REPORT S2-R05-RR-1

Precast Concrete Pavement Technology

SHRP2 RENEWAL RESEARCH

SHRP 2
STRATEGIC HIGHWAY RESEARCH PROGRAM
Accelerating solutions for highway safety, renewal, reliability, and capacity

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

The Second
STRATEGIC HIGHWAY RESEARCH PROGRAM

SHRP 2 REPORT S2-R05-RR-1

Precast Concrete Pavement Technology

Shiraz Tayabji and Dan Ye
Fugro Consultants, Inc.
Columbia, Maryland

Neeraj Buch
Michigan State University
East Lansing, Michigan

TRANSPORTATION RESEARCH BOARD
WASHINGTON, D.C.
2013
www.TRB.org

Subscriber Categories

Construction
Highways
Pavements

The Second Strategic Highway Research Program

America's highway system is critical to meeting the mobility and economic needs of local communities, regions, and the nation. Developments in research and technology—such as advanced materials, communications technology, new data collection technologies, and human factors science—offer a new opportunity to improve the safety and reliability of this important national resource. Breakthrough resolution of significant transportation problems, however, requires concentrated resources over a short time frame. Reflecting this need, the second Strategic Highway Research Program (SHRP 2) has an intense, large-scale focus, integrates multiple fields of research and technology, and is fundamentally different from the broad, mission-oriented, discipline-based research programs that have been the mainstay of the highway research industry for half a century.

The need for SHRP 2 was identified in *TRB Special Report 260: Strategic Highway Research: Saving Lives, Reducing Congestion, Improving Quality of Life,* published in 2001 and based on a study sponsored by Congress through the Transportation Equity Act for the 21st Century (TEA-21). SHRP 2, modeled after the first Strategic Highway Research Program, is a focused, time-constrained, management-driven program designed to complement existing highway research programs. SHRP 2 focuses on applied research in four areas: Safety, to prevent or reduce the severity of highway crashes by understanding driver behavior; Renewal, to address the aging infrastructure through rapid design and construction methods that cause minimal disruptions and produce lasting facilities; Reliability, to reduce congestion through incident reduction, management, response, and mitigation; and Capacity, to integrate mobility, economic, environmental, and community needs in the planning and designing of new transportation capacity.

SHRP 2 was authorized in August 2005 as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). The program is managed by the Transportation Research Board (TRB) on behalf of the National Research Council (NRC). SHRP 2 is conducted under a memorandum of understanding among the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), and the National Academy of Sciences, parent organization of TRB and NRC. The program provides for competitive, merit-based selection of research contractors; independent research project oversight; and dissemination of research results.

SHRP 2 Report S2-R05-RR-1

ISBN: 978-0-309-12944-2

Library of Congress Control Number: 2013935791

Copyright Information

Note: SHRP 2 report numbers convey the program, focus area, project number, and publication format. Report numbers ending in "w" are published as web documents only.

Notice

SHRP 2 Reports

Available by subscription and through the TRB online bookstore:

www.TRB.org/bookstore

Contact the TRB Business Office:

202-334-3213

More information about SHRP 2:

www.TRB.org/SHRP2

SHRP 2 STAFF

ACKNOWLEDGMENTS

This work was sponsored by the Federal Highway Administration in cooperation with the American Association of State Highway and Transportation Officials. It was conducted in the second Strategic Highway Research Program, which is administered by the Transportation Research Board of the National Academies. The project was managed by James Bryant, Senior Program Officer for SHRP 2 Renewal.

The authors of this report gratefully acknowledge the technical support provided in the preparation of this report by the following:

- Dennis Morian and Shervin Jahangirnejad, Quality Engineering Solutions, Inc., Conneaut Lake, Pennsylvania;
- Ernest Barenberg, Consultant, Urbana, Illinois;
- Raymond Rollings, Consultant, Beaufort, South Carolina;
- Lambert Houben, Consultant, Delft University of Technology, Netherlands;
- Marc Stet, Consultant, Netherlands; and
- E. B. Lee, Consultant, Berkeley, California.

A special thank you is extended to the many highway agencies and organizations and individuals who provided information on field projects and precast concrete pavement systems and who provided support for the precast concrete pavement field testing program. Specifically, a thank you is extended to the following:

- Jonathan den Hartog, Kirsten Stahl, Tinu Mishra at Caltrans;
- Jim Pappas at Delaware DOT;
- Sam Tyson at Federal Highway Administration;
- Peter Smith at Fort Miller Company;
- Steve Gillen at Illinois Tollway;
- Tommy Nantung at Indiana DOT;
- Mark Dunn at Iowa DOT;
- Tatsuo Nishizawa at Ishikawa National College of Technology, Japan;
- John Donahue at Missouri DOT;
- John Stanton and Andy Bennett at Michigan DOT;
- Becca Lane at Ministry of Transport, Ontario, Canada;
- Denis Thebeau at Ministry of Transport, Quebec, Canada;
- Tom Burnham and Bernard Izevbekhai at Minnesota DOT;
- Robert Sauber (retired) and Robert Blight at New Jersey DOT;
- Michael Brinkman (retired) and Roy Reissig at New York DOT;
- Tom Gemmiti at New York State Thruway;
- Michael Griswold at Nevada DOT;
- Scott Murrell at Port Authority of New York and New Jersey;
- Tom Montalbine at Roman Stone Construction Company;
- Dar Hao Chen at Texas DOT;
- David Merritt at The Transtec Group;
- Daniel Hsiao at Utah DOT; and
- David Shiells at Virginia DOT.

FOREWORD

James W. Bryant, Jr., PhD, PE, *SHRP 2 Senior Program Officer, Renewal*

The use of precast concrete pavement (PCP) technology has been steadily increasing over the last 10 years. While there are several precast concrete pavement systems, until recently, there was little guidance available for transportation agencies on the design, fabrication, and installation of precast concrete pavements. This report provides guidance on the design, fabrication, construction, and maintenance of precast concrete pavement systems. The guidance in this report, as well as documentation of the performance of precast concrete pavements that are currently in service, will be of value for the transportation community as a whole.

Precast concrete pavement systems have shown great potential for rapid rehabilitation and reconstruction of deteriorated pavement sections. Applications include, but are not limited to, isolated intermittent repairs, intersection and ramp rehabilitation, pavement replacement under overpasses, and construction of longer mainline pavement segments. The use of precast concrete pavement systems can speed up construction without sacrificing quality while minimizing lane closures and traffic disruption. Off-site fabrication has the potential to permit lighter, thinner, or more-durable pavement sections through more stringent quality control and use of design details not feasible for in-place construction.

Over the last 10 years, several transportation agencies—including Caltrans, Illinois Tollway Authority, New Jersey DOT, New York State DOT, and Utah DOT—have implemented PCP systems. Demonstration projects have been constructed in Delaware, Missouri, Michigan, and Hawaii. The systematic application of PCP technology in the United States is a recent occurrence; and information on the design, fabrication, installation, and in-service performance is not well documented.

This report provides an assessment of the state of the practice for PCP technology and guidance on the design, fabrication, installation, and maintenance of PCPs. Specifically, it includes the following:

1. Guidelines for selection of precast concrete pavements
   a. The PCP use decision-making process;
   b. PCP System approval process; and
   c. Model specifications for PCP systems.
2. Guidelines for design of precast concrete pavements
   a. Technical considerations: design related; and
   b. Design of PCP.
3. Guidelines for fabrication and installation of precast concrete pavements
   a. Technical considerations: fabrication related;
   b. Technical considerations: installation related;
   c. Fabrication of PCP systems;
   d. Installation of PCP systems; and
   e. Repair of PCP systems.

PCP technology is ready for use in the United States. With this report's guidance, the transportation community will be able to move forward with implementation.

CONTENTS

Online version of this report: www.trb.org/Main/Blurbs/167788.aspx.

LIST OF TERMS AND ABBREVIATIONS

Cast-in-Place Concrete Pavement (Traditional Use)

CIP	cast-in-place
CIP-PCP	cast-in-place prestressed concrete pavement
CRCP	continuously reinforced concrete pavement
JCP	jointed concrete pavement
JPCP	jointed plain concrete pavement
JRCP	jointed reinforced concrete pavement

Precast Concrete Pavement

ICPCP	incrementally connected precast concrete pavement
ICPCP/P	incrementally connected precast concrete pavement with prestressed panels
ICPCP/R	incrementally connected precast concrete pavement with reinforced panels
JPrCP	jointed precast concrete pavement
JPrCP/P	jointed precast concrete pavement with prestressed panels
JPrCP/R	jointed precast concrete pavement with reinforced panels
PCP	precast concrete pavement
PCRP	precast concrete repair panel
PCRP/P	precast concrete repair panel/prestressed
PCRP/R	precast concrete repair panel/reinforced
PPCP	precast prestressed concrete pavement (posttensioned)
PTSection	posttensioned section (a continuous slab section formed by post-tensioning a number of individual precast concrete panels)

Other Terminology and Abbreviations

AC	asphalt concrete
ASR	alkali-silica reactivity
ATB	asphalt-treated base
base	the structural layer, granular or stabilized, immediately below the concrete slab of an existing pavement or below the precast panel for PCP applications; for PCP applications, a bedding layer may be used between the panel and the base
bedding	a thin granular layer or a thicker nongranular material layer used over the base to provide firm and uniform support under the precast concrete panels; the nongranular bedding material may be rapid-setting cementitious grout or flowable fill, rapid-setting lean concrete, or high-density polyurethane foam
CA4PRS	construction analysis for pavement rehabilitation strategies
CTB	cement-treated base
CTE	coefficient of thermal expansion
CTPB	cement-treated permeable base

DBR	dowel bar retrofit
ESAL	equivalent single-axle loading
FDBR	full dowel bar retrofit
FDR	full-depth repair
FRP	fiber-reinforced polymer
FWD	falling weight deflectometer
HVS	heavy-vehicle simulator
IRI	international roughness index
LCB	lean concrete base
LCCA	life-cycle cost analysis
LTE	load transfer efficiency or load transfer effectiveness
LTR	load transfer restoration
LWD	lightweight deflectometer
MOT	maintenance of traffic
MRR	maintenance, repair, and rehabilitation
NPCA	National Precast Concrete Association
PCI	Precast/Prestressed Concrete Institute
PDBR	partial dowel bar retrofit
PTI	Posttensioning Institute
QC/QA	quality control and quality assurance
RSFF	rapid-setting flowable material
RSLCB	rapid-setting lean concrete base
SCC	self-consolidating concrete
SFRC	steel-fiber-reinforced concrete
vpd	vehicles per day

Executive Summary

Background

The objective of the SHRP 2 Renewal program is to achieve highway renewal that is performed rapidly, causes minimum disruption, and produces long-lived facilities. In most U.S. urban areas, high traffic volumes seriously restrict the length and duration of lane closures, limiting the options for effective repair and rehabilitation of distressed pavements at these locations. The use of precast concrete pavement (PCP) technology addresses the SHRP 2 objective with respect to rapid and longer-lasting pavement repair and rehabilitation in highway corridors with high traffic volumes.

The demonstration and production use of PCP technology began in earnest during 2001. Over the past 10 years, several U.S. highway agencies, including the California Department of Transportation (DOT), Illinois Tollway, New Jersey DOT, New York DOT, and Utah DOT, have implemented PCP technology, and several other agencies have constructed demonstration projects. The implemented PCP systems include both proprietary and nonproprietary systems. Because the production use of PCP technology in the United States is of recent origin and information on PCP practices and performance is not well documented, many highway agencies and industry partners have not fully embraced the technology. SHRP 2 Renewal Project R05, Modular Pavement Technology, was aimed at developing the necessary information and guidelines to encourage rapid and successful adoption of this new technology.

PCP systems are used in highway corridors with high traffic volumes and where lane closures are a challenge. For production use, PCP work is performed at night, typically from about 8 p.m. to 6 a.m., and with short closures. The production rate per lane closure is about 15 to 20 repair locations and about 30 to 40 continuously placed panels (about 400 to 600 ft [122 to 183 m] lengthwise).

Project R05 Key Work Items

The key work items under SHRP 2 Project R05 include the following:

1. Identification of PCP systems and U.S. and international practices;
2. Evaluation of PCP performance;
3. Development of guidelines for selection, design, fabrication, and installation of PCP systems; and
4. Development of model specifications.

The following PCP applications were investigated:

1. Intermittent repairs for full-depth repairs or full slab replacement, generally used on jointed concrete pavements.

2. Continuous applications for longer-length or larger-area pavement rehabilitation. The existing pavement can be asphalt concrete or cement concrete pavement.

   Two PCP types are used for these applications:
   - Jointed precast concrete pavement. These pavements perform similarly to conventional cast-in-place (CIP) jointed concrete pavements.
   - Precast prestressed concrete pavement. A number of precast panels, typically 10 ft or more in length, are connected by posttensioning. This approach results in fewer active joints at a spacing of about every 100 to 300 ft (30 to 90 m). Prestressing also allows the use of thinner panels compared with jointed precast concrete pavement systems.

Study Highlights

PCP technology is maturing, with an increase in the number of projects constructed every year and an increase in the number of agencies specifying PCP for concrete pavement repair and rehabilitation. The performance of projects constructed in the United States indicates that sufficient advances have been made to reliably achieve the following four key attributes of PCPs:

1. Constructability: Techniques and equipment are now available to ensure acceptable production rates for installation of PCP systems.
2. Concrete durability: Plant fabrication of the precast panels results in excellent concrete quality with respect to strength and durability.
3. Load transfer at joints: Reliable and economical techniques are now available to incorporate effective load transfer at transverse joints of PCP systems.
4. Panel support conditions: The techniques to provide adequate and uniform support conditions continue to be improved.

Findings Based on Field Testing

Field testing performed at 16 PCP projects as part of SHRP 2 R05 indicates that the currently used PCP systems are capable of performing well under traffic loading. This finding should provide confidence to highway agencies using or contemplating using PCP technology to achieve rapid pavement repair and rehabilitation. The behavior and performance of constructed PCP systems appear to be similar to that of CIP concrete pavements.

Guidelines for PCP Use

The following guidelines are incorporated in this report:

1. Guidelines for PCP project selection: These project selection guidelines provide guidance to highway agencies that are considering PCP systems for repair or rehabilitation.
2. Guidelines for PCP system acceptance: These guidelines address the requirements for approval of PCP systems. The approval process consists of two parts: (a) submittal and review of fabricator standard drawings and standard installation procedures and (b) construction and evaluation of trial installations.
3. Guidelines for improved practices related to design of PCP systems: These guidelines provide highway agencies with defined procedures for the design of PCP systems. The guidelines are based on practices for CIP concrete pavements, use of the newly developed AASHTO *Mechanistic–Empirical Pavement Design Guide* (2008), and a consideration of differences in the behavior of CIP concrete pavements and PCPs.
4. Guidelines for PCP fabrication: These guidelines, which provide highway agencies an understanding of the issues involved in concrete pavement fabrication, address precast plant

certification, plant technician certification, concrete requirements, panel hardware (e.g., reinforcement, lifting inserts, prestressing hardware), the generic panel fabrication process, pretensioning if required, panel tolerances, and quality assurance and quality control requirements. Precast concrete fabrication is an established technology and is governed by industry standards and highway agency specifications.

5. Guidelines for improved practices related to PCP installation: These guidelines provide highway agencies and contractors improved guidance for installing PCP systems.

Model Specifications

Model specifications have been developed to provide highway agencies a framework for developing agency-specific plans for using PCP systems on their projects. The model specifications are available online at www.trb.org/Main/Blurbs/167788.aspx.

Summary

PCP technology is ready for implementation, and many of the proprietary and nonproprietary PCP systems available in the United States are capable of meeting the four key attributes of PCP systems:

1. Constructability: availability of techniques and equipment to ensure acceptable production rates for installation of the PCP systems.
2. Concrete durability: confidence that plant fabrication of the precast panels results in excellent concrete quality with respect to strength and durability.
3. Load transfer at joints: availability of reliable and economical techniques to incorporate effective load transfer at transverse joints of PCP systems.
4. Panel support condition: availability of techniques to provide adequate and uniform support conditions.

The cost of PCP systems is expected to be routinely competitive with CIP concrete pavement repair and rehabilitation in the near future as the market size increases and more fabricators and contractors enter the market.

CHAPTER 1

Introduction

Pavement rehabilitation and reconstruction are major activities for all U.S. highway agencies. These activities have a significant impact on agency resources, and their extensive and extended lane closures are a source of traffic disruptions. Traffic volumes on the primary highway system, especially in urban areas, have increased tremendously over the past 20 years, leading in many instances to an earlier than expected need to rehabilitate and reconstruct highway pavements. Pavement rehabilitation in urban areas is a serious and ongoing challenge for highway agencies because of construction-related traffic congestion and safety issues. Many agencies also continue to wrestle with the chronic dilemma of longer delays now and longer service life versus shorter delays now but shorter service life.

In recent years, many agencies have investigated strategies for pavement rehabilitation and reconstruction that are faster but can produce durable pavements. Expedient rehabilitation that results in a shorter pavement lifespan is no longer considered acceptable by most highway agencies. A promising alternative rehabilitation strategy is the effective use of modular pavement technologies, principally precast concrete pavement (PCP) systems, which provide for rapid repair and rehabilitation of pavements and also result in durable, longer-lasting pavements. Rapid construction techniques can significantly minimize the impact on the driving public, as lane closures and traffic congestion are kept to a minimum. Road user and worker safety is also improved by reducing road users' and workers' exposure to construction traffic.

PCP technologies have been investigated sporadically for over 40 years. In the early years, the technology was considered as a technical curiosity (to learn whether PCP technology was technically feasible) or as an emergency repair technique (with minimal concerns regarding long-life performance). Until recently, no serious attempts were made to fully develop the technology as a cost-effective strategy or to implement the technology on a production basis. Today, the maturing highway system in high-traffic-volume urban corridors makes the need for timely pavement repair and rehabilitation urgent, and highway agencies are looking at innovative technologies, including PCP technologies, which require shorter lane closures and result in economical, long-life pavements that will not require major interventions for repair or rehabilitation during their service life. Over the past 10 years, new PCP technologies have been developed whose use is becoming technically feasible and economically justifiable on a project-by-project basis. From 2001 to the end of 2011, over 200,000 yd^2 (167,225 m^2) of PCP have been constructed in the United States.

Over the last few years, many initiatives have been undertaken to develop better guidance for use of PCP technology, and many repair and rehabilitation projects have been constructed using this technology. However, a lack of well-documented design and construction guidelines is deterring wider use of the technology. In addition, the performance of the installed PCP projects is not well documented, resulting in many questions related to field performance of PCPs.

The Renewal focus area under SHRP 2 emphasizes the need to complete highway pavement projects rapidly, with minimal disruption to highway users and local communities, and to produce pavements that are long lasting. A goal of this focus area includes applying new methods and materials to preserve, rehabilitate, and reconstruct roadways. The effective use of PCP technologies for rapid repair, rehabilitation, and reconstruction of pavements addresses this goal.

The objective of one of the projects funded under SHRP 2, Renewal Project R05, Modular Pavement Technology, was to develop better guidance for highway agencies to design, construct, install, maintain, and evaluate modular pavement systems. Most of the effort under Project R05 was devoted to PCP technology, as this is the dominant modular system under development and use in the United States and other regions (Canada, Europe, Indonesia, Japan, and Russia). The project team also addressed the development and use of modular pavement technologies that involve nonrigid systems. The only reported nonrigid modular pavement system, RollPave, is under development in the Netherlands; however, at present U.S. highway agencies and the industry have no plans to develop or implement nonrigid modular pavement technologies, such as RollPave, in the United States.

Report Content

This report documents the findings and products developed as part of SHRP 2 Renewal Project R05. The focus of the report is on PCP technology, and the report documents design and construction guidelines for different PCP applications. An implementation plan and a long-term evaluation plan are also included. Model specifications developed as part of this project are available online at www.trb.org/Main/Blurbs/167788.aspx.

Because of the recent origin of PCP technology and the development of a range of applications and systems, many new terms and acronyms have come into common use. The list of terms and abbreviations provided in the front matter of this report is meant to serve as a standard for the use of PCP-related terminology and acronyms.

The term “pavement rehabilitation” is typically used to refer to pavement reconstruction and to pavement resurfacing (overlay applications). In this report, the term “rehabilitation” is typically used to denote reconstruction, and where specifically noted, it is used to denote resurfacing applications.

CHAPTER 2

Background

General

PCPs use prefabricated concrete panels for rapid repair of existing concrete pavements and for rehabilitation of existing concrete and asphalt pavements. PCPs may also be used for reconstruction or as an overlay application. PCP applications include but are not limited to isolated repairs, intersection and ramp rehabilitation, urban street rehabilitation, and rehabilitation of longer mainline pavement sections. A generic definition of a PCP system is as follows:

> Precast pavement systems are fabricated or assembled off-site, transported to the project site, and installed on a prepared foundation (existing pavement or regraded foundation). The system components require minimal field curing or time to achieve strength before opening to traffic. (Federal Highway Administration 2010)

The specific advantages of using PCPs versus cast-in-place (CIP) concrete pavements include the following:

1. Better-quality concrete: There are no issues related to the quality of fresh concrete delivered to the project site, CIP paving equipment operation, or uniform placement of concrete.
2. Improved concrete curing conditions: Curing of the precast panels occurs under controlled conditions at the precast concrete plant.
3. Minimal weather restrictions on placement: The construction season can be extended as panels can be placed in cooler weather or during light rainfall.
4. Reduced delay before opening to traffic: On-site curing of concrete is not required. As a result, PCPs can be installed during nighttime lane closures and be ready to be opened to traffic the following morning.
5. Elimination of construction-related early-age failures: Issues related to late or shallow sawing do not develop.

Over the past 10 years, several U.S. highway agencies have begun to implement PCP technology, and a few others have constructed demonstration projects. The implemented PCP systems include proprietary and nonproprietary systems. Because PCP technology is new and the information on PCP practices and performance is not well documented, many highway agencies and industry partners have not fully embraced the technology. SHRP 2 Project R05 is aimed at developing the necessary information and guidelines to encourage the rapid and successful adoption of this new technology.

PCP systems are used in highway corridors with high traffic volumes and where lane closures are a challenge. For production use, PCP work is performed during the night, typically from about 8 p.m. to 6 a.m., and with short closures. The production rate per lane closure is about 15 to 20 repair locations and about 400 to 600 ft (122 to 183 m) lengthwise for continuous rehabilitation. The key issues of concern for PCPs are constructability, concrete durability, and pavement performance as primarily affected by joint load transfer and panel support condition. Sufficient advances have been made in PCP technology to reliably achieve the following four key attributes:

1. Constructability: Techniques and equipment are now available to ensure acceptable production rates for rapid installation of PCP systems.
2. Concrete durability: Plant fabrication of the precast panels can result in excellent concrete quality with respect to strength and durability.
3. Load transfer at joints: Reliable and economical techniques are now available to incorporate effective load transfer at the transverse joints of jointed PCP systems.
4. Panel support conditions: The techniques to provide adequate and uniform support conditions continue to be improved.

However, it must be emphasized that PCPs are not “super pavements” and should not be expected to perform at a significantly superior level to CIP concrete pavements unless the prestressing technique is used. Once installed, PCP systems can be expected to behave, under traffic and environmental loadings, similarly to comparable CIP concrete pavement systems. The primary difference in the two technologies is how each system is constructed. The main advantage of PCP is that it is a truly rapid rehabilitation technology that can also result in longer-lasting treatments. In addition, as discussed below, prestressing techniques allow PCP to achieve higher load-carrying capacity within a constrained pavement cross section when reconstructing existing pavements.

For highway agencies considering or involved in the implementation of PCP technology, the following technology issues are of interest:

1. Warrant for use of PCP technology: Such a warrant is based on available successful alternative technologies for rapid pavement repair and rehabilitation.
2. Suitability of a pavement for PCP application: Site access, maintenance of traffic, and availability of nearby precasting plants are key decision criteria.
3. Precast pavement system approval, selection, and design: Once a decision is made to use PCP, the most cost-effective PCP system needs to be selected. Typically, the PCP systems used by an agency are preapproved based on submittal of shop drawings and construction of trial installations. These systems include both proprietary and nonproprietary systems. In addition, the selected system needs to be designed to accommodate project-specific requirements.
4. Precast pavement fabrication: The fabrication process for PCP systems is based on decades of well-established practices for precast concrete systems and is regulated by industry standards that result in durable concrete and durable structural components. Precast pavement panel fabrication is typically a routine process and may incorporate specific details related to the following:
   a. Provisions for load transfer along panel sides that form the transverse joints and for tie bars along panel sides that form the longitudinal sides;
   b. Provisions for pretensioning of the panels;
   c. Provisions to allow for later posttensioning a series of connected panels;
   d. Provisions to allow for undersealing of the panels; and
   e. Provisions for surface texture as required by the specifying agency.
5. Precast pavement installation: The installation of precast pavement includes the removal of the existing pavement, reestablishing the base, providing for bedding material over the base as necessary, and installing the panels. Depending on the specific PCP system used, additional considerations include provisions for load transfer at transverse joints, connectivity along longitudinal joints, establishing expansion joints, and accommodating post-tensioning operations.
6. Precast pavement acceptance testing: As PCP technology is of recent origin, procedures for acceptance of PCP are not well established. Acceptance testing typically includes standard testing for concrete quality at the precast plants and smoothness testing of the completed work. Testing is not routinely performed to validate the installed load transfer system at transverse joints, to evaluate the readiness of the base or bedding support, or to measure the effectiveness of prestressing in precast prestressed concrete pavement (PPCP) systems.

Precast Pavement Applications

PCP technology can be used for projects of different sizes, as the three illustrations in Figure 2.1 show.

1. Localized repair of distressed areas of existing jointed concrete pavements (JCPs) and continuously reinforced concrete pavements (CRCPs). These localized areas may include deteriorated joints and cracks and shattered slabs in JCP (Figure 2.1, top) and punchouts and deteriorated cracking in CRCP.
2. Rehabilitation of short lengths of distressed concrete pavements (Figure 2.1, center). Such rehabilitation may include pavement lengths of 200 ft (61 m) to more than 1,000 ft (305 m), typically within individual lanes.
3. Rehabilitation of longer lengths of existing distressed concrete or asphalt pavements. Such rehabilitation may extend several miles in length and may include one or more lanes (Figure 2.1, bottom).

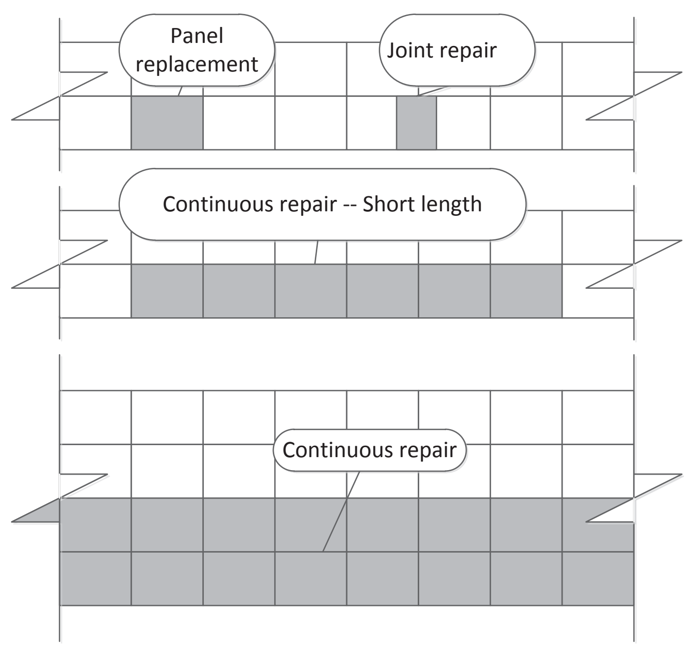


Figure 2.1. Applications of PCP for (top) localized, (center) short-length, and (bottom) continuous repair.

Because of this versatility, PCP systems are often used to rehabilitate special pavement facilities, such as toll plazas, intersections, freeway ramps, bridge approach slabs, and tunnels. In addition, PCP systems can be used for new construction where new roadways cross the paths of existing high-volume roadways.

The primary warrants for use of PCPs in the United States are to minimize lane closure requirements and to obtain long-life pavement performance. The PCP installation is typically required to be performed during nighttime lane closures, and the facility is required to be fully operational during daytime hours.

Precast Concrete Pavement Concepts

The application of PCP technology can be classified as follows:

1. Intermittent repairs of concrete pavements; and
2. Continuous applications.

Intermittent Repairs of Concrete Pavements

Under this approach, isolated pavement repairs are conducted using precast concrete slab panels. Two types of repairs are possible:

1. Full-depth repairs (FDRs) to repair deteriorated joints or cracking. This technique can also be used to repair punchouts and deteriorated cracks in CRCP.
2. Full-panel replacement to replace severely cracked or shattered slab panels.

The repairs are always full-lane width. The process is similar for FDRs and full-panel replacement, except for the length of the repair area. A schematic of the repair is shown in Figure 2.2 (Hall and Tayabji 2008).

Under the scheme shown in Figure 2.2, dowel bars are embedded in the precast panel. Slots for the dowel bars are cut in the existing concrete pavement, similar to the dowel bar retrofit (DBR) method, as illustrated in Figure 2.3. The dowel slots are then filled with fast-setting patching material. In a variation of this scheme, no dowel bars are embedded in the precast panel, and dowel bars are installed after panel installation using the DBR technique, as shown in Figure 2.4.

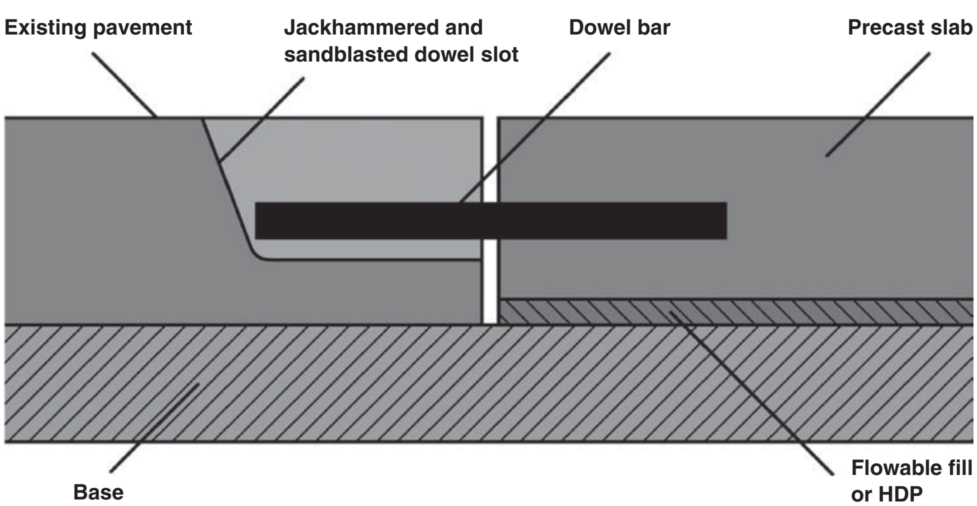
In another scheme for intermittent repairs, the dowel bars are positioned in the existing concrete pavement by drilling and epoxy grouting, similar to CIP FDRs or full-slab repairs, and the slots for the dowel bars are fabricated in the repair panels along the bottom of the transverse sides, as shown in Figure 2.5. The slots and the joint perimeter gap are then filled with fast-setting grout.

The advantages and disadvantages of each of the above methods of panel installation with respect to load transfer provisions are discussed below. The actual panel installation and the base support under the panel can be achieved using several techniques as follows:

1. Panel placed directly over the prepared base;
2. Panel placed and raised to proper elevation using expandable polyurethane foam;
3. Panel held in place using strongback beams and bedding material injected under the panel; and
4. Panel positioned at the proper elevation using setting bolts and bedding material injected under the panel.

Key features of intermittent repair applications are

1. The need to accurately saw-cut the repair area;
2. The need to establish good support under the panels;
3. The need to provide adequate load transfer at transverse joints;



Note: Dowel bar caps should be used; HDP = high-density polyurethane.

Figure 2.2. Schematic of intermittent repair application.

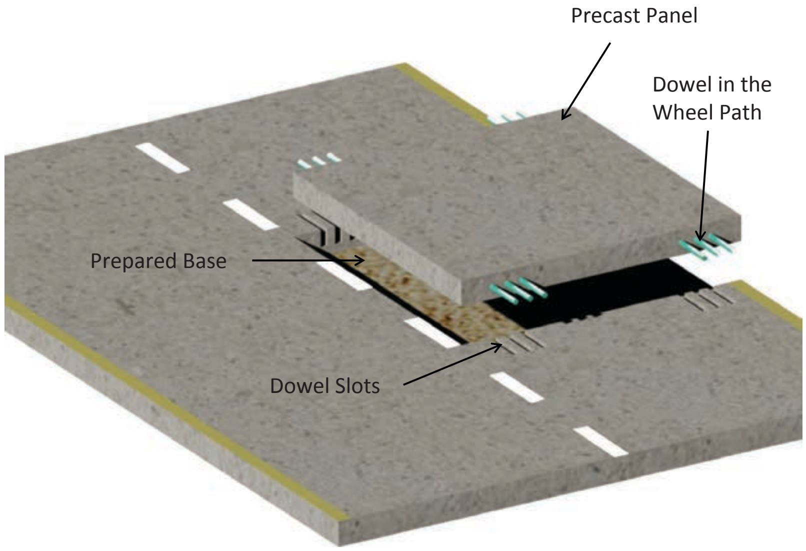


Figure 2.3. Variation of intermittent repair technique with slots for dowel bars cut in existing concrete pavement.

Figure 2.4. Variation of intermittent repair technique with dowel bars installed after panel installation using DBR method.

4. The need to install the panel so that the elevation differences between the panel and the existing pavement are minimized; and
5. Acceptable long-term performance of the repair area.

Continuous Application

Under this approach, full-scale project-level rehabilitation (reconstruction or overlay application) of asphalt and concrete pavements is performed using precast concrete panels. Two types of systems, discussed in detail below, have been used in the United States:

1. Jointed precast concrete pavement (JPrCP) systems
   a. Reinforced concrete panels
   b. Prestressed (pretensioned) concrete panels.
2. Precast prestressed concrete pavement (PPCP) systems.

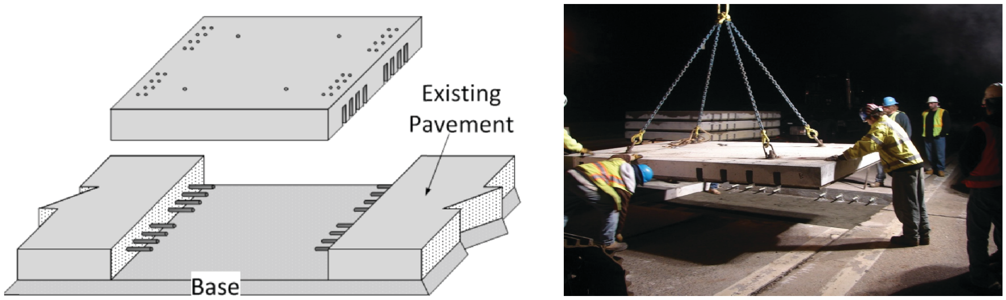


Figure 2.5. Variation of intermittent repair technique with dowel bars positioned in existing concrete pavement.

As part of the SHRP 2 Project R05 study, a third category of continuous systems has been established. This category is referred to as the incrementally connected precast concrete pavement (ICPCP) systems and includes systems that simulate hinged jointed reinforced concrete pavement (JRCP) behavior. The panels for ICPCP systems may be reinforced or prestressed.

Jointed Precast Concrete Pavements

JPrCPs are very similar to CIP-JCPs. Once installed, JPrCPs behave similarly to CIP-JCPs. Specific differences that influence the performance of the JPrCP are as follows:

1. The panels are installed flat. As a result, the panels do not exhibit construction-related, built-in curl or warp behavior.
2. The panels incorporate steel reinforcement. Therefore, any in-service cracking that may develop over time due to traffic loading can be tightly contained.
3. The panel transverse joint faces are smooth (fabricated), and therefore aggregate interlock cannot be counted on for load transfer at these joints.

All JPrCP systems used in the United States incorporate load transfer at transverse joints. In fact, it is necessary that load transfer provisions be incorporated in all JPrCP systems. All currently used JPrCP systems use round dowel bars, typically steel bars, for load transfer. Figure 2.6 shows a scheme used to incorporate load transfer that is similar in concept to the system shown in Figure 2.5 for intermittent repairs. Under this scheme, one side of the panel has slots along the slab bottom to accommodate the dowel bars, and the other side has embedded dowel bars at locations that match the dowel slot locations. After installation, the slots and the joint perimeter gap are filled with fast-setting grout.

A simpler scheme using the DBR technique can also be used for JPrCP applications. The wide-mouth dowel slots used in this scheme require patching of the dowel slots during the same lane closure as the panel installation. The primary reason for not using this scheme is not related to performance but to avoid leaving open, wide-mouth slots exposed to highway traffic for a day or two. The retrofitted dowel bar scheme was used at an airfield demonstration application. The dowel bars were embedded along one transverse side of the panel, and dowel bar slots were placed at the

Figure 2.6. A scheme for providing load transfer in JPrCP using dowel slots and embedded dowel bars.

Figure 2.7. An alternate scheme for providing load transfer in JPrCP.

top side of the panel along the other transverse side. The panels were then interconnected by positioning one panel with the embedded dowels adjacent to another panel with the dowel slots, as shown in Figure 2.7. This demonstration project used both reinforced panels and thinner prestressed panels.

A scheme developed under Project R05 and discussed in this report uses the DBR technique with narrow-mouth dowel bar slots. In this scheme, the narrow-mouth dowel slots can be left open to traffic until the next lane closure (within a day or two) when the slots are patched.

Precast Prestressed Concrete Pavements

PPCP systems simulate CIP prestressed concrete pavements (CIP-PCP). These systems incorporate longer lengths of post-tensioned sections (PTSections) and expansion joints between these sections. The PTSections are formed by posttensioning together a series of panels. The PTSection length may vary from about 150 to 250 ft (46 to 76 m). The individual panel width may be single lane or multiple lane, and panel length can vary from 8 to 10 ft (2.4 to 3 m) for multilane panels to 10 to 30 ft (3 to 9 m) or more for single-lane panels. A project in California (I-680 near Oakland in May 2011) used panels up to 36 ft (11 m) long.

Three types of PPCP systems have been developed. In the original version, used at the first PCP project in Texas (Merritt et al. 2000, 2002), base, central stressing, and expansion joint panels were used:

1. Base panels: the majority of the connected (posttensioned) panels.
2. Central stressing panels: to apply posttensioning from the midportion of the connected panels using slots prefabricated in the panels.
3. Expansion joint panels: one at each end of the PTSections. These panels include dowel bars for load transfer and provisions for joint sealing.

In a second version of the PPCP system, used at the Delaware, Missouri, and Virginia projects (Merritt et al. 2008), only base and expansion joint panels were used:

1. Base panels: the majority of the connected (posttensioned) panels.
2. Expansion joint panels: one at each end of the PTSections. These panels include dowel bars for load transfer, provisions for joint sealing, and provisions for applying posttensioning using slots prefabricated in the panels.

In a third version of the PPCP system, at the I-680 project in California, base, end joint, and expansion joint gap panels were used:

1. Base panels: the majority of the connected (posttensioned) panels.
2. End joint panels: one at each end of the PTSections. These panels include dowel bars for load transfer, provisions for joint sealing, and provisions for applying posttensioning from the face of the panel using anchorage system pockets prefabricated in the end panels.
3. Expansion joint gap panels: one expansion joint gap panel, about 4 ft (1.2 m) long to fill the gap left between adjacent panels to accommodate the posttensioning operation. For new construction where lane closure is not a concern, the gap panel may be cast in place. The gap panel includes provisions for dowel bars for load transfer and for joint sealing.

The gap slab concept was successfully used in CIP-PCPs constructed during the 1970s and 1980s (Tayabji et al. 2001;

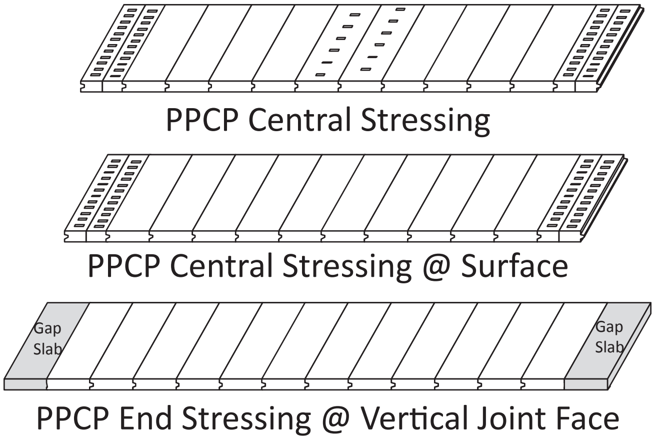


Figure 2.8. Schematic of three PPCP systems.

Nussbaum et al. 1983). These CIP-PCPs were posttensioned from the joint face, and a CIP gap slab was constructed between adjacent PTSections after the posttensioning was completed.

The posttensioning of a series of panels induces compressive stress in the connected panels that allows for reduction in the panel thickness by 2 to 4 in. (50 to 100 mm) compared with an equivalently designed JCP. The three versions of PPCP are illustrated in Figure 2.8. The top drawing illustrates the original version, using base panels, central stressing panels, and expansion joint panels. The middle drawing illustrates the second version, using only the base panels and joint panels. The bottom drawing illustrates the third version, using the gap panel. These three versions of the PPCP system are also shown in Figure 2.9.

As indicated, the required PPCP panel thickness is less than that of CIP-JCP or JPrCP. This reduced panel thickness results in the need for less concrete, making PPCP a more sustainable alternative with respect to material consumption and carbon dioxide production. Based on a small number of demonstration-type PPCP projects in the United States, PPCP costs are comparable to those for JPrCP.

Incrementally Connected Precast Concrete Pavements

As discussed, ICPCP is a new category of PCP systems that has been established as part of SHRP 2 Project R05. ICPCP systems simulate a JRCP with hinged joints and incorporate panels of varying lengths, typically 15 to 30 ft (4.5 to 9 m), which are connected to achieve a continuous section length of 60 to 100 ft (18 to 30 m). The panels are connected using deformed dowel bars that lock up the connected joint and also provide the required load transfer across these joints. A small-width expansion joint is provided between connected panels.

(a)

(b)

(c)

Figure 2.9. Views of the installation of three current versions of PPCP systems with stressing pockets (a) in central panel, (b) at expansion panel, and (c) with posttensioning performed at joint face.

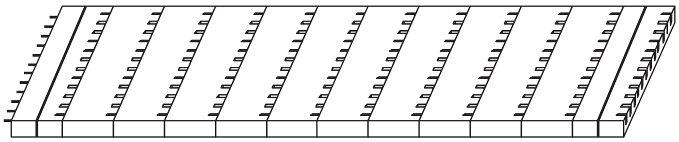


Figure 2.10. Incrementally connected PCP.

The advantages of ICPCP are the reduction in the number of active joints and the use of smaller-width expansion joints. Both nominally reinforced and prestressed panels can be used. The ICPCP system is illustrated in Figure 2.10. Prestressed panels allow use of thinner panels, but they require good support under the panel, similar to the good support needed for PPCPs.

The differences between the JPrCP, PPCP, and ICPCP systems are summarized in Table 2.1.

Historical Development of PCP in the United States

FHWA Initiatives

Experimental use of PCP for repairs of JCPs in the United States began before the 1990s (Simonsen 1971; Tyson 1976). However, no serious efforts were made at that time to refine the PCP technologies to facilitate their production use. Recognizing the need to develop effective solutions for rapid rehabilitation of the nation's highway system, the Federal Highway Administration (FHWA) and the Texas Department of Transportation (DOT), as part of FHWA's Concrete Pavement Technology Program, sponsored a study at the University of Texas during the late 1990s that resulted in a concept for PPCP (Merritt et al. 2000). In March 2002, Texas DOT completed the first pilot project using this innovative concept, incorporating the use of PPCP along a frontage road near Georgetown, Texas (Merritt et al. 2002). Since then, FHWA has actively promoted the concept of PCP systems to state DOTs, and demonstration projects have been constructed in California, Delaware, Iowa, Missouri, and Virginia to develop field experience with this technology.

Under the Concrete Pavement Technology Program, FHWA also sponsored the development of PCP technology for FDR of JCPs. This work was conducted at Michigan State University (Buch 2007) and has resulted in several field trials of this technology in Michigan and Ontario, Canada.

Over the past 5 years, FHWA, under the Highways for LIFE program, has also supported several open houses to demonstrate PCP technology as a ready-to-implement vanguard technology for rapid rehabilitation of existing deteriorated pavements.

Industry Initiatives

Parallel to FHWA-sponsored efforts, several organizations in the United States have initiated independent development activities to refine PCP technologies. Some of these technologies have certain proprietary features and require licensing for use. Privately developed technologies include the following:

1. Fort Miller Company's (FMC) Super-Slab system (Fort Miller Company 2011);
2. Kwik Slab system (Kwik Slab 2011); and
3. Roman Stone Construction Company's Roman Road system (Roman Stone Construction Company 2011).

Since about 2001, the FMC system has been used on many continuous and intermittent production projects for repair and rehabilitation applications. In continuous application, this system simulates a conventional JCP. The Kwik Slab system has been used on a limited basis in Hawaii. This system simulates JRCPs, and is an example of an ICPCP system. A PCP system incorporating Uretek USA's "Stitch-in-Time" joint load transfer process has also been used for intermittent repairs (Uretek 2013).

Highway Agency Initiatives

In the last few years, several agencies, including Caltrans, New York State DOT, New Jersey DOT, and the Illinois Tollway

Table 2.1. Comparison of PCP Systems

Specification	Precast Jointed (JPrCP)	Precast Prestressed (PPCP)	Incrementally Connected (ICPCP)
Thickness	Conventional: 10 to 14 in. Prestressed: 8 to 10 in.	Thinner: 8 to 10 in.	Conventional: 10 to 14 in. Prestressed: 8 to 10 in.
Active joint spacing	15 ft, typical	150 to 250 ft	Up to 100 ft
Active joint width, typical	0.25 to 0.35 in.	1.0 to 2.0 in.	0.25 to 0.50 in.
Base support	Good	Very good	Good to very good
Base–panel interface	Bedding layer, if needed	Friction-reducing treatment needed	Bedding layer, if needed

Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

Authority, have developed specifications that allow use of PCP systems, and several agencies have installed test sections to demonstrate the feasibility of PCP systems. Accelerated testing of the Fort Miller PCP system by Caltrans indicated that the precast pavement system tested is capable of long-life service (Kohler et al. 2007). Caltrans also has an active task force developing standard plans and specifications for PCP use in California (M. Parvini, Caltrans Precast Concrete Pavement Sub-Task Group, personal communication, 2011). Recently, the Illinois Tollway and the Utah DOT have developed plans and specifications for nonproprietary PCP systems for intermittent repairs and continuous applications (Illinois Tollway Authority 2009; FHWA HfL 2011).

Airfield Applications

Use of PCP is considered to be a high-payoff alternative for rapid repair and rehabilitation of airfield pavements. Several airport agencies have recently investigated use of these technologies:

1. The Port Authority of New York and New Jersey (PANY/NJ) installed two generically developed PCP test sections at La Guardia International Airport in New York during 2002 to investigate the feasibility of rapid rehabilitation of a primary taxiway there (Yue et al. 2003):
   a. A section with nominally reinforced precast panels 16 in. (400 mm) thick
   b. A section with two-way prestressed (pretensioned) precast panels 12 in. (305 mm) thick.
2. St. Louis International Airport, for slab panel replacement (generic system) during 2000 (E. Barenberg, personal communication, 2001).
3. Dulles International Airport, for slab panel replacement during 2005 (Switzer et al. 2003; Farrington et al. 2003).

The U.S. military has also evaluated PCPs for expedient airfield pavement repair and rehabilitation. To support the U.S. Air Force mission, the U.S. Army Corps of Engineers is investigating the performance of precast concrete panels under airfield-type loading.

Developments Outside the United States

The Ontario Ministry of Transportation has developed specifications that allow use of PCP systems, and several European countries have recently started to investigate the use of PCP for rapid repair and rehabilitation of pavements. In the Netherlands, the ModieSlab system (Houben 2004; Smits 2004) has been developed and is being field tested. In France, precast hexagonal panels are used for some urban roadway rehabilitation. In Japan, precast concrete slab systems have been used for high-speed slab track applications, for tunnel roadways, at roadway intersections, and at airports. In Russia, there is a long history of PCP use for highway and airport applications, and PCPs were installed by the Soviet army in former Soviet republics during the 1980s. A 22-mi (35-km) project using PPCP technology was constructed in Indonesia in 2009 (Nantung et al. 2010), and as of 2011, additional PPCP projects are being implemented in Indonesia.

AASHTO Technology Implementation Guidelines

Recognizing the increasing interest in PCP technologies by U.S. highway agencies and to provide an effective platform for technology transfer activities, in 2006 the American Association of State Highway and Transportation Officials' (AASHTO) Technology Implementation Group (TIG) selected PCP as one of its focus technologies and established a lead states team for it. In June 2008, the AASHTO TIG completed work on three relevant documents, which are available online (AASHTO TIG 2011):

1. Generic Specification for Precast Concrete Pavement System Approval (AASHTO TIG 2008b);
2. Guidance and Considerations for the Design of Precast Concrete Pavement Systems (AASHTO TIG 2008c); and
3. Generic Specification for Fabricating and Constructing Precast Concrete Pavement Systems (AASHTO TIG 2008a).

The AASHTO TIG, in cooperation with the FHWA Highways for LIFE program, has supported several technology outreach activities, including open houses, related to PCP systems.

U.S.-Developed Precast Concrete Pavement Systems

This section discusses the various PCP systems that are available for production use or have been used on an experimental basis in the United States.

Precast Prestressed Concrete Pavement System

The PPCP system, illustrated in Figures 2.8 and 2.9, was developed at the University of Texas at Austin under the sponsorship of FHWA and the Texas DOT. This PCP technology is well suited for continuous paving. The basic PPCP system consists of a series of individual precast panels that are posttensioned together in the longitudinal direction after installation on site. Each panel may also be pretensioned in the transverse or the longitudinal direction, or both, during fabrication. Ducts for longitudinal posttensioning are cast into each of the panels during fabrication. The posttensioning and pretensioning introduce compressive stress in the concrete that helps offset some of the tensile and flexural stress that develop in the precast panels under traffic and environmental loadings.

The compressive stress (or the prestress) introduced by the longitudinal posttensioning varies along the length of the PTSection, with a maximum prestress developing at the ends of the PTSection and a minimum (effective) prestress developing near the midsection. The reduction in the prestress is caused by the panel–base friction and other prestress losses (discussed below). The effective prestress in the concrete allows for a reduction in the thickness of the panel for PPCP systems.

The basic features of the PPCP system are as follows:

1. Panel size (per design requirements)
   a. Width: up to 40 ft (12 m);
   b. Length: typically 10 to 30 ft (3 to 9 m); and
   c. Thickness: between 8 to 10 in. (200 to 250 mm).
2. Panel types
   a. System 1: base, joint, and central stressing panels (as originally developed);
   b. System 2: base and joint stressing panels; and
   c. System 3: base, end stressing, and gap panels.
3. A mechanism for connecting intermediate joints: a keyway detail.
4. Posttensioning details
   a. Typically, use of 0.6-in. (15-mm)-diameter, 7-wire monostrand tendons, typically spaced at 18 to 24 in. (455 to 610 mm). If two strands are used in a duct, the duct spacing may be up to 36 in. (910 mm).
   b. Tendon load: 75% of ultimate tendon load, typically.
   c. Applied prestress: sufficient to ensure about 100 to 200 lbf/in.^{2} (0.7 to 1.4 MPa) effective prestress at the midpoint of each series of PTSections, after accounting for prestress losses caused by panel–base interface friction, concrete creep, concrete shrinkage, and steel relaxation. The smoother the panel–base interface, the greater is the effective prestress at the midpoint of the PTSection.
   d. Grouted posttensioning ducts.
5. Pretensioning details
   a. Typically, use of 0.5-in. (13-mm)-diameter, 7-wire monostrand tendons.
   b. Tendon load: 75% of ultimate tendon load, typically.
   c. Pretensioning is achieved as part of the panel fabrication process.
6. Expansion joint spacing: 150 to 250 ft (46 to 76 m), typically.
7. Base type: Because of the thinner panels used for the PPCP systems, a stabilized base is preferred (to keep panel deflections under truck traffic as low as possible).
8. Panel–base interface treatment: a membrane, typically 6-mil polyethylene or geotextile, is used to ensure low frictional resistance between the panel and the base during posttensioning.
9. Injection of bedding grout to firmly seat panels (after posttensioning).

Fort Miller Super-Slab System

The Fort Miller Company's Super-Slab system, shown in Figures 2.5 and 2.6, is a proprietary PCP technology suitable for both intermittent and continuous paving operations. This paving system consists of precast panels placed on graded and compacted bedding material or over a graded existing granular base. This particular PCP technology allows production of nonplanar (also referred to as warped) panels with varying cross slopes. This system has the most production paving experience to date in the United States and Canada.

Precast Concrete Panels for Full-Depth Repair: Michigan Method

The Michigan method, a nonproprietary PCP technology, is a doweled FDR system that can be used for intermittent repair applications. This system was refined at Michigan State University under a project sponsored by FHWA and the Michigan DOT (Buch 2007). The repair panels are typically 6 ft (1.8 m) long and 12 ft (3.6 m) wide, fitted with three or four dowel bars in each wheelpath. The Michigan method can be used for FDR as well as full-panel replacement. This method uses a partial or full DBR technique to install dowel bars at the transverse joints formed by the precast panel, as shown in Figure 2.2.

Roman Road System

The Roman Road system was introduced in 2009 by the Roman Stone Construction Company for intermittent repairs. In this system, dowel bars are not embedded in the panels, but rather are installed using the DBR technique after the panels are placed. The slots for dowel placement are cut in the existing concrete, as well as in the panel after the panel is set in final position (elevation). The unique feature of this system is the use of polyurethane foam as a bedding material. The panel is cast about 1 in. (25 mm) less in thickness than the existing pavement. When the panel is placed in the prepared hole after removal of the deteriorated portion of the existing pavement, it sits about an inch below final elevation. The polyurethane material is then injected

Figure 2.11. Roman Road system.

under the panel, raising the panel to the desired elevation and providing uniform seating of the panel over the existing base. The Roman Road system is shown in Figure 2.11: the left photo shows the injection of the urethane grout and the raising of the panel, and the right photo shows the final position of the panel before cutting of the dowel slots. The dark shading on the panel indicates the locations of the dowel slots.

Kwik Slab System

The Kwik Slab system (shown in Figure 2.12), which includes the patented Kwik joint steel couplers, interlocks reinforced precast concrete panels, allowing reinforcement continuity throughout the length of the connected section. The system essentially simulates JRCP sections. As such, there is a limit to the total length of the connected panels, as well as a need to provide expansion joints between connected sections. Use of active or expansion joints has not yet been incorporated into the Kwik Slab system.

Port Authority of New York and New Jersey System

During 2000, PANY/NJ investigated the use of PCP to rehabilitate Taxiway A at La Guardia International Airport. PANY/NJ considered use of precast paving to rehabilitate sections of a taxiway over several 55-hour weekend closures. PANY/NJ constructed two 200-ft (61-m) test sections at a noncritical taxiway during 2002. One test section used nominally reinforced 16-in. (400-mm)-thick, 12.5 × 25 ft (3.8 × 7.6 m) panels, and the second test section used 12-in. (300-mm)-thick, 12.5 × 25 ft (3.8 × 7.6 m) prestressed panels. The two systems were developed as generic systems. A unique feature of this system is that the panel elevation was controlled using threaded setting bolts, and a 0.5- to 1-in. (13- to 25-mm) gap was maintained under the panels. The gap was then filled with fast-setting cementitious grout. Another unique feature was that the dowel slots were fabricated at the plant. The panels used and the installation process are shown in Figure 2.7. PANY/NJ continues to evaluate

Figure 2.12. Kwik Slab joint interlocking system.

the performance of the two test sections as they are subjected to aircraft loadings.

Highway Agency–Developed Systems

Highway agencies have shown increased interest in developing generic PCP systems, not only because many states prohibit procurement of proprietary products, but also to encourage competitive bidding. In such cases, the highway agencies have developed end-product specifications or have developed plans and specifications for nonproprietary systems. The Illinois Tollway and the Utah DOT have developed nonproprietary systems.

The Illinois Tollway began specifying the Tollway-developed intermittent repair system or equivalent for projects beginning in 2010. The Tollway-developed system uses standard panel details for panels 6 ft (1.8 m) long and 12 to 14 ft (3.7 to 4.3 m) wide and allows use of customized panels as needed. Figure 2.13 shows a drawing for one of the standard panel designs developed by the Tollway (left) and a trial installation of the system (right). A test section was installed along a ramp during 2010, and additional installations of this system were planned for 2012.

The nonproprietary system developed by the Utah DOT had a trial installation planned for June 2010, with additional installations planned for 2011. The precast panels in this system are positioned at the desired elevation using a threaded setting bolt system, similar to the PANY/NJ-designed system. The gap between the panel and the base is filled with fast-setting cementitious grout. The DBR technique is used for joint load transfer after the panels are set. A 600-ft-long section of I-215 was rehabilitated using this technique during June 2011. Figure 2.14 shows an illustration of the Utah DOT system (left) and a photograph of the installation process (right).

Non-U.S.-Developed Precast Concrete Pavement Systems

Several countries have implemented or are investigating the use of PCP technologies. These systems and approaches are discussed next.

The Netherlands

A proprietary PCP technology referred to as the ModieSlab was developed in 2001 in the Netherlands in response to the Roads to the Future program challenge sponsored by the Dutch Ministry of Transport (Bax et al. 2007). As initially conceived, the ModieSlab system was designed as a bridge system with a design life of 100 years. The system incorporated short panels (11.8 ft [3.6 m]) supported by precast concrete beams placed over precast foundation piles. The first pilot project was installed in 2001 at an access road to a rest area along the A50 motorway near Apeldoorn in the Netherlands. The ModieSlab concept has evolved since

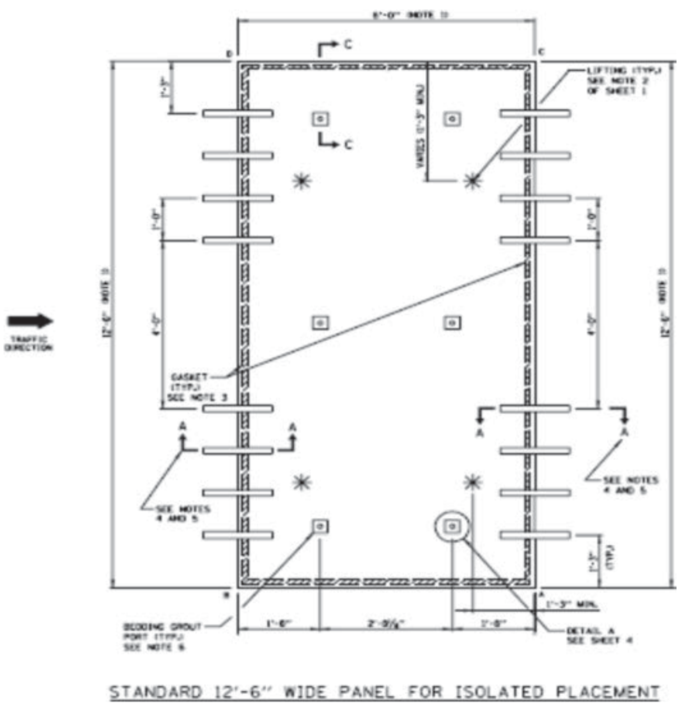


Figure 2.13. Illinois Tollway intermittent repair system.

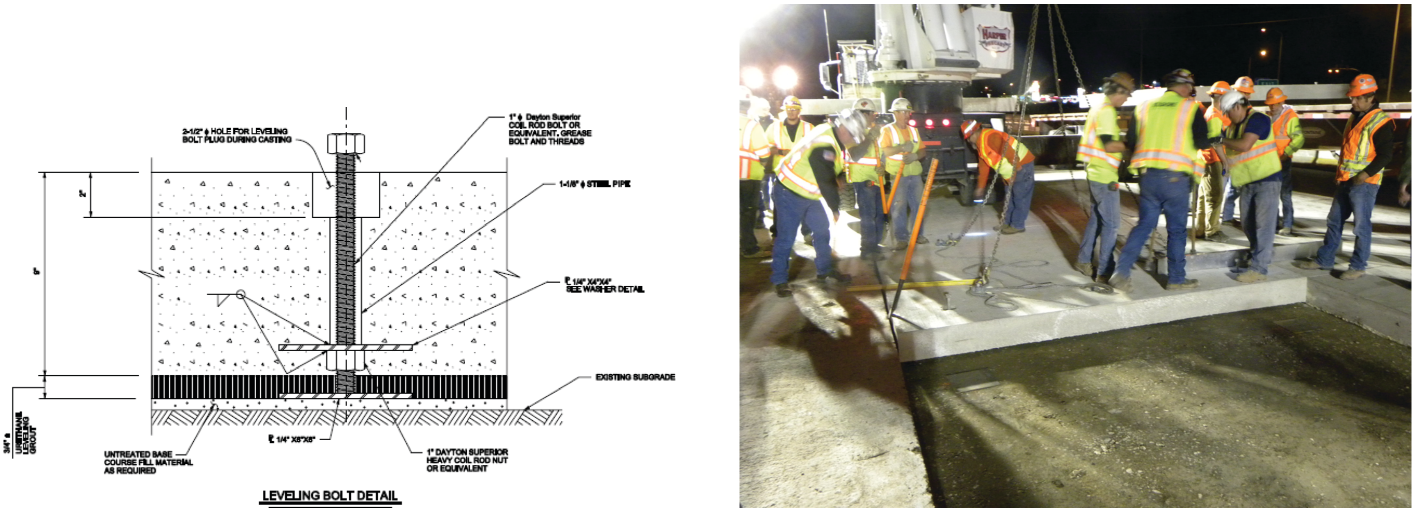


Figure 2.14. Utah PCP system.

then with additional demonstration projects along sections of the A12 motorway near Utrecht, a bus–tramway in Belgium, and at-grade applications. For at-grade applications, a feature was developed to provide load transfer across joints.

For bridge-type applications or for use over poor soil conditions, the panels are 15 in. (380 mm) thick and consist of a 12.25-in. (311-mm) high-quality base concrete with two-layer reinforcement topped by a 2.75-in. (70-mm)-thick two-layer porous concrete. A fine-grained porous layer is used on the surface because a fine texture reduces the amount of tire–pavement noise. The second porous layer uses coarser aggregates; the larger pores allow water coming through the porous surface layer to drain easily and prevent clogging of the surface layer. ModieSlab has been tested in LINTRACK, the accelerated load testing facility at Delft University, to investigate the structural integrity of the system (Houben 2004). In general, the researchers reported a positive technical and economical experience with this technology.

Russia

PCP technology was developed in Russia in the 1960s during the Soviet Union era and is used for roads in the northern and hard-to-reach areas of Russia, including oil- and gas-field access roads and access roads to industrial and agricultural facilities. PCP road construction expanded intensively after the 1970s, reached a peak in the 1980s and 1990s, and continues until the present due to the continued need for access roads to the Western Siberia oil and gas fields. More than 3,728 mi (6,000 km) of roads were paved with PCP in Western Siberia between the 1960s and 1980s. In urban areas, PCPs are used in exceptional cases only, along small stretches of secondary streets and primarily in smaller cities that have facilities to produce the precast concrete panels. The PCPs are typically overlaid with asphalt concrete (AC) or machine "milled" to correct the profile.

The PCP technology, although simple in concept, incorporates several unique features, such as electrothermic prestressing, use of thinner panels, and a unique method for connecting panels. The technology has been standardized at the national level in Russia. Standard dimensions of the PCP panels are 6.5 × 13.12 ft and 6.5 × 19.6 ft (2 × 6 m and 2 × 4 m). The road slabs are 6.3, 7.0, 7.8, and 8.6 in. (16, 18, 20, and 22 cm) thick; the panel brands are PDN-16, PDN-18, PDN-20, PDN-22, PAG 14, and PAG 16. The panel concrete is prestressed by stretching longitudinal steel rods using the electrothermic process, followed by force transfer to the hardened concrete. This PCP technology has been widely used for airfield applications in Russia and was used previously in the Soviet Union (Sapozhnikov and Ray 2007).

A unique aspect of the Russian system is the use of lifting loops positioned along the long edge of the panels. These lifting loops are welded together. Good welding technique is mandatory. If the spacing between the adjacent loops is 0.15 in. (4 mm) or less, the loops are welded together in a single weld. If the spacing is greater than 0.15 in., a reinforcing bar whose diameter is three to four times greater than the gap is placed on the lifting loops and two welds are made, as shown on the right in Figure 2.15.

Japan

PCPs were used in Japan for production paving at container yards and airports in the early 1970s, and by the early 1990s researchers began examining the use of PCP for roadway applications. Early projects were constructed using reinforced concrete panels on stabilized bases, but without load transfer at joints. Later projects incorporated the prestressing

Figure 2.15. Soviet-era precast panels (left) and lifting loops with reinforcing bar (right).

technology. Typically, for roadway applications, the PCP is placed on an asphalt interlayer to prevent pumping in the granular base course underneath. Gaps between the slabs and interlayer are filled with a grouting material. The standard dimensions of the slab are 4.9 ft (1.5 m) wide by 18 ft (5.5 m) long by about 8 to 10 in. (200 to 250 mm) thick.

For tunnel applications, it has been reported that when the surface of the precast panel is worn, the panels are turned over and reused. For airport applications, the precast panels are about 8 ft (2.4 m) wide, 47 ft (14.3 m) long, and 10 in. (250 mm) thick. The panels are prestressed (pretensioned) in the long direction. Examples of PCP projects are shown in Figure 2.16 (Nishizawa 2008).

The use of PCP increased in Japan when a special load transfer system called the "horn device" was developed (Hachiya et al. 2001). The jointing for airfield pavements typically incorporates a compression joint device (Hachiya et al. 2001). For the compression joint device, stressing tendons (unbonded) are installed through the joint, tensioned to a predetermined force, and fixed at both ends to the slabs. The compression joint device is considered to be more efficient in transferring the load across the joint and allows easier replacement of damaged panels.

Another PCP joint load transfer innovation introduced in Japan is the sliding dowel bar joint concept (Tomoyuki 1996).

France

In France, in the pursuit of "removable urban pavements," researchers at the Pont et Chaussées Laboratories (LCPC), in cooperation with other French organizations, have developed a hexagonal-shaped PCP system (CERTU, LCPC, and CIMBÉTON 2008; de Larrard 2006; de Larrard et al. 2013). A unique advantage of the French PCP is that the base course used is easy to place and grade and can be worked with light equipment available locally. A second type of hexagonal

Figure 2.16. Roadway in Kasugai City (left) and applications at Osaka Airport (right) in Japan.

Figure 2.17. Installation of keyed hexagonal panels in France.

PCP has also been developed. The panels for this system are smaller in size and incorporate keyed joints to provide some level of load transfer at the joints. According to the LCPC experts, the size, base support, and optional keyway connections between panels allow the PCPs to carry 1,500,000 truck loadings. The system was tested successfully at an accelerated load testing facility. Views of the French hexagonal PCP are shown in Figure 2.17.

