Based on this analysis, and

[4] VDOT Engineer/Research Scientist, phone interview conducted by Greg Bucci (evaluation team), Kaitlin Coppinger (evaluation team), Matthew Keen (evaluation team), and Sam Tyson (FHWA), November 2017.

as described later in this section, the evaluation team found that both installation- and travel-time savings exist when using PCP instead of traditional CIP concrete and that PCP is comparable to other rapid-repair alternatives, such as high-early-strength concrete. However, PCP is comparable to CIP concrete in terms of longevity and performance and is far superior to high-early-strength concrete in this regard. Additionally, PCP provides options for innovative maintenance techniques, such as reusing and recycling pavement slabs.

Hypothesis: Use of PCP leads to installation-time savings (based on the ability to install in varying weather conditions or at night) compared to a conventional ready-mixed concrete project (baseline).

All agencies interviewed described the significant installation-time savings associated with using PCP. Caltrans views PCP as a primary option for repaving projects that require short working windows and fast construction. The agency feels PCP is equal to high-early-strength concrete in terms of installation times and allows for overnight closures only, opening the roadway to traffic during peak times. Conventional portland cement concrete, in contrast, requires a 10-day closure for curing. For California, it takes an 8-hour night closure to install 500 linear feet of PCP with a crew time requirement of 5 hours.

NJDOT installs an average of 8 to 15 slabs during a 6- to 8-hour work shift, which equates to approximately 200 to 250 linear feet per night, before opening to traffic immediately. Based on these average installation rates, NJDOT feels that CIP concrete takes approximately 50 percent longer than PCP, creating additional work shifts.

UDOT considers PCP installation to be considerably faster than rapid-setting or high-early-strength concrete. It typically uses PCP for 5- to 12-hour work windows during summertime construction. The agency feels PCP provides greater reliability and consistency under controlled conditions than high-early-strength concrete, particularly during time-sensitive nighttime work. This increased reliability and consistency is particularly true when adjacent to interstate traffic, indicating that PCP can reduce crew time in this precarious situation and consequently enhance safety for the crew as well. High-early-strength concrete would be expected to take 5 to 50 percent longer to install, and a traditional concrete repair would require roadway closures of 7 to 10 days.

In Caltrans's experience, weather has a minimal impact on PCP installation compared to conventional concrete placements, on which ambient temperatures and precipitation create limitations and restrictions on pouring concrete. However, NJDOT noted that weather is equally detrimental to PCP and CIP concrete. While weather is less of a concern for PCP, in New Jersey, contractors cannot close lanes and work when precipitation is imminent. For UDOT, weather is a factor for all projects. As a result, construction is limited to the summer season only.

KDOT noted that using PCP allows for rapid installation and provides significant flexibility. PCP allows the agency to work outside of the traditional summer construction season and, as a result, avoid heat warnings. This increases safety and productivity for the agency.

HDOT noted in its user survey that PCP reduces onsite construction time and allows for overnight installation, whereas traditional concrete road repairs require 7 days for the concrete to cure.

ALDOT emphasized not only installation-time savings, but also installation flexibility of PCP. During one PCP-project installation in Mobile, contractors installed six test panels prior to the area being hit by a hurricane. The hurricane temporarily shut the project down as resources were diverted to recovery efforts. However, evacuation traffic was able to be routed through the project intersection because the PCP panels were installed, unlike projects using other concrete options, which require road closures for the concrete to cure and dry. Due to the evacuation, the project area experienced an unexpected and significant increase in traffic volumes. Being that PCP panels were used rather than typical repair techniques, there were no construction-related materials blocking traffic, no new safety hazards were created by partially completed repair work, and both lanes were completely open. ALDOT was particularly impressed with the flexibility of the project installation; the project area could be reopened midrepair to accommodate hurricane traffic and remaining repairs could be completed at a later date after the recovery was underway.

Finding: PCP allows for overnight installation and is faster to install than traditional CIP concrete.

Agencies universally noted that PCP is faster to install than CIP concrete and is equally fast or faster to install than rapid-setting or high-early-strength concrete. However, these time savings were based largely on the ability to conduct overnight roadway closures. Weather or the ability to have an expanded construction season, while noted by some States, was not considered a driving factor in the installation-time savings that PCP provides.

