EVALUATION OF PRECAST RIGID PAVEMENT

A Thesis Submitted

In partial fulfillment of the requirement
For the Degree of

Master of Technology

In

Transportation Engineering

By

ASHUTOSH SINGH

1170465001

Under the guidance of

Prof. D. S. RAY

PROFESSOR

In

Department Of Civil Engineering

BABU BANARSI DAS UNIVERSITY, LUCKNOW

2018 – 2019

EVALUATION OF PRECAST RIGID PAVEMENT

A Thesis Submitted
In partial fulfillment of the requirement
For the degree of

MASTER OF TECHNOLOGY

In
Transportation Engineering
By

ASHUTOSH SINGH
(University roll no. 1170465001)

Under the Guidance of
Prof. D. S. RAY
Department of Civil Engineering

BABU BANARASI DAS UNIVERSITY
LUCKNOW
2018 – 19

CERTIFICATE

This is to certify thesis entitled **“EVALUATION OF PRECAST RIGID PAVEMENT”** which has being carried out by Mr. ASHUTOSH SINGH (Roll No. 1170465002) for partial fulfillment of requirement for the award of **MASTER OF TECHNOLOGY** (TRANSPORTATION ENGINEERING) of Babu Banarasi Das University, Lucknow, is a record of her work carried out by her under the guidance and supervision. The result embodied in this thesis has not been submitted elsewhere for award of any other degree or diploma.

D. S. RAY
(Professor)
(Project Guide)
Department of civil Engineering
BBD University, Lucknow

DECLARATION

I, hereby declare that the work which is being presented in the **M.Tech** Thesis Report entitled **“EVALUATION OF PRECAST RIGID PAVEMENT”,** in fulfillment of the requirements for the award of the MASTER OF TECHNOLOGY in **Transportation Engineering (Civil Engineering)** and submitted to the Department of Civil Engineering of Babu Banarasi Das University, Lucknow (U.P.) is an authentic record of our own work carried out during the period from August 2017 to June 2019 under the guidelines of **Prof. D.S. Ray, Department of Civil Engineering**. The matter presented in this thesis has not been submitted by me for the award of any other degree elsewhere.

Mr. ASHUTOSH SINGH
(Roll No. 1170465001)

ACKNOWLEDGEMENT

First and foremost, I praise God, the almighty for providing me this opportunity and granting me the capability to complete my research work successfully, I would like to express my sincere appreciation and deepest gratitude to my advisor, **Prof. D.S. Ray**, for his support, help and guidance during my graduate study. His guidance has made my learning experience a very special one and I am truly fortunate to have had the opportunity to work with him. I would like thank **Mr. Anupam Mehrotra, (HOD, BBDU)** for his encouragement during the project. I would also like to thank Mr. Mohammad Afaque Khan for his friendly guidance, valuable suggestions and constructive criticism throughout the progress of the study.

Finally, I want to express my deep gratitude to my friends and family who always loved, supported and encouraged me throughout this challenging process.

Thank You

ASHUTOSH SINGH
(1170465001)

TABLE OF CONTENTS

Page No.

CHAPTER 4: STUDY AND EVALUATION…………………………….... 65 – 104

CHAPTER 5: CONCLUSIONS ………………………………………...…. 104 – 108

LIST OF TABLE

LIST OF FIGURES

DECLARATION

I, hereby declare that the work which is being presented in the **M.Tech** Thesis Report entitled **"EVALUATION OF PRECAST RIGID PAVEMENT",** in fulfillment of the requirements for the award of the MASTER OF TECHNOLOGY in **Transportation Engineering (Civil Engineering)** and submitted to the Department of Civil Engineering of Babu Banarasi Das University, Lucknow (U.P.) is an authentic record of our own work carried out during the period from August 2017 to June 2019 under the guidelines of **Prof. D.S. Ray, Department of Civil Engineering**. The matter presented in this thesis has not been submitted by me for the award of any other degree elsewhere.

Mr. ASHUTOSH SINGH
(Roll No. 1170465001)

ABSTRACT

The use of PCP technology can significantly reduce traffic impacts of roadway repair and reconstruction projects, particularly on heavily traveled routes. The technology is applicable to both small segments, enabling flexibility in construction phasing, as well as for use in corridor-wide pavement rehabilitation/reconstruction. study on technical consideration of jointed precast concrete pavement (JPrCP) system and cost comparison between cast in place concrete pavement system and precast concrete pavement system . Prefabricated concrete pavements use pre-fabricated concrete panels for rapid construction of concrete footpaths and rehabilitation of concrete and asphalt pavements. The precast concrete pavement can also be used for reconstruction or as an overlay. Precast concrete pavement applications include the isolation repair, intersection and ramp rehabilitation, urban road rehabilitation, and long term rehabilitation of pavement sections. The precast concrete pavement system is fabricated or collected on site, taken to the project site, and installed on a laid foundation (existing pavement or regraded foundation). Prior to opening traffic, system components require minimal field treatment or time to gain strength. Using PCP technology can significantly reduce the traffic impact of road repair and reconstruction projects, especially on heavy travel routes. Technology is applicable to both small sections, which are meant to be used in the construction of corridor-wide sidewalk rehabilitation / reconstruction along with enabling flexibility in construction phase

Key Words: Precast concrete pavement, jointed precast concrete pavement, panel , PAVEMENTS

ASHUTOSH SINGH

(1170465001)

CHAPTER – 1

INTRODUCTION

1.1 General:

The precast concrete footpath (PCP) system is a set of specific panel descriptions, materials and associated installation methods that are used to make fast concrete pavements that work fully in concert. High quality materials are used in the carefully controlled manufacturing process for the production of durable precast panels. Combines effective and fast method of keeping those panels in roadway, applying beds and adding, so that a precast concrete pavement is formed.

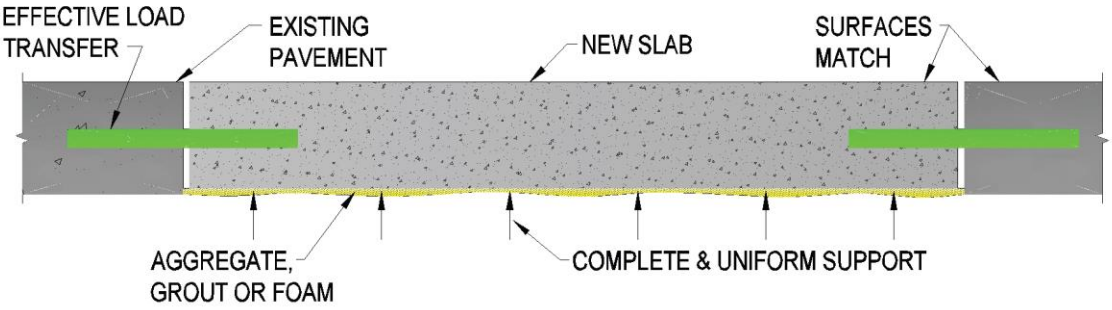


Fig 1.1, Rigid Pavement Section

Well-designed PCP system enable rapid replacement of concrete pavement with minimal impact of concrete pavement with minimal impact on traffic flow and provide pavement that offers the potential for decades of service. These attributes are especially valuable in meeting pavement maintenance and repair needs heavily trafficked area Precast paving is a process where a precast panel or series of panels is installed on a properly prepared foundation. The panel or series of panels must be fully supported and properly connected to perform as a completely functional concrete pavement system. Although the PCP construction process differs from conventional concrete paving, it must still provide key features of successful cast-in-place paving operations to produce a finished pavement that behaves and performs comparably to good cast-in-place concrete pavement. It is beneficial to recognize those features to better understand their importance in PCP systems. Consider the slip-form paver system shown Low-slump concrete is extruded to the correct grade and cross slope over a carefully prepared base. The paver consolidates the plastic concrete, ensuring that full contact with and support by the base is achieved. At the same time, placement and consolidation processes allow the concrete to fully encase load transfer dowels. Finally, the paver uses pre-placed string lines or laser-based stringless paving systems to control the concrete extrusion and screeding and to produce a pavement surface with the correct grade and cross slope.

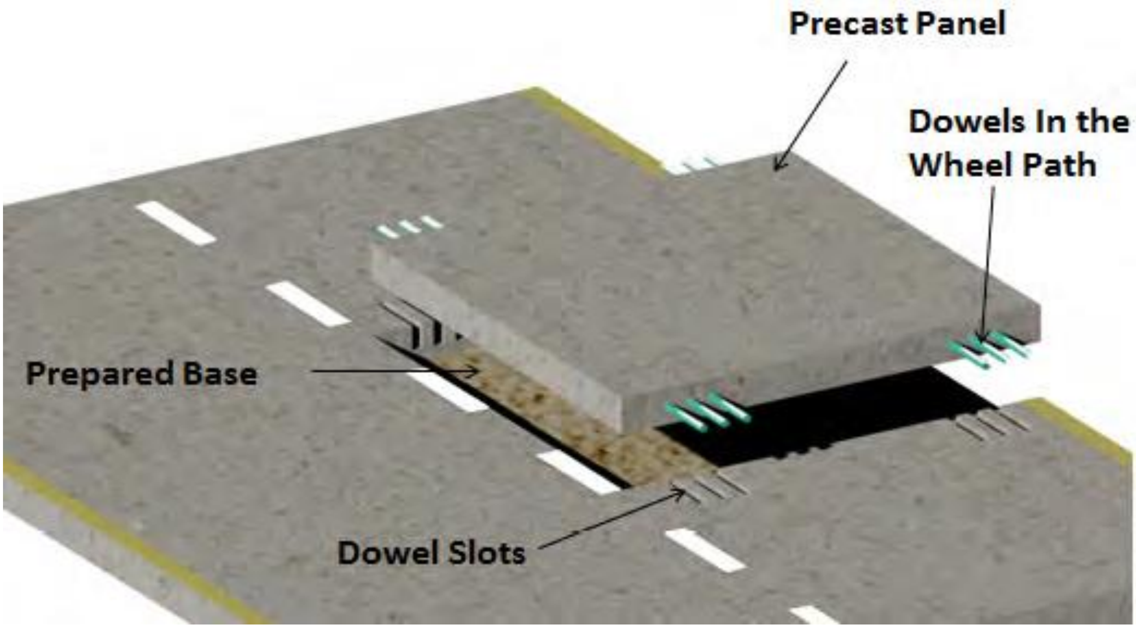


Fig 1.2 panel placement

Fig 1.3 panel installation site view

The four key elements of the slip-form paving process are:

1. Providing full contact between the concrete pavement and the properly prepared base.
2. Completely encasing the load transfer dowels at transverse joints.
3. Placing extruded concrete to the correct elevation and grade.
4. Producing a smooth pavement surface with the correct cross slope.

These same key elements must be achieved or developed in the precast paving process to ensure comparable pavement behavior and performance. In other words, the results of the precast pavement construction process must emulate those of the slip-form pavement construction process to achieve a comparable finished product. The primary differences are that rigid precast panels, rather than plastic concrete materials, are used in the construction process and that the same key elements must be achievable in short work windows (typically overnight work windows of eight hours or less) to be viable for rapid repairs. A well-developed jointed precast concrete pavement (JPrCP) system will offer this capability

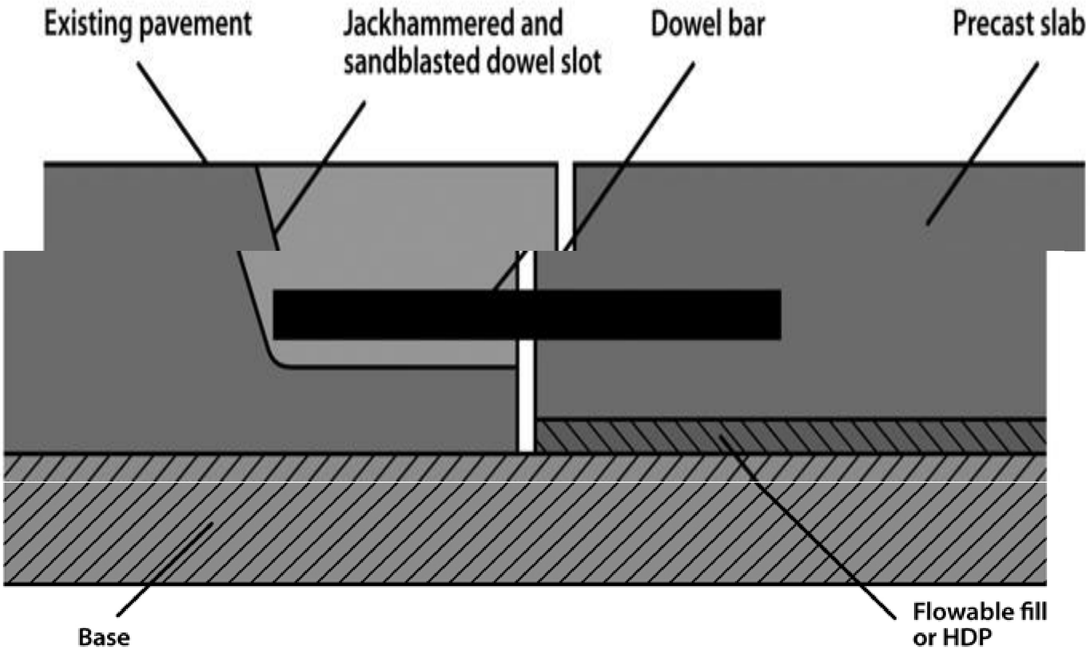


Figure 1.4. Schematic of the intermittent repair application

In our country recent years a lot of research has been done in precast concrete construction in many fields like buildings bridges metros etc. In highway and road construction we do not use this technology where as many country like Japan America china etc. also use this system which is very use full for improving the service life of the pavement as compare to the cast-in-place pavement system. With the help of precast concrete we provide a well-established construction technique. Concrete columns, beams, panels, slabs and other structural elements are cast in a specified place and then transported to the construction site for assembly.