Indonesia

During 2008, a PPCP project was completed on a portion of the Kanci-Pejagan Toll Road near Cirebon on the island of Java in Indonesia (Nantung et al. 2010). The four-lane project, which is about 22 mi (35 km) in length, is located between the seaport city of Cirebon (a north coastal city of the West Java province) and Semarang (a north coastal city of the Central Java province). This particular toll road will become a section that connects the Trans-Java Toll Way System, which will have a total length of more than 515 mi (829 km). The PPCP design was based on the PPCP practices used in the United States, principally the pilot PPCP project constructed in Georgetown, Texas. The final design selected for the Cirebon required 8-in. (200-mm)-thick panels placed over a 2-in. (50-mm) lean concrete base (LCB). This project was the first large-scale use of the PPCP system and was the first PPCP project to be constructed in a remote area. The panels, as fabricated, were 8.2 ft (2.5 m) long × 27 ft (8.2 m) wide. Thirty-seven panels were posttensioned together to result in PTSections 320 ft (97.5 m) long. Typically, 40 panels were placed each day. Panel installation views are shown in Figure 2.18.

The toll agency is planning to use the PPCP system over additional lengths of the new toll roadway. In addition, several Indonesian agencies are investigating the use of PPCP to rehabilitate existing pavements, typically asphalt pavements, in congested urban areas. One innovation being tested in Indonesia is the use of end prestressing at the joint face together with the use of CIP reinforced gap slabs.

Figure 2.18. Indonesia PPCP installation.

North American Precast Concrete Pavement Use

Since about 2000, many highway agencies in North America have expressed interest in using precast concrete panels for intermittent repair or continuous applications in heavily trafficked urban areas where extended lane closures are difficult. The following U.S. and Canadian highway agencies have accepted the use of PCP for production work:

1. Caltrans;
2. Illinois Tollway Authority;
3. Iowa DOT (as an alternate for bridge approach slabs);
4. Ministry of Transport, Ontario;
5. Ministry of Transport, Quebec;
6. New Jersey DOT;
7. New York State DOT;
8. New York State Thruway Authority; and
9. Utah DOT.

The following U.S. agencies have investigated or are investigating use of PCP:

1. Colorado DOT;
2. Delaware DOT;
3. Florida DOT (demonstration project planned for construction in 2011);
4. Various Hawaiian agencies;
5. Indiana DOT;
6. Michigan DOT;
7. Minnesota DOT;
8. Missouri DOT;
9. Nevada DOT;
10. Pennsylvania DOT;
11. Texas DOT;
12. Virginia DOT;
13. Airport authorities
    a. Port Authority of New York and New Jersey
    b. Metropolitan Washington Airport Authority; and
14. U.S. Air Force.

The major U.S. and Canadian PCP projects are listed in Appendix A.

Summary

PCP technology and use in the United States have evolved dramatically over the past 10 years. There is considerable U.S. interest in implementing the technology, and the construction industry is gearing up to take advantage of the potentially large market being created for rapid repair and rehabilitation of existing pavements.

CHAPTER 3

Performance of Installed Precast Concrete Pavements

General

The early effort under Project R05 identified a serious lack of field performance data from installed PCP systems. Only a limited amount of field monitoring of installed PCPs had been carried out by highway agencies, and existing field data were generally not publicly reported. The lack of well-documented data on the performance of the installed PCP projects has resulted in many questions related to PCP field performance and has detracted from wider implementation of PCP technology.

Two significant efforts to evaluate PCP performance include the accelerated pavement testing sponsored by Caltrans (Kohler et al. 2007) and the instrumentation of the PPCP project in Missouri sponsored by the Missouri DOT and FHWA (Gopalaratnam et al. 2007). These projects are discussed in greater detail below.

FHWA has published construction reports on several PPCP demonstration projects that document the items related to fabrication and installation of the precast panels and specific issues that were addressed. These reports provide useful discussion on lessons learned during the construction of the documented PPCP projects. The construction of the early intermittent repair projects and continuous jointed PCP has also been documented (Buch 2007; Lane and Kazmierowski 2005; Smith and Barenberg 2005).

To obtain a better understanding of the performance of PCP projects, field testing was conducted under Project R05 at selected PCP installations. The testing was conducted in cooperation with participating highway agencies. This chapter documents the information available on the performance of the installed PCP projects and summarizes the results and findings from the Project R05 field testing.

Caltrans Accelerated Precast Pavement Testing

In May 2005, the Super-Slab JPrCP system was tested in San Bernardino County in Southern California (Kohler et al. 2007). The purpose of the installation was to evaluate the system through accelerated pavement testing using a heavy-vehicle simulator. The test site consisted of two lanes with five panels in each lane. The details of the test slab installation were developed to mirror the pavement details of a project that was being considered by Caltrans. Traffic loads were applied at the beginning of the experiment to each section to simulate the exposure to traffic from the time of placement of the slabs to the time of grouting, which would normally occur during the next nighttime closure. Later, the sections were loaded for extended periods under different loading conditions. The following conclusions were drawn from the heavy-vehicle simulator testing:

1. The Super-Slab system of precast panels can be safely opened to traffic in the ungrouted condition; that is, panels can be installed over consecutive nights rather than completing the entire installation at one time. The existing pavement slabs can be removed and the precast panels can be placed in one night, and the grouting of the dowel slots and panel undersealing can be completed the following night;
2. The service life of this PCP system, if used as tested, was estimated to be between 140 million and 240 million equivalent single-axle loads (ESALs). This estimate is based on the estimated traffic applied in Section 2, which did not fail, and in Section 1, which failed under very heavy load levels. Taking as an example the I-15 highway in San Bernardino County, California, this number of ESALs can be assumed to be equivalent to more than 25 years of service, and up to about 37 years before reaching structural failure; and

3. The failure mechanism for this PCP system was similar to failure in CIP-JCP. Corner cracks, which result from loss of support, created conditions indicative of the end of usable pavement life.

Missouri Precast Pavement Instrumentation

For the Missouri I-57 PPCP demonstration project, constructed near Sikeston, Missouri, an extensive instrumentation and monitoring program was conducted by the University of Missouri–Columbia. The panels for this project were fabricated in Tennessee between October and mid-December 2005, and panel installation took place between December 12 and 20, 2005. The purpose of the instrumentation program was to monitor pavement performance through construction and during service to verify the assumptions made during the design process and to evaluate the overall PPCP fabrication and installation processes. Key activities of the instrumentation program were as follows (Gopalaratnam et al. 2007):

- Measuring concrete properties;
- Monitoring hydration temperatures and curing strains at the fabrication plant;
- Measuring strains during prestress transfer at the fabrication plant;
- Measuring strains during posttensioning on site; and
- Measuring in-service slab temperatures and strains.

The instrumentation provided data on tendon strains for posttensioning assessment. However, no definitive data were developed for the prestress distribution in the concrete for the panels instrumented. Gopalaratnam et al. noted that

> uneven distribution of compressive strains in the concrete from the posttensioning operation was observed. This was likely caused by uneven gaps between the individual panels across the pavement width (joints on the left side of the pavement were generally closed tighter than those on the right side) and also the use of shims between precast panels at the outside edge of the right side of the pavement. (2007)

Lessons Learned from Installed Projects

Lessons learned from PPCP projects are summarized as follows:

1. Posttensioning ducts: One issue observed early in the fabrication process for the Texas PPCP projects was movement of the posttensioning ducts as the concrete was placed in the forms. Even with the bar stiffeners placed in the posttensioning ducts to hold the ducts straight, the movement of a large mass of fresh concrete caused some of the ducts to bow horizontally. This issue was resolved by tying the ducts to the pretensioning strands and by moving the concrete hopper along the length of the panel as concrete was being placed, rather than pouring the concrete at one end and vibrating it down the length of the panel.
2. Strand wires: While pushing the strands through the ducts at the Texas project, friction in the ducts caused some of the strand wires to slide back, leaving only five of the seven wires going through the dead-end anchors. Use of a steel bullet-nose on the end of the strand before pushing it through the duct solved this problem.
3. Alignment of adjacent panels: The misalignment of the ducts, primarily caused by panel misalignment, created difficulties at several projects with pushing strands through at the intermediate transverse joints. These misalignments make it difficult to push the strands through the duct and cause friction between the duct and the strand. It is important to ensure that adjacent panels are aligned well horizontally (transversely). If the strands bind at the intermediate joints, the effective prestress in the concrete is reduced. In addition, panel misalignment will increase the risk of tendon grout leakage at the intermediate joints due to poorly performing gaskets or tendon splice.
4. Steam curing: If the panels are steam cured, care must be taken with exposing the panels to ambient conditions, especially in cooler weather.
5. Strand grout leakage: At several PPCP projects, leakage of strand grout at intermediate joints was an issue. The rubber gasket used at these projects and the epoxy coating at the intermediate transverse keyway joints did not completely prevent grout leakage.

Lessons learned from intermittent repair and JPrCP projects are summarized as follows:

1. Variable thickness of existing slab: The variability of the existing concrete pavement slab thickness should be accounted for when establishing the precast panel thickness. This is very important for pavements that incorporate stabilized bases. If the existing pavement thickness is less than the panel thickness, there is no time available to trim the stabilized base, especially for intermittent repair applications.
2. Importance of existing base: The base type for the existing concrete pavement must be clearly identified. At one project, the slab removal process resulted in removal of the 3- to 4-in. (75- to 100-mm)-thick permeable AC base, which

remained stuck to the pavement slab being removed. As a result, a thicker bedding of fine-grained material had to be used to make up the base grade for one day's panel placement.

3. Base compaction: Observations at a few PCP projects indicate that no effort was made to control the compaction of the granular base (existing or new) and the finer-grained bedding material. Compaction of these materials was attempted, but it was done without regard to controlling the moisture content of the material. At many projects, deep footprints can be observed after final compaction and final grading of the base or bedding materials, indicating poor compaction of these materials.
4. Capping of dowel bars at ungrouted joints: It is important to use dowel caps for any joints at which the joint gap is not filled with cementitious grout. If dowel caps are not used, there is a risk for joint spalling or pavement blowup to occur.

Field Testing Under the R05 Project

Several U.S. highway agencies were asked to support field testing of the installed PCP projects. All agencies contacted agreed to cooperate with the field testing and data collection effort. A summary of the field testing program and the findings from the field testing are reported here.

Precast Pavement Projects Tested

The following precast pavement projects were tested between December 2009 and November 2010:

1. PPCP projects (all based on the Texas PPCP system)
   a. Georgetown frontage road, Texas;
   b. I-57, Missouri;
   c. Route 896, Delaware; and
   d. I-66, Virginia.
2. Continuous jointed PCP projects (all Fort Miller Super-Slab JPrCP system)
   a. Tappan Zee Toll Plaza, New York;
   b. TH-62, Minnesota;
   c. I-66, Virginia;
   d. I-15, California (with and without panel subsealing);
   e. Illinois Tollway (repair or continuous); and
   f. NJ-130, New Jersey (with fiber-reinforced polymer [FRP] dowel bars).
3. Intermittent repair projects
   a. I-295, New Jersey (Fort Miller Super-Slab system);
   b. I-280, New Jersey (Fort Miller Super-Slab system);
   c. I-675, Michigan (Michigan system); and
   d. Route 27, New York (Roman Road system).

Field Testing Plan

The following data were planned for collection at each project to assess the structural and functional performance of the installed and in-service precast pavement systems:

1. Condition data: A visual condition survey looked for specific distresses, including slab panel cracking, joint spalling, poor surface condition (original or ground), joint sealant condition, dowel slot condition, PPCP prestress pocket condition, PPCP joint hardware, and joint grout material condition for the jointed PCP systems. Photographs of representative distresses were obtained.
2. Ride (smoothness): A high-speed profiler was used to determine the section's International Roughness Index values.
3. Joint elevation difference: A Georgia faultmeter was used to ascertain elevation differences. This measure can include the built-in joint elevation difference for newer projects, as well as traffic-related faulting for older projects.
4. Joint width measurement: Joint width was measured for the jointed PCP and PPCP systems.
5. Deflection testing: A falling weight deflectometer (FWD) was used for
   a. Midpanel (basin) testing
   b. Testing at joints (wheelpath) for load transfer effectiveness (LTE) and void detection.

Deflection Testing Protocols

The testing sequences for JPrCP projects (intermittent repair and continuous application) and PPCP projects are described below.

JPrCP Deflection Testing

For JPrCP systems, testing was conducted at the outer wheelpath locations at transverse joints and at the midslab location of the precast panel and control slabs of the existing pavement, as shown in Figure 3.1.

For JPrCP intermittent repair projects, a two-part procedure was followed. A precast panel test was conducted at Locations 1 to 5, as shown in Figure 3.1. In addition, testing was conducted at the first existing slab panel that was not adjacent to a precast panel, using only Locations 6, 7, and 8 (Figure 3.1).

For continuous application projects, testing was conducted for as many precast panels as possible within the allowable traffic closure period. The sequence of testing was Locations 1, 2, and 3, as shown in Figure 3.1, for each panel. The number of load drops and the target load levels used are shown in Table 3.1. The LTE test was conducted with deflection sensors located approximately 6 in. (150 mm) from the center of

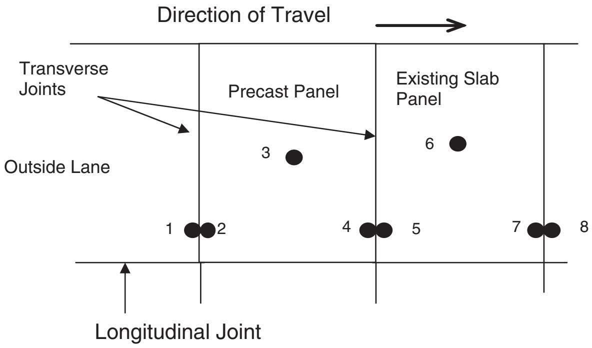


Figure 3.1. FWD test locations for jointed systems.

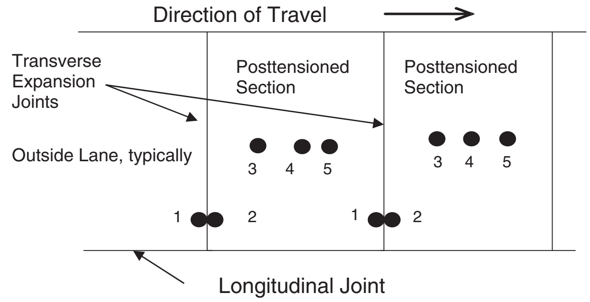


Figure 3.2. FWD test locations for PPCP projects.

the joint on each side and the load located tangential to the joint on the loaded side of the joint. LTE was determined as follows:

$$\text{LTE}(\%) = (\text{deflection unloaded joint side}/\text{deflection loaded joint side}) \times 100$$

The interior (basin) load test was conducted at an approximate midslab location for Locations 3 and 6. The test loads were the same as shown in Table 3.1. Deflection sensors were spaced at 12-in. (305-mm) intervals, and a minimum of six sensors, including the load plate sensor, were used. The number of precast panels tested at a site was governed by the site access conditions. The plan was to test at least 20 precast panels and at least 10 existing slab panels.

PPCP Deflection Testing

For PPCP systems, testing was typically conducted at the outer wheelpath locations at transverse expansion joints of the outside lane and at several midslab locations of the PTSections, as shown in Figure 3.2. At the Missouri and Delaware projects, similar testing was also conducted on several conventional JCP slabs.

Table 3.1. LTE Test Load Levels

Drop No.	No. of Drops	Target Load [lbf (kN)]
Seating	2	9,000 (40.0)
1	2	6,000 (26.7)
2	2	9,000 (40.0)
3	2	12,000 (53.4)
4	2	15,000 (66.7)

The number of load drops and the target load levels for the PPCP testing were the same as shown in Table 3.1. LTE testing was performed similarly to the procedure used for the jointed precast pavements. The interior (basin) tests were conducted at Locations 3, 4, and 5. Deflection sensors were spaced at 12 in. (305 mm); a minimum of six sensors were used, including the load plate sensor. LTE testing was planned for all expansion joints, and basin testing was planned within all PTSections.

Testing of Intermittent Repair Projects

I-295, New Jersey

Precast panel repairs were installed on I-295 in New Jersey between late 2007 and mid 2008. Panel details are as follows:

- Precast pavement system: FMC's Super-Slab system;
- Panel thickness: 8.75 in. (222 mm) (existing JRCP thickness was 9 in. [229 mm]);
- Panel dimensions: length: 8, 10, or 12 ft (2.4, 3.0, or 3.7 m); width: 12 ft (3.7 m);
- Number of panels installed: 277;
- Base: existing sandy granular base;
- Joints: doweled transverse joints with longitudinal joints not tied;
- Traffic level: high-volume freeway traffic with heavy truck volume (~140,000 vehicles per day [vpd]); and
- Existing JRCP joint spacing: 78 ft (24 m).

The project was tested during the daytime in April 2010. Twenty precast panels and 20 existing pavement slab panels (adjacent to the precast panels) were tested. Two of the 20 precast panels tested exhibited tightly held cracking. There was no evidence of faulting at the transverse joints between the precast panels and the existing pavement. However, the precast panels exhibited settlement (as measured along the outside longitudinal joint) of up to 1 in. (25 mm). This slab settlement also corresponded to a transverse crack in the leave side of the existing slab panel located about 8 to 12 ft (2.4 to 3.7 m) from the end of the repair. The pavement condition is shown in Figure 3.3.

The deflection at the transverse joints between the precast panels and the existing pavement averaged about 6 mils (0.15 mm) for a normalized 9,000-lbf (40-kN) load; LTE at these joints averaged about 80%. However, the panel settlement indicates that a better technique may be needed for preparing the bedding when granular bases are used, as these bases, if disturbed during removal of the existing pavement slab, cannot be effectively recompacted as part of the precast panel installation process.

I-280, New Jersey

Precast panel repairs were conducted between mid 2008 and mid 2009 on I-280 in New Jersey. Panel details are as follows:

- Precast pavement system: FMC's Super-Slab system;
- Panel thickness: 8.75 in. (222 mm) (existing JRCP thickness was 9 in. [229 mm]);
- Panel dimensions: length: 8, 10, or 12 ft (2.4, 3.0, or 3.7 m); width, 12 ft (3.7 m);
- Number of panels installed: 281;
- Base: existing sandy granular base;
- Joints: doweled transverse joints with longitudinal joints not tied;
- Traffic level: heavy commuter traffic with a large volume of trucks; and
- Existing JRCP joint spacing: 78 ft (24 m).

The project was tested during the nighttime in April 2010. Ten precast panels and 10 existing JRCP slab panels (adjacent to the precast panels) were tested. At the time of testing the project had been milled in anticipation of an AC overlay. Overall condition of the repair panels tested appeared to be good, considering the surface had been milled. The joint condition could not be determined because of the milling and the nighttime condition. The pavement condition is shown in Figure 3.4.

The deflection at the transverse joints between the precast panels and the existing pavement averaged about 7 mils (0.17 mm) for a normalized 9,000-lbf (40-kN) load; LTE at these joints averaged about 82%. The panel settlement was similar to that noticed at the I-295 project, but it could not be assessed as the project had been milled.

Route 27, New York State

Precast panel repairs were conducted on Route 27 in New York during November 2009. Panel details are as follows:

- Precast pavement system: Roman Stone Construction Company's Roman Road system (first project);
- Panel thickness: 8 in. (203 mm) (existing JRCP thickness was 9 in. [229 mm]);
- Panel dimensions: length: 6, 8, or 10 ft (1.8, 2.4, or 3.0 m); width: 12 ft (3.7 m);
- Number of panels installed: 35;
- Base: existing granular base (sandy loam);
- New bedding material: about 1-in. (25.4-mm)-thick polyurethane foam injected under each panel;
- Joints: doweled transverse joints with longitudinal joints not tied;

Figure 3.3. Views of the I-295 precast panels in New Jersey.

Figure 3.4. Views of the precast panels at the I-280 project in New Jersey.

- Traffic level: moderate traffic with moderate truck volume; and
- Existing JRCP joint spacing: 60.5 ft (18.4 m).

The project was tested during the daytime in May 2010. Twelve precast panels, 2 CIP full-depth patches, and 12 existing pavement slab panels (adjacent to each precast panel and a CIP patch) were tested. There was no cracking in the tested precast panels. The repair panels are shown in Figure 3.5. The joint sealing in the repair was in good condition.

The deflection at the transverse joints between the precast panels and the existing pavement averaged about 7 mils (0.17 mm) for a normalized 9,000-lbf (40-kN) load; LTE at these joints averaged about 70%.

I-675, Michigan Project

Precast panel repairs were conducted on I-675 in Michigan during 2003. Panel details are as follows:

- Precast pavement system: Michigan generic system (demonstration project);
- Panel thickness: 10 in. (254 mm) (existing JPCP thickness was 9 in. [229 mm]);
- Panel dimensions: length: 6 ft (1.8 m); width: 12 ft (3.7 m);
- Number of panels installed: eight (a ninth panel was not installed due to poor fit);
- Base: regraded existing dense granular base;
- Bedding: fast-setting flowable fill concrete (two panels) or injected polyurethane (six panels) (both 1 in. [25.4 mm] thick);

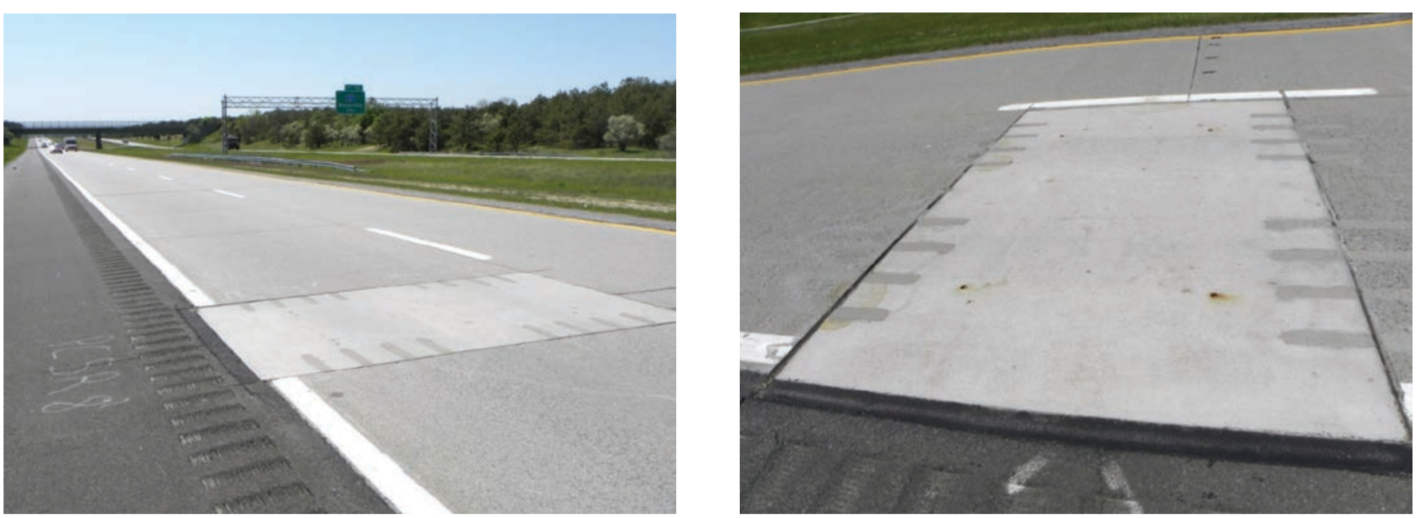


Figure 3.5. Views of the precast panels at the Route 27 project in New York.

Figure 3.6. Views of a deteriorated panel at the I-675 project (planned for replacement) in Michigan.

- Joints: doweled transverse joints (three dowel bars per wheelpath) with longitudinal joints not tied;
- Traffic level: light freeway traffic with a moderate volume of trucks (10,400 vpd with 6% trucks); and
- Existing JRCP joint spacing: 71 ft (22 m).

The project was tested during the daytime in April 2010. Five precast panels (remaining of the nine installed) and six existing pavement slab panels adjacent to the precast panels were tested. Overall performance of the repairs was mixed. A few of the panels had deteriorated and been replaced, and one, shown in Figure 3.6, was planned to be replaced. However, the remaining five panels were still considered to be performing well, as shown in Figure 3.7.

Figure 3.7. View of a well-performing panel at the I-675 project in Michigan.

The deflection at the transverse joints between the precast panels and the existing pavement for the precast panels in service averaged about 8 mils (0.20 mm) for a normalized 9,000-lbf (40-kN) load; LTE at these joints averaged about 80%.

Testing of Continuous Jointed Precast Pavement Systems

Tappan Zee Toll Plaza, New York State

This is the oldest JPrCP project, constructed during October 2001 and July 2002 at the Tappan Zee Toll Plaza in New York. Pavement details are as follows:

- Precast pavement system: FMC's Super-Slab system;
- Panel thickness: 10 in. (254 mm);
- Panel dimensions: length: 18 ft (5.5 m); width: 10 ft (3 m);
- Number of toll plaza drive lanes: 12;
- Number of panels installed: 1,071;
- Base: existing granular base (top 2 in. [51 mm] removed) with 1.5 in. (38 mm) leveling stone dust;
- Joints: doweled transverse joints with longitudinal joints tied;
- Total project area: >40,000 yd^2 (33,445 m^2) (both sides of the toll booths); and
- Traffic level: heavy commuter traffic from the New York City area with a large number of trucks per day (72,000 vpd eastbound through toll plaza).

The project was tested during the daytime in May 2010. The joint seals were in good condition. Some very tight transverse cracking was noted on a few panels but was not

Figure 3.8. Leave (left) and approach (right) views of the Tappan Zee Toll Plaza in New York.

considered to be of concern because of the steel reinforcement in each panel. The pavement condition is shown in Figure 3.8.

The deflection at the transverse joints generally ranged from 4 to 6 mils (0.10 to 0.15 mm) for a normalized 9,000-lbf (40-kN) load; LTE at these joints averaged about 90%.

TH-62, Minnesota

This JPrCP project on TH-62 was constructed in Minnesota during June 2005. Pavement details are as follows:

- Precast pavement system: FMC's Super-Slab system;
- Panel thickness: 9.25 in. (235 mm);
- Panel dimensions: length: 12 ft (3.7 m); width: 12 ft (3.7 m) (single lane of a two-lane roadway; existing adjacent lane was JRCP with 40-ft [12-m] joint spacing);
- Number of panels installed: 18;
- Base: granular base;
- Joints: doweled transverse joints with longitudinal joints not tied to adjacent existing lane;
- Total project length: 216 ft (65.8 m); and
- Traffic level: moderate traffic (Minneapolis International Airport location) with moderate truck volume (63,000 vpd).

The project was tested during the daytime in April 2010. The pavement condition is shown in Figure 3.9. The precast panels did not exhibit any cracking. The joint seals were generally in good condition. However, at a few locations the

Figure 3.9. Views from the Minnesota TH-62 project (precast panels in right-hand lane).

dowel slot grout material in the joint had separated from the panel face, resulting in the appearance of a raveled joint.

The deflection at the transverse joints averaged about 7 mils (0.17 mm) for a normalized 9,000-lbf (40-kN) load; LTE at these joints averaged about 90%.

I-66 Ramp, Virginia

This JPrCP project, along a ramp exiting from I-66 in Virginia, was constructed between August and October 2009. Only the outside lane of the two-lane exit ramp was rehabilitated. The precast pavement section, with typical 15-ft (4.6-m) joint spacing, was tied to the inside lane JRCP, which is 9 in. (229 mm) thick with a joint spacing of 60 ft (18 m). (Note: It is not considered good practice to tie different pavement types with different joint spacing.) Several precast panels were custom fabricated to account for the curvature in the ramp. Pavement details are as follows:

- Precast pavement system: FMC's Super-Slab system;
- Panel thickness: 8.75 in. (222 mm);
- Panel dimensions: length: 15 ft (4.6 m), with a few shorter panels to accommodate ramp curvature; width: 12 ft (3.7 m);
- Number of panels installed: 224;
- Base: existing granular base with up to 0.25 in. (6 mm) of leveling stone dust;
- Joints: doweled transverse joints with inside longitudinal joint (ramp centerline joint) tied to existing JRCP with a joint spacing of 60 ft (18.3 m);
- Total project length: 3,552 ft (1,083 m); and
- Traffic level: moderate commuter traffic from the Washington, D.C., area with low-level truck traffic (55,000 vpd).

Figure 3.10. View of the I-66 JPrCP project in Virginia.

The project was tested during the nighttime in December 2009 before opening to traffic. The pavement condition in May 2010 is shown in Figure 3.10. Some very tight transverse cracking was noted on 52 panels before opening to traffic, but this was not considered to be of concern because of the steel reinforcement in each panel. About 50% of the cracking in the precast panels was associated with a joint or patch in the adjacent JRCP lane and the tying of the two lanes with different joint spacing and different joint or slab behavior. Such a crack is shown in Figure 3.11.

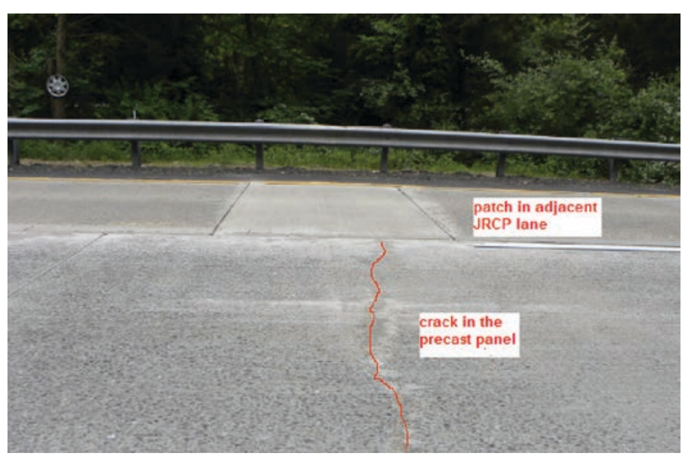


Figure 3.11. Crack in a precast panel associated with a patch in the adjacent lane on I-66 in Virginia.

The deflection at the transverse joints ranged from about 5 to 20 mils (0.13 to 0.50 mm) for a normalized 9,000-lbf (40-kN) load; LTE at these joints averaged about 90%.

I-15, Ontario, California

As part of a rehabilitation project, the outside two lanes of a five-plus-lane roadway on northbound I-15 near Ontario, California, were rehabilitated using PCP. The existing pavement incorporated randomly skewed joints. The PCP project details are as follows:

- Precast pavement system: FMC's Super-Slab system;
- Panel thickness: 8 in. (203 mm);
- Panel dimensions: length: repeat pattern of 15, 13, 14, and 12 ft (4.50, 3.96, 4.27, and 3.66 m); width: 12 and 13 ft (3.66 and 3.96 m) (two outside lanes of a five-plus-lane roadway);
- Number of panels installed: 730;
- Base: cement-treated base (CTB). The CTB was milled as necessary to ensure that a minimum 0.5-in. (13-mm) bedding layer of washed concrete sand could be placed;
- Joints: doweled transverse joints with longitudinal joints not tied to the adjacent existing lane;

Figure 3.12. View of the I-15 JPrCP project in California.

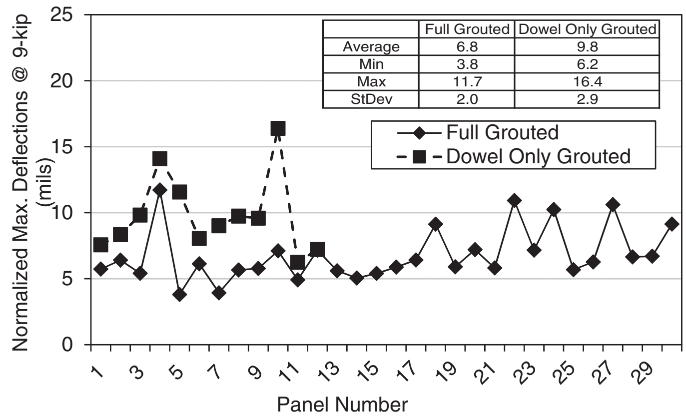


Figure 3.13. Normalized maximum deflections for interior testing of I-15 JPrCP project in California.

- Total project length: ~1.8 lane miles (2.9 km); and
- Traffic level: heavy traffic with high-volume truck traffic.

The project was tested during the daytime in June 2010. The tested panels were behind a safety barrier and had not been subjected to traffic. The overall PCP condition in June 2010 is shown in Figure 3.12.

Deflection testing was conducted along two sections of the precast panels. One section, with 30 panels, had the dowel slots grouted and the panel undersealing performed. The second section, with 12 panels, had only the dowel slots grouted. An objective of the deflection testing was to determine if there was a difference in the deflection response between the two sections.

Figure 3.13 shows the normalized deflections and their statistics for the interior testing. The fully grouted precast panels had an average of 3 mils less interior deflection than the precast panels with only the dowel slots grouted.

Figure 3.14 shows the normalized deflections for the joint testing. The fully grouted precast panels had on average 5 mils less joint deflection than the precast panels with only the dowel slots grouted. The panels with only dowel slot grouting exhibited higher variation in the joint deflection.

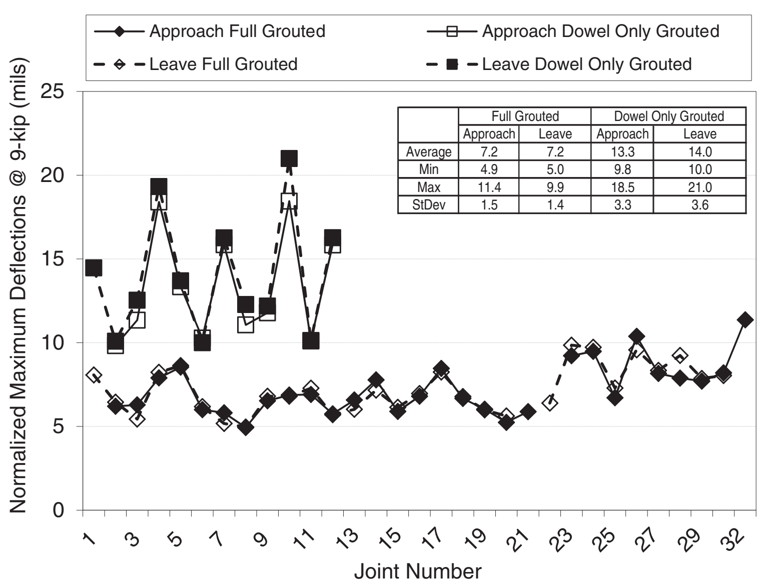


Figure 3.14. Normalized maximum deflections for joint testing of I-15 JPrCP project in California.

All tested precast panels exhibited very good LTE (averaging about 90%), indicating that regardless of the support condition, the load transfer along the joints was well established. For this project, the deflection testing indicated that the bedding grout (undersealing) significantly reduced both the interior and joint deflection. The interior load test data suggest that the sand bedding at the undersealed locations did not appear to affect the structural response. The interior test deflection values measured at this project were similar to values measured at other PCP projects. However, the sections tested had not been trafficked at the time of testing. A few months after the PCP installation was completed, a large number of panels developed cracking. An investigation of the cause of the cracking was undertaken in June 2011.

NJ-130, Trenton Area, New Jersey

FWD testing and visual condition surveys were performed along two JPrCP test sections of the four-lane divided Route 130 near Trenton, New Jersey. The precast panel continuous repairs were conducted during October 2010. Panel details are as follows:

- Precast pavement system: FMC's Super-Slab system;
- Panel thickness: 8.75 in. (222 mm) (existing JRCP thickness was 9 in. [229 mm]);
- Panel dimensions: length: 8 or 12 ft (2.4 or 3.7 m); width: 12 ft (3.7 m);
- Number of panels installed
  - 14 with 1.25-in. (32-mm)-diameter epoxy-coated steel dowels spaced at 12 in. (305 mm) (northbound lane)
  - Seven with 1.5-in. (38-mm) FRP dowels spaced at 12 in. (305 mm) (southbound lane);
- Base: existing sandy granular base;
- Joints: doweled transverse joints with longitudinal joints tied at centerline; 11 dowels per joint with first dowels 12 in. (305 mm) from panel edge;
- Traffic level: suburban traffic with light truck volume; and
- Existing JRCP joint spacing: 78 ft (24 m).

Deflection testing was conducted along the two sections of this PCP project. An objective of the deflection testing was to determine if there was a difference in the deflection response between the two sections incorporating different types of dowel bars. Figure 3.15 shows the normalized joint deflections for the panels with steel dowels and FRP dowels. The statistics for steel dowel joints are for joints JS 1 through JS 15, and those for FRP joints are for joints JF 1 through JF 6. The joints with FRP dowels exhibited deflections approximately 1.5 mils higher than those with steel dowels. Figure 3.16 shows the LTE values for all the tested joints. The LTE values were consistently good for both dowel types.

Testing of Continuous PPCP Projects

Georgetown, Texas

This is the oldest U.S. PPCP project, constructed during November 2001 in Georgetown, Texas. Pavement details are as follows:

- Panel thickness: 8 in. (203 mm);
- Panel dimensions: length: 10 ft (3 m); width: 16, 20, or 36 ft (5, 6, or 11 m) (two 12-ft [3.7-m] lanes and 4- and 8-ft [1.2- and 2.4-m] shoulders);

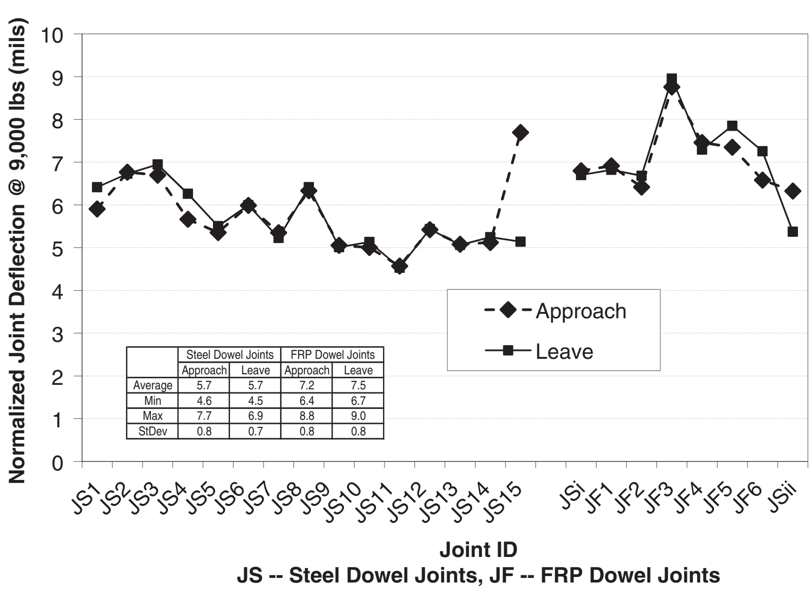


Figure 3.15. NJ-130 normalized joint deflections.

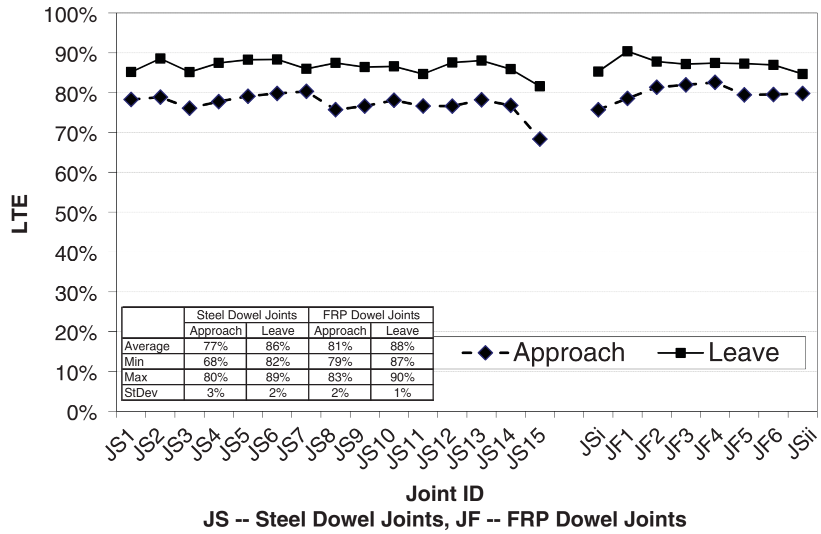


Figure 3.16. NJ-130 LTE data.

- Base: asphalt-treated base;
- Panel–base interface: polyethylene sheet;
- Number of panels in a PTSection: 25 (typical), 32 (first section), and 22 (last section);
- Posttensioning method: from midsection location;
- Total project length: 2,300 ft (701 m) (both sides of a bridge);
- Number of expansion joints: 11 (including one each at the beginning and end); and
- Traffic level: light with few trucks per day; one-way traffic.

The project was tested at night in December 2009 and during daytime in January 2010. Overall condition of the project was good. There was tight longitudinal cracking in a few 36-ft (11-m)-wide panels. The expansion joint seals were not in good condition. The seals were torn, and the expansion joints were filled with debris. Joint widths at the time of the daytime testing ranged from 0.8 to 3.1 in. (20 to 79 mm). The temperature during the daytime testing was about 55°F (13°C). The pavement condition is shown in Figure 3.17.

The deflection testing indicated that the LTE at the expansion joints, as shown in Table 3.2, was poor. Load level was 9,000 lbf (40.0 kN).

I-57, Missouri

This PPCP project was constructed on I-57 in Missouri during December 2005. Pavement details are as follows:

- Precast pavement system: PPCP;
- Panel thickness: 5.625 in. (143 mm) (outside shoulder edge) to 10.875 in. (276 mm) (at centerline) due to cross slope. The panels tapered to 7.5 in. (190 mm) at the inside edge;
- Panel dimensions: length: 10 ft (3 m); width: 38 ft (12 m) (two 12-ft [3.7-m] lanes and 4- and 10-ft [1.2- and 3-m] shoulders);
- Base: permeable asphalt-treated base;
- Panel–base interface: polyethylene sheet;
- Number of panels in a PTSection: 25;
- Posttensioning method: from expansion joints;
- Total project length: 1,010 ft (308 m);
- Total number of expansion joints: five (including one each at the beginning and end); and
- Traffic level: moderate, with a high level of trucks per day.

The project was tested during daytime in March 2010. Overall condition of the project was good. The expansion joints along this project had been reconstructed during October 2009. The sealant material was in good condition. Many panels exhibited transverse or longitudinal cracking or both. The transverse cracking was generally located within the two driving lanes and did not continue all the way to the edges of the shoulders. The joint width at the time of the daytime testing was about 2 in. (51 mm), and the temperature during testing was about 60°F (16°C). The pavement condition is shown in Figure 3.18. Spalling was observed at the intermediate transverse joints at a few locations. A spall resulting from high steel location and steel corrosion is shown in Figure 3.19.

LTE at the expansion joints averaged about 70%. The joint deflections at the expansion joints ranged from about 7 to 8 mils (0.178 to 0.203 mm) for the 9,000-lbf (40.0-kN) load level. Joint deflections for the 9,000-lbf (40.0-kN) load at the PPCP expansion joints, the PPCP interior keyway joints (between individual 10-ft [3-m]-long panels), and at transverse joints of the adjacent JPCP section are shown in

Figure 3.17. Georgetown, Texas, PPCP project views.

Table 3.2. Load Transfer Efficiency Data

Joint	Nighttime LTE Testing	
	Approach Side (%)	Leave Side (%)
1	4	3
2	17	14
3	17	8
4	15	26
5	18	38
6	41	20
7	31	21
8	11	40
9	17	13
10	15	9
11	20	22

Figure 3.18. PPCP-reconstructed expansion joint on I-57 in Missouri.

Figure 3.19. Spalling at an intermediate transverse joint on I-57 in Missouri.

Figure 3.20. The deflections at the PPCP expansion joints are about two times the deflections at the transverse joints of the adjacent JPCP section. Also, the deflection at an interior joint in PPCP Section 2 was very high, as shown in Figure 3.20. There is a transverse crack in one of the panels adjacent to that joint. LTE at this interior joint was about 30%, compared with an LTE of about 90% to 95% for the other PPCP interior joints tested. The deflection data indicate that there may not be adequate residual prestress at the midsection location in that section.

Route 856, Delaware

This PPCP project was constructed at an intersection on Route 856 in Delaware from May to July 2009. One section (with 24-ft [7.3-m]-wide panels) comprised a left-hand turn, and one section incorporated through traffic and a right-hand turn. Pavement details are as follows:

- Precast pavement system: PPCP;
- Panel thickness: 8 in. (203 mm) (replacement of an existing 12-in. [305-mm]-thick JRCP);
- Panel dimensions: length: 9 ft 10 in. (2.9 m); width: 12 ft (3.7 m) (single lane) and 24 ft (7.3 m) (two lanes or lane and shoulder);
- Base: 4-in. (102-mm)-thick permeable CTB;
- Panel–base interface: geotextile fabric;
- Number of panels in a PTSection: 12, 13, or 14;
- Posttensioning method: from expansion joints;
- Total project length: about 1,280 ft (390 m) (1,044 ft [318 m] right-turn lanes and 236 ft [72 m] left-turn lanes);
- Number of expansion joints: nine in right-turn-lane section and three in left-turn-lane section (including one each at the beginning and end for each section); and
- Traffic level: moderate with few trucks per day.

This PPCP project was tested during daytime in April 2010. Five panels of the existing 12-in. (305-mm)-thick JRCP were also tested. Overall condition of the PPCP project was very good. There were a few partial-depth patches used to repair damage to the panels during installation. The expansion joint seals were in good condition. The joint width at the time of the daytime testing was about 1.5 in. (38 mm), and the temperature during testing was about 78°F (26°C). The PPCP condition is shown in Figure 3.21.

The deflection data for the outer wheelpath test indicated an LTE at the expansion joints of about 60% to 70%, compared with an LTE at the existing JRCP joints of 50% to 70%. Joint deflections ranged from about 6 to 10 mils (0.152 to 0.254 mm)

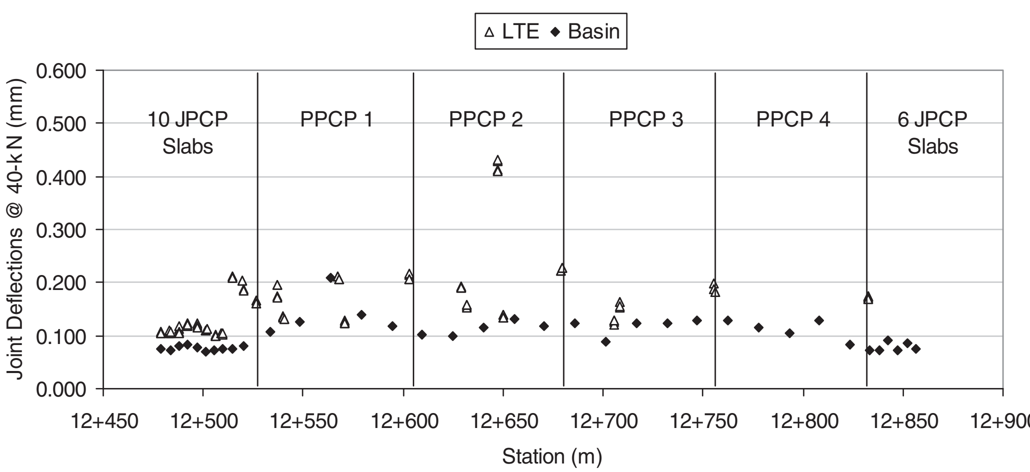


Figure 3.20. Average deflections at transverse joints with a 9,000-lb (40.0-kN) load level.

Figure 3.21. Views of the Route 856 PPCP project in Delaware.

for the 9,000-lbf (40.0-kN) load level, compared with 4 to 7 mils (0.102 to 0.178 mm) for the existing JRCP. Basin testing resulted in maximum deflections of about 4 to 12 mils (0.102 to 0.305 mm) for the 9,000-lbf (40.0-kN) load level, compared with about 2 mils (0.050 mm) for the existing JRCP.

I-66, Virginia

This is the newest PPCP project, constructed between August and October 2009 on I-66 in Virginia. Pavement details are as follows:

- Precast pavement system: PPCP;
- Panel thickness: 8.75 in. (222 mm);
- Panel dimensions: length: 10 ft (3 m); width: 12 ft (3.7 m) (two inside lanes) and 27 ft (8.2 m) (two 12-ft [3.7-m] outside lanes and a 3-ft [0.9-m] shoulder);
- Base: existing aggregate with up to 0.5 in. (13 mm) of leveling stone dust;
- Subbase: 6-in. (152-mm) cement-stabilized subgrade;
- Panel–base interface: geotextile fabric;
- Number of panels in a PTSection: 11 (end sections) or 16;
- Posttensioning method: from expansion joint stressing pockets;
- Total project length: 1,020 ft (311 m);
- Number of expansion joints: eight (including one each at the beginning and end); and
- Traffic level: heavy commuter traffic (Washington, D.C., area) with a large number of trucks per day (184,000 vpd with 5% trucks).

The project was tested at night in December 2009 before opening to traffic. Overall condition of the project as of May 2010 was good. The expansion joint seals were in good condition. The joint width for the I-66 project was not measured. The pavement condition is shown in Figure 3.22. The outermost lane (a peak-hour lane) and the 3-ft (0.9-m) shoulder have been treated with an asphaltic surfacing material.

The deflection testing was conducted in the inner wheelpath of Lane 3 (third lane from the median side with 27-ft [8.2-m]-wide panels) as a result of construction activity in the outermost lane. Test data for the inner wheelpath test indicated an LTE at expansion joints of about 75% to 90%. Joint deflections ranged from about 15 to 30 mils (0.381 to 0.762 mm) for the 9,000-lbf (40.0-kN) load level and are considered very high compared with basin test deflections. Void analysis indicated 5 to 15 mils (0.127 to 0.381 mm) of voids under the joints. Basin testing resulted in maximum deflections of about 3 to 6 mils (0.076 to

Figure 3.22. View of the I-66 PPCP project in Virginia.

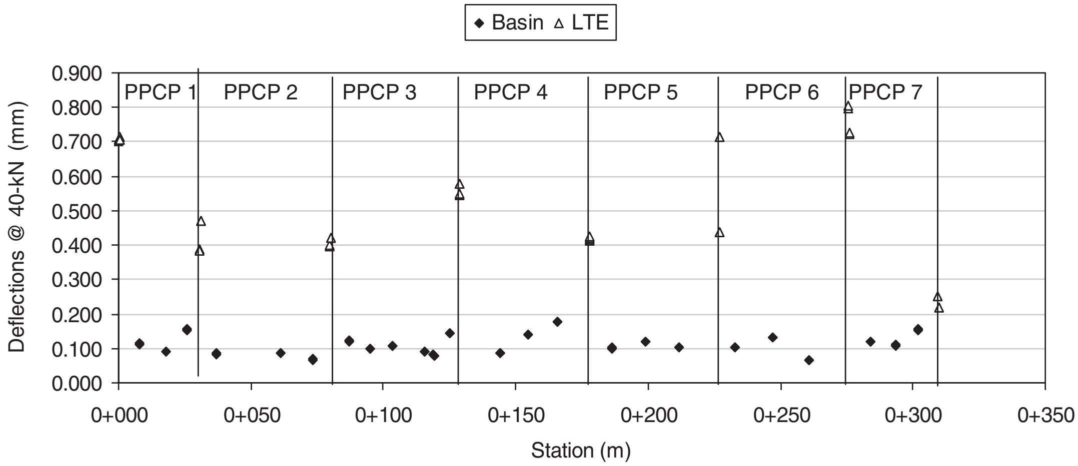


Figure 3.23. Deflections along the project length on I-66 in Virginia.

0.152 mm) for the 9,000-lbf (40.0-kN) load level. Deflection data for the 9,000-lbf (40.0-kN) load are shown in Figure 3.23.

Summary of Findings from Field Testing

Evaluation to date of the field data, as summarized here, indicates that well-designed and well-installed precast pavements perform well and have the potential to provide long-term service for both intermittent and continuous applications. The service expectations for continuous PCP applications would be about 40 years, similar to what is currently expected for new CIP concrete pavements. For intermittent repair applications, the proprietary systems (such as FMC's Super-Slab system) and generic systems (such as the Michigan system or the Illinois Tollway system) both appear to have the potential to provide service life ranging from 15 to 20 or more years.

Specific observations based on evaluations of PCP field-performance tests for PPCP systems and jointed systems for continuous and repair applications are discussed below.

PPCP Systems

The wider joint opening of the expansion joints results in variable LTEs. Limiting the length of the PTSections may allow reduction in the expansion joint width and improve the LTE at these joints. Good LTE (greater than 90%) is necessary in new construction for highways that carry higher levels of truck traffic.

Even though some PPCP panels have exhibited cracking, this cracking is not considered a concern because the reinforcement used in each panel and the "bonded" prestressing will keep the cracks tight. However, it is necessary that adequate prestress is available in the panels in the midsection area.

The spalling over the reinforcement at the Missouri project indicates a need to redesign the reinforcement details. Reinforcement should be epoxy-coated and should have at least 2 to 2.5 in. (51 to 64 mm) of concrete cover to minimize the potential for steel corrosion and subsequent surface spalling.

The Virginia I-66 project indicated higher deflections and loss of support at the expansion joints. This may be a result of nighttime slab curling over the full length of the PTSections, the use of thicker stone dust bedding and leveling material, or both.

The Delaware project shows potential for use of PPCP systems for specific applications, such as high-volume intersections.

Jointed Systems for Continuous Applications

The jointed Super-Slab system for continuous applications has performed well. The oldest project (the Tappan Zee Toll Plaza in New York) and the Minnesota project indicate good structural performance, with low deflections at joints and at the panel interiors and good LTE values.

Similar to the cracking in the PPCP panels, the tight cracking observed in the jointed panels at the Tappan Zee project is not considered a concern because of the reinforcement used in these panels. For long-term service, it is important that the top layer of the reinforcement in the panels be at least 2.5 in. (64 mm) below the panel surface.

Extensive cracking developed at the Virginia I-66 ramp project and the California I-15 project soon after opening to traffic. Extensive cracking also developed at a project constructed in Reno, Nevada, during the fall of 2010. The cause of cracking is under investigation. The following possible causes of cracking have been noted in preliminary discussions:

- Virginia I-66 ramp
  - Longitudinal tie-in between the outside lane 15-ft (4.6-m)-long PCP panels and the inside lane JRCP with 60-ft (18.3-m) joint spacing;

  - Inadequate compaction of the granular bedding material placed over the existing base and nonuniform support condition caused by uneven grading of the existing base; and
  - Use of the PCP by traffic for several days before the dowel slots were grouted and the panels were undersealed.
- California I-15 mainline
  - Use of a thinner JPrCP panel than the 12-in. (300-mm)-thick panels used for CIP-JCP at the same project;
  - Inadequate compaction of the granular bedding material placed over the existing base and nonuniform support conditions over the existing CTB; and
  - Use of the PCP by traffic for several days before the dowel slots were grouted and the panels were undersealed.
- Reno project
  - Use of short panels (6 ft [1.8 m] long);
  - Use of thinner panels than the 12-in. (300-mm)-thick panels used for CIP-JCP at the same project; and
  - Inadequate compaction of the granular bedding material placed over the existing base and nonuniform support conditions over the existing CTB.

Several conclusions can be drawn from the observations of extensive premature cracking at the three projects discussed above. First, PCP systems require good support conditions. These systems cannot perform satisfactorily over poorly compacted or nonuniform support. Second, PCP systems do not result in "super pavements" that can accommodate heavy truck traffic unless they are structurally designed to do so. Unless PCP panels incorporate higher-strength concrete or prestressed panels are used, the PCP panel thickness should be similar to CIP-JCP.

Finally, for the FMC Super-Slab system, the current practice of joint sawing for joint sealing may leave a sliver of the dowel slot grout material (not bonded to the joint face) at the surface. This practice can result in ineffective joint sealing, raising the question of whether these joints should be sawed and sealed. Care must be exercised to make certain that the saw-cut along the unbonded side of the grout material in the joint or the sealing is done across the full width of the joint gap by sawing across the full width of the joint.

Jointed Systems for Repair Applications

For full-depth or full-slab repair applications, there is a critical need to ensure that there is adequate LTE at the joints and good support under the repair, regardless of whether the repairs involve precast panels or CIP concrete. The Super-Slab system, with dowel slots at the bottom, appears to provide good load transfer at joints. The systems incorporating dowel slots at the surface, similar to the conventional DBR method, are also capable of providing good LTE at joints. However, these systems require care with the installation of the dowel slot patch material.

The use of dowel bar caps is strongly recommended to minimize failure of the dowel-bar slot patches, especially when the repairs are used for repairs of joints in JRCP.

The panel settlement at the New Jersey I-295 project indicated that more attention needs to be paid to improving the bedding support under precast panels placed over disturbed granular bases. This weakness in the FDR technique is a major cause of the failure of CIP full-depth patches. The use of precast panels is not a warrant to pay any less attention to making sure the support under the precast panels is not compromised during removal of the existing concrete and installation of the panel. It is important that agencies specify base and bedding compaction requirements and enforce these requirements during panel installation.

Summary

The experience to date with PCPs in the United States indicates that different PCP systems can be fabricated and installed successfully in most regions of the country. A wide range of projects have been constructed using different precasters and different contractors.

Overall, there does not appear to be any concern about the long-term performance of the PCP systems that are designed well and installed well. The quality of the concrete used for the precast panels appears to meet the expectations for durable concrete, and there is no evidence of early-age concrete failures. Load testing indicates that once installed, PCP systems behave similarly to CIP concrete pavements. The PCP systems tested and evaluated do not exhibit any unusual distress or failure mechanisms. However, as discussed, there is concern about the risk of cracking in the JPrCP systems used for continuous applications. A primary cause of such early cracking is considered to be the use of thicker fine-grained granular bedding material placed over the existing base. As discussed in Chapter 6, care must be exercised in specifying the type and thickness of the bedding material for PCP systems subjected to heavy truck traffic.

CHAPTER 4

Technical Considerations: General

General

Several PCP systems are available for repair and continuous applications. Although these systems differ with respect to certain aspects of design, fabrication, and installation, they share many common features and requirements. These common features include the following:

1. Proprietary PCP components;
2. Concrete requirements;
3. Jointing and load transfer at joints;
4. Support condition (bedding);
5. Prestressing;
6. Panel reinforcement;
7. Panel lifting, storage, and shipping requirements;
8. Surface characteristics;
9. Nonplanar panels;
10. Production rates;
11. Preconstruction meetings;
12. Maintenance of traffic and site logistics; and
13. Emergency management plan.

Proprietary PCP Components

Several PCP systems incorporate proprietary components, and several proprietary components have been developed for use with any PCP system. PCP systems using proprietary components, as patented in the United States, include the following:

1. Fort Miller Company's (FMC) Super-Slab System
   a. Joint load transfer system: use of dowel slots at the bottom of the slab and use of grout holes to fill the slots with fast-setting cementitious grout;
   b. Panel undersealing system: use of shallow channels at the slab bottom to allow undersealing grout material to spread along the bottom of the panel;
   c. Foam gaskets: attachment of foam gasket at the bottom of the panels; and
   d. Nonplanar panels: fabrication and installation of precast panels on which all edges are vertically and horizontally straight; the slopes of opposite edges are unequal; and the cross slope, taken at right angles from any side, varies linearly from one end of the slab to the other.
2. Kwik Slab: Joint load transfer and joint connectivity system: use of joint hardware to connect adjacent precast panels and to allow for load transfer across the joint.

Proprietary components that may be used with any PCP system include the following:

1. Joint load transfer systems: Many joint load transfer systems have been developed for use with PCP systems, including the following systems developed in Japan:
   a. Horn joint system;
   b. Compression joint system; and
   c. Sliding dowel system.
2. Prestressing hardware: Many components, such as post-tensioning anchorage systems, prestressing strands and bars, duct gaskets, and prestressing grouts, may be available as proprietary or nonproprietary items.
3. Expansion joint components.

Proprietary components should be used in accordance with established commercial and regulatory practices.

Concrete Requirements

Concrete requirements need to be similar to those specified by the governing highway agency for CIP concrete pavements. However, because precast pavements are to be used for highways with high traffic volumes where lanes closures are at a premium, concrete durability is of great importance. Although the fabricator may optimize the aggregate size and gradation to achieve an economical and sustainable concrete mixture that is workable for fabrication of the panels, it is imperative that the concrete not fail because of materials-related distress or poor-quality construction (during fabrication). To ensure that load transfer by aggregate interlock is available at panel cracking locations if any panels develop cracking under long-term traffic loading, the maximum size aggregate should not be less than 0.75 in. (19 mm). Use of larger-size aggregate is encouraged as it results in sustainable concrete mixtures requiring less cementitious materials. Concrete volume changes related to early-age drying shrinkage are not of significant concern since these effects take place over a smaller panel length and typically before panel installation.

A typical paving concrete specification should include the following requirements:

1. Concrete strength, typically at 14 or 28 days
   a. Flexural strength for design purposes: 650 lbf/in.^{2} (4.5 MPa)
   b. Compressive strength for acceptance testing purposes: 4,000 lbf/in.^{2} (27.5 MPa) (or established through a project-specific strength correlation study).
2. Ratio of water to cementitious materials
   a. Maximum: 0.45 (freeze areas) or 0.50 (nonfreeze areas)
   b. Minimum: 0.37.
3. Air content: as appropriate for the maximum aggregate size used and severity of exposure (climatic region), as defined in ASTM C 94.
4. Aggregate gradation: Mandating a well-graded aggregate gradation is unnecessary because the workability of concrete is not a significant concern. Workability of concrete is primarily of concern for the low-slump concrete used for slipform paving. However, use of well-graded aggregate can result in the need for less cementitious materials.
5. Durability: Concrete must be durable and should not be susceptible to materials-related distress, such as alkali–silica reactivity, sulfate attack, or D-cracking. Scaling resistance of the precast panel is also of concern, necessitating that the panels be cured under controlled conditions and not be overfinished.

Concrete used for fabrication may be slump concrete or self-consolidating concrete. Precasters may use higher-slump concrete as long as the allowable water–cementitious materials ratio is not compromised. Precasters typically use concrete with a slump of about 6 to 8 in. (150 to 200 mm) to facilitate manual placement and finishing of the concrete. When self-consolidating concrete is used, the concrete flow characteristics are based on the plant's experience. Any concrete type used must enable rapid placement and finishing at the plant.

Many of the concerns related to CIP concrete, such as hot weather placement, cold weather placement, placement during rainfall, equipment breakdown, concrete delivery delays, and stop-and-go operations, are not applicable to PCP panel fabrication. Also, concrete material compatibility is not a direct concern as corrective measures can be easily incorporated at the precast plant without seriously affecting production rates, and any affected concrete can be easily discarded. In other words, one of the significant benefits of PCP systems is that only quality concrete can be allowed for panel fabrication, ensuring that only panels with quality concrete are allowed to reach the project site. However, quality concrete can only be produced if the precast plant has established quality procedures and these procedures are strictly followed. It should also be stressed that concrete durability is of great concern as PCPs are expected to be used primarily for high-volume roadways where lane closures for future repair activities cannot be accommodated easily. Therefore, early concrete materials-related distress or failure is not an acceptable option for PCP projects.

Strength requirements for concrete used for precast panels are listed in Table 4.1 for a few highway agencies.

Another important strength requirement for panel fabrication is the stripping-strength requirement. Since most precasters need to strip the panels within 24 hours to maintain panel production, the concrete strength at the time of stripping is determined by conducting a panel lifting stress analysis (discussed below). Most precasters try to achieve concrete strength of about 2,000 lbf/in.^{2} (13.8 MPa) at 16 to 24 hours of age or at the time of form stripping. The early strength level generally results in higher ultimate strength of the concrete.

The concrete material properties that affect concrete pavement response and performance include the following:

1. Strength
   a. Flexural strength or modulus of rupture: needed for structural design of the panels
   b. Compressive strength: surrogate for flexural strength for acceptance testing;
2. Elastic modulus: needed for structural design of the panels and prestressing design for PPCP;

Table 4.1. Concrete Strength Requirements

Agency	28-Day Compressive Strength [lbf/in.^{2} (MPa)]
Michigan DOT	4,300 (30)
Minnesota DOT	3,900 (27)
Illinois Tollway Authority	4,500 (31)
Ministry of Transportation, Ontario	4,500 (31)
New England Tollway	5,000 (34)
New York DOT	4,500 (31)
AASHTO PCPS TIG	4,000 (28)
Virginia DOT	5,000 (34)

Note: PCPS = precast concrete pavement systems.

3. Coefficient of thermal expansion (CTE): needed for structural design of the panels and prestressing design for PPCP; and
4. Ultimate shrinkage strain: needed for structural design of the panels and prestressing design for PPCP.

For typical CIP highway paving applications, the 28-day concrete flexural strength specified in the United States is about 650 lbf/in.^{2} (4.5 MPa). For precast pavement applications, a concrete strength of about 700 to 750 lbf/in.^{2} (4.8 to 5.2 MPa) at 28 days can be easily achieved and should be specified.

The modulus of elasticity of paving concrete typically ranges from about 4,000,000 to 5,000,000 lbf/in.^{2} (27.6 to 34.5 GPa). The modulus value is typically not measured for project-specific concrete but is estimated from the value of the compressive strength.

CTE is another important parameter in the design of concrete pavements and influences the slab (panel) curling behavior, stress development in the slab, and the variation in expansion joint width with changes in concrete temperature. CTE is influenced by the concrete aggregate type. Typical CTE values are listed in Table 4.2.

Concrete shrinkage is another important concrete property that affects the long-term behavior of concrete pavements. For PCP applications, concrete shrinkage is not significant because a large portion of shrinkage occurs while the precast panels are in storage. Also, there is little concern related to early-age moisture warping or built-in curling as the precast panels are cured for about a day under a controlled environment inside a precast plant. As discussed below, it is assumed in PCP system design that the precast panels will not exhibit significant concrete shrinkage after panel installation.

Table 4.2. Typical CTE Values for Concrete

Coarse Aggregate	Typical CTE, 10^{-6}/°F
Andesite	5.3
Basalt	5.2
Diabase	4.6
Gabbro	5.3
Granite	5.8
Schist	5.6
Chert	6.6
Dolomite	5.8
Limestone	5.4
Quartzite	6.2
Sandstone	6.1
Expanded shale	5.7
Marble	2.2 to 4.0
Unknown coarse aggregate (default value)	5.5

Source: AASHTO 2008.
Note: 10^{-6}/°F = 1.8 10^{-6}/°C.

Panel Reinforcement

A double mat of reinforcement is typically used for jointed precast concrete panels to mitigate any cracking that may develop due to lifting and transporting operations. The amount of reinforcement is typically at least about 0.20% of the panel cross-sectional area in both directions, depending on the panel dimensions. The reinforcement is not necessary for pavement performance unless the panels are designed for use in reinforced concrete pavements. Some agencies require a higher level of reinforcement if the installed precast panels are subjected to traffic before panel subsealing is carried out. For pretensioned panels, a single layer of reinforcement, transverse to the pretensioning strands, is used.

An advantage of panel reinforcement is that if the PCP panels develop cracking over the long term due to traffic loading, the cracking can be expected to remain tight and not affect pavement serviceability.