Hypothesis: Use of PCP leads to overall travel-time savings (based on no field cure time) compared to conventional ready-mixed concrete projects (baseline).

Similar to the installation-time savings described previously in this section, PCP provides overall travel-time savings for drivers. This benefit was the primary reason interviewees chose to use PCP compared to CIP or conventional ready-mixed concrete.

NJDOT noted that a significant advantage of PCP is the quick return to traffic, opening the roadway in the morning and allowing for morning peak traffic to proceed uninterrupted without lane closures. Similarly, NYSDOT noted that its interest in PCP arose from a desire to decrease closure times and reduce the impact that construction had on travel times and congestion. Given these impacts, the agency noted that the decision to use PCP versus its alternatives is based on how long the agency can reasonably close the road without causing significant delays. There is not a specific traffic volume cutoff point, and the decision depends instead on the construction area itself. For example, PCP is used in cases where congestion will be significant and detours or other mitigations are not sufficient.

UDOT also noted the advantages of driver-time savings and having an emphasis on the maintenance of traffic when speaking more broadly about the benefits of PCP. The agency stated that, if a lane closure would have a significant impact on delays, then PCP is considered as it allows for shorter delays. If closing a lane will provide minimal or no delays, the agency prefers traditional methods, and this preference emphasizes the belief that PCP is useful for minimizing travel-time delays. Similar to NYSDOT, UDOT does not have a specific cutoff for traffic volumes that would lead them to use PCP. Instead, the agency looks at traffic windows on the given section of roadway to determine the effect delays would have on the system as a whole. This mindset emphasizes overall traffic flow and travel times for network users.

In some cases, the general commitment to maintain traffic flow, reduce travel-time delays, and reopen the roadway to traffic for the morning peak was written into the contracts by the State transportation departments. For KDOT, a $2,000 penalty was owed by the contractor for each day past 30 days of lane closures (on each of the three sections of the project). Additionally, a $2,000 penalty was owed for every 30 minutes that the lane was closed past 5 a.m.

WisDOT, likely as a result of greater congestion concerns, had a more aggressive penalty structure, as can be seen in table 6.

Table 6. WisDOT lane-closure penalties.

Time Over Schedule (min)	**Penalty** ($)	**Cumulative Penalty** ($)
1st 15	750	750
2d 15	1,500	2,250
3d 15	2,250	4,500
Every additional 15	3,000	7,500+

It is of note that some projects selected PCP not based on congestion, but because the location of the project would cause significant travel-time delays either from the required detour or because closing the roadway was otherwise unfeasible. In Kansas, a bridge-approach section would lead to a 20-mile detour if the bridge was closed completely. Additionally, another section of roadway in front of Fort Leavenworth was repaired. As access to the fort is critical, closing this section of roadway was not an option. Finally, TxDOT chose PCP for the intersection between State Highway 97 and State Highway 72, in part, because the detour in the rural area would be lengthy and lead to a significant travel-time increase for roadway users, many of which are commercial trucks. Based on these circumstances, potential negative economic impacts exist as well.

Finding: PCP generates travel-time savings by reducing road-closure times and avoiding significant detours in areas that are difficult to repair (bridge approaches, shoulders, and ramps).

Using PCP allows for overnight closures and construction that can be completed prior to the morning peak, reopening the roadway to traffic. This capability leads to a significant reduction in travel times compared to alternatives that would keep the roadway closed during peak periods. Reopening the roadway reduces congestion by allowing for additional volume. This benefit is significant in areas where volume and congestion are already high even without roadway closures. These travel-time savings are an integral part of using PCP, and as a result, State transportation departments often write penalties into their contracts if the contractor is delayed in reopening the roadway. Additionally, PCP reduces travel time by mitigating the need for significant detours. Closing certain intersections or bridge approaches, as avoided in Texas and Kansas, respectively, would require drivers to divert their routes significantly and increase travel times accordingly.

Hypothesis: Use of PCP leads to increased durability and longer service life compared to a conventional ready-mixed concrete project (baseline).