The design of PCP is based on the assumption that, once constructed (installed), the overall behavior of the PCP under traffic loading and environmental loading is not significantly different than that of a like cast-in-place concrete pavement. Thus, a jointed PCP is expected to behave similar to a cast-in-place (CIP) jointed concrete pavement (JCP) and a PPCP is expected to behave similar to a cast-in-place prestressed concrete pavement. However, the performance of the PCP systems is expected to be better than like cast-in-place concrete pavements because of better quality of concrete used, better control of panel fabrication process and better installation/construction practices.

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:

- 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, for joint resealing, and minor repairs.

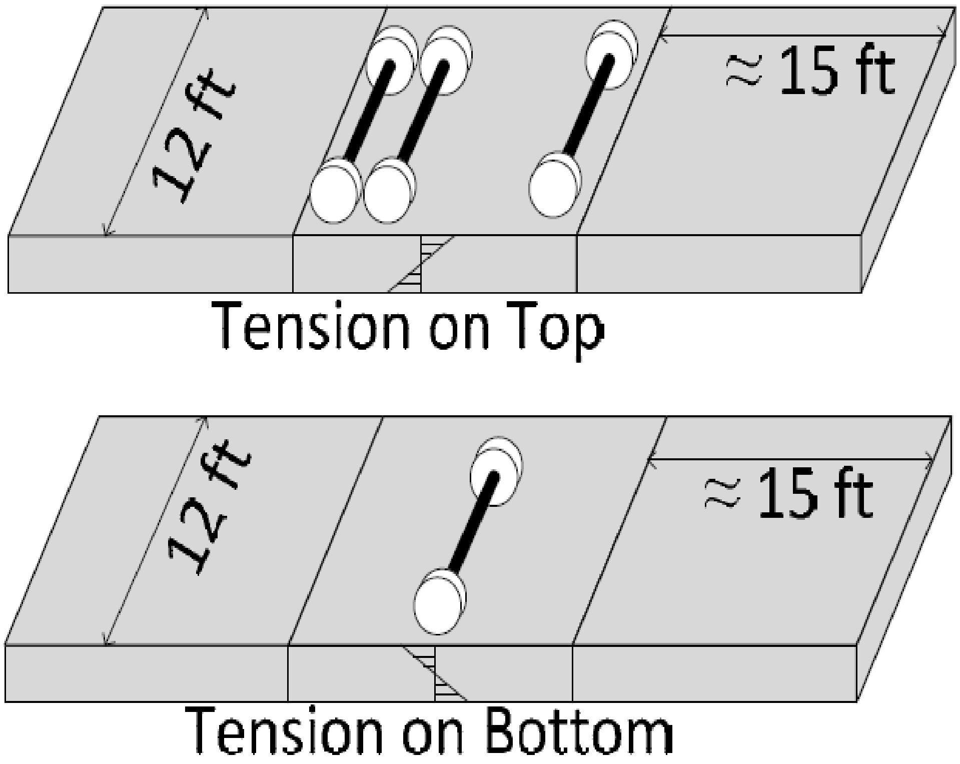
Although PCPs are of recent use and in-service performance information of the oldest U.S. projects is available for about 10 years, PCPs can be designed to provide long-term service. In fact, the warrant for use of PCPs is rapid repair and rehabilitation with recognition of the need for long-term service.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

- Design strength of concrete from Day 1 of installation, thereby assuring no structural damage due to early traffic loading;
- No early-age concrete curling and warping issues;
- No built-in curling to account for since precast concrete panels are typically fabricated flat 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 jointed concrete pavements. This is because the PPCP expansion joint spacing may range from about 150 to about 300 feet. The joint spacing for cast-in-place JCP is typically about 15 feet. In addition, PPCP is constructed on good quality stiff bases that results in lower joint deflections under traffic loading and less risk of joint-related distress.

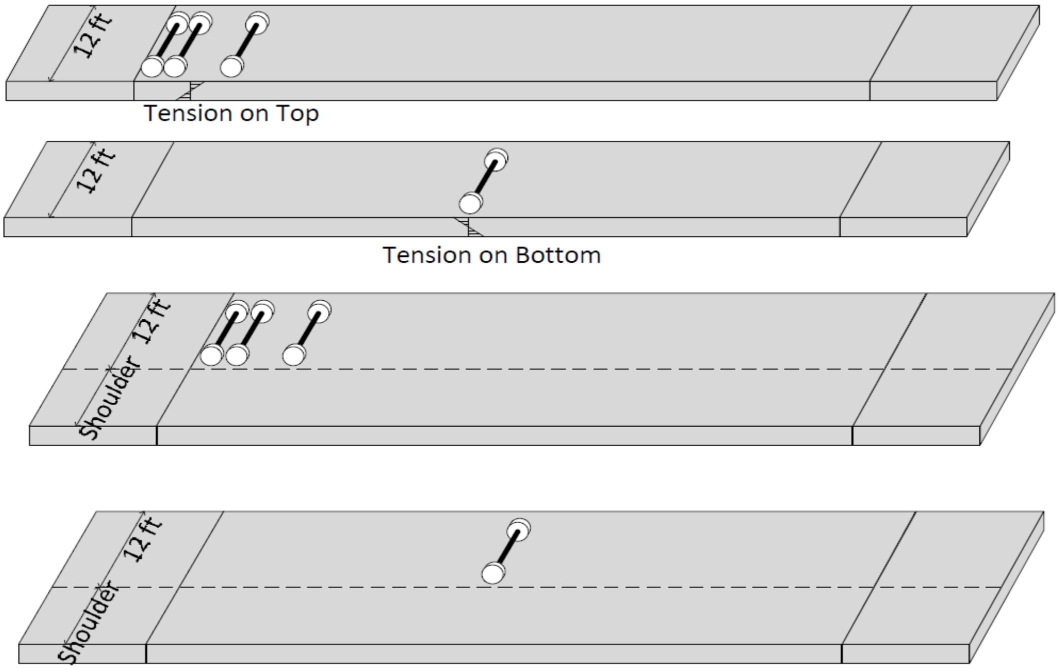
For any pavement system, the structural requirements are defined on the basis of anticipated structural distress (failures) under traffic for a given environmental condition. Typical distresses that can develop in CIP JCP include the following:

1. **Cracking -** transverse cracking may develop over a period of time due to repeated truck loadings. Cracking is typically referred to as a stress-based distress.
2. **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** - may develop along joints or cracks and may develop due to incompressible in joints or cracks and/or poor quality concrete.
4. **Materials Related Distress -** the more significant materials related distress may include alkali-silica reactivity and D-cracking in a freezing environment. These distresses are mitigated by using the right materials for concrete.
5. **Roughness -** pavement roughness (or smoothness) is affected by the initial as-constructed smoothness and development over time of various distresses in the concrete pavement.

The truck loading conditions to be considered for JCPs (CIP or precast) and PPCP systems are shown in Figure 1.5. The critical truck axle positions in Figure 1.5(a) are for stresses that result in top-down cracking and in 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 1.5(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 8.1(b), the loading condition is always an interior loading condition. This is the most efficient design for the PPCP, and, as shown later, 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.



a. Truck Axle Loading for Critical Slab Stresses CIPJCP and PJCP



b. Truck Axle Loading for Critical Slab Stresses for PPCP with Panels Fabricated as Single-Lane and Multiple-Lane Panels

Figure 1.5. Concrete pavement truck loading conditions.

Precast concrete pavement (PCP) technology is of recent origin. The production use of the PCP technology began in earnest during 2001. The PCP systems are used in highway corridors with high volume of traffic and where lane closures are a challenge. Over the last 10 years, several US highway agencies, including California DOT (Caltrans), Illinois Tollway, New Jersey DOT, New York State DOT, and Utah DOT, have implemented the PCP technology and a few other agencies have constructed demonstration projects. The implemented PCP systems include proprietary as well as non-proprietary systems. Because the production use of PCP technology in the US is of recent origin and the information on PCP practices and performance is not well documented, the PCP design processes are not yet fully developed.

The following PCP applications have been implemented by Caltrans at several rehabilitation projects:

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.

Two PCP types have been used for this application.

1.2 General Categories of Precast Pavement System:

Precast concrete pavement (PCP) system can generally be grouped into two broad families these are:

a. **Precast prestressed concrete pavements (PPCP) -** A number of precast panels, typically 10 feet (3 m) or more in length, are connected together by post-tensioning. This approach results in fewer active joints - at a spacing of about every 100 to 300 feet (30 to 90 m). The prestressing also allows use of thinner panels compared to the jointed precast concrete pavement systems. These systems are also referred to as posttensioned precast concrete pavement systems.

b. **Jointed precast concrete pavement (JPrCP) -** these pavements perform similar to conventional cast-in-place jointed concrete pavements.

1.3 Precast prestressed concrete pavement (PPCP):

These pavement can be characterized as precast pavement built by post-tensioning a series of transversely prestressed precast panel together to create much longer pavement slabs (typically 150 to 250 feet in length) that are effectively “jointless” due to the effect of post tensioning. The resulting assembly is a pavement slab that is prestressed in two directions. Prestressing forces enhance the structural characteristics of the slab in both directions, counteract load-and temperature-related stresses, and keep joints within the slab tightly closed. A dowelled expansion joint panel- a gap panel not include in the existing pavement or the next PPCP slab. In all case panels are constructed on polyethylene sheeting or a similar low friction surface to facilitate slab movement during the post tensioning operation. While a bedding material may be placed and graded on the foundation to provide reasonably uniform support prior to panel placement, injectable void-filling material (like grout, urethane etc.) are not always used in the construction process.

1.4 Principle Benefit and Advantage of PPCP:

The primary advantage of PPCP is that the pre-tracing forces increase the structural capacity of the panels, thereby reducing the thickness of the panel's design and providing safe handling of long panels. This saves solid material costs and it is particularly beneficial in that situation where the thin pavement should be used due to high underlying subbase layer or overhead clearance issues. In addition, in the prestressing assistance, it also helps to compensate for non-equities which can be present before the installation of cement-based grout or other bedding material used to fill small voids under the slab.

Another advantage of PPCP is that the pre-tracing force applied in the field works to keep the joints close and tightly locked between the precast panel, essentially converting every assembly of panels into a "combined" slab. When the appropriate design and construction facilities are provided for producing good vertical alignment between the precast panels, the result of low number of effective joints can result in better ride quality in the length of each assembled slab.

Suitable Application for Post-Tensioned PPCP:

The most common applications for post-tensioned PPCP system can be grouped into two categories: Short-length continuous construction (less than 150 feet in length typically with a single lane) and continuous construction (greater than 150 feet in length and in one or more contiguous lanes).

1.5 Jointed Precast Concrete Pavement (JPrCP):

The jointed precast concrete pavement (JPrCP) is designed to expand and contract on each panel joint: This panel is not tense together and each panel is independently spread and contract. Transverse joint load transfers between precast panels and other precast panels or between the precast panel and the existing pavement are obtained with standard load transfer dowel.

JPrCP panel are typically sized to be one lane wide (typically about 12 feet) and about 16 feet or less in length. Panel thickness varies with the application. JPrCP panels placed in continuous applications may be equivalent in thickness or thicker than the adjacent pavement as dictated by design. As stated previously, a PCP system is a set of specific panel details, materials and associated installation methods used in concert to create a fully functional concrete pavement. To be effective and to emulate cast-in-place paving, the installation of jointed PCP systems must include the four basic requirements listed in Table 1.1. Note that these four requirements correspond directly with the four key elements of slip-form paving described previously.

The four basic requirements of jointed precast concrete Pavement (JPrCP):

1. Place or adjust panels to the correct grade.
2. Install bedding material to uniformly support panels.
3. Establish effective load transfer between panels.
4. Provide a geometrically correct pavement surface (by grinding , using nonplanar panels or means)

Table 1.1 basic requirements of jointed precast concrete Pavement (JPrCP)

These four basic requirements are shown schematically in Figure 1.1, which is a drawing of a single, generic precast concrete panel installed in an existing pavement. Not shown in Figure 1.1 is a specific mechanism or technique for positioning the precast panels at the correct vertical grade to “generally” match adjacent pavement surfaces. Bedding material – shown in yellow – is introduced, by various means, as an interlayer of grout, fine aggregate polyurethane foam or a combination of these materials. Efficient joint load transfer, typically required for pavements subjected to a significant volume of heavy traffic loads, must be achieved with mechanical devices such as dowels because the formed edges of precast concrete panels provide no aggregate interlock load transfer. Load transfer dowels, shown spanning both transverse joints in Figure 1.1, must be installed in grout-filled slots either fabricated in the precast concrete panels or saw cut into the existing pavement. Finally, the top surface of the panel must be fabricated or diamond-ground to conform to and reasonably match the surfaces of adjacent panels or pavement.

Every proposed JPrCP system should be evaluated in terms of how well it achieves the four basic requirements listed in Table 1.1. Successful JPrCP systems already in use accomplish these basic criteria differently and all provide a pavement structure equal to (and sometimes better than) conventional cast-in- place concrete placed in similar, abbreviated work windows. Details of these systems are presented in the following chapters so designers, fabricators and contractors may determine which, if any, of these systems best meet their needs. JPrCP is designed to function similarly to jointed cast-in-place pavement, so no structural reinforcing steel is required for service loads. However, precast panel do need to reinforce for handling and transportation conditions. A minimum amount of steel is used. In this system additional reinforcing steel placed in two layers, to provide additional resistance to temporary stresses that may be include when traffic is allowed to use grade-supported panels before they are fully supported by grout. Prestressing may also be used to reduce panel thickness, making it the reinforcing method of choice when thinner planner panels are required.