All steel used in the precast pavement system needs to be protected against corrosion. The requirements for steel should follow established highway agency practices. The top panel reinforcing should have at least 2.5 in. (64 mm) clear cover after allowing for up to 0.5 in. (13 mm) for future grinding. The bottom panel reinforcing should have at least 2 in. (50 mm) clear cover. Transverse and longitudinal bars should have at least 2 in. (50 mm) cover at the bar ends. If there is a possibility that the panel width may be trimmed at the site to accommodate the width of the repair area, the cover at the transverse bar ends should be sufficient to allow for 2 in. (50 mm) cover at the bar ends after panel trimming.

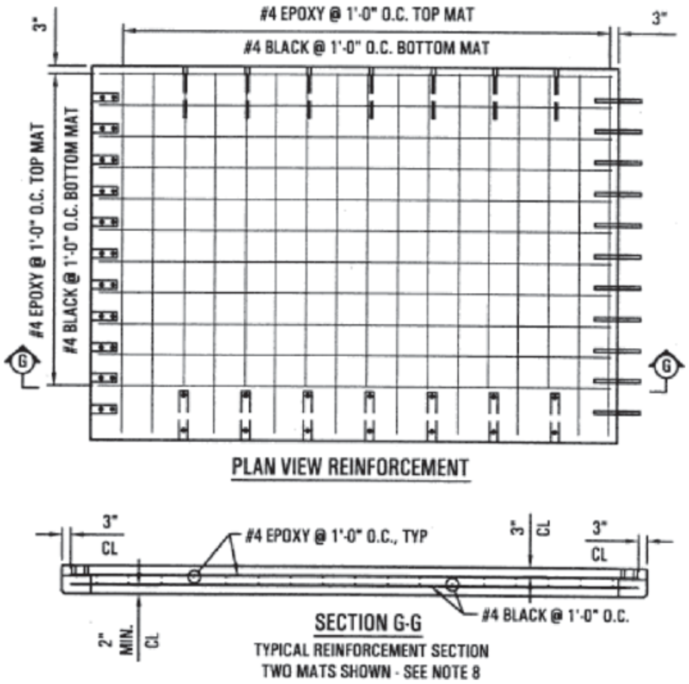
A typical reinforcement arrangement for a jointed PCP panel is shown in Figure 4.1.

Panel Lifting and Shipping Requirements

An important design aspect for PCP installation is related to lifting and hauling of the panels from the precast plant to a temporary storage site at the plant and then to the work site. In addition to the overload transit permit requirements for larger panels, it is important to consider panel size and panel weight to ensure that the lifting and shipping processes are safe. Table 4.3 shows the typical weight of panels of various dimensions.

Panel Lifting

Panel lifting typically uses a four-point lifting method. The lifting anchors are embedded in each panel at four symmetrically



Courtesy of FMC.

Figure 4.1. Typical reinforcement layout.

Table 4.3. Weight of Precast Concrete Panels

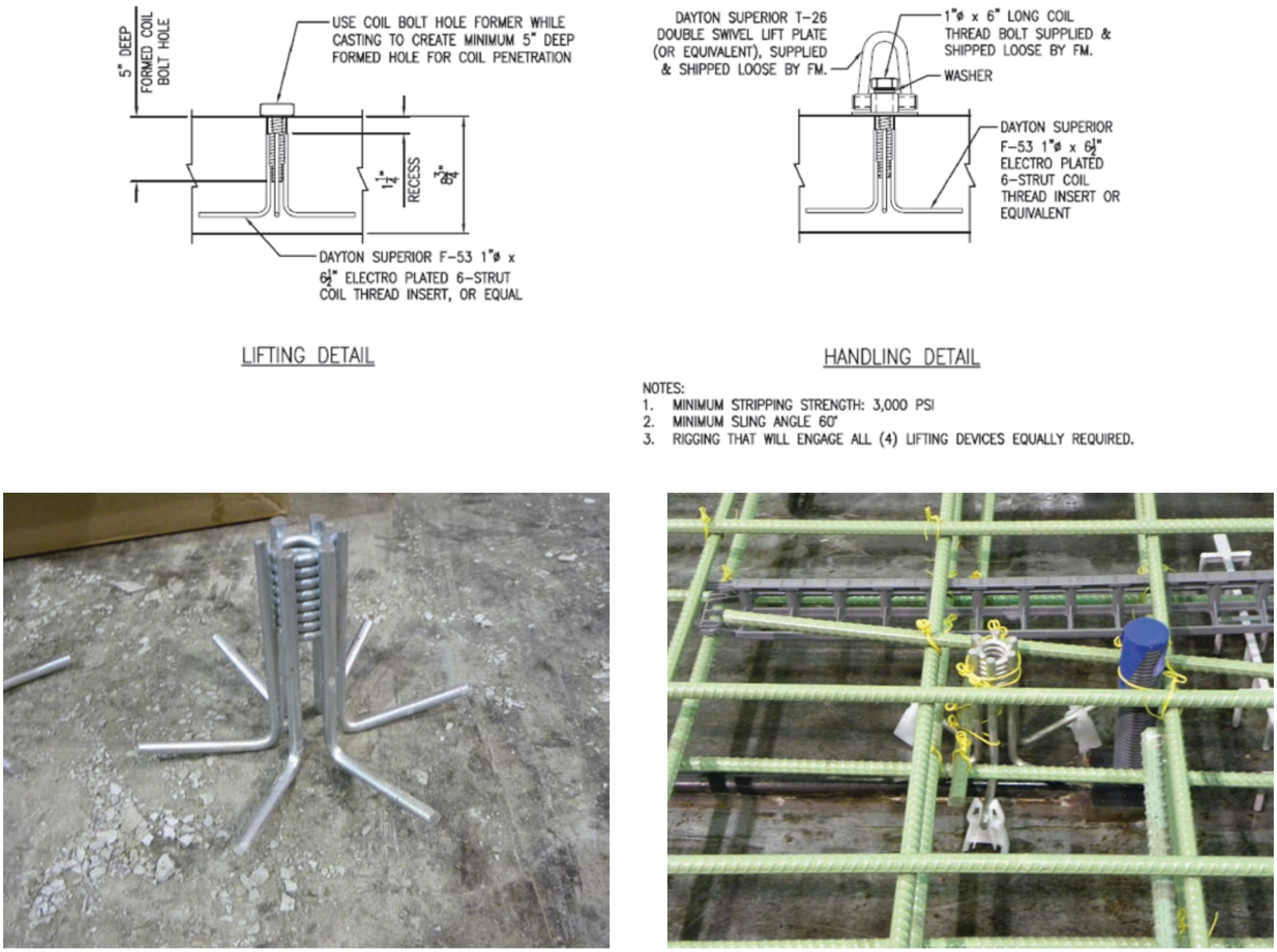
Panel Size (ft)	Panel Thickness (in.)	Panel Weight (lb)	Four-Point Lift Anchor Load (Static) (lb)
12 × 6	8	7,000	1,750
	10	8,700	2,175
	12	10,400	2,600
12 × 12	8	13,900	3,500
	10	17,300	4,325
	12	20,800	5,200
12 × 15	8	17,300	4,325
	10	21,600	5,400
	12	26,000	6,500
12 × 20	8	23,100	5,775
	10	28,800	7,200
	12	34,600	8,650
12 × 36	8	41,500	10,375
	10	51,900	12,975
	12	62,200	15,550

Note: 1 ft = 0.305 m; 1 in. = 25.4 mm; 1 lb = 0.454 kg.

offset locations that ensure the least tensile stresses in the panel. An example of the four-point lifting arrangement is shown in Figure 4.2. The lifting anchors used are commercially available and are rated by the load that can be carried by each anchor. A typical lifting anchor (threaded coil insert) is shown in Figure 4.3. Many contractors use a lifting frame for lifting individual panels; other contractors use chains directly connected to the lift hooks.

A detailed analysis conducted according to precast concrete industry (e.g., Precast/Prestressed Concrete Institute [PCI]) guidelines should be performed by the panel designer to ensure that the lifting anchors, anchorage-related localized reinforcement, and rigging used for lifting are compatible with the panel's weight and dimensions and the concrete strength at the time of the first lift soon after casting. Most major suppliers of threaded lifting anchors provide recommendations for the anchorage area reinforcement to ensure that the lifting anchors perform safely and do not allow the

Figure 4.2. Typical four-point lifting of a precast panel.



Courtesy of FMC.

Figure 4.3. Lifting anchors.

anchors to pull out under load. In addition, any dynamic loading during lifting and installation at the work site should be accounted for in the design of the anchorage system. A static analysis should also be conducted using the proposed lifting system to ensure that the tensile stresses that develop in the panel are within acceptable limits, especially during the initial lift soon after casting.

It is important that the technical information related to the anchors, rigging, lifting, hauling, and storage should be included in the shop drawings. Any lifting hardware left in place must have 2.75 in. (70 mm) top cover and 2 in. (50 mm) bottom cover after installation.

Examples of concrete lifting (flexural) stresses resulting from the four-point lifting arrangement, determined using PCI guidelines (PCI 2004), are given in Table 4.4.

Table 4.4 shows that for panels 12 ft (3.7 m) wide and up to 15 ft (4.6 m) long, the concrete flexural stresses resulting from the four-point lifting arrangement are very small. For wider or longer panels, the higher concrete stress development during the first lift (within 24 hours) is mitigated by pretensioning in the panel's long direction. For the wider and longer panels, the use of pretensioning will also help mitigate the effect of curling stresses during service.

For prestressed panel design, the pretensioning applied to meet the structural requirements may be adequate to meet the needs for lifting.

Surface Characteristics

Surface characteristics include smoothness (ride) and surface texture. Surface texture affects safety and pavement–tire noise.

For intermittent repair applications, the installation and seating of individual panels affect only local roughness. Typical specifications limit the elevation difference at a joint between

Table 4.4. Maximum Flexural Stress in Precast Panels Resulting from Four-Point Lifting

Panel Length (ft)	Panel Width (ft)	Panel Thickness (in.)	Maximum Concrete Lifting Stress ($lbf/in.^2$)
10	12	9	39
	24	9	154
	36	9	347
	12	10	35
	12	11	32
	12	12	29
12	12	9	39
	24	9	154
	36	9	347
	12	10	35
	12	11	32
	12	12	29
15	12	9	60
	24	9	154
	36	9	347
	12	10	54
	12	11	49
	12	12	45

Note: The lifting stresses incorporate a load multiplier of 1.5 to account for forces resulting from stripping, handling, and travel. The lifting insert locations are at 0.207 times the edge dimensions for each of the four locations.

the precast panel and the existing pavement to not more than 0.25 in. (6 mm). On many projects, the elevation difference is controlled by grinding after the panel installation.

For continuous applications, the ride requirements should be the same as for CIP concrete pavements. Typical specifications require elevation differences at joints and other bumps in the surface profile to be smoothed by grinding. Although the ground surface may be considered acceptable, grinding requires another operation and additional lane closure periods.

Surface texture requirements for the installed panels should match those for new construction. However, as discussed, it is likely that the panel surface may be ground to meet profile requirements for repair projects and for continuous application projects. The ground surface should be considered acceptable. The controlled conditions of a precast plant also present the opportunity to imprint textures that will provide a quieter ride and adequate friction or incorporate two-lift concrete placement that allows use of better-quality and possibly more expensive aggregates in the thin top lift of the panel. However, this is effective only if the panels can be installed without requiring grinding to correct surface profile. Most precasters do provide some form of texture at the panel surface. This may include brooming, turf-drag, or tining transversely or longitudinally.

Nonplanar Panels

For roadways with tangent alignment, precast panels that are rectangular in shape and flat in geometry are appropriate. For pavements in curved alignment or where there are cross-slope (superelevation) transitions, such rectangular flat panels may not be adequate, and custom panel fabrication to match the site geometry may be needed. Currently, only FMC's Super-Slab system has been used in applications that require nonplanar panels. All nonplanar panels must be placed at their prespecified locations at the work site. Except for the need for customized formwork and a possibly higher cost for each nonplanar panel, the fabrication and installation of nonplanar panels is similar to that of flat panels. However, nonplanar panels need to be inventoried and delivered for installation at designated locations where the base elevations conform to the three-dimensional warp in each panel.

Use of nonplanar panels requires the following:

1. Accurate existing roadway survey data in the three dimensions to an accuracy of ±0.125 in. (3.2 mm). The survey data are needed along the left and right edges of the existing pavement at about 10-ft (3.1-m) intervals. For larger areas, such as toll plazas or intersections, the survey data are needed at a grid of about 10 × 10 ft.
2. Custom drawings for each panel based on site survey data, the panel design thickness and nominal panel size, and the required final profile for the precast pavement.
3. Customized formwork that allows fabrication of each unique nonplanar panel.
4. Accurate grading of the base and any bedding material using a calibrated rail system placed along each side of the lane being rehabilitated.
5. Precise location of each nonplanar panel at the planned location.

Nonplanar panels have not been used on highway PPCP projects installed to date. The two primary considerations for use of nonplanar panels for PPCP include (1) the minimum-radius horizontal or vertical curve that can be posttensioned, and (2) the impact of panel curvature on stress loss due to tendon or duct friction during the posttensioning operation.

The ICPCP approach can be considered for PPCP projects that include curved sections without varying cross slopes.

In this case, use is made of prestressed panels that are rigidly connected at the panel transverse joints or use of shorter lengths of PPCP along the curved sections. However, if the roadway incorporates varying cross slopes, nonplanar panels would be required regardless of how the panels are connected.

Production Rates

The panel installation rate, which determines productivity and lane closure requirements, is one of the most critical factors when considering the use of PCP technology. Panel installation includes all activities conducted during a given lane closure, as listed below:

1. Existing pavement removal, including a portion or all of the existing base material. This operation may require milling of a stabilized base according to design requirements.
2. Drilling and grouting of the dowel bars for repair applications (based on system design).
3. Base preparation by regrading the existing base or placing a new base and placing bedding material to achieve proper base grade. Granular base materials are compacted, and cementitious (rapid-setting LCB) bases are placed and finished. The bedding material may be granular, fast-setting flowable fill, or polyurethane foam material.
4. Placement of the panel–base interface treatment, typically, polyethylene fabric or geotextile membrane.
5. Panel placement.
6. Use of a temporary transition at the end of the PCP installation to the existing pavement for a given lane closure.

Good production can be achieved for a given work window when use of the work crew is optimized and specific work is assigned to specific workers. Once the panels start arriving at the work site and the base is ready, the production is determined by how fast each panel can be installed.

For intermittent repairs within a given lane closure area, the typical production rate is about 14 to 18 panels per 6- to 8-hour lane closure, or about one panel per 20 to 25 minutes. Ideally, two crews should be used for repair installations: one crew preparing the repair area, including drilling and epoxy grouting the dowel bars, and the second crew installing the panels.

For continuous applications, a higher panel installation rate per 6- to 8-hour lane closure can be achieved since work is performed along a longer rehabilitation area. The typical production rate for panel installation is about 30 to 40 panels for jointed systems or about 400 to 600 ft (122 to 183 m) of installation length. The production rate can vary for PPCP systems and is dependent on the panel width and length. Greater production can be achieved using longer panels, as fewer panels need to be set and temporarily posttensioned. PPCP panel installation can range from about 200 ft to over 600 ft (61 to 183 m) per lane closure, depending on the panel length and width.

Productivity may be affected when an existing base requires significant reworking and compaction effort or if a new base is placed. Every 15 to 20 minutes of extra effort or delay results in one less panel installation. It is expected that as better base grading equipment becomes available, the panel installation rate will increase.

The installation finishing-up operations are typically conducted during the next lane closure, often during the next night. These operations may include joint slot patching or grouting, panel undersealing, posttensioning, stressing pocket grouting, and duct grouting. These operations do not affect the production rate.

Preconstruction Meetings and Training

Most highway pavement construction projects require preconstruction meetings. As soon as possible after the project has been awarded, the owner–agency typically arranges a meeting with the contractor and all other interested parties to review contract requirements, construction details, work schedules, and any items peculiar to the project. Arranging for one or more (as needed) preconstruction meetings is essential for PCP projects because of the newness of the PCP applications and technologies being used. Two types of meetings, a prefabrication meeting and a preconstruction meeting, are typically held.

A prefabrication meeting should be held before any panels are cast. This important first meeting makes sure the owner–agency, contractor, and fabricator have the same understanding regarding project requirements and the quality of the panels to be fabricated. Any proposed changes in the panel design or fabrication process must be discussed at this time. This meeting should be carefully prescribed to make sure all key parties are present and any ambiguities in the plans and specifications are resolved at this meeting. This is particularly important when special processes are required to fabricate and install the panels.

A preinstallation meeting should be held within two weeks of the start of panel installation to review panel installation logistics, including panel installation schedule, panel installation process (including removal of existing pavement and establishment of the support condition [base or base and bedding], panel placement, and joint load transfer provisions), on-site QA/QC testing, maintenance of traffic plans, and emergency management plan. This meeting is key to ensuring that field inspectors and senior contractor staff who are new to PCP projects not only understand the proper installation techniques of the particular PCP system being installed, but also understand that precisely following the correct procedures for panel installation is critical to the project's long-term success.

Finally, the need for a trained panel installation crew and a trained inspector staff cannot be overemphasized. The project site is not a place for training, as the production rate and quality of installation must be maintained from Day 1. The contractor crew should be trained off site, either during the trial (test section) installations or in a nonproduction setting.

Maintenance of Traffic and Site Logistics

Lane closure requirements differ for repair and continuous applications. The lane closure for a repair application may be spread over several miles because the 15 to 20 repair locations designated for treatment during a given lane closure may require this distance. The lane closure requirement for continuous applications involves less spread as the actual work area may be limited to 200 ft (61 m) to over 400 ft (122 m) in length. However, traffic control requirements for a given site may dictate longer lane closures, depending on the number of lanes being closed and anticipated traffic volumes. In any case, all lane closures are carried out in accordance with the requirements specified in the *Manual of Uniform Traffic Control Devices* (2009) and the agency's work zone traffic control guidelines. The traffic control devices and lane closure distances to be used are intended to reduce construction workers' exposure to traffic hazards and to offer road users consistent and positive guidance through work zone areas.

Lane closure requirements are indicated by the facility type and traffic volumes during the lane closure period:

1. For freeway applications, a sequential lane closure is typically used. A precast panel installation typically requires a multilane lane closure. It is desirable to have an adjacent lane available for trucks being used to dispose of the removed existing pavement material and for trucks delivering the precast panels to the work site. Therefore, installation along a single lane will typically require a minimum two-lane closure, and a two-lane installation will require a three-lane closure. For multilane closures, the lane closures are typically done in a sequential manner. For example, the first lane is closed at 8 p.m., the second one at 9 p.m., and the third one at 10 p.m. The lane closure sequence depends on the volume of traffic during off-peak hours. Pavement removal and equipment mobilization begin as soon as the first lane closure begins.
2. For arterial highways with only one or two lanes in each direction, full-lane closures may be used. A two-way traffic pattern is then managed in the adjacent lanes. For repair applications, a single-lane closure may be adequate during the existing pavement removal process and base preparation. An intermittent full closure is then used for 15 to 20 minutes to allow panel installation in the prepared area, with the panel delivery truck positioned in the adjacent lane, next to the prepared area.
3. For single-lane ramp applications, the ramp is typically closed to traffic during the panel installation.

For continuous PCP installation, the positioning of the crane is a critical space management issue for lane closure. During its operation, the crane rests on the newly installed precast panel, and the crane's outriggers (usually four supporting legs) typically stretch out and are grounded on an adjacent or shoulder lane (on each side adjacent to the lane being rehabilitated). As shown in Figure 4.4, the outriggers for the crane's stabilization may require about 2 to 3 ft (0.6 to 0.9 m) additional space beyond the edges of the lane being rehabilitated. The precast panel delivery trucks (as well as trucks delivering bedding material and hauling away demolition) need to pass along one side of the outrigger, and the work zone traffic needs at least one lane to be operational, separated by traffic barriers (rubber cones or plastic barrels). Considering the logistics and on-site equipment space requirements, any lane repair or rehabilitation may require a minimum of about one and a half additional lanes to support removal of the existing pavement, hauling, and panel installation activities.

The contractor should check the overload permit regulations of local authorities along the travel route from the precast plant to the work site, because permit regulations vary widely from state to state and from municipality to municipality. Overload permit regulations should be checked before any panels are fabricated to ensure they can be delivered to the work site at the time of day required by the contractor.

Precast panels are transported to the work site by delivery trucks (flat-bed trailer) as needed during installation. The size of the panels may result in the delivery truck being classified as an oversize load, which may require a special permit.

Figure 4.4. Outrigger positioning of lifting crane.

The contractor can obtain a blanket permit for all precast delivery trucks to be used for a given project, instead of individual delivery permits, which simplifies the permit process.

On-Site Contingency Management Plan

Contractors for rapid renewal projects are required to develop and submit a maintenance-of-traffic plan before any major lane closure or freeway closure. The maintenance-of-traffic plan should contain a detailed contingency plan to ensure opening of the freeway by the designated time, typically 6 a.m. the next morning.

As a requirement of the PCP installation process, the contractor must provide appropriate personnel to monitor traffic flow and to make decisions regarding activation of the contingency plan. As soon as it becomes evident during any construction activity that it will not be possible to complete that activity and effectively end the lane closure at the designated time (usually before commuter traffic begins), that activity must be halted and postponed until a later date.

The contingency plan should identify key operational decision points with a timeline listing the expected completion time of each critical path activity. Clearly defined trigger points should be identified with each critical path activity to establish when the contingency plan will be activated. The plan should list and describe all standby equipment and secondary material suppliers to be available to complete the operations in the event of equipment failure, base preparation issues, unavailability of panels, or work zone accidents.

For intermittent repair projects, the contractor is required to have cold-mix asphalt readily available to fill any opened areas that cannot be completed with precast panel installation.

For continuous projects, contractors have the option of using granular base material or cold-mix or hot-mix asphalt to fill open areas that cannot be completed with precast panel installation. In an extreme situation, closure of the lane being worked on may need to be maintained if the contingency measures cannot be applied to restore lane operability.

A decision tree with clearly defined lines of communication and authority must be provided in the contingency plan. The names, telephone numbers, and pager numbers of the contractor's project manager, agency's resident engineer, construction inspector, traffic control police, and other personnel involved in the traffic-related decision-making process should be available to all key personnel at the project site. The contingency plan should outline actions the contractor will undertake in the event of an emergency (such as major work zone incidents) and, in particular, should specify how emergency service vehicles will enter and leave the construction areas in the most expeditious manner.

It is important that all key personnel regularly review the contingency management plan and related potential issues during the construction phase.

Summary

The implementation of PCP technology requires consideration of a range of technical issues, including use of proprietary components and systems, concrete quality, panel design (e.g., reinforcement and lifting hardware), and maintenance of traffic, to ensure that the desirable panel installation rate is achieved. PCP technology will be given serious consideration by highway agencies only if the production rate for panel installation is high enough to reduce lane closure requirements. Advances in better control of the work area and more mechanized techniques to prepare the work area and for panel placement will help increase the panel placement rate from the current 400 to 600 ft (122 to 183 m) per lane closure to over 1,000 ft (305 m) per lane closure for continuous applications. A placement rate of at least 1,000 ft (305 m) per lane closure will ensure consideration of PCP systems as the primary choice for rapid rehabilitation of existing pavements in the United States.

CHAPTER 5

Technical Considerations: Jointing and Joint Load Transfer

General

Jointing and load transfer provisions at transverse joints are two important design features for PCP. Joint spacing must be optimized for intermittent repair and for continuous applications by considering constraints on panel size fabrication and shipping and structural performance requirements. In addition, it is necessary to ensure that adequate load transfer will be available at all active transverse joints, including the PPCP expansion joints, over the long term. PCP installations with poor or no load transfer provisions at active transverse joints cannot be expected to provide the desired level of service under truck traffic. PCP joints incorporate smooth joint faces and are typically wider than the joints in CIP-JCP. As a result, aggregate interlock at the joints does not exist and cannot be counted on.

For specific applications, provisions may need to be made for longitudinal tie bars to prevent panel or lane drift. Tie bars may be needed for continuous placement for panel placement lengths greater than about 50 ft (15 m).

Transverse Joint Spacing

Transverse joint spacing requirements for PCP systems are similar to the requirements for CIP concrete pavements and are as follows:

1. Intermittent repairs. Transverse joint spacing is not directly considered for intermittent repair projects. Rather, the feature of interest is the panel length. Panels are typically single-lane width, and panel length may range from a minimum of 6 ft (1.8 m) to about 15 ft (4.6 m). On many repair projects involving existing JRCPs with joint spacing of 60 to 78 ft (18 to 24 m), standard panel lengths of 8, 10, and 12 ft (2.4, 3.0, and 3.7 m) have been used to repair distressed cracking or joint areas. For JPCPs with shorter joint spacing, standard 6-ft-long panels may be used to correct joint-related distress (typically severe joint spalling) or midslab cracking. Longer panels up to 20 ft (6.1 m) may be used for individually prestressed panels.
2. Continuous jointed applications. The widely used standard joint spacing for CIP-JCP of 15 ft (4.6 m) has provided good performance throughout the United States and has significantly reduced the risk of early-age cracking for CIP-JCP. The use of 15-ft joint spacing is recommended for jointed PCP applications for panel thicknesses of 8 to 13 in. (200 to 330 mm). However, a longer joint spacing, up to 20 ft (6.1 m), may be used for thicker (10 to 12 in. [250 to 300 mm]) individually prestressed panels.
3. Continuous PPCP applications. To date, an expansion joint spacing of 110 to 325 ft (34 to 99 m) has been used on U.S. projects. The selection of the expansion joint spacing is project-dependent and involves several factors, as discussed below, such as base type, prestressing system, load transfer at the expansion joints, climatic condition, and cost. Using too short a joint spacing may not be economical. Using larger joint spacing may result in a need for a wider joint gap to accommodate larger seasonal joint end movements, which would also affect LTE at the expansion joints.
4. Continuous ICPCP applications. The spacing for ICPCP systems should be limited to about 100 ft (30 m). This system simulates JRCP with hinged joints. The joint spacing limitation is determined based on the acceptable joint width.

Joint Load Transfer Analysis

When an axle load is located near a joint, sound design requires that a large part of the axle load be transferred across the joint to the adjacent slab. In fact, for new construction it is required that the joint load transfer system is capable of transferring almost 50% of the axle load across the joint. For an axle load of 20,000 lb (9,072 kg) each wheel set (single or dual) carries 10,000 lb (4,536 kg), and about 5,000 lb (2,268 kg) of that needs to be transferred across the joint for a fully efficient joint load

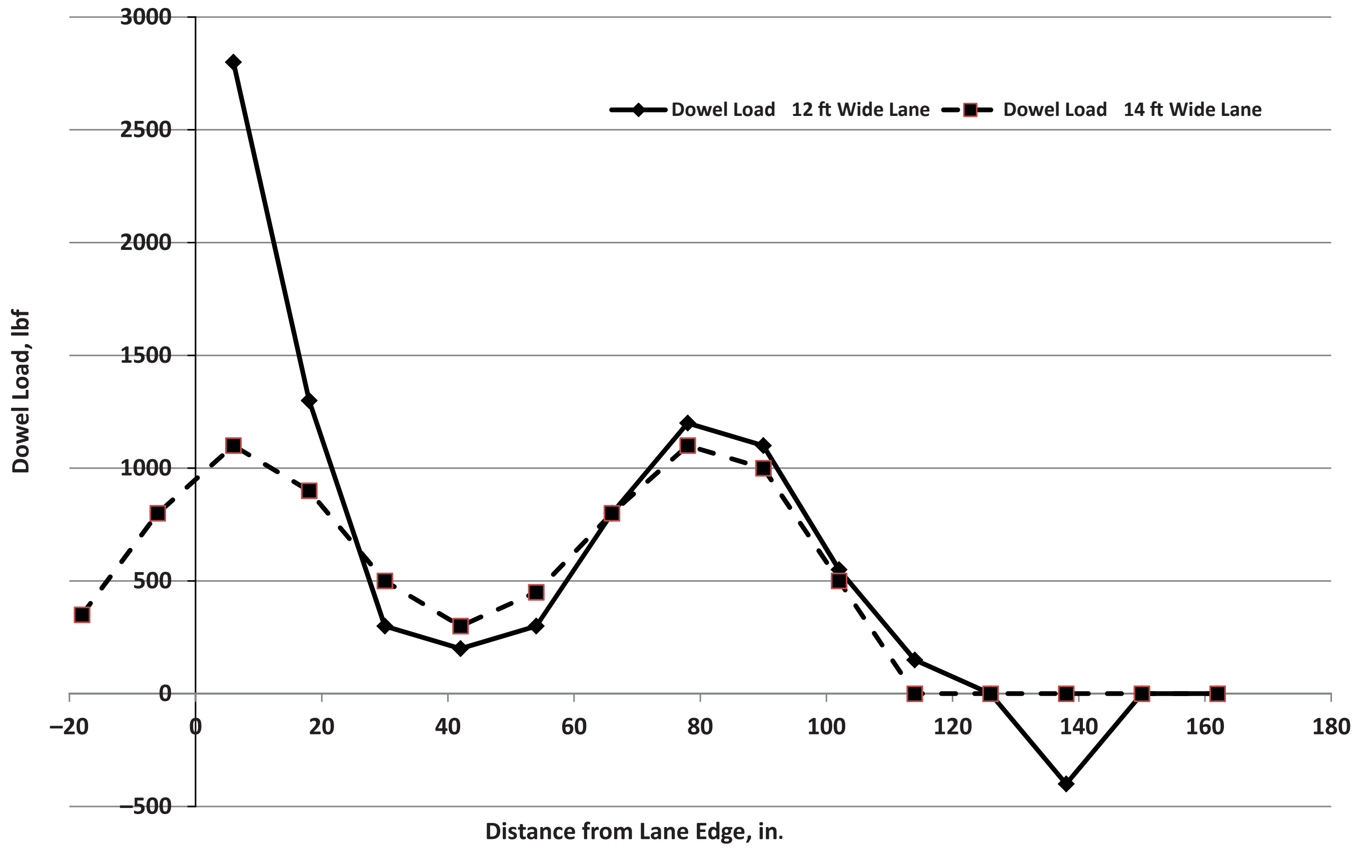


Figure 5.1. Load transfer along a joint.

transfer system. When the axle load is located at the corner, the dowel bar closest to the outside transfers about 3,000 lb (1,361 kg) of the 5,000 lb that needs to be transferred at the outside wheelpath, as shown in Figure 5.1. When the axle load is located at the lane edge of a 14-ft (4.3-m) widened lane or 2 ft (0.6 m) away from the edge of a 12-ft (3.7-m)-wide lane, the maximum load transferred by a dowel is about 1,200 lb (544 kg).

For repair or continuous application, the dowel bar design is dependent on the axle load location. Use of 12-ft-wide precast panels would require consideration of the 3,000-lbf load transferred by the critical dowel, but use of a widened panel would require consideration of only about a 1,200-lbf load transferred by the critical dowel. It is important that the dowel bars be spaced such that the critical axle-loading condition is accounted for. In any case, dowel bars should not be placed more than 12 in. (0.3 m) from the outside corner location for a 12-ft (3.7-m)-wide lane.

The joint LTE can be determined by computing the deflection LTE. The deflection is commonly measured with an FWD. The most common mathematical formulation for expressing LTE is

$$\text{LTE}\,(\%) = \frac{\Delta_{UL}}{\Delta_L} \times 100$$

where

LTE = Load transfer efficiency;

Δ_{UL} = deflection at the unloaded side of the joint; and

Δ_L = deflection at the loaded site of the joint.

The concept of deflection load transfer is illustrated in Figure 5.2. If no load transfer exists, then the unloaded side of the joint experiences no deflection when the wheel is applied on the approach side of the joint, and the LTE computed from the equation above is 0%. If perfect load transfer exists, both sides of the joint experience the same magnitude of deflection under the wheel loading, and the LTE computed using the equation above is 100%.

For long-term service, it is necessary that the joint LTE be maintained over 70%.

Load Transfer Provisions for Jointed Systems

Current JPrCP systems use a dowel–slot design, similar to the DBR technique. This section discusses the techniques used by the Fort Miller Company, the Michigan method, and Kwik Slab.

The Fort Miller Company's Super-Slab system incorporates the slot at the slab bottom, requiring use of a flowable grout and

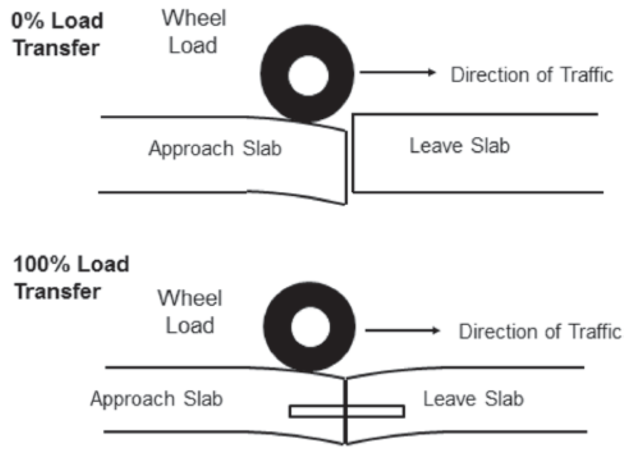


Figure 5.2. Definition of LTE.

the need to fill the space (about 0.5 in. [13 mm]) along the periphery of the joints on four sides. An advantage of this system is that the panels can be placed during one lane closure, and the slots can be grouted during the next lane closure. The PCP section can be opened to traffic before the slot grouting is performed without concern about having open slots at the surface.

The Michigan method and other generic systems typically incorporate the dowel slots at the surface of the adjacent existing pavement or the panel. This approach is based on the DBR technique. The options under this technique include the following:

1. Full DBR: dowel slots along both sides of the joint
   a. For repair applications, conventional DBR-type dowel slots are cut along both sides of the joint after the panel has been placed.
   b. For continuous applications, dowel slots are located in the panels at both sides of the joint when using the narrow-mouth surface slots. Conventional DBR-type dowel slots may be used, but these slots require patching during the same lane closure as the panel installation if the slots are fabricated in the panels.
2. Partial DBR: dowel slot along one side of the joint
   a. For repair applications
      - Dowel slots are located in the existing concrete pavement side of the joint, and the panel will have embedded dowels along both sides of the panel.
      - Dowel slots are located in the panel side of the joint when using narrow-mouth surface slots. Dowel holes are drilled in the existing pavement side of the transverse joints, and dowel bars are epoxied in the holes.
   b. For continuous applications, a panel will have embedded dowel bars along one side of the panel and matching surface dowel slots (narrow-mouth or conventional) along the other side of the panel.

A possible disadvantage of the surface-slot panel system is that the conventional wider-mouth slots cannot be left exposed under traffic. The options available to overcome this disadvantage include the following:

1. If slots are part of the fabricated panels or sawed into the existing pavement at the time of panel installation, the slots need to be patched with rapid-setting patching material during the panel installation lane closure.
2. If the slots are not part of the fabricated panels, the slots can be sawed during the next lane closure and patched before opening to traffic.
3. A narrow-mouth slot at the surface can be used according to the scheme developed as part of this study. The narrow slot mouth allows the panels to be placed during a given lane closure and opened to traffic without any risk to traffic operations. The slots are then patched during the next lane closure.

The proprietary Kwik Slab joint connection device has been used to provide load transfer and connectivity at transverse joints. However, this technique may not be applicable to connecting more than a few slabs at a time because the connecting device locks the joints and does not allow for joint opening and closing.

Other retrofitted load transfer systems that have been investigated for use with CIP-PCP are not recommended for PCP applications at this time. Such devices are based on postinstallation coring at the joint or using preformed, semicylindrical spaces along the joints and installing a circular Double-Vee–type shear-load transfer device. Such an approach can minimize issues related to dowel misalignment. However, some of these systems may be too rigid and may not be applicable to connecting more than a few slabs. Other load transfer systems under investigation include systems that incorporate plate dowels. However, to date there have been no reported installations of such devices as part of PCP systems.

For expansion joints, the joint load transfer system is incorporated in the expansion joint panels or the gap panels with round dowel bars spaced at 12 in. (0.3 m).

Design of the Load Transfer System

Typically, most dowel bars used in highway pavement construction are smooth, round, solid steel bars conforming to ASTM A615 or AASHTO M31. Corrosion protection is typically provided by a fusion-bonded epoxy coating, about 0.008 to 0.012 in. (0.203 to 0.305 mm) thick, which acts as a barrier against moisture and chloride intrusion. In recent years, because of concerns about the long-term effectiveness of epoxy coating and with the movement toward longer-life pavement

Table 5.1. Summary of Dowel Design Recommendations

Dowel Design Property	Recommendation
Diameter	For precast panels <10 in. in thickness, dowel diameter of 1.25 in. is recommended. For slab thicknesses between 10 and 14 in., dowel diameter of 1.5 in. is recommended.
Length	Typical dowel length used in the United States is 18 in. However, since precise locations of the dowel bars are known, use of 16-in.-long dowel bars is considered adequate, allowing for embedment of at least 7 in. at each side of the joint and accounting for a joint width of 0.5 to 1.0 in.
Spacing	Dowels are typically placed at a spacing of 12 in. However, the middle dowels do not contribute to the load transfer at a joint. Therefore, a cluster of four to five dowels per wheelpath, spaced at 12 in., is considered adequate for both intermittent and continuous applications.

Note: 1 in. = 25.4 mm.

designs, a number of agencies have started specifying use of alternative dowel bar materials. These materials either are constructed of a corrosion-resistant material or contain a corrosion-resistant cladding for protection against degradation caused by moisture and deicing chemicals. Examples of alternative dowel bar materials include the following:

- Fiber-reinforced polymer constructed with a range of composite materials and manufactured in solid form.
- Stainless steel of varying grades (most commonly Type 304 and Type 316) manufactured as a solid bar or as a hollow tube that is filled with cement grout. In some cases, stainless steel may also be used as a cladding on a conventional carbon-steel bar.
- Microcomposite steel (also referred to as MMFX), a more corrosion-resistant steel material than conventional carbon steel, used to produce solid dowel bars.
- Rolled zinc alloy used as a cladding over conventional carbon steel for corrosion protection.

Several dowel features are critical to ensure the long-term effectiveness of the load transfer system, including diameter, length, spacing, and coating. Dowel design recommendations are summarized in Table 5.1.

Dowel Bar Alignment

In addition to the LTE at the joint, the load transfer system must allow slab end movement at the active transverse joints due to concrete expansion and contraction. When dowel bars are used, at least half of the bar's length is coated with a debonding material, and the dowels need to be aligned properly, within the tolerances established by the highway agency. Dowel alignment is as critical for jointed PCPs as it is for CIP-JCPs.

Figure 5.3 illustrates the possible types of dowel bar misalignments. In general, rotational misalignments (skew or tilt) affect free joint movement; translational misalignments (or misplacements) decrease the effectiveness of individual dowel bars in performing their intended function (i.e., providing load transfer). The critical level of rotational misalignment is the level at which the joint may lock or the concrete around the bar may spall. The critical level of translational misalignment is the level at which the LTE of the dowel bar is adversely affected. In the case of depth error, the critical level is the acceptable minimum cover. In general, the margin for placement error is much greater on translational misalignments than on rotational misalignments. For example, the typical specification in the United States for longitudinal translation (or side shift) and vertical translation is 1 in. (25 mm), but the requirement on horizontal or vertical skew misalignments is ¼ to ⅜ in. (6 to 10 mm) for dowel bars 18 in. (457 mm) long.

The agency-specified dowel placement tolerances for CIP-JCP construction should be specified for PCP projects.

Use of Dowel Bar Caps

Dowel bar caps are necessary for all JPrCP systems that either use dowel slots at the surface and do not fill the joint space with grout material or have panels located at an expansion joint in an existing JRCP. The load transfer system should allow for expansion and contraction of the precast panels and, if applicable, the adjacent existing concrete pavement. If expansion of the concrete pavement is prevented, joint spalling or cracking

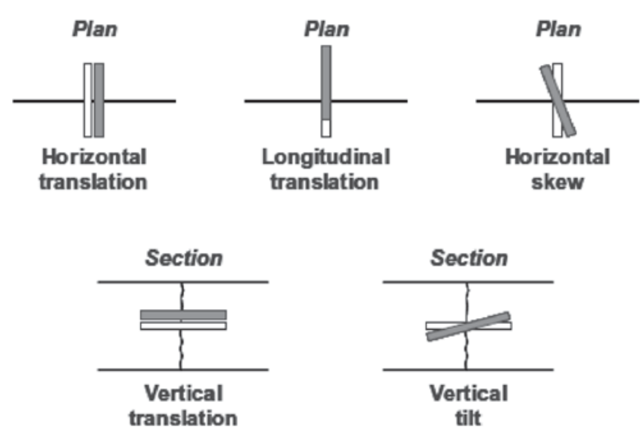


Figure 5.3. Types of dowel bar misalignment.

adjacent to the affected joints may develop. In addition, a potential for blowups during warm summer days will exist.

Many older JRCPs that are good candidates for intermittent repairs incorporate expansion joints at spacings ranging from 60 to 80 ft (18 to 24 m). When areas with expansion joints are repaired using precast concrete panels, expansion joints must be recreated at these locations. Otherwise, a potential for blowups during warm days will exist. Dowels at the expansion joints must be fitted with appropriately sized dowel caps.

The use of dowel bar caps may not be necessary when FMC's Super-Slab system is used because this technique fills the perimeter joints with rapid-setting dowel slot grout material. As a result, the joints have negligible width at the active transverse joints, and any concrete expansion is resisted by the full joint face and not by the dowel bars. However, dowel caps are necessary with the FMC's system for repair of active expansion joints in existing JRCP.

Drilling and Epoxy Grouting of Dowel Bars

For repair applications using either FMC's Super-Slab system with dowel slots at the panel bottom or the Project R05–developed narrow-mouth surface-slot method, it is necessary to drill holes in the existing pavement and install dowel bars in the drilled holes using epoxy. Holes approximately ⅛ to ¼ in. (3 to 6 mm) greater in diameter than the dowel bar are drilled at the designated locations using rotary-type core drills. The drills are gang-mounted and must be held securely in place to drill perpendicularly into the vertical joint face of the existing pavement slab. The drilled holes are cleaned of dust using compressed air and then partially filled with epoxy grout by injecting the epoxy into the back of the hole and displacing it forward by the insertion of the dowel bar. Bars need to be completely inserted into the hole using a twisting motion as soon as the epoxy grout has been injected. The twisting motion of the bar helps distribute the grout around the dowel bar. The bars should not be withdrawn and reinserted as this would create air pockets in the epoxy around the bar. The dowel bars should be checked for alignment before the epoxy sets.

A grout-retention disk (a thin, donut-shaped plastic disk) should be used over the dowel and against the slab face to prevent the epoxy grout from flowing out of the drilled holes and to create an effective face at the entrance of the dowel hole (the location of the critical bearing stress). After placement, the protruding end of the dowel should be lightly oiled or greased to facilitate concrete movement around the dowel bars. A schematic of the epoxy-grouted dowel bar anchoring is shown in Figure 5.4.

Dowel Bar Retrofit Technique

The DBR technique refers to the placement of load transfer devices across joints in JCP to restore or provide for load transfer across these joints, thereby reducing pavement deflections and subsequent load-related distress at these joints. For PCP applications, a full DBR (FDBR) or a partial DBR (PDBR) approach may be used. For an FDBR, dowel slots are used along both sides of the joint; for a PDBR, dowel slots are used along only one side of the joint. The DBR technique is widely used for joint load transfer restoration in existing JCPs, and most agencies have established practices for its use. The agency specifications, as applicable, should be used to design and specify FDBR or PDBR used with any PCP application.

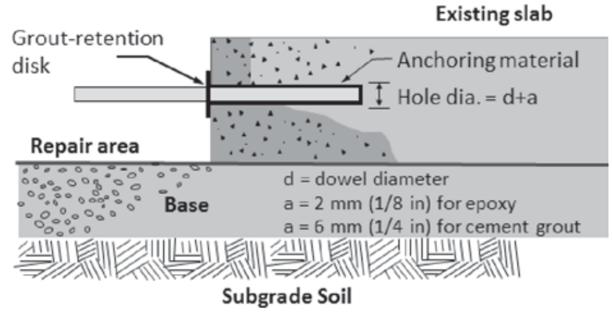


Figure 5.4. Epoxy-grouted dowel bar anchoring in a drilled hole.

Key features of the DBR technique are summarized below:

1. Round dowel bars are used for load transfer.
2. A no-shrinkage, rapid-setting patching material is used to backfill the slots and encase the dowel bars. The material should be thermally compatible with the panel and existing pavement concrete material.
3. Dowel slots are provided as follows:
   a. Saw-cut in the existing pavement
   b. For panel slots, fabricated or saw-cut at the site.
4. The slots must be parallel to the centerline of the pavement and cut to the prescribed dimensions:
   a. Typically, the maximum depth of the slot is just slightly over half the slab thickness, so that the dowel is located at middepth.
   b. The slot length is about 12 in. (305 mm) on each side of the joint, depending on the dowel length, so that the dowel can lie flat near the bottom of the slot without hitting the curve of the saw-cut.
   c. The slot width is typically between 2.5 and 3 in. (64 and 76 mm). Figure 5.5 provides a cross section of a DBR installation.
5. The saw-cut slots are thoroughly sandblasted to remove dust and sawing slurry and to provide a prepared surface to which the repair material can bond. This is followed by air blasting and a final check for cleaned surfaces before the dowel and patch material are placed.
6. Immediately before placement of the dowels or patch material, the joint perimeter in the slot is caulked with a

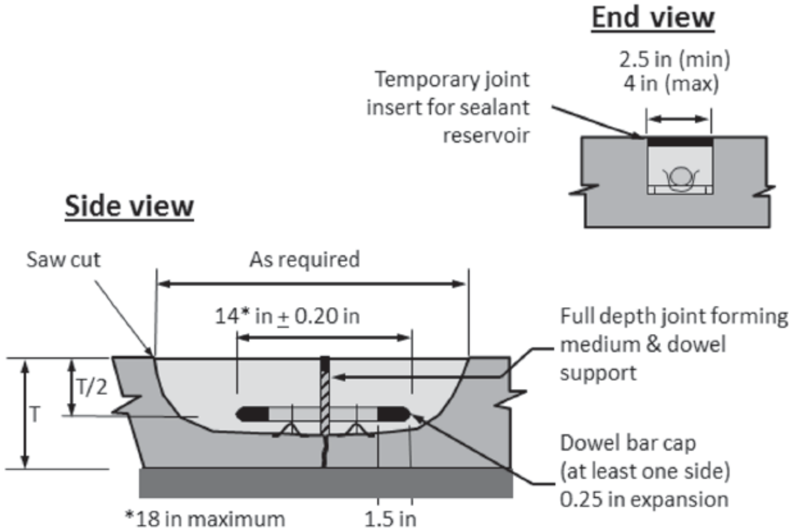


Figure 5.5. Dowel bar retrofit features.

sealant to prevent intrusion of the backfill material into the joint.

7. Before placement of the dowel bar in the slot, the dowel should be coated with a bond-breaking material to facilitate concrete movement. Expansion caps are placed at the protruded end or both ends of the dowel, as applicable, to allow for any joint closure after installation of the dowel.
8. For FDBR, the dowels are typically placed on support chairs and positioned in the slot so that the dowels rest horizontally and parallel to the centerline of the pavement at middepth of the slab.
9. A rigid filler board material is placed at the midpoint of the dowel to maintain the integrity of the joint or crack and prevent the repair material from infiltrating the joint gap and resisting slab end movement.
10. The slot patching material is carefully placed in the slot, making sure not to bump the dowel bar out of position (in case of FDBR) or displace the filler board. If required, a small spud vibrator should be used to consolidate the patching material. Also, if required, a curing compound should be placed on the patching material to minimize shrinkage.
11. Depending on the type of backfill material, the pavement may be opened to traffic within 2 hours of placing the patching material.

Joint Hardware Patching Materials

For intermittent repairs and for new JPrCPs, patching material is required to fill the dowel bar slots. The slots may be patched right after the panel installation; that is, they may be patched during a single lane closure or during the next night's lane closure. In any case, the joint slot patching material needs to develop strength rapidly. Typical strength requirements are 2,000 to 3,000 lbf/in.^{2} (13.7 to 20.7 MPa) within 4 hours or by the time of opening the PCP section to traffic. All patching materials need to be durable and have a fail-safe bonding ability. The strength requirement for the patching material is critical for two reasons: to ensure adequate dowel bearing strength and to ensure adequate bonding strength between the patch material and the precast panel concrete or the existing slab concrete.

For the 12-ft (3.7-m)-wide panels with the axle load placed at the corner, the critical dowel load is about 3,000 lb (1,361 kg). The dowel-bearing stress in this case for a 1½-in. (38-mm) dowel bar would be about 2,500 lbf/in.^{2} (17.2 MPa). The patching material with 2,000 to 3,000 lbf/in.^{2} (13.7 to 27.4 MPa) compressive strength at the time of opening to traffic should be able to accommodate this level of bearing stress.

The dowel slot sides typically have a bonding area greater than 120 in.^{2} (774 cm^2) (i.e., two sides, each 10 in. [250 mm] long and 6 in. [150 mm] deep). The bonding strength for a 3,000-lbf (13.3-kN) dowel load would need to be about 25 lbf/in.^{2} (172 kPa) when the lane was opened to traffic. This requirement can be easily met by a patching material with 2,000- to 3,000-lbf/in.^{2} (13.7- to 27.4-MPa) compressive strength at the time of opening to traffic. However, if the dowel slot sides are not properly prepared and are contaminated, even 25-lbf/in.^{2} (172-kPa) bonding strength may not develop. Most fabricated dowel–slot designs incorporate a trapezoidal cross section that helps wedge the patching material within the slot even if the bonding fails. Thus, there is sufficient safeguard in the fabricated slot design to ensure that the slot-based load transfer system will not fail due to pop-off of the patching material.

The patching materials are typically rapid-setting proprietary materials and may be free flowing (as in the case of FMC's Super-Slab system, with dowel bar and tie bar slots at the slab bottom) and polymer based, or concrete-like, with or without aggregate beneficiation, for use with the Michigan-type intermittent or continuous jointed PCP systems that have dowel bar slots at the surface. For the Michigan-type systems, agency specifications typically require materials approved for use with the DBR technique. These materials should be erosion-resistant when subjected to traffic loading.

As an example, the Illinois Tollway's patching material requirements are as follows (Illinois Tollway Authority 2009):

1. For cementitious or concrete-like materials
   - Minimum compressive strength, opening to traffic: 2,500 lbf/in.^{2} (17.2 MPa);
   - Compressive strength, 28-day: 4,000 lbf/in.^{2} (27.6 MPa);
   - Expansion: 0.40%;
   - Contraction: 0.05%;
   - Freeze–thaw loss (25 cycles at 10% NaCl): 1.0%;
   - Bond strength (to dry portland cement concrete [PCC]): 300 lbf/in.^{2} (2.1 MPa);
   - Initial set time: 15 minutes;
   - Chloride content: 0.05%; and
   - Sulfate content: 5.0%.
2. For urethane polymers (cured)
   - Minimum compressive strength (ASTM C-39): 3,200 lbf/in.^{2} (22.1 MPa);
   - Hardness, durometer D (ASTM D-2240): 70;
   - Specific gravity (ASTM D-792): 1.07;
   - Tensile strength (ASTM D-412): 4,300 lbf/in.^{2} (29.6 MPa);
   - Elongation at break (ASTM D-412): 10%;
   - Tear strength (ASTM D-624): 275 lbf/in.^{2} (1.9 MPa); and
   - Bond strength to PCC: 350 lbf/in.^{2} (2.4 MPa).

Patching material for filling the pockets used for the prestressing operations for PPCP systems should meet the same requirements as the DBR patching materials.

Tie Bar Provisions

To minimize or eliminate lane drift, tie bars should be considered for the PCP longitudinal joints for any continuous PCP placement that exceeds about 50 ft (15.2 m). Tie bar use should be in accordance with the agency's practice for CIP concrete pavements with respect to tie bar size, length, and spacing.

Several methods are available for installing tie bars in PCP systems, including the following:

1. Using tie bar slots at the slab bottom, similar to the use of bottom dowel bar slots in the Super-Slab system. The tie bars are installed in the adjacent lane using the same procedure used for drilling and epoxy grouting of dowel bars.
2. Using cross-stitching, as allowed by the Illinois Tollway.
3. Using slot-stitching.

Tie bars should not be used under the following situations:

1. For single panels used for intermittent repairs;
2. When a JPrCP or a PPCP is used to rehabilitate a lane and the adjacent lane is a different pavement type, such as a JRCP or a CRCP; or
3. When an ICPCP is used to rehabilitate a lane and the adjacent lane is a different pavement type, such as a JPCP or a CRCP.

Summary

For jointed PCPs, the incorporation of a well-designed load transfer system at active transverse joints is critical to long-term PCP performance. The practice for providing load transfer at active transverse joints should be similar to the well-established and well-performing practices used for CIP-JCP. If a practice has not been successful for CIP-JCP or has not yet been used, it should not be considered for PCP systems without additional investigation or field verification. The risk of failure of the load transfer system should be as low as possible.

Long-term performance should not be sacrificed by using marginal or unproven joint load transfer systems for construction expediency.

CHAPTER 6

Technical Considerations: Support Conditions

General Requirements

For new construction, as well as for repair application, pavement support is critical to the long-term performance of PCP systems. The proper seating of the panels on the base is a critical design and construction element. The support under the panels needs to be both firm (strong) and uniform. All PCP applications require an interlayer of material between the base and the bottom of the precast panels because these two surfaces will not match each other perfectly. The choice of the interlayer material should be carefully considered because it is affected by the manner in which the panels are installed. In the case of repair applications, in which the new panels are placed directly on the existing base surface, a flowable cementitious grout may be injected to fill the voids between the panel bottom and the base. In most cases, the existing base surface will not be accurate enough to provide the necessary grade control for the new panels. To compensate for this, a bedding layer (interlayer), as discussed below, must be used to serve as a grade control and void filler to ensure the panels are fully supported. After the panels are placed, a void-filling grout is injected directly beneath the panels to fill any voids.

For most PCP repair or rehabilitation (reconstruction) applications, the following support alternatives may need to be considered:

1. Existing base use
   a. Granular base may be reworked, graded, and compacted; the panel is placed on the compacted granular base.
   b. Granular base may be reworked, trimmed, graded, and compacted; additional bedding material is used to make up the difference in the base grade needed. The bedding material may be
      - A thin layer of cemented granular material or cemented sand;
      - Fast-setting flowable cementitious grout or flowable fill; or
      - Polyurethane foam material, applied after the panel is placed or set in position. For repair application, a foam thickness of up to 1 in. (25 mm) may be used.

   c. Stabilized base (cement-treated base [CTB] or LCB), if not damaged in the existing slab removal process, may be used as is. A thin layer of rapid-setting cementitious material may be used to provide a level surface for setting the panels.
   d. Stabilized base (CTB or LCB) may be trimmed, as necessary, to accommodate the panel thickness. A thin layer of rapid-setting cementitious material will provide a level surface for setting the panels.
2. New base use
   a. A new base may be used if it is determined that the existing base will not serve the long-term needs of the new PCP. Because of time constraints, it is necessary that the new base material be of good quality and can be placed, graded, and compacted, if granular, fairly quickly within the same nighttime lane closure as the panel installation. This option is common when PCP is used to rehabilitate existing AC pavements. The new base type may include the following:
      - Dense-graded, free-draining granular base
      - Rapid-setting LCB (RSLCB).

   b. Cement-treated or asphalt-treated bases are not considered viable options for PCP installed during nighttime lane closures, but may be considered if full-lane closure is available and duration of lane closure is not a concern.

For both repair and continuous applications, the granular bedding material should be cemented and kept as thin as possible (not greater than 0.25 in. [6 mm]). If thicker bedding is necessary, then the use of a fast-setting cementitious fill material should be considered. In addition, for lane replacement applications, the use of new base should not result in a "bathtub" detail. If adjacent lanes incorporate a free-draining granular base, use of an LCB in the repair lane may affect the subsurface drainage condition, possibly resulting in early failure of adjacent lanes.

The current practice when using an existing or a new granular base is to rework the granular material and compact it as is. No attempt is made to optimize the compaction process by ensuring that the granular material is at an optimum moisture content to allow for maximum compaction density. This is a serious limitation that can result in nonuniform settlement under traffic. The requirements for the panel's support condition should be no less than the requirements for a CIP concrete pavement's support condition. The best-constructed panels cannot perform well if they are placed on a poor support condition.

Bedding for Repair Application

The bedding and base system must be well designed and well installed and constructed for repair applications. If there is any consolidation of the bedding or base material, the panel will exhibit the bridge syndrome and will be held in place only by the joint load transfer mechanism. Such a repair will not last long. Neither the bedding nor base provision should lead to a "bathtub" detail; otherwise, the potential for pumping will be high. For repair applications, the use of certain bedding materials may meet short-term needs, but these bedding types will not perform adequately over the long term under traffic loading if the base support is not adequate. For existing concrete pavements with a granular base, it is important that damage to the base be minimized when the existing pavement is removed. Use of the slab lift-out method is strongly recommended for repair applications. If the granular base is damaged, it is difficult to achieve proper compaction of the disturbed base using plate compactors within the small repair area.

When a granular bedding material is used over an existing granular base, the thickness of the bedding should be limited to 0.50 in. (13 mm). There is no benefit in providing thicker granular bedding material for repair applications, and the use of thicker, noncompactible granular material may be detrimental to long-term pavement performance. Recently, use of a cement-treated concrete–sand bedding material has been proposed by FMC. Under this approach, the dry sand–cement mixture is placed and graded. It is expected that over a period of time the sand–cement mixture will harden in the presence of moisture and provide a stable, nonerodible bedding layer.

Various methods of providing thicker (up to 1 in. [25 mm] thick) nongranular bedding may be considered for repair applications. These methods include the following:

1. A cementitious grout is pumped beneath the slab while steel strongbacks bolted to the top of the slab span the repair area, holding the panel at the proper elevation.
2. Threaded setting bolts are used to hold the slab at the proper elevation, and a cementitious grout is pumped beneath the slab.
3. A flowable grout is placed in the repair area and is screeded to the desired elevation before the panel is installed. The slab is installed while the grout is still in a plastic state, allowing it to conform to the shape of the bottom of panel, thus providing full support to the panel.
4. A high-density polyurethane foam is injected under the panel placed in the prepared repair area, about an inch below the final panel elevation. The foam expansion raises the panel to the desired elevation. The polyurethane foam becomes the permanent bedding for the panel.

For both subsealing and cementitious bedding materials, the compressive strength requirement is about 500 lbf/in.^{2} (3.4 MPa) at the time of opening to traffic. These materials also need to be nonerodible.

Polyurethane Material

The polyurethane material consists of polymer resin components that are injected through small drilled holes (⅝ in. [16 mm] in diameter) directly through the concrete. As the resin mixture expands, voids are filled, and a controlled mold pressure is exerted on a limited area of the slab (panel) to both stabilize and, when required, lift it back to profile. The composite polymer material quickly cures into a strong and stable high-density bedding layer.

Base and Bedding Support for Continuous Application

The support requirements for JPrCP, ICPCP, and PPCP systems are similar. For long-term performance, a good support condition is necessary. The level of attention paid to ensuring a good support should be similar to that paid for panel fabrication. For most continuous applications, the following base support may be considered:

1. Existing base
   a. As is or with shallow trimming to allow the use of panels having about the same thickness as the existing pavement
   b. Trimmed to allow a thicker PCP system to be installed; and
2. New base
   a. Granular base
   b. RSLCB.

Existing granular base that is damaged during the removal of the existing pavement or is trimmed needs to be reworked, regraded, and recompacted. A ¼-in. (6-mm) thick bedding material may be used to provide a uniform grade for panel placement. Placement of new granular base should follow agency requirements, including the requirements for compaction equipment, granular material moisture control, and compaction testing.

RSLCB has not been widely used to date for PCP applications. Its use is allowed in California if an existing base is determined to be inadequate because of constructability issues or pavement performance requirements. The strength and durability requirements for RSLCB should be the same as for CTB or conventional LCB, except that RSLCB needs to be workable for manual placement. The strength requirements for RSLCB are as follows:

1. A minimum compressive strength of 100 lbf/in.^{2} (0.7 MPa) within 2 hours of placement to allow installation of panels;
2. A minimum compressive strength of 500 lbf/in.^{2} (3.4 MPa) at the time of opening to traffic; and
3. A minimum 750 lbf/in.^{2} (5.2 MPa) compressive strength at 7 days, but not to exceed 1,200 lbf/in.^{2} (8.3 MPa).

For PPCP systems, the quality of the base should not be sacrificed for construction expediency. The design of PPCP requires the use of a stiff, strong base that ensures lower deflections at the wider expansion joints under traffic loading. The base needs to be smooth for PPCP systems. A smooth base, together with a friction-reducing treatment, will minimize prestress loss at the panel–base interface. A rougher base will make it difficult to interconnect the adjacent panels tightly, resulting in less residual prestress and possible misalignment of adjacent panels at the intermediate transverse joints.

Base Grading

Base grading is another critical operation for a well-performing PCP system. Proper base grading ensures uniform support under the panel. Currently, base grading for granular bases is performed using an auger-based trimming device moved manually along a railing system placed on the adjacent lanes, as shown in Figure 6.1. This is a slow operation and may require several passes of the trimmer to achieve the desired grade. This operation cannot be easily performed on granular bases with aggregates larger than about ½ in. (13 mm), and therefore a finer-grained bedding material must be used to achieve the desired grade. A thin bedding layer may be used, but a thicker, noncompactable bedding material should not be allowed as it may result in a nonuniform support condition and premature panel settlement.

An RSLCB used as a base can be finished to the desired grade using a conventional concrete screed operated along a railing system placed on the adjacent lanes. However, since no formwork is used to place the RSLCB, the edge grade must be achieved manually using floats, requiring care to ensure that high or low spots are not built into the edges of the RSLCB.

Figure 6.1. Auger-based granular base grading system.

Regardless of the base type used, the base surface should be smooth and not exceed a roughness of ⅛ in. (3.2 mm) over 10 ft (3 m) in any direction, as measured with a straightedge.

Panel Undersealing

If panels are not seated well, or if voids or point loading exist at the panel underside, there is a fairly good possibility that there will be early failure of the panels due to cracking or excessive faulting. Although sufficient precautions are taken during the base preparation to ensure a smooth and firm base, the base surface cannot precisely match the underside surface of the precast panels. Thus, it is necessary to use panel bedding or seating material and to carry out undersealing after the precast panels are installed to ensure uniform and firm seating of the panels on the base. The use of thin bedding layers and thin undersealing layers will perform adequately over the long term only if the underlying base support is adequate.

Subsealing is performed to fill voids that may exist under the slab panels. The subsealing does not strengthen the base or change any other characteristics of the base material. If the base is porous, such as a permeable base, the use of subsealing may not be effective and may be potentially detrimental to the performance of the base. The subsealing materials are free flowing and are introduced through uniformly spaced grout holes at the panel surface. To ensure uniform distribution under the panel, grout channels may be used in the slab bottom. Certain aspects of the grout channel design are proprietary.

For both undersealing and cementitious bedding materials, the compressive strength requirement is about 500 lbf/in.^{2}

(3.4 MPa) at the time of opening to traffic. These materials also need to be nonerodible.

Interface Treatment for PPCP Systems

An interface treatment is necessary for PPCP systems to ensure a very low level of friction between the PPCP panels and the base. Typically, a friction-reducing membrane is used over the finished base. This practice is based on the use of polyethylene membrane for CIP-PCPs. The membrane recommended for PPCP systems is a 6-mil-thick polyethylene sheet that comes in rolls and can be placed the full width of the lane. Alternatively, a nonwoven geotextile fabric, as used at the Virginia I-66 PPCP project, can be used. The geotextile fabric should be at least 0.1 in. (3 mm) thick.

The panel–base interface for PPCP is much smoother than the panel–base interface that develops in CIP-PCP, as illustrated in Figure 6.2. The CIP-PCP slab bottom incorporates the undulations (roughness) that may exist in the finished base surface. In contrast, the PPCP panel bottom is fabricated smooth and does not incorporate the undulations that may be present in the finished base. As a result, the PPCP panel–base interface friction can be expected to be less that the slab–base interface friction of the CIP-PCP.

The PPCP panel–base interface friction factor (coefficient of panel–base friction), incorporating the interface treatment, may range from 0.5 to 1.5; conservatively, this factor may be assumed to be about 1.0. The friction factor is an important property of the PPCP system in that it affects the level of effective prestress that develops in the PTSection and also affects the seasonal expansion joint width changes.

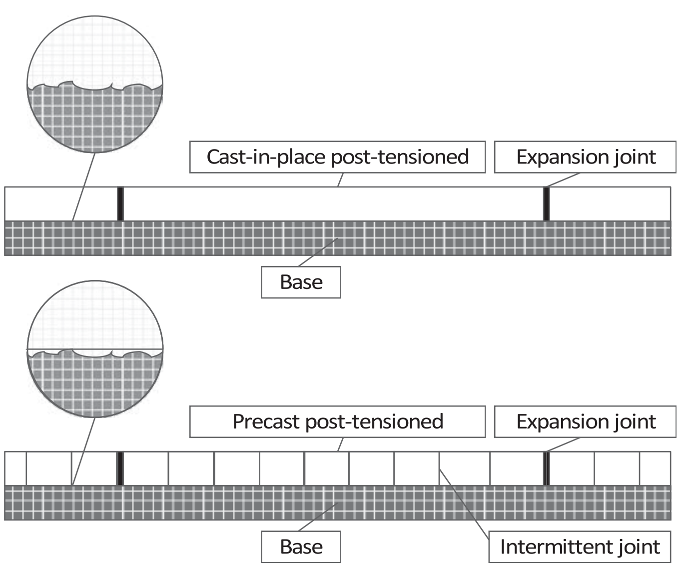


Figure 6.2. Slab–base interface conditions for (top) CIP-PCP and (bottom) PPCP.

A range of friction factors, from 0.5 to over 10, has been measured for slab–base friction for CIP concrete pavements. Friction factors over 5.0 are considered to be fully "bonded" conditions, based on the consideration that such a level of restraint would result in slab cracking as a result of slab contraction caused by temperature changes. Little testing has been performed to determine the friction factors for slab–base (panel–base) interfaces that incorporate a friction-reducing membrane and a smooth panel bottom. The conservative value of 1.0 typically used for CIP-PCP is considered applicable for PPCP systems, especially considering the smooth base of the PPCP panels.

Overestimating or underestimating the friction factor value for a specific PPCP system has specific implications. Overestimating the friction factor would result in a lower computed effective prestress level, which may require use of a higher level of prestress application or use of shorter lengths of PTSections. Overestimating the friction factor would also result in less change in the expansion joint width caused by seasonal temperature changes and may result in underdesigning the joint width.

In contrast to the effects of overestimating the friction factor, underestimating the friction factor would result in a higher computed effective prestress level. This may result in use of a lower level of prestress application or use of longer lengths of PTSections. Underestimating the friction factor would also result in more change in the expansion joint width caused by seasonal temperature changes and may result in overdesigning the joint width.