As described in section 4.2 regarding maintenance costs over time, PCP provides significantly longer service life compared to high-early-strength concrete and is similar to traditional CIP concrete in durability.

Caltrans noted that PCP provides superior performance and significantly longer service life compared to high-early-strength concrete. This experience is rooted by the fact that the agency uses lifecycle cost analysis to compare alternative project costs with respect to performance. With an expected service life of over 40 years for PCP, the technology performs well under this analysis in terms of repairs. This service life is in line with conventional portland cement concrete and conventional concrete, which is estimated to last 40 years, and in stark contrast to the fact that, in Caltrans's experience, high-early-strength concrete has a service life as low as 6 months.

NJDOT also noted that it chooses PCP over alternative materials, in part, because of its performance and, in part, because, in NJDOT's experience, CIP concrete is expected to last 8 years and PCP is expected to last 20 to 50 years. In other words, NJDOT views the service life of conventional concrete to be less than half that of PCP.

UDOT noted that PCP is more consistent than high-early-strength concrete. The agency primarily uses high-early-strength concrete for 5- to 7-year repairs, which are generally viewed as smaller repairs. The agency expects PCP repairs to last at least 10 to 15 years and, in some cases, up to 40 years, comparable to the industry standard for conventional concrete.

Finding: PCP is more durable and requires less maintenance and fewer repairs compared to CIP and high-early-strength concrete.

Based on research and interviews conducted, the durability of PCP is comparable to conventional concrete and significantly better than high-early-strength concrete. This durability is largely due to the fact that the panels are fabricated in a controlled environment and are given time to reach sufficient strength.

Hypothesis: Use of PCP leads to other advantages, including innovative approaches, compared to a conventional ready-mixed-concrete project (baseline).

The evaluation team identified several benefits related to PCP that were not originally described in the evaluation plan. Most notably, these benefits include the ability to reuse panels for repair purposes. Caltrans installs panels for short-term repairs prior to full-depth rehabilitations of roadways. The agency then salvages, stores, and reinstalls those panels. This provides additional maintenance savings based on the fact that PCP is more durable than its alternatives.

ALDOT has begun developing the use of prefabricated PCP panels for maintenance repairs in high-traffic areas of Birmingham. Additionally, PCP provides opportunities for other unique innovations with potential benefits. Specifically, during an interview, Caltrans reported that it is working on a project that would embed solar panels within PCP panels. The panels would be installed at a rest stop, and the solar energy captured would be used to power the rest area. While the applications of this technology may be limited, PCP provides the flexibility to explore and further develop it.

Finding: PCP provides additional benefits such as innovative maintenance techniques and applications.

Three interviewees indicated that their agencies were using or planned to use single panels for roadway repairs. Per INDOT, at least two other States (not interviewed) had systems in place for rapid, intermittent patching using panels. This innovation allows State transportation departments to make rapid repairs using preexisting panels. Additionally, some interest in reusing panels was mentioned, though this has not been explored sufficiently to assess feasibility.

In addition to rapid repairs and improved durability, PCP provides numerous other benefits. These include innovative maintenance techniques and potential for unique applications, such as pavement panels with embedded solar panels.

5. Recommendations

The findings discussed in this report highlight the benefits and costs of PCP implementation and the role FHWA has played in furthering the technology's adoption. While adoption of PCP is continuing to occur, there are several actions that FHWA and other stakeholders can take to continue promoting PCP and make best use of the technology.

Based on these findings as well as input from interviewees and other research conducted, the evaluation team developed a set of specific recommendations. The purpose of the recommendations is to highlight and emphasize best practices that can be enacted to facilitate adoption, usage, and development of PCP. In many ways, FHWA and other stakeholders are already enacting these recommendations. However, the evaluation team feels highlighting these actions will lead to the greatest impact. The recommendations are intended for two groups: the FHWA Resource Center and potential adopters of PCP. The recommendations are detailed in this chapter.

5.1 FHWA Resource Center Recommendations

Recommendation: Establish and maintain a strong FHWA Resource Center advocate.