It is possible that new systems will be developed as the industry grasps the challenges and advantages associated with precast pavement. However, a system is more than a sketch or a set of procedures shown on a piece of paper and no system should be considered for use until it has been demonstrated to meet the four basic requirements listed in Table 1.1.

Figure. 1.6, panel section layout

1.6 Typical Characteristics of JPrCP:

JPrCP is designed to expand and contract at every panel joint; that is, panels are not post-tensioned together and each panel expands and contracts independently. Transverse joint load transfer between precast panels and other precast panels or between precast panels and existing pavement is achieved with standard load transfer dowels.

JPrCP panels are typically sized to be one lane wide (typically about 12 feet) and about 16 feet or less in length. Panel thickness varies with the application. For example, intermittent repair (patching) panels are typically specified to approximately match the thickness of the surrounding pavement. JPrCP panels placed in continuous applications may be equivalent in thickness or thicker than the adjacent pavement, as dictated by design. JPrCP is designed to function similarly to jointed cast-in-place pavement, so no structural reinforcing steel is required for service loads. However, precast panels do need to be reinforced for handling and transportation conditions. A minimum amount of steel (typically taken as the amount required by ACI 318 for temperature and shrinkage requirements in structures) is used. Some system manufacturers use additional reinforcing steel (often double the previously mentioned ACI requirements) placed in two layers, as shown in Figure 1.2, to provide additional resistance to temporary stresses that may be induced when traffic is allowed to use grade-supported panels before they are fully supported by grout.

1.7 Benefits and Advantages of JPrCP:

Our major benefit of JPrCP is that the structural design is generally accomplished using the same thickness design procedures using the same thickness design procedures used for jointed cast-in-place concrete pavements. Since these procedures are well understood by concrete pavement engineering across the word, the designs can be performed with confidence and are easily verified. The design of panel sizes and load transfer system is essentially the same for both cast-in-place and JPrCP systems.

Another major benefit of JPrCP is that the panels are more easily fabricated than are PPCP panel because there are no Post-Tensioning blockouts and prestressing ducts, which must be placed with great prestressing to ensure constructability. PCP systems include high-quality, prefabricated concrete panels that become offsite and are installed during off-peak journey. Using versatile approach can be done for the construction of new roadway, roadways, toll plazas, ramps, intersections, bridges, slabs and tunnels for rehabilitation. Under ideal conditions, cast, precast panels are subject to high quality control standards during the construction process, resulting in the surface of a durable and ready-to-traffic road. The essential greasy is usually obtained from regular grinding of panels immediately after the placement. Coupled with the fact that the cost of PCP panels has dropped significantly in the past decade, PCP offers transportation agencies significant short- and long-term advantages, such as:

- Shorter installation time
- Reduced construction-related closures, and therefore reduced exposure of workers and drivers to work zone hazards
- Pavement is ready for traffic upon installation—no curing time
- Slabs are cast in plants under ideal conditions for optimum quality and durability
- Installation can take place at night or under adverse weather conditions, extending the construction season
- Longer-life performance than traditional cast-in-place (CIP) solutions

1.7.1 Improved Durability and Performance:

Precast is a proven track record in Concrete as a durable high performance product for bridging and commercial building construction. This is the result of high quality quality control which can be obtained at a precast fabrication plant. A low water-cement ratio with high strength, low permeability concrete mixing and the same total grading is used regularly by the precast fabrication plant. In most plants, concrete batching and quality control are done on-site and concrete is taken from batch plant to forms only a short distance, reducing the change in the concrete properties between mixing and keeping the operation. What's more, the precast fabrication plants provide tremendous flexibility in the operation of the treatment. Precast concrete elements can be woven inside the house, they can be cured with wet-mat, can be cured with steam, and can be continued until after the casting, the treatment can be continued. Problems that can prevent the construction of pavements in place, such as the strength of the surface, the "underlying" curling, and insufficient air entry, all can be eliminated with precast concrete.

1.7.2 Reduced Slab Thickness:

While the underlying pavement structure is also a factor, the primary control factor in the sidewalk thickness design is the magnitude and number of wheel load repetition on the pavement on its expected design life. For a given pavement support structure and a given wheel load, tensile stress in a thin pavement will be higher than a rough pavement. These high tension gets worn or tired of fast concrete pavement. Prestresing can be used to reduce tension of tension in a thicker pavement slab of thin pavement slab, which enhances the design of the pavement. Why is it important? Firstly there is savings in solid materials. The construction of an 8-inch thick pavement slab instead of a 12-inch thick sidewalk slab will save more than 780 cubic yards of concrete per mile per concrete. Secondly, to remove and replace it is usually necessary to match the thickness of the existing slab. Most existing pavements that require replacement, are on the order of 8-10 inches thick. The prepressing pavement allows for the replacement of the existing pavement with slab, in which the design of a thicker slab will be life. Finally, the thickness of the slab can often be controlled by overhead clearance hurdles. For example, when making the place of pavement under the bridge overpass, it is not possible to make a thick sidewalk than the first place without digging the base material.

1.7.3 Bridging Capability:

The prestresing gives the pavement a definite "bridging" capability, which allows the pavement slab to spread smaller voids and "soft" base material beneath the pavement. It is important for pavement removal and replacement works that are limited to the small (overnight) construction windows when it is not possible to repair or replace the underlying base material.

1.7.4 Reduced Cracking:

Although conventional pavement is "designed" to crack in specific places (on junk joint for JCP) or to crack in regular intervals (CRCP), it is not desirable to crack normally. Cracks can be missed, they can allow the water to penetrate into the underlying base, they can make mistakes, and they can eventually cause serious sidewalk failures like punching. It also helps in reducing prepressing or eliminating crack. Due to tension of stress by putting a sidewalk in compression, the possibility of cracking is less. What's more, the so-called "elasto-plastic" behavior of precasted concrete will help to maintain any crack which tightens down.

1.7.5 Faster Construction:

What do we mean by the fast creation? We are not necessarily talking about how fast the pavement can be built, rather, how fast it can be opened for traffic. Traditional cast-in-place pavement requires several days of additional treatment time after the concrete is placed before it is strong enough to withstand traffic loading. While “fast-setting” concrete mixtures have been developed for this purpose, these can be cost-prohibitive for large-scale pavement construction

1.7.6 Reduced User Delay Costs:

What are the user delay costs? These are the cost of road drivers that are responsible for the crowd directly due to construction activities. Increase in fuel consumption, decrease in work time, increase in vehicle wear and tear, and increase in air pollution are some of these costs. Only by limiting the production of off-peak travel time (overnight or over a week), savings in the cost of the user can be considerable. This is where the primary economic benefits of the precast pavement will be realized

1.8 Principal Criteria for Using Precast Pavement:

1.8.1 Short Work Windows and/or Heavy Traffic:

When travel lane reconstruction or repairs can be accomplished during lengthy closures, many options are available for constructing durable repairs. In these cases, PCP systems may not be the most productive and cost-effective option. However, as work windows become shorter, fewer suitable repair options are available. When work windows shrink to eight hours or less (e.g., because of the need to maintain traffic flow capacity on heavily traveled roads or other essential routes), repair options become much more limited. Work window activities typically include setting up (and removing) traffic control/protection devices, locating and marking the repair area(s), sawing and removing deteriorated concrete, preparing the repair area(s) (including performing foundation repairs and installing dowels and tie bars), placing or installing the repair product and allowing the product to come to a strength or condition that will support traffic (e.g., concrete curing).

1.8.2 Long-Term Durability Required:

Assuming the use and production of durable materials at the precast plant, PCP systems offer the potential for service life that will match or exceed that of any cast-in-place pavement repair/replacement material. When the expected service life of the repaired pavement is relatively short, other less costly materials and repair techniques may be preferred. However, consideration should be given to the possibility that repair construction efforts may need to last longer than anticipated due to reallocations of resources or other factors. In addition, the use of long-life repairs may facilitate "incremental reconstruction," where additional long-life repairs are placed adjacent to existing installations during future rehabilitation activities, effectively resulting in pavement reconstruction in stages.

1.8.3 Project Suitability: Other Factors for Consideration:

While work window duration and durability requirements may drive design and construction decisions toward the use of precast pavement systems, there are many additional factors that must be considered in both the decision-making process and in project planning and design. These considerations can be grouped into two major categories: general constructability and site-specific factors impacting design and construction.

1.9 General Constructability Considerations:

Constructability may be a concern when construction must take place in difficult locations, such as on ramps and other narrow facilities with only one or two travel lanes and limited shoulder space, the inner lanes of multi-lane facilities, beneath bridges and overpasses with limited shoulder space, or inside of tunnels (Tayabji et al., 2013). In addition, providing access to the site for large, heavy construction equipment and for the transport of precast panels can require special permitting and even temporary roadway and traffic control modifications along the access route, particularly in urban areas. The following sections discuss these considerations in more detail.

Figure 1.7. Example use of two lanes to perform repairs in a single lane

1.10 Balancing Work Space and Traffic Maintenance/Protection Requirements:

Precast panels can also be installed using a single-lane closure while allowing some traffic use of at least one adjacent lane. Delivery trucks approach the installation site with traffic in the adjacent lane. Upon reaching the off-loading site, the traffic is stopped just long enough for the crane, which is set up in working lane, to remove the panel from the delivery truck in the adjacent lane – typically five minutes or less. The crane lifts the panel from the delivery truck and swings 90 degrees to install the panel in the prepared area. PCP systems are installed most efficiently (i.e., with the highest installation rates) when an adjacent lane is available for delivering the precast panels to the work site and for the panel lift equipment. In this manner, a single-lane repair requires a minimum two-lane closure (or one lane plus a shoulder), and three lanes (or two lanes and an adjacent shoulder) are required for placing repairs in two lanes, etc. Figure 1.3 shows the installation of precast panels using one outside lane and an existing 10-foot shoulder. Split-traffic configurations may be necessary for maintaining adequate traffic flow and worker safety when repairing the interior lanes of some multi-lane facilities.

1.11 Vertical Clearance Requirements:

Figure 1.8. Sources of potential vertical clearance issues during installation.

Typical PCP placement operations involve the use of a crane to pick the panels from the delivery vehicle and move them into position for placement. The required crane size varies with the weight of the panels being placed and the reach required to place them. Larger cranes require more space (width) to accommodate the crane stabilizing outriggers and longer pick distances typically require higher booms. While the presence of bridges and overpasses can present special construction challenges, it is important to identify and address other potential installation clearance restrictions, such as potential conflicts with overhead signs, lighting standards and power lines (Figure 1.4). It may be necessary to temporarily remove these conflicts or to use special installation equipment in these locations. The installation of PCP systems beneath bridges and overpasses or within tunnels represents a good potential alternative to the placement of overlays that would reduce vehicle clearances after rehabilitation.

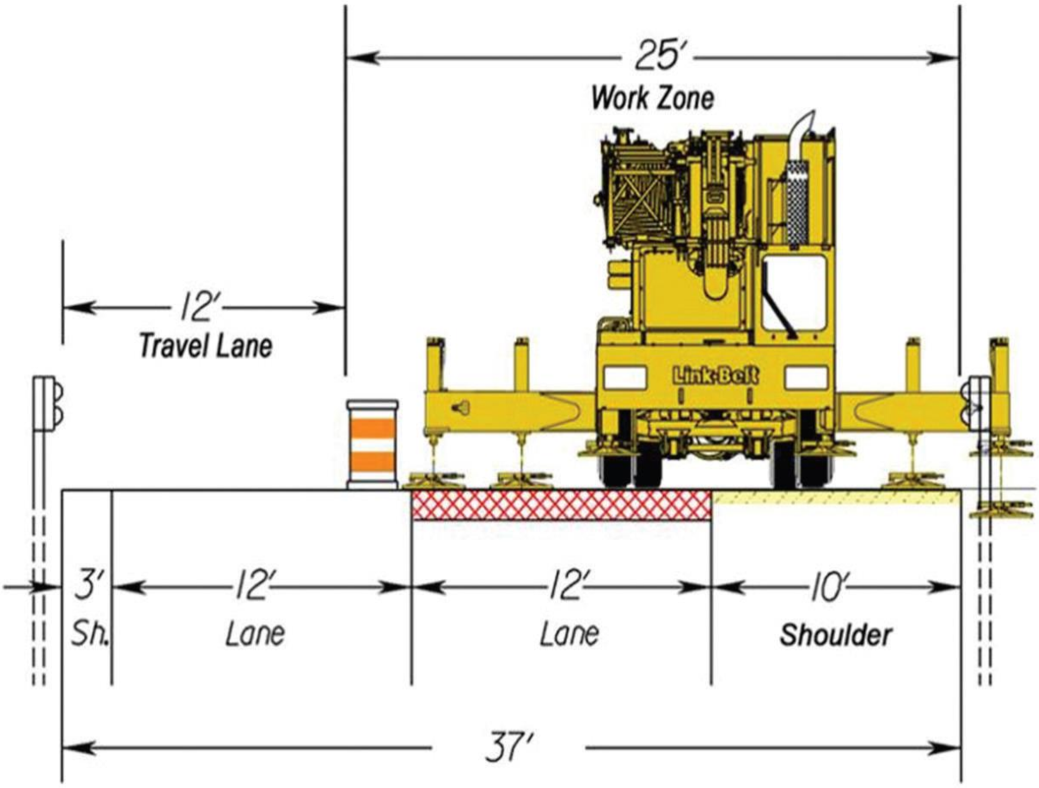


Figure 1.9 Installation and Panel Handling Equipment

1.12 Installation and Panel Handling Equipment: Size/Weight and Site Access Considerations:

The project site must be accessible for the heavy construction equipment that is necessary for removing the existing pavement and installing the new PCP panels. While the question of site access is usually not an issue on most major highways and truck routes, urban applications may require special evaluation of the strength and thickness of the existing mainline and/or shoulder pavement to determine if it is adequate for handling heavy construction equipment and highway truck loads. In some cases, shoulders may need to be replaced with thicker pavement before the project begins to handle temporarily diverted traffic. Consideration should also be given to pavement adequacy as it may relate to possible damage to underlying utilities and associated structures. Work space configuration must be able to accommodate the footprint of the properly positioned lift equipment, which may include outriggers (supporting legs that typically extend a few feet on either side of the lift equipment for added stability). The fully stabilized position of the lift equipment (i.e., with outriggers down and fully extended) may result in some encroachment of adjacent lanes or shoulders, as shown in Figure 1.5.