Granular Base Compaction Testing

Very little testing is performed on site to ensure that the granular base used for PCP applications (repair or continuous) is adequately compacted. Poor compaction of the granular base or the fine-grained bedding layer can lead to excessive nonuniform settlement and early distress development in the PCP. The support condition requirements for PCP systems should be as good or better than those for CIP concrete pavements. An example of poor support condition is shown in Figure 6.3. At this project, a 0.5- to 1-in. (13- to 25-mm)-thick manufactured sand was used over a trimmed existing CTB. As the footprints in Figure 6.3 show, the bedding material is not stable and will most likely not provide good uniform support under the precast panels. The use of thicker, noncompactible fine-grained bedding material is not a good practice.

It is recommended that agencies specify QC/QA testing of the granular bases using the lightweight deflectometer (LWD) to monitor the level of compaction. The LWD was introduced in the United States during the 1990s, and several agencies use it for acceptance testing of granular paving material (base,

Figure 6.3. Footprints indicate a poorly compacted fine-grained bedding layer.

subbase, and subgrade) (Minnesota DOT 2008, 2011). The device, shown in Figure 6.4, is light weight, fairly simple to use, and performs the testing rapidly and nondestructively.

LWD testing assesses the stiffness of the unbound granular material by measuring the deflection of the compacted material to a repeatedly dropped weight. The test significantly reduces inspection time for determining the compaction of granular materials. LWD testing involves the following steps:

1. Measure the deflection caused by the dropped weight.
2. Estimate the stiffness modulus, E, based on the applied force and the measured deflection.
3. Repeat the test three times at a given location. Calculate the average estimated stiffness modulus, E_{av}.

Courtesy of Minnesota DOT.

Figure 6.4. Lightweight deflectometer.

4. Compare E_{av} to the target stiffness modulus, E_{target}, which is based on previous testing on a trial section that was compacted at maximum dry density and optimum moisture content, or by using historical data.
5. If E_{av} is less than E_{target}, additional compaction of the tested area should be considered.

When working with an existing granular base, there may not be data available to establish E_{target}. In such a case, sufficient testing should be conducted during the first few lane closures to establish E_{target} for a specific project. In any case, LWD testing should be required for PCP projects to monitor the uniformity of compaction, especially when fine-grained bedding material is used.

Compaction of granular material is dependent on the moisture content, and maximum compaction is achieved only when the material is at optimum moisture content, as determined using a maximum density test method (e.g., the Proctor method). A comprehensive procedure developed by the Minnesota DOT (2011) for using the LWD for granular material compaction control is recommended for PCP installations if the in-place density of compacted restored or new base material cannot be reliably determined.

Base and Bedding Issues

Several issues have been noted with respect to PCP base and bedding in both intermittent repair applications and jointed continuous PCP systems. The condition survey of an intermittent repair project along a section of I-295 in New Jersey indicated that the repair panels are exhibiting settlement. The settlement is noticeable when the panel surface profile is compared with the surface profiles of adjacent lanes along the common longitudinal joints. The settlement was about ½ in. (13 mm) for the many panels inspected. The field survey was conducted about 2 years after panel installation. LTE at the panel transverse joints was good, and there was no joint elevation difference at these joints. The panel settlement is considered to be due to inadequate compaction of the regraded and recompacted existing granular base that exists at this project.

In jointed continuous PCP systems, extensive cracking developed within a few months of opening to traffic at the following projects that used FMC's Super-Slab system:

1. I-66 ramp, Fairfax, Virginia: granular bedding used over existing granular base;
2. I-15, Ontario, California: manufactured sand bedding used over existing milled CTB; and
3. US-395 to I-80 ramp, Reno, Nevada: granular bedding used over existing granular base.

At the Virginia I-66 ramp project, 50 of 215 panels exhibited cracking soon after the panel installation was completed.

About 64% of the cracking (32 of the 50 panels) was considered to be related to the tie-in with the adjacent inside lane, a JRCP with 60-ft (18.3-m) joint spacing, as these cracks developed at or adjacent to an expansion joint or a crack in the adjacent JRCP. The outside lane PCP had a joint spacing of about 15 ft (4.6 m). The remaining cracking is considered to be caused by nonuniform base or bedding support.

At the California I-15 project, the existing 8½-in. (213-mm)-thick concrete pavement with variable joint spacing on a CTB was replaced with an 8-in. (203-mm)-thick JPrCP with variable joint spacing and placed on a manufactured sand bedding layer with a minimum thickness of 0.40 in. (10 mm). In certain areas, the existing CTB had to be milled to allow for a minimum bedding thickness of 0.40 in. (10 mm). Soon after opening to traffic, 170 panels of a total of 730 panels were found to exhibit cracking. The cracking at this project is considered to be caused by poor control during the placement and compaction of the manufactured sand bedding material. An investigation by Caltrans to determine the specific causes of the premature cracking was in progress as of June 2011.

The Nevada ramp project was a small demonstration project in the Reno area that involved replacing an existing AC pavement with about 227 ft (70 m) of 8-in. (203-mm)-thick JPrCP. The panel lengths averaged about 6 ft (1.8 m) to allow every second or third joint in the JPrCP to match the transverse joints in the adjacent concrete pavement. The panels, which incorporated three dowels per wheelpath, were placed on a new granular base. Soon after opening to traffic, all 52 panels exhibited cracking. The cracking at the Nevada project is surprising because of the short panel lengths used. All panels were nonplanar panels. The cracking is attributed to poor support condition, inadequate load transfer at joints, and poor quality of concrete. The cracking is under investigation by the Nevada DOT.

Summary

The support condition under the precast panels is a key requirement for successful performance of PCP systems. The quality of base and bedding materials must be controlled to ensure that these materials provide the desired support and that the support is uniform along the length of each panel. To date, no serious attempts have been made to control the compaction of granular base or bedding materials by controlling the moisture content of these materials. It is important that testing of the granular base or bedding, or both, be performed to monitor the compaction level.

A bedding layer is routinely used with PCP systems to ensure uniform support under the panels. If a fine-grained granular bedding material is used, its thickness should be limited to ¼ in. (6 mm). If a thicker bedding layer is necessary, then rapid-setting cementitious grout or flowable fill may be considered. As a general rule, any base or bedding material that would not be allowed during the construction of CIP concrete should not be used with a PCP system.

Finally, if the opportunity does not exist to improve the base or bedding system and the subgrade is of marginal quality, more attention should be paid to the design of the JCP system. The load transfer system at transverse joints must be adequate, and the panels may need to be prestressed if thicker nominally reinforced panels cannot be accommodated. Panels of only one size (thickness) cannot be expected to meet all design needs, especially when marginal support conditions are encountered.

CHAPTER 7

Technical Considerations: Prestressed Pavement

General

This chapter discusses a variety of features and issues that must be considered when using prestressed pavement, including the following:

1. Prestressing tendons;
2. Prestressing accessories;
3. Posttensioning methods;
4. Prestress losses for posttensioned system;
5. Pretensioning considerations;
6. Expansion joint system; and
7. Load transfer at expansion joints.

Prestressing Tendons

For PPCP applications, the tendons used are low-relaxation, 7-wire strands (six helically wound outer wires and one center [king] wire) conforming to ASTM A416. The most commonly used tendons are 0.5 or 0.6 in. (13 or 15 mm) in diameter, with a preference for 0.6-in.-diameter tendons for posttensioning applications. Because these tendons are used for pretensioning and grouted posttensioning applications, the tendons are not greased. The basic properties of the tendons are given in Table 7.1 (PCI 2004).

Epoxy-Coated Strands

The low-relaxation, 7-wire strand is available with epoxy coating for use in severe exposure conditions that increase the risk of strand corrosion, typically for concrete directly exposed to seawater. Epoxy-coated strands may be impregnated with a grit to ensure development of bond. Without grit, the epoxy-coated strand has virtually no bond strength (PCI 2004). With proper grit application, the bond strength of the epoxy-coated strand is comparable to uncoated strands. Epoxy-coated strands are not necessary for pavement applications, as the grout used for the bonded applications provides adequate additional corrosion protection, and the cost of epoxy-coated strands is significantly higher.

Prestressing Bars

Threaded prestressing bars are used in limited applications for specific PPCP systems. Typically, the bars are used to achieve temporary posttensioning of adjacent panels by applying a posttensioning stress of about 30 to 50 lbf/in.^{2} across the width of the panels being connected. The temporary posttensioning is necessary to tightly connect two adjacent panels at the common intermediate transverse joints. Typically, two bars are used at about one-quarter to one-third the distance from each side of the panels. The threaded bars feature continuous hot-rolled ribs, providing a right-handed thread along the entire length. The threaded bars can be cut anywhere and are threadable without additional preparation. The bars are available in diameters of 1, 1.25, and 1.3 in. (26.5, 32, and 36 mm). The threaded bars are hot-rolled and proof-stressed alloy steel conforming to ASTM A722. The basic properties of the bars, corresponding to an ultimate stress of 150,000 lbf/in.^{2} (1,034 MPa), are given in Table 7.2 (PCI 2004).

For a PPCP panel 9 in. (225 mm) thick and 12 ft (3.7 m) wide, the applied load per bar would need to be about 32,000 lbf (142.3 kN) to achieve an average prestress of about 50 lbf/in.^{2} (344 kPa) across the width of the panel.

Prestressing Accessories

Prestressing accessories for PPCP systems include the anchorage, posttensioning ducts, duct couplers, duct gaskets, and duct grout. Protecting posttensioning tendons from corrosion is an important consideration in selecting prestressing hardware.

Anchorage

Anchorages transfer the prestressing tendon force to the concrete. The anchorage system includes a bearing plate and a

Table 7.1. Tendon Properties

Property	0.5-in. Tendon Diameter	0.6-in. Tendon Diameter
Tendon cross-sectional area (in.^{2})	0.153	0.217
75% of ultimate load (lbf)	31,000	43,000
80% of ultimate load (lbf)	33,000	46,900
Ultimate load (lbf)	41,300	58,600

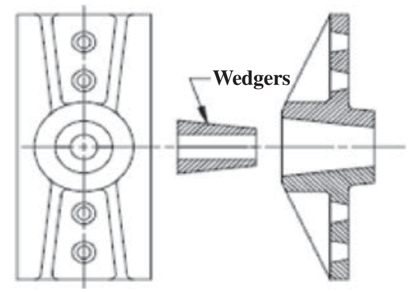


Figure 7.1. Monostrand anchorage system.

chuck assembly that grips the strand and holds it in place. For prestressing bars, the anchorage system includes an anchor nut that holds the bar in place. Anchorage types include stressing-end anchorage and fixed-end anchorage. The stressing-end anchorage stresses the strands or bars from one end only. A fixed-end anchorage is used at the other end of the strand or bar when the stressing is done from only one end.

A common type of single-strand anchorage system is shown in Figure 7.1.

Posttensioning Ducts

Corrugated ducts house the prestressing strands or bars, allowing installation and movement of the prestressing steel during stressing. The ducts cover the prestressing steel from anchorage to anchorage and are an essential element of tendon durability. The ducts may be made from galvanized steel or a plastic material. Plastic ducts have been used in the United States for several PPCP projects and are recommended for PPCP applications.

The duct size is selected to accommodate a single strand or multiple strands. To date, most PPCP projects have been designed using single-strand ducts. However, the design of the recently completed I-680 PPCP project in California incorporated a large duct to accommodate two strands plus another strand for a temporary posttensioning operation.

The ducts serve as a barrier to mitigate corrosion of the tendons, and their corrugations form an interface between prestressing steel, grout, and structure to transfer bond forces. Once the final posttensioning of the panels is completed, the ducts are grouted to bond the strands or the bars to the concrete. The grout also protects the strands or bars from corrosion. When prestressing bars are used, the duct size should be selected to accommodate the couplers used to connect the shorter lengths of the bars.

Table 7.2. Prestressing Bar Properties

Property	1.0-in. Bar Diameter	1.25-in. Bar Diameter
Bar cross-sectional area (in.^{2})	0.85	1.25
70% of ultimate load (lbf) (lock-off stress)	89,300	131,300
80% of ultimate load (lbf) (jacking stress)	102,000	150,000
Ultimate load (lbf)	127,500	187,500

Duct Couplers

Duct couplers connect the couplers of adjacent panels during panel installation. Different designs of couplers are available commercially. A heat-shrink plastic coupler may be used, as illustrated in Figure 7.2. This design, which was proposed for use at the Florida PPCP project, ensures that grout does not leak out at the intermediate joints of the PPCP system.

Duct Gaskets

When duct couplers are not used, a compressible gasket is needed to prevent any grout leaks at the intermediate joints. The gasket, a donut-type sealer, is made from a rubberized material that is positioned in a receptacle at the end of a duct before the adjacent panel is installed, as shown in Figure 7.3. At the California I-680 PPCP project, a better seating for the gasket was designed to ensure a more positive sealing at the intermediate transverse keyway joints.

Duct Grout

The currently used PPCP systems are based on the use of bonded tendons. Cementitious or proprietary grouts are used to fill the void between the tendon and the duct to ensure a positive bond between the tendon and the concrete. To be effective, the grout needs to completely fill the spaces between the tendon and the duct. The grouts typically achieve compressive strength that is higher than the concrete's compressive strength, although specifications typically require grout strength to be equal to the concrete strength. The grout must be chloride-free.

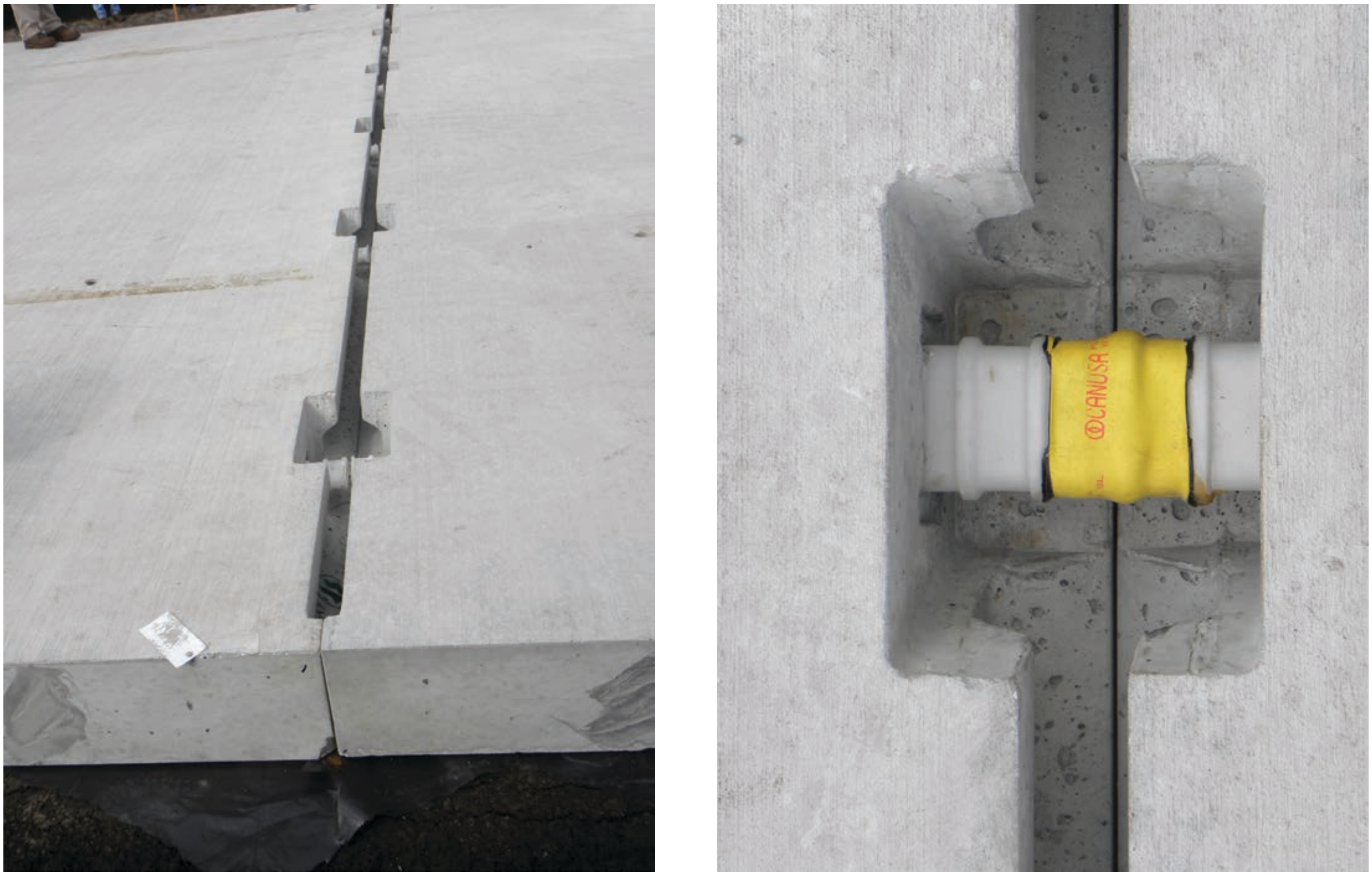


Figure 7.2. Shrink-wrap coupler use with the double keyway detail.

Figure 7.3. Gasket use.

In addition to providing a bonded tendon system, the grout also provides cementitious cover for the tendon, improving the corrosion resistance of the tendon system.

Tendon Enclosure Considerations

Protecting posttensioning tendons from external corrosive sources such as water, oxygen, airborne chlorides, and the infiltration of deicing chemicals is an important consideration in selecting the prestressing hardware (the duct, coupler or gasket system, grout, and anchorage system) (Krauser 2011a, 2011c). Tendon corrosion can lead to concrete spalling and loss of PTSection continuity across the intermediate joint.

Tendon protection levels are discussed in several documents, such as *Durability of Posttensioning Tendons* (*fib* 2005) and a PTI–ASBI draft report, *Guide Specification for Grouted Posttensioning* (PTI–ASBI 2010). Selecting the required tendon protection level for the segmental project is based on the aggressivity of the environment, exposure of the structure or element, and the protection provided by the structure. The posttensioning tendons' protection level combined with the protection provided by the structure provide the resistance against the aggressivity of the environment and particular exposure conditions of the structural element (*fib* 2005). The protection levels are defined in Table 7.3.

Environments with low aggressivity occur when there is no risk of corrosion in a very dry environment or when corrosion is induced by carbonation and the environment is dry or permanently wet. For most pavement applications, an environment's aggressivity would typically be classified as medium or high because of the exposure to deicing salts and the large number of intermediate joints. Protection Level 2, which is recommended for pavement application, incorporates the following elements (Krauser 2011b):

1. Corrugated plastic duct;
2. Leak-proof duct coupler or gasket system;
3. Thixotropic engineered grout;
4. Full grout coverage within the ducts;
5. Permanent grout cap;
6. Tendon enclosure pressure test; and
7. Epoxy-coated or galvanized anchorage components.

It is clear that several elements are necessary to protect prestressing strands from corrosion: the tendon enclosure (duct), a means of maintaining duct continuity across segment joints, and quality grouting. These elements are vital in keeping contaminated water from accessing tendons and causing corrosion of the highly stressed steel (Krauser 2011a).

Posttensioning Methods

Posttensioning is performed in a single operation. To date, three posttensioning methods have been used:

1. Posttensioning from the central panel prestressing pockets;
2. Posttensioning from the joint panel prestressing pockets; and
3. Posttensioning from the end panel joint face.

Posttensioning from Central Panel Prestressing Pockets

Posttensioning from the central panel prestressing pockets is done from the pavement surface using specially configured jacks that can be used within the stressing pockets. This method involves the following:

1. Placement of dead-end anchorages in the joint panels;
2. Use of couplers at the stressing pocket to connect the strands extending from each end; and
3. Posttensioning the strands from each end at the central stressing pocket.

Table 7.3. Tendon Protection Levels

fib **Bulletin 33**	**PTI–ASBI Guide Specification**
Protection Level 1 (PL1)	
A duct with filling material (grout) providing durable corrosion protection.	PL1A: A duct with grout providing durable corrosion protection.
	PL1B: PL1A plus engineered grout and permanent grout cap.
Protection Level 2 (PL2)	
PL1 plus a watertight, impermeable envelope providing a leak-tight barrier.	PL1B plus an envelope, enclosing the tensile element bundle over its full length, and providing a permanent leak-tight barrier.
Protection Level 3 (PL3)	
PL2 plus integrity of tendon or encapsulation to be inspectable or monitorable.	PL2 plus electrical isolation of tendon or encapsulation to be monitorable or inspectable at any time.

Posttensioning from Joint Panel Prestressing Pockets

Posttensioning from the joint panel prestressing pockets is done from the pavement surface using specially configured jacks that can be used within the stressing pockets. This method involves the following:

1. Placement of a dead-end anchorage at one of the joint panels; and
2. Posttensioning the strands from the stressing pockets in the joint panel at the other end.

Posttensioning from End Panel Joint Face

Posttensioning from the end panel joint face is done within the gap area and involves the following:

1. Placement of a dead-end anchorage at the back-end joint panel; and
2. Posttensioning the strands from the joint face at the other end, where a gap is left to accommodate the posttensioning operation.

Tendon Location

Tendons should be located about ½ in. (13 mm) below the middepth of the panel. The downward eccentricity provided will minimize loss of support caused by curling and load-related deformations along the expansion joints. This practice has been used for CIP-PCPs.

Temporary Posttensioning to Connect Panels

Temporary posttensioning is used to tightly connect the adjacent panels of a PTSection as soon as a panel is placed and positioned. The posttensioning ensures a good bond between the epoxied faces of the adjacent panels at each intermediate joint. The temporary posttensioning also ensures that the adjacent panels are aligned correctly and that alignment errors do not build up over the full length of the PTSection. Two methods have been used for temporary posttensioning: using strands and using prestressing bars.

Using strands is feasible only when full lane closure is available to allow unused strands to be left on the pavement surface until the strands can be used for the final posttensioning or if the temporary and final posttensioning operations can be performed within a single lane closure.

Using prestressing bars requires an appropriately sized duct that is prefabricated in each panel. Only two tendons (strands or bars) are needed for the temporary posttensioning operation. These tendons are located at about one-quarter to one-third point from each corner of the panels. The posttensioning force applied to each tendon should be such as to apply an average prestress in the panel of about 50 lbf/in.^{2} (344 kPa).

Prestress Losses for Posttensioned Systems

Prestress losses are an important consideration in post-tensioned PCPs because the structural capacity of the pavement is dependent on the effective prestress in the concrete from posttensioning. These losses must be accounted for to ensure that the required prestress level is maintained over the length of the slab over the design life of the pavement. Losses of 30% to 50% of the applied prestress force can be expected for a well-constructed posttensioned concrete pavement. Several factors contribute to prestress losses:

1. Elastic shortening of the concrete (negligible prestress loss);
2. Creep of the concrete;
3. Concrete shrinkage;
4. Relaxation of the stressing tendons;
5. Slippage of the stressing tendons in the anchorage (accounted for during the posttensioning operation);
6. Friction between the stressing tendons and ducts (negligible loss for tangent sections); and
7. Frictional resistance between the panel and base material (most significant component).

Extensive testing and experience in prestressed concrete practice have produced methods to reliably predict the effects of these factors. Typically, about 200 to 300 lbf/in.^{2} (1.4 to 2.1 MPa) end prestress is used. This prestress results in about 100 to 200 lbf/in.^{2} (0.7 to 1.4 MPa) at the midpoint of the PTSections, based on the losses due to the factors listed above.

The losses due to the elastic shortening of the concrete, the slippage of the stressing tendons in the anchorage, and the friction between the stressing tendons and the ducts can be computed, but they are small and can be ignored. The largest component of the prestress loss is the result of the panel–base friction. This component of the prestress loss is kept low by ensuring a smooth base finish and using a panel–base friction-reducing membrane.

The computation of the primary components of prestress loss is described below.

Prestress Loss Caused by Panel–Base Friction

Prestressing loss caused by friction (σ_F) between the PCP panel and subbase is given by the following equation:

$$\sigma_F = \frac{\mu \gamma L}{288}$$

where

μ = panel–base friction factor (coefficient of friction);
γ = concrete unit weight (lb/ft^3); and
L = panel length.

The above equation can be simplified to the following form for a concrete unit weight of about 142 to 146 lb/ft^3 (2,274 to 2,238 kg/m^3):

$$\sigma_F = \frac{\mu L}{2}$$

The panel–base friction factor value may range from 0.5 to about 1.5 for prestressed CIP or PCP, depending on the finish of the base and the interface friction treatment used. A conservative value of 1.0 may be used for the panel–base friction factor. The prestress loss is assumed to be linear along the length of the PTSection.

Prestress Loss Caused by Concrete Shrinkage

Prestress loss caused by concrete shrinkage (f_s) is given by the following equation:

$$f_s = \varepsilon_s E_s \left(\frac{A_s}{A_c} \right)$$

where
- ε_s = concrete shrinkage strain;
- E_s = modulus of elasticity of tendon steel (lbf/in.^{2});
- A_s = area of tendon per unit width of slab (in.^{2}); and
- A_c = area of slab per unit width of slab (in.^{2}).

Concrete shrinkage is a property of a specific concrete mixture and is dependent on the water–cementitious materials ratio, aggregate type, and curing environment. Long-term shrinkage of concrete may range from 300 to 600 millionth in./in., depending on the drying environment (one-sided versus multiple-sided drying) and the concrete dimensions. For precast concrete panels, it is expected that a significant amount of drying shrinkage will occur during storage at the plant or project site. The storage period may range from a few weeks to several months. In addition, after installation, concrete panels exhibit shrinkage mostly in the upper 2 to 3 in. (50 to 75 mm) of the panel. The rest of the panel remains sufficiently moist (high relative humidity) and does not exhibit significant long-term drying shrinkage. For computation of the prestress loss caused by concrete shrinkage and the end movements of the PTSection (discussed below), a reasonably conservative average drying shrinkage value of about 200 millionth in./in. is recommended (PCI 2004).

Prestress Loss Caused by Concrete Creep

Prestress loss caused by concrete creep (f_{cr}) is given by the following equation:

$$f_{cr} = C_u \frac{E_s}{E_c} f_{pe} \left(\frac{A_s}{A_c} \right)$$

where
- C_u = ultimate concrete creep coefficient;
- E_c = modulus of elasticity of concrete (lbf/in.^{2}); and
- f_{pe} = applied end prestress.

C_u is dependent on the hardness and gradation of the concrete aggregates, cement content, the water–cementitious materials ratio, curing environment, and age at time of sustained stress application. A C_u value of 2.5 is recommended (PCI 2004).

Prestress Loss Caused by Steel Relaxation

Prestress loss caused by steel relaxation is given by the following equation (PCI 2004):

$$f_r = \rho f_{pe}$$

where ρ is the steel relaxation coefficient for the appropriate stress level, 0.04.

Example Computation of Prestress Losses

An example computation of prestress losses is given below for the following design parameters:

1. PTSection length = 200 ft (61 m);
2. Tendon (strand) diameter = 0.6 in. (15 mm);
3. Tendon cross-sectional area = 0.217 in.^{2} (140 mm^2);
4. Tendon spacing = 24 in. (610 mm);
5. Panel thickness = 8.0 in. (200 mm);
6. Concrete modulus of elasticity = 4,000,000 lbf/in.^{2} (27.58 GPa);
7. Steel modulus of elasticity = 28,000,000 lbf/in.^{2} (193.1 GPa);
8. Tendon force at 75% of yield stress = 43,000 lbf (191.3 kN);
9. Panel–base friction factor = 1.0 (conservative value used);
10. Concrete shrinkage strain = 200 millionth in./in.;
11. Concrete ultimate creep coefficient = 2.5;
12. Steel relaxation coefficient = 0.04 (for low relaxation strands);
13. Area of concrete per tendon = 24 × 8 = 192 in.^{2} (0.12 m^2); and
14. Applied end prestress = 43,000/192 = 224.0 lbf/in.^{2} (1.5 MPa).

Example prestress losses are as follows:

- Prestress loss caused by panel–base interface friction = 100 lbf/in.^{2} (0.7 MPa);
- Prestress loss caused by concrete shrinkage = 6.3 lbf/in.^{2} (43.4 kPa);
- Prestress loss caused by concrete creep = 4.4 lbf/in.^{2} (30.3 kPa);

- Prestress loss caused by steel relaxation = 9.0 lbf/in.^{2} (62.0 kPa); therefore,
- Total prestress losses = 100 + 6.3 + 4.4 + 9.0 = 119.7 lbf/in.^{2} (MPa).

The long-term effective prestress at the midpoint of the PTSection is (224.0 – 119.7) or 104 lbf/in.^{2} (rounded) (0.7 MPa).

Pretensioning Considerations

Pretensioning of the panels may be necessary to accommodate panel lifting for longer or wider panels and to allow the use of thinner panels as part of the structural design of prestressed panels.

Pretensioning is done using 0.5-in. (13-mm)-diameter 7-wire low-relaxation strands. A strand force of 31,000 lbf (138 kN) (75% of yield strength) is typically used. This strand force results in a strand stress of 202,000 lbf/in.^{2} (1,392 MPa). After the prestress losses caused by concrete creep, concrete shrinkage, and steel relaxation are accounted for, a long-term strand stress of about 165,000 lbf/in.^{2} (1,138 MPa) is available to prestress the concrete. This level of strand stress is available beyond the prestress transfer length of about 25 in. (635 mm) from each end of the strand. The immediate and long-term prestresses per strand available within the panel beyond the prestress transfer length are summarized in Table 7.4.

Expansion Joint Systems

PPCP systems incorporate PTSections about 150 to 250 ft (46 to 76 m) in length, and expansion joints are required to accommodate the daily and seasonal expansion and contraction of the PTSections. The expansion joint width ranges from about 1 to 3 in. (25 to 75 mm), depending on the PTSection length, the concrete CTE, and the seasonal temperature changes. Three concepts for PPCP posttensioning can be used. Two of the concepts require use of a joint panel that incorporates an expansion joint, allowing the expansion joint system to be fabricated at the precasting plant as part of the panel fabrication process. The third concept, incorporating the use of a gap slab, requires installation of the expansion joint system at the time of panel installation.

There is good experience with the use of wide expansion joints, which are used at bridge approach slabs and have been used at all of the CIP-PCPs.

The following requirements are necessary for expansion joint systems for PPCP:

1. Constructability and maintainability;
2. Effective joint sealing;
3. Effective load transfer at the joint; and
4. Allowance for future grinding along the joint.

Table 7.4. Immediate and Long-Term Effective Prestress in the Panel

Panel Thickness (in.)	Immediate Effective Prestress (lbf/in.^{2}) for Strand Spacing of			Long-term Effective Prestress (lbf/in.^{2}) for Strand Spacing of		
	24 in.	30 in.	36 in.	24 in.	30 in.	36 in.
8	161	129	108	131	105	88
9	144	115	96	117	94	78
10	129	103	86	105	84	70
11	117	94	78	96	77	64
12	108	86	72	88	70	58

Constructability and Maintainability

Any expansion joint designed for use with PPCP systems must be easily constructible at the precast plant and during the panel installation. If the expansion joint assembly is built into the joint panel at the precast plant, the joint assembly should not overly complicate the panel fabrication process or result in significantly higher costs. The expansion joint assembly and the connectivity to the panel should be sufficiently robust to accommodate the passage of millions of trucks across these joints and be functional enough to allow the passage of millions of automobiles without increasing the roughness at the joints.

The expansion joint assemblies, including the sealant system, must be durable and easy to maintain because of the difficulties with lane closures on high-volume roadway facilities. Ideally, the routine maintenance period for the expansion joints should not be less than about 15 years. The only routine maintenance needed should be restoration of the sealing system. This may involve removal and replacement of strip seals or compression seals.

Joint Sealing Systems

The expansion joint sealant design, discussed below, requires maintaining a minimum joint width during the first summer and allowing for a maximum joint width in later years after concrete shrinkage and creep have occurred. Thus, the sealant used must accommodate the full range of joint width changes over the long term.

Expansion joint systems can be either armored or non-armored expansion joint assemblies. A range of armored joint assemblies are commercially available. These assemblies use strip seals and extruded steel holders to hold the seal in place.

The steel holders should not extend into the gap between the adjacent joint faces. Any such intrusion requires a greater distance between the joint faces, resulting in a longer unsupported length of the dowel bars and a lower level of LTE at the joint. If used, armored joints should allow for construction time or future grinding activities to restore pavement ride quality. As a result, and because of their higher costs, armor-based joint assembles are not considered viable options for routine applications of PPCP systems.

Nonarmored expansion joint systems include systems that use a header and systems without a header. Header-based expansion joints can be constructed using impact-absorbing elastomeric headers or higher-strength headers using concrete or proprietary products. Preformed seals are typically used with header-based joints because of the anticipated large range of movements. For PPCP systems that are designed for smaller joint-width changes, poured sealants can be considered. However, poured sealants may require more frequent joint resealing involving joint refacing and subsequent joint "reservoir" widening. Expansion joints that do not use headers are the simplest to fabricate and install. These joints use compressible, typically preformed, seals. To accommodate the larger joint-width changes, the seals are typically placed along the joint face shoulders.

Bridge-type sliding-plate or finger-joint assemblies are not recommended for use with the PPCP expansion joints because of the added costs of installing such joint assemblies.

Load Transfer at Expansion Joints

The LTE at the PPCP expansion joints is a critical design feature. Because of the larger joint widths, especially during cooler weather, a high level of joint LTE cannot be achieved and should not be expected. A good level of joint LTE can be achieved for joint widths under about 1.5 in. (38 mm). It is strongly recommended that, regardless of the panel thickness, dowels should be 1.5 in. (38 mm) in diameter and spaced at 12-in. (305-mm) intervals. As emphasized above, it is important that the PPCP support condition be of good quality. This requires the use of free-draining, dense-graded granular materials or stabilized bases, especially for higher levels of truck traffic. Thicker, noncompactable granular bedding material should not be used because it can result in large deflections at the expansion joints under heavy truck traffic.

Summary

The use of prestressed pavement requires consideration of a variety of features related to prestressing. The U.S. experience with PPCP is based on the bonded tendon technique. This method is considered safer for highway applications and allows localized repair work in the PPCP to be performed without concerns related to prestress loss in the system. Prestressing allows the use of thinner panels to achieve a desired structural capacity for the pavement for jointed applications and PPCP applications.

CHAPTER 8

Design of Precast Concrete Pavement Systems

General Concepts

The design of PCP is based on the recognition that, once constructed (installed), the overall behavior of the PCP under traffic loading and environmental loading is not significantly different from that of a similar CIP concrete pavement. Thus, a JPrCP is expected to behave similarly to a CIP-JCP, and a PPCP is expected to behave similarly to a CIP-PCP. Concrete pavements are typically designed, constructed, and rehabilitated to provide long-life performance. The U.S. definition for long-life concrete pavements is as follows:

- Pavement will have an original concrete service life of +40 years;
- Pavement will not exhibit premature failures and materials-related distress;
- Pavement will have reduced potential for cracking, faulting, and spalling; and
- Pavement will maintain desirable ride and surface texture characteristics with minimal intervention activities to correct for ride and texture, joint resealing, and minor repairs.

Although PCPs are of recent use and in-service performance information for even the oldest U.S. projects spans less than 10 years, PCPs can nevertheless be designed to provide long-term service. In fact, the warrant for use of PCPs is rapid repair and rehabilitation with recognition of the need for long-term service. The off-site fabrication of PCPs provides certain design-related advantages, including

- Design strength of concrete from Day 1 of installation, thereby assuring no structural damage caused by early traffic loading;
- No early-age curling and warping issues to account for;
- No built-in curling to account for, because precast concrete panels are typically fabricated indoors in a flat profile and remain flat during storage and installation;
- Precast panels incorporate substantial reinforcement. As a result, any cracks that may develop under traffic loading remain tightly closed and do not deteriorate with time; and
- The faulting that may develop in PPCP is less critical than faulting in JCPs because the PPCP expansion joint spacing may range from about 150 to 250 ft (45.7 to 76.2 m), but the joint spacing for CIP-JCP is typically about 15 ft (4.6 m). In addition, PPCP is constructed on good-quality, stiff bases, which results in lower joint deflections under traffic loading and less risk of joint-related distress.

The structural requirements for any pavement system are defined on the basis of anticipated structural distress (failures) under traffic for a given environmental condition. Typical distresses that can develop in CIP-JCP include the following:

1. Cracking: Transverse cracking may develop over a period of time as a result of repeated truck loadings. Cracking is typically referred to as a stress-based distress.
2. Joint faulting: Joint faulting may develop with or without outward signs of pumping. Faulting is typically referred to as a deflection-based distress. Joint faulting is significantly affected by the type of load transfer provided at transverse joints, base type, and drainage needs.
3. Spalling: Spalling may develop along joints or cracks as a result of incompressibles in joints or cracks or poor-quality concrete.
4. Materials-related distress: The more significant materials-related distresses may include alkali–silica reactivity and D-cracking in a freezing environment.
5. Roughness: Pavement smoothness is affected by the development of various distresses in the concrete pavement. The effect of each distress type is additive, and over time pavement roughness increases.

The truck loading conditions to be considered for JCPs (CIP or precast) and PPCP systems are shown in Figure 8.1. The

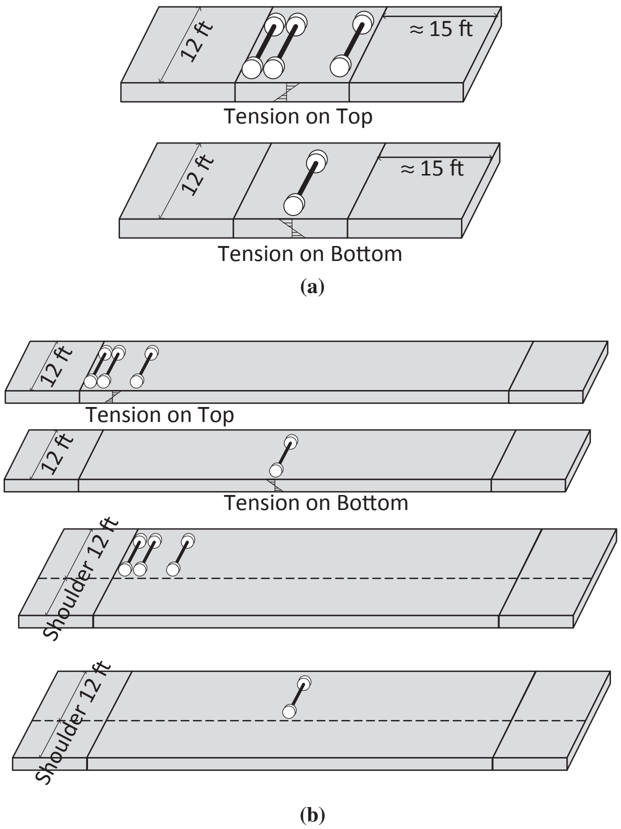


Figure 8.1. Truck axle loading for critical slab stresses for (a) CIP-JCP and precast JCP and (b) PPCP with (top) single- and (bottom) multiple-lane panels.

critical truck axle positions in Figure 8.1(a) are for stresses that result in top-down cracking and bottom-up cracking. These loading conditions are applicable for 12-ft (3.7-m)-wide lanes, widened lanes, and for lanes with a tied concrete shoulder. The critical truck axle positions for longer-length PPCP sections are shown in Figure 8.1(b). As shown, the critical stresses can develop for bottom-up cracking and for top-down cracking for single-lane applications. When the PPCP panels are multiple lane in width, as shown in Figure 8.1b, the loading condition is always an interior loading condition. This is the most efficient design for the PPCP, and, as shown below, a minimum PPCP panel thickness of 8 in. (200 mm) is adequate for a range of truck loading needs when an interior loading condition exists for the PPCP system.

Distress development over the service life of all pavements is expected; however, the rate of distress development is managed by incorporating sound designs, durable paving materials, quality construction practices, and timely preservation activities. In short, structural distress development should take place in accordance with design expectations, but not prematurely.

To understand the structural requirements for PCP, it is necessary to understand the loading that a concrete pavement may be subjected to. Pavements are designed on the basis of truck traffic. Without truck traffic, pavements would exhibit only materials-related distress. For new concrete pavement systems, the following loading-related items need to be considered:

1. Design traffic. Most new concrete pavements are being designed for an initial service life of at least 40 years. Assume a roadway carries 50,000 vpd in one direction and that trucks account for 20% of the vehicles. The design lane will carry over 100 million trucks over 40 years, without accounting for traffic growth. Most primary highway system pavements in the United States are now routinely being designed for truck traffic in the range of 100 to 200 million trucks over the pavement design period. When PCP systems are used for such applications, the PCP components need to be designed to accommodate such high levels of traffic loading. The allowable truck axle loads range from 20,000 lb (9,072 kg) for a single axle to 36,000 lb (16,329 kg) for a tandem axle, and to 45,000 lb (20,412 kg) for a tridem axle. The stresses and deflections in the concrete slab (panel) resulting from the traffic loadings are accounted for in traditional mechanistic-based design procedures (AASHTO 2008).
2. Load transfer at joints. When fully effective, a doweled transverse joint will have an LTE of 90% to 95%, as constructed. Over time, as a result of traffic loading, the LTE will decrease. For CIP-JCP, an LTE of about 70% is considered the limit at which some load transfer restoration treatment may need to be provided. The load carried (transferred) by a dowel bar at a joint may range from about 3,000 lb (1,361 kg) for the outermost dowel bar with the axle load positioned along the lane edge to about 1,200 lb (544 kg) with the axle load positioned about 2 ft (0.6 m) away from the lane edge. On the primary highway system, these loads are expected to be carried by the dowel bars in excess of 100 million times, assuming most trucks drive along the lane edge.
3. Temperature-related curling. Temperature variations with depth in the concrete panel induce curling-restraint stresses. These stresses vary throughout the day and from day to day and can be very high. These stresses are accounted for in traditional mechanistic-based design procedures.

In summary, the design of the various components of any new PCP system must take into account the volume of truck traffic expected to use the facility and the environmental conditions to which it will be exposed. Design, material, and construction flaws cannot be tolerated under high traffic loadings. The discussion above also applies to intermittent precast repair applications. The only difference is that the amount of design truck traffic may be less for such applications if the repairs are designed for a shorter service life.

Specific design procedures have not been developed for PCP systems. Development of reliable pavement design procedures requires a sound understanding of the pavement's behavior and validation of the design concepts on the basis of field performance. At this time, there are not enough projects available with long service to allow field validation. As a result, the design of PCP systems needs to be based on current design procedures for conventional CIP-JCP.

As the primary difference between CIP concrete pavement systems and PCP systems is the method of construction (installation), once the PCP has been installed, the behavior of the system should not significantly differ from that of a CIP concrete pavement. Some differences do exist and are listed below:

1. Less slab warping in the precast panels, if cured properly at the plant;
2. Less variability in concrete strength for the precast panels;
3. More precise embedment of dowel bars in precast pavements;
4. A smoother bottom surface for PCP systems; and
5. Smoother vertical faces at transverse joints of precast panels. The installation process results in a gap of up to 0.5 in. (13 mm) at the joints, so that aggregate interlocking does not develop at these joints.

For repair and rehabilitation applications, it is important to ensure that the projects selected for PCP applications are good candidates for the selected PCP system. The existing pavements need to be evaluated using project-level evaluation techniques, such as deflection testing, coring, and borings. The thickness and other dimensions of precast panels are typically matched with the features of the existing pavement. The panel thickness for the repair application is typically about 0.5 in. less than the existing pavement to ensure the panel elevation will not be higher than the existing pavement, especially when a stabilized base is present. For new construction, the structural design of the PCP system can be developed using any of the accepted concrete pavement design procedures, balanced with local experience.

PPCP systems are typically 3 to 4 in. (75 to 100 mm) thinner than equivalently designed new JCPs as a result of the effective prestress in the prestressed pavement. The effective prestress at the midlocation of the PTSection, typically 150 to 250 ft (45.7 to 76.2 m) between expansion joints, needs to be about 100 to 200 lbf/in.^{2} (0.7 to 1.4 MPa). These levels are achieved by properly designing the prestressing system for the anticipated slab–base interface condition and considering long-term prestress losses. The effective prestress is additive to the concrete flexural strength, and the resulting effective flexural strength is used as the design concrete flexural strength. When using PPCP systems, caution must be exercised. Because these systems incorporate thinner panels, the panel support (base and foundation) become critical. The thinner PPCP systems require a stiff (strong) base or foundation to reduce slab deflections at the expansion joints and along the panel edges (along the shoulder joint), especially for 12-ft (3.7-m)-wide outside lane panels.

For repair applications, the precast pavements should be designed with the extended service life of the existing pavement in mind. For new construction, the precast pavement should be designed to achieve a service life of 30 to 40 years, in accordance with the agency requirements for long-life concrete pavements.

Guidelines and approaches for the structural design of PCPs are discussed in the following section.

Design for Intermittent Repair Applications

Two types of intermittent repairs are possible: (1) full-panel replacement to replace cracked or shattered slabs and (2) isolated FDRs to repair deteriorated joints, corner cracking, cracking adjacent to the joint, or midslab cracking. This technique can also be used to repair punchouts and deteriorated cracks in CRCP.

Concrete pavements exhibiting various types of structural distresses and serving high-volume traffic may be good candidates for intermittent precast concrete repairs. When appropriately used, PCP repairs are an effective means of restoring the ride quality and structural integrity of deteriorated concrete pavements and, therefore, extending their service life. Typical distresses that can be addressed using precast panels include transverse cracking, corner breaks, longitudinal cracking, deteriorated joints, and blowups in JCPs and punchouts and deteriorated cracks in CRCPs. Intermittent full-depth PCP repairs are also used to prepare distressed concrete pavements for a structural overlay.

Because intermittent repairs are performed in isolated areas along the length of a roadway and typically match existing concrete pavement features, it is difficult to establish performance-based design criteria, as the performance of the roadway is predominantly affected by the performance of the existing pavement and the existing base, support, and drainage conditions. As a result, there is a greater emphasis on ensuring good repairs by focusing on good materials and good installation practices.

Key design features of the intermittent repair application are

1. Precast panel design (panel plan dimensions and thickness);
2. Reinforcement;
3. Transverse joint load transfer systems; and
4. Slab panel support system.

The precast panel requirements for intermittent repairs are discussed below.

Plan Geometry

The precast panel geometry should match the geometry of the portion of the existing pavement that is removed, less about ⅜ to ½-in. (10- to 13-mm)-perimeter gap to allow for placement of the panel in the excavated area in the existing pavement, as shown in Figure 8.2. Care must be exercised in the field to ensure that the dimensions of the existing concrete pavement removal area are not exceeded, because larger gaps along the transverse joints can lead to poor load transfer at these joints and result in maintenance issues with respect to joint sealing. Complex roadway geometries such as superelevation, horizontal curves, and exit and entry ramps will require the fabrication of customized nonplanar panels. This type of panel design requires a detailed survey of the roadway repair areas. For tangent sections placed next to an existing lane, the common longitudinal should be surveyed to document any lateral deviations. If the deviations along the common joint are significant, the deviations should be accounted for in the panel profile (width).

The precast panel dimensions should (1) accommodate the existing pavement geometric constraints; (2) optimize material usage; and (3) optimize panel thickness, length, and width to reduce panel weight, which in turn facilitates the transportation, handling, and placement of the panels. For intermittent applications, the panels are typically one lane wide (11 to 14 ft [3.4 to 4.3 m], depending on the geometry of the existing concrete pavement) and 6 ft to about 15 ft (1.8 to 4.6 m) or more in length.

For projects for which accurate panel width cannot be determined in advance or the lane width is variable, on-site trimming of the panels may be necessary. On-site trimming of the panel width should be done carefully to ensure that the dowel bar positioning in the panel with respect to the positioning in the existing pavement is not affected and to ensure that any steel reinforcement in the panel is not cut or left exposed. It is

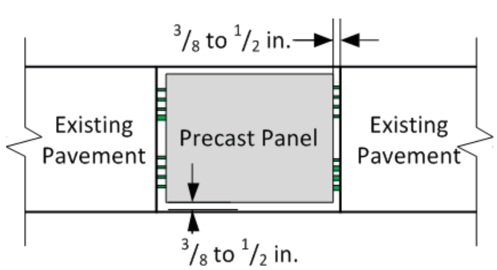


Figure 8.2. Placement of panel in excavated area in existing pavement.

best to predetermine the panel width dimension for each repair panel to minimize site work that may slow the panel installation rate.

Panel Thickness

Panel thickness may vary as a function of the base type. Ideally, the panel thickness should closely match the thickness of the existing concrete pavement, as follows:

- Granular base: Panel thickness should be at least 0.25 in. (6 mm) less than existing pavement thickness to allow for use of bedding material.
- Stabilized base: Panel thickness should be at least 0.5 in. (13 mm) less than existing pavement thickness. The thickness reduction will account for any variability in the thickness of the existing pavement at the location of the panel placement.
- Polyurethane or rapid-setting flowable bedding: Panel thickness should be about 1 in. (25 mm) less than the existing pavement thickness.

It is important that sufficient effort be made to determine the thickness of the existing concrete pavement at most, if not all, intermittent repair locations when stabilized bases are involved. For stabilized bases, if the panel thickness is slightly larger than the thickness of the removed pavement, the panel will extend above the riding surface, resulting in an elevation difference that can affect vehicle operation over the repair area. During short lane closure periods, it is difficult to try to regrade the base material within a small work area. It is best to be conservative and specify a thinner panel, with a higher concrete strength, for such projects.

Concrete Requirements

The concrete flexural strength should be equal to or greater than the strength of the existing concrete. By default, the panel's concrete flexural strength should be at least 650 lbf/in.^{2} (4.5 MPa) at the time of installation. All other concrete-related requirements should meet the requirements established for CIP concrete paving.

Panel Reinforcement

Panel reinforcement is necessary to mitigate any distress related to shipping and handling of the panels. The reinforcement is introduced typically in two layers, top and bottom. Depending on the panel dimensions, the reinforcement may range from about 0.15% to 0.20% of the concrete cross-sectional area. This level of reinforcement is sufficient to keep any cracks that may develop tightly closed during service. Most agencies require that panels exhibiting full-depth cracking before installation be rejected.

Jointing and Joint Load Transfer

The provision for load transfer at transverse joints is necessary for all intermittent repair projects. The specific details related to load transfer requirements are discussed above. A minimum LTE of 90% is recommended for intermediate repair projects. LTE-related deflection testing should be conducted on representative panels after installation of the repair panels is completed.

For repair projects, there is no need to establish load transfer or connectivity along the longitudinal joints of individually installed repair panels. When multiple panels are installed at a given repair location, lane-to-lane connectivity should be maintained using tie bars when the repair length exceeds about 50 ft (15.2 m). Tie bars may then be installed (1) using cross-stitching or slot-stitching or (2) using slots at the panel bottom and drilling and grouting tie bars in existing adjacent lanes, as in the FMC Super-Slab system.

Panel Support (Bedding)

For most repair and rehabilitation applications, it is preferable to use the existing base. If the existing granular base is disturbed or damaged during the concrete pavement removal process, the base must be regraded and compacted. Additional base material or bedding material may be needed to bring the base to the required grade. The added fine-grained granular bedding material thickness should be kept as small as possible, preferably not more than 0.25 in. (6 mm).

The fine-grained granular bedding material should be used to allow for uniform seating of the panel, but it should not be used as a fill-in material because such a material cannot be easily compacted and can create an unstable support condition if too thick. For repair applications, disturbed granular material and the granular bedding material cannot be effectively compacted using the small plate compactors often used for such applications. As a result, the potential for panel settlement is high for roadways with heavy truck traffic.

For repair applications requiring the addition of bedding material exceeding 0.25 in. (6 mm) in thickness, the bedding may be designed using properly compacted dense-graded base material, rapid-setting cementitious grout or flowable fill material, or an injected polyurethane foam material. The thickness of such bedding material should be limited to about 1 in. (25 mm) and is recommended for roadways with heavy truck traffic.

Structural Requirements for Continuous Applications

To date, there have been two primary types of PCP systems used in the United States for continuous applications:

1. Jointed systems
   a. The most widely used jointed system is FMC's Super-Slab system, which has been installed during the past 8 years in a number of states.
   b. An individually prestressed panel system was installed in 2000 at a test site at New York's LaGuardia International Airport and in 2011 at the Caltrans I-680 rehabilitation project. The LaGuardia Airport system incorporates dowel slots at the surface of the panels. The I-680 system incorporates full-depth dowel slots.
2. Prestressed systems
   a. The only precast prestressed system used is the PPCP system developed for FHWA at the University of Texas. CIP-PCP systems were installed in five states during the 1970s and have provided satisfactory service.

In addition to the U.S. PCP systems, different jointed continuous systems have been used in Russia and Japan. These systems include both nominally reinforced and individually prestressed panels.

This report describes three categories of continuous PCP systems: (1) precast jointed systems (JPrCP), (2) prestressed systems (PPCP), and (3) incrementally connected PCP systems.

JPrCP uses nominally reinforced precast panel systems or individually prestressed panel systems. The nominally reinforced precast panel systems simulate conventional CIP jointed plain concrete pavements, except that the panels incorporate reinforcement and possibly higher-strength concrete. The individually prestressed panel systems are similar to the nominally reinforced precast panels systems, except that the panels are individually prestressed (by pretensioning), resulting in thinner panels. This approach ensures that the desirable level of effective prestress is available in each panel. Site conditions, such as the panel–base friction, do not affect the effective prestress in the panels. Pretensioning is required in the pavement longitudinal directions only, but may be used in the transverse direction to provide a more structurally efficient panel. Use of pretensioning allows the use of thinner panels with higher structural capacity to fit within an existing pavement profile, especially when single lanes are being rehabilitated.

PPCP systems are continuously prestressed systems such as the FHWA–University of Texas PPCP system. PPCP systems simulate conventional CIP-PCPs and use posttensioning to connect and prestress a number of reinforced or prestressed panels to form a single-slab section.

Incrementally connected PCP systems simulate a JRCP with hinged joints and incorporate panels of varying lengths. Panels are typically 15 to 30 ft (4.6 to 9.1 m) and are connected to achieve a connected length of 60 to 100 ft (18.3 to 30.5 m). The connected panels form a single-slab section using deformed dowel bars that lock the connected intermediate joints and also provide the required load transfer across these joints. An expansion joint is provided between connected slabs. The advantages of this system are the reduction in the number of active joints and the use of smaller-width expansion joints.

The structural requirements for continuous applications of precast pavements focus on reducing both cracking and joint faulting. Cracking is a stress-based distress, and joint faulting is a deflection-based distress. Long-term performance necessitates that concrete slab (panel) stresses and slab (panel) deflections be kept as low as possible to accommodate the millions of truck loadings over the expected 20 to 40 or more years of service life.

Concrete pavement design features that reduce slab stresses and deflections and are also applicable to PCP systems are discussed in the following sections.

Concrete Slab Thickness

For major urban and rural highways, a minimum slab thickness of 10 in. (250 mm) should be considered for jointed systems. For heavy truck volumes, an appropriately designed thick (11 to 14 in. [280 to 350 mm]) slab should be considered on the basis of the pavement design computations using the recently approved AASHTO *Mechanistic–Empirical Pavement Design Guide* (2008) (MEPDG) procedure or an equivalent agency-approved procedure. For PPCPs, the thickness used is typically about 3 to 4 in. (75 to 100 mm) less than that required for a jointed pavement system. This recommendation is based on the availability of about 100 to 200 lbf/in.^{2} (0.7 to 1.4 MPa) residual prestress at the midpoint location of each prestressed slab section; a slab section is typically about 150 to 250 ft (45.7 to 76.2 m) in length.

Widened Lane or Tied Concrete Shoulder

Use of a widened outside lane or integrated, tied concrete shoulder is a recommended practice for long-life concrete pavements. Lane widening involves extending the outside lane by about 2 ft (0.6 m). The widening keeps the truck loading away from the edge and results in lower slab stresses. The tied shoulder is typically about 10 ft (3.0 m) wide or full-lane width and the same thickness as the mainline pavement. A superior version of this feature is the combination of a widened outside lane and a tied concrete shoulder. For PPCP pavement, the outside lane and the shoulder can be fabricated monolithically. This practice results in a superior design for the PPCP system, as the PPCP is subjected to interior loading only. For this condition, a default thickness of 8 or 9 in. (200 to 225 mm) can be sufficient for most levels of truck traffic.

Joint Layout

Joint layout is a critical design item. Poor joint layout (e.g., longer slabs) can result in higher curling stresses, leading to the development of load-related cracking at an earlier age as a result of higher combined stress levels. The effect of joint spacing is now considered by the new MEPDG procedures. In the United States, a 15-ft (4.6-m) transverse joint spacing for slab thickness ≥10 in. (250 mm) has become standard for pavements with doweled joints. A similar practice is recommended for long-life precast JCP. Precast JCP systems are typically installed one-lane wide using panels 12 to 14 ft (3.7 to 4.3 m) wide.

For PPCP, individual panel lengths typically have been 10 to 40 ft (3.0 to 12.2 m). Length is limited only by the precast plant capabilities, the contractor's equipment availability, and project site constraints, if any. A 10-ft panel length has been used for several U.S. projects to date. A project constructed in California in 2011 used 36-ft (11.0-m)-long panels. The PPCP panels are interconnected by means of posttensioning to create slab sections 150 to 250 ft (45.7 to 76.2) long. An expansion joint is needed between adjacent PTSections to accommodate the larger joint opening and closing. The expansion joint spacing is dependent on various factors, including panel thickness, base type, prestressing design, and prestress losses. The PPCP panels may be one lane or multiple lanes in width.

Base Type and Drainage Considerations

It is important to use a uniformly graded, nonerodible base with the desired structural properties. Bases recommended for new long-life concrete pavements include cement-stabilized base, LCB, or asphalt-treated base. The cement-stabilized base does not need to be strong: a compressive strength of 750 lbf/in.^{2} (5.2 MPa) at 28 days is adequate. If a permeable base is needed, then a stabilized permeable base is recommended, although the permeable base does not need to be highly permeable. Permeability in the range of 300 to 500 ft/day (91 to 152 m/day) is considered adequate. Base stability should not be sacrificed to achieve higher levels of permeability. Typical PPCP projects involve rehabilitation of existing concrete or asphalt pavements, and the existing base or a new base that can be constructed rapidly may be used. The existing base removal and placement needs to be done within the same lane closure as the one for panel installation. In addition, the base surface needs to be smooth so that panel–base friction during post-tensioning is kept low to minimize prestress losses.

Load Transfer Mechanism

An effective means of load transfer across transverse joints is necessary for long-life concrete pavements subjected to medium-to-heavy truck traffic. Effective load transfer across joints reduces the potential for corner cracking. The standard practice to ensure load transfer across joints is to use round dowel bars. To achieve effective load transfer, the dowel bars need to

- Be corrosion-resistant;
- Provide a high level of load transfer across the joint. For long-life PCPs subjected to medium-to-heavy truck traffic, 1.5-in. (38-mm)-diameter bars are recommended for slab thicknesses of 10 in. (250 mm) or greater; and
- Provide adequate dowel–concrete bearing area. The use of properly sized dowel bars to reduce concrete bearing stress around the dowel bar and good quality concrete and patching material are considered necessary to resist void formation over the extended 30 to 40 or more years of service life.

The load transfer capability of the dowel bar should not be compromised during construction by not providing sufficient embedment length on each side of the joint (minimum of 7 in. [175 mm]) or by not providing sufficient concrete cover around the dowel bar (minimum of 3 in. [75 mm]).

Concrete Properties

Progressive cracking in concrete pavement develops when the repeated load-related stresses are relatively high in relation to the in-place concrete strength. Concrete strength of about 650 lbf/in.^{2} (4.5 MPa) at 28 days is considered adequate to withstand the effect of repeated load-related stresses over 30 to 40 or more years of service life. However, the precasting operation routinely results in much higher concrete strength, as precasters typically design the concrete to attain high strength levels at about 16 to 24 hours to allow for form stripping. Consequently, a higher level of concrete flexural strength may be considered in the design process. The durability characteristics of the concrete are considered as important as the strength properties.

Continuous Application Design Criteria

Long-life performance is expected for continuous applications and must be designed for. It is essential that PCP systems used in continuous applications be able to meet the requirements for long life.

Design Criteria for Jointed PCP Systems

For continuous jointed PCP systems, the following long-term failure manifestations are possible:

1. Structural distress
   a. Slab cracking;
   b. Joint faulting; and
   c. Joint spalling.
2. Functional distress
   a. Poor ride quality (smoothness); and
   b. Poor surface texture (surface friction and tire–pavement noise).

The design criteria recommended for CIP-JCPs for long-life service are considered applicable to jointed PCPs. However, because the individual panels of the precast pavement are reinforced, any cracks in the panels will be held tightly closed and would not be expected to deteriorate and affect ride quality. As a result, the criteria for cracking can be relaxed. The design criteria recommended for jointed PCPs for long-life service are given in Table 8.1.

Design Criteria for PPCP Systems

For PPCP systems, the following long-term failure manifestations are possible:

1. Structural distress
   a. Joint faulting at expansion joints;
   b. Cracking; and
   c. Expansion joint or joint hardware failure.
2. Functional distress
   a. Poor ride quality (smoothness); and
   b. Poor surface texture (surface friction and tire–pavement noise).

Table 8.1. Recommended Design Criteria for Jointed PCP Systems

Distress Type	Value
Structural distress	
Cracked slabs (%)	25–30
Faulting (in.)	0.15
Spalling (length, severity)	Minimal
Materials-related distress	None
Functional distress	
Smoothness (IRI) (in./mi)	150–180
Surface texture (friction)	Long lasting (FN >35)
Surface texture (noise)	No criteria available, but surface should produce accepted level of pavement–tire noise

Note: FN = friction number.

The design criteria recommended for PPCP for long-life service given in Table 8.2 are based on the criteria recommended for JCPs. The criterion related to cracking is not considered directly applicable to PPCP systems; because of the higher level of effective prestress in the PTSections of the PPCP system, this criterion can be relaxed considerably. The PPCP design is based on the weakest panel at midlength of the PTSection, and cracking (failure condition) in such panels would result in one crack every 150 to 250 ft (45.7 to 76.2 m) or about 20 to 30 cracks/mi (13 to 19 cracks/km). This level of cracking is still superior to an allowable level of about 15% of slabs cracked for CIP-JCP with 15-ft (4.6-m) joint spacing, which would result in about 50 cracks/mi (31 cracks/km). Thus, the recommended cracking criterion for PPCP is set at 10 to 15 cracks/mi (6 to 9 cracks/km) for 20 to 35 PTSections/mi (12 to 22 PTSections/km), or 50% of the sections exhibiting cracking.

The joint faulting criterion is based on the faulting at shorter joint spacing (typically 15 ft), but for PPCP, an active expansion joint is spaced at 150 to 250 ft (45.7 to 76.2 m). However, even though the faulting criterion is considered applicable, it is not designed for directly. The faulting reduction is ensured by using a high-quality base for PPCP projects to reduce joint deflections under truck traffic.

The MEPDG cracking criterion is based on fatigue damage resulting from a combination of top-down and bottom-up cracking. Top-down cracking can be due to flexural stress development at the slab surface that develops as a result of the specific placement of the steering axle and the first tractor axle on a given slab panel. For jointed pavements, this condition can be critical because of the shorter slab length between transverse joints. This condition is not considered critical for the longer PPCP sections. However, the fatigue damage resulting from both top and bottom tensile stresses are considered in the PPCP design. The MEPDG procedure identifies the components of the fatigue damage due to top tensile stresses and bottom tensile stresses, and thus it is possible to consider only the bottom-up fatigue damage, but this approach would need to be validated in the field. For now, the use of the total fatigue damage is recommended to develop the preliminary design of the PPCP system.

Table 8.2. Recommended Design Criteria for PPCP

Distress Type	Value
Structural distress	
Cracking (% of sections)	50
Faulting (in.)	Not considered
Materials-related distress	None
Functional distress	
Smoothness (IRI) (in./mi)	Not considered
Surface texture (friction)	Long lasting (FN >35)
Surface texture (noise)	No criteria available, but surface should produce accepted level of pavement–tire noise

Note: FN = friction number.

Design of Nominally Reinforced Jointed Systems

The structural design of jointed PCP can be developed using the new MEPDG procedure (AASHTO 2008). However, other concrete pavement design procedures may be used following the guidelines presented in this report. MEPDG provides a state-of-the-practice tool for the design of new pavements, and its design procedures have been field validated. Although the MEPDG design procedures are primarily applicable to conventional pavements, the MEPDG design procedure for JCPs is recommended for the design of jointed PCPs, with modifications to the design criteria discussed above and with specific adjustments discussed in the following paragraphs.

The current version (Version 1.1 as of March 2011) of the MEPDG software is used in the analysis mode to determine the distress development in a pavement subjected to the design traffic over the designated design period. The designer determines whether the distress development is acceptable and performs additional analysis using a revised pavement structure until an acceptable level of distress development results.

For JCPs, the following distresses are considered in the MEPDG:

- Cracking;
- Faulting; and
- Smoothness.

For PCPs, the following end-of-service distress criteria are recommended:

1. Initial service life: 40 years;
2. Cracking: 25% to 30% of panels cracked;
3. Faulting: 0.15 in.; and
4. Smoothness (IRI): 180 in./mi.

It is assumed that as the pavement smoothness deteriorates with time, grinding will be performed to restore smoothness and surface texture. Two cycles of grinding are assumed over the 40-year design life. As a result, any design thickness that is determined is increased by 0.5 in. (13 mm) to account for the two cycles of grinding.

The following adjustments need to be considered in the MEPDG design inputs:

1. Permanent (built-in) curl or warp effective temperature difference. The default value for conventional JCP is −10°F

(–23.3°C). Since the PCP panels are fabricated in a plant, there is very little, if any, built-in curl resulting from construction. However, it is assumed that some built-in curl develops during service as a result of surface drying of the concrete panels. This feature will require additional review as more field data are collected on PCP performance. For now, the use of the default value of –10°F (–23.3°C) is recommended.

2. Ultimate concrete shrinkage. As much as 50% of the ultimate value can be used because a large portion of the concrete shrinkage occurs during storage (most precast panels are stored for several weeks or months before installation).
3. Contact friction time. This is the time over which full contact friction is assumed to exist between the concrete slab (precast panel) and the underlying base layer. MEPDG recommends the use of a 136-month period over which full contact friction exists. For jointed PCP, the contact friction is considered to be low as the bottom of the precast panels is not expected to bond to the underlying layer because bedding material is used over the existing base, and the panel bottom surface is smooth. Panel undersealing is performed after panel installation, but is not expected to significantly affect the panel–base interface condition for the jointed PCP systems. This feature will require additional review as more field data are collected on PCP performance. For now, the use of the default 136-month contact period is recommended.

Sample Design Analyses

An example of the design of a jointed PCP using the criteria listed above and design input adjustment is given in this section for a project site in Washington, D.C., with Default Level 3 Traffic (equivalent to 100 million ESALs in the design lane) and a 90% design reliability. Other design parameters are as follows:

- Distress limits
  - Cracking: 25%;
  - Faulting: 0.15 in.; and
  - Smoothness (IRI): 180 in./mi.
- Structure
  - Layer 1: precast panel
    - Thickness: 10 in. (250 mm);
    - Design lane width: 12 ft (3.7 m);
    - Transverse joint spacing: 15 ft (4.6 m);
    - Dowel bar: 1.5 in. (38 mm) at 12-in. (300-mm) spacing;
    - Concrete modulus of rupture at 28 days: 750 lbf/in.^{2} (5.1 MPa);
    - Concrete CTE: 5.5 millionth in./in./°F;
    - Built-in curl: –10°F (–23.3°C); and
    - Concrete ultimate drying shrinkage (50% of actual).
  - Layer 2: permeable granular base
    - Thickness: 6 in. (150 mm);
    - Modulus of elasticity: 15,000 lbf/in.^{2} (103.4 MPa);
    - Base Erodability Index: erosion resistant (Level 3); and
    - Loss of full friction (age in months): 136.
  - Layer 3: subgrade (A-5)
    - Modulus of elasticity: 8,000 lbf/in.^{2} (55.2 MPa).