Beginning in the mid-1990s, FHWA has conducted research relating to PCP. This research has evolved over time to current SHRP2 efforts relating to promoting and facilitating the adoption and implementation of PCP across the country. These efforts have included hosting or cohosting numerous workshops, webinars, briefings, field demonstrations, and peer exchanges with over 400 total participants learning and teaching the principles of PCP.

Based on these activities, it is clear that FHWA staff and contractors are viewed as subject-matter experts within the concrete and precast concrete fields. Additionally, FHWA has built and fostered relationships with State transportation departments, contractors, and private and public entities within the industry. As noted in chapter 4, FHWA activities and resources were found to promote usage of PCP, and funding for FHWA demonstration projects directly contributed to an increase in the number of PCP installations nationwide.

The importance of FHWA support in the adoption phase of the technology and as a source of institutional knowledge during the design and construction phases was frequently mentioned in State transportation department interviews. As the program transfers from FHWA headquarters to the Resource Center, it will be important to establish and maintain a Resource Center advocate who will continue to champion PCP. The role of the advocate would be twofold: acting as a resource and support for States undertaking PCP projects and continuing outreach and education to States considering undertaking a project or demonstration.

Recommendation: Formalize PCP outreach materials and presentations and expand efforts to document institutional knowledge.

In addition to establishing and maintaining a strong Resource Center advocate, the formalization of PCP outreach materials and presentations will help facilitate the transfer of PCP technology management to the Resource Center. This formalization can be done primarily though the expansion of efforts to document institutional knowledge of industry experts. State transportation departments consistently mentioned the same FHWA personnel and the same FHWA contractor as providing outreach, support, and problem mitigation. As these individuals transition out of championing PCP on FHWA's behalf and PCP promotion transfers to the Resource Center, the evaluation team believes the loss of institutional knowledge could act as a detriment to PCP adoption and implementation.

Formalization of outreach materials and documentation of institutional knowledge may help mitigate some of these challenges by providing Resource Center personnel with access to outreach materials and information guides developed by industry experts. These materials can be made directly available to potential State adopters, ensuring they continue to receive the necessary support for PCP adoption and use.

Recommendation: Continue to support the adoption of PCP technology without endorsing specific systems.

For a number of years, FHWA has actively supported the development and advancement of PCP technology, including the numerous methods used to design and install the panels. These methods include nominally reinforced panels and prestressed panels for intermittent repairs and jointed, posttensioned, or incrementally connected panels for continuous applications. In addition, there are several ways to place or insert the dowels, joints, or tensioning systems. Some systems have been developed by private entities and are proprietary; others have been designed specifically by State transportation departments for use in their States. Generally, each PCP system has its own advantages and disadvantages. Depending on the type of repair required, the preferences and specifications of the State transportation department, and the expertise and experience of the contractors bidding for the project, certain systems are more advantageous than others.

The evaluation team recommends that the Resource Center continue to promote PCP without endorsing any particular installation method or procedure. Promoting a specific system or set of systems would likely limit the options for State transportation departments as contractors would begin to focus on the FHWA-endorsed systems. Additionally, while PCP technology is mature in terms of applications and system options, the technology is likely to continue to evolve as adoption of PCP continues. New systems and applications will be developed, and this innovation should be encouraged rather than discouraged. Finally, whether the system or set of systems are proprietary or not, choosing to endorse a PCP system would likely have an impact on the existing precast-concrete market as it relates to pavement. This impact could be disruptive and should be avoided.

FHWA has avoided endorsing a particular system and has, instead, encouraged the development of specifications and the adoption of systems per the preferences of State transportation departments. The evaluation team recommends that FHWA and the Resource Center continue this course of action even as potential systems and options continue to grow.

Recommendation: Continue an active role within industry, spurring collaborative research.

Based on the progress made to this point and the likelihood that PCP will continue to be adopted and utilized, the evaluation team recommends that FHWA and, specifically, the Resource Center continue to foster collaborative research and remain active within the industry, connecting and facilitating relationships between relevant stakeholders. This collaboration and these relationships will lead to better project outcomes and greater efficiency as the adoption and use of PCP grows. As pointed out by Ted Neff of the Post-Tensioning Institute at the 2015 ETG meeting, "each State should not have to relearn what has already been known in other States."(11) The evaluation team recommends that FHWA researchers continue to facilitate the transfer of knowledge between State adopters and other PCP users either formally or informally.