1.13 Panel Transport to the Project Site:

One of the keys for successful PCP system installation is the ability to deliver the correct panels to the project site in the most efficient manner possible. Delivery directly from the precast plant to the project site, often referred to as “just-in-time” delivery, is generally more efficient and is usually preferred because there is no need for a storage or staging yard. However, when this technique is used, it is important to determine what limitations, if any, may affect panel delivery operations, including local freight regulations (e.g., weight, width and night delivery restrictions), permits, limitations on turning movements (intersection geometry), overhead restrictions, etc. Shipping weight and width restrictions highly impact the sizes of panels that can be efficiently transported and placed. Contractors typically prefer panel sizes that best match placement equipment and simultaneously minimize freight cost because more panel area can be placed on any given hauling vehicle. Panel sizing to meet width limitations must consider not only the panel but also any protruding reinforcing steel or dowel bars.

1.14 Site-Specific Factors That May Impact Design and Construction:

There are many site-specific factors and conditions that may affect the feasibility of using a PCP system. These include: the condition of the surrounding pavement and existing foundation materials; drainage issues and the roles that they may have played in the deterioration of the existing pavement (and may play in the performance of the PCP system); the presence of utilities beneath the pavement surface and the presence of penetrations (e.g., manholes, outlets, etc.) through the pavement surface; the presence of stabilized base/subbase layers and their repair and/or grading; and the need to match the surface geometry of the existing and surrounding pavement. Some of these factors must be considered in laying out and constructing cast-in-place repairs as well as PCP systems, but some present unique challenges for PCP systems.

1.15 Contractor Experience with PCP Systems:

PCP systems represent a relatively new technology. Because of this and the recent increase in the number of available precast paving and repair systems, it is not uncommon for contractors with little or no prior experience with PCP systems to perform installations. Despite this lack of experience, almost all precast paving projects executed to date in the

U.S. have been completed successfully within both budget and time constraints The key to successful installations appears to involve the use of proven or well-developed PCP systems, the availability of well-developed project plans and specifications, the availability and use of system-specific installation training for both contractors and inspectors, and diligence in the application of that training during the installation process.

Geometry and Planarity of the Pavement Surface:

The use of PCP systems to replace flat, rectangular cast-in-place panels on tangent (straight) pavement sections is relatively straightforward and can be accomplished with standard panel fabrication processes and installation procedures. Flat precast panels typically compose the majority of work on many precast pavement installation projects.

Figure 1.10. Super-Paver RUP system.

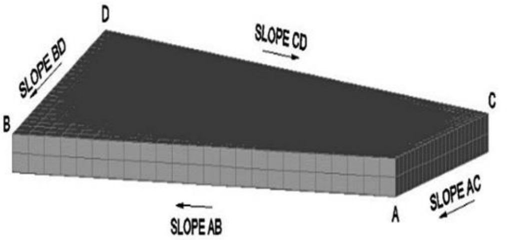


Figure 1.11. Schematic of non-planar pavement surface where opposite sides always have different Slopes.

The presence of planned nonplanar surfaces (i.e., vertical and horizontal curves and their transitions) can be identified on original project plan sheets. The actual in-service surface shape of both planned and developed surface nonplanarity can be easily identified and measured using modern surveying techniques, including high-speed 3-D noncontact profiling. Fabrication of nonplanar, trapezoidal and other shaped panels requires special precasting forms. It is important that project plans and specifications clearly indicate the need for, or at least the possibility of the need for, such special panels. The fabrication of nonplanar panels requires precasting techniques that typically require special precasting beds, forms or both. Some nonplanar panel fabrication processes are covered by patents that require licensing agreements for use. Special care must be taken to mark or label each unique slab during fabrication so that the proper slabs are transported to the project site and installed in the correct sequence and location, thereby ensuring the best possible fit. Therefore, this approach may not be practical or suitable when the amount of nonplanarity in any given panel is much more than 1/4 inch. The designer should be aware that it is not uncommon to encounter warps of up to 2 inches in a single, 12-foot-by-15-foot precast panel and that it is unacceptable to grind away that amount of precast panel thickness unless that magnitude of sacrificial thickness has been provided in the panel.

CHAPTER 2

Literature review

Nasser M. Alwehaidah and Bruce W. Russell[2] (2018): Three full-scale precast, prestressed concrete pavements with variable thicknesses were constructed on a granular base and tested under static and repeated loads. The test pavements were modeled using the finite element method, with the supporting foundation modeled as a series of linear springs and *k* values calculated using the experimental data. The pavement testing was performed using a movable testing frame designed for the research project. To monitor the response of the pavement, linear variable differential transformers and a load cell were installed and displacements were recorded to a data acquisition system during the entire testing period. The testing frame and data acquisition system that were used were found to be practical and effective tools for the testing performed for this project. In repeated load testing and in static load testing, the pavement showed a linear relationship between load and deflection and the deformation of the panels was calculated accurately using the finite element method. Furthermore, as expected, some cracking did occur in the pavement panels when loads of 30 kip (130 kN) were applied at the edges of the panels.

Ameen Ibn Zafir[3] (2017): One of the major hindrances in the construction and renewal of rigid pavement is the obstruction of traffic for extended periods of time. The time period required for the completion of a regular concrete pavement is inclusive of its base preparation, pouring and curing of concrete. This period can be reduced considerably by the application of prestressed precast concrete pavement. In this method of construction, pre-tensioned concrete panels are casted in a precast yard and once they have gained sufficient strength, they are transported to the site and placed on a prepared base. Pre-tensioning is required to indirectly reduce the thickness of the panels which in turn makes the process of transporting and placing the panels easy. The duration for which the traffic gets hindered reduces considerably as the time consuming activities are performed in the yard. The quality of concrete can be maintained at its best as the concrete mixing, pouring and curing occur in a controlled environment. Another major advantage of these panels is the ease with which they can be replaced. This paper aims at behavior the behavior of the panel using finite element analysis. A commercially available software SAP2000 has been used for this purpose. It is observed that the critical stresses are developed at the panel edges for a combination of temperature stresses and vehicular stresses developed due to a vehicle travelling at the edge of the panel.

Youn su Jung, Dan G. Zollinger, and Thomas J. Freeman[7] (2016): This paper is to provide assistance for the pavement evaluation and selection of method of repair for routine maintenance relative to the extension of service life. The visual identification of various distress types is discussed, and evaluation techniques using nondestructive testing are introduced that are key to determining proper routine maintenance activities. According to the areas selected from the simplified checklist of visual distress types, ground penetration radar for detecting voids below the slab and the presence of trapped water, falling weight deflectometer for structural condition evaluation, and dynamic cone penetrometer for estimating the in situ strength of base and subgrade soils are used to provide current information on pavement condition for selection of needed repair methods using a simple, systematic decision process. During field investigations, poorly performing areas were identified and possible fixes determined as a means of guideline development. Key routine maintenances activities are categorized in five levels; performance monitoring, preservative, functional concrete pavement repair (CPR), structural CPR, and remove and replace. Each level of maintenance is arranged for the use of repair treatments in a consistent, logical framework to ensure their effective and timely use and employment. Since the decision process is focused on monitoring the early stages of deterioration, it should result in more cost effective maintenance programs.

Shiraz Tayabji (2015)[6]: Precast concrete pavement (PCP) technology is gaining wider acceptance in the U.S. for rapid repair and rehabilitation of concrete pavements, as well as for reconstruction of heavily trafficked asphalt concrete intersections. Widespread use in the U.S. is fairly recent, with most projects in service less than about 14 years. Nonetheless, dozens of projects have been constructed, and advances continue to be made in all aspects of the technology, including panel design, fabrication, and installation. PCP technology is being used for intermittent repairs (both full-depth repairs and full panel replacement) and for continuous applications (longer-length/wider-area rehabilitation) with service life expectations of at least 20 years for repairs and at least 40 years for continuous applications, without significant future corrective treatment. Available PCP systems include jointed. Available PCP systems include jointed PCP with reinforced or prestressed panels installed singly or in a continuous series, as well as PCP that typically incorporates thinner reinforced or prestressed panels installed and posttensioned in a continuous series, resulting in fewer joints. The use of both jointed PCP and posttensioned PCP systems has advanced during the last decade due to a combination of work sponsored by the Federal Highway Administration (FHWA), projects constructed by highway agencies, and innovations by the highway agencies and the construction industry. One area of innovations relates to improvements in the load transfer features used at PCP transverse joints. The load transfer features currently used at transverse joints in PCP systems are described in this Tech Brief.

Alwehaidah, N., and B. Russell[5] (2013): Three full-scale precast, prestressed concrete pavements with variable thicknesses were constructed on a granular base and tested under static and repeated loads. The test pavements were modeled using the finite element method, with the supporting foundation modeled as a series of linear springs and k values calculated using the experimental data. The pavement testing was performed using a movable testing frame designed for the research project. To monitor the response of the pavement, linear variable differential transformers and a load cell were installed and displacements were recorded to a data acquisition system during the entire testing period. The testing frame and data acquisition system that were used were found to be practical and effective tools for the testing performed for this project. In repeated load testing and in static load testing, the pavement showed a linear relationship between load and deflection and the deformation of the panels was calculated accurately using the finite element method. Furthermore, as expected, some cracking did occur in the pavement panels when loads of 30 kip (130 kN) were applied at the edges of the panels.

Priddy L P, Bly P G and Flintsch G W[9] (2012): Long-term traffic restrictions belong to the key disadvantages of conventional cast-in-plane concrete pavements which have been used for technical structures such as roads, parking place and airfield pavements. As a consequence, the pressure is put on the development of such systems which have short construction time, low production costs, long-term durability, low maintenance requirements etc. The paper presents the first step in the development of an entirely new precast concrete pavement (PCP) system applicable to airfield and highway pavements. The main objective of the review of PCP systems is to acquire a better understanding of the current systems and design methods used for transport infrastructure. There is lack of information on using PCP systems for the construction of entirely new pavements. To most extensive experience is dated back to the 20th century when hexagonal slab panels and system PAG were used in the Soviet Union for the military airfields. Since cast-in-situ pavements became more common, the systems based on precast concrete panels have been mainly utilized for the removal of damaged sections of existing structures including roads, highways etc.. Namely, it concerns Fort Miller Super Slab system, Michigan system, Uretek Stitch system and Kwik system. The presented review indicates several issues associated with the listed PCP systems and their applications to the repair and rehabilitation of existing structures. Among others, the type of manufacturing technology, particularly the position of slots for dowel bars, affects the durability and performance of the systems. Gathered information serve for the development of a new system for airfield and highway pavement construction.

Nantung, T.E., Fimansjah, J., Suwarto, E., Hidayat, H. M^3. (2010): In the last few years, Indonesia has become the largest economy in Southeast Asia. In 2010, the country's economic growth was above 6% with a prediction per capita income between $4,500 to $5,000 in 2014. In 2010, the Ministry of Public Works implemented a strategic plan with an ambitious target to reach their goals in 2014. The vision of the strategic plan is to create National Routes that are reliable, coordinated, and sustainable to support national economic development and the prosperity of the people. However, this strategic plan is based on the "accelerated development" principle, which depends on the deliveries of the projects to meet the goals. In addition, there are some challenges regarding how these National Routes will be constructed to solve the issues of "time" and "construction in under-developed areas." Resolving these two issues will require fast construction using Precast Prestressed Concrete Pavement (PPCP). Following the first PPCP project in Indonesia, the second PPCP project implemented some modifications in the areas of design, construction, and evaluation. This paper discusses these modifications in these three areas to resolve issues during construction and to increase the reliability of design for heavy-duty routes.

Neeraj Buch (2011): The precast, prestressed concrete pavement system is well suited for continuous paving. The basic precast, prestressed concrete pavement system consists of a series of individual precast concrete panels that are posttensioned together in the longitudinal direction after installation. Each panel may also be prestressed in the transverse and/or longitudinal direction. Ducts for longitudinal posttensioning are cast into each of the panels during fabrication. The posttensioning and pretensioning offset some of the tensile/flexural stress that develops in the precast concrete panels under traffic and environmental loadings

Erwin Kohler (2009): The California Department of Transportation evaluated use of the Super-Slab System of pre-cast concrete pavement as a strategy for the long-life rehabilitation of concrete pavements by conducting accelerated pavement testing using the Heavy Vehicle Simulator (HVS) on a specially constructed experimental pavement in San Bernardino County. HVS testing of the pre-cast pavement occurred in 2005- 2006. Caltrans had conducted similar HVS tests on Jointed Plain Concrete Pavements (JPCP) on between 1998 and 2001 at SR-14 in Palmdale. This report compares the results of the accelerated tests on these two pavement types. A difference in the location of the loading made it necessary to apply conversion factors to the Palmdale JPCP data for the comparison. Tests on that pavement used edge loading, while testing on the San Bernardino pre-cast slabs used wheel path loading. The comparison results suggest that similar service life ranges can be obtained from this pre-cast system and jointed plain concrete pavements. A rough estimate of about 200 million ESALs seem to represent this service life. There is insufficient data to judge the variability in the expected life of pre-cast pavements; however, significant variability was observed in the cast-in-place JPCP slabs tested.