For the above example, a base with a lower modulus of elasticity was used to simulate a poorly compacted, thick, granular bedding layer over a poorly compacted granular base. The analysis results are presented below for design reliability of 90% at 40 years:

- Cracking: 5.3%;
- Faulting: 0.12 in.; and
- Smoothness: 159 in./in./mi.

An analysis for a comparable conventional CIP concrete pavement was also conducted using the default standard design inputs and a concrete modulus of rupture of 650 lbf/in.^{2}. The results of the analysis are given below:

- Cracking: 29.5%;
- Faulting: 0.12 in.; and
- Smoothness: 181 in./in./mi.

Table 8.3 provides a comparison of the slab (panel) thickness required for conventional JCPs and jointed PCPs for a

Table 8.3. Comparison of MEPDG-Based Designs for a Jointed PCP System

Traffic Level (estimated ESALs)	Jointed PCP (in.)	CIP-JCP (in.)
Poor Support Condition (base modulus = 15,000 lbf/in.^{2})		
50,000,000	8.5	10.0
100,000,000	9.5	10.5
200,000,000	11.5	11.0
Granular Base (base modulus = 30,000 lbf/in.^{2})		
50,000,000	8.5	10.0
100,000,000	9.5	10.5
200,000,000	11.5	11.0
CTB (base modulus = 2,000,000 lbf/in.^{2})		
50,000,000	8.5	10.0
100,000,000	9.5	10.5
200,000,000	11.0	11.5

Note: Design criteria for jointed PCP are cracking = 25%; faulting = 0.15 in.; smoothness = 180 in./mi. Design criteria for CIP-JCP are cracking = 15%; faulting = 0.15 in.; smoothness = 180 in./mi.

range of traffic conditions and the example design inputs presented above with three types of base or bedding.

In the design examples above, the faulting, as affected by the poor base type, controls the smoothness development over the design period for lower-stiffness bases. As the base condition improves, the cracking criterion controls the design thickness selection. Regardless of the base type, the precast pavement with a higher concrete flexural strength and the relaxed cracking criterion has a slight advantage over the CIP concrete with respect to anticipated long-term performance.

The structural design approach discussed above is applicable for any jointed PCP, regardless of the method used for providing load transfer (i.e., dowel slots at the surface or at the bottom). The primary requirement is that the method chosen should result in a load transfer system with a very good LTE (greater than 90% at time of installation), and a high level of LTE (greater than 70%) should be retained over the service period.

Additional items to note include the following:

1. Jointed PCP can be designed using standard 12-ft (3.7-m)-wide lanes or widened lanes up to 14 ft (4.3 m), as well as using tied concrete shoulders.
2. Jointed PCP typically will incorporate concrete mixtures that result in higher flexural strength, which can be accounted for in the design.

Design of Individually Prestressed Panel Systems

The design of the individually prestressed panel system can be performed in a similar manner to that described for the nominally reinforced precast panel systems. The only adjustment to be made is to add the effective prestress level in the panel to the modulus of rupture. Therefore, if the effective prestress in the prestressed panel is 200 lbf/in.^{2} (1.4 MPa) and the concrete modulus of rupture is 650 lbf/in.^{2} (4.5 MPa), then the effective modulus of rupture would be 650 + 200 lbf/in.^{2}, or 850 lbf/in.^{2} (5.8 MPa). The higher level of the effective modulus of rupture would allow a reduction of panel thickness of about 2 to 3 in. (50 to 75 mm). However, the faulting criteria will control the design unless a higher-quality base support is available that reduces joint and corner deflections.

Design of Prestressed Pavement Systems

PPCP Design Factors

Several specific factors that must be considered for the design of a PPCP are discussed in this section.

Slab–Base Interaction

PPCP systems require placement of the panels on a smooth base or interlayer to ensure that the panel–base friction is as low as possible. Otherwise, a larger portion of the prestressing force is consumed in overcoming the panel–base friction. Precast panels have a smooth bottom surface, which helps to reduce friction between the slab and base. However, a bond-breaking, friction-reducing material, such as polyethylene sheeting, is generally required to further reduce frictional restraint while also preventing bonding between the panel and the base.

Effective Prestress

PPCP can be designed to achieve an effective prestress of about 100 to 200 lbf/in.^{2} (0.7 to 1.4 MPa) at the midlength of the PTSection of panels. This effective prestress adds to the concrete's flexural strength and allows use of PPCP systems that are about 3 to 4 in. (75 to 100 mm) less in thickness than conventional JCPs for the same traffic loading and environmental conditions.

Expansion Joints

PPCP systems can be designed to incorporate expansion joints at about 150 to 250 ft (45.7 to 76.2 m). The choice of shorter or longer expansion joint spacing requires several considerations:

- Shorter expansion joint spacing may not be cost-effective.
- Longer joint spacing requires use of more prestressing tendons (more prestressing force) to balance the higher prestress losses caused by the longer prestressing lengths involved.
- Longer joint spacing results in larger movement at expansion joints, which affects load transfer at these joints. This may require more robust joint hardware and more frequent sealant maintenance.

The expansion joint should be designed to allow for large PTSection end movements (typically 1 to 3 in., depending on environmental conditions, concrete creep and shrinkage, and posttensioned panel section length) and to provide the desired level of load transfer across the wider joints. The base and the foundation need to be of high quality and stiff to minimize slab deflections at the expansion joint.

Stressing System

The prestressing tendon size (diameter) and spacing should be selected to achieve the desired stress level in the concrete at the midlength of each section of the posttensioned panels. The U.S. experience is based on the use of 0.6-in. (15-mm)-diameter, Grade 270, 7-wire stress-relieved tendons for highway applications for posttensioning and 0.5-in. (12.5-mm)-diameter, Grade 270, 7-wire stress-relieved tendons for pretensioning.

Flexural Strength

The AASHTO MEPDG procedure can be used to determine the required thickness of the PPCP. The flexural strength used should be the concrete's flexural strength plus the effective prestress at midlength of the PTSection. The deflection-related distress (joint faulting) at expansion joints is not directly applicable, and concern with deflection-related distress can be mitigated by specifying a strong, preferably stabilized, base and paying careful attention to the overall foundation support.

Prestress Losses

Prestress losses are an important consideration in posttensioned precast pavements, as the strength of the pavement relies on the effective prestress in the concrete from posttensioning. These losses must be accounted for to ensure that the required prestress level is maintained over the length of the slab over the design life of the pavement. Long-term losses of 40% to 50% of the applied prestress force can be expected for a well-constructed PPCP.

Intermediate Joints

Prestressing (posttensioning) keeps the intermediate joints (the joints between adjacent panels in each PTSection) tightly closed. The standard method for the design of the intermediate joints uses a keyway system. The panel on one side of the joint has the keyway tongue, and the panel on the other side has the keyway groove. The use of the keyway, a coating of epoxy, and prestressing (posttensioning) ensures a tight, almost monolithic, connection at intermediate joints. As a result, there is no need to provide additional load transfer at these joints, and they do not need to be accounted for in the structural design of the PPCP systems.

If there is a failure to attain the desired level of prestress in the middle portion of the PTSection, the affected adjacent intermediate joints may not remain connected under truck traffic, which may result in higher deflections at these joints and cause joint spalling. The failure to attain the desired level of prestress in the middle portion will also have other consequences, such as panel cracking and settlement at the affected intermediate joints.

PPCP Structural Design Process

The design input requirements for PPCP are similar to those required for conventional JCP design, except that the value of the panel–base interface friction parameter must be established.

The PPCP design process includes the following steps:

1. Determine the PPCP panel thickness and effective prestress needed;
2. Design the prestressing system;
3. Finalize the prestressing system and panel thickness; and
4. Design the expansion joint.

Determination of PPCP Panel Thickness and Effective Prestress

Two approaches can be used estimate the design PPCP panel thickness or to verify that the selected PPCP thickness will accommodate the future design traffic. Both approaches are based on determining an equivalent thickness of the PPCP panel that will provide long-term performance equal to or better than a conventional JCP for the same design conditions. The two approaches are the stress equivalency concept (also referred to as the thickness equivalency concept) and the strength equivalency concept (which uses the new AASHTO MEPDG procedure).

It must be emphasized that no validated or calibrated design procedures are available for PPCP. However, based on experience with CIP-PCP constructed during the 1970s and 1980s in the United States, there is evidence that PPCP 3 to 4 in. (75 to 100 mm) thinner than comparable CIP concrete pavements will provide good long-term performance. The CIP-PCP constructed in 1985 along a section of I-35 near Waco, Texas, continues to perform well and has not required any significant level of maintenance or repair during more than 25 years of service.

The procedures to estimate PPCP panel thickness and the effective prestress level needed in the PTSection should be used as a part of the process to develop the design PPCP panel thickness and prestressing requirements. The final decision should be based on experience to date with similar PPCP systems at other projects, traffic level, and anticipated support conditions under the pavement to be rehabilitated. In any case, the following minimum design parameters are recommended:

1. Minimum panel thickness: At least 8 in. (200 mm) or enough thickness to accommodate the reinforcing and prestressing hardware (tendon ducts, anchorage systems) is needed.

2. Minimum support condition: A good-quality, stiff base is preferred to minimize joint deflections as a result of using thinner panels. A free-draining dense granular base or a stabilized base is preferred. If the existing base can be removed or needs to be removed, use of a fast-setting LCB should be considered.
3. Expansion joint width: The maximum long-term joint width should be limited to 3.0 in. (75 mm) to ensure good-performing joint sealing and to ensure good LTE at the expansion joints.

Stress Equivalency Concept

The stress equivalency concept is illustrated in Figure 8.3.

The stress equivalency approach considers edge stress loading and interior stress loading:

1. Edge stress loading (for single-lane-wide PPCP panels). Compare the edge stress (from a 9,000-lb [4,082-kg] load or any other loading) for the designed CIP jointed system (e.g., 13-in. [330-mm] concrete thickness) and the edge stress in the PPCP panel (e.g., 8-in. [200-mm] concrete thickness). The difference in the edge stresses would be the effective prestress needed at the midlocation of the PTSection. Lane widening can also be considered for this case.
2. Interior stress loading (for multilane-wide PPCP panels with no active longitudinal joints, similar to the Texas and Missouri PPCP projects). Compare the edge stress (from a 9,000-lb [4,082-kg] load or any other loading) for the designed CIP jointed system (e.g., 13-in. [330-mm] concrete thickness) and the interior stress in the PPCP panel (e.g., 8-in. [200-mm] concrete thickness). The difference in the stresses would be the effective prestress needed at the midlocation of the PPCP section. This is the most efficient design, as the interior loading allows a significant reduction in the required PPCP thickness. Thus, for the same PPCP panel thickness and effective prestress, the interior-loaded PPCP can have a much higher load-carrying capacity.

In both the edge stress loading and interior stress loading cases described above, joint-related analysis is not considered. The assumption is that if a strong or stiff base is used, there will be no deflection-related issues, especially with fewer active joints.

It is very important that if the PPCP design is based on the interior load condition and use of multilane-width panels, the designs should not be changed in the field to accommodate installation phasing or maintenance of traffic that may require use of single-lane-width panels. If single-lane width panels are necessary to expedite construction, the panels should be redesigned as single-lane-width panels, or a higher prestress level should be applied.

The midslab edge stresses and the interior stresses for a 12-ft (3.65-m)-wide and 15-ft (4.67-m)-long slab panel are determined using a finite element–based procedure. The stresses as a function of the panel thickness are plotted in Figure 8.4 for a modulus of subgrade reaction of 300 pci (82 MPa/mm). The plot is generic and is independent of traffic level and other design parameters. All these factors are incorporated in the computation of the reference CIP-JCP slab thickness. Two example cases of this approach are given below.

Case 1: Edge-Loaded PPCP System (single-lane-width panels)

1. Using the AASHTO MEPDG procedure or another agency-approved procedure, the thickness of the JCP is determined to be 13 in. (330 mm) for a given set of design parameters. The midslab edge stress for this pavement, determined from Figure 8.4, is 150 lbf/in.^{2} (1.0 MPa).
2. Assuming the PPCP thickness is to be 9 in. (225 mm), the midslab edge stress for the PPCP, determined from Figure 8.4, is 275 lbf/in.^{2} (1.9 MPa).
3. Thus, the effective prestress required at the midsection of the PPCP is 125 lbf/in.^{2} (0.9 MPa).

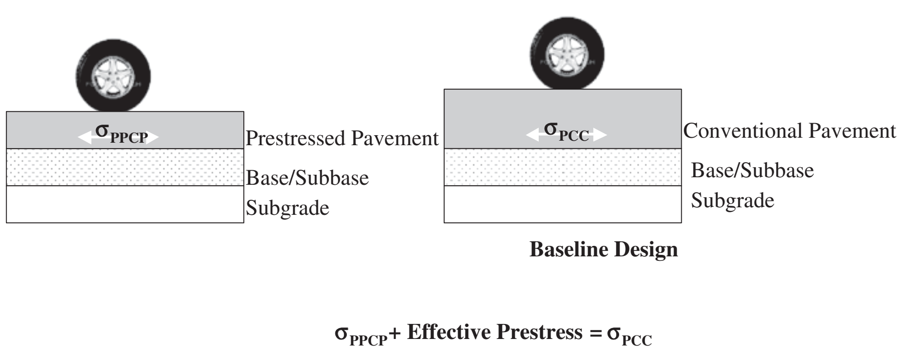


Figure 8.3. Stress equivalency concept.

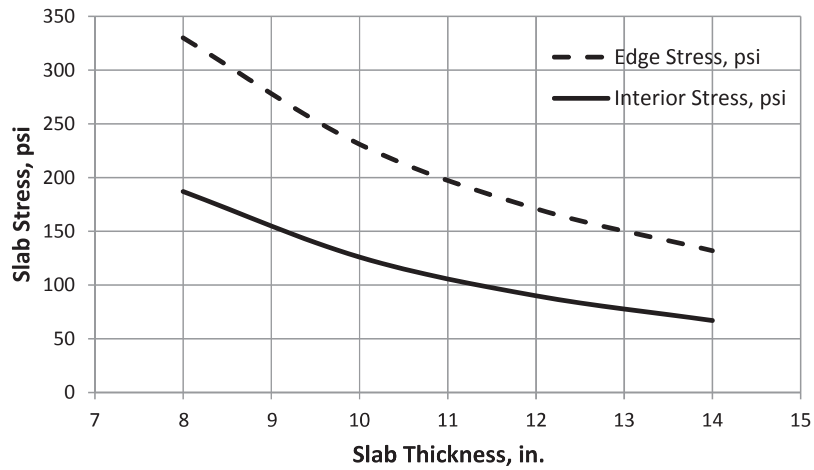


Figure 8.4. Stresses as a function of panel thickness.

Case 2: Interior-Loaded PPCP System (multilane-width panels)

1. Using the AASHTO MEPDG procedure, the thickness of the JCP is determined to be 13 in. for a given set of design parameters. The midslab edge stress for this pavement, determined from Figure 8.4, is 150 lbf/in.^{2}.
2. Assuming the PPCP thickness is to be 8 in. (200 mm), the interior stress for the PPCP, determined from Figure 8.4, is 185 lbf/in.^{2} (1.3 MPa).
3. Thus, the effective prestress required at the midsection of the PPCP is 35 lbf/in.^{2} (241 kPa).

Case 2 shows that the interior load condition, achieved using multilane-wide panels, allows use of thinner PPCP panels and requires less effective prestress. Alternatively, using a thicker (e.g., 9-in.) PPCP panel and applying an effective prestress of 125 lbf/in.^{2} would allow the use of a longer PTSection when multilane-wide panels are used.

The stress equivalency concept is simple to use. However, it does not directly consider the effect of repeated truck loadings or joint-related behavior. The utility of this approach is that it allows the development of a preliminary thickness for the PPCP system for a given set of design parameters. The PPCP thickness and the applied effective prestress level can then be refined based on additional design considerations, including the minimum thickness necessary for fabrication and base support considerations.

Strength Equivalency Concept

Under the strength equivalency approach, the concrete flexural strength is adjusted to account for the effective prestress in the PPCP. Thus, if the effective prestress at the midsection of the PTSection is 150 lbf/in.^{2} (1.0 MPa), the effective flexural strength of the concrete is equal to the design flexural strength of the concrete (typically 650 to 750 lbf/in.^{2} [4.5 to 5.2 MPa]) plus the effective prestress. The effective flexural strength is used in the pavement structural design procedure. This approach can be used with any currently available mechanistic–empirical design procedure. However, in all cases the PPCP design will be conservative because the PPCP distresses do not develop in the same manner as conventional jointed pavements, which are the basis for the development of these design procedures. The 1993 AASHTO *Pavement Design Guide Procedure* is not considered applicable as it is not a mechanistic-based procedure. The new MEPDG procedure is recommended as an alternate approach for the design of PPCP systems (AASHTO 2008). This approach is discussed next.

For PPCP, only the cracking distress criterion is considered. The following end-of-service distress criteria are recommended:

1. Initial service life: 40 years.
2. Cracking: 50% of panels cracked. However, as discussed below, this criterion is typically not a governing criterion for most traffic levels and good support condition as the PPCP thickness requirement is typically less than the recommended default minimum thickness value of 8.0 in. (200 mm).
3. Faulting: not considered. It is expected that joint faulting will not be a concern because of the use of stiffer bases and fewer joints per mile that may exhibit any faulting distress.
4. Smoothness (IRI): not considered as computed using the MEPDG procedure because the computation incorporates the effect of the computed faulting.

The following adjustments, similar to the adjustments needed for JCPs, must be considered in the MEPDG design inputs:

1. Permanent (built-in) curl or warp effective temperature difference. The default value for conventional JCP is −10°F (−23.3°C). Since the PCP panels are fabricated in a plant, there is very little, if any, construction-related built-in curl in the panels. However, it is assumed that some built-in curl develops during service near the joint areas as a result of surface drying of the concrete panels. This feature will require additional review as more field data on PCP performance are developed. For now, the default value of −10°F is recommended.
2. Ultimate concrete shrinkage. As much as 50% of the ultimate value can be used because a large portion of the concrete shrinkage occurs during storage (most precast panels are stored for several weeks or months before installation).
3. Contact friction time. This is the time over which full contact friction is assumed to exist between the concrete slab (panel) and the underlying base layer. MEPDG recommends use of a 136-month period over which full contact friction exists. For PPCP, the contact friction is considered to be very low as the bottom of the precast panels is not expected to bond to the underlying layer because of the panel–base friction reducing treatment, and the panel bottom surface is smooth. Panel undersealing is performed after panel installation, but this is not expected to significantly affect the panel–base interface condition for PPCP systems. This feature will require additional review as more field data on PCP performance are developed. For now, the default 136-month contact period is recommended.

An example of PPCP design using the criteria and design input adjustments listed above is given for a project site in Washington, D.C., with Default Level 3 Traffic (equivalent to 100 million ESALs in the design lane) and a 90% design reliability. Other design parameters are as follows:

- Distress limits
  - Cracking: 50%;
  - Faulting: not applicable; and
  - Smoothness (IRI): not applicable.
- Structure
  - Layer 1: precast panel
    - Thickness: 8 in. (203 mm);
    - Design lane width: 12 ft (3.7 m);
    - Transverse joint spacing: 15 ft (4.6 m);
    - Dowel bar: 1.5 in. (38 mm) at 12-in. (305-mm) spacing;
    - Effective concrete modulus of rupture: 850 lbf/in.^{2} (5.8 MPa) (28-day), includes an effective prestress value of 150 lbf/in.^{2} (1.0 MPa);
    - Concrete CTE: 5.5 millionth in./in./°F;
    - Built-in curl: −10°F (−23°C); and
    - Concrete ultimate drying shrinkage (50% of actual).
  - Layer 2: permeable granular base
    - Thickness: 6 in. (152 mm);
    - Modulus of elasticity: 15,000 lbf/in.^{2} (103.4 MPa);
    - Base Erodability Index: erosion resistant (Level 3); and
    - Loss of full friction (age in months): 136.
  - Layer 3: subgrade (A-5)
    - Modulus of elasticity: 8,000 lbf/in.^{2} (55.2 MPa).

The analysis results are presented below for design reliability of 90% (at 40 years):

- Cracking: 19.4%;
- Faulting: not applicable; and
- Smoothness: 59 in./in./mi.

An analysis for a comparable conventional CIP concrete pavement was also conducted using the default standard design inputs and a concrete modulus of rupture of 650 lbf/in.^{2} (4.5 MPa). The results of the analysis are given below:

- Cracking: 29.5%;
- Faulting: 0.12 in. (3 mm); and
- Smoothness: 181 in./in./mi.

Table 8.4 provides a comparison of the slab (panel) thickness required for conventional JCPs and jointed PCPs for a

Table 8.4. Comparison of MEPDG-Based Designs for PPCP System

Traffic Level (estimated ESALs)	PPCP (in.)	CIP-JCP (in.)
Poor Support Condition (base modulus = 15,000 lbf/in.^{2} [103 MPa])		
50,000,000	<8.0	10.0
100,000,000	<8.0	10.5
200,000,000	8.0	11.0
Granular Based (base modulus = 30,000 lbf/in.^{2} [207 MPa])		
50,000,000	<8.0	10.0
100,000,000	<8.0	10.5
200,000,000	8.0	11.0
CTB (base modulus = 2,000,000 lbf/in.^{2} [13,789 MPa])		
50,000,000	<8.0	10.0
100,000,000	<8.0	10.5
200,000,000	8.0	11.5

Note: Design criterion for JPrCP is cracking = 50%. Design criteria for CIP-JCP are cracking = 15%; faulting = 0.15 in.; smoothness = 180 in./mi.

range of traffic conditions and the example design inputs presented above with three types of base or bedding. Based on the information developed and using 12-ft (3.7-m)-wide PPCP panels, the design for the PPCP system would be as follows:

1. Low traffic level (equivalent to 50 million ESALs)
   a. Panel thickness: 8 in. (200 mm) (minimum default value); and
   b. Effective prestress: 150 lbf/in.^{2} (1.0 MPa).
2. Medium traffic level (equivalent to 100 million ESALs)
   a. Panel thickness: 8 in. (minimum default value); and
   b. Effective prestress: 150 lbf/in.^{2} (1.0 MPa).
3. High traffic level (equivalent to 200 million ESALs)
   a. Panel thickness: 8 in. (computed); and
   b. Effective prestress: 150 lbf/in.^{2} (1.0 MPa).

In the above example, additional trial computations can be made using a lower effective prestress level for the low- and medium-traffic cases to optimize the prestressing system design, typically by using fewer strands. If it is determined that the minimum panel thickness needs to be greater than 8 in., say 9 in. (225 mm), additional refinements can be made to further optimize the prestressing design.

Design of Prestressing System

The steps used to design the prestressing system are detailed below:

1. Design the prestressing system
   a. Tendon size: typically, 0.6-in. 7-wire tendons used;
   b. Tendon force: 75% of the ultimate load (43,000 lbf); and
   c. Tendon spacing: to be determined (12 to 18 in. [300 to 450 mm]) depending on posttensioned length (typically 150 to 250 ft [45.7 to 76.2 m]).
2. Assume the PTSection length and tendon spacing.
3. Determine end prestress that can be applied. The end prestress levels for a range of tendon spacings and panel thicknesses are summarized in Table 8.5.

Table 8.5. End Prestress Levels

Panel Thickness (in.)	End Prestress (psi) for Strand Spacing of			
	18 in.	24 in.	30 in.	36 in.
8	299	224	179	149
9	265	199	159	133
10	239	179	143	119
11	217	163	130	109
12	199	149	119	100

The end prestress levels for the PPCP projects constructed in the United States are summarized in Table 8.6.

4. Determine prestress losses as discussed above. The prestress losses during initial posttensioning and during the long term, as a percentage of the applied end prestress, are as follows:
   a. Slab–base friction (largest component): 20% to 60%, a function of the section length;
   b. Concrete shrinkage: ~3%;
   c. Concrete creep: ~2%; and
   d. Steel relaxation: ~10%.
5. Determine the effective prestress ($P_{effective}$) at the midpoint of the PTSection as follows:

$$P_{effective} = \text{applied end prestress} - \text{prestress losses.}$$

The long-term effective end prestress levels are shown in Figure 8.5 for a range of panel–base friction factors for a PTSection length of 250 ft (76.2 m) and applied end prestress level of 260 lbf/in.^{2} (1.8 Pa). As shown in Figure 8.5, the higher the friction factor, the lower the midsection effective prestress level. A summary of the prestress losses and $P_{effective}$ levels is given in Table 8.7.

Table 8.6. Applied End Prestress Levels for U.S. PPCP Projects

Project	Tendon Spacing (ft)	Panel Thickness (in.)	PTSection Length (ft)	Average Applied End Prestress (lbf/in.^{2})
Delaware NB Route 896 at US-40	2.5	8	118, 128, 138	194
Virginia I-66 WB	2.5	8¾	110, 160	178
Texas NB I-35 frontage road	2	8	250, 225, 325	243
Missouri NB I-57	2	5⅝ to 10⅞	250	228
California EB I-10	3	10 to 13.1	124	112
California I-680	2 (two tendons per duct)	8⅝	220	225

Note: NB, WB, and EB = northbound, westbound, and eastbound, respectively.

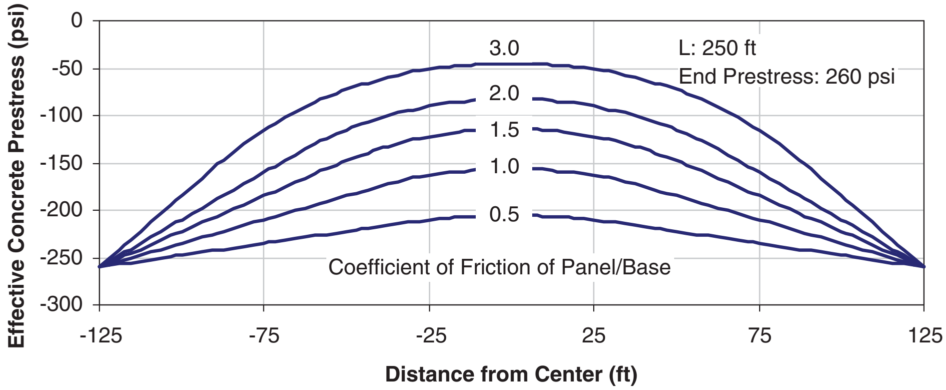


Figure 8.5. Effective prestress levels.

Finalize Prestressing System

The steps used to finalize the design of the prestressing system are as follows:

1. Compare $P_{effective}$ (as determined above) to the effective prestress needed (P_{needed}).
2. Adjust posttensioned length and tendon spacing and panel thickness, as necessary, to ensure $P_{effective}$ is equal to or greater than P_{needed}.

A sample calculation of $P_{effective}$ is detailed below:

1. Assume selected precast panel thickness: 8 in. (200 mm) and $P_{needed} = 130$ lbf/in.^{2} (0.9 MPa);
2. Select tendon size: 0.6-in (15-mm) 7-wire tendons (41 kips);
3. Select tendon spacing: 18 in. (450 mm);
4. Select end of slab prestress: 285 lbf/in.^{2} (2.0 MPa);
5. Select posttensioned length (of panels): 200 ft (61.0 m);
6. Prestress losses (using the example presented in the previous section) = 133 lbf/in.^{2} (0.9 MPa); then
7. $P_{effective}$: 285 – 133 = 152 lbf/in.^{2} (1.0 MPa).

Since $P_{effective} > P_{needed}$ (152 > 130 lbf/in.^{2}), the tendon spacing is acceptable and can be increased to about 20 in. (500 mm).

Design Expansion Joint

Once the posttensioned length has been selected, the final step is to establish the expansion joint width parameters, which include the following:

1. Minimum joint width during the first summer: A minimum joint width of 0.5 in. (13 mm) for the first summer should be used. This minimum width should accommodate the minimum width required for the joint sealant.

Table 8.7. Prestress Losses and Effective Prestress Levels

Panel thickness (in.)	8	8	8	8	9	9	9	9
Section length (ft)	100	150	200	250	100	150	200	250
Tendon spacing (in.)	24	24	24	24	24	24	24	24
Prestress loss due to friction (lbf/in.^{2})	50	75	100	125	50	75	100	125
Prestress loss due to shrinkage (lbf/in.^{2})	6.3	6.3	6.3	6.3	5.6	5.6	5.6	5.6
Prestress loss due to creep (lbf/in.^{2})	4.4	4.4	4.4	4.4	3.5	3.5	3.5	3.5
Prestress loss due to relaxation (lbf/in.^{2})	22.4	22.4	22.4	22.4	19.9	19.9	19.9	19.9
Total prestress loss (lbf/in.^{2})	83	108	133	158	79	104	129	154
Effective long-term prestress ($P_{effective}$) (lbf/in.^{2})	141	116	91	66	120	95	70	45

2. Long-term minimum joint width: The long-term minimum joint width includes the minimum width established for the first summer plus the effect of long-term concrete creep and shrinkage.
3. Maximum joint width: The maximum joint width includes the long-term minimum joint width plus the total annual joint opening changes caused by seasonal temperature changes.
4. Joint width at time of installation: The joint width at the time of installation should be based on the concrete panel temperature at the time of installation of the joint panels.

The various joint widths are determined on the basis of anticipated PTSection end movements. As indicated above, the joint widths or the PTSection end movements are affected by daily and seasonal concrete temperature variations and concrete creep and shrinkage. The panel–base interface friction may affect the PTSection end movements, but, as shown below, over time the effect of panel–base friction is very small and can be ignored. Good estimates of the minimum joint width during the first summer and the maximum joint width are necessary for proper design of the sealant material or the sealant system to be used.

Immediate PTSection Shortening Caused by Posttensioning

The PTSection shortens immediately as a result of the prestress applied during the posttensioning process. The immediate PTSection shortening can be determined as follows:

1. Assuming zero panel–base interface friction, the total PTSection shortening (dL_{pt}) is as follows:

$$dL_{pt} = \left(P_{end}/E_c\right) \times L$$

where
P_{end} = prestress applied at the end;
E_c = concrete modulus of elasticity; and
L = PTSection length.

If P_{end} = 300 lbf/in.², E_c = 4,000,000 lbf/in.², and L = 200 ft (2,400 in.), then

$$dL_{pt} = (300/4{,}000{,}000) \times 2{,}400 = 0.18 \text{ in.}$$

Thus, the PTSection shortening is 0.09 in. at each end of the PTSection.

2. Assuming panel–base friction restraint to PTSection shortening, the total PTSection shortening (dL_{pt}) is as follows:

$$dL_{pt} = \left(P_{end}/E_c\right) \times (L) - (f \times L \times L)/E_c$$

where f is the panel–base friction factor.

If P_{end} = 300 lbf/in.², E_c = 4,000,000 lbf/in.², L = 200 ft (2,400 in.), and f = 1.0, then dL_{pt} = (300/4,000,000) × 2,400 − (1.0 × 2,400 × 2,400)/4,000,000 = 0.12 in.

Thus, the PTSection shortening is 0.06 in. at each end of the PTSection when frictional restraint is considered.

Because of the small magnitude and the sequence of installation of the adjacent PTSection, the immediate PTSection shortening that results from prestressing is ignored in any joint width or PTSection end movement computations.

Temperature-Associated PTSection End Movements

Temperature-associated end movements are dependent on the PTSection length and the concrete CTE. Such movements are affected by daily and seasonal temperature changes. For the purpose of joint width determination, daily temperature variations are ignored and only seasonal temperature variations are considered. Both daily and seasonal temperatures are cyclic in nature. Because expansion and contraction of the concrete occur gradually on a daily basis, any restraint to the daily and seasonal end movements due to panel–base friction can be ignored. It is expected that the friction factor will be less than 1.0 when a base grade is smooth and an interface friction treatment is used. The restraint to movement, even if considered, ranges in value from about 0.05 to 0.15 in., depending on the PTSection length and friction factor. Ignoring the restraint due to panel–base friction provides a slightly conservative estimate of the PTSection end movements.

The PTSection total end movement (total for both ends) (dL_{temp}) is computed as follows:

$$dL_{temp} = \left(T_{cmax} - T_{cmin}\right) \times \text{CTE}_c \times L$$

where
T_{cmax} = maximum concrete temperature during the summer;
T_{cmin} = minimum concrete temperature during the winter; and
CTE_c = concrete coefficient of thermal expansion.

If $T_{cmax} = 120°F$, $T_{cmin} = 20°F$, $CTE_c = 0.000005$ in./in./°F, and $L = 200$ ft (2,400 in.), then $dL_{temp} = (120 - 20) \times (0.000005) \times (2{,}400) = 1.20$ in.

Concrete Creep–Associated PTSection End Movement

Creep is the long-term shortening of concrete subjected to sustained stress. In the case of a PPCP system, the sustained stress is due to the effective prestress along the length of the PTS. The concrete strain (CS_c) due to creep is typically computed as follows:

$$CS_c = C_u \times (P_{end} + P_{effective})/2 \times (1/E_c)$$

where C_u is the ultimate concrete creep coefficient.

C_u is dependent on the hardness and gradation of the concrete aggregates, cement content, water–cementitious materials ratio, curing environment, and age at time of sustained stress application. A C_u value of 2.5 is recommended.

If $P_{end} = 300$ lbf/in.², $P_{effective} = 150$ lbf/in.², and $E_c = 4{,}000{,}000$ lbf/in.², then $CS_c = 140$ millionth in./in.

The PTSection total end movement due to creep (total for both ends) (dL_{creep}) is computed as follows:

$$dL_{creep} = CS_c \times L$$

If $L = 200$ ft (2,400 in.) and $CS_c = 140$ millionth in./in. as computed above, then $dL_{creep} = (140/1{,}000{,}000) \times 2{,}400 = 0.30$ in.

The effect of panel–base friction is ignored as the concrete creep takes place gradually over many years.

Concrete Shrinkage–Associated PTSection End Movement

Concrete shrinkage is a property of a specific concrete mixture and is dependent on the water–cementitious materials ratio, aggregate type, and curing environment. Long-term shrinkage of concrete may range from 300 to 600 millionth in./in., depending on the drying environment (one-sided versus multiple-sided drying) and the concrete dimensions. For precast concrete panels, it is expected that a significant amount of drying shrinkage will take place during storage at the plant or the project site. The storage period may range from a few weeks to several months. After installation, the concrete panels exhibit shrinkage mostly in the upper 2 to 3 in. (50 to 75 mm) of the panel. The rest of the panel remains sufficiently moist (high relative humidity) and does not exhibit significant long-term drying shrinkage. For computation of the PTSection end movements, a reasonably conservative average drying shrinkage value (DS) of about 200 millionth in./in. is recommended. Using this value, the total slab end movement (both ends) ($dT_{shrinkage}$) is computed as follows:

$$dT_{shrinkage} = DS \times L$$

If $DS = 200$ millionth in./in. and $L = 200$ ft (2,400 in.), then $dT_{shrinkage} = (200/1{,}000{,}000) \times 2{,}400 = 0.48$ in.

The effect of panel–base friction is ignored as the concrete drying shrinkage takes place gradually over many years.

Total PTSection End Movements

The total long-term PTSection end movement (both ends) (dL_{total}) is the sum of the individual slab end movements:

$$dL_{total} = dL_{temp} + dL_{creep} + dL_{shrinkage}$$

For the example values used above, dL_{total} for a PTSection length of 200 ft is $dL_{total} = 1.20 + 0.30 + 0.48 = 1.98$ in.

Allowing for a minimum joint width (dL_{min}) of 0.5 in. for the first summer, joint width parameters will be as follows for the example used:

1. Minimum joint width during the first summer: $dL_{min} = 0.5$ in.;
2. Long-term minimum joint width: $dL_{min} + dL_{creep} + dL_{shrinkage} = 1.28$ in.; and
3. Maximum joint width: $dL_{min} + dL_{total} = 2.48$.

The joint width change over the long term is illustrated in Figure 8.6.

Joint Sealant Selection

Joint selection should be based on the minimum joint width during the first summer and the maximum joint width. For the example used above, the sealant should allow for a range in joint width changes from 0.5 in. to 2.48 in. (13 to 63 mm) over the long term. A range of sealant systems is available to accommodate the computed seasonal and long-term joint width changes.

Minimum joint width refers to a clear distance between the two sides of the expansion joint. This clearance should include the prestressing hardware (anchorages), the sealant-holding system (as in the case of strip seals), and the armored expansion joint assemblies.

Joint Width at Time of Installation

Joint width needs to be set at the time of PTSection installation and is dependent on the concrete temperature at the time

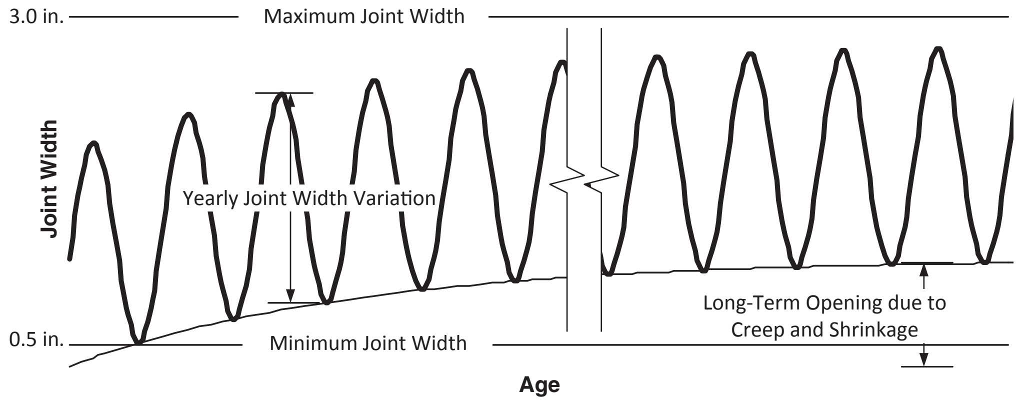


Figure 8.6. Long-term joint width changes.

of installation ($T_{install}$). The joint width to be set ($JW_{install}$) is computed as follows:

$$JW_{install} = dL_{min} + (T_{max} - T_{install}) \times CTE_c \times L$$

If dL_{min} = 0.5 in., T_{max} = 120°F, $T_{install}$ = 70°F, CTE_c = 0.000005 in./in., and L = 200 ft (2,400 in.), then $JW_{install}$ = $0.50 + (120 - 70) \times 0.000005 \times 2{,}400 = 0.50 + 0.60 = 1.10$ in.

For the example used, the joint width at the time of installation should be set at 1.10 in. (28 mm) to accommodate the PTSection expansion during the first summer and allow for a minimum joint width of 0.50 in. over the long term. The minimum joint width during successive summers will increase due to concrete creep and shrinkage.

The best estimates for the data needed for the PTSection end movement computation should be used. Underestimating the minimum joint width requirement for the sealant can lead to early sealant failure or joint failure. Overestimating the maximum joint width can result in an overdesign of the sealing system.

The long-term maximum joint width should not exceed 3.0 in. as a larger joint width will compromise the effectiveness of the joint load transfer system used at the expansion joints.

A gap panel, such as used at the California I-680 PPCP project, allows two expansion joints between adjacent PTSections. If a gap panel is used, each expansion joint width parameter computed above can be reduced by 50%. The joint width at the time of installation at each of the two expansion joints can also be reduced by 50%.

Summary

PCP design is based on the recognition that, once constructed (installed), the overall behavior of the PCP under traffic loading and environmental loading is not significantly different from that of a like CIP concrete pavement. Thus, a JPrCP is expected to behave similarly to a CIP-JCP, and a PPCP is expected to behave similarly to a CIP-PCP. Therefore, PCP systems can be designed for long-term performance using design procedures currently used for CIP concrete pavements. The use of these design procedures requires some refinements to allow consideration of some of the specific characteristics of PCP systems.

A significant advantage of PCP systems is that the panels used are either reinforced or reinforced and prestressed. As a result, if any panel cracking develops prematurely or as a result of the design traffic loading, the panels can be expected to perform well because the cracking will be held tightly and will not deteriorate. The performance of the thinner prestressed systems, jointed or PPCP, is greatly dependent on the quality of the support condition. The support for such systems should be good to ensure that joint deflections under loading remain low.

CHAPTER 9

Fabrication of Modular Rigid Pavement System Panels

General Considerations

The production of precast concrete is a well-established practice. Industry practices have been developed to regulate the quality of precast concrete products and precast concrete production processes. Most highway agencies also have developed requirements for the production of precast concrete. As a result, the fabrication of the precast panels for PCP applications is the most controllable process in PCP technology. In the United States, two national technical organizations, the National Precast Concrete Association (NPCA) and the Precast/Prestressed Concrete Institute (PCI), have developed certifications programs for precast concrete plants.

Both NPCA and PCI have well-documented plant certification programs (PCI 1999; NPCA 2011), and member organizations are strongly encouraged to maintain certification for their plants. The industry certification programs are dedicated to setting high standards for precast plant facilities, production operations, and internal quality control procedures. To be certified, each plant must pass a comprehensive inspection of its entire manufacturing process to ensure that the plant is capable of meeting the requirements demanded by the construction industry. Typically, once a plant is certified, the plant maintains its certification by passing annual on-site, unannounced, certification inspections by independent third-party inspection agencies.

For PCP applications, there are efficiency and cost benefits in producing multiple (typically four to eight or more) panels per day, depending on the space available at the plant. The casting is done inside the plant under controlled conditions. For larger projects requiring hundreds of panels, production of the panels must begin months in advance of the start of the panel installation.

The process for PCP panel fabrication includes the following:

1. Setting up the formwork;
2. Installing the hardware (e.g., reinforcement, prestressing steel and prestressing steel hardware per design, lifting inserts);
3. Providing for blockouts and grout ports for dowel bars and tie bars or other joint-related devices;
4. Providing for panel undersealing (panel bottom channels and grout ports, per design);
5. Placing concrete;
6. Stripping forms;
7. Applying finishing details to each panel;
8. Curing and storing panels; and
9. Conducting QA/QC activities.

Panel Formwork

The formwork and the casting beds are a high-cost item for a precaster and require significant investment and long-term commitment by the precaster to enter the PCP market. The formwork used for fabricating PCP panels is made of sturdy steel members and is locked into place on flat steel casting beds. The formwork and the casting bed must be capable of retaining tight dimensional tolerances over repeated use. The straightness of each side form member must be checked regularly. A typical formwork used for a continuous jointed PCP system is shown in Figure 9.1. For panels that require pretensioning, the formwork is modified to allow for pretensioning strands, as shown in Figure 9.2.

Concrete Mixture

The concrete specification used by most highway agencies for precast panels is the same as that used for CIP concrete

Courtesy of FMC.

Figure 9.1. Typical formwork used for a continuous jointed PCP system.

pavements. These specifications pertain to the following concrete properties:

1. Water–cementitious materials ratio: maximum of 0.45 for freeze areas to a maximum of 0.50 for nonfreeze areas. A minimum ratio of 0.37 may sometimes be specified.
2. Strength: typically about 4,000 lbf/in.^{2} (27.5 MPa) compressive strength at 28 days. However, precasters routinely may use early-age higher-strength concrete to accommodate pretensioning operations within about 16 hours of casting the panels.
3. Air content: as dictated by the climatic zone and maximum aggregate size.
4. Aggregate quality: aggregate durability with respect to materials-related distress.
5. Maximum aggregate size: may range from ¾ to 2 in. (19 to 50 mm).

The concrete for precast panels has no slump requirements, and, in fact, some precasters may use self-consolidating concrete (SCC) for the panel production. Most precasters involved in producing panels for PCP applications have on-site concrete production facilities. As a result, concrete is produced as needed on a just-in-time basis. Panel production is not affected by external factors such as weather conditions and traffic delays, and the concrete placement rate can be maintained even if a few concrete batches are rejected for not meeting fresh concrete test requirements, principally, the air content requirement or in the case of SCC, the flow requirement.

Panel Hardware Installation

Factors to be considered in panel hardware installation include reinforcement for panel shipping and handling, the type and size of prestressing steel-related hardware, and the supplies needed for installation.

Nominal reinforcement is required to mitigate the concrete stress effects encountered in shipping and handling. The reinforcement is placed in both directions and is typically placed in two layers, as shown in Figure 9.3. The reinforcement in each direction may range from about 0.15% to 0.20% of the concrete cross-sectional area.

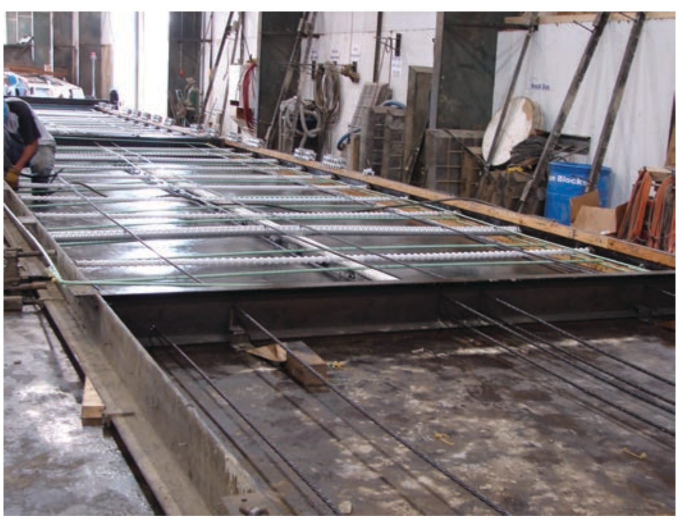


Figure 9.2. Formwork modified to allow for pretensioning strands.

Courtesy of FMC.

Figure 9.3. Reinforcement placed in both directions.

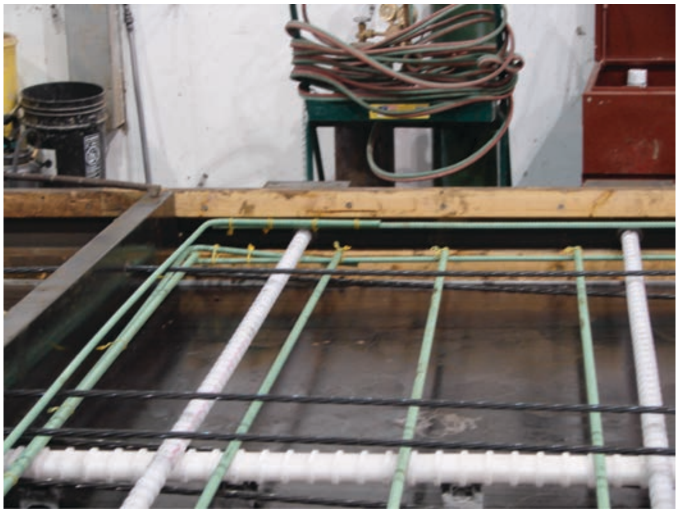


Figure 9.4. Prestressing steel-related hardware.

Prestressing steel-related hardware, as shown in Figure 9.4, may include

a. Strands used for pretensioning. These should be at least 0.375-in. (9.5-mm)-diameter, 270-ksi (1,862-MPa), low-relaxation steel strands; and
b. Ducts used for posttensioning. Ducts must be positioned straight and not allowed to bow under the weight of the concrete as it is discharged into the formwork. Solid tubes may be used within the ducts to keep the ducts straight, and the ducts should be tied to the reinforcement or the prestressing strands.

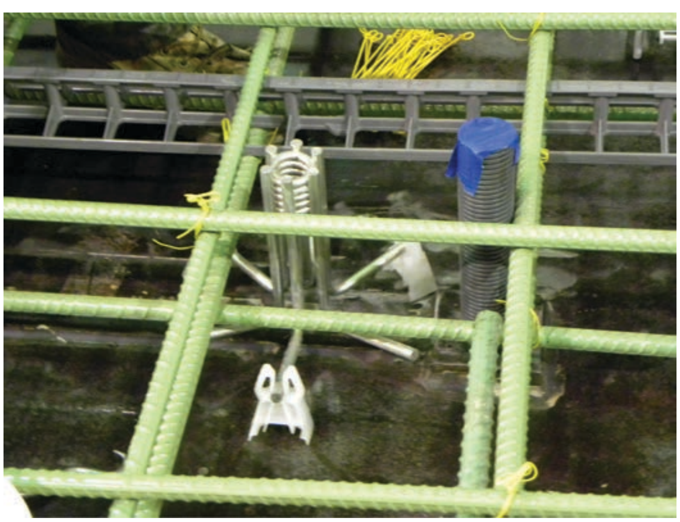
For PPCP panel fabrication, the prestressing steel hardware together with the reinforcement may result in hardware congestion that may affect the thickness of the concrete cover and the ability of the concrete to flow through the hardware during concrete placement. For currently used PPCP systems, hardware congestion dictates that the PPCP panel thickness should not be less than 8 in. (200 mm).

Additional hardware and supplies necessary for panel installation include

1. Blockouts for the following
   a. Dowel bars and tie bars and any other load transfer devices; and
   b. Undersealing channels per design.
2. Grout tubes for the following
   a. Dowel bar slots per design;
   b. Undersealing or bedding grout per design; and
   c. Grouting ducts (after posttensioning of the tendons).
3. Expansion joint hardware. The expansion joint hardware is a PPCP feature associated with the fabrication of expansion joint panels. The expansion joint panel may include the following:
   a. Dowel bars with dowel caps; and
   b. Armored joint assembly per design. Armored joints were used in some of the initial PPCP projects and are often used when the spacing between expansion joints is large, typically over 200 ft (61.0 m).
4. Lifting inserts, as shown in Figure 9.5.

Nonplanar Panels

The fabrication of nonplanar panels requires special formwork that maintains three corners of the rectangular formwork flat and allows adjustment to the elevation of the fourth corner to obtain the necessary warp in each panel. This requires use of vertically adjustable (floating) side forms.



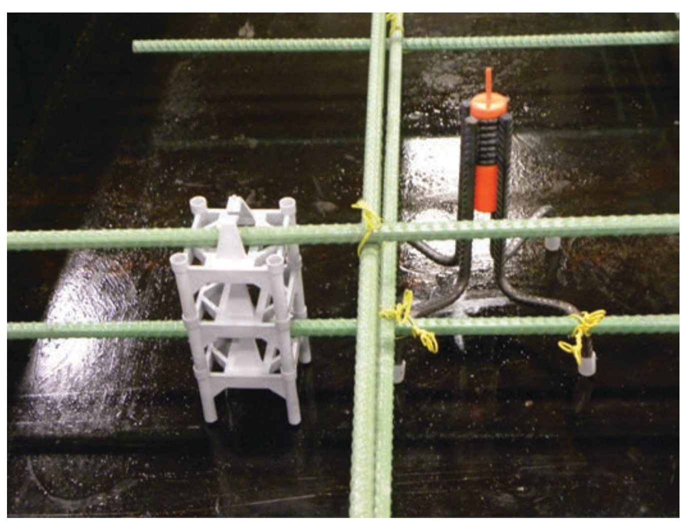


Figure 9.5. Lifting inserts.

The formwork needs to allow adjustments to fabricate non-planar panels with different plan geometries.

Concrete Placement

As soon as the formwork is set up and the panel hardware is in position, it is important to check the formwork dimensions to ensure that the panels can be fabricated to meet the specified geometric tolerances (see the section on panel testing below). The concrete placement can then begin. Concrete is typically produced at an on-site concrete plant with a smaller capacity than commercial ready-mix concrete plants. Concrete is produced in accordance with the requirements of ASTM C94 and those of the highway agency, if applicable. Concrete plants need to be certified by the highway agency or in accordance with the requirements of the National Ready Mix Concrete Association's QC3 checklist.

Concrete is delivered to the panel formwork using a transit mixer or buckets, depending on the location of the concrete plant within the precast plant complex and the batch size of the concrete plant. The concrete delivery operations are shown in Figure 9.6.

Two concrete types and placement processes, as shown in Figure 9.7, are available:

1. Slump concrete with a design slump of about 8 in. (200 mm) is placed using conventional procedures. This process requires moving the concrete manually within the formwork. Concrete is consolidated using a spud vibrator and finished with a metal straightedge screed or a hydraulic-powered roller screed.
2. SCC is deposited gently across the formwork and allowed to flow within the formwork. This process requires no compaction effort, and the concrete attains the final surface without much manual manipulation.

The concrete texture is applied after the concrete bleed water has disappeared and the concrete surface is beginning to set. The texture applied may be AstroTurf drag or tining, in accordance with agency requirements. The formwork is then covered with plastic sheeting for overnight cure. The surface texture applied may have a short life

Figure 9.6. Concrete delivery options (transit mixer and bucket).

Figure 9.7. Placement processes for slump concrete and SCC.

because most PCP projects tend to be diamond ground to achieve the required surface smoothness. However, some form of texture is necessary for the new panels to ensure that safety is not compromised during the first few days of opening to traffic before the diamond grinding can take place.

If the panel is to be pretensioned (see next section), the strands are pretensioned before the concrete is placed.

Pretensioning

The panel design and shop drawings may include requirements for pretensioning of the panels. Pretensioning is typically achieved using at least ⅜-in. (9.5-mm)-diameter strands.

For PPCP systems, pretensioning may be required in the direction of the panel dimension that is 12 ft (3.7 m) or longer. Pretensioning for PPCP panels is used primarily to accommodate lifting stresses and is designed accordingly.

For individually prestressed panels (for use with jointed continuous PCP systems), prestressing is used to allow the use of thinner panels. The effective prestress in the panel in this case may range from 100 to 200 lbf/in.^{2} (0.70 to 1.4 MPa).

Pretensioning of the strands is performed before concrete placement, as shown in Figure 9.8. The strands are typically pretensioned using external vertical bulkheads that can accommodate pretensioning of a single panel or multiple panels. The strands are stretched in two steps:

1. Initial tensioning, which removes the slack in the strands and allows for marking reference points in the strands to measure the strand elongation due to final tensioning; and
2. Final tensioning, which is performed according to the design requirements.

Figure 9.8. Pretensioning process.

At about 15 to 20 hours, just before the formwork is stripped and the concrete has attained the desired strength, the strands are released from the anchorage at the bulkheads. The pretensioning method requires a good bond between the strands and concrete to allow direct transfer of tension from the strands to the concrete, thus adding compressive strength to the concrete. The bond development takes place over the prestress transfer length, about 25 to 30 in. (635 to 762 mm) from each end of the strand for the 0.5-in. (13-mm)-diameter strands.

The strands are typically flame-cut after the formwork is stripped.

Formwork Stripping and Panel Finishing Details

The panels are stripped of formwork within about 15 to 20 hours to allow the next set of panels to be fabricated. The concrete compressive strength when the formwork is stripped needs to be at least 2,000 lbf/in.^{2} (13.8 MPa) to ensure that the concrete will not be damaged during the stripping process and to allow for the lifting of the panels. Some agencies require stripping strength of 2,500 to 3,000 lbf/in.^{2} (17.2 to 20.7 MPa).

For pretensioned panels, the concrete strength needs to be between 3,000 and 4,000 lbf/in.^{2} (20.7 to 27.5 MPa) to safely transfer the prestressing force from the prestressing strands to the panel.

The day-old panels may be moved to other areas within the plant to take care of the panel finishing details, which may include the following:

1. Cleaning up the blockouts;
2. Installing foam strips (gaskets) along the bottom edges of the panel, along the undersealing slots, and along the perimeter of the dowel slots per design;
3. Applying project- and panel-specific marking on each panel; the marking should include panel width and length and date of fabrication;
4. Cutting of pretensioning tendons, if applicable;
5. Checking for any damage to the panel, repairing minor surface damage, and filling small surface voids over 0.5 in. (13 mm) in diameter using a sand–cement paste or an approved proprietary patching material;
6. Rounding the top edges of the panels with a hand stone to prevent chipping during handling and installation; chamfering on the top edge is typically not allowed;
7. Checking for dowel bar alignment per design; and
8. Checking for dimensional tolerances.

Figure 9.9 shows a stripped panel being moved to another location and a panel with project-specific markings.

Once the finishing details are taken care of, the panel surfaces and sides are sprayed with an approved concrete-curing compound.

All forms and casting bed areas should be cleaned after each use.

Panel Storage and Curing

Storage

The panels are moved to an outdoor storage location after the finishing details have been completed and the curing membrane has been applied. The panels are cured at the plant and stored until the panel installation begins. The panels may be in storage for a few weeks to a few months. For large projects, hundreds of panels are fabricated in advance and stored at the plant until needed.

It is important that the panels be stacked on solid dunnage at locations that minimize panel warping due to self-weight

Figure 9.9. Stripped panel being moved to another location and panel with project-specific markings.

and creep. The dunnage location should be shown on shop drawings. The storage of nonplanar panels may require shimming at the dunnage to accommodate the warp. The upper panels of a stacked tier should not be used as storage areas for smaller panels or equipment.

The panels should be stored using an order that will facilitate shipment of panels in order of need. During on-site storage and shipping, the dowel bars and tie bars, if installed, should be protected against damage during lifting, handling, and shipping.

Steam Curing

Steam curing of the panels is not necessary and should not be mandated. Steam curing at atmospheric pressure should be the precasting plant's option and is typically used to accelerate the concrete strength gain to shorten the period to stripping and detensioning (if pretensioning is used), especially during cooler weather. The following sequence of steps is typically used for steam curing:

1. An initial period of curing, typically 3 to 4 hours, for concrete to achieve initial set;
2. A period for increasing the panel temperature;
3. A period for holding the maximum temperature, about 140°F (60°C), constant; and
4. A period for decreasing the temperature.

Steam curing at atmospheric pressure is generally done in an enclosure to minimize moisture and heat losses. Tarpaulins are frequently used to form the enclosure. Steam-curing temperatures above 140°F should be avoided to avoid heat-induced delayed ettringite expansion and undue reduction in ultimate strength. The temperature in the enclosure surrounding the concrete should not be increased or decreased more than 40°F (25°C) per hour. The curing temperature in the enclosure should be held until the concrete has reached the desired strength.

Once the steam curing has ended, the panels should not be exposed to ambient conditions until the concrete has cooled to about 30°F (18°C) above the ambient temperature. In addition, the steam-cured panels should be protected before exposing the panels to windy conditions. Rapid concrete cooling or loss of surface moisture can lead to premature cracking in the steam-cured panels.

For pretensioned panels, detensioning and flame-cutting of the tendons is done at the end of steam curing.

Quality Assurance and Quality Control Activities

One of the warrants for considering PCP systems is that the precast panels can be fabricated to ensure concrete durability and strict dimensional tolerances to minimize any installation-related issues. At the precast plant, QC comprises many tests and certifications that assure that the specific materials and equipment used in the panel fabrication processes meet the project specification requirements. QA is normally provided by the highway agency's personnel or representatives of an independent third-party organization, who observe that the quality control process is in place and functioning properly, the submittals conform to the specification requirements, and the designated tests for acceptance are met.

Two distinct types of quality requirements and associated quality testing are needed for precast panel fabrication: concrete quality and panel quality. The test requirements and test procedures are based on routine and accepted industry practices and are therefore not discussed in detail here.

Concrete Quality

Concrete quality testing is performed in accordance with project specifications. Important requirements for concrete testing are that the plant's on-site testing laboratory be accredited and meet the requirements of ASTM C1077 for concrete and aggregate testing and that the laboratory technicians are certified. The concrete testing performed at the plant typically includes tests for the following:

1. Aggregate gradation;
2. Concrete strength, typically compressive strength;
3. Concrete air content;
4. Concrete slump for slump concrete;
5. Concrete flow for SCC; and
6. Unit weight.

Views of concrete quality testing being performed at precast plants are shown in Figure 9.10.

Panel Quality

Panel quality testing typically includes the following:

1. Checking dimensional (geometric) tolerances. Panel dimensional tolerances are necessary for panels used for intermittent repairs and for continuous applications. These tolerances are standardized by the precast concrete industry and can be easily met with quality fabrication practices. The dimensional tolerances applicable to PCP panels are listed in Table 9.1. These tolerances do not supersede tolerances established by the highway agency for specific projects.
2. Checking dowel alignment.
3. Inspecting for panel surface damage or signs of early age distress.
4. Checking strand elongation to ensure that strands are tensioned to the proper load level.

Figure 9.10. Views of concrete quality testing at precast plants.

Table 9.1. Geometric Tolerance Requirements

Panel Feature	Tolerance
Length or width	±¼ in.
Thickness	±¼ in.
Squareness of corner in plan view	±¼ in. over 12 in.
Squareness of sides in section view	±¼ in. over the thickness
Local smoothness of any surface	¼ in. over 10 ft in any direction
Vertical location of reinforcement	±½ in.
Vertical location of pretensioning strand	±¼ in.
Blockout dimensions (if applicable)	±¼ in.
Location of lifting inserts	±½ in.

Source: PCI 2004.

The panel-related tolerances applicable to PPCP panels listed in Table 9.2 are based on tolerances specified for the Missouri I-57 PPCP project (Merritt et al. 2008).

Summary

The production of precast concrete is a well-established practice. Industry practices have been developed to regulate the quality of precast concrete products and precast concrete production processes. In addition, most highway agencies have developed requirements for production of precast concrete. As a result, the fabrication of the precast panels for PCP applications is the most controllable process in PCP technology. It is important that precast plants used to fabricate the panels participate in the highway agency or industry-managed precast plant certification programs. The industry certification programs are dedicated to setting high standards for precast plant facilities, production operations, and internal QC procedures.

Table 9.2. Panel Tolerances Used for Missouri I-57 PPCP Project

Measurement	Tolerance
Length (parallel to long axis of panel)	±6 mm (¼ in.)
Width (normal to long axis of panel)	±3 mm (⅛ in.)
Nominal thickness	±1.5 mm (1⁄16 in.)
Squareness (difference in measurement from corner to corner across top surface, measured diagonally)	±3 mm (⅛ in.)
Horizontal alignment (on release of stress) (deviation from straightness of mating edge of panels)	±3 mm (⅛ in.)
Vertical alignment-camber (on release of stress)	±3 mm (⅛ in.)
Deviation of ends (horizontal skew)	±3 mm (⅛ in.)
Deviation of ends (vertical batter)	±3 mm (⅛ in.)
Keyway dimensional tolerance	±1.5 mm (1⁄16 in.)
Position of strands	±3 mm (⅛ in.) vertical[a] ±6 mm (¼ in.) horizontal
Position of posttensioning ducts at mating edges	±3 mm (⅛ in.) vertical[a] ±3 mm (⅛ in.) horizontal
Straightness of posttensioning ducts	±6 mm (¼ in.) vertical[a] ±6 mm (¼ in.) horizontal
Vertical dowel alignment (parallel to bottom of panel)	±3 mm (⅛ in.)[a]
Horizontal dowel alignment (normal to expansion joint)	±3 mm (⅛ in.)
Dowel location (deviation from shop drawings)	±6 mm (¼ in.) vertical[a] ±6 mm (¼ in.) horizontal
Dowel embedment (on either side of expansion joint)	±25 mm (1 in.)
Position of lifting anchors	±75 mm (3 in.)
Position of nonprestressed reinforcement	±6 mm (¼ in.)
Straightness of expansion joints	±3 mm (⅛ in.)
Initial width of expansion joints	±3 mm (⅛ in.)
Dimensions of blockouts and pockets	±3 mm (⅛ in.)

[a] Measured from bottom of panel.

CHAPTER 10

Panel Installation for Intermittent Repairs

General

The guidelines presented in this chapter for the installation of precast concrete panels for intermittent repair applications are based on the state of the practice and incorporate lessons learned from several demonstration and production projects. The guidelines are applicable to the repair of existing concrete pavements where the existing pavement profile and geometry are to be maintained. The information presented in this chapter is specific to the installation of precast panels for repair applications. Other information common to other PCP applications and installation processes is presented in Chapters 4 through 7.

The specific guidelines presented in this section for intermittent repairs include the following:

1. Panel installation staging and lane closures;
2. Removal of distressed concrete slab sections;
3. Base preparation;
4. Bedding placement;
5. Load transfer provisions;
6. Panel placement;
7. Dowel slot grouting or patching;
8. Panel undersealing; and
9. Surface preparation.

Overview of Panel Installation Process

An overview of a typical intermittent repair installation is summarized below:

- For large production projects, the repair panel installation may be carried out over several months. The installation will almost always need to be performed during the night hours, typically between 8 p.m. and 6 a.m., and typically under traffic.
- The work area for each lane closure for panel installation will range from a few hundred feet to several miles, depending on the planned number of panels to be installed during a specific lane closure, the traffic level, and site constraints such as entry and exit ramps.
- Before the night of panel installation, all areas to be repaired are saw-cut full-depth along the proposed repair perimeter.
- During the night of panel installation, the damaged or deteriorated areas of the concrete pavement are removed. Care is taken not to damage the existing base during the concrete removal process.
- Depending on the design requirements (e.g., use of a panel thicker than the existing slab), part of the existing base may also need to be removed. The base restoration treatment may include the following actions:
    - The existing base is regraded to the specified grade and compacted if granular.
    - A thin granular bedding layer may be placed over the base if the existing base is stabilized (asphalt treated or cement treated).
    - A fast-setting bedding grout or polyurethane material may be used.

      Because of time constraints, it is very unlikely that a new base will be used. If new base material is required, RSLCB should be used. RSLCB will require additional time to allow the LCB to set before placing the panels on the freshly placed LCB.
- Depending on the design for providing load transfer at the joints, the following activities may be performed:
    - Drilling holes for dowel bars in adjacent existing slabs and installing dowel bars in the drilled holes after introducing epoxy in the holes.
    - Sawing slots for dowel bars in adjacent existing slabs.
- The panel installation process begins with the placement of the panel in the repair area. Several methods are available for panel placement:
    - Method 1: The panel is placed directly on the finished base or bedding.

  - Method 2: The panel is set at the desired elevation using strongback beams spanning the repair area.
  - Method 3: The panel is set at the desired elevation using threaded setting bolts.
  - Method 4: The panel is placed in the repair area about ½ to 1 in. (13 to 25 mm) below final elevation. The panel is then raised to the desired elevation using polyurethane foam.
- For panel placement Methods 2, 3, and 4, the bedding needs to be provided during the same lane closure as the panel placement.
- The load transfer features are installed during the same lane closure as the panel placement or during the next lane closure, typically the next night, depending on the design of the load transfer system.
- The finishing operations, such as panel undersealing, joint sawing and sealing, and surface grinding, are performed.

A panel installation requires about 15 to 20 minutes. Typically, about 15 to 20 panels can be installed during a single nighttime lane closure. Any activity that delays the panel installation or any added activity that requires additional time to complete can affect panel installation productivity for a given lane closure.

Panel Installation Staging and Lane Closures

The accessibility to the project site influences (1) entry and exit of material-haul trucks, (2) positioning of construction-related equipment, and (3) panel delivery. Furthermore, the construction window available for the intermittent installation will influence the sequencing and planning of pre-installation and installation activities. The installation will take place during nighttime hours, and the allowable closure time will range from about 8 to 10 hours, typically starting at 8 p.m. and ending at 6 a.m. the next morning. Nighttime construction requires on-site lighting. All lane closures must be done in accordance with MUTCD (2009) and the agency's work zone traffic control guidelines.