5.2 Potential Adopter Recommendations

Recommendation: Develop and maintain institutional knowledge.

The value of maintaining a PCP knowledge base for contractors and State transportation department staff was identified in ETG meetings and during interviews with State transportation departments. During the 2015 ETG meeting, it was noted that there is a correlation between increased industry knowledge and reduced risk, which in turn, leads to reduced costs.(11) A 2014 ETG noted that, in addition to the contractor knowledge base reducing costs, developing clear specifications also reduces contractor uncertainty.(12) Despite the value of maintaining a contractor knowledge base, given the infrequency of PCP installation in some small or rural States, there may be extended periods in which the technology is not used.

In interviews, State transportation departments suggested several means of maintaining their PCP knowledge bases. These suggestions included relying on FHWA's contractor for new PCP knowledge. As noted by ALDOT, support by the contractor "gave our people in Mobile a lot of confidence. It gave them someone they thought was on their side and made sure things were going the way they should."[1] However, as FHWA's role regarding PCP technology changes, States will require tools to maintain their institutional knowledge.

Interviewees from VDOT indicated that they are developing or planning to develop workshops to refresh staff and train newer staff on PCP uses. As part of the motivation for these training workshops, VDOT personnel noted that detailed knowledge is needed for PCP installation and that it cannot expect people to install PCP correctly the first time. VDOT and other interviewees noted the need for both experienced contractors and transportation department personnel to be knowledgeable of PCP.

The evaluation team recommends that States develop and maintain workshops or training programs to refresh staff on PCP use to reduce knowledge decay. In support of this, States should maintain contact with FHWA staff responsible for maintaining institutional knowledge of PCP technology.

Recommendation: Collaborate with other States and stakeholders to reduce the learning curve.

The value of observing and discussing PCP installations with other States has been a consistent theme in discussions at ETG meetings (2014, 2015, and 2017) and in stakeholder interviews.(12,11,10) State transportation departments have noted the value of both training and technology transfer. For example, PennDOT employees attended the 2017 ETG in California and noted it was "very beneficial."[2] PennDOT and several other State transportation department interviewees noted the value of having seen other systems and designs when developing their own specifications. Viewing other States' efforts also allowed for the comparison of proprietary and other PCP systems without requiring them to develop and install several systems in their own States.

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[1]ALDOT Engineer, phone interview conducted by Greg Bucci (evaluation team), Kaitlin Coppinger (evaluation team), Matthew Keen (evaluation team), and Sam Tyson (FHWA), November 2017.

[2]PennDOT Engineer, phone interview conducted by Greg Bucci (evaluation team), Kaitlin Coppinger (evaluation team), Matthew Keen (evaluation team), and Sam Tyson (FHWA), November 2017.

The evaluation team recommends States consult with PCP practitioners in other States or regions, particularly when initially considering using PCP.

Recommendation: Emphasize test trials to reduce the learning curve.

All four of the SHRP2 Round 3 IAP awardees conducted trial installations prior to beginning construction. HDOT installed three panels as a test in the outside lanes (lanes five and six) of Hawaii Interstate H1. KDOT oversaw a test section of five panels, which occurred roughly 3 months prior to the full installation. TxDOT conducted a trial installation of four panels at the precast plant yard approximately 6 months prior to the full installation. The trial included testing procedures for dowel-bar grout installation and panel undersealing. WisDOT oversaw a test-section installation of 30 panels at the project site. During the test, the agency learned that saw cuts in some areas were not straight or square due to inadequate marking and poor lighting. Consequently, the test installation was useful in preventing this error from occurring during the full installation, leading to more efficient panel placement and, ultimately, a more efficient nighttime installation.

In its initial work on PCP, AASHTO developed a specification that included a process for trial sections. Additionally, discussion among users at the 11th ICCP focused on the need for trial installations, particularly to verify and demonstrate the effectiveness of new types of PCP or methods for its installation, such as new ways to insert dowels or create tension.