Cliff Schexnayder (2007): Precast concrete panels offer a means whereby a road can be closed, reconstructed, and reopened with minimal inconvenience to the motoring public. The use of such panels is a very viable and cost effective Portland cement concrete pavement reconstruction solution for repairing short lengths of distressed pavement that does not justify the mobilization of paving spreads or where closures cannot be of such duration to accommodate long curing times. Additionally, by casting the panels in a fixed facility it is possible to increase quality control of the pavement’s mix and casting. Three construction scenarios are described here to illustrate the effect project work site constraints have on construction operations when precast concrete panels are used to reconstruct a busy roadway.

Shiraz Tayabji[8] (2005): Precast concrete pavement (PCP) technology is gaining wider acceptance in the US for rapid repair and rehabilitation of concrete pavements as well as for reconstruction of heavily trafficked asphalt concrete intersections. While widespread use of PCP technology in the US is of recent origin, with most projects in service less than about 14 years, tens of projects have been constructed and many advances have been made and continue to be made in all aspects of the technology including panel design, fabrication, and installation. In the US, PCP technology is being used for intermittent repairs (both full-depth repairs and full panel replacement) and for continuous applications (longer-length/wider-area rehabilitation) with service life expectations of at least 20 years for repairs and at least 40 years for continuous applications, without significant future corrective treatment. Available PCP systems include jointed PCP with reinforced or prestressed panels installed singly or in a continuous series; and, prestressed PCP that typically incorporates thinner panels installed and posttensioned in a continuous series resulting in fewer joints. The use of PCP technology can significantly reduce traffic impacts of roadway repair and reconstruction projects, particularly on heavily traveled routes. The technology is applicable to both small segments, enabling flexibility in construction phasing, as well as for use in corridor-wide pavement rehabilitation/reconstruction. The review of projects constructed in the US and field testing of selected projects indicate that sufficient advances have been made to reliably design and construct PCP systems to achieve five key attributes of successful pavements.

C. Rao, W. Tabet ,R. Stubstad[10] (2005): Concrete maturity is being recognized as a viable test method to measure in-situ strengths of early age concrete and to assist agencies in making informed decisions on construction schedules. This increased interest is partly due to improved data collection technology in recent years coupled with a better understanding of the effects of construction and curing temperature on early age and long term performance of rigid pavements. The "maturity index", which is correlated to strength gain in a concrete mixture, is determined from the time-temperature history of the mixture. This paper presents a study conducted by Caltrans to evaluate the accuracy of this technology in predicting both flexural and compressive strength. The study involved a comprehensive laboratory study using two mix designs cured under four different temperature regimes. The test results indicate that calibration regression equations developed from samples cured in standard room temperature conditions are sufficient to predict concrete strengths associated with both cooler (∼10°C) and warmer (∼37°C) curing temperatures with reasonable accuracy. Further, actual field-measured maturity from a recent paving project, using the same mix design as the present study, yielded similarly accurate in-situ concrete strength predictions. The importance of proper curing for accurate strength predictions is demonstrated in the project.

David Merritt, Frank McCullough Ned Burns[4] (2003): The use of precast concrete is rapidly becoming a viable method for repair and rehabilitation of Portland cement concrete pavements, with several projects under construction or in development throughout the United States. Construction with precast concrete offers numerous benefits over conventional cast-in-place pavement construction. Most notable is how quickly a precast pavement can be opened to traffic. Precast panels can be placed during overnight or weekend operations and opened to traffic almost immediately. In addition, because precast panels are cast in a controlled environment, the durability of a precast pavement is also improved. In March 2002, the Texas Department of Transportation completed construction of a precast pavement pilot project aimed at testing and further developing a precast pavement concept developed by the Center for Transportation Research at The University of Texas at Austin. Thus project was constructed on a section of frontage road along Interstate 35 near Georgetown, Texas. The project incorporated the use of posttensioned precast concrete panels. The panels were posttensioned in place not only to tie all the panels together but also to reduce the pavement thickness required and improve durability. The finished pavement demonstrated not only the viability of precast pavement-construction but also the benefits of incorporation of posttensioning. Although the project was constructed without the time constraints and complexities that will eventually need to be considered for precast pavement construction, it ultimately helped to develop viable construction procedures for future precast prestressed concrete pavements.

Hachiya et al. (2001): The construction project was to replace distressed slabs at the Sendai Airport taxiway with a series of pretensioned slabs connected at transverse joints through the application of posttensioning. Each slab was 10 m (33 feet) long, 2.5 m (8 feet) wide, and 240 mm (9.5 in.) thick. An appropriate posttensioning force was applied to prevent joint opening due to typical negative temperature gradients at the construction site. The entire construction process from removal of distressed slab to interconnection of slabs through posttensioning was completed within 10 nighttime hours, from 9 p.m. to 7 a.m.

.

CHAPTER – 3

METHODOLOGY

3.1 General Concepts:

Today's concrete pavements are typically selected and designed with an expectation of long service life (e.g., 30 or more years). Some agencies have developed designs and construction specifications that are intended to produce "long-life concrete pavements" having service lives of 40 years or more with no premature failures and reduced potential for cracking, faulting and spalling. 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 like CIP concrete pavement. Thus, a JPrCP is expected to behave similarly to a CIPJCP, 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. Several factors in the fabrication of PCP panels contribute to the potential for good performance:

Precast panels typically include substantial amounts of reinforcement for transport and handling conditions (and sometimes for structural considerations as well). Any panel cracks that might develop generally remain tight and do not deteriorate.

Precast panels typically do not develop significant curl or warp during fabrication and storage, which reduces total curl/warp stresses present during pavement service.

The strength of precast concrete panels typically exceeds design requirements before the panels are installed. As a result, there is no potential for additional structural damage due to the application of early-age traffic loads.

The design of PCP systems is based, in part, on the expectation that the behavior of the installed precast pavement should not be significantly different from that of a cast-in-place (CIP) pavement under the same traffic, environmental and support conditions, and that the performance of the PCP should be comparable to (or, perhaps, somewhat better than) that of CIP pavement in the same application. The system design must also address mechanical and functional details that are not present in CIP pavement.

Therefore, the design of PCP systems must address many considerations and features, including:

- Determination of the structural design criteria (i.e., service life and performance requirements)
- Joint layout and selection of panel sizes
- Selection of the slab support system
- Thickness design
- Slab reinforcing design
- Joint design (including load transfer systems, tie bars and other details)
- Slab surface geometry (flat vs. non-planar)
- Slab surface texture
- Other details47, including grout ports, lifting mechanisms, utility openings, bedding grout distribution system etc.

3.2 Structural Design Criteria:

The structural design criteria for any pavement system are based on the types of structural distresses that might be expected to develop under service conditions. The distresses that are most commonly considered directly in CIP jointed concrete pavement (JCP) design are transverse cracking, joint faulting and joint spalling. The structural design of JPrCP should be performed with consideration of these same factors. In addition, direct consideration must be given to transportation and handling conditions, which can impart stresses that are very different from service conditions and are not considered in conventional pavement design thickness procedures. These conditions generally drive minimum panel reinforcing requirements for safety in transportation and handling, but typically do not impact pavement thickness design. There are other distress types that may indicate a structural failure of JCP systems (e.g., corner breaks, longitudinal cracking, blowups and some forms of materials-related distress). These are generally not considered directly in pavement structural design because they are related to the same mechanisms that cause transverse cracking, faulting and spalling, or because they are handled through materials and construction quality specifications. Pavement design procedures that are specific to PCP have not yet been developed; therefore, the design of JPrCP is currently based on available procedures for CIP concrete pavement systems. The AASHTOWare Pavement ME Design software is generally acknowledged as the most sophisticated pavement design system currently available. It was developed for use with asphalt and CIP concrete pavements, but is considered suitable for use with many PCP systems as well. The design criteria typically considered for JCP in the AASHTOWare Pavement ME Design software are: transverse cracking, joint faulting, spalling and International Roughness Index (IRI, a measure of ride quality).

3.3 Strength and Reinforcing Considerations:

Most highway agencies use concrete design compressive strengths at 28 days (f’c-28 days) of 3,000 to 4,000 psi, which results in average required compressive strengths of 4,000 to 5,200 psi to ensure that design strength is achieved with a high degree of statistical reliability. PCP can easily be produced with this level of strength and often with less variability in strength than for CIP concrete. PCP panels must also be reinforced to resist temperature and shrinkage stresses during curing and yard storage – as required by ACI specifications – and to prevent cracking or catastrophic and dangerous panel failures during lifting and handling. Conventional steel reinforcing is typically included at a rate of at least 0.2% (by area of concrete) in one mat in the lower half of the panel to satisfy both requirements. A second mat of temperature and shrinkage reinforcing steel is frequently added to the top half of the panel as further protection against cracking in panels that are opened to traffic before they are fully grouted. Conventional steel reinforcing should be protected from corrosion when used in environments with deicing chemicals or other corrosive agents.

Criterion	**Value (after fugro consultant, 2012)**	**Value (after Tayabji et al., 2013)**
Structural		
Cracked Slab, percent	< 20	25 – 30
Joint Faulting, in	< 0.10	< 0.15
Joint spalling	Minimal length, only low-severity	Minimal
Materials related Distresses	None	None
Functional		
International Roughness Index, in./mile	< 160	150 -160
Surface Texture – Friction	SN > 35, long-lasting	FN (SN) > 35
Surface Texture – Tire-Pavement Noise	No criteria available, but tire-pavement noise levels should be acceptable for the specific application and location.	No criteria available, but surface should produce accepted level of tire pavement noise

Table.3.1. Recommended Design Criteria for JPrCP Systems (after Fugro Consultants, 2012 and Tayabji et al., 2013)

3.4 Typical Thickness Design Criteria:

The design criteria presented in Table 3.1 have been recommended for JPrCP systems that are intended to provide long service life (Fugro Consultants, 2012; Tayabji et al., 2013): The above criteria represent values for each distress or condition that are not to be exceeded within the service life of the pavement. Periodic corrective action (e.g., diamond grinding) may be required over the pavement service life for some functional criteria (e.g., IRI and friction). The tabulated values are similar to those that would be applicable to any long-life concrete pavement with the exception of the cracked slabs criterion, for which much lower values (5% to 15%) would be typical in jointed, unreinforced CIP concrete pavement. As noted previously, the reinforcing typically provided in JPrCP panels for transport and handling is usually sufficient to ensure that most precast panel cracks remain tight and do not deteriorate over the pavement service life. Therefore, a higher value can be applied to this criterion for JPrCP to account for cracks that might develop during transport, handling or placement of the panels, but that will not deteriorate.

3.5 Typical Thickness Design Constraints:

Maximum and minimum PCP panel thickness may be limited by the thicknesses of existing pavement layers, overhead clearances, fabrication and constructability concerns, or pavement behavior considerations. Examples include:

- Panel thickness may be limited if the pavement profile is to be maintained and excavation of foundation material is either difficult (e.g., cement-treated or lean concrete base is present) or the use of thicker replacement panels may result in drainage problems, differential frost heave or other soil movements.
- The use of bedding material or mandated slab leveling material (e.g., grout-supported panels) will further reduce precast panel thickness if a preexisting pavement profile is to be maintained and foundation materials cannot be excavated to accommodate a thicker slab.
- Minimum panel thickness may be limited by cover requirements for embedded steel, minimum web thickness over (or under) load transfer dowel or tie bar slots, etc.
- Minimum panel thickness to control slab deflections (even when stress requirements are met through prestressing). Maximum thickness limitations may drive the need for prestressing and/or higher-strength concrete, depending on structural and service life requirements.

3.6 Panel Size Selection and Joint Layout Considerations:

The precast panel geometry should match the geometry of the portion of the existing pavement that is removed, less about 3⁄8 to.-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 super elevation, horizontal curves, and exit and entry ramps will require the fabrication of customized nonplanar panels. Panel size impacts many aspects of the production, installation and performance of the precast panel and surrounding slabs, including:

- Fabrication efficiency (given a finite number of casting beds) and unit costs (reflecting both production efficiency and the need to purchase new forms for unusual panel sizes)
- Ability to transport via truck (typically a 12-foot maximum trailering width, including any protruding reinforcement or other features) without special permitting.
- Efficiency in transport (i.e., selection of panel sizes that can be shipped in combinations that fully use load-carrying capacity, thereby minimizing the number of trucks and trucking costs required for any given project; see Chapter 6 for more information)
- Impact of panel size on required installation equipment (e.g., size of crane or other lifting equipment and job space requirements to accommodate the equipment and delivery trucks) and location (see Chapter 9 for more information)
- Number and location of embedded lifting anchors
- Impact of panel size on panel transport and lifting stresses
- Impact of panel size on joint layout with respect to the joint layout of adjacent panels (repair applications)
- Impact of panel size and dimensions on resulting load placements and service stresses (both curl/warp and load-related)

3.7 Panel Dimensions: Limiting Maximum Size and Aspect Ratio:

Panel dimension requirements for jointed precast pavement systems are typically considered to be the same as for conventional jointed plain (unreinforced) cast-in-place concrete pavement (JPCP) systems in similar applications. Panel widths are typically for the full paving lane (i.e., 10 to 14 feet) and panel lengths typically vary from a minimum of 6 feet for intermittent joint and mid-slab cracking repairs to 15 feet or more. These dimensions are rooted in conventional panel dimensioning guidance for cast-in-place JCP, which suggests that the maximum panel dimension in feet should not exceed 1.5 to 2 times the slab thickness in inches and that the ratio of the panel length and width should not exceed 1.5 in order to prevent uncontrolled cracking. For an 8-inch-thick slab, for example, the maximum panel dimension would be limited to 12 to 16 feet (with lower values for placement on stabilized foundation materials and higher values for placement on softer, lower-friction granular materials). The corresponding ratio of panel length to width for 12- to 16-foot panels in a 12-foot lane width would be 1.0 to 1.33, a range lower than the 1.5 limit. Using these "rules of thumb," thicker pavements could have significantly longer panels, especially when placed on softer, lower friction foundations, but performance records in many states have resulted in a cap of 15 feet on JCP panel length (and JPrCP panel length, by extrapolation) in most states to prevent panel cracking. Improved prediction of potential cracking can now be performed using the AASHTOWare Pavement ME Design software, which may result in length/width combinations that fall outside of the guidelines described here and still provide good performance without panel cracking.