The intermittent repair work zone requires closure of two lanes: the lane undergoing repairs and an additional lane for construction traffic, especially for trucks delivering the panels. When two lanes cannot be closed, all work in preparation for the repair panel installation is done within the lane being repaired. This preparatory work includes the positioning of the crane and the concrete removal and disposal equipment. The second lane is then intermittently closed to traffic to allow unloading and placement of the panels at the designated repair areas.

Depending on the design of the repair panels, one or two lane closures may be required. For one closure, all activities involving existing concrete pavement removal, panel installation, load transfer provision, and undersealing must be completed during a single lane closure. For two lane closures, the existing concrete pavement removal and panel placement are carried out during the first closure, and the remaining activities are carried out during the next closure, typically the next night.

Grinding and joint sealing activities may be performed when all repair panels have been installed and may be done a few days to a few weeks after panel installation.

Removal of Distressed Concrete Slab

The saw-cutting of the distressed concrete pavement areas should be carried out as close as possible to the installation time of the precast panels. It is important that the repair boundaries include all of the significant deterioration in the existing pavement slab and underlying layers. The extent of deterioration beneath the slab surface may be identified through coring and deflection testing. Saw-cuts are made to the full depth of the concrete slab, and any tie bars along the affected longitudinal joints should be cut. Each damaged slab should be removed in one or more pieces without damaging the adjacent pavement or the underlying base.

Repair Area Dimensional Tolerances

It is important that the repair area dimensions be measured accurately for the saw-cutting operation, because the repair panels are fabricated with standardized dimensions. An excavated repair area that is too large will result in larger joint widths, and an excavated area that is too small will not allow panel placement. Most agencies require that the joint width along the repair area perimeter not exceed about ⅜ to ½ in. (10 to 13 mm). Issues to consider for the repair area dimensions include the following:

1. The repair should be full width. The longitudinal joint sealant should be exposed to determine the width of the repair area. The slab width within the repair area may vary, and the repair area dimensions must incorporate the variable slab width to ensure that the panels are fabricated with the correct dimensions. Poor dimensioning of the panel can lead to a large longitudinal joint width.
2. When full-slab panels are to be removed and replaced, the length of the repair area should be marked about 1 ft

Courtesy of Roman Stone Construction Company.

Figure 10.1. Template used for marking the repair area perimeter.

(305 mm) beyond each transverse joint to ensure that the existing dowel bars are removed.

3. It is recommended that a template, such as the one shown in Figure 10.1, be used to mark the location of the repair area perimeter saw-cuts.

Existing Pavement Removal Equipment

A variety of pavement removal equipment can be used to remove the designated areas of the existing pavement. For intermittent repair applications, the slab lift-out method is recommended. The slab lift-out operation requires a crane or other equipment that can accommodate the largest panel size to be removed. The same crane is then used for installing the repair panels. Many contractors prefer to use excavation equipment to remove the existing pavement, but such equipment can damage the base, resulting in additional time and effort to regrade and recompact the base.

Base Preparation and Bedding Materials

The support condition under the precast panel is critical to long-term performance of the intermittent repairs. The support condition needs to be uniform within the repair area, and it should be stable and firm. Unlike CIP concrete pavement, precast panels do not conform to the geometry of the existing base or bedding, which therefore must be regraded or finished to within the established tolerance to provide uniform support under the panel.

Depending on the design requirements, part of the existing base may need to be removed. The base treatment may include the following:

1. The existing base is regraded to the specified grade and compacted if granular. A thin finer-grained granular bedding material may be used to provide a smoother grade.
2. A thin granular bedding layer may be placed over the base if the existing base is stabilized (asphalt treated or cement treated).
3. A fast-setting bedding grout or polyurethane material may be used.

Because of time constraints, it is very unlikely that a new base will be used. RSLCB should be used if new base material is needed. RSLCB will require additional time to allow the LCB to set before placing the panels on the freshly placed LCB.

An existing granular base will need to be reworked and regraded. Additional base material will be needed if the base grade needs to be adjusted. This situation is typical when the base material is removed during the removal of the existing concrete. The grading and compaction of a granular base is a time-consuming process. The base is graded manually, as shown in Figure 10.2, and may require multiple passes of a manually operated trimmer before the grade is considered acceptable. The granular base is typically compacted using a vibratory plate compactor.

On most projects constructed to date, no effort has been made to compact the granular bases to maximum density using an optimum moisture content for the granular material. In addition, no testing has been performed to ensure that the granular base has achieved maximum density. This is a serious gap in the installation process. Agencies must specify appropriate procedures for compaction of the granular bases and require that compaction testing is performed on the completed bases.

The use of stone dust–like material or manufactured or river sand to achieve a smooth base surface or as filler should be carefully considered. These poorly graded materials cannot be compacted well and are not structurally stable. The stone dust or the sand bedding thickness should be limited to 0.25 in. (6 mm). As a general rule, any base or bedding material that would not be allowed during the construction of CIP concrete should not be allowed in precast concrete systems.

If the existing base is concrete- or asphalt-treated, the base grade cannot be manipulated. In that case, a granular bedding material, a rapid-setting flowable fill (RSFF) material, or a polyurethane material may be used to establish the smooth grade and uniform support needed for installing the panels. The granular bedding material thickness should be limited to 0.25 in. (6 mm). The RSFF or polyurethane bedding material should be at least 0.5 to 1 in. (13 to 25 mm) thick to ensure

Figure 10.2. Base being graded and compacted within the repair area.

point support conditions do not develop. The RSFF should be allowed to set before placing the panels over it; otherwise the potential for damage to the bedding surface will be high.

The following criteria may be used to allow operation on RSFF: the earlier of attaining 100 lbf/in.^{2} (0.9 MPa) compressive strength or 2 hours after placement of the RSFF.

Load Transfer Provisions

Load transfer provision is a critical design requirement for intermittent precast panel application. Load transfer for intermittent repair can be provided as follows:

1. Drilling and installing dowel bars in the existing pavement. Dowel bars may be located in the wheelpaths (typically four dowels per wheelpath) or up to 11 dowels, spaced at 12 in. (305 mm), may be used per 12-ft (3.7-m)-wide panel. This method requires panels with the dowel slots at the slab bottom, as used by the Fort Miller Company.
2. Using conventional dowel slots at the surface. In this method, the dowel slots have wider mouths, about 2.5 in. (63 mm) wide at the surface, and as a result the dowel slots must be patched during the same lane closure as the one used for cutting the dowel slots. The following options are available:
   a. Partial DBR technique. Dowel slots are cut in the existing pavement before panel placement. Typically four slots per wheelpath are used. The panel is fabricated with embedded dowels to match the existing pavement slot locations.
   b. Full DBR technique. Dowel slots are cut in the existing pavement and in the panel, typically four slots per wheelpath. The slots may be cut at the time of panel placement or during the next lane closure.
3. Using narrow-mouthed dowel slots at the surface (a procedure developed as part of the Project R05 study). This technique allows the panels fabricated with surface dowel slots to be left in place in the repair area without immediately patching the slots. The unpatched, narrow-mouth surface slots do not pose any safety issues with vehicle operations. This technique requires the following steps:
   a. Dowel holes are drilled in the existing pavement before the placement of the panel.
   b. Dowels are positioned in the longer surface slots before panel placement.
   c. During the same or the next lane closure, the drilled hole is filled with epoxy just before sliding the dowel bars in the hole. The dowel bars are held in place, at proper alignment, using a magnetic clamp or a similar device.
   d. After the epoxy is set, the dowel slots are patched using the DBR procedure during the same or the next lane closure.

Dowel Bar and Slot Location

The holes to be drilled in the existing pavement for dowel bars should be located as accurately as possible, both vertically and horizontally, so that they match the corresponding dowel slots in the panels. Use of a wooden or metal template is recommended to mark the locations of the holes at the joint face. The holes should be marked with a sharp point and not spray painted. The dowel holes should be located within ±0.25 in. (6 mm) of the locations shown on the plans and should be drilled in a direction parallel to the longitudinal joint. If the saw-cut at the planned joint location is not perpendicular to the longitudinal direction, adjustment must be made when drilling the dowel holes to ensure that the holes are not drilled perpendicular to the misaligned joint face.

Dowel slots to be provided in the existing pavement should also be located as accurately as possible in the horizontal plane. The dowel slots should be located within ±0.25 in. (6 mm) of the locations shown on the plans.

A tight tolerance for the dowel bar and corresponding dowel slot location is necessary because there is little room for error if narrower dowel slots are used. For a 2.5-in. (63-mm)-wide dowel slot and a dowel diameter of 1.5 in. (38 mm), the available gap in the slot is about 0.5 in. (13 mm) on each side of the bar. If the dowel is offset by 0.25 in. and the slot is offset by 0.25 in. in the other direction, there will be no room available to position the panel and to spread the grout or patching material completely around the dowel. If the dowel and slot tolerance cannot be achieved, use should be made of wider slots, up to 3.34 in. (83 mm) wide at middepth.

Panel Installation

Once the base (or base and bedding) is ready and the dowel bars have been installed in the drilled holes (if required by the repair design), the panel installation process can begin. The panel installation requires the panel delivery trucks to be positioned in the adjacent lane, next to the repair area. Four installation methods are available that can be used to place the panel in the prepared repair area. These four methods, detailed below, can be used regardless of the technique used for providing load transfer at the joints.

Method 1: Panel Directly Placed on Finished Base or Bedding

This is the simplest method to place the panel in the repair area. The repair area is graded to the desired elevation using a template that matches the thickness of the panel. The panel is positioned so that it is centrally located within the repair area and the dowel slots, whether used at the panel bottom or at the surface (narrow-mouth slots), match the drilled location of the dowel bars in the existing pavement. If RSFF bedding material is used, it should be allowed to set sufficiently before placing the panels over it without displacing the RSFF. If the panel cannot be placed within the specified vertical tolerance, the panel should be lifted out and the base and bedding regraded and recompacted if necessary to allow the panel to be placed within the specified vertical tolerance. The panel placement technique is illustrated in Figure 10.3.

If the panels are opened to traffic before the dowel slots are grouted, shims should be used at the approach joint side of the panels to prevent the forward drift of the panels under traffic.

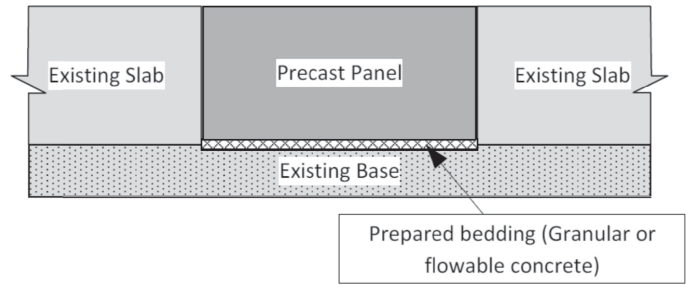


Figure 10.3. Panel placed directly on prepared bedding over existing base.

Method 2: Panel Set Using Strongback Beams

This method allows the panels to be set at the desired elevation using the elevation of the existing pavement at each side of the repair area. The panel is fastened to the two strongback beams that extend about 2 ft (0.6 m) beyond the repair area. The beams are fastened to the panel using the lift inserts and long bolts with the lifting hooks while the panel is on the delivery truck. The beams allow quicker positioning of the panel in the repair area. Bedding material, typically RSFF, is used to fill the gap between the finished base and the panel bottom. This panel placement technique is illustrated in Figure 10.4. The strongback beams can be removed from the panel as soon as the RSFF material has attained a compressive strength of 50 lbf/in.^{2} (345 kPa).

Method 3: Panel Set Using Threaded Setting Bolts

This method also allows each repair panel to be set at the desired elevation using the elevation of the existing pavement at each side of the repair area. Four symmetrically located threaded setting bolts control the elevation of the panel. Four steel plates, 6 × 6 in. and 0.75 in. thick (150 × 150 × 18 mm), are prepositioned on the prepared base before placing the panel in the repair area. The plates are

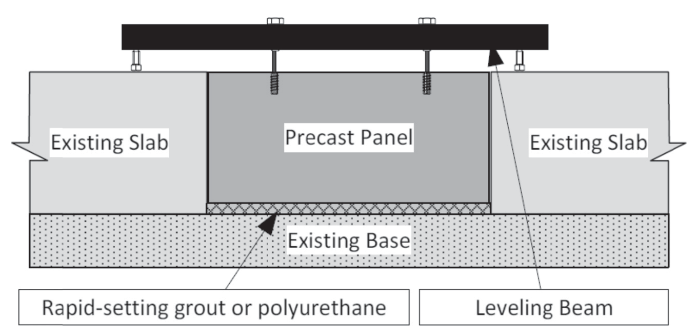


Figure 10.4. Panel placement using strongback beams.

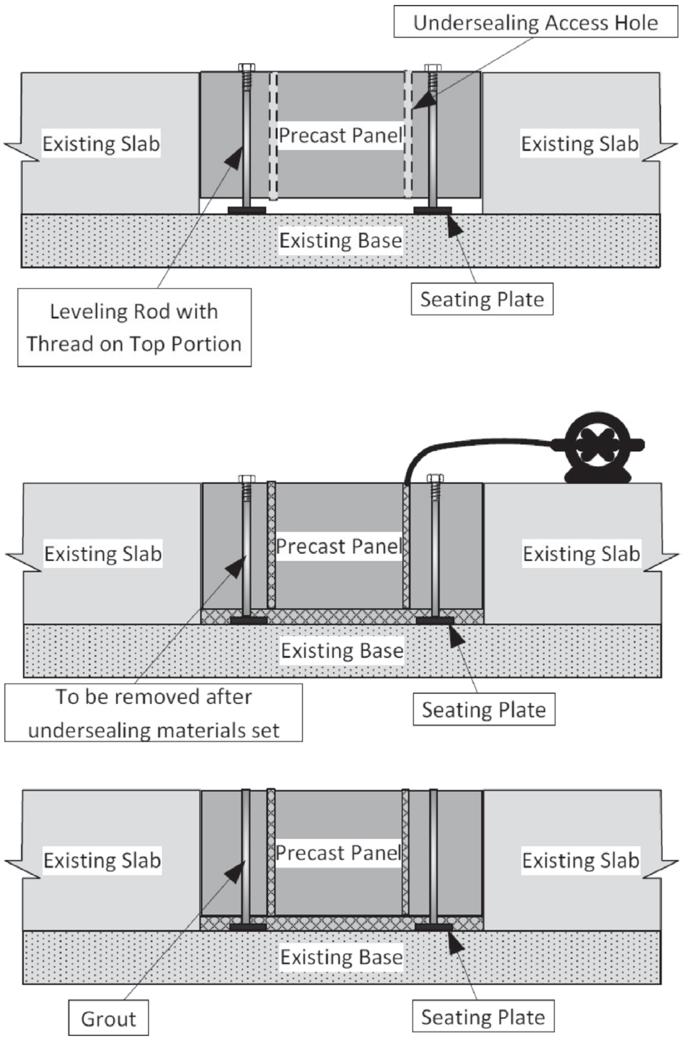


Figure 10.5. Panel placement using threaded setting bolts.

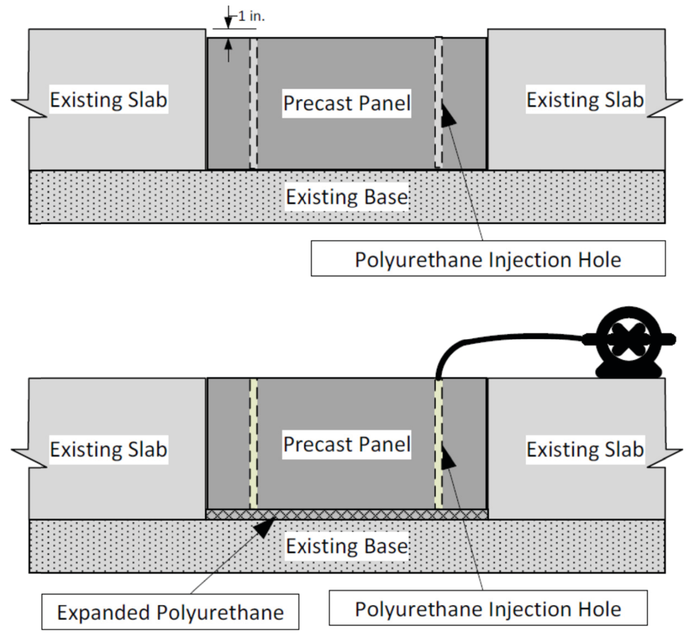


Figure 10.6. Panel placement using polyurethane foam.

positioned to coincide with the location of the setting bolts. Once the panel is set at the correct elevation, the bedding material, typically RSFF, is used to fill the gap between the finished base and the panel bottom. This panel placement technique is illustrated in Figure 10.5.

This technique requires fabricating threaded sleeves in the panel. The sleeves must be properly anchored (secured) in the concrete; otherwise, there is a risk that the sleeves will pop out during the panel-setting operation.

The setting bolts can be removed from the panel as soon as the RSFF material has attained a compressive strength of 50 lbf/in.^{2} (345 kPa).

Method 4: Panel Set Using Polyurethane Foam

This method, used by the Roman Stone Construction Company, requires grading the base about 0.5 to 1 in. (13 to 25 mm) below the design elevation of the panel bottom. The panel is placed in the repair area and raised to the correct elevation by injecting polyurethane grout under the panels using grout holes. This technique, shown in Figure 10.6, requires care to ensure that there is no excessive uplift of the panel and that the panel is raised uniformly across the full panel.

When the FMC system is used, the joint faces of the existing pavement must be coated with a bond-breaking material, such as form oil. This will prevent the dowel slot grout from bonding to the existing pavement joint face.

Activities After Panel Installation

The finishing-up activities to be conducted after the repair panel is installed include the following:

1. Load transfer–related activities;
2. Panel undersealing;
3. Pavement surface grinding; and
4. Joint sealing.

Load Transfer–Related Activities

The activities involved with load transfer relate primarily to patching or grouting the dowel slots.

For the FMC system, a rapid-setting dowel slot grout is poured through grout ports into each slot, as shown in Figure 10.7. The grout must also be poured into the panel perimeter joint gap until the grout material is at the top of

Figure 10.7. Dowel slot grouting.

the joints. Using this system, a joint gap does not exist around the perimeter of the panel. This technique requires use of bond-breaking material on the joint faces of the existing pavement so the dowel grout material will not bond to the existing pavement.

During the joint sawing for the sealing reservoir, care must be taken to align the saw-cut along the existing pavement beside the joint; otherwise, spalling of the dowel grout material will result, and the joint sealant will be ineffective.

For systems with conventional dowel slots at the surface, the DBR process is used to patch the dowel slots; no patching material should be allowed to flow into the joint gap. This technique is shown in Figure 10.8.

For the new system with narrow-mouth surface slots, the following steps need to be carried out:

1. The dowels are positioned in the longer surface slots before panel placement.
2. The drilled hole is cleaned by air blasting and filled with epoxy just before the dowel bars are slid into the hole.
3. The dowel bars are held in place, at proper alignment, using a magnetic clamp or a similar device.
4. After the epoxy is set, the panel slots are patched using the DBR procedure. It is emphasized that the dowel slot sides must be cleaned of dirt, dust, and debris before applying the patching material. No patching material should be allowed to flow into the joint gap.

Figure 10.8. Slot patching for DBR.

Whether a grout material or a rapid-setting patching material is used for the dowel slots, the material should attain the required strength, typically 2,500 lbf/in.^{2} (17.2 MPa), before opening the repair area to traffic.

The grout material or the dowel patching material or other repair material can be used to fill the lift insert holes and to repair any surface damage to the panel.

Panel Undersealing

Regardless of the base type or the bedding material used, it is still necessary to underseal the panel area. Undersealing helps fill any voids that may exist under the panel and ensure full contact between the panel and the base or bedding material. Undersealing does not strengthen the support: weak supports will remain weak. Undersealing helps reduce and possibly eliminate voids under the panel, thereby reducing any moisture-related issues in the base and bedding material.

The undersealing material is typically a rapid-setting cementitious grout that will attain a compressive strength of 500 lbf/in.^{2} (3.4 MPa) at the time of opening to traffic. The grout can be a generic cementitious grout or a proprietary material. When the grout is pumped, the grout flow rate should be within the range specified. The grout is typically mixed in a batch pump in batches and pumped continuously from a grout hopper, as shown in Figure 10.9.

Shallow channels, about 0.25 in. (6 mm) deep and 1 to 2 in. (25 to 50 mm) wide, at the underside of the panel may be used to distribute the grout more efficiently. Certain features of the underside channels may be proprietary. For undersealing to be effective, it is necessary to use foam strips along the bottom perimeter of each panel to prevent the grout from flowing beyond the repair area. The undersealing grout ports should be filled with the undersealing grout up to middepth. The rest of the port depth should be filled with a higher-strength rapid-setting patching material.

Opening to Traffic

Repair areas can be opened to traffic as follows:

1. At the end of the first lane closure
   a. When the FMC system with slots at the panel bottom is used or narrow-mouth surface slots are used, the repair areas can be opened to traffic even if the slots have not been grouted or patched.
   b. When conventional DBR slots are used at the surface, the completed repair areas should be opened to traffic only after the grout for dowels and tie bars (if applicable) and the bedding grout have reached the minimum acceptable strength.
2. At the end of the next lane closure after the FMC panels are grouted or the narrow-mouth slots are patched and the panels are undersealed.

Surface Grinding

Most intermittent repair applications allow up to a 0.25-in. (6-mm) elevation difference between the existing pavement and the panel at the repair area transverse joints. If the elevation difference is larger, the joint areas may be ground to bring the repair area under compliance. On larger repair projects, most agencies typically require the full length of the pavement undergoing repair to be ground to restore overall smoothness and surface texture.

Figure 10.9. Undersealing grout pump and grouting operation.

Joint Sealing

All transverse and longitudinal joints of the repair areas should be sealed in accordance with the agency's joint sealing practices. Joint widths will vary from repair area to repair area and may range from ¼ in. to ½ in. (6 to 13 mm) or more. This variation in joint width should be kept in mind if backer rods are used as part of the joint sealing operation.

Quality Assurance and Quality Control Requirements

The following QA/QC activities should be required for repair panel installation:

1. Granular base and bedding material compaction testing using an LWD;
2. Testing of the dowel slot grout material and the undersealing grout material for strength;
3. Testing of the dowel slot patching material for strength;
4. Testing for panel alignment; and
5. Deflection testing at the repair area transverse joints to determine joint LTE.

Summary

The guidelines presented in this chapter are based on the state of the practice and incorporate lessons learned from several demonstration and production projects. Experience in Illinois (Illinois Tollway), New York State, and New Jersey indicates that precast panels can be routinely specified for intermittent repairs of existing concrete pavements and that contractors with no previous experience with PCP systems can successfully undertake such projects.

Intermittent full-depth or whole-slab panel repairs using precast concrete panels ensures that quality concrete is used. The major causes for failure of CIP intermittent repairs (poor quality of concrete resulting from a high water–cement ratio, poor concrete consolidation, and poor curing conditions) are mitigated by using precast concrete panels.

The quality of support for the intermittent repairs needs attention, especially if the existing base is granular, as the recompaction of a granular base in small work areas is not very effective. The use of thicker granular bedding material must be avoided. As a general rule, no base or bedding material should be used that would not be allowed during the construction of CIP concrete.

CHAPTER 11

Installation of Continuous Jointed Precast Concrete Pavement Systems

General

The guidelines presented in this chapter for the installation of precast concrete panels for jointed PCP systems are based on the state of the practice and incorporate lessons learned from several demonstration and production projects. They are primarily applicable to the reconstruction of existing pavements where the existing pavement profile and geometry are to be maintained. However, these guidelines also apply to new construction and unbonded overlay applications that typically would not involve lane closure constraints. The information presented here is specific to the installation of jointed PCP (JPrCP and ICPCP) systems. Other information common to other PCP applications and installation is presented in Chapters 4, 5, and 6.

The specific guidelines presented in this section for jointed PCP systems include the following:

1. Panel installation staging and lane closures;
2. Removal of distressed concrete slab sections;
3. Base preparation;
4. Bedding placement;
5. Load transfer provisions;
6. Panel placement;
7. Dowel slot grouting and patching;
8. Panel undersealing; and
9. Surface preparation.

Overview of Panel Installation Process

An overview of a typical jointed PCP installation is summarized below:

- For large production projects, the jointed PCP installation may be carried out over several months. The installation will almost always need to be performed during the night hours, typically between 8 p.m. and 6 a.m.
- The work area for each lane closure panel installation will range from about 300 to 600 ft (91 to 183 m). This estimate is based on the number of panels planned for installation during a specific lane closure, which will also dictate the length of the existing pavement that needs to be readied for panel installation.
- The existing areas to be readied may include the following:
  - For existing pavement reconstruction, the existing concrete or asphalt pavement will need to be removed. Depending on the design requirements, all or part of the existing base may also need to be removed. The base treatment may include the following actions:
    - The base is regraded or reconstructed to the specified grade and compacted if granular.
    - The base is trimmed, and a thin granular bedding layer placed if the existing base is stabilized (asphalt treated or cement treated).
    - The base is trimmed, and a thin fast-setting bedding grout may be used as part of the elevated panel installation approach.
    - The base is consolidated (vibrated) and finished if it is an RSLCB.

    It is unlikely that a new asphalt-treated base (ATB) or cement-treated base (CTB) will be used because of construction time constraints and the need to maintain good grade control for the base. RSLCB will require additional time to allow the LCB to set before placing the panels on the freshly placed LCB.
  - For an unbonded overlay application, any needed pre-overlay treatment of the existing pavement and the AC interlayer placement will have been completed before the panel installation. For new construction, panel installation can proceed soon after base construction.
- The panel installation begins by placing a transition panel. For a continuing operation, a temporary transition panel

may need to be removed. The panel installation process proceeds as follows:
  - The first panel is placed at the designated location.
  - Each successive panel is then placed.
  - At the end of each lane closure, a temporary transition panel is placed to allow the work area to be opened to traffic the next morning.
  - At the end of the project, a permanent transition panel is used to transition from the PPCP section to the existing pavement.
- Options available for panel placement include
  - Method 1: The panel is placed directly on the finished base or bedding.
  - Method 2: The panel is set at the desired elevation using threaded setting bolts. For Method 2, the bedding needs to be provided for during the same lane closure as the panel placement.
- The load transfer features are installed during the same lane closure as the panel placement or during the next lane closure, typically the next night, depending on the design of the load transfer system.
- The finishing operations are carried out. These operations may include panel undersealing, joint sawing and sealing, and surface grinding.

A panel installation requires about 10 to 15 minutes. Typically, about 30 to 40 panels can be installed during a single nighttime lane closure. Any activity that delays the panel installation or any activity that requires additional time to complete can affect panel installation productivity for a given lane closure.

Installation Staging and Lane Closures

The accessibility to the project site influences (1) entry and exit of material-haul trucks, (2) positioning of construction-related equipment, and (3) panel delivery. Furthermore, the construction window available for the panel installation will influence the sequencing and planning of preinstallation and installation activities. Installation will usually occur during nighttime hours, and the allowable closure time will range from about 8 to 10 hours, typically starting at 8 p.m. and ending at 6 a.m. the next morning. Nighttime construction also requires on-site lighting and additional constraints concerning lane closures. All lane closures must be done in accordance with MUTCD (2009) and the agency's work zone traffic control guidelines.

The work zone requires closure of at least two lanes: the lane undergoing repairs and an additional lane for construction traffic, especially for trucks delivering the panels. If the roadway section undergoing repair has only two lanes, a full nighttime lane closure may be necessary. When more than two lanes are available, at least one lane is kept open for public traffic.

Depending on the design of the jointed PCP system, one or two lane closures may be required. For one lane closure, all activities involving existing concrete pavement removal, panel placement, load transfer provision, and undersealing are carried out during the same lane closure. For two lane closures, the existing concrete pavement removal and panel placement are carried out during the first closure, and the remaining activities are carried out during the next closure, typically the next night.

Grinding and joint sealing activities may be carried out when all repair panels have been installed and may be done a few days to a few weeks after panel installation.

Removal of Distressed Concrete Slab

The saw-cutting of the concrete pavement areas to be rehabilitated should be carried out as close as possible to the installation time of the precast panels. Saw-cuts are made the full depth of the concrete slab, and any tie bars along the affected longitudinal joints should be cut. A variety of pavement removal equipment can be used to remove the designated areas of the existing pavement. Contractors often prefer to use excavation equipment to remove the existing concrete or asphalt pavement. However, such equipment can damage a granular base, requiring more effort and time to regrade and recompact the base.

It is also important that the contractor avoid any removal technique that causes spalling or damage to any concrete pavement that is left in place.

Rehabilitation Area Dimensional Tolerances

For continuous application of PCP, the rehabilitation area dimensions must be defined accurately with respect to the width of the repair area. Most agencies require that the longitudinal joint width along the repair area perimeter not exceed about ½ in. (13 mm). The width of the repair area is typically bounded by longitudinal joints that may include a slipformed edge or a contraction longitudinal joint. In either case, it is likely that the longitudinal joint lines bounding the rehabilitation area are not parallel and may exhibit some waviness. As a result, the distance between the two longitudinal joints may vary by ±½ in. (13 mm) or more.

It is not good practice to follow the existing longitudinal joint lines for establishing the rehabilitation work area. The preferable good practice is to establish more definitive and better controlled lines for the longitudinal saw-cuts to remove the existing concrete pavement areas. It is recommended that the longitudinal saw-cuts be established to ensure a uniform width for the repair area; this may require encroaching into adjacent lanes or the shoulder area by ½ to 1 in. (13 to 25 mm) or more. This practice will ensure that the precast panels that are fabricated to standard width can easily fit into the work area and do not leave wide gaps along the longitudinal joints of the rehabilitation area. At several continuous application projects, wide gaps have resulted along the longitudinal joints or have required trimming of the width of the precast panel to ensure fit within the work area.

Base Preparation

The base is a critical design element. The base types that can be considered for jointed PCP include

1. Existing bases in good condition
   a. Granular base;
   b. ATB;
   c. CTB; and
   d. LCB.
2. New bases (if warranted by poor condition of the existing base or by design)
   a. Granular base;
   b. Cement-treated permeable base (CTPB) (or pervious concrete); and
   c. RSLCB.

New ATBs and CTBs are not considered practical choices for reconstruction applications with tight lane closures because these bases require paving equipment to place them, which would affect panel installation productivity. In addition, hot-mix AC will require additional time to cool before placement of the panel–base interface treatment and before placement of the panels.

An existing granular base will need to be reworked and regraded. Additional base material will be needed if the base grade needs to be adjusted. This situation is typical when the PPCP panels are thinner than the pavement being reconstructed, which can occur if base material is removed during removal of the existing concrete slab panels. The grading and compaction of a granular base is a time-consuming process. The base is graded manually, as shown in Figure 11.1, and may require multiple passes of a manually operated trimmer before the grade is considered acceptable. The availability of a compact auto-trimmer can greatly speed up the granular base trimming operation. The granular base should be compacted using a full-size (10-ton) roller.

On most projects constructed to date, no effort has been made to compact the granular bases to maximum density using an optimum moisture content for the granular material. In addition, no testing has been performed to ensure that the granular base has achieved maximum density. This is a serious gap in the installation process. Agencies must specify appropriate procedures for compaction of the granular bases and require that rapid compaction testing is performed on the completed bases.

The use of stone dust–like material or manufactured or river sand to achieve a smooth base surface or as filler should be carefully considered. These materials cannot be compacted well and are not structurally stable. The stone dust or the sand bedding thickness should be limited to 0.25 in. (6 mm). As a general rule, any base or bedding material that would not be allowed during the construction of CIP concrete pavement should not be allowed in JPrCP.

An existing CTB or ATB may require some trimming. In that case, a granular bedding material or an RSFF material may be used to establish a smooth grade for installing the panels. The granular bedding material thickness should be limited to 0.25 in. (6 mm). The RSFF bedding material should be at least 0.5 to 1 in. (13 to 25 mm) thick to ensure that point support conditions do not develop. RSFF should be allowed

Figure 11.1. Manual base grading.

Figure 11.2. Material being directly deposited in PPCP work areas: (left) CTPB placement during Delaware project and (right) LCB placement during California I-680 project.

to set before placing the panels over it; otherwise, the potential for damage to the bedding surface will be high.

When CTPB or RSLCB is used, the material is typically brought to the work site in ready-mix transit mixers and directly deposited in the work area, as shown in Figure 11.2. Depending on the size of the work area and the thickness of the base, six to 10 truckloads may be required per lane closure. CTPB is placed without applying any compactive effort and can be finished using laser-controlled auto-float equipment or hand screeding. RSLCB is typically brought to the site at a high slump, about 2 to 4 in. (50 to 100 mm). The higher slump allows the RSLCB to be workable enough to be screeded and finished manually. RSLCB needs to be consolidated. Typically, a vibrating screed is used to finish RSLCB. The RSFF, CTPB, and RSLCB should be allowed to set before any operations are conducted on these surfaces; otherwise, the potential for damage to the surface will be high.

The following criteria may be used to allow operation on these freshly placed cementitious bases: the earlier of attaining 100 lbf/in.^{2} (0.7 MPa) compressive strength or 2 hours after placement of the base.

Base Grade Requirements

Regardless of the base type used or the bedding material applied, the final base should be well graded to achieve a smooth surface. Base surface variation should not exceed 1/8 in. (3 mm) in a 10-ft (3-m) straightedge. Base smoothness is important and ensures that panel–base interface friction is kept as low as possible. An advantage of using precast panels is that the panel bottoms are very smooth, and minor variations or undulations in the base surface will not affect panel–base friction during the final posttensioning operations.

Load Transfer Provisions

Provision for load transfer is a critical design requirement for JPrCP. Load transfer for JPrCP can be provided as follows:

1. Using panels with the dowel slots at the slab bottom (FMC procedure). For this procedure, each panel has the bottom dowel slots along one transverse edge and dowel bars embedded along the opposite transverse edge. For continuous placement, the dowel slot side of each successive panel is placed over the dowel bars embedded in the previously placed panel.
2. Using conventional dowel slots at the surface. These dowel slots have wider mouths, about 2.5 to 3 in. (65 to 75 mm) wide at the surface, and as a result the dowel slots must be patched during the same lane closure as the one used for placing the panels. For this procedure, each panel has surface dowel slots along one transverse edge and dowel bars embedded along the opposite transverse edge. For continuous placement, the embedded dowels along the side of each successive panel are placed inside the surface slots fabricated in the previously placed panel.
3. Using narrow-mouthed dowel slots at the surface according to the procedure developed as part of the Project R05 study. This procedure is discussed in detail below. This technique allows the panels fabricated with surface dowel slots to be left in place in the repair area without immediately patching the slots. The use of the unpatched narrow-mouth surface slots does not pose any safety issues with vehicle operations. The dowels are positioned in one of the longer surface slots before panel placement, and the dowel bars are slid into the matching slot in the adjacent panel. The dowel bars are held in place, at proper alignment, using a magnetic clamp or a similar device during the patching of the slots using the DBR procedure.

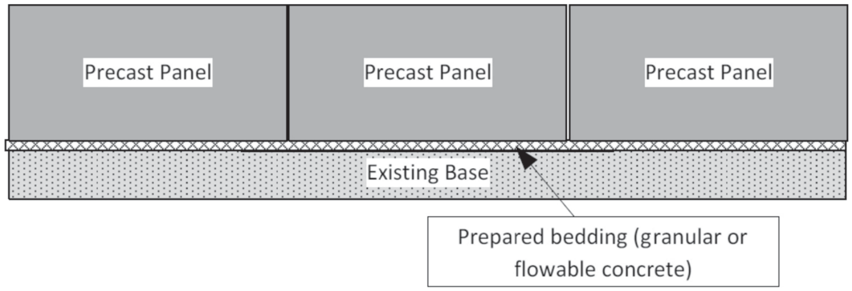


Figure 11.3. Panel placed directly on prepared bedding over existing base.

Panel Placement

Once the base (or base and bedding) is ready, the panel installation process can begin. The panel installation requires the panel delivery trucks to be positioned in the adjacent lane, next to the repair area. Two methods can be used to place the panel in the prepared repair area. These methods can be used regardless of the technique to be used for providing load transfer at the joints:

Method 1: The panel is placed directly on the finished base or bedding.
Method 2: The panel is set at the desired elevation using threaded setting bolts.

Method 1: Panel Directly Placed on Finished Base or Bedding

This is the simplest method for panel placement. The base or bedding is graded to the desired elevation. The panel is positioned so that it is centrally located within the lane that is being rehabilitated, and the dowel slots (if used) at the panel bottom or the narrow-mouth slots at the surface are matched to the dowel slots in the adjacent previously placed panel. If RSFF bedding material is used, it should be allowed to set before placing the panels over it. This panel placement technique is illustrated in Figure 11.3.

If the panels are opened to traffic before the dowel slots are grouted, shims should be used at the approach joint side of the panels to prevent forward drift of the panels under traffic.

Method 2: Panel Set Using Threaded Setting Bolts

This method also allows panels to be set at the desired elevation using precalculated panel corner elevations. A surveyor is required to monitor the setting of each panel at the specified elevation. Four symmetrically located threaded setting bolts control the elevation of the panel. Four steel plates, 6 × 6 in. and ¾ in. thick (150 × 150 × 19 mm), are positioned on the prepared base for each panel before placing the panel. The plates are positioned to coincide with the location of the setting bolts. Once all the panels are set at the specified elevation, the bedding material, typically RSFF, is used to fill the gap between the finished base and the bottom of the panels. This panel placement technique is shown in Figure 11.4, as used at New York's LaGuardia International Airport.

This technique requires fabricating threaded sleeves in the panels. The sleeves must be securely anchored in the concrete; otherwise, there is a risk that they will pop out during the panel-setting operation.

The setting bolts can be removed from the panels as soon as the RSFF material has attained a compressive strength of 50 lbf/in.^{2} (345 kPa).

Panel Connection Sequence

The panel placement sequence depends on which of the three main JPrCP systems is used.

For FMC's Super-Slab system, the panels are laid so that at each transverse joint, one panel side includes embedded dowel bars, and the next panel with the dowel slots is positioned so that the slots enclose the embedded dowel bars while

Figure 11.4. Panel placement using setting bolts at New York's LaGuardia International Airport.

maintaining the specified joint gap (width). Each panel is set to a theoretical leading-edge mark previously laid out by a surveyor so that proper joint widths are maintained and the entire assembly does not creep long or short. The marks are set to a theoretical layout length such that the maximum joint width is not exceeded when the shortest possible panel, as permitted by allowable tolerance specification, is placed. Since joint widths between panels placed in this manner may vary from 0 to ½ in. (0 to 13 mm) maximum because of panel fabrication tolerances, the final panel may need to be trimmed by sawing full depth to allow for a uniform joint width of ½ in. (13 mm). This procedure is particularly important when multiple lanes of new precast pavement are placed side by side.

For a system that incorporates dowel slots at the surface, the panels are laid so that at each transverse joint one panel side includes the surface slots, and the next panel with the embedded dowel bars is positioned so that the dowel bars fit into the dowel slots while maintaining the specified joint gap (width).

For a system using narrow-mouth surface slots, the panels are placed next to each other so that the matching slots line up.

During panel placement, the following issues should be considered:

1. Panels should be handled carefully to minimize any impact damage at the corners and along the sides of the panels.
2. For single-lane application, a joint gap former may be used to ensure that the transverse joints will be uniform in width and panel creep does not develop. Panel creep can create difficulties at the end of the repair area for a given lane closure. Since the panel length may vary from panel to panel because of panel fabrication tolerances, the final panel may need to be trimmed by sawing full depth to allow for a uniform joint width of ½ in. (13 mm).
3. For the FMC system, the joint face with the embedded dowel bars should be coated with a debonding material to prevent the dowel slot grout from bonding to that joint face.
4. The adjacent panels must be aligned well to ensure that the embedded dowels are positioned with the center portion of each matching slot.

Activities After Panel Installation

The finishing-up activities to be conducted after the repair panel is installed include the following:

1. Load transfer–related activities;
2. Panel undersealing;
3. Pavement surface grinding; and
4. Joint sealing.

Load Transfer–Related Activities

Load transfer–related activities relate primarily to patching or grouting the dowel slots.

For the FMC system, the rapid-setting dowel slot grout is poured through grout ports into each slot, as shown in Figure 10.7. The grout also has to be poured into the panel's perimeter joint gap until the grout material is at the top of the joints. Using this system, a joint gap does not exist around the perimeter of the panel. This technique requires use of a bond-breaking material on the joint faces with embedded dowel bars to prevent the dowel grout material from bonding to these faces. During the joint sawing for the sealing reservoir, care must be taken to align the saw-cut along the embedded dowel beside of the joint; otherwise, spalling of the dowel grout material will result, and the joint sealant will be ineffective.

For the systems with conventional dowel slots at the surface, the DBR process, as shown in Figure 10.8, is used to patch the dowel slots. Care should be taken that no patching material flows into the joint gap.

For the new system with narrow-mouth surface slots, the following steps need to be carried out, either during the same lane closure as the panel placement or during the next lane closure:

1. The dowels are positioned in the longer surface slots before panel placement.
2. The dowel bars are slid into the matching slots in the adjacent panel.
3. The dowel bars are held in place, at proper alignment, using a magnetic clamp or a similar device.
4. The panel slots are patched using the DBR procedure. The dowel slot sides must be cleaned of dirt, dust, and debris before applying the patching material. No patching material should be allowed to flow into the joint gap.

Whether a grout material or a rapid-setting patching material is used for the dowel slots, the material should attain the required strength, typically 2,500 lbf/in.^{2} (17.2 MPa), before opening the repair area to traffic.

The grout material, dowel patching material, or other repair material can be used to fill the lift insert holes and to repair any surface damage to the panel.

Panel Undersealing

Regardless of the base type or the bedding material used, it is still necessary to underseal the panel area. Undersealing helps fill any voids that may exist under the panel and ensure full contact between the panel and the base or bedding material. Undersealing does not strengthen the support: weak supports will remain weak. Undersealing helps reduce and possibly eliminate voids under the panel, thereby reducing any moisture-related issues in the base and bedding material.

The undersealing material is typically a rapid-setting cementitious grout that will attain a compressive strength of 500 lbf/in.^{2} (3.4 MPa) at the time of opening to traffic. The grout can be a generic cementitious grout or a proprietary material. When the grout is pumped, the grout flow rate should be within the range specified. The grout is typically mixed in a batch pump in batches and pumped continuously from a grout hopper.

Shallow channels, about 0.25 in. (6 mm) deep and 1 to 2 in. (25 to 50 mm) wide, at the underside of the panels may be used to distribute the grout. Certain features of the underside channels may be proprietary. For undersealing to be effective, it is necessary to use foam strips along the bottom perimeter of each panel to prevent the grout from flowing beyond the repair area. The undersealing grout ports should be filled with the undersealing grout up to middepth. The rest of the port depth should be filled with a higher-strength rapid-setting patching material.

Opening to Traffic

The repair areas can be opened to traffic as follows:

1. At the end of the first lane closure
   a. When the FMC system with slots at the panel bottom is used or narrow-mouth surface slots are used, the repair areas can be opened to traffic even if the slots have not been grouted or patched.
   b. When conventional DBR slots are used at the surface, the completed repair areas should be opened to traffic only after the grout for dowels and tie bars (if applicable) and the bedding grout have reached the minimum acceptable strength.
2. At the end of the next lane closure after the FMC panels are grouted or the narrow-mouth slots are patched and the panels are undersealed.

Surface Grinding

Most highway agencies allow up to a 0.25-in. (6-mm) elevation difference at the joint between adjacent panels. If the elevation difference is larger, the joint areas may be ground to bring the repair area under compliance. However, most agencies typically require that the full length of the pavement undergoing rehabilitation be ground to ensure overall smoothness and uniform surface texture. As discussed in the design section, it is good practice to incorporate about 0.5 in. (13 mm) extra thickness in the panels to accommodate initial and future grinding of the PCP surface.

Joint Sealing

All transverse and longitudinal joints of the rehabilitated section should be sealed in accordance with the agency's joint sealing practices. Joint widths will vary and may range from 0.25 to 0.5 in. or more. This variation in width should be kept in mind if backer rods are used as part of the joint sealing operation.

For the FMC system, it is important that the saw-cut for the sealant reservoir be aligned with the side of the panel with embedded dowels. If the saw-cut is aligned with the side of the panel with the slots, joint sealing will not be effective, and the dowel slot grout material will spall off at the surface of the joint.

Quality Assurance and Quality Control Requirements

The following QA/QC activities should be required for repair panel installation:

1. Granular base and bedding material compaction testing using an LWD;
2. Testing of the dowel slot grout material and the undersealing grout material for strength;
3. Testing of the dowel slot patching material for strength;
4. Testing for panel alignment; and
5. Deflection testing at the repair area transverse joints to determine joint LTE.

Summary

This chapter provides guidelines for the installation of precast concrete panels for jointed PCP systems based on the state of the practice and incorporates lessons learned from several demonstration and production projects. Experience in several U.S. states indicates that precast panels can be routinely specified for rehabilitation of existing asphalt and concrete pavements and that contractors with no previous experience with PCP systems can successfully undertake such projects.

As with intermittent repairs using precast panels, the quality of support for continuous PCP applications also needs attention, especially if the existing base is granular. To date, little attention has been paid to ensuring that the granular base is adequately compacted and that the thickness of the granular bedding layer is not too large. The compaction of disturbed or new granular base material needs to be carefully controlled, and the use of thicker granular bedding material must be avoided. As a general rule, no base or bedding material should be used that would not be allowed during the construction of CIP concrete.

CHAPTER 12

Installation of Continuous Precast Prestressed Concrete Pavement Systems

General

The guidelines presented in this chapter for the installation of precast concrete panels for PPCP systems are based on the state of the practice and incorporate lessons learned from several demonstration and production projects. They are primarily applicable to the reconstruction of existing pavements where the existing pavement profile and geometry are to be maintained. However, the guidelines also apply to new construction and unbonded overlay applications that typically would not involve lane closure constraints. The information presented in this chapter is specific to the installation of PPCP systems. Other information common to other PCP applications and installation is presented in Chapters 4 through 7. Chapter 11 also presents information that is common to all continuous PCP systems.

The guidelines presented in this chapter include the following:

1. Panel–base interface treatment;
2. Panel placement;
3. Temporary posttensioning;
4. Final posttensioning;
5. Expansion joint panel installation;
6. Temporary transition panel installation;
7. Subsealing and grouting;
8. Anchoring; and
9. Surface preparation.

Overview of Panel Installation Process

An overview of a typical PPCP installation is summarized below:

- For large production projects, PPCP installation may be carried out over several months. The installation will almost always need to be performed during the night hours, typically between 8 p.m. and 6 a.m.
- The work area for each lane closure panel installation will range from about 200 to 400 ft (61 to 122 m). This estimate is based on the number of panels planned for installation during a specific lane closure, which will also dictate the length of the existing pavement that needs to be readied for panel installation.
- The existing areas to be readied may include the following:
  - For existing pavement reconstruction, the existing concrete or asphalt pavement will need to be removed. Depending on the design requirements, all or part of the existing base may also need to be removed. The base treatment may include the following actions:
    - The base is regraded or reconstructed to the specified grade and compacted if granular.
    - The base is trimmed and a thin granular bedding layer is placed if the existing base is stabilized (ATB or CTB).
    - The base is consolidated and finished if it is an RSLCB.

    It is unlikely that a new ATB or CTB will be used because of construction time constraints and the need to maintain good grade control for the base. RSLCB will require additional time to allow the freshly placed LCB to set before placing the panels.
  - For an unbonded overlay application, any needed pre-overlay treatment of the existing pavement and the AC interlayer placement will have been completed before the panel installation. Panel installation can proceed soon after the placement of the panel–base interface treatment, which typically consists of 6-mil-thick polyethylene sheet to reduce panel–base friction. For new construction, panel installation can proceed soon after base construction and placement of the panel–base interface treatment.
- As soon as the work area is ready to receive the panels, the panel–base interface treatment is applied. As indicated, this involves placing a 6-mil polyethylene sheet or other

equivalent material over the full width and full length of the work area.

- The panel installation begins by placing a transition panel or an expansion joint panel. For a continuing operation, a temporary transition panel may need to be removed. The panel installation process proceeds as follows:
  - The first panel is installed at the designated location.
  - Each successive panel is then installed and connected to the previously placed panel using temporary posttensioning.
  - When all panels for a given section are placed, including the end panels, final posttensioning is carried out. Several alternatives are available for the final posttensioning:
    - Central panel prestressing;
    - End panel prestressing; and
    - End prestressing.
  - The end prestressing is performed from the end panel face and requires about a 4-ft (1.2-m) gap to allow for the posttensioning operation. A short panel is used at these 4-ft gaps. Expansion joints are placed at one or both sides of the 4-ft panels. For the central and end panel prestressing, slots accessible from the panel surface are used to perform the posttensioning operations. If all panels for a given section cannot be placed during a lane closure, a temporary transition panel is placed to allow the work area to be opened to traffic the next morning.
  - At the end of the project, a permanent transition panel is used to transition from the PPCP section to the existing pavement.
- Once a section is completed, follow-up activities that need to be completed during the same closure or successive closures include the following:
  - Panel undersealing to ensure full contact between the panel and base;
  - Tendon duct grouting;
  - Dowel bar slot grouting or patching;
  - Anchorage installation in the section central area;
  - Joint sealing; and
  - Surface grinding, as specified or as necessary.

A panel installation requires about 12 to 15 minutes. Any activity that delays the panel installation or any activity that requires additional time to complete can affect panel installation productivity for a given lane closure.

Panel–Base Interface

A panel–base interface treatment is necessary to reduce panel–base interface friction, which needs to be as low as possible. This is typically achieved by using a 6-mil-thick, low-friction polyethylene sheet (film) (ASTM D2103) or a nonwoven geotextile fabric. When an LCB is used, a 3- to 5-mm geotextile fabric should be considered. In addition to providing a low-friction interface, the fabric also provides some cushioning that helps overcome minor undulations at the LCB surface and reduces the impact of panel curling. The polyethylene sheet or geotextile fabric should be placed over the full width and full length of the area being worked on, as shown in Figure 12.1. These materials are available in rolls and in a range of widths. If the materials need to be lapped, a minimum 2-ft (0.6-m) overlap should be used in the longitudinal direction and a minimum 4-ft (1.2-m) overlap should be used in the transverse direction.

The friction-reducing membrane should be held in place without folds or ridges, and its edges must be held down against wind.

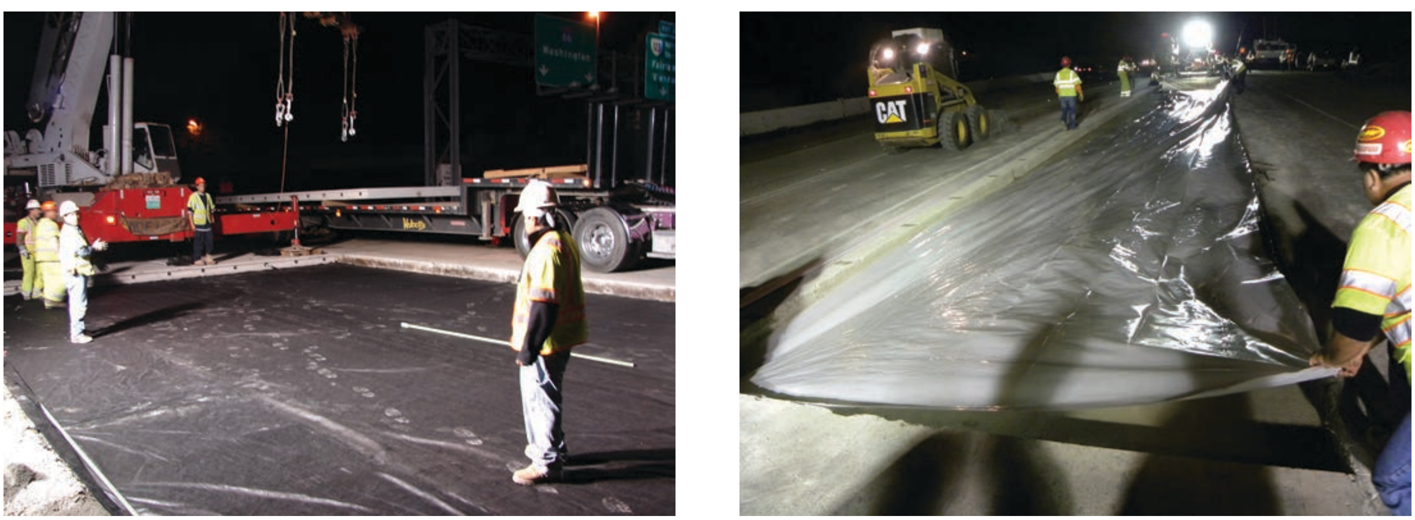


Figure 12.1. Placement of polyethylene sheet or geotextile fabric.

Figure 12.2. Panel placement.

Panel Placement

The panel placement operation includes lifting the panels from the truck and positioning and posttensioning the panels. These operations are described in detail below.

Lifting the panel from the truck is typically accomplished using a four-point lifting arrangement, as discussed above and as shown in Figure 12.2. This operation needs to be done quickly and should not require more that 2 to 3 minutes per panel.

The first panel should be (1) positioned as close to the point of placement as possible and (2) placed over the base without damaging the friction-reducing membrane. The first panel must be properly aligned. Errors in panel alignment can build up with successive panels. Therefore, each panel needs to be positioned and aligned carefully. To facilitate the placement process, the contractor should hang the slab from the crane such that is as parallel as possible to the grade on which the panel is to be placed. This can be accomplished by using lifting cables that can be varied in length as required.

The successive panels are installed one at a time using the following sequence:

1. Position the panel ahead of the previously placed panel.
2. Apply epoxy along the transverse keyway joint face of the previously placed panel, as shown in Figure 12.3. Care should be taken not to place epoxy in the tendon ducts. The epoxy should be putty-like in consistency and should be spread liberally within the groove portion to ensure that the middle tongue and groove portions are fully bonded, without leaving a gap, as shown in Figure 12.3. When the full depth of the keyway is not bonded tightly, the intermediate joints are not fully effective in carrying traffic loads. The use of a double-groove keyway detail eliminates this concern.
3. Thread two tendons to apply temporary posttensioning to bring the new panel in tight contact with the previously placed panel. The tendons may be strands or threaded bars per design requirements, as discussed below. The two temporary posttensioning tendons are located symmetrically about one-quarter to one-third point from each corner of the panel. The use of the threaded bars requires the use of a larger size duct.
4. Apply a duct-sealing treatment to ensure a tight seal around each connected duct between adjacent panels. This may include a gasket at each tendon duct (as shown in Figure 12.4), a heat-shrink wrap, or a commercially available gasket, seal, or connector device.

Figure 12.3. Applying epoxy along the transverse keyway joint face.

Figure 12.4. Gasket placed on tendon duct.

5. Connect adjacent panels by means of temporary posttensioning. The two tendons are stressed in tandem using two jacks. Care must be exercised to ensure that the new panel is correctly aligned with respect to the previously placed panel and with respect to the lane geometry. The lane geometry dictates the final positioning of the new panel. Because slab dimensions may vary by virtue of allowable fabrication tolerances, it may be necessary to leave the intermediate joints partially open to maintain panel alignment. Partially opened joints must be immediately filled with epoxy to retain the integrity of the posttensioning process. For temporary posttensioning to hold adjacent panels tightly together while the epoxy sets, the tendon load applied should correspond to an average panel cross-sectional prestress level of about 50 $lbf/in.^2$ (340 kPa).

   The temporary posttensioning should provide a very tight intermediate keyway joint, as shown in Figure 12.5. If the adjacent panels cannot be aligned well, several attempts may be needed to obtain a tight intermediate keyway joint, and in some cases, only the bottom faces may be in contact. These repeated attempts can affect the panel installation production rate and the effectiveness of the intermediate joints. The double-groove keyway with a narrow opening at the surface overcomes the panel alignment difficulties as only the bottom faces of the keyways need to be in contact. The double-groove keyway also ensures proper load transfer and connectivity at the intermediate joints.
6. Once all panels in a section are installed, the section is ready for final posttensioning. For the final posttensioning,

Figure 12.5. Intermediate keyway joint.

the tendons are pushed full length in each duct and anchored at the dead-end anchorage location. The panels should be stressed from alternate ends to more uniformly distribute the prestress along the length of the section. Final posttensioning can be performed using the following three techniques:

- Central panel posttensioning: Posttensioning is performed using pockets in the central panels, as illustrated in Figure 2.9a. A special coupler is used to connect the tendons from each of the two dead-end anchors.
- Joint panel posttensioning: Posttensioning is performed using pockets in the joint panels, as illustrated in Figure 2.9b. The stressing is done only from one end of the tendon. A dead-end anchorage is used at the other end of the tendon.
- End (joint face) posttensioning: Posttensioning is performed at the joint face, as shown in Figure 2.9c. This is the simplest approach for posttensioning as the panel fabrication is simplified and stressing pocket grouting is not necessary. This approach requires a gap panel (filler panel) that is typically 4 ft (1.2 m) long and may have provisions for a single expansion joint or two expansion joints, one on each side of the gap slab. The use of a single expansion joint is recommended to reduce future joint maintenance needs.

7. During the posttensioning operation, tendon elongation needs to be measured to an accuracy of ⅛ in. (3 mm) and compared with a theoretically computed elongation. The measured elongation should be within 7% of the calculated elongation, as indicated in the shop drawings. If there is a discrepancy exceeding 7%, additional tendons should not be stressed until the discrepancy is resolved and corrected. Some causes of the tendon elongation discrepancy are listed below:
   - Inaccurate measurement;
   - Improper stressing procedure;
   - Malfunctioning jack; and
   - Excessive friction in the duct, possibly due to misaligned ducts in adjacent panels.

Finishing Activities

This section describes the finishing activities that can be initiated once the posttensioning of a section is completed.

Tendon Duct Grouting

Duct grouting, using the approved grout material and equipment, should be carried out as soon as possible after the final posttensioning of the tendons is accomplished, but no later than 7 days after the final posttensioning of the tendons. The grouting operation should be supervised or performed by a person who is certified under the American Segmental Bridge Institute's Grouting Certification Training Program (PTI 2006).

The grouting is done continuously (uninterrupted) from the low end of the PTSection until the grout completely fills the duct. Grouting of each tendon must be completed in one operation. The optimum rate of grouting will depend on the type of grout, the size of the duct, the number of tendons inside the duct, and grouting equipment (PTI 2006).

Grouting may be done using a grout port near the end anchorage or a port in the end anchorage assembly. When grout ports are used, the filling of the duct enclosure is monitored using grout ports spaced at regular intervals along the length of the PTSection. When end anchorage ports are used, grout flow out of the uphill end anchorage grout port indicates that the duct has been completely filled with grout.

PPCP Section Anchoring

An anchoring system is used to secure the center of each PPCP section in place so that each section only contracts and expands relative to its center. The anchoring system prevents the sliding of the PPCP sections, which may result in excessive closure in some expansion joints and excessive opening at others. The midslab anchors may be installed before or after the posttensioning process. However, the anchors should be installed before any diamond grinding to correct the surface profile.

The anchors are installed in the middle portion of the PPCP sections: at the midportion of a long central panel or in two adjacent short panels. Five anchors should be used for each 12-ft (3.7-m) width of the panel. If the panels are 20 ft (6.1 m) or longer, the anchors should be installed in the middle portion of the central panel and staggered, as shown in Figure 12.6. For shorter panels, the anchors should be installed in the two central panels and staggered, as shown in Figure 12.7.

The anchors use No. 8 deformed bars, about 30 in. (762 mm) long, placed in 3-in. (75-mm)-diameter holes that are cast in the panel or cored through the panel and bored about 2 ft (610 mm) into the base, subbase, or subgrade, as shown in Figure 12.8. The deformed bars are positioned in the hole

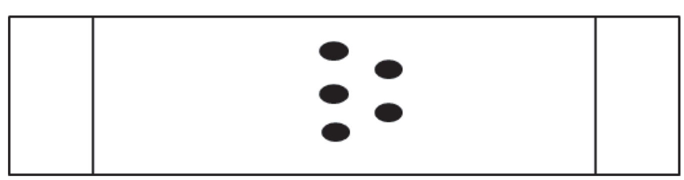


Figure 12.6. Anchor locations in a longer central panel.

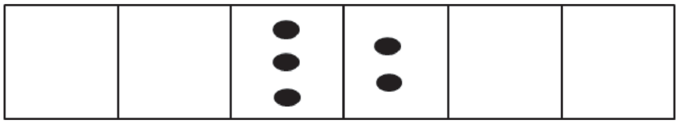


Figure 12.7. Anchor locations in shorter central panels.

until the bar top is at about midpanel location. The hole is then filled with a high-strength, rapid-setting cementitious grout material.

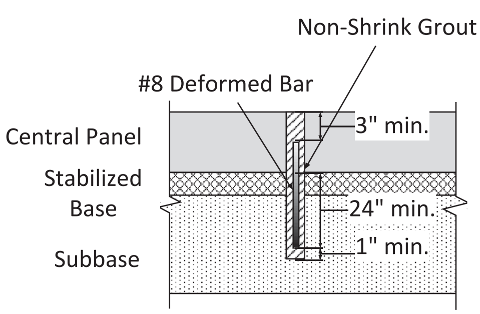
Panel Undersealing

Regardless of the base type or the bedding material used, it is still necessary to underseal the panels. Undersealing helps fill any voids that may exist under the panels and ensure full contact between the panels and the base and bedding material. Undersealing does not strengthen the support: weak supports will remain weak. Undersealing helps reduce and possibly eliminate voids under the panels, thereby reducing any moisture-related issues in the base and bedding material.

The undersealing material is typically a rapid-setting cementitious grout that will attain a compressive strength of 500 lbf/in.^{2} (3.4 MPa) at the time of opening to traffic. The grout can be a generic cementitious grout or a proprietary material. When the grout is pumped, the grout flow rate should be within the range specified. The grout is typically mixed in a batch pump in batches and pumped continuously from a grout hopper. The undersealing grout ports should be filled with the undersealing grout up to middepth. The rest of the port depth should be filled with a higher-strength rapid-setting patching material.

Joint Sealing

All longitudinal joints of the rehabilitated section should be sealed in accordance with the agency's longitudinal joint sealing practices. Longitudinal joint widths will vary and may range from 0.25 in. to 0.5 in. or more. The transverse expansion joints should be sealed as specified in the plans. Typically, the transverse expansion joints will be sealed using appropriately sized compression seals.



Source: Merritt et al. 2008.

Figure 12.8. Anchor detail for the Missouri I-57 PPCP project.

Surface Treatment

Most PPCP projects require surface grinding because of high-speed-traffic use. Surface grinding serves two purposes: it ensures a smooth surface and results in a surface texture that has the desirable friction characteristics. As discussed in the design section, it is good practice to incorporate about 0.5 in. (13 mm) extra thickness in the panels to accommodate initial and future grinding of the PCP surface.

Opening to Traffic

The primary warrant for use of PCP technology is that work can be accomplished during short nighttime lane closures and that the roadway can be opened to traffic the following morning. Depending on specific project logistics and PPCP design, it is likely that only a partial section of the PPCP may be installed during any nighttime lane closure. As a result, full posttensioning of the installed partial PPCP section may not be achieved. However, the temporary posttensioning of the PPCP allows the installed panels to be interconnected, especially when the threaded bar system is used for the temporary posttensioning. If strands are used for temporary posttensioning, the strands are required to be pulled out or be cut and left in place in case of emergency stoppage of work. A temporary transition panel is used to transition to the existing pavement at the end of a given lane closure if the PPCP installation in any work area is not complete. A permanent transition panel is used when the installation is completed.

Quality Assurance and Quality Control Considerations

The following QA/QC activities should be required for repair panel installation:

1. Granular base and bedding material compaction testing using an LWD;
2. Prestressing system checks
   a. Applied strand load
   b. Tendon elongation
   c. Effective prestress at the midpoint of the PTSection at the completion of posttensioning of a PTSection;
3. Testing of the tendon and the undersealing grout material for strength;

4. Testing of the dowel slot patching material for strength;
5. Testing for panel alignment; and
6. Deflection testing at the repair area transverse joints to determine joint LTE.

Summary

This chapter provides guidelines for the installation of precast concrete panels for PPCP systems based on the state of the practice and incorporates lessons learned from several demonstration and production projects. Experience in several U.S. states indicates that PPCP systems can be routinely specified for rehabilitation of existing pavements and that contractors with no previous experience with PCP systems can successfully undertake such projects. A successful PPCP project requires a qualified prestressing subcontractor, and a partnering relationship must be established between the general contractor, the prestressing subcontractor, and the precaster to ensure that the prestressing features of the PPCP are optimized to facilitate panel production and panel installation.

CHAPTER 13

Maintenance, Repair, and Rehabilitation of Rigid Modular Pavement Systems

General

The use of PCP is of relatively recent origin, and the PCP projects constructed to date have not been in service long enough to exhibit the full range of distresses that eventually will characterize the performance of this type of pavement. Compared with CIP concrete pavements, PCPs inherently incorporate better quality concrete, and the installation process is better controlled, so the development of distresses can be expected to occur at a slower pace; some of the common types of concrete pavement distresses may never develop. Still, it can be expected that PCPs will develop some of the distresses that are common for CIP concrete pavements, and in general, the maintenance, repair, and rehabilitation (MRR) of PCPs can be expected follow the established procedures for CIP concrete pavements.

A significant advantage of PCP is that PCPs do not experience early-age failures caused by construction-related issues such as late or shallow joint sawing, poor curing, and weather-related impacts on concrete. Although a few PCP projects have exhibited early distress, most instances are explainable and generally involve poor design details or poor construction processes. These distresses should be viewed as necessary learning steps in developing new technology.

The PCP distresses that require treatment can be classified as either distresses that develop during panel installation or distresses that develop under service conditions.

Distresses that may develop during panel installation include the following:

1. Panel edge or corner spalling; and
2. Panel cracking.

Distresses that may develop during service may include the following:

1. Joint sealant failure;
2. Joint or slot patch spalling;
3. Panel cracking;
4. Joint faulting;
5. Pumping and erosion under slab panels;
6. Poor ride quality; and
7. Surface texture loss.

The potential distresses for PCPs are similar to distresses that may develop in CIP concrete pavements, and it is necessary that treatment of these distresses, if they develop, be addressed in a timely and proactive manner to ensure that the structural integrity and functional performance of the PCP are not compromised. A warrant for use of PCPs is long-term service without requiring major future lane closures to maintain and rehabilitate these pavements. Timely treatment of PCP distresses will ensure long-term service without major lane closures for repair and rehabilitation.

The MRR of concrete pavements incorporates well-established practices, and most highway agencies have developed standard procedures for addressing these needs. In addition, several guideline documents have been developed that provide comprehensive guidance on MRR of concrete pavements (Smith et al. 2008). All such guidance is directly applicable to MRR of PCPs. Typical guidelines for MRR of concrete pavements include the following:

1. Concrete pavement evaluation techniques
   a. Distress surveys;
   b. Drainage surveys;
   c. Deflection testing;
   d. Profile testing;
   e. Surface texture testing; and
   f. Coring and boring.
2. MRR techniques
   a. Joint resealing;
   b. Partial-depth repairs;
   c. Full-depth, full-panel repairs;
   d. Slab undersealing
      - Slab stabilization
      - Slab jacking;

e. Load transfer restoration (LTR) at joints using DBR;
f. Grinding; and
g. Overlay.