Based on the beneficial experiences of first-time PCP users conducting trials, feedback from routine users who described a learning curve when utilizing the technology, and the need for routine users to verify new ways of using PCP, the evaluation team recommends that potential State adopters conduct trial installations before using PCP for the first time or in a new way. Conducting trial installations, in these instances, will reduce the potential learning curve and will ultimately lower costs from unforeseen complications that could occur during the full installation and increase benefits through added efficiency.

Recommendation: Consider how applicable the technology is in each State.

While interviewee responses to PCP technology were positive overall, the evaluation team noted that PCP may not be applicable in some States. For example, VDOT found few opportunities to use PCP as it generally does not use concrete pavement. The State completed one installation in the early 2000s and has not completed any other projects using PCP. VDOT is currently using its SHRP2 Round 6 IAP User Incentive award to further explore use of the technology.

During the interviews with transportation departments of several largely rural States, the applicability of the technology outside urban areas was noted and questioned. For example, an ALDOT employee noted limited use outside the Birmingham area and along major highways.

The evaluation team recommends each State consider the development and knowledge-retention costs relative to the applicability of PCP on its roadways when determining whether to pursue the use of PCP.

6. Conclusions

As the use and adoption of PCP technology continues to grow, the role FHWA has played in the technology's development and the benefits and costs of PCP installations have become clear.

In terms of the diffusion of R&T, the evaluation team found that FHWA and SHRP2 publications, funding, and programming contributed to the development and use of PCP in an array of settings. FHWA activities have provided guidance to numerous States that have made significant use of the agency's materials.

Similar to other concrete methods, PCP costs vary based on a number of factors, including project size and geographic location. Costs for PCP or CIP concrete can vary significantly within each State, let alone around the country. Based on this cost variation, the numerous application types and PCP systems in use, and the existence of alternatives such as high-early-strength concrete, it is difficult to precisely extrapolate the costliness of PCP compared to conventional ready-mixed concrete. To do so, the evaluation team spoke with routine users of the technology and evaluated several specific projects. In general, societal costs for PCP are less than costs for CIP and traditional concrete solutions. This cost difference is particularly true when comparing PCP to high-early-strength concrete, which is similar in terms of installation times and costs; however, PCP performs better and is more durable over time.

Despite being cost beneficial from a societal perspective, PCP does lead to various unique costs that are not engendered by traditional methods. New users, in particular, experience a learning curve that can lead to increased costs when attempting to adopt and implement PCP for the first time. These costs deter adoption; however, as agencies become more familiar and experienced with PCP, these costs will decline, and the benefits will be fully realized.

Along with increased performance and durability, the key benefit of using PCP technology is its installation flexibility. By allowing overnight closures and opening the roadway for the morning peak, PCP limits network impacts and congestion and facilitates efficient repairs or construction in sensitive areas, such as bridge approaches or areas where access cannot be limited. Additionally, using PCP can lead to innovative or unique practices on a system level, such as adaptive maintenance in which precast slabs are recycled and reused based on future construction plans.

As a result of these findings, the evaluation team recommends that FHWA continue to champion PCP technology and document institutional knowledge without endorsing particular systems even as it transitions the responsibility of PCP promotion to the Resource Center. Additionally, the evaluation team recommends that potential adopters and users of PCP develop and maintain their own institutional knowledge. When attempting innovative techniques, potential adopters should consider the applicability of PCP and conduct test trials.

These actions will make installations more efficient and increase quality, providing better project outcomes. As the learning curve diminishes and project outcomes improve, PCP will continue to gain attention, and usage and adoption will increase.

Overall, the evaluation team found FHWA's efforts to be largely successful and contributory to the development and adoption of PCP technology. FHWA has overseen initial research and prototypes and has helped the use of the technology to become routine in some States. In its continued efforts, FHWA has facilitated and adopted initial use in several States. PCP is an effective and efficient way to conduct roadway maintenance, repairs, and reconstruction. Benefits most exceed costs in high-volume areas or unique roadway sections that would lead to significant detours if closed for long periods of time.

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