3.8 Considerations for Retaining the Existing Longitudinal Joint Layout:

For both CIP and precast concrete pavement, longitudinal joints are generally placed to coincide with (or be very close to) designated lane lines because it is commonly believed that this minimizes the potential for driver error in mistaking a longitudinal joint for a lane line. It is sometimes necessary or desirable to locate longitudinal joints away from the pavement lane lines. Examples of this include:

- The use of widened outside travel lanes that are striped at the lane line but which extend 1 to 2 feet beyond that stripe to reduce load-related edge stresses (Figure 3.1).
- The addition of longitudinal joints down the center of ramps and other paving elements with widths that are significantly greater than 12 feet (Figure 3.2).
- The use of small pavement panels is common with concrete pavements that are 6 inches or less in thickness. For slab thicknesses of 5 to 6 inches, the panels are typically 6 feet square. Smaller panels have been used for thinner pavements, which typically places a longitudinal joint in the middle of the travel lane.
- For precast concrete installations, it may be convenient to cast and place wider single panels that extend over more than one travel lane. For example, Figure 3.1 shows the placement of a single panel that extends over a travel lane and an adjacent parking lane in an urban setting. In this case, the precast panel was sawed at the lane line location to develop a weakened plane that would control the location of any eventual cracking and to provide a visual lane line cue for traffic

Figure 3.1. Concrete pavement with ramp Construction

Figure 3.2. Wide precast widened concrete pavement

3.9 Consideration of Existing Expansion Joints:

Expansion joints are constructed in new pavements to accommodate potential excessive slab expansion or movement without developing high compressive forces in the pavement that might otherwise result in joint spalling and blowups or damage to adjacent structures (e.g., bridge decks and approach panels).

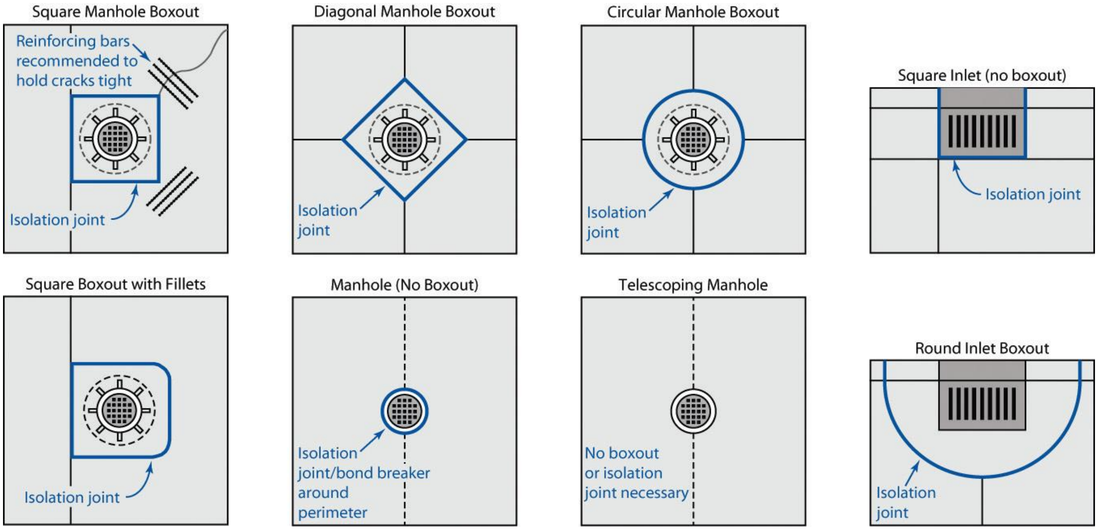


Figure 3.3 Examples of jointing adjustments to accommodate utility access points without inducing panel cracking

When an expansion joint is present in adjacent lanes within the boundaries of a precast panel installation, an expansion joint of similar width should be placed transversely at one end of the new precast panel, as close as possible to the existing expansion joint in the adjacent lane. When expansion joint is not provided, the transverse joints on either side of the precast panel will close first and the panel will be subjected to very high compressive forces as it restrains the expansive forces of the adjacent lanes, resulting in the likelihood of joint spalling and/or a blowup. When expansion joints are used, the pavement often moves to close the unrestrained expansion joint over a period of a few years. As this happens, several of the preceding and following contraction joints may open, eliminating the effectiveness of their seals.

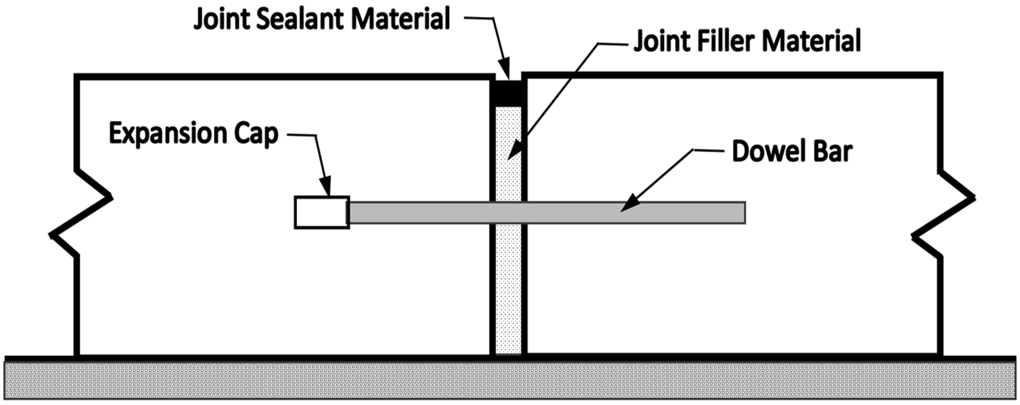


Figure 3.4. Example expansion joint schematic.

3.10 Selection of Slab Support System and Impact on System Design:

Uniform, durable support is crucial to the long-term performance of any concrete pavement system and the provision of full contact between the precast panel and the prepared foundation is one of the four critical elements in the precast paving process described in Chapter 1 and listed in Table 1.1.

3.10.1 Grout- or urethane-supported systems:

where the panel eventually rests on a relatively thick (approximately 1/2- inch) layer of cementitious grout or urethane that is injected between the slab and prepared foundation. Each of these systems offers specific advantages and draw-backs during installation, and each has implications for the design of the JPrCP system. These aspects of slab support system selection are described below.

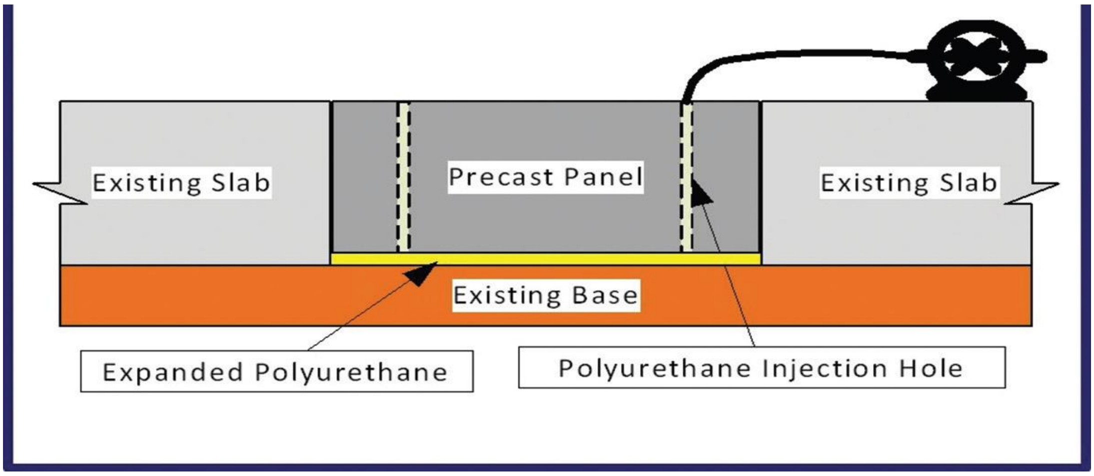
Grade-Supported JPrCP Systems:

Figure 3.5. Placement of grade-supported precast panel for over-night use prior to installation of bedding grout

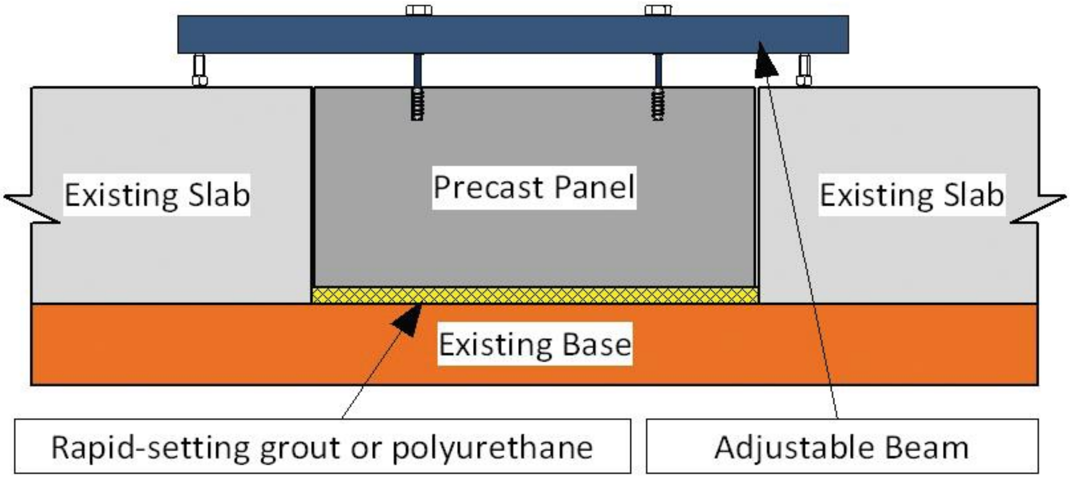
Grade-supported systems feature the construction of a precisely graded foundation that allows JPrCP panel placement to the proper elevation and with reasonably complete support, thereby allowing immediate opening to short-term traffic (Figures 3.4 and 3.5). This allows more effective use of short construction windows because installation activities do not need to be stopped to allow bedding grout to harden before opening to traffic – a second crew can perform that task during the next closure. The primary disadvantage to grade-supported systems is the time and expense required for precise grading and trimming of the subbase and bedding material. The selection of a grade-supported system requires special design details. There will still be small, intermittent support gaps, even with the most precisely graded and bedded foundation materials. These small gaps must be filled with low-viscosity, high-strength material – typically a specialized rapid-setting, cementitious grout – to ensure full contact with and uniform support of the slab. Bedding grout delivery is typically accomplished through ports from the panel surface to the bottom of the slab.

Figure 3.6. Proprietary grout distribution channels and gasket material on a Super-Slab JPrCP panel.

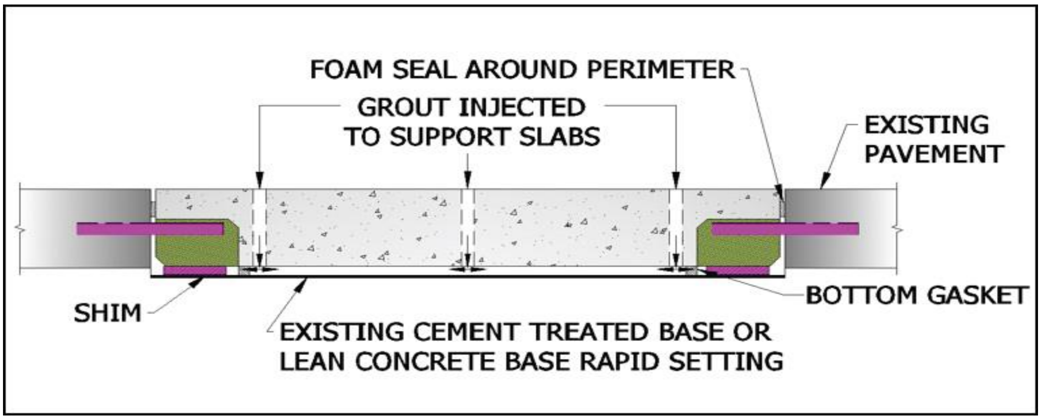
Distribution of the grout can be achieved by using several delivery ports located using a sufficiently close pattern to allow complete distribution beneath the panel, or through a series of channels on the panel bottom that connects to the grout ports (Figure 4.10). This latter detail is a proprietary feature developed by The Fort Miller Co., Inc.