MRR Considerations for Precast Concrete Pavements

Current MRR practices for CIP concrete pavements can be directly adopted for MRR of PCPs as the needs arise and specific distresses develop during installation and under service conditions. The need for MRR for PCPs is expected to be much less than that for CIP concrete pavements because of the better inherent durability of PCPs. This section discusses specific considerations that must be made when considering MRR for PCPs.

Before any MRR activity is initiated, the specific causes of the distress should be established and corrected. Otherwise, it is likely that the treatment being applied will not be successful or will be short lived.

The lane closure requirements applicable to the installation of PCP systems also apply for correcting any distress in these systems.

Joint Resealing

Well-maintained and effective joint sealing serves two purposes: (1) it minimizes water infiltration (thereby reducing distresses such as pumping and faulting), and (2) it prevents the intrusion of incompressibles into the joints (thereby reducing distresses such as joint spalling and blowups). Joint sealing practices for JCPs are in a state of flux in the United States. Several highway agencies no longer require joint sealing when single-cut joint sawing is used. Many agencies continue to require joint sealing and conduct joint resealing on an as-needed basis. Because joint resealing requires joint refacing, frequent joint resealing can lead to a wider joint mouth and less-long-lasting joint sealing.

If joint sealing is required for repair or jointed PCP applications, joint resealing should be performed as part of the MRR of the pavement itself. Joint resealing should be performed when the existing sealant material is no longer performing its intended function, as indicated by missing or debonded sealants or sealed joints that contain incompressibles. Considerations for PCP joint resealing include the following:

1. For applications using the FMC system, the joints are completely filled with a grout material during panel installation, and a single-cut saw-cut is made for joint sealing. Joint resealing can then follow conventional joint resealing practices.
2. For applications using dowel slots at the surface, the joint gap may range from 0.25 to 0.5 in. (6 to 13 mm) in width and may be larger in some cases. For such cases, it may be possible to manage only one resealing cycle.

Partial-Depth Repairs

Partial-depth repairs address surface defects and shallow joint spalling. They are an alternative to FDRs in areas where slab deterioration is located primarily in the upper one-third of the slab and where the existing load transfer devices (if present) are still functional. Partial-depth repairs restore structural integrity to the pavement and improve its overall ride quality.

For jointed PCP and PPCP systems, partial-depth patching to treat spalling is similar to that for CIP concrete pavements, except that PCP panels incorporate reinforcing steel within the top third of the panel. As a result, it would be necessary to cut through the steel or remove the unsound concrete around it when removing the distressed areas of the spalled concrete.

Full-Depth, Full-Panel Repairs

FDRs extend through the full thickness of the concrete slab (panel) and are used to restore the rideability of the pavement, prevent further deterioration of distressed areas, or prepare the pavement for an overlay.

Full-depth patching of PCP panels should be carried out in accordance with the practices discussed in this report for intermittent repairs using precast panels.

Slab Undersealing

Slab undersealing may be used for two purposes: slab stabilization and slab jacking. Slab stabilization is the pressurized insertion of a flowable material beneath a concrete slab. The purpose of slab stabilization is not to lift the slab, but rather to fill voids beneath the slab so that deflections under truck loading are reduced and, consequently, deflection-related distresses such as pumping or faulting are prevented or minimized. In contrast, slab jacking is used expressly to lift the slab to the desired elevation if the slab has experienced settlement.

For repair or jointed PCP applications, slab stabilization should be performed when there are indications of loss of support under the panels as evidenced by pumping or deflection testing. The grout ports used for the initial undersealing may be reused, or new grout ports may be drilled. The grout material may be a cementitious grout or polyurethane.

Although slab jacking is not common for highway applications, it should be considered for lifting repair panels that have settled and to reestablish a smooth profile. This is accomplished through the pressurized injection of a grout material beneath the slab and careful monitoring of the lift at different insertion holes until the desired profile is obtained. The grout material may be a cementitious grout or polyurethane. Slightly stiffer cementitious grouts than those used for slab stabilization are required for slab jacking. During slab jacking, the stringline method is typically used to control slab lift. Careful monitoring of slab lift is essential to minimize the development of slab stresses. As indicated in this report, many repair applications have used thick bedding material or incorporated disturbed existing granular material that is not adequately compacted before panel placement. It is likely that under heavy truck traffic, such repairs may exhibit panel settlement. It is important to implement a slab jacking program as soon as there is evidence of slab settlement.

Load Transfer Restoration at Joints

As discussed in this report, LTR refers to the placement of load transfer devices across joints or cracks in an existing JCP, typically using the DBR technique. This increases the transfer of loads across the discontinuities, thereby reducing pavement deflections and subsequent pumping, faulting, and corner breaks.

For repair and jointed PCP applications, it is not likely that any LTR will be necessary at transverse joints or cracking that may develop. Good load transfer across joints is one of the primary requirements for jointed PCP applications. It is also unlikely that any LTR will be necessary at any midpanel cracking, because the midpanel cracking that may develop is expected to remain tight as a result of panel reinforcement, which allows good aggregate interlock to develop.

For PPCP applications, LTR may be considered for restoration of LTE across poorly performing intermediate transverse joints that incorporate keyways. This is expected to be an uncommon situation as well-installed PPCP systems should have well-performing intermediate transverse joints. However, if the LTR technique is to be used, then the DBR technique may be considered. Use of this technique will require sawing through the top layer of the reinforcing steel or the pretensioning tendons, as applicable.

Grinding

Diamond grinding is the removal of a thin (generally about 0.25 in. [6 mm]) layer of concrete from the surface of the concrete pavement. Sawing is accomplished using special equipment outfitted with a series of closely spaced diamond saw blades. Major applications for diamond grinding are to remove surface irregularities (most commonly joint faulting or joint elevation differences), restore a smooth-riding surface, increase pavement surface friction, and reduce pavement noise.

For PCP applications, diamond grinding is typically performed at the time of panel installation to eliminate any installation-related joint elevation differences and to provide good (as specified) pavement surface smoothness. Most new concrete pavement designs incorporate additional thickness to allow for at least two cycles of grinding at an interval of about 12 to 15 years. The design of PCPs should incorporate such additional thickness, typically about ½ in. (13 mm) more than required to meet structural needs. The future grinding of the extra thickness should be accounted for when designing the layout of the panel reinforcement. As necessary, diamond grinding of PCPs should be performed to restore smoothness and surface texture.

Overlay Applications

PCPs can be considered for overlay treatment in a manner similar to that for CIP concrete pavement. Both AC and unbonded concrete overlays can be considered. Bonded concrete overlays are not recommended for jointed PCP systems because of the difficulty in matching the joint width in the bonded concrete overlay with the actual joint width of the PCP system.

The decision-making process for selecting the overlay type and the design of the overlay should follow established highway agency procedures and protocols.

Timing of PCP MRR

The timing for corrective work on PCP systems should be based on the same considerations typically used for conducting corrective work on CIP concrete pavements. User safety and timely corrective work should be key factors in determining the timing of specific corrective work.

Summary

The use of PCP is of relatively recent origin, and the PCP projects constructed to date have not exhibited the range of distresses that a pavement would experience during its service life. PCPs can be expected to behave similarly to CIP concrete pavements and are likely to develop some of the distresses that are common for such pavements. However, because PCPs inherently incorporate better-quality concrete and the installation process is better controlled, the development of distress is expected to be at a slower pace, and some of the common distresses may never develop. In any case, the MRR of PCPs will generally follow the established MRR procedures for CIP concrete pavements.

CHAPTER 14

New Features and New Applications

General

As discussed in this report, the most significant application of PCP technology in the United States is for rapid repair and rehabilitation of existing highway pavement facilities where it is difficult to maintain extended lane closures because of the high volume of traffic or because alternate routes are not readily available to carry diverted traffic. PCP technology has been successfully applied in the United States to meet the following needs:

1. Intermittent repairs of JCPs;
2. Rehabilitation of asphalt and concrete pavements (removal of existing pavement and replacement with PCP systems)
   a. Mainline pavements
   b. Freeway ramps;
3. Use of PCP systems in unbonded overlay applications (demonstration project, at the time this was written, was planned for construction in Florida in 2011);
4. Rehabilitation of bridge approach slabs;
5. Repair and rehabilitation of busy urban highways and intersections; and
6. Rehabilitation of toll plaza pavements.

For the above applications, PCP technology has been used or will be used to achieve rapid repair or rehabilitation, using short lane closures, mostly at night. A few demonstration-project PCP applications have been installed during the daytime using full lane closures. However, such applications of PCP technology for production use are considered exceptions and not the rule. An inherent assumption or requirement for all PCP applications is that these applications will be long lasting. On-site system design changes and construction expediencies in the name of innovation should be reviewed carefully by agencies to ensure that long-term system performance will not be compromised.

In addition to highway applications of PCP technology, a limited amount of work has been performed in the United States to study the application of PCP technology for repair and rehabilitation of civilian and military airport pavement facilities.

Several other countries have also been involved in the implementation of PCP technologies for repair and rehabilitation of existing pavement facilities and for constructing new facilities. The following summarizes PCP technology use in other countries:

1. Canada's PCP use is similar to that in the United States.
2. Russia was one of the earliest production users of PCP technology. Currently, there is limited use for airfield applications. Precast panels are typically prestressed.
3. Japan was also involved in early production use of PCP technology and uses PCP systems for highway, airfield, container port, tunnel, and urban street applications. Precast panels are typically prestressed.
4. Indonesia is a recent user of PCP technology, with large-scale use of PPCP for toll highway facilities. Applications of PCP technology to urban pavement rehabilitation are under study.
5. The Netherlands has recently developed the pier-supported ModieSlab system, which is currently being investigated for on-grade applications.
6. France recently developed a removable PCP system for urban street applications.

A range of possibilities exists for additional applications of PCP technology in the United States, including

1. Rapid rehabilitation of tunnel pavements using the PPCP system or using the JPrCP system with thinner prestressed panels;
2. Use of the thinner PPCP systems or JPrCP systems with thinner prestressed panels as new long-life pavements for

underpasses where there are constraints due to height restrictions; and
3. Rapid rehabilitation of AC bus pads and bus lanes.

The following sections discuss some of the refinements proposed or developed under Project R05, including

1. Intermittent repair of CRCP;
2. Narrow-mouth dowel bar slots for load transfer; and
3. ICPCP systems.

Intermittent Repair of CRCP

A CRCP is a concrete pavement with continuous longitudinal steel reinforcement and no intermediate contraction or expansion joints. CRCPs develop a transverse cracking pattern with cracks generally spaced at about 2 to 6 ft (0.6 to 1.8 m). The steel reinforcement induces the closely spaced cracking and then holds the cracking tight. CRCPs have an excellent record of performance in the United States. When designed and constructed well, CRCPs can provide a service life of 40 or more years with minimal maintenance. The maintenance needed in older CRCPs is related to punchout distress (as shown in Figure 14.1), severely distressed cracking, and steel rupture. These distresses affect ride quality and safety. FDR is a common corrective action for these distress types. These repairs must be performed correctly; otherwise, the likelihood of early FDR failure will be high.

Many agencies have developed standard techniques for performing FDR of CRCPs, most of which are based on maintaining the continuity of the longitudinal steel within the patch area, as illustrated in Figure 14.2.

The conventional FDR method has had mixed performance, especially when performed under short lane closure requirements. Many FDRs fail within 1 to 5 years, creating a need to keep extending the repair area with subsequent repairs. Typical examples of failed conventional FDR of CRCP are shown in Figure 14.3.

Early FDR failures have typically been due to the following:

1. Inability to adequately restore the base under the exposed steel after concrete removal;
2. Poor quality concrete because the time required to jackhammer the end concrete area limited the time available for properly placing and finishing the repair concrete; or
3. Poor steel-lapping practices.

The South Carolina DOT has developed a simpler, innovative FDR method for CRCP repairs that is typically performed along a single lane. The South Carolina DOT approach uses the technique used for FDR of JCPs. Under this approach, epoxy-grouted dowel bars are installed in the existing pavement, longitudinal steel continuity is not attempted, and rapid-setting concrete is used. The South Carolina method allows for proper load transfer across the transverse edges of the repair area. In addition, since the repair is applied to a single lane of a roadway with two or more lanes, there is no concern

Figure 14.1. CRCP punchout distress.

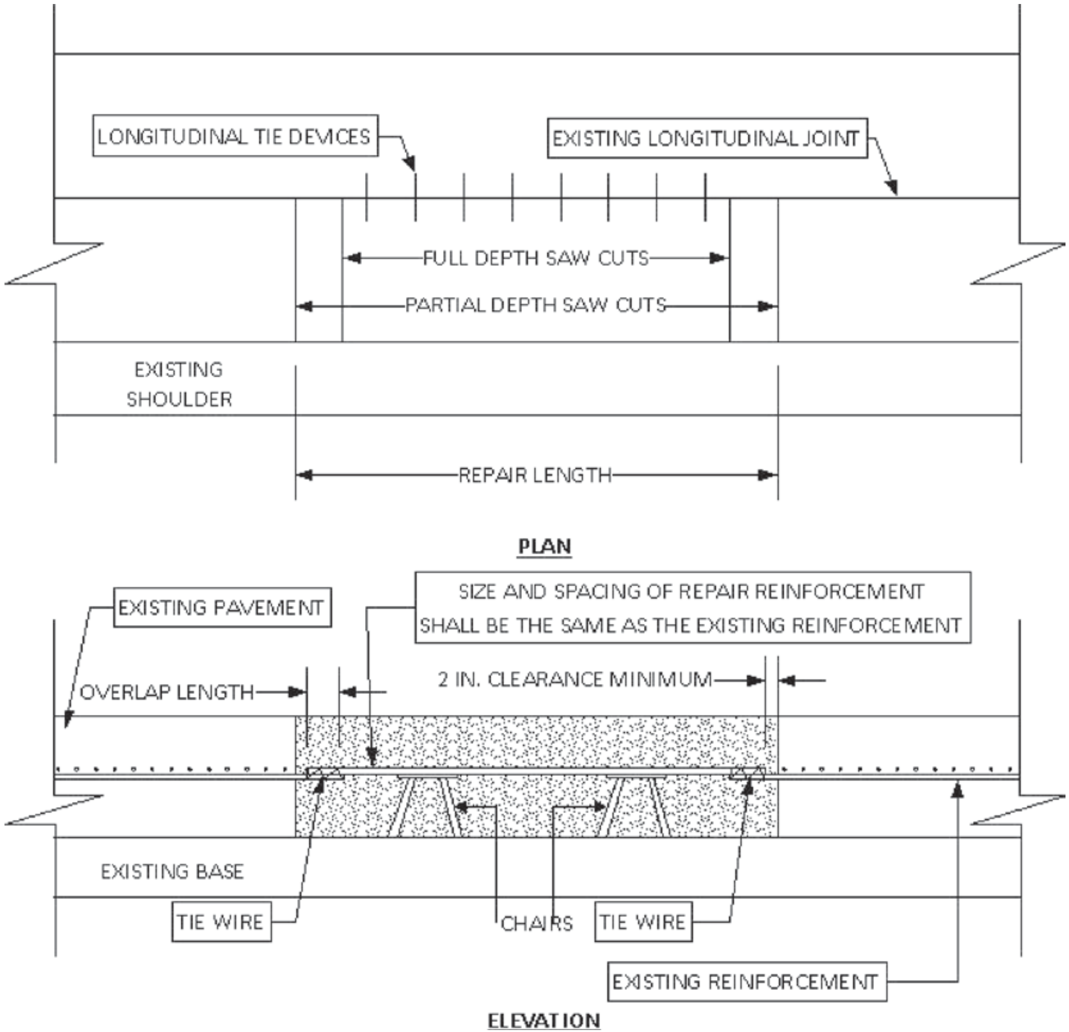


Figure 14.2. Continuity of longitudinal steel within the FDR area.

Figure 14.3. Failed FDRs in CRCP.

regarding any movement of the two free ends of the CRCP in the repair area. This repair option would not be recommended for repairs across all lanes of a CRCP, as this would necessitate the installation of a transverse expansion joint at the repair area. The key details of the South Carolina method are as follows:

1. Repairs are full-lane width and mostly in a single lane only, typically the outside lane of a two-lane, one-direction roadway. However, a few repairs have been carried out in two lanes of a three-lane roadway.
2. Full-depth perimeter cuts are made in the repair area.
3. Longitudinal steel continuity is not maintained in the repair area. In fact, longitudinal steel is not used in the repair area.
4. Tie bars are used along the centerline longitudinal joint for longer patches. Tie bars are nominally spaced at 30 in. (762 mm), but the spacing may be varied to avoid any cracking in the adjacent lane and to be at least 15 in. (375 mm) away from the repair area's transverse joints.
5. Dowel bars are placed at middepth at a nominal spacing of 12 in. (305 mm), starting and ending about 12 in. from the corners of the repair area. The dowel bar spacing is adjusted to miss any longitudinal steel in the existing pavement.
6. Intermediate transverse joints are required for repair lengths greater than 16 ft (4.9 m). Dowel baskets are used at these intermediate joints, with dowels spaced at 12 in. (305 mm). The intermediate joints are sawed to a depth of one-third of the depth of the repair area and sealed.
7. Rapid-setting concrete is used.

Overall, the jointed FDRs are performing well at several projects in South Carolina. A typical FDR of a CRCP punchout along a section of I-95 is shown in Figure 14.4.

Figure 14.4. View of I-95 jointed FDRs in South Carolina.

PCP technology for intermittent repair is ideal for rapid repair of CRCP punchouts. The process proposed is similar to the process developed by South Carolina DOT, except precast panels are used instead of CIP concrete. The use of precast panels and positive load transfer along the transverse joints of the repair area can ensure repair area concrete durability and long-term performance of the transverse joints under heavy truck traffic.

The specific issues to be considered when using precast concrete panels for FDR of CRCP are as follows:

1. Concrete removal and base preparation steps should follow standard procedures for jointed FDR, except that the repair area boundary should be selected so that the transverse joints are at least 24 in. (610 mm) from the nearest crack and at least 12 in. (305 mm) from the nearest transverse reinforcement.
2. The location of the dowel bar slots in the precast panel should be laid out to ensure that the slots and the companion drilled and grouted dowel bars will not interfere with the longitudinal steel.
3. The gap around the perimeter of the panel can be filled with an approved rapid-setting cementitious grout.
4. The transverse and the longitudinal joints should be sawed and sealed.

Narrow-Mouth Dowel Bar Slots for Load Transfer

The currently available JPrCP systems require dowel slots as part of the load transfer system at transverse joints. The dowel slots can be located along the panel bottom, as in the FMC system, or they can be located along the panel surface, similar to the DBR technique. A disadvantage of the currently designed surface slots is that they have wide mouths, about 2.5 to 3 in. (68 to 75 mm). As a result, the slots cannot be left exposed to traffic and need to be patched during the same lane closure as the panel placement, affecting the productivity per lane closure.

An approach developed under Project R05 is to use narrow-mouth surface slots, as shown in Figure 14.5. The slots are about 1 in. (25 mm) wide at the surface, tapering to about 3 in. wide approximately an inch below panel middepth. The slots are about 16 to 18 in. (406 to 457 mm) long to accommodate a 14- to 16-in. (355- to 406-mm)-long dowel bar within the slot. The dowel bars are slid into the slots just before the slab is placed over the base or bedding.

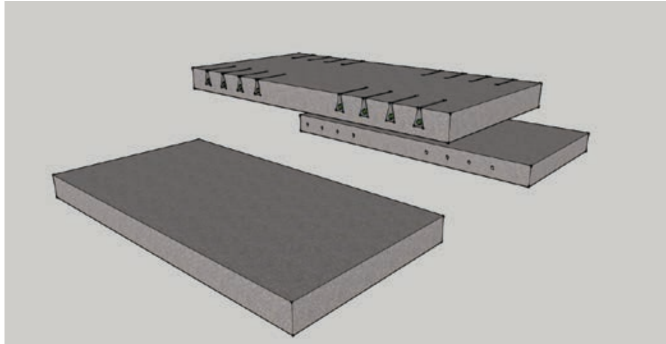


Figure 14.5. Narrow-mouth surface dowel slots.

During the next lane closure, the dowel bars are slid into companion drilled holes in the existing pavement after the holes are partially filled with epoxy (for repair applications), as shown in Figure 14.6. For continuous applications, the dowels are slid into companion dowel slots, and the dowel slots are then patched using the DBR technique.

For repair applications, the following actions need to be considered:

1. Holes about 7 to 8 in. (178 to 203 mm) long for dowel bars are drilled in the existing pavement before panel placement in the repair area. The drilled hole diameter should

Figure 14.6. Narrow-mouth dowel slot use for repair applications.

equal the diameter of the dowel bar plus about 0.125 to 0.25 in. (3 to 6 mm) when epoxy is used as the bonding agent.
2. The dowel bars are slid into the slots just before the panel is placed over the base or bedding.
3. The repair panel needs to be positioned correctly in the repair area to ensure that the companion dowel slots and the drilled holes are aligned well.
4. During the next lane closure, epoxy is injected into the cleaned drilled holes. The dowel bars are then slid from the slot into the holes with a twisting motion to ensure epoxy coverage around the dowel bars. Before the dowel bars are slid, an epoxy-retaining ring is placed around the dowel bars to prevent the outflow of the epoxy.
5. Once the dowel bars are slid into the cleaned drilled hole and covered with epoxy, they are held by clamps to ensure proper horizontal and vertical alignment. The clamps are released as soon as the epoxy hardens.
6. The dowel slots are patched using the DBR technique and an approved rapid-setting patching material. The dowel slot sides must be kept clean from dirt, dust, and debris before applying the patching material.

The steps for installing the dowel bars in the narrow-mouth slots are illustrated in Figure 14.7.

For continuous applications, the following actions need to be considered:

1. After the work area has been prepared, panel placement begins. Each successive panel is set adjacent to the previously placed panel.
2. The dowel bars are slid into the slots just before the panel is placed over the base or bedding.

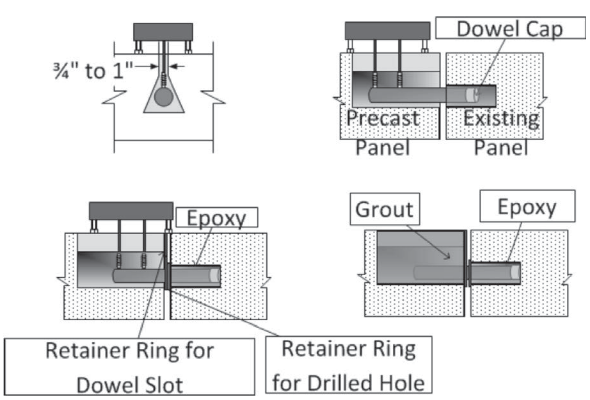


Figure 14.7. Steps for installing dowel bars in narrow-mouth dowel slots.

3. The panels need to be positioned correctly to ensure that the companion dowel slots of the adjacent panels are aligned well.
4. During the next lane closure, the dowel bars are slid into the adjacent slots so that the dowel bars are centrally located at the joint.
5. The dowel bars are then held by a clamp at each end of the bars to ensure proper horizontal and vertical alignment.
6. The dowel slots are patched using the DBR technique and an approved rapid-setting patching material. The dowel slot sides must be kept clean from dirt, dust, and debris before applying the patching material.

A demonstration installation of panels with narrow-mouth slots was carried out during the weeks of August 22 and 29, 2011, by the Illinois Tollway along an eastbound entrance ramp from Beverly Road onto I-90 eastbound near Elgin, Illinois. For this demonstration project, three panels were used. Panel details are as follows:

1. Panel thickness: 10 in. (254 mm);
2. Panel width: 147 in. (3.73 m);
3. Panel length: 72 in. (1.83 m);
4. Base: existing granular base;
5. Bedding: graded coarse aggregate, 1.5 to 2 in. thick (38 to 51 mm);
6. Load transfer: four dowel bars per wheelpath;
7. Dowel bar details: 1.5 in. (38 mm) diameter and 14 in. (355 mm) long;
8. Slot length: 16 in. (406 mm);
9. Existing JCP joint spacing: 20 ft (6.1 m); and
10. Dowel–slot design
    Panel 1: Standard version with narrow-mouth slots.
    Panel 2: Standard version incorporating a widened slot at the joint face. The widening was provided to allow hand access within the slot for easier pushing of the bars into the drilled holes and to allow for the twisting motion of the dowel bar for better epoxy distribution around the dowel bars.
    Panel 3: Slots with two surface openings to allow the use of two hands to push the dowel bars into the drilled holes and to allow for the twisting motion of the dowel bar for better epoxy distribution around the dowel bars.

The slot details for the three panels are shown in Figure 14.8. The details of the standard slot and of the standard slot with a wider opening at the joint face are given in Figure 14.9.

The panels for the Illinois Tollway project were installed by a contractor who lacked prior experience with PCP installation. However, the installation operation proceeded

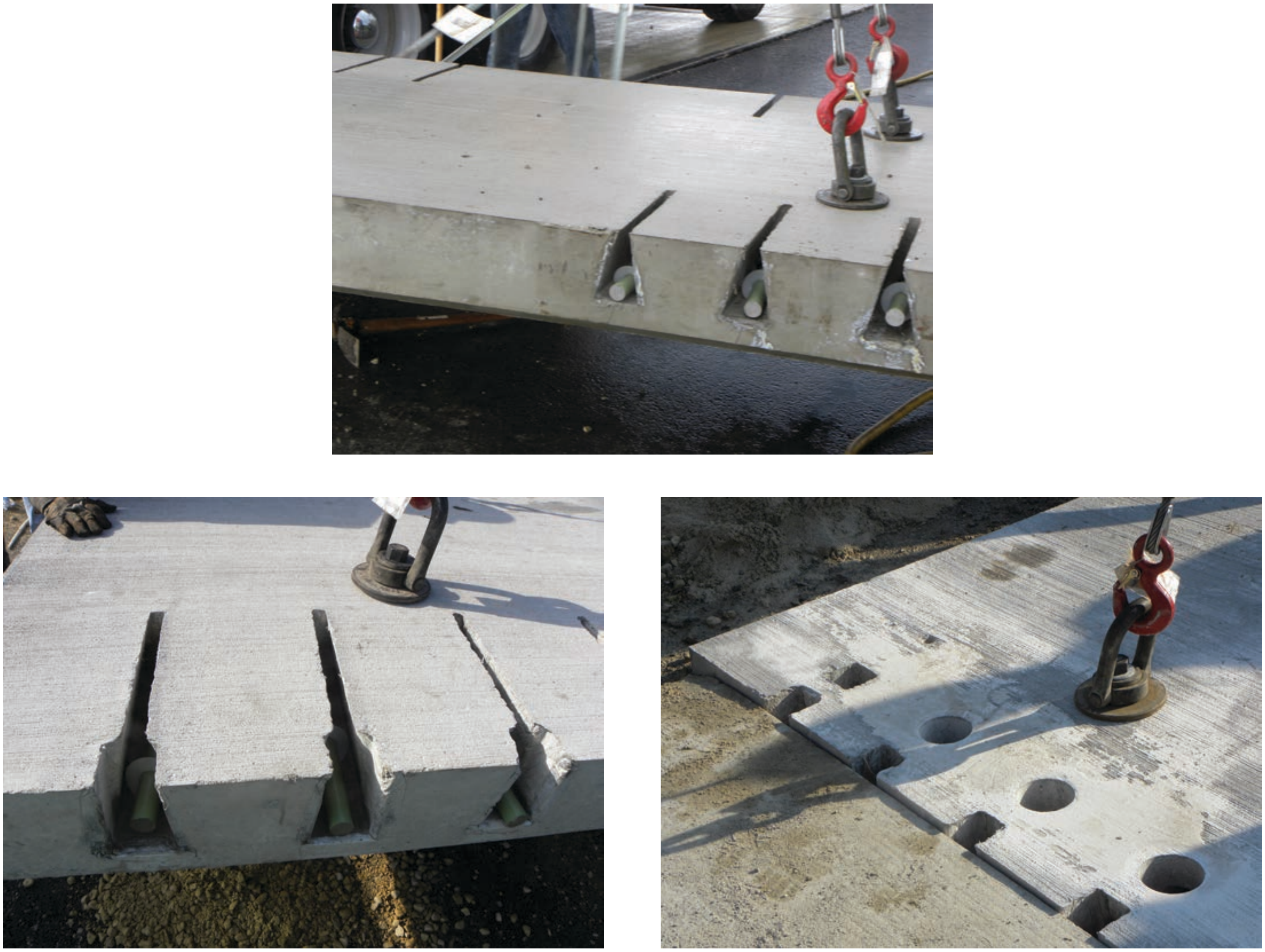


Figure 14.8. Three versions of the sliding dowel bar technique used in a 2011 Illinois Tollway demonstration project.

reasonably smoothly. All three panels were installed during one afternoon. The installation work included removal of the existing concrete at crack locations, preparation of the base and bedding, drilling of the dowel bar holes in the existing slabs, panel placement, and sliding of the dowel bars into the drilled holes partially filled with epoxy. The slots for one panel were patched using the DBR technique the next day. The slots for the other two panels were patched the following week. Overall, there were no surprises during the installation, and the contractor was prepared with customized tools to facilitate the sliding of the dowel bars and holding the bars in place. Some of these tools (clamps and a magnetic holder) are shown in Figure 14.10.

Based on its experience with the panel installation process, the Illinois Tollway will be implementing the narrow-mouth slot technique incorporating the wider opening at the joint face.

For continuous applications, the standard narrow-mouth slots (without the wider opening at the joint face) can be used. For this application, the dowel bars are held in position and the slot patching material is applied using the DBR technique.

Incrementally Connected PCP Systems

A new category of PCP systems, ICPCPs, has been established as part of Project R05. These systems simulate a JRCP with hinged joints and incorporate panels of varying lengths, typically 15 to 30 ft (4.6 to 9.1 m), which are connected together to achieve a connected section 60 to 100 ft (18.3 to 30.5 m) long. The panels are connected using deformed dowel bars that lock the connected joint and also provide the required load transfer across these joints. An active sealed joint is provided between connected panels.

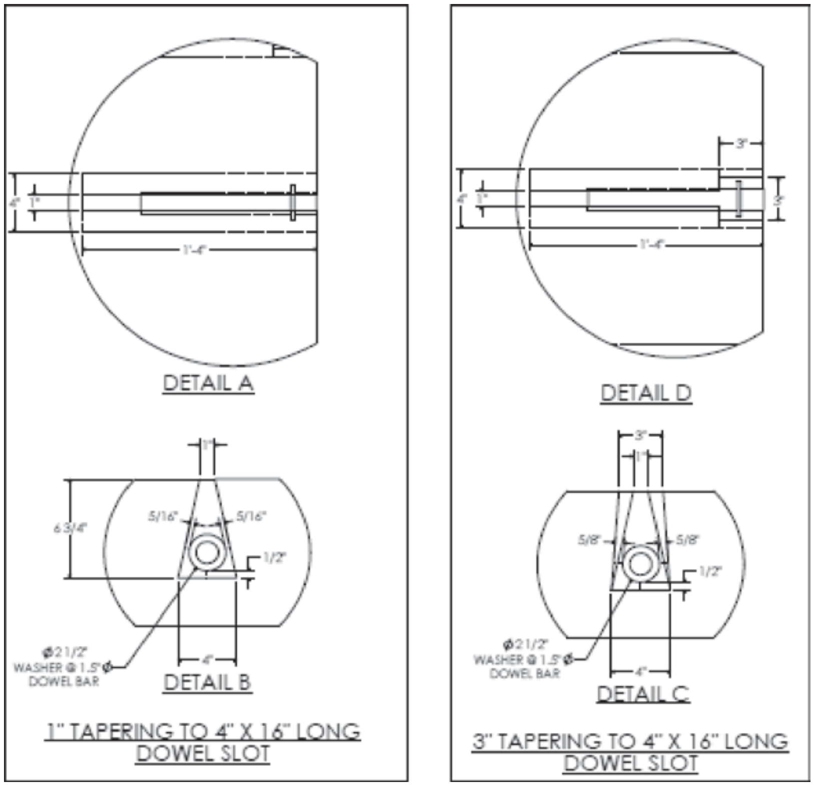


Figure 14.9. Details of the standard slot and of the standard slot with wider opening at the joint face.

Figure 14.10. Tools to facilitate sliding the dowel bars in the slots and holding the bars in place.

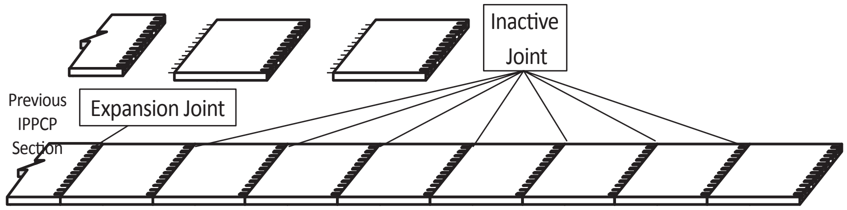


Figure 14.11. Incrementally connected PCP.

The advantage of ICPCP is the reduction in the number of active joints, which means less future maintenance related to joint sealing. Both nominally reinforced and prestressed panels can be used. The system can be used with dowel slots at the surface or along the bottom. The ICPCP system is illustrated in Figure 14.11. Prestressed panels allow the use of thinner panels, but good support is needed under the panels, similar to the good support needed for PPCPs.

ICPCP systems are designed and installed similarly to JPrCP systems. The only design change is the use of deformed bars for the intermediate connected joints. Examples of ICPCP systems include the following:

1. Active joint at 60-ft (18.3-m) spacing
   a. Four 15-ft (4.6-m)-long panels connected;
   b. Three 20-ft (6.1-m)-long panels connected; and
   c. Two 30-ft (9.1-m)-long panels connected.
2. Active joint at 90-ft (27.4-m) spacing
   a. Six 15-ft (4.6-m)-long panels connected;
   b. Five 18-ft (5.5-m)-long panels connected;
   c. Four 22½-ft (6.9-m)-long panels connected; and
   d. Three 30-ft (9.1-m)-long panels connected.

A joint gap is not necessary at the intermediate connected joints in an ICPCP system. A sealant may be used to seal the intermediate inactive joints, or the joint gap may be filled with a cementitious grout, as in the FMC system, or a polymer-based grout.

The expansion of the 60- to 100-ft (18.3- to 30.5-m)-long connected sections can be accommodated at the active transverse joints without requiring the use of an expansion joint.

An advantage of ICPCP over conventional JRCP is that the intermediate joints are doweled, and the joint-load transfer is not dependent on aggregate interlock.

Future PCP Refinements and New Applications

Precast pavement technology is ripe for further innovation. Various technical challenges need to be overcome to make the installation process fail-safe and more efficient, the performance longer-lasting, and the use cost-competitive. For the currently available systems and techniques used, there is need for improvements in the panel installation procedures:

1. Automated grading equipment for more rapidly trimming granular base and the bedding material already exists, but the equipment must be made smaller to be able to operate in the typically small work areas encountered on most overnight precast pavement installations. At present the cost of auto-graders is very high, rendering their use economically untenable on the typically small present-day PCP projects. Grading equipment capable of grading three-dimensional surfaces also exists, but the purchase cost and the cost of operating them on the job site should be carefully considered.
2. The development and availability of a low-height mobile or segmental rail-mounted gantry crane would allow rapid placement of single-lane width panels.

PCP technology, with its controlled panel fabrication process, lends itself to the development of a range of new systems. These systems include two-lift concrete panels and systems whose panel geometry is based on the tessellation concept of repeating patterns, such as the removable hexagonal-shaped panels for urban roadway applications used in France.

Systems with Two-Lift Concrete

CIP two-lift concrete pavements are widely used in Europe to provide a roadway surface texture that is less noisy and incorporates the desired texture for friction needs. This approach allows use of marginal and recycled aggregates in the thicker lower lift and use of better-quality aggregates in the thinner top lift. For PCP applications, the following two-lift concepts can be considered:

1. Two-lift fabrication with marginal or recycled aggregates in the lower lift. The lower lift is typically about 70% to 75% of the total panel thickness. The top lift texture can be tined or can incorporate exposed aggre-

gate treatment. However, the tined or exposed aggregate treatment may not be effective if the installation process necessitates surface grinding to correct for panel elevation irregularities.

2. Two-lift fabrication with steel fiber–reinforced concrete in the lower lift. Steel fiber–reinforced concrete has high flexural strength (up to 1,000 to 1,200 lbf/in.^{2} [6.7 to 8.3 MPa] at 28 days) and would allow for the design of thinner panels, similar to the use of prestressed panels. Thinner panels are more economical to transport and handle in the field. If properly designed, thickness reductions of up to 20% to 25% can be achieved using this material. Steel fiber–reinforced concrete use is not practical for the top lift because of problems with loose steel fibers at the surface. The top lift can be designed using conventional concrete or concrete that allows the use of an exposed aggregate surface treatment.
3. Two-lift fabrication with colored concrete for the top lift. The colored panels can be used to delineate lanes or other special-use roadway areas.

PCP Systems Based on Tessellation Concepts

A tessellation of the plane is a collection of plane figures that fills the plane with no overlaps and no gaps. The conventional square or rectangular layout is a simple example of tessellation. Another example is the hexagonal panel layout, as shown in Figure 14.12. Tessellation can be used very effectively in urban areas at intersections and other high-profile roadway areas. The concept allows integration of colored concrete and creative shapes to make urban roadways and intersections appealing and environmentally friendly. The removable urban precast pavement system developed in France is an example of this concept.

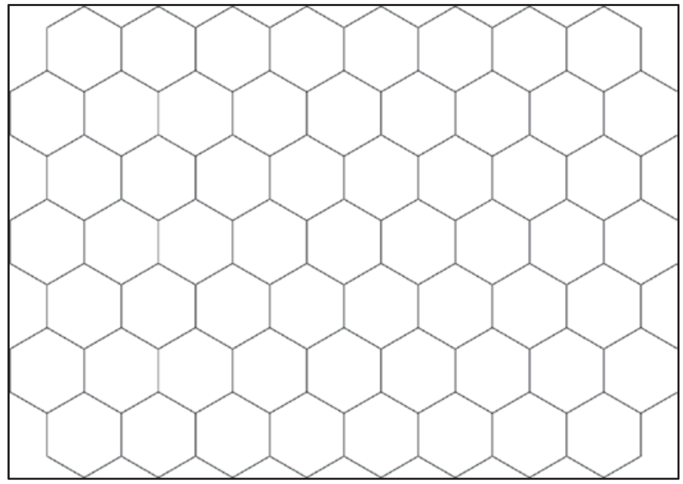


Figure 14.12. Geometric pattern for precast concrete panels using the tessellation concept.

For this approach, the precast panels are all one size, and the panels can be dimensioned and laid out to meet the needs of each facility. For example, the panels can be dimensioned half-lane width, about 6 ft (1.8 m) in length and width, to provide a symmetrical pattern.

Summary

Precast pavement technology is maturing, and every new project aids in refining existing PCP systems and developing new systems. There is still considerable room for refining existing systems, and new systems and new applications await further development and implementation. For the precasters and contractors who install precast pavement systems, these are exciting times as the market potential for application of precast pavement systems is potentially very large. Their continuing innovations and successful installations will define the market potential for PCPs.

CHAPTER 15

Modular Pavement Decision-Making Process

General Considerations

Highway pavement repair and rehabilitation are major activities undertaken by all U.S. highway agencies that involve significant agency resources of manpower and monetary cost. They also have a significant effect on worker safety. In addition, highway pavement repair and rehabilitation affect the user public significantly with respect to work zone–related delays and safety. Although it is recognized that highway pavements need to be repaired and rehabilitated at various times in their service life, it is also recognized that highway agencies and the user public are best served if pavement repair and rehabilitation activities are conducted under an accelerated schedule that results in less need for extended lane closures but also provides longer-lasting treatments. Thus, many highway agencies continue to seek alternative pavement repair and rehabilitation techniques that result in longer-lasting rapid repair and rehabilitation of existing pavements. Although PCP technology is of recent origin, it shows great promise for meeting highway agencies' needs for rapid rehabilitation.

Most highway agencies have an established process for making pavement repair and rehabilitation decisions to ensure that such decisions are made systematically and that cost-effective treatments are identified and implemented.

An example from the Ohio DOT is that there is policy that establishes uniform procedures to assure that the objectives listed below are achieved and the experience, collective knowledge, and technical expertise of all involved in the pavement design and selection process [are] considered. The objectives as stated in this policy are:

> Must select projects and design new pavements and rehabilitations of existing pavements such that they: are structurally adequate to serve the anticipated loadings, employ cost-effective materials, require a minimum amount of maintenance, and result in long-term customer satisfaction. This goal is brought about by assuring a consistent, statewide strategy exists for identifying how resources will be utilized, that proper pavement treatments are applied at the proper time, cost-effective materials and techniques are used and best-practice construction methodologies are pursued.

A generic process for selecting the repair or rehabilitation treatment involves, at a minimum, selecting the projects for repair and rehabilitation and developing project-level repair or rehabilitation designs. Candidate projects are selected based on needs identified by the agency's pavement management system, capital improvement program review, and feedback from district offices. The candidate projects may be selected at the central office or by the district offices.

The selection of an appropriate repair or rehabilitation design for a given pavement project requires a systematic, step-by-step approach that considers existing pavement condition, determination of the distress causes (if applicable), treatment identification, feasible treatment development, life-cycle cost analysis, and selection of the preferred treatment. The design process includes a review of available historical data and the collection of new data for the generation of alternative repair or rehabilitation strategies. When more than one strategy is considered feasible, a decision process involving life-cycle cost analysis, constructability analysis, construction traffic management analysis (using tools such as the Construction Analysis for Pavement Rehabilitation Strategies [CA4PRS]), policy directives, and expert knowledge may be used to select the optimal strategy for a given project. It is under this step that new or innovative technologies, such as PCP, may be considered.

Concrete Pavement Rehabilitation Alternatives

Many alternatives exist for rehabilitation of concrete pavements, including the following:

1. Intermittent repairs at isolated locations. These repairs typically include FDRs at distressed joint and crack locations or full-panel replacements

   a. Using AC (generally considered as a temporary repair);
   b. Using CIP concrete; and
   c. Using precast panels.
2. AC overlay
   a. Conventional policy overlay with nominal 3- to 4-in. (75- to 100-mm) AC thickness; and
   b. Overlay over fractured concrete pavement (thicker AC overlay)
      - Concrete pavement cracked and seated
      - Existing pavement rubblized.
3. Concrete overlay
   a. Bonded overlay, typically 2- to 4-in. (50- to 100-mm) concrete thickness; and
   b. Unbonded overlay (thickness determined; typically thicker)
      - Using CIP concrete
      - Using a jointed or prestressed PCP system.
4. Reconstruction
   a. Using AC pavement; and
   b. Using concrete pavement
      - Using CIP concrete
      - Using a jointed or prestressed PCP system.

Not all of the rehabilitation alternatives listed above are suitable candidates for rapid rehabilitation of severely distressed concrete pavements where lane closures are difficult. Certain features of PCP should be emphasized in the repair or rehabilitation treatment selection process, including the following:

1. The repairs or rehabilitation can be performed rapidly.
2. The repairs or rehabilitation will cause minimum disruption to traffic.
3. The repairs or rehabilitation will extend the service life of existing pavements or result in long-life pavements.
4. The rehabilitation can be performed selectively, along lengths of pavement requiring the most attention. As a result, there will be no need to consider the multilane rehabilitation that both AC and concrete overlays would require.

All of these features are important and necessary when considering the use of PCP technology. The production use of PCP over the past 10 years and PCP experimental projects constructed to date have demonstrated that PCP can be constructed rapidly without significant impact on traffic operations.

Lengthy traffic closures are not necessary to accommodate CIP concrete placement, finishing, texturing, curing, and joint-sawing operations. Several U.S. highway agencies, including the Georgia DOT, Washington State DOT, and Illinois Tollway Authority, have successfully used rapid-setting concrete for rapid repairs and rehabilitation of concrete pavements. However, many highway agencies have not been able to use the rapid-setting concrete technology successfully because of the marginal concrete durability achieved on many of their projects. In addition, use of rapid-setting concrete does not allow for an increase in the structural capacity of the rehabilitated pavement when the repairs are confined to the existing profile (thickness) of the pavement. To address CIP repair durability issues, the Illinois Tollway has developed and implemented a set of performance-based specifications for high-early-strength concrete mixture designs.

Asphalt Pavement Rehabilitation Alternatives

PCP is well suited for reconstruction of existing AC pavement facilities. If an agency is considering a concrete pavement alternative to rehabilitate an existing AC pavement where lane closure requirements are difficult, PCP may be advantageous. Both jointed PCP and PPCP may be considered for such applications. Possible applications include busy arterial highway intersections and freeway ramps. During 2009 and 2010, several distressed AC pavement intersections along busy Rockaway Boulevard, adjacent to John F. Kennedy International Airport in New York City, were rehabilitated using a jointed PCP system that was installed during the night hours. The work involved removing the existing AC pavement and base layer, adding new base material, grading and compacting the base, and placing the precast panels. The PCP areas were opened to traffic the next morning. The daytime traffic at the intersections being worked on was not affected. Views of the PCP installation and the completed installation at an intersection along Rockaway Boulevard are shown in Figure 15.1.

The following sections discuss specific issues that should be taken into account when considering PCPs for repair (intermittent repairs) or rehabilitation (continuous application), including agency considerations, the suitability of a project for PCP application, and PCP system selection.

Agency Considerations

Adoption of New Technology

In the United States, there is generally a hesitation to use new technology on a production basis until there is sufficient experience with the technology. This hesitation is caused by safety concerns and the perceived potential for early failures that are likely to result in unanticipated lane closures. This conservative but practical approach is followed by most highway agencies, especially for high-volume urban highways. However, such an approach delays the widespread adoption of new technologies. As detailed in this report, the performance of PCPs in service indicates that PCP technology can potentially provide long-lasting pavement repair and rehabilitation treatments. Many U.S. highway agencies have implemented PCP technology for both intermittent repair and continuous applications, and many others are investigating the adoption of this

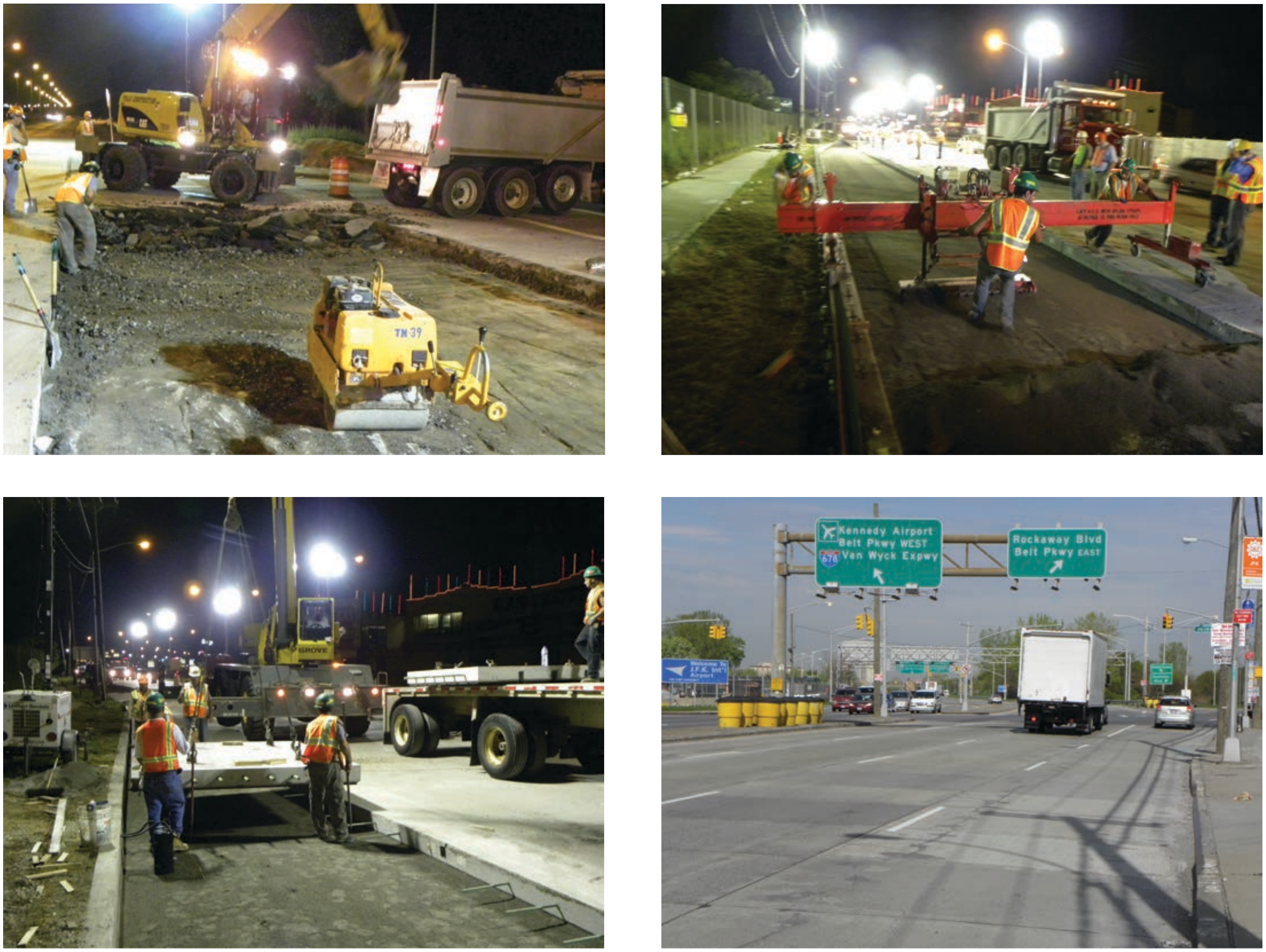


Figure 15.1. PCP installation at an intersection along Rockaway Boulevard in New York.

technology. PCP technology satisfies the following key criteria for implementing a new technology:

1. Constructability: Numerous projects have been constructed in different parts of the United States under a range of site conditions, using contractors with no previous experience with PCP construction and using different PCP systems. The constructability of PCP should no longer be an issue of concern.
2. Concrete durability: One of the key advantages of PCP is that the technology results in durable concrete as a result of the process used for producing the concrete and fabricating the precast concrete panels in a controlled environment at the precast plants.
3. Structural performance: Long-lasting repairs and rehabilitation using PCP require that adequate provisions be made for load transfer at joints and for ensuring good support under the precast panels. PCP technology, as detailed in this report, is available to ensure these requirements.

Cost of PCP Systems

The PCP systems constructed to date on an experimental (demonstration) or production basis have been more expensive as a first cost than conventional CIP concrete pavement repair and rehabilitation, primarily because of the lack of a robust competitive environment and the perceived construction-related risks associated with the new technology. It may be more appropriate to compare precast pavement costs to those of the rapid-setting CIP concrete currently in use, because precast pavement is more likely to be the substitution for that material. Currently, the cost of PCP is about the same as or slightly higher than some rapid-setting concretes, depending on the geographic location and the type of rapid-setting material with which PCP is compared. As more PCP systems become available and more contractors and precasters become involved in this technology, it is expected that the cost of installing PCP will be competitive with conventional rapid repair and rehabilitation techniques. PCP pricing in 2001 and 2002 ranged from about \$700 to \$900/yd^2 (\$840 to \$1,080/m^2). As of 2010, PCP pricing was about \$250 to \$500/yd^2 (\$300 to \$600/m^2).

Proprietary Products

Many agencies find it difficult to specify proprietary products because of agencywide procurement rules. Therefore, agencies need to develop their own generic plans and specifications for PCP systems or adopt well-formulated end-product specifications that allow for consideration of both proprietary and nonproprietary PCP systems. Several proprietary and nonproprietary systems are now available. The availability of competitive proprietary and nonproprietary systems is expected to result in competitive pricing for future PCP projects.

Safety

Safety is a serious issue with all highway agencies. If a precast system cannot be installed on schedule, some of the installation activities may need to be completed during the next installation period. This situation may result in a potentially unsafe driving surface when the facility is opened to traffic after the first installation period. For example, leaving the surface slots for installing dowel bars unpatched after the first period of the precast panel installation may be considered unacceptable by many highway agencies. As presented in this report, installing a load transfer device based on using a narrow slot at the surface can mitigate any concern related to leaving wider slots open under traffic. All PCP projects require an emergency management plan that details how the contractor will respond to ensure that traffic operations are not affected. This is typically done by ensuring that the existing pavement removal operation maintains pace with the panel installation rate.

Acceptance Testing

Comprehensive procedures have not yet been implemented for acceptance testing of PCP components and the final installed product. This report presents an acceptance testing plan for precast panel installation that includes testing for joint LTE, panel support (base and bedding, if any bedding), and for PPCP systems, the effectiveness of prestressing.

Loss of Revenue

For tollway agencies, loss of revenue is an important issue. Pavement repair and rehabilitation techniques should not have a negative impact on the flow of traffic moving through the tollway facility, especially at the toll collection areas. The repair and rehabilitation activities need to be rapid and low-risk. PCP technology accommodates these requirements.

Design Responsibility

Design responsibility is an issue that needs to be addressed by each agency. What is the role of the agency in specifying a PCP system? An agency will typically specify the precast panel geometry, including the thickness and load transfer requirements (dowel size, number of dowels, and dowel spacing). However, the bedding support requirement may be left to the PCP system vendor as the bedding support provisions may be unique for a given system. For example, one system may require the use of finely graded granular material to seat the panels, and another may require polyurethane foam. If a PCP system requires a specific bedding material, the agency's PCP system design must incorporate these details, and the suitability of these features must be demonstrated during the system acceptance process or at the project-specific field test section.

Constructability

Constructability can be an important consideration when repairs have to be performed in difficult areas such as the inner lanes of multilane highways, under overpass areas, and in tunnels. Currently, heavy cranes are used to unload and position the panels at the work site. There is a need to develop low-rise gantry cranes that can facilitate panel installation at sites that are difficult to access.

Project Suitability for PCP Application

Not all existing pavements are good candidates for a given repair or rehabilitation treatment. This is also true for PCP technology; that is, not all projects are good candidates for application of PCP technology. The key items to consider when determining the suitability of a project for application of PCP technology include the following:

1. Traffic warrants;
2. Lane closure requirements;
3. Pavement structural capacity improvement and vertical clearance requirement;
4. Site access for heavy construction equipment;
5. Contractor and precaster experience; and
6. Proximity of certified precast concrete plants.

Traffic Warrants

Traffic flow is the most important factor when considering using a PCP system. If highway operations dictate that peak period traffic flow, typically during the daytime hours, cannot be affected negatively by active work zones, then use of PCP becomes more favorable. PCP systems have been used favorably for repair and continuous applications under the following situations:

1. Multilane freeways carrying over 100,000 vpd;
2. Arterial highways that carry urban or suburban commuter and freight traffic;
3. Single- or multilane ramps; and
4. Bridge approach slabs.

In the situations listed above, it was necessary that highway operations during peak hours not be affected. Typically, this required installation of the precast panels between the hours of 8 p.m. and 6 a.m. The production rate for PCP installation for intermittent repairs is about is 15 to 20 repairs per lane closure. For continuous applications, the rate is about 20 to 40 panels per lane closure, depending on the system and panel geometry used; this is equivalent to about 300 to 500 ft (91.4 to 152.4 m) of production for the lane or lanes being worked on. Most PCP installation require two lane closures: the first for existing pavement removal, base (or base and bedding) improvement, and panel installation; and the second (within 24 hours), for load transfer provisions and panel undersealing for jointed systems and posttensioning and panel undersealing for PPCPs.

It is important that the second lane-closure activities be performed within 24 hours, typically during the second night of lane closure, especially if the highway section carries a moderate to high volume of truck traffic. If the second lane-closure activities, particularly undersealing, are not performed in a timely manner, the risk of premature panel cracking increases because of nonuniform panel support conditions.

Lane closure strategies and specific rehabilitation strategies can be analyzed in detail using the CA4PRS software. CA4PRS is a schedule and traffic analysis tool that helps planners and designers select effective, economical rehabilitation strategies. The software's scheduling module estimates highway project duration (total number of closures) and incorporates alternative strategies for pavement designs, lane closure tactics, and contractor logistics. CA4PRS's traffic module (using the *Highway Capacity Manual* demand capacity model) quantifies the impact of construction work zone closures on the traveling public in terms of road user cost and time spent in queue.

Lane Closure Requirements

Lane closure requirements are dictated by the facility type and traffic volumes during the lane closure period.

1. For freeway applications, a sequential lane closure pattern is typically used. Precast panel installation requires a multilane lane closure because it is necessary to have an additional lane available for trucks delivering the precast panels to the work site. Therefore, installation along a single lane will require a minimum two-lane closure, and a two-lane installation will require a three-lane closure. For multilane closures, the lane closures are typically done sequentially. For example, the first lane is closed at 8 p.m., the second one at 9 p.m., and the third one at 10 p.m. The sequence depends on the volume of traffic during the off-peak hours. Pavement removal and equipment mobilization begin as soon as the first lane closure begins.

   Whenever possible, a three-lane closure should be considered for even single-lane repairs along a high-traffic-volume highway. Lane shifts onto shoulders or split traffic configurations may be needed to allow for lanes or shoulder on either side of a repair area to be closed during installation.
2. For arterial highways with only one or two lanes in each direction, full lane closures may be used. A two-way traffic pattern is then managed in the opposite-direction lanes.
3. For single-lane ramp applications, the ramp is typically closed to traffic during the panel installation.

Lane closure requirements differ for repair and continuous applications. The lane closure for a repair application may be spread over several miles because the 15 to 20 repair locations designated for treatment during a given lane closure may be spread over this distance. The lane closure requirement for continuous applications involves less spread as the actual work area may be limited to 300 to 500 ft (91 to 152 m) in length. However, traffic control requirements for a given site may dictate the use of lengthier lane closures, depending on the number of lanes being closed and anticipated traffic volume. In any case, all lane closures are carried out in accordance with the requirements specified in MUTCD (2009) and the agency's work zone traffic control guidelines. The traffic control devices and lane closure distances to be used are intended to reduce construction workers' exposure to traffic hazards and offer road users consistent and positive guidance through work zone areas.

A lane closure scenario for a four-lane divided highway is shown in Figure 15.2. For this project, the repairs were being performed in the outside lane. The outside lane and shoulder were closed to allow for removal of the existing concrete pavement and for preparatory work to be performed. When the site was ready for panel installation, traffic was completely stopped for a period of 15 to 20 minutes to allow the truck transporting the panels to position next to the prepared site and for the crane to place the panel in the prepared area as shown in Figure 15.2.

A lane closure scenario for a continuous PCP application is shown in Figure 15.3. On this project the outside three lanes of four lanes in the northbound direction were closed to allow work in the outermost lane. The innermost lane (Lane 1) was

Figure 15.2. Crane placement of panel on four-lane divided highway project.

Figure 15.3. Lane closure scenario for a continuous PCP application.

open to traffic. The trucks transporting the panels were positioned in the lane adjacent to the one being worked on. The second lane from the median (Lane 2) served as the buffer zone between live traffic and the active work area.

Traffic control requirements for lane closures are based on project specifics that include traffic volumes during off-peak hours, availability of alternate routes, and the number of lanes available to carry out the panel installation work.

Panel placement productivity is extremely important. On the average, a single panel installation requires about 15 minutes. Any delay in lane closures or traffic-related disruptions to the panel installation process can result in a serious loss in productivity.

Pavement Structural Capacity Improvement and Vertical Clearance Requirement

A unique benefit of PCP is that it can be used to rehabilitate thinner existing concrete pavements (8 to 10 in. [200 to 250 mm] thick) that would otherwise require a thicker (12 to 14 in. [300 to 350 mm]) conventional JCP for the higher volume of future traffic and for longer service life, as discussed below:

1. For jointed PCP, the increased structural capacity can be built in by using higher-strength concrete and prestressed (pretensioned) precast panels. Prestressing effectively increases the structural capacity of precast panels.
2. PPCP offers an even better advantage over jointed prestressed precast panels. PPCP panels designed to be two or more lanes wide (including an outside shoulder) result in interior load conditions for truck loadings. The wider panels and the longer PTSection behave as a jointless (infinite dimensions) slab. Such a slab system, installed over a good or improved base, has superior load-carrying capacity. For such cases, an 8- to 10-in. (200- to 250-mm) PPCP can be designed to carry traffic that would otherwise require a 13- to 14-in. (325- to 350-mm)-thick conventional JCP.
3. For overlay applications, the thinner PPCP can help maintain the vertical clearance under bridges and possibly require no change to the height of the existing guardrails.

Typically, no significant changes are required in the road profile and the cross section of the existing pavement when jointed prestressed panels or a PPCP system is used to rehabilitate individual lanes of a multilane pavement. Depending on the existing base type and condition, a new CTB or an LCB may be considered. Such an approach was used at the 2011 PPCP project along a section of I-680 near Oakland, California. At this project, the existing 9-in. (225-mm) JCP and the underlying CTB were removed and replaced with a 6- to 7-in. (150- to 175-mm)-thick LCB and an 8⅝ in. (219-mm)-thick PPCP.

Site Access for Heavy Construction Equipment

Site access and operational areas must be available for the heavy equipment required for PCP installation. The key equipment needed is discussed below.

Pavement Removal Equipment

A variety of pavement removal equipment can be used to remove the designated areas of the existing pavement. For intermittent repair applications, the slab lift-out method is commonly used and is recommended. The slab lift-out operation requires a crane that can accommodate the largest panel size to be removed. The crane can be positioned in the lane that is being repaired. The same crane is the used for installing the repair panels. Many contractors use excavation equipment to remove the existing pavement, especially for continuous PCP projects. However, the use of excavation equipment results in damage to the base. Different types of pavement removal equipment are shown in Figure 15.4.

Panel-Handling Equipment

Typically, cranes sized to the weight of the panels are used to place the panels. The operation requires lifting the panels from trucks positioned in an adjacent lane and placing the panels in the prepared area. Typical panel-lifting equipment is shown in Figure 15.5. As shown, the excavating equipment used to lift out damaged existing concrete slab panels for repair projects may be used to install the new panels. For continuous projects, cranes are typically used.

One of the critical space management issues for lane closure is the crane's positioning for the precast installation and the crane's footprint. During its operation, the crane's outrigger (usually four supporting legs) usually stretches out and is grounded on both lanes adjacent to the lane being rehabilitated, and the crane is positioned on the newly installed precast panel. As shown in Figure 15.6, the outrigger for the crane's stabilization requires about 2 to 3 ft (0.6 to 1.2 m) beyond the rehabilitation lane on each side.

The crane footprint for the four-lane Virginia I-66 PPCP project is illustrated in Figure 15.7. The crane footprint for the two-lane I-66 ramp where the jointed PCP system was used to rehabilitate the outside lane is shown in Figure 15.8. For the ramp project, the ramp was closed to traffic during panel installation.

Panel Delivery Trucks

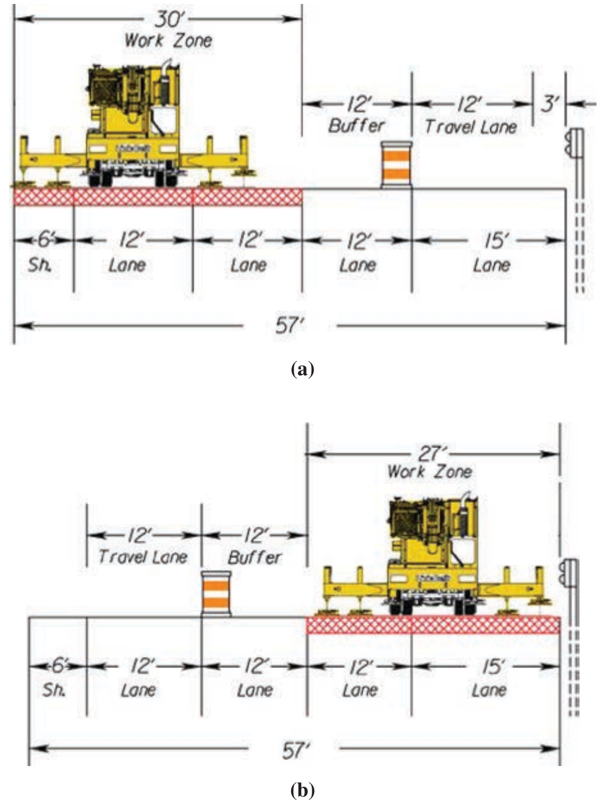
Access is needed to position the panel delivery trucks in a lane adjacent to the lane being rehabilitated. As a result, a

Figure 15.4. Different types of pavement removal equipment.

Figure 15.5. Typical panel-lifting equipment.

Figure 15.6. *Crane stabilization requires 2 to 3 additional feet away from the rehabilitation lane on each side.*

minimum of two lanes needs to be closed. This requirement is applicable to both intermittent repair and continuous application projects. As shown in Figure 15.8, for the Virginia I-66 ramp project, the inside lane (designated as "Travel Lane") was used by the panel delivery trucks, necessitating a full ramp closure. For intermittent repairs, if traffic needs to be maintained on a two-lane facility, short-period full closures may be considered to allow for panel placement at each repair area.

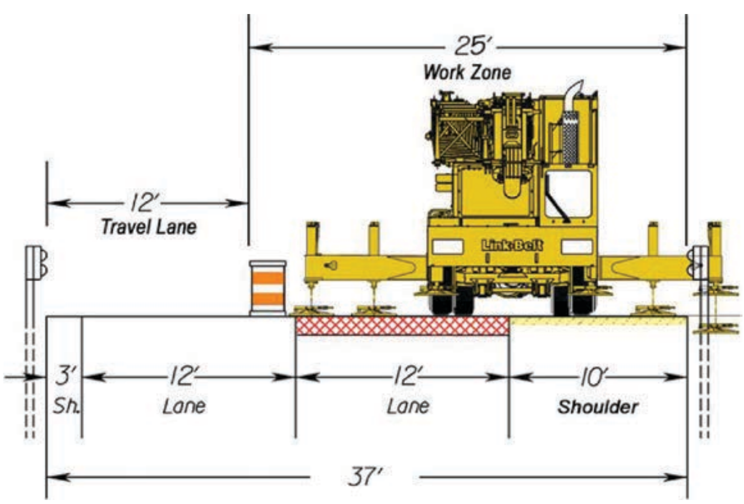


Courtesy of Virginia DOT.

Figure 15.7. Crane footprints for I-66 PPCP project for panel placement in (a) inside two lanes and (b) outside two lanes.

Contractor and Precaster Experience

PCP is a recent technology, and most PCP installations have been carried out by contractors with no previous experience with this technology. These contractors have been diligent about learning the new technology and have successfully completed most projects within budget and under the allocated time. Experience to date indicates that contractor inexperience with PCP technology is not a serious handicap. As long as project plans and specifications are well developed, the contractors, in partnership with the precasters, are able to meet PCP project requirements.



Courtesy of Virginia DOT.

Figure 15.8. Crane footprint for I-66 ramp project.

Any PCP system used must be approved by the highway agency. For large projects, the agency should require the construction of a test section that demonstrates all key panel installation features, including the proposed equipment and materials.