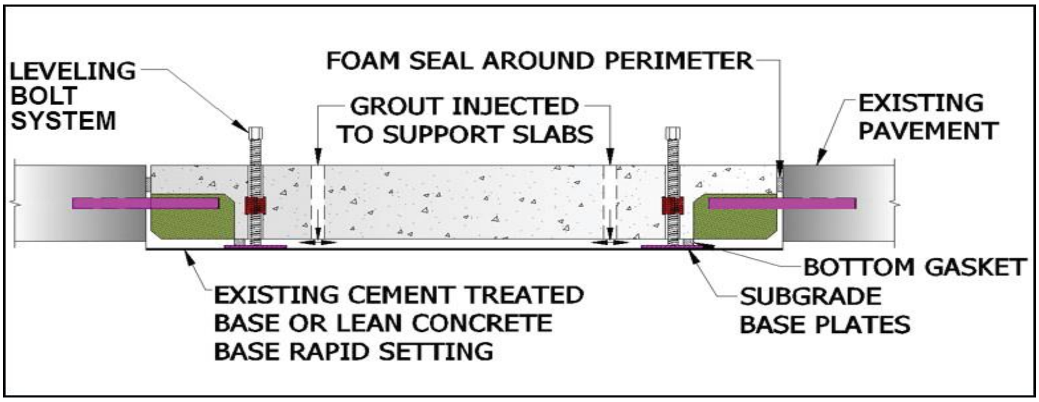
a. Pressure injection lifting using urethane.



b. Panel profile control using "strong-back" adjustable beam before grout injection.



c. Panel profile control using shims before grout injection.



d. Panel profile control using leveling bolt system before grout injection.

Figure 3.7 Illustrations of several variants of grout- and urethane-supported JPrCP systems.

3.10.2 Grout- and Urethane-Supported JPrCP Systems:

Grout- and urethane-supported systems involve the support of the JPrCP panel by a layer of rapid-setting structural grout or expansive urethane foam approximately 1/2 inch to 1 inch thick. There are several options for establishing the desired pavement profile and gap for the grout or foam. Grout- and urethane-supported systems offer the presumed advantage of reduced time and costs for precision-grading the foundation. The disadvantages of these systems include:

- Increased cost of panel fabrication for some systems (e.g., for installing lift device hardware)
- Need to cure the grout (typically 1 to 3 hours) or urethane (typically 15 to 60 minutes) before opening to traffic, thereby shortening the installation work window and reducing production rates.
- High cost of the much greater volume of grout or urethane that must be used to fill the gap between the panel and the foundation.
- Potential for slab cracking during installation – especially for the slab-jacking and leveling lift approaches – if the leveling process is not performed correctly.

3.11 Thickness Design:

As noted at the beginning of this chapter, thickness design procedures that are specific to JPrCP have not yet been developed, so the design of JPrCP is currently based on available procedures for CIP concrete pavement systems. While any agency-approved design approach for CIP concrete pavements can be used for designing JPrCP, the AASHTOWare Pavement ME Design software is the most sophisticated pavement design system currently available and is recommended for use with JPrCP with appropriate inputs and performance criteria (AASHTO, 2014). Recommended structural and functional performance design criteria for JPrCP systems are presented in Table 2. In addition, an assumed initial service life of 40 or more years is appropriate for most JPrCP installations. Most other aspects of performing a design using the AASHTOWare Pavement ME Design software are identical to what is done or assumed for conventional CIP concrete pavement. However, the following design inputs deserve some additional consideration:

- The default value for permanent (built-in) curl/warp temperature difference for conventional JCP is -10 degrees F, which implies that the pavement surface sets and hardens in a condition that is similar to being cooler or drier on the top surface than the bottom surface. Since PCP panels are fabricated in rigid forms in a plant and usually stored on dunnage with free flow of air above and below the panels, they likely have very little built-in curling due to fabrication. However, it can be assumed that some permanent moisture gradient (warping) will develop after the panels are in contact with the ground after installation.

Therefore, it is recommended that the Pavement ME Design default value of -10 degrees F be used for JPrCP thickness design until sufficient field data has been collected and analyzed to justify the use of a different value (Tayabji et al., 2013).

- Up to 50% ultimate shrinkage can be used in JPrCP thickness design because it is reasonable to assume that a large amount of the anticipated concrete shrinkage occurs during panel storage and before installation.
- Contact friction time is the time over which full contact friction between the slab and underlying base is assumed to exist. The Pavement ME Design default value for this parameter for conventional concrete pavements is 136 months (more than 11 years). The time to reduce that minimal bond is likely irrelevant to the thickness design. Despite this, Tayabji et al. (2013) recommend using the default 136-month contact friction period.

A sample thickness design analysis performed using an early version of the AASHTOWare Pavement ME Design methodology is presented in Tayabji et al. (2013).

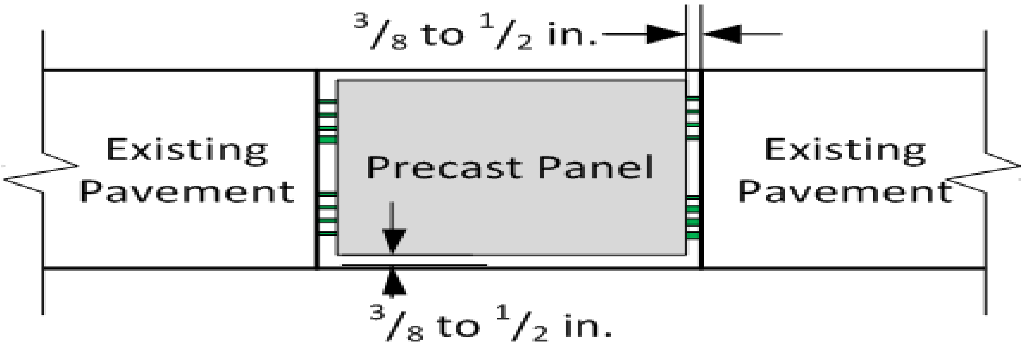


Figure 3.8 Placement of panel in excavated area in existing pavement.

The precast panel geometry should match the geometry of the portion of the existing pavement that is removed less about 3/8- 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 3.8.

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.

3.11.1 Impact of Slab Reinforcing on Thickness Design:

Conventional JPrCP is typically designed with up to 0.2% (by area of concrete) deformed steel reinforcing in both the transverse and longitudinal directions (often in two layers, near the top and bottom of the panels). This reinforcing is intended primarily to meet ACI's requirement for resisting Manual for Jointed Precast Concrete Pavement - temperature and shrinkage stresses and to prevent catastrophic panel failures in shipping and handling (e.g., when being lifted by cranes in close proximity to workers). The relatively small quantities of reinforcing used and the position of the reinforcing in the panel (at or near mid-depth of the slab) make its contribution to panel structural capacity relatively small for typical panel thicknesses.

3.11.2 JPrCP Panel Reinforcing:

Planar (flat) JPrCP panels are typically reinforced using one or more of the following materials:

- Deformed "mild" steel reinforcing bars.
- Synthetic or steel structural reinforcing fibers in the concrete mixture.
- Pretensioned steel strand installed at the time of panel fabrication.

While fiber reinforcing can be used in conjunction with either mild steel or prestressing strands, prestressing strands should generally not be used in the same direction as mild steel reinforcing because the mild steel would resist the prestressing, reducing the effectiveness of that technique. Mild steel is sometimes used around the perimeter of prestressed panels; mild steel that is oriented parallel to prestressed steel should be located far enough away to avoid reducing the effectiveness of the closest prestressing strands.
Individual panels may be reinforced using different techniques in the transverse and longitudinal directions (i.e., mild steel in the 12-foot transverse direction and prestressing in the longer longitudinal direction). Concrete prestressing (placing the

concrete in compression to offset anticipated tensile stresses due to structural and environmental loads) can be accomplished in two different ways:

- Pre-tension panels.
- Post tension panels.

Pre-tensioning is the most common form of prestressing for JPrCP systems. Post-tensioning is rarely used.

3.12 Design of Slab Reinforcing:

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 as 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.Typical reinforcement arrangement for a jointed PCP panel is shown in Figure 3.9

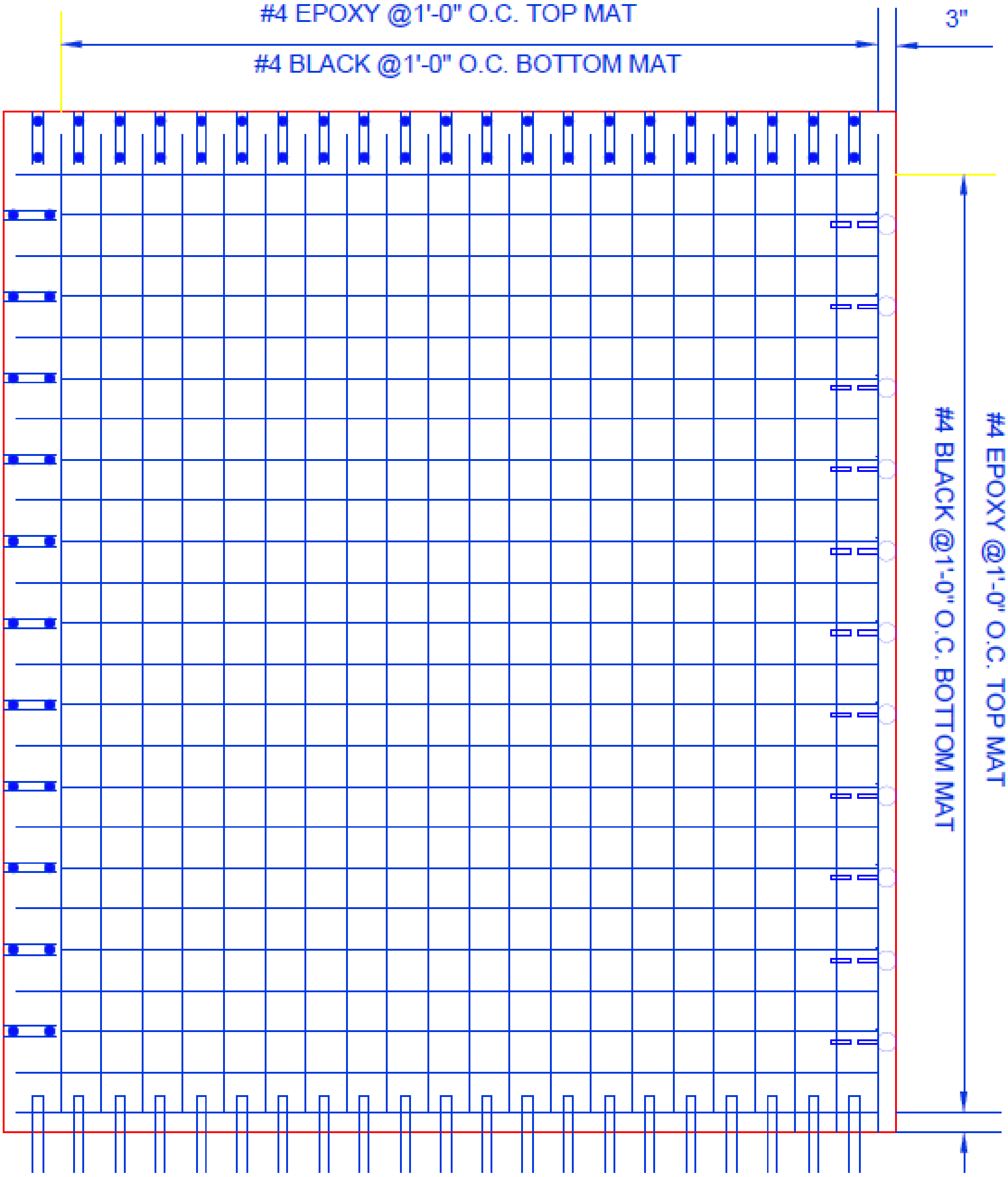


Figure 3.9. Typical reinforcement layout.

The 0.2% reinforcing quantity appears to be based on experience and typical American Concrete Institute requirements for minimum steel content to resist temperature and shrinkage in structural concrete members (ACI, 2014). Panels are typically reinforced in each direction to prevent catastrophic and dangerous panel failures during lifting and handling operations. Long, narrow panels can be reinforced in only the long direction if there is no risk of panel failure in the short direction.

3.13 Pre-tensioned Strand:

The use of embedded, pretensioned strand is the method most commonly used in JPrCP to offset the additional slab stresses that are developed when unusually long or wide panels must be fabricated. Pretensioning can also be used to provide adequate structural capacity while reducing panel thickness Pretensioning is typically accomplished using 1/2-inch-diameter 7-wire low-relaxation strands. These strands are tensioned to a stress of approximately 202,000 psi (75% of the 270,000-psi yield stress) using a force of 31,000 pounds per strand. The reduction in slab tensile stress in the direction of pre-stressing at any given point can be estimated as the effective prestress force (a function of the strand tension, the spacing of the strands and the distance of the point of interest from the panel edge/end of the strand) divided by the cross-sectional area of affected concrete. For example, for an 8-inch slab with strands spaced 24 inches apart, the affected area of concrete for each strand is 8 x 24 = 192 square inches. Therefore, the immediate effective prestress at a distance of more than 25 inches from the panel edge is 31,000 pounds/192 square inches = 161 psi and the long-term effective prestress is 25,300 pounds/192 square inches = 131 psi. Immediate and long-term effective prestress values for common panel thicknesses and strand spacings are present ed in Table 4.2.

Panel thickness (in)	**Immediate Effective Prestress Level (psi) for Strand Spacing of:**			**Long-term Effective Prestress Level (psi) 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

Table 3.2. Immediate and Long-Term Effective Prestress Levels for Various Panel Thicknesses and Strand Spacings – 1/2-inch-diameter, low-relaxation strand, 202,000-psi initial strand stress (after Tayabji et al., 2013).

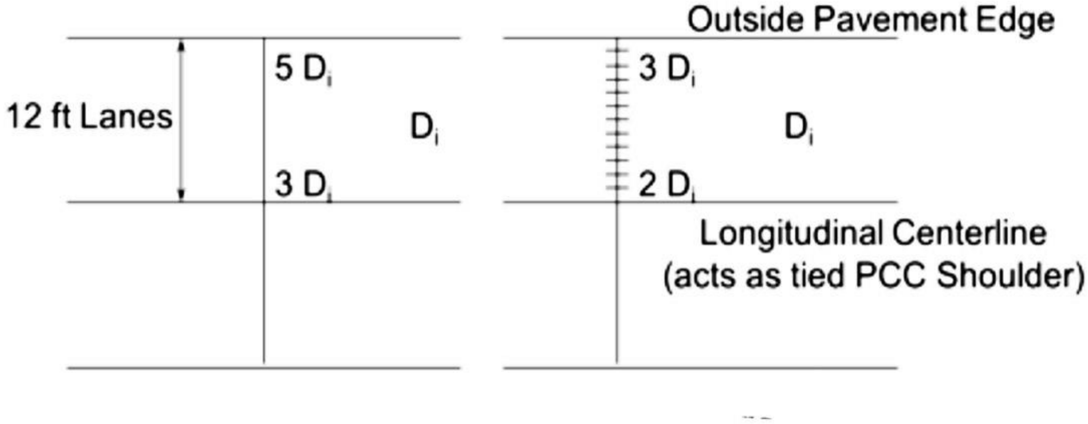


Figure 3.10. Illustration of relative concrete pavement deflections under loads placed at the slab interior and corners for un-doweled and doweled transverse joints. Di = deflection due to interior loading.

It is possible to use pre-tensioned strand to reduce critical stresses in thin precast paving panels to acceptable levels, but the thin pavement may still exhibit unacceptable deflection characteristics that can be addressed only with added pavement thickness or increased panel support.

3.14 Load Transfer Systems:

"Load transfer" refers to the action or ability of a joint to share a portion of applied loads across the joint. This is most reliably accomplished using mechanical devices like smooth dowels, but can also be achieved to varying degrees with deformed reinforcement bars (i.e., tie bars), formed keyways in the joint faces and aggregate interlock (the irregular texture that exists when a crack forms below the sawed joint in CIP concrete pavements). This section describes factors that should be considered in the design of load transfer systems, another of the four critical elements for JPrCP systems listed in Table 1.1.

3.14.1 Importance of Joint Load Transfer:

Concrete pavement slabs deflect in response to applied vehicle loads. The magnitude of the deflection depends on many factors, including the magnitude and position of the load, the slab thickness and stiffness, and the overall stiffness of the foundation system. Loads applied in the interior of the slab – away from panel edges – produce the lowest deflections (shown as D_i in Figure 3.9) while loads applied at unsupported pavement edges and corners produce much higher deflections because they are effectively supported by only 1/2 or 1/4 of a slab (for example, see the much higher deflections shown for the slab corners in the undoweled example in Figure 3.9).

Load Transfer Measures and Evaluation Criteria – LTE vs. Relative Deflection:

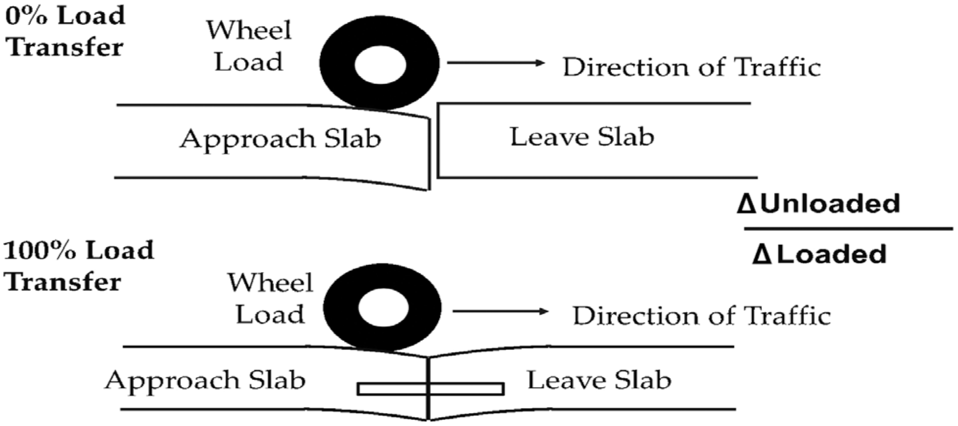


Figure 3.10. Illustration of load transfer efficiency calculation for a range of joint behaviors.

The effectiveness of any given load transfer system is typically tested in the field using a falling weight deflectometer (FWD), a sophisticated piece of trailered equipment that drops a mass package through a fixed distance onto a 12-inch-diameter load plate positioned adjacent to the joint (to simulate the passage of a 9,000-pound single wheel load) and then determines the deflection directly beneath the load and the corresponding deflection on the other side of the joint (Figure 4.14).

Historically, the load transfer system effectiveness has been assessed by computing the deflection-based load transfer efficiency as follows:

$$LTE\ (\%) = 100(\Delta UL / \Delta L)$$

Where

LTE = load transfer efficiency of the joint in percent,
ΔL = deflection at the center of the load plate
ΔUL = deflection 6 inches from the joint on the unloaded side of the joint.

LTE values theoretically range from 0 to 100 shown in figure 3.10. In practice, LTE values rarely approach 0 and are usually slightly less than 100 but can slightly exceed 100 due to testing anomalies with certain pavement structures.

Unfortunately, deflection-based LTE reflects the effects of many pavement design factors, including soil stiffness, foundation stiffness, slab thickness, joint opening, dowel design, temperature and moisture gradients in the slab at the time of testing (and more), so it cannot be used alone to assess the quality of the load transfer system. Furthermore, LTE measures alone can lead to incorrect assessments of load transfer system quality. A more reliable and pure measure of load transfer system effectiveness is relative or differential deflection, which is expressed simply as:

$$DD \text{ or } D_{rel} = \Delta L - \Delta UL.$$

3.14.2 Panel Support (Bedding):

The fine-grained granular bedding material should be used to allow for uniform seating of the panel but not as a fill-in material because such a material cannot be easily compacted and can create an unstable support condition if too thick. It should be noted that 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 heavier truck traffic. If the existing granular base is disturbed or damaged during the concrete pavement removal process, the base would then need to be regraded and compacted. Additional base material or bedding material may need to be used to bring the base to the required 120 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).

3.15 Dowels, Tie Bars and Keyways – Uses and Limitations:

The devices and mechanisms most commonly relied upon for load transfer in concrete pavements are dowel bars, tie bars, Figure 3.10. Illustration of load transfer efficiency calculation for a range of joint behaviors. Manual keyways and aggregate interlock. The uses and limitations of the first three are discussed here; aggregate interlock is not present at the formed faces of PCP systems so it is not discussed further.

3.15.1 Dowel Bars:

Dowels are smooth-surfaced mechanical devices that are installed parallel to the direction of primary slab expansion and contraction (usually the longitudinal axis of the highway) to provide vertical load transfer while also allowing longitudinal movements to take place at contraction and expansion joints Dowels are most commonly made from cylindrical carbon steel (with or without a corrosion-protective layer, such as epoxy) and are typically 18 inches long, 1.25 to 1.5 inches in diameter and are spaced on 12-inch centers across the joint.

3.15.2 Tie Bars:

Tie bars are devices placed across pavement joints to provide restraint in both the vertical and horizontal directions. Deformed reinforcing bars are most commonly used for this purpose, with a diameter of 1/2 to 3/4 inch (#4, #5 or #6 bars), placed on 24- to 48-inch centers and with sufficient length to allow the transfer of tensile forces (to prevent joint opening) from the bar into the concrete slabs on either side.

3.14.3 Keyways:

Keyways (or “keyed joints”) are formed during the slab fabrication process for both CIP and precast paving slabs. A designed slot (indentation) or key (extrusion) is formed along the length of the vertical surface of the joint to provide vertical interlock with slots or keys formed in adjacent slabs (Figure 3.11). JPrCP panels are often constructed with keyway slots on the joint faces of slabs on either side of the longitudinal joint. The key or load transfer mechanism is then formed by filling this double-slot with cementitious grout during construction (Figure 3.11).

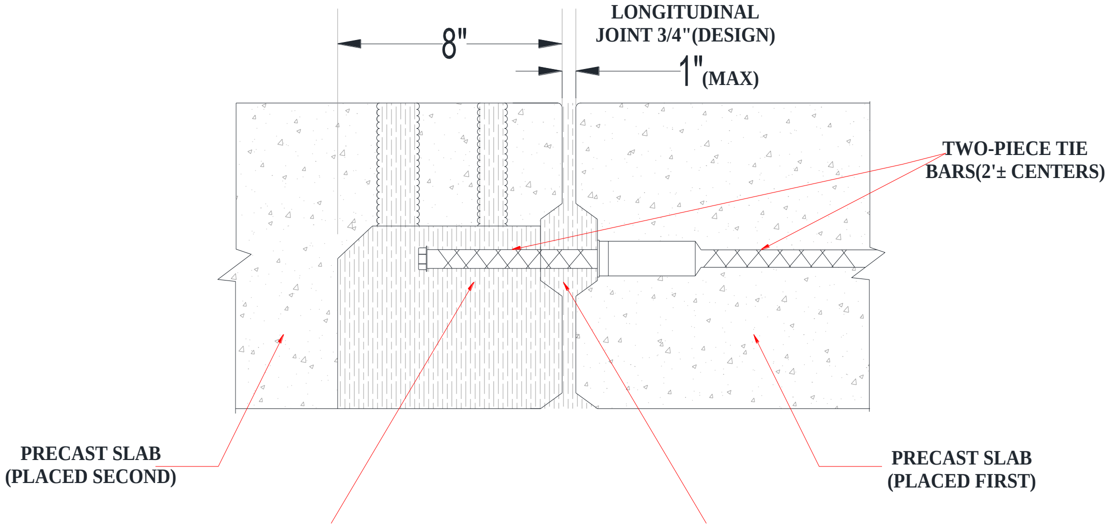


Figure 3.11. Schematic of typical double-keyway load transfer system for longitudinal joints in JPrCP systems.

3.16 Dowel Load Transfer System Design:

To be equivalent to cast-in-place concrete pavement, dowels or other qualified load transfer devices must be embedded in two adjacent slabs, across transverse joints. Embedment is accomplished by encasing dowels, pre-placed in slots, with non-shrink structural grout.

3.16.1 Dowel Top Slot System:

Slots in generic top-slot systems utilize top slots that are cut in the field or formed in the new precast slab. Dowels are either placed in the full slots prior to encasement or are cast in the new slab to match slots that are field-cut in the adjacent existing pavement. Load transfer is accomplished by bond strength between the new grout and the sandblasted sides of the slots, as shown in Figure3.12. Open slots on the top of any slab must be filled with permanent grout or with temporary filler devices before the slabs can be opened to traffic.

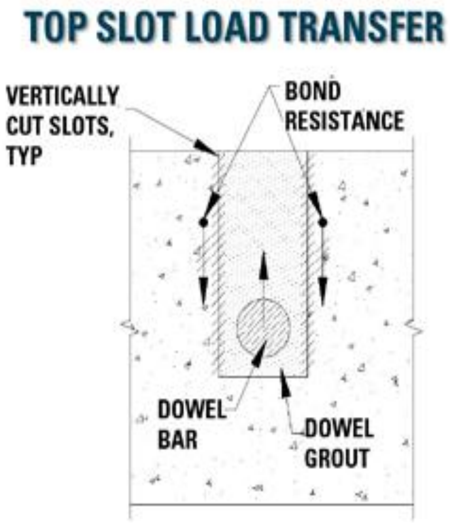


Figure 3.12: Generic top slot systems showing vertical sides

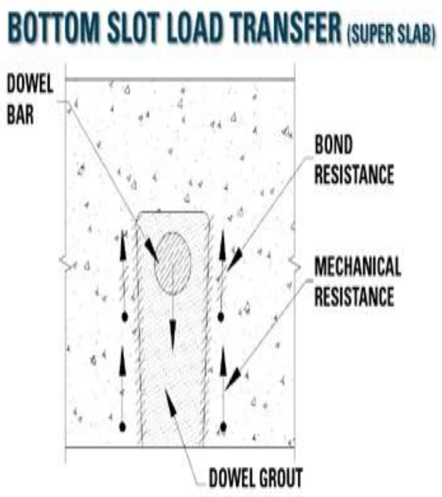


Figure 3.13: Proprietary dove-tail-shaped bottom slot system

3.16.2 Dowel Connection for Bottom Slot System:

Slots in the proprietary system shown in Figure 11 are cast in the bottom of the slabs. The slots are cast in a dove-tail shape to provide a mechanical, as well as a bond resistance to dowel bar pull-out. Super-Slab panels may be opened to traffic before the slots are filled since they provide no impediment to traffic. The bottom slot detail shown in Figures 11 and 12 is proprietary to the Super-Slab System. The bottom slots of the Super-Slab System are filled by injecting a flowable non-shrink structural grout in grout ports. The grout must be of proper consistency to ensure the dowels are fully encased and the slots are completely filled.

3.16.3 Tie Bar Across Longitudinal Joint:

Tie bars for the Super-Slab system are embedded in the same fashion as the dowel bars. In the Illinois Tollway process, precast slabs are tied with standard pavement stitches that are standard in the pavement industry.

3.16.4 Dowel Diameter or Size:

“Dowel bar diameter [or size] is an integral part of the design of the rigid pavement structural system [cast-in-place or precast] and should be determined as a part of the overall pavement design/evaluation process because it directly affects pavement performance. Dowel diameter should not be selected independently of pavement design, nor even as a simple function of pavement thickness”.

Dowel load transfer systems must be designed to prevent