Proximity of Certified Precast Concrete Plants

Another key factor to evaluate when considering the use of PCP is the local availability of a certified precast concrete plant that can produce the precast panels. For PPCP applications, the precast concrete plant will need to have the capability for pretensioning tendons, and if specified by the highway agency, for steam curing. The driving distance from the precast concrete plant to the project site is a critical item. Longer distances may not result in competitive pricing for PCP alternatives. Many projects constructed to date have accommodated 3 to 4 hours of driving from the plant to the project site. However, longer driving times may affect the panel installation production rate and overall cost. On several projects, a nearby staging area was used to store the panels. However, this practice necessitates the use of an additional crane and crew at the staging site.

Preparatory Time Requirements

It is important that highway agencies recognize that a PCP project will require longer preparatory time than a CIP concrete pavement repair or rehabilitation project. Construction work for CIP projects can begin within a month of bid opening because advanced preparatory work is not extensive. For PCP projects, a longer time may be required before actual construction (panel installation) can begin. PCP projects require a more detailed site survey to develop site-specific data to customize the precast panel dimensions, to finalize the design of the precast panels, and to stockpile enough panels to ensure a good supply of panels once field installation work begins.

Summary

Highway pavement repair and rehabilitation are major activities undertaken by all U.S. highway agencies and involve significant agency resources of manpower and monetary cost. Although it is recognized that highway pavements need to be repaired and rehabilitated during their service life, it is also recognized that the highway agencies and the user public are best served if the pavement repair and rehabilitation activities are conducted under an accelerated schedule that results in less need for extended lane closures but also provides longer-lasting treatments. Although PCP technology is of recent origin, it shows great promise for meeting highway agencies' needs for rapid rehabilitation.

Some of the current limitations that detract from wider and more routine adoption of PCP technology include the higher initial cost, the lower panel installation rate, the lack of long-term performance information, and the risk-averse nature of the highway construction industry. It is hoped that the findings related to PCP technology documented in this report will motivate the stakeholders (highway agencies and the construction industry) to get more involved in implementing PCP technology and in fostering innovations that will continue to improve the technology and make PCP systems more economical.

CHAPTER 16

System Approval and Trial Installation

Introduction

Although PCP technology, as used today, is of recent origin, many different PCP systems have been implemented in the United States, and it is likely that refinements to the existing systems will continue to be made and new systems or system components will be developed. It is therefore necessary that highway agencies establish an independent process for evaluating and approving new PCP systems or components. As discussed in this chapter, new components are considered the same as new systems, because the performance of any new component needs to be demonstrated as being an integral part of any PCP system. As a minimum, the following attributes of a new PCP system need to be evaluated before approval of the system:

1. Constructability within the constraints of the lane closure requirements;
2. Productivity of installation;
3. Concrete quality; and
4. Structural performance
   a. Transverse joint load transfer provisions
   b. Specific base and bedding support requirements.

The process for evaluating and approving any PCP system should be the same for a generic system developed by the highway agency or for proprietary systems or systems that incorporate proprietary features. Requiring PCP system vendors (precasters or contractors, or both) to have their systems approved before they are used at a project reduces the risks associated with implementing a new system under difficult lane closure and other site constraints, including nighttime work and limited work hours.

Because the design requirements and performance requirements are unique for intermittent repairs or continuous applications, PCP system approval should be based on the specific type of application.

This chapter addresses the requirements for evaluation and approval of PCP systems. The evaluation and approval process consists of two distinct parts: (1) the submittal and review of standard drawings and proposed installation procedures and (2) the construction and evaluation of a trial installation.

System Design Requirements

The PCP system approval process can be based on the agency-specified standard design for system approval or based on specific project needs. The design features that need to be specified by the agency for non-project-specific PCP system approval should include the following as a minimum:

1. Precast concrete panel–related features
   a. Panel width;
   b. Panel length;
   c. Panel thickness;
   d. Concrete requirements;
   e. Minimum reinforcement; and
   f. Minimum prestressing, if applicable.
2. Trial installation–related features
   a. Base support;
   b. Bedding requirements, if any;
   c. Rapid-setting materials used as grouts and for patching;
   d. Transverse joint LTE;
   e. Applied end prestress level for PPCP systems; and
   f. Expansion joint details for PPCP.

For approval of a PCP system without reference to a specific project, the standard design features given in Table 16.1 are recommended.

The standard design features listed in Table 16.1 provide flexibility to the system vendor in terms of determining the panel geometry that will satisfy the PCP system approval process and that matches the vendor's fabrication process and available formwork.

Table 16.1. Standard Design Features for System Approval

Design Feature	Value
Panel width (ft)	12
Panel thickness (in.)	8 to 12
Panel length, jointed systems (ft)	6 to 15 (repair)
	12 to 15 (continuous)
Panel length, PPCP systems (ft)	8 to 40
Base support type	Granular
Modulus of subgrade reaction over base (pci)	200 to 400
Minimum LTE, jointed systems	90
Minimum LTE, PPCP systems with expansion joint width of 2 in.	80
Minimum concrete compressive strength at 28 days (lbf/in.^{2})	650
Concrete and concrete aggregates	Meet requirements for agency's paving-class concrete
Minimum panel reinforcement in each direction (% of cross-sectional area)	0.18
Strength of rapid-setting dowel slot grout and patching materials at 4 hours (lbf/in.^{2})	2,500
Strength of rapid-setting undersealing grout material at 4 hours, if applicable (lbf/in.^{2})	500
Reinforcement type	Epoxy-coated deformed bars, Grade 420, or other approved reinforcement
Minimum applied panel prestress for pretensioning (lbf/in.^{2})	200
Minimum PTSection end prestress for PPCP systems (lbf/in.^{2})	200

PCP System Standard Drawings and Supplemental Information

The vendor-developed drawings for the PCP system approval should be stamped by a registered professional engineer and should include, as a minimum, a cover sheet, a drawing sheet (or sheets, as needed), and a PCP system installation detail sheet (or sheets, as needed).

Cover Sheet

1. General notes
   a. Reference to the agency specification related to PCP system approval;
   b. References to agency specifications and special provisions applicable to PCP systems;
   c. Reference to any proprietary components or techniques used, including patent and trademark information;
   d. Estimated panel placement rate per 6-hour nighttime work window after removal of existing pavement; and
   e. Limitations, if any, to opening the placed panel section to traffic
      - Before effecting joint load transfer provisions and undersealing, if applicable
      - Before posttensioning the PTSections of the PPCP system, if applicable.
2. Precast concrete plant certification-related information.
3. PCP system name and brief description.
4. Test panel dimensions
   a. Identification for each panel; and
   b. Width, length, thickness, and weight of each panel.
5. Concrete requirements
   a. Reference to agency's paving concrete requirements;
   b. Form stripping strength, typically a minimum of 2,500 lbf/in.^{2} (17.2 MPa);
   c. Design strength and age, typically a minimum of 4,000 lbf/in.^{2} (27.6 MPa) at 28 days;
   d. Shipping strength, typically same as the design strength; and
   e. Curing requirements, including steam-curing requirements, if applicable.
6. Reinforcement details
   a. Reinforcement type, typically epoxy coated;
   b. Reinforcement layout: number of mats (single or top and bottom);

   c. Reinforcement amount: bar size and spacing; and
   d. Reinforcement clear cover.
7. Panel lifting and handling details
   a. Lifting insert, swivel lift plate, and lifting bolt details;
   b. Lifting assembly (rigging) details (to ensure equal loading at each insert);
   c. Insert locations on the panel; and
   d. Lifting and insert–related safety information.
8. Panel fabrication tolerances.
9. Bedding material information, as applicable
   a. Fine-grained granular material;
   b. Rapid-setting flowable material; and
   c. Polyurethane foam.
10. Rapid-setting dowel slot grout and patching material information.
11. Rapid-setting undersealing grout information, if applicable.
12. PPCP system: prestressing system details
    a. Tendon type and diameter;
    b. Tendon duct grout;
    c. Tendon connectivity at intermediate joints;
    d. Intermediate joint keyway epoxy; and
    e. Intermediate joint grout and patching material information, as applicable.
13. Prestressed panels: prestressing system details
    a. Tendon type and diameter; and
    b. Tendon detensioning details.
14. On-site equipment requirements
    a. For panel lifting and placing (crane rating);
    b. For bedding material application, if applicable;
    c. For undersealing material application; and
    d. For stressing tendons (loading jacks).
15. Panel shipping-related cautions.

Drawing Sheet(s)

1. Panel geometry details for each panel type submitted for approval
   a. Plan details;
   b. Cross-section details (transverse and longitudinal); and
   c. Panel tolerances.
2. Reinforcement layout
   a. Bar details;
   b. Bar spacing; and
   c. Clear cover.
3. Load transfer provision details, as applicable (Note: Dowel bars used as an example; for other load transfer devices, provide similar relevant details.)
   a. Dowel bar properties (diameter, length, and spacing);
   b. Layout of dowel bar slots; and
   c. Layout of embedded dowel bars.
4. Lift insert details
   a. Layout; and
   b. Lift insert embedment details.
5. Panel lifting stress calculations (PCI 2004).
6. Layout of grout ports, as applicable.
7. Jointing details, as applicable
   a. Transverse joints; and
   b. Longitudinal joints.
8. For PPCP systems
   a. Tendon duct layout;
   b. Tendon details (type and diameter);
   c. Tendon anchorage details;
   d. Location of tendon duct grout ports;
   e. Tendon stressing–related details, as applicable
      - Stressing pockets
      - Anchorage pockets;
   f. Intermediate joint connectivity, as applicable
      - Conventional keyway
      - Double keyway; and
   g. Expansion joint details, as applicable
      - Joint sealing
      - Load transfer provision
      - Expansion joint panel details
      - Gap panel details.
9. For prestressed panels
   a. Tendon type and diameter; and
   b. Tendon spacing.
10. Any other detail deemed necessary for the specific system under review.

PCP System Installation Detail Sheet(s)

All necessary information and requirements related to the PCP system installation should be detailed on these sheets. This information should include the following as a minimum:

1. Base requirements
   a. Type; and
   b. Grading.
2. Bedding requirements
   a. Type;
   b. Thickness; and
   c. Placement method.
3. For repair applications
   a. Repair area dimensional tolerances;
   b. Load transfer provisions in the existing concrete pavements, as applicable
      - Provisions for dowel bar slots
      - Provisions for drilled and grouted dowel bars;
   c. Panel placement method
      - Placed directly on prepared base or bedding
      - Placed using strongback beams

- Placed using setting bolts
- Placed using polyurethane grout;

d. Panel alignment requirements
- Panel alignment within repair area
- Vertical alignment with respect to existing concrete pavement;

e. Load transfer provisions after panel placement
- Grouting or patching of dowel bar slots;

f. Longitudinal joint–related provisions;
g. Undersealing requirements; and
h. Opening to traffic
- At the end of lane closure before dowel bar slot grouting or patching and before undersealing
- At the end of next lane closure after dowel bar slot grouting or patching and before undersealing
- Cautionary notes related to opening to traffic.

4. For continuous jointed system applications

a. Panel placement method
- Placed directly on prepared base or bedding
- Placed using setting bolts
- Panel placement sequence;

b. Panel alignment requirements
- Panel alignment with respect to existing adjacent lanes and adjacent precast panels
- Vertical alignment along transverse and longitudinal joints;

c. Load transfer provisions after panel placement
- Grouting or patching of dowel bar slots;

d. Longitudinal joint–related provisions;
e. Undersealing requirements; and
f. Opening to traffic
- At the end of lane closure before dowel bar slot grouting or patching and before undersealing
- At the end of next lane closure after dowel bar slot grouting or patching and before undersealing
- Cautionary notes related to opening to traffic.

5. For PPCP applications

a. Panel placement method
- Placed directly on prepared base or bedding;

b. Panel alignment requirements
- Panel alignment with respect to existing adjacent lanes and adjacent precast panels
- Vertical alignment along transverse and longitudinal joints;

c. Connecting of adjacent panels
- Treatment of keyways
- Duct connection details
- Temporary posttensioning details;

d. Longitudinal joint–related details;
e. Posttensioning details
- Tendon load application
- Tendon elongation monitoring;

f. Expansion joint–related activities
- Setting expansion joint width
- Use of gap panel, as applicable
- Provisions for load transfer;

g. Longitudinal joint–related provisions;
h. Undersealing requirements;
i. PTSection anchoring details; and
j. Opening to traffic
- At the end of lane closure before dowel bar slot grouting or patching and before undersealing
- At the end of next lane closure after dowel bar slot grouting or patching and before undersealing
- Cautionary notes related to opening to traffic.

6. Post-installation activities, as applicable
- Joint sealing; and
- Surface grinding.

The removal of existing pavement is not incorporated in the PCP system approval process because such pavement removal is typically project-specific and contractor-specific and is independent of any PCP system that may be used. The PCP system approval process should be based on a standard granular base type.

In addition to the standard drawings submittal, the PCP vendor should provide supplemental information related to the materials and systems used. This supplemental information may include the following:

1. Cementitious materials mill reports per agency requirements;
2. Concrete aggregate test data per agency requirements;
3. Concrete test data per agency requirements;
4. Concrete admixture technical data sheets;
5. Lifting insert technical data sheets;
6. Proprietary grout and patching material technical data sheets;
7. Prestressing hardware technical data sheets;
8. Copies of plant certification;
9. Copies of plant personnel certification; and
10. Crane technical data sheet.

The standard drawings and supplemental information should be submitted to the highway agency at least 30 days before the trial installation of the system.

Trial Installation

The trial installation of a PCP system is an important part of the PCP system approval process. The trial section is the demonstration by the PCP system vendor that the proposed PCP system can be installed, within an imposed time constraint, using the panels as fabricated and using the prescribed materials, techniques, and equipment.

The trial installation of the PCP system provides an opportunity for the agency to identify potential problem areas and to require adjustments to be made before system approval or use of the system on a production project. The trial installation should be closely observed by representatives of the agency and the PCP system vendor. A full suite of the required acceptance tests should be conducted to verify compliance with specification requirements or test installation requirements.

The trial installation should meet all acceptance testing requirements without any corrective work needed for the as-placed test section panels. If the trial installation cannot be constructed without corrective work, it is unlikely that the contractor will be able to construct a quality PCP system in accordance with any project-specific specification. For the highway agency, the most successful outcome for the trial installation is full compliance with the specification. Therefore, it is important that the PCP system vendor demonstrate during the trial installation that a quality PCP system can be constructed in accordance with the agency specification.

The PCP system vendor is responsible for arranging the trial installation, at no cost to the highway agency, at a facility agreeable to the agency. The trial section should incorporate the following:

1. Work area
   a. For repair application: Work area bounded by an existing pavement or a simulated existing pavement. Work area dimensions must allow a 0.5-in. (13-mm)-perimeter gap around the panel to be used.
   b. For continuous application: Work area bounded by an existing pavement or a simulated existing pavement along the longitudinal joints. Work area dimensions must allow a 0.5-in. (13-mm) gap along the two longitudinal joints of the panels to be used.
2. Granular base: compacted and graded.
3. Number of panels
   a. For repair applications: two panels;
   b. For continuous jointed system: three panels placed contiguously; and
   c. For PPCP systems: a PTSection incorporating at least two end panels for a minimum length of 50 ft (15.2 m) and an expansion joint panel or a gap panel.

As a minimum, the following items should be evaluated:

1. The sequencing and duration of each installation activity;
2. Base compaction using an LWD;
3. Granular bedding compaction using an LWD;
4. Damage to panel(s) during placement;
5. Assessing the PCP system installation process with respect to the documented system installation process;
6. Understanding of the installation process by the installation crew;
7. Panel alignment with respect to specified alignment tolerances;
8. Vertical panel alignment with respect to adjacent panels or existing pavement or simulated existing pavement;
9. Effectiveness of tendon grouting for PPCP systems, including observations of grout leakage;
10. Observation of temporary posttensioning of adjacent panels for PPCP systems, including the treatment at the intermediate joints;
11. Observation of the posttensioning process for PPCP systems, including monitoring of tendon elongation;
12. LTE at transverse joints for repair applications and for jointed continuous systems;
13. LTE at transverse expansion joint(s) for PPCP systems; and
14. Observation of safety protocols by the work crew.

The following materials-related tests, as applicable, should be performed:

1. Grout sampling and testing;
2. Patching material sampling and testing; and
3. Polyurethane material sampling and testing.

The following tests should be performed on the installed PCP system:

1. Joint deflection testing
   a. LTE at transverse joints for repair applications and for jointed continuous systems; and
   b. LTE at transverse expansion joint(s) for PPCP systems.
2. Coring
   a. Cores over the dowel slots to examine grout and patching material coverage and to examine panel concrete quality; and
   b. Cores at several locations to evaluate the condition of the bedding material, if used.

Deflection Testing Requirements

Deflection testing should be performed using an FWD. The load applied for the LTE testing should be about 9,000 lb (4,082 kg). Tests should be performed about 2 ft (0.6 m) away from the lane edge (wheelpath location) and at the approach and leave sides of each tested joint.

Deflection testing at the joint is conducted to verify the ability of the load transfer system to transfer the wheel load across a joint. The testing also provides an indication of the overall response of the PCP system to the applied loading.

However, the overall response of the PCP system depends on the support system (subgrade, subbase, base, and bedding if used), and the support system is not an item of evaluation in the PCP system approval process. The adequacy and coverage of the bedding material, if used, should be determined by coring.

With respect to the ability of a load transfer system to transfer the applied load across a joint, the following two assessment approaches have been used:

1. LTE: The deflection at the joint of the unloaded side (d_u) is compared with the deflection at the joint of the loaded side (d_l). For new construction, an LTE of at least 90% is expected.
2. Relative deflection across the joint: The relative deflection across the joint (d_{rel}) is determined. This is simply the deflection at the joint of the loaded side minus the deflection at the joint of the unloaded side.

The relationship between LTE and d_{rel} is shown in Table 16.2 for a range of support conditions and an FWD load of 9,000 lb.

As Table 16.2 shows, no global relationship exists between LTE and d_{rel} because the LTE for a given d_{rel} is greatly influenced by the support condition and panel thickness. The stiffer the support and thicker the panel, the lower the LTE will be. Field testing of the PCP projects indicates that the joint deflection for repair applications and jointed PCP systems typically ranges from about 5 to 10 mils under FWD testing using a 9,000-lb (4,082-kg) load, indicating medium-stiff to stiff support for these projects. It is unlikely that any PCP trial section will be constructed over softer support conditions that result in joint deflections at the loaded side of 15 mils or greater under an FWD load of 9,000 lb (4,082 kg).

It is therefore recommended that for the purpose of a PCP system approval that incorporates the approval of a specific joint load transfer system, that the joint deflection criteria be based on the d_{rel} value, not to exceed 1.5 mils. This restriction will allow the LTE values to range from about 70% for a stiffer support condition to about 90% for a softer support condition. The proposed criterion is for system approval process only and is for assessment of the load transfer device itself and not for the evaluation of the entire PCP system. The proposed criterion is independent of slab (panel) curling and time of testing.

Although other deflection-based criteria may be used for a test section of a specific repair or rehabilitation project and for acceptance testing during the installation of the PCP system, it is recommended that the $d_{rel} \leq 1.5$ mils criterion be used for these purposes, as well. Using this criterion will allow acceptance of LTE <80% for a stiffer support condition; however, for stiffer support conditions the overall deflection is relatively small, and the joint deflection and the corresponding LTE value are less critical for long-term pavement performance.

For PPCP systems, the large joint width has a significant influence on the measured LTE and d_{rel} values. With that consideration, for the purpose of PCP system approval that incorporates the approval of a specific joint load transfer system, the joint deflection criteria for PPCP systems can be based on a d_{rel} value not to exceed 2.5 mils.

Table 16.2. LTE and Relative Deflection

Support Condition	d_l (mil)	LTE (%) for				
		d_{rel} = 0.5 mil	d_{rel} = 1 mil	d_{rel} = 1.5 mil	d_{rel} = 2 mil	d_{rel} = 5 mil
Stiff	4	88	75	63	50	NA
Stiff	5	90	80	70	60	0
Stiff	6	92	83	75	67	17
Stiff	8	94	88	81	75	38
Medium stiff	10	95	90	85	80	50
Medium stiff	12	96	92	88	83	58
Medium stiff	14	96	93	89	86	64
Softer	16	97	94	91	88	69
Softer	18	97	94	92	89	72
Softer	20	98	95	93	90	75

Note: NA = not available.

Approval of a PCP System by Comity

A highway agency may approve a PCP system without requiring a trial installation if the system has been approved for use by another agency within the past 12 months and the approval is based on the system described by the submitted standard drawings.

Summary

PCP technology is of recent origin, and it is likely that refinements to the existing systems will continue to be made and new systems or system components will be developed. It is therefore necessary that highway agencies establish an independent process for evaluating and approving new PCP systems or components. Guidelines for evaluating and approving new PCP systems or components were presented in this chapter. As a minimum, the following attributes of a new PCP system need to be evaluated before approval of the system:

1. Constructability within the constraints of the lane closure requirements;
2. Productivity of installation;
3. Concrete quality; and
4. Structural performance
   a. Transverse joint load transfer provisions
   b. Specific base and bedding support requirements.

Requiring PCP system vendors (precasters and contractors) to have their systems approved before use at a project reduces the risks associated with implementing a new system under difficult lane closures and other site constraints, including nighttime work and limited work hours.

CHAPTER 17

Summary and Recommendations

Summary

This report presents the information and findings developed under SHRP 2 Project R05. As discussed in the report, PCP technology is considered to be ready for implementation, as shown by the increasing use of this technology by many highway agencies in the United States. Other highway agencies are beginning to investigate the feasibility of these systems to meet their needs. The work carried out under Project R05 included the following:

1. Field testing at 15 projects in California, Delaware, Illinois, Michigan, Minnesota, Missouri, New Jersey, New York, Texas, and Virginia, in cooperation with highway agencies (with respect to traffic control, site access, and testing support);
2. Participation in prebid and preconstruction meetings organized by highway agencies;
3. Visits to construction projects and precast concrete fabrication plants; and
4. Interactions with the Illinois Tollway and agencies in California, Delaware, New Jersey, Nevada, and Virginia concerning the implementation of PCP technologies by these agencies.

This report details the current state of PCP technology in the United States and provides guidelines for the design, fabrication, and installation of PCP systems based on lessons learned to date and investigations carried out as part of Project R05. As described in this report, the products developed under Project R05 include the following:

1. Overall findings related to viability of PCP technology;
2. Findings based on SHRP 2 field testing;
3. Guidelines for PCP project selection;
4. Guidelines for PCP system acceptance;
5. Guidelines for design of PCP systems;
6. Guidelines for PCP fabrication; and
7. Guidelines for PCP installation.

The review of projects constructed in the United States and SHRP 2 field testing indicate that sufficient advances have been made to reliably achieve the following four key attributes of PCPs:

1. Constructability: Techniques and equipment are now available to ensure acceptable production rates for installation of PCP systems under a range of site conditions.
2. Concrete durability: Plant fabrication of the precast concrete panels results in excellent concrete quality with respect to strength and durability.
3. Load transfer at joints: Reliable and economical techniques are now available to incorporate effective load transfer at the transverse joints of jointed PCP systems.
4. Panel support condition: A range of techniques is available to provide adequate and uniform support conditions under the installed precast concrete panels. These techniques continue to be improved.

A few refinements are proposed as part of the Project R05 study. These include

1. Structural design changes
   a. Use of the AASHTO MEPDG, with PCP-specific distress criteria, to develop the structural design of PCP systems; and
   b. Systematic development of the prestressing requirements for PPCP systems.
2. Panel support condition changes
   a. Limiting the granular bedding material thickness to less than 0.25 in. (6 mm);
   b. Use of an LWD to test the compaction of reworked existing granular base or new granular base; and
   c. Use of rapid-setting materials as a new base or for thicker bedding.

3. Use of the relative deflection at active transverse joints to assess the effectiveness of the load transfer device to transfer load across the joint
   a. Limiting the relative deflection of the load transfer device at transverse joints to 2 mils; and
   b. The use of LTE to assess the effectiveness of the load transfer device is not recommended.
4. For transverse joint load transfer, use of narrow-mouth dowel bar slots at the surface, which allows opening to traffic before the dowel slots are patched.
5. For ICPCP systems, use of panels that are connected together using mechanical load transfer devices at the intermediate (nonactive) joints. This practice allows for a reduction in the number of active joints and less joint-related maintenance in the future.
6. For CRCP patching, use of precast panels using jointed FDR based on the CIP jointed FDR approach successfully used in South Carolina.

To date, the primary use of PCP technologies has been to achieve construction time savings in high-traffic-volume highway applications. Under current pricing scenarios, without the benefit of time savings, PCP technologies cannot be justified economically. To be applicable to rapid renewal situations, use of PCP technologies must result in reduced lane closures or better-managed lane closures that result in less traffic disruption and improved safety at construction zones. In addition, PCP systems must be capable of providing low-maintenance service life for the desired duration. Applications for new construction or rehabilitation (overlay or reconstruction) must be viewed as long-life pavements with the expectation of 40 or more years of low-maintenance service life.

The following considerations are basic to any PCP project:

1. PCPs, once installed, behave similar to like CIP concrete pavements; only the method of construction is different.
2. PCPs are not super pavements, even if the panels are fabricated with superior quality. Ultimately, the success of the PCP rests on the successful integration of all components of the PCP system. The quality of installation is critical to long-term performance of PCP systems.
3. All requirements related to concrete quality, load transfer at joints, and support conditions for CIP concrete pavements are applicable to PCP systems.
4. Installation productivity should not be an excuse for sacrificing design requirements and performance expectations.

Recommendations

PCP technology is maturing and continues to evolve. Significant improvements have been made in PCP technology over the past 10 years, and the next 10 years promise to be full of innovations that will ensure a permanent place for the application of PCP technology for longer-lasting rapid repair and rehabilitation of existing pavements. These innovations are expected to reduce the cost of panel fabrication and panel installation. Needed innovations include increasing the production rate for installing panels by simplifying or streamlining many of the site activities.

The following list suggests ways in which technical improvements can ensure efficient PCP systems and improve installation productivity:

1. Improvement in production rates for placing PCP systems to allow reduction in lane closure requirements
   a. For intermittent repairs, the minimum number of repairs to be performed per 8-hour nighttime lane closure should be 16
   b. For continuous applications, the minimum length of panel placement per 8-hour nighttime lane closure should be 400 ft (122 m);
2. Development of a low-height gantry crane to speed panel placement;
3. Development of auto-grading equipment for rapid trimming and grading of granular base and bedding material;
4. Implementation of QA/QC procedures for granular base and thicker bedding material, incorporating compaction testing;
5. Implementation of deflection testing as an acceptance testing protocol for ensuring load transfer effectiveness at active transverse joints; and
6. More effort during project development, as part of prebid surveys by owner–agencies or preconstruction surveys by the contractor, to establish the boundaries for repair or rehabilitation areas more accurately to minimize delays during panel placement resulting from trying to fit panels in very tight areas or leaving larger gaps along longitudinal and transverse joints.

Advances in better control of the work area and more mechanized techniques to prepare the work area and for panel placement will help extend the panel placement rate from the current 400 to 600 ft (122 to 183 m) to over 1,000 ft (305 m) per lane closure for continuous applications. The placement rate of at least 1,000 ft (305 m) per lane closure will ensure consideration of PCP systems as the primary choice for rapid rehabilitation of existing pavements in the United States.

A better competitive environment is needed so that engineers, contractors, and precasters continue to improve PCP technology and provide innovations that will lead to more efficient PCP system design, improved panel installation productivity, and reductions in PCP system costs. As PCP technology continues to evolve and new generic and proprietary PCP systems and PCP components are brought to the market place, technically supported assurances must be provided to owner–agencies that the new PCP systems and components will be capable of low-risk or risk-free implementation for rapid and durable repair of existing concrete pavements and for rapid and durable rehabilitation of existing asphalt and concrete pavements.

References

AASHTO. 2008. *Mechanistic–Empirical Pavement Design Guide: A Manual of Practice.* American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO TIG. 2008a. Generic Specification for Fabricating and Constructing Precast Concrete Pavement Systems. AASHTO Technical Implementation Group on Precast Concrete Pavement Systems, Washington, D.C.

AASHTO TIG. 2008b. Generic Specification for Precast Concrete Pavement System Approval. AASHTO Technical Implementation Group on Precast Concrete Pavement Systems, Washington, D.C.

AASHTO TIG. 2008c. Guidance and Considerations for the Design of Precast Concrete Pavement Systems. AASHTO Technical Implementation Group on Precast Concrete Pavement Systems, Washington, D.C.

AASHTO TIG. 2011. AASHTO Technical Implementation Group on Precast Concrete Pavements. http://tig.transportation.org. Accessed Jan. 5, 2013.

Bax, N., A. van Duerzen, and A. Molenaar. 2007. New Technique for Rapid Construction and Rehabilitation of Concrete Pavements. Proc., International Conference on Optimizing Concrete Mixtures and Accelerated Concrete Pavement Construction and Rehabilitation, Atlanta, Ga.

Buch, N. 2007. *Precast Concrete Panel Systems for Full-Depth Pavement Repairs: Field Trials.* Report HIF-07-019. FHWA, U.S. Department of Transportation, Washington, D.C.

CERTU, LCPC, and CIMBÉTON. 2008. *Chaussées Urbaines Démontables: Guide Technique 2008.* Technical publication. Paris.

de Larrard, F. 2006. Development of a Removable Urban Pavement Technology. Proc., 10th International Symposium on Concrete Roads, Brussels, Belgium.

de Larrard, F., T. Sedran, and J.-M. Balay. 2013. Removable Urban Pavements: An Innovative, Sustainable Technology. *International Journal of Pavement Engineering,* Vol. 14, No. 1, pp. 1–11.

Farrington, R., W. C. Rovesti, D. Steiner, and W. J. Switzer. 2003. Overnight Concrete Pavement Replacement Using a Precast Panel and Expanding Polymer Positioning Technique: Washington Dulles International Airport Case Study. Proc., Conference on Airfield Pavements: Challenges and New Technologies, American Society for Civil Engineers, Las Vegas, Nev.

Federal Highway Administration. 2010. *Precast Concrete Panels for Repair and Rehabilitation of Jointed Concrete Pavements.* Tech brief. IF-09-003. FHWA, U.S. Department of Transportation, Washington, D.C. www.fhwa.dot.gov/pavement/concrete/pubs/if09003/if09003.pdf. Accessed March 5, 2013.

Federal Highway Administration HfL. 2011. Utah Precast Concrete Pavement Showcase. Highways for LIFE Program Office, Federal Highway Administration, and Utah Department of Transportation, Salt Lake City.

fib. 2005. *Durability of Post-Tensioning Tendons.* Recommendation. Bulletin No. 33. Fédération Internationale du Béton, Lausanne, Switzerland.

Fort Miller Company. 2011. www.fmgroup.com. Accessed Jan. 5, 2013.

Gopalaratnam, V., B. M. Davis, C. L. Dailey, and G. C. Luckenbill. 2007. *Performance Evaluation of Precast Prestressed Concrete Pavement.* Report No. OR08-008. University of Missouri, Columbia.

Hachiya, Y., F. Akamine, O. Takahashi, and Y. Miyaji. 2001. Rapid Repair with Precast Prestressed Concrete Slab Pavements Using Compression Joint System. Proc., 7th International Conference on Concrete Pavements, International Society for Concrete Pavements, Orlando, Fla.

Hall, K., and S. Tayabji. 2008. *Precast Concrete Panels for Repair and Rehabilitation of Jointed Concrete Pavements.* Tech brief IF-09-003. FWHA, U.S. Department of Transportation, Washington, D.C.

Houben, L. 2004. Accelerated Load Testing and Modeling of "Modieslab" Concrete Pavement Structure. Proc., 5th International CROW Workshop on Concrete Pavements, Istanbul, Turkey.

Illinois Tollway Authority. 2009. Precast Concrete Pavement Slab System. Downers Grove.

Kohler, E., L. du Plessis, P. J. Smith, J. Harvey, and T. Pyle. 2007. Precast Concrete Pavements and Results of Accelerated Traffic Load Test. Proc., International Conference on Optimizing Paving Concrete Mixtures and Accelerated Concrete Pavement Construction and Rehabilitation, Atlanta, Ga.

Krauser, L. 2011a. Achieving Protection of Internal Tendons Through Continuous Duct Enclosures in Segmental Bridge Construction. Proc., Fédération Internationale du Béton Symposium, Prague, Czech Republic.

Krauser, L. 2011b. FHWA ACPT Precast Pavement Task Force Meeting. Pleasanton, Calif.

Krauser, L. 2011c. Selecting Posttensioning Tendon Protection Levels. Proc., Fédération Internationale du Béton Symposium, Prague, Czech Republic.

Kwik Slab. 2011. www.kwikslab.com. Accessed Jan. 5, 2013.

Lane, R., and T. Kazmierowski. 2005. Use of Innovative Pre-Cast Concrete Slab Repair Technology in Canada. Proc., 8th International Conference on Concrete Pavements, Colorado Springs, Colo., pp. 771–789.

Manual of Uniform Traffic Control Devices. 2009. FHWA, U.S. Department of Transportation, Washington, D.C.

Merritt, D. K., B. F. McCullough, and N. H. Burns. 2002. *Construction and Preliminary Monitoring of the Georgetown, Texas Precast Prestressed Concrete Pavement.* Report TX-03-1517-01-IMP-1. FHWA, Texas Department of Transportation, Austin.

Merritt, D. K., B. F. McCullough, N. H. Burns, and A. K. Schindler. 2000. *The Feasibility of Using Precast Concrete Panels to Expedite Highway Pavement Construction.* Report TX-01/1517-1. FHWA, Texas Department of Transportation, Austin.

Merritt, D. K., R. B. Rogers, and R. O. Rasmussen. 2008. *Construction of a Precast Prestressed Concrete Pavement Demonstration Project on Interstate 57 near Sikeston, Missouri.* Draft report RD-08-XXXX. FHWA, U.S. Department of Transportation, Washington, D.C.

Merritt, D., and S. Tayabji, 2009. *Precast Prestressed Concrete Pavement for Reconstruction and Rehabilitation of Existing pavements,* Report FIF-09-008, FHWA, U.S. Department of Transportation, Washington, D.C.

Minnesota DOT. 2008. *Putting Research into Practice: Using the DCP and LWD for Construction Quality Assurance.* Publication IMPL-LWDTS. Minneapolis.

Minnesota DOT. 2011. *Pilot Light Weight Deflectometer (LWD) Deflection Method: Provisional Specification.* Minneapolis.

Nantung, T. E., J. Firmansjah, E. Suwarto, and H. M. Hidayat. 2010. Design and Construction of Precast Prestressed Concrete Pavement in Indonesia. Presented at 89th Annual Meeting of the Transportation Research Board, Washington, D.C.

Nishizawa, T. 2008. Japanese Experience of Precast Concrete Pavement. Presented at 9th International Conference on Concrete Pavements, International Society for Concrete Pavements, San Francisco, Calif.

NPCA. 2011. *NPCA Quality Control Manual for Precast and Prestressed Concrete Plants,* 8th ed. National Precast Concrete Association, Carmel, Ind.

Nussbaum, P., S. Tayabji, and A. Ciolko. 1983. *Prestressed Pavement Joint Designs.* Report RD-82/090. FHWA, U.S. Department of Transportation, Washington, D.C.

PCI. 1999. *Manual for Quality Control for Plants and Production of Structural Precast Concrete Products,* 4th ed. Document MNL-116-99. Precast/Prestressed Concrete Institute, Chicago, Ill.

PCI. 2004. *PCI Design Handbook: Precast and Prestressed Concrete,* 6th ed. Precast/Prestressed Concrete Institute, Chicago, Ill.

PTI. 2006. *Posttensioning Manual,* 6th ed. Posttensioning Institute, Farmington Hills, Mich.

PTI–ASBI. 2010. *Guide Specification for Grouted Posttensioning.* Draft. Posttensioning Institute, Farmington Hills, Mich., and American Segmental Bridge Institute, Buda, Tex.

Roman Stone Construction Company. 2011. http://www.romanstoneco.com. Accessed Jan. 5, 2013.

Sapozhnikov, N., and R. Ray. 2007. Soviet Precast Prestressed Concrete Pavement Construction for Airfields. Presented at FAA Worldwide Airport Technology Transfer Conference, Atlantic City, N.J.

Simonsen, J. E. 1971. *Concrete Pavement Joint Repair with Pre-Cast Slabs: Progress Report.* Research report R-762. Michigan State Highway Commission, Lansing.

Smith, K. D., T. E. Hoerner, and D. G. Peshkin. 2008. *Concrete Pavement Preservation Workshop: Reference Manual.* National Concrete Pavement Technology Center, Ames, Iowa.

Smith, P., and E. Barenberg. 2005. Using Precast Super Slab for Rapid Repair of Concrete Pavements. Proc., 8th International Conference on Concrete Pavements, International Society for Concrete Pavements, Colorado Springs, Colo.

Smits, F. 2004. ModieSlab: Innovative Prefabricated Modular Concrete Slab for Concrete Roads and Airfields. Presented at 9th International Symposium on Concrete Roads, Istanbul, Turkey.

Switzer, W. J., A. Fischer, G. K. Fuselier, P. J. Smith, and W. Verfuss. 2003. Overnight Pavement Replacement Using Precast Panels and Conventional Subgrade Material: Washington Dulles International Airport Case Study. Proc., Conference on Airfield Pavements: Challenges and New Technologies, American Society for Civil Engineers, Las Vegas, Nev.

Tayabji, S. 2005. Framework for Design and Construction of Long-Life Concrete Pavements. Proc., 8th International Conference on Concrete Pavements, International Society for Concrete Pavements, Colorado Springs, Colo.

Tayabji, S. D., E. J. Barenberg, W. Gramling, and P. Teng. 2001. Prestressed Concrete Pavement Technology Update. Proc., 7th International Conference on Concrete Pavements, International Society for Concrete Pavements, Orlando, Fla.

Tomoyuki, T. 1996. Joint Structure for Coupling Precast Concrete Pavement Slabs. United States Patent No. 5586834.

Tyson, S. S. 1976. *Full-Depth Repair of Jointed PCC Pavements Cast-in-Place and Precast Procedures.* VHTRC 76-R44. Virginia Highway and Transportation Research Council, Charlottesville.

Uretek. 2013. www.uretekusa.com. Accessed Jan. 5, 2013.

Yue, S. C., S. Murrel, and E. Larrazabal. 2003. Precast Concrete Pavement Tests on Taxiway D-D at LaGuardia Airport. Proc., Conference on Airfield Pavements: Challenges and New Technologies, American Society for Civil Engineers, Las Vegas, Nev.

APPENDIX A

List of U.S. and Canadian Precast Concrete Pavement Projects

Table A.1. Intermittent Repair and Jointed PCP Projects

Project	Location	Area (ft^2)	System Type	Installation Type	Panel Type	Date of Installation	Thickness (in.)
Test section	Fontana, Calif.	1,950	Super Slab	Test section	Single plane	May 2005	8¾
I-15	Ontario, Calif.	NA	Super Slab	Continuous	S and W plane	2010	8
I-680	Pleasanton, Calif.	NA	Caltrans	Intermittent	Single plane	2011	8¾
I-680	Pleasanton, Calif.	NA	Caltrans	Continuous	Single plane	2011	8¾
I-25 Colorado	North of Denver, Colo.	16,200	Uretek	Intermittent	Single plane	2003	7½ to 8½
US-63 over CR C-50	Denver, Colo.	3,465	Iowa DOT Generic	Continuous	NA	NA	NA
NA	Chicago, Ill.	768	Super Slab	Trial	Single plane	Sept. 2007	12
I-88	Chicago, Ill.	476	Super Slab	Special	Single plane	Oct. 2007	12
I-294	Chicago, Ill.	2,672	Super Slab	Continuous	S and W plane	Nov.–Dec. 2007	12
I-88	Chicago, Ill.	4,338	Super Slab	Continuous	S and W plane	June 2008	13
I-675 and M25	Michigan	1,080	Michigan and Uretek	Intermittent	Single plane	2003	9
I-94	Benton Harbor, Mich.	NA	Michigan and Uretek	Intermittent	Single plane	June 2002	10
TH-62	Minneapolis, Minn.	2,592	Super Slab	Continuous	Single plane	June 2005	9¼
I-295	Burlington County, N.J.	30,395	Super Slab	Intermittent	Single plane	Fall 2007–Spring 2008	8¾
Route 21	Newark, N.J.	69,810	Super Slab	Intermittent and continuous	Single plane	Summer–Fall 2008	8¾
I-280	Essex County, N.J.	38,000	Super Slab	Intermittent	Single plane	Fall 2008–Summer 2009	8¾
Route 42	Camden and Gloucester, N.J.	32,034	Super Slab	Intermittent and continuous	S and W plane	Summer 2009	8¾
Route 130	New Jersey	NA	Super Slab	Intermittent (or continuous)	Single plane	Summer 2009	8¾
US 395	Reno, Nev.	NA	Super Slab	Continuous	Nonplanar	2010	8
Marine Parkway	New York	6,815	Super Slab	Continuous	Nonplanar	June 2005	8¾

Table A.1. Intermittent Repair and Jointed PCP Projects (continued)

Project	Location	Area (ft^2)	System Type	Installation Type	Panel Type	Date of Installation	Thickness (in.)
Tappan Zee Bridge Toll Plaza	Tarrytown, N.Y.	158,000	Super Slab	Continuous	Single plane	Oct. 2001–July 2002	10
High-speed EZ Pass slabs	New York	576	Super Slab	Special	Single plane	Aug. 2006	11
I-95	New Rochelle, N.Y.	84,700	Super Slab	Intermittent	Single plane	Summer 2007	9¾
9A ramp	Tarrytown, N.Y.	15,750	Super Slab	Continuous	Nonplanar	Aug. 2003	10
Korean Veterans Parkway	Staten Island, N.Y.	8,850	Super Slab	Intermittent	Single plane	Nov.–Dec. 2003	8
Port Jefferson	New York	2,650	Super Slab	Crosswalks	Nonplanar	July 2005	9
I-90	New York	56,400	Super Slab	Intermittent	Single plane	Summer 2005	8¾
Route 7 cross town	Schenectady, N.Y.	26,586	Super Slab	Continuous and intermittent	S and W plane	July 2006	8¾
NA	Schuylerville, N.Y.	1,152	Super Slab	Trial	S and W plane	Oct. 2006	8¾
Southern State Parkway	New York	2,483	Super Slab	Intermittent	Single plane	June 2007	8
Route 17	Binghamton, N.Y.	544	Super Slab	Bridge approaches	Single plane	Summer 2009	14¾
W. Shore Expressway	Staten Island, N.Y.	22,473	Super Slab	Bridge approaches	Nonplanar	Fall 2008–Summer 2009	9½ and 11½
NA	Nassau and Suffolk County, N.Y.	3,640	Super Slab	Intermittent	Single plane	Fall 2008–Summer 2009	8
Belt Parkway ramps	New York, N.Y.	16,030	Super Slab	Continuous	Nonplanar	Aug. 2003	10
Fordham Road	Bronx, N.Y.	3,852	Super Slab	Continuous	S and W plane	Dec. 2006	8
Memorial Hwy and Division St.	New Rochelle, N.Y.	3,041	Super Slab	Continuous	Single plane	Fall 2008	9¾
Nassau Expressway	Queens, N.Y.	85,000	Super Slab	Continuous	Nonplanar	Summer 2009	8¾
SH-27	Westhampton, N.Y.	NA	Roman Stone	Intermittent	Single plane	Nov. 2009	8
LaGuardia Airport	Queens, N.Y.	5,000	Michigan	Test	Single plane	Sept. 2002	16 and 12
Lincoln Tunnel	New Jersey	8,100	Super Slab	Intermittent	Single plane	July 2003	12
NA	Toronto, Ontario	1,220	Super Slab	Intermittent and continuous	Single plane	Nov. 2004	8¾
Autoroute 427	Toronto, Ontario	15,156	Super Slab	Intermittent	Single plane	July 2008	8¾
Autoroute 427	Toronto, Ontario	31,366	Super Slab	Intermittent	Single plane	Fall 2008–Summer 2009	8½ and 8
I-676 Vine Street Expressway	Philadelphia, Pa.	5,699	Super Slab	Intermittent	Single plane	Summer 2009	10 and 12
Autoroute 13	Montreal, Quebec	31,000	Super Slab	Continuous	Single plane	July–Aug. 2008	15¾ and 10½

(continued on next page)

Table A.1. Intermittent Repair and Jointed PCP Projects (continued)

Project	Location	Area (ft²)	System Type	Installation Type	Panel Type	Date of Installation	Thickness (in.)
I-15	Layton to Clear Field, Utah	28,800	Super Slab	Intermittent and continuous	Single plane	Summer 2009	8
F-R199(28)	Utah	NA	Super Slab	Intermittent and continuous	Single plane	Awarded March 11, 2010	NA
F-I15-8(128)352, I-15	Box Elder County, Utah	NA	Utah DOT generic	Intermittent and continuous	Single plane	2011	9¾
Dulles Airport Taxiway repair	South Riding, Va.	3,500	Super Slab	Intermittent	Nonplanar	Nov. 2002	13
US-60	Virginia	432	Michigan	Intermittent	Single plane	June 2005	9
I-66 ramp to Route 50	Fairfax, Va.	NA	Super Slab	Continuous	Nonplanar	Summer 2009	8¾

Note: NA = not available; S and W plane = single plane and warped.

Table A.2. Eight PPCP Projects: Basic Information

Project	Location	Date of Installation	No. of Posttensioned Sections	Panels/ Section	Total No. of Panels	Panel Dimensions	Panel Thickness (in.)
Eastbound I-10	El Monte, Calif.	April 2004	2	15	31	37 × 8 ft	10 to 13.1
I-680	Oakland, Calif.	May–July 2011	NA	3 to 6	NA	Single lanes: 12 × 18 ft to 12 × 36 ft	8¾
I-5 to Route 14 ramp	Sylmar, Calif.	Feb. 2011	4	11.5, 12, 13, or 7.5	43	36 Single and dual lanes: 17.7 × 8 ft	8
Northbound Route 896 at US-40	Newark, Del.	May–July 2009	10	12, 13, or 14	130	Seven panels: 29.5 × 8 ft	8
Highway 60	Sheldon, Iowa	Aug.–Sept. 2006	2	4	12 Typical panels and four skewed panels	Typical: 14 × 20 ft Skewed: 14 ft × variable length	12
Northbound I-57	Sikeston, Mo.	Dec. 2005	4	25	101	38 × 10 ft	5⅝ to 10⅞
Northbound I-35 frontage road	Georgetown, Tex.	Fall 2001	9	22, 25 (typical), or 32	339	Double lane: 36 × 10 ft Single lane: 16 × 10 ft, 20 × 10 ft	8
Westbound I-66	Fairfax, Va.	Aug.–Oct. 2009	7	11 or 16	306	Single lane: 12 × 10 ft Double lane: 27 × 10 ft	8¾

Note: NA = not available.

Table A.3. Eight PPCP Projects: Specific Parameters

Project	Base Type	Expansion Joint	Friction-Reducing Treatment	Pretensioning Details	Longitudinal and Transverse Posttensioning Details	Remarks
Eastbound I-10	LCB	Preformed compression seal	Polyethylene sheet	Six 0.5-in. Grade 270 strands	Monostrand tendons, 0.6-in. Grade 270 strand at 3 ft on center	None
I-680	Rapid-setting LCB	Compression seal	Polyethylene sheet	NA	Six monostrand tendons, 0.6-in. Grade 270 strand; two per duct	Each post-tensioned section completed and tendon grouted per lane closure
I-5 to Route 14 ramp	Rapid-setting LCB	Compression seal	Polyethylene sheet	Longitudinal: Six 0.5-in. Grade 270 strands	17.7-ft-wide panels: Six 0.6-in. Grade 270 tendons 29.5-ft-wide panels: 10 0.6-in. Grade 270 tendons	None
Northbound Route 896 at US-40	4-in. Pervious concrete base over existing base/subbase	Preformed compression joint seal	Geotextile fabric	Base panels: Seven 0.5-in. Grade 270 strands Joint panels: Eight 0.5-in. Grade 270 strands	Monostrand tendons, 0.6-in. Grade 270 strand at 2 ft 6 in. on center with two 1-in. threaded bars replacing the strands at quarter points	None
Highway 60	Aggregate base trimmed to pavement crown	NA	Polyethylene sheet	NA	Monostrand tendons, 0.6-in. Grade 270 strand at 2 ft on center	None
Northbound I-57	4-in. Permeable asphalt-stabilized base over 4-in. Type 1 base	Header joint with poured joint compound	Polyethylene sheet	Base panels: Eight 0.5-in. Grade 270 strands Joint panels: 12 0.5-in. Grade 270 strands	Monostrand tendons, 0.6-in. Grade 270 strand at 2 ft on center	Installation rate: 12 panels/ 6 hours. Instrumented.
Northbound I-35 frontage road	2-in. Dense graded asphalt base over compacted embankment	Armored joint	Polyethylene sheet	Six 0.5-in. Grade 270 strands	Longitudinal: monostrand tendons, 0.6-in. Grade 270 strand at 2 ft on center (posttensioned in 250-, 225-, and 325-ft sections) Transverse (partial-width panels only): two 0.5-in. strands per tendon, one tendon per panel	Installation rate: 25 panels/ 6 hours
Westbound I-66	1- to 3-in. No. 10 stone leveling course over existing base/ subbase	Preformed compression joint seal	Geotextile fabric	Eight 0.5-in. Grade 270 strands	Monostrand tendons, 0.6-in. Grade 270 strand at 2 ft 6 in. on center with two 1-in. threaded bars replacing the strands at the quarter points	None

Note: NA = not available.

APPENDIX B

Precast Concrete Pavement Technology Implementation Plan

The success of any new technology lies in successful implementation of the technology. Typically, implementation of technologies by public agencies can take many years because of the need to fully validate the new technology before production use. At present, several highway agencies have fully adopted PCP technology for production use in intermittent repair or continuous rehabilitation applications. Some highway agencies have carried out demonstration projects, and others are investigating the feasibility of the technology. It is hoped that the SHRP 2 Renewal Project R05 findings and documentation will provide a stimulus to many agencies to consider implementation of PCP technology for rapid repair and rehabilitation of existing pavements.

PCP technology is maturing and continues to evolve. Significant improvements have been made in PCP technology over the past 10 years, and the next 10 years promise to be full of innovations that will ensure a permanent place for the application of PCP technology for longer-lasting rapid repair and rehabilitation of existing pavements. These innovations are expected to reduce the cost of panel fabrication and panel installation. The success of PCP technology depends on the market demand for the technology. For contractors and precasters to be fully involved in PCP technology and to invest in supporting improvements in the technology, it is necessary that an expanding market develop for PCP systems.

The key work items under Project R05 include the following:

1. Identification of PCP systems and U.S. and international practices;
2. Evaluation of PCP performance;
3. Development of guidelines for the selection, design, fabrication, and installation of PCP systems; and
4. Development of model specifications.

The final report for SHRP 2 Renewal Project R05 includes the following:

1. Technical information developed under Project R05;
2. Guidelines for design of PCPs;
3. Guidelines for fabrication and installation of PCPs;
4. Guidelines for repair of PCP systems;
5. Guidelines for selection of PCPs;
6. PCP system approval process; and
7. Model specifications for PCP systems.

To implement PCP technology most expeditiously, it is important that the relevant Project R05 findings be disseminated appropriately to specific target groups. These target groups include the following:

1. Highway agencies
   a. Senior management staff
   b. Engineering staff;
2. Contractors;
3. Precasters;
4. Industry trade associations;
5. Engineering and testing consultants; and
6. Academia.

In addition, the current momentum generated by SHRP 2 Project R05, FHWA PCP-related activities, and highway agency support of the technology needs to be maintained by follow-up activities that showcase current PCP technologies and new developments.

Proposed PCP Technology Implementation Strategies

It is proposed that PCP technology implementation efforts be directed as follows:

1. Stakeholder buy-in;
2. Technology transfer activities; and
3. Technology improvement.

These proposed efforts are discussed next.

Stakeholder Buy-In

Successful implementation of Project R05 findings and products will require a partnership between SHRP 2, FHWA, highway agencies, academia, and industry groups (contractors, precasters, and trade associations) to ensure there is buy-in of the PCP technology by all stakeholders. Proper channels should be available to obtain input and feedback from the stakeholder groups. Implementation-related activities to consider include the following:

1. Organizing an expert task group of stakeholder representatives to provide feedback to SHRP 2 and FHWA on PCP technology implementation directions and to develop action items to address potential barriers to wider implementation of the technology;
2. Presenting information at FHWA, state highway agency, and industry-organized regional meetings and open houses (2011 to 2013); and
3. Presenting information at meetings of the construction community, such as the American Concrete Pavement Association (ACPT), the Precast/Prestressed Concrete Institute, and the National Precast Concrete Association, to encourage buy-in by precasters and contractors.

Technology Transfer Activities

In the current economic environment, most state DOTs have administered severe travel restrictions and have cut back on training and technology transfer activities. Therefore, this marketing plan incorporates various mechanisms for personalized technology transfer activities, including web-based training. The proposed approach for the deployment and delivery of Project R05 findings and products is summarized below:

1. Develop a briefing paper on the Project R05 study, documenting findings and products.
2. Organize a half-day workshop on PCP technology at the 2012 TRB annual meeting. Expand the workshop material to develop a webinar-type series of presentations on specific PCP topics.
3. Develop a construction (installation) video on specific PCP applications, using case studies. (Note: the FHWA HfL Program has developed video content from several open houses that can be integrated in any SHRP 2 technology transfer activities.)
4. Organize a forum on PCP technology at the FHWA ACPT Conference on Long-Life Concrete Pavements, to be held in Seattle in September 2012.
5. Organize a 2-day national conference on design and construction of PCPs (2013).
6. Present technical papers at TRB annual meetings and at other conferences (2012 and 2013).
7. Develop National Highway Institute (NHI)–style 1-day workshop training materials and develop programs to provide such training to stakeholder groups.
8. Establish through SHRP 2, FHWA, or other public or private organizations a dedicated website for currently available technical information and information that may be developed in the future, such as reports, case studies, technical briefs, video clips, and state DOT plans, special provisions, and specifications.

Technology Improvement

PCP technology is an implementable technology for rapid repair and rehabilitation of existing pavements in high-volume traffic applications where lane closures are difficult. Although significant improvements have been made in PCP technology over the past 10 years, the future promises innovations that will ensure a permanent place for the application of PCP technology for longer-lasting rapid repair and rehabilitation of existing pavements. These innovations are expected to reduce the cost of panel fabrication and installation. As the technology evolves, it will be necessary to continue to validate the new developments by means of demonstration projects, by accelerated testing, and by monitoring the long-term performance of constructed PCP projects. The following activities are proposed:

1. Continue to showcase PCP systems and applications by supporting the construction of demonstration projects by highway agencies and by sponsoring open houses at these demonstration projects. The demonstration projects will provide a clear vision to highway agencies of how PCP applications can serve to enhance their strategies for performance management of pavement facilities in high-volume traffic corridors.
2. Validate new developments in PCP technology using accelerated pavement testing (APT) facilities. These facilities could be located in different regions of the United States. Such testing will provide needed performance data for specific innovative features in a short period of time. APT data will also provide additional assurance to user agencies of the long-term performance of precast pavement systems.
3. Validate existing and new PCP technologies using road test facilities, such as the MnRoad facility in Minnesota. These facilities can be used to evaluate, under actual highway traffic conditions, various features of a PCP system over several seasonal cycles, including seasonal sensitivity of the PCP design features, materials used, and construction techniques.
4. Establish a national long-term monitoring program for constructed PCP projects. Details of such a program are given in Appendix C. The national PCP long-term performance monitoring program will do the following:
   a. Provide a performance database to support calibration of pavement structural design procedures for each PCP system;
   b. Identify successful design and installation practices
      - Best practices for joint load transfer techniques
      - Best practices for base and bedding use; and
   c. Identify the performance of any repairs performed on the PCP systems.

APPENDIX C

Long-Term Performance Evaluation Plan

Introduction

PCP technology is of recent origin, and the age of in-service PCP systems is less than 10 years. As indicated in the final report, no national effort has documented the performance of the in-service PCP systems used for intermittent repair and continuous application projects. A limited amount of testing was performed at 15 PCP projects under the SHRP 2 Renewal Project R05 study. The objectives of this testing were to develop performance data to provide highway agencies immediate feedback on how typical PCP systems are performing and to identify any performance-related issues that need to be addressed. However, there is a critical need to establish a national PCP performance monitoring program that will

1. Provide a performance database to support calibration of pavement structural design procedures for each PCP system;
2. Identify successful design and installation practices
   a. Best practices for joint load transfer techniques
   b. Best practices for base and bedding use; and
3. Identify the performance of any repairs performed on PCP systems.

This appendix provides guidelines and instructions for collection of data for a systematic long-term performance monitoring plan for PCP systems. This plan is designed to establish a precast pavement performance database that will help identify the best practices for PCP technologies.

This plan should be used in conjunction with the following manuals and standards:

- *Distress Identification Manual for the Long-Term Pavement Performance Program*, 4th rev. ed., June 2003;
- *Long-Term Pavement Performance Program Manual for Falling Weight Deflectometer Measurements*, Version 4.1, December 2006;
- *LTPP Manual for Profile Measurements and Processing*, November 2008; and
- ASTM E274/E274M-11 Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire, 2011.

Data elements for the long-term performance evaluation plan are classified into three main groups:

1. Inventory database;
2. Construction database; and
3. Performance database.

Inventory Database

Project information

1. Project ID
2. Location
3. Agency and contact
4. General contractor and contact
5. Panel fabricator and contact
6. Traffic data
   - Construction year and annual average daily traffic
   - Construction year truck percentage
   - Construction year traffic growth rate
7. Climatic data
   - Climatic zone
   - Annual rainfall
   - Average annual maximum temperature
   - Average annual minimum temperature
   - Cooling degree days

8. Traffic management information (comment box)
9. Existing pavement data (for repair projects)
    - Year of construction
    - Slab thickness
    - Specified concrete strength
    - Base type and thickness
    - Subbase type and thickness
    - Subgrade type
    - Distress types being addressed by precast pavement repair or rehabilitation
10. Preparatory repairs (e.g., drainage, shoulder strengthening)

Panel design information

1. Panel dimensions
    - Thickness
    - Length
    - Width
2. Reinforcement
    - Longitudinal
    - Transverse
3. Pretensioning data
    - Longitudinal pretensioning (if applicable)
        - Tendon diameter
        - Tendon spacing
        - Tendon force
    - Transverse pretensioning (if applicable)
        - Tendon diameter
        - Tendon spacing
        - Tendon force
4. Panel concrete data
    - Required strength and age
    - Fresh concrete test data (e.g., slump, air, unit weight)
    - Early-age strength and age (for installing and opening to traffic)
    - Mixture design information (comment box)
5. Transverse joint load transfer data
    - Slot location (surface, bottom, or special configuration)
    - Dowel diameter
    - Dowel length
    - Dowel spacing
    - Number of dowels per joint
    - Allowable joint gap
    - Slot patching material strength requirement and age
6. Longitudinal joint data
    - Tie bar installation method (slot or cross-stitching)
    - Slot location (if applicable)
    - Tie bar diameter
    - Tie bar length
    - Allowable joint gap
7. Base preparation
    - Bedding layer thickness
    - Undersealing material strength requirement and age; and

Panel fabrication data

1. Plant location
2. Modifications to original plans and specifications
3. Form type
4. Form release age
5. Steam curing, if any, and length
6. Panel age at time of shipping
7. Panel transportation distance to project site
8. Number of panels shipped per truck load
9. Challenges during fabrication
10. Process control test data
11. Acceptance testing test data.

Construction Database

Field installation data

1. Panel installer and contact
2. Dates of installation (start and end)
3. Rate of panel installation per closure
4. Modifications to original plans and specifications
5. Field crane type and capacity
6. Rate of placement (number of panels per night)
7. Number of actual days of placement (requiring lane closures)
8. Challenges during field installation
9. Process control test data
10. Acceptance testing data
11. Slot patch material data
12. Undersealing material data
13. Posttensioning duct grout data
14. Surface grinding data
15. Posttensioning data (if applicable)
    - Posttensioning contractor and contact
    - Longitudinal posttensioning (if applicable)
        - Tendon diameter
        - Tendon spacing
        - Tendon force
    - Transverse posttensioning (if applicable)
        - Tendon diameter
        - Tendon spacing
        - Tendon force; and

Traffic management data

1. Lane closure times (start and end)
2. Weekday and weekend lane closure requirements

3. Number of lanes closed
4. Length of closures
5. Challenges during traffic management
6. Other information.

Performance Database

For the performance database, it will be necessary to establish a test section of each included project that is considered representative of the project features. The test section characteristics should be as follows:

1. Intermittent repair projects: 20 representative repair panels within a length that allows for lane closure optimization; and
2. Continuous application projects
   a. PPCP projects: at least three posttensioned sections
   b. JPrCP projects: a 500-ft section.

The performance database should include the following items:

1. Distress;
2. Joint width;
3. Deflection;
4. Profile; and
5. Friction (skid resistance).

A 2-year interval is recommended for collecting the field performance data. This length of time acknowledges that most locations with PCP projects will have high traffic volumes and that lane closures for routine testing would be difficult.

Distress

Distress condition surveys of the precast panels should be carried out in general accordance with the procedures outlined in the *Distress Identification Manual.* Specific distresses to look for include slab panel cracking, joint spalling, poor surface condition, condition of dowel slot pockets (if applicable), and joint sealant condition. Photographs of representative distresses should be obtained. For PPCP systems, the condition of the expansion joint hardware and the patched boxed-out areas (e.g., stressing pockets) should be noted.

In addition to the general distress survey, faulting (elevation difference) measurements should be taken. Faulting should be measured for joints associated with the installed precast panels. Joint location and air temperature should be noted for each measurement. Joint differential elevations should be measured to the nearest 0.1 in. A Georgia faultmeter may be used for this measurement, in accordance with the protocol established under the LTPP program.

Distress data should be collected once every 2 years.

Table C.1. FWD Test Load Levels

Drop No.	No. of Drops	Target Load [lbf (kN)]
Seating	2	9,000 (40.0)
1	2	6,000 (26.7)
2	2	9,000 (40.0)
3	2	12,000 (53.4)
4	2	15,000 (66.7)

Note: FWD = falling weight deflectometer.

Joint Width

Joint width should be measured for joints associated with the installed precast panels. Joint location and air temperature should be noted for each measurement. Joint widths should be measured to the nearest 0.1 in. using an ordinary scale.

Joint width data should be collected twice every 2 years, once during the winter season and once in the summer.

Deflection

Deflection testing should be performed in accordance with the *Long-Term Pavement Performance Program Manual for Falling Weight Deflectometer Measurements.* Two types of testing should be conducted: interior (basin) testing and joint testing. The recommended load levels and number of drops per load level are presented in Table C.1.

Table C.2 shows the recommended sensor offsets.

Table C.3 lists the description of each of the testing locations.

For intermittent repair projects, testing locations are 1 through 8, as shown in Figure C.1. For continuous rehabilitation projects, testing locations are 1 through 3 for each precast panel to be tested, as shown in Figure C.1. Testing as many locations as possible during a given closure is recommended.

Table C.2. Deflection Sensor Offsets for a Six-Sensor FWD

Deflection Sensor	Offset	
	mm	in.
D1	0	0
D2	–305	–12
D3	305	12
D4	610	24
D5	914	36
D6	1,524	60

Table C.3. Drop Locations for Intermittent Repairs

Location	Description
1	Approaching LTE at an approaching joint
2	Leaving LTE at an approaching joint
3	Interior testing for a precast panel
4	Approaching LTE at a leaving joint
5	Leaving LTE at a leaving joint
6	Interior testing for an existing panel
7	Approaching LTE at an existing joint
8	Leaving LTE at an existing joint

Note: LTE = load transfer effectiveness.

For PPCP projects, testing should be conducted at the outer wheelpath at transverse expansion joints and at several midslab locations of the PPCP sections, as shown in Figure C.2.

Deflection testing should be conducted once every 2 years. For PPCP projects, additional nighttime testing may be necessary during some years to investigate the effect of upward curling on the long posttensioned sections.

Profile

Profile testing should be conducted along the outside wheelpath of the highway section that incorporates precast concrete panels. Test data should be reported as International Roughness Index values. Although a single pass is adequate for each lane that incorporates the precast concrete panels, additional passes may be made if feasible. Profile testing should conform to the *LTPP Manual for Profile Measurements and Processing*. Profile data should be collected every 2 years.

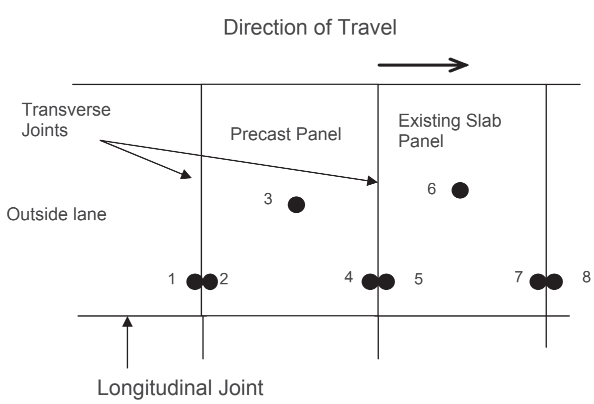


Figure C.1. FWD test locations for jointed systems.

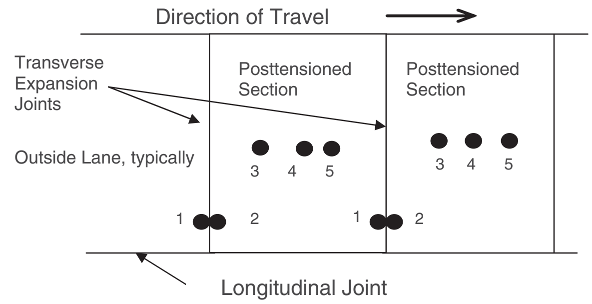


Figure C.2. FWD test locations for PPCP projects.

Friction

Friction testing (skid resistance) should conform to ASTM E274. Friction testing should be performed along the center of the inner wheelpath and at an interval of one test per 100 feet (47 m) at most. Friction data should be collected every 2 years at about the same time of the year.

Other Testing

Other testing may be performed on a case-by-case basis to assess some specific or unique feature of the PCP. This testing may include

1. Coring to determine the effectiveness of subsealing and concrete quality; and
2. Coring at dowel bar slots to evaluate the effectiveness of dowel bar slot patching or grouting (for jointed systems).

Calibration of Design Procedures

As the PCP databases mature, rational mechanistic–empirical pavement design procedures can be calibrated to refine the currently proposed design methods, which are based on the design methods for CIP concrete pavements due to the lack of systematic and well-documented field performance data for the PCP technology.

In the long term, the performance database will be able to identify primary distresses and failure mechanisms for different PCP systems. The distresses will be linked to the design and construction features documented in the inventory and construction databases, allowing future refinements in PCP technology.

Related SHRP 2 Research

Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform (R02)

Performance Specifications for Rapid Renewal (R07)

Composite Pavement Systems (R21)

Using Existing Pavement In Place and Achieving Long Life (R23)

Preservation Approaches for High-Traffic-Volume Roadways (R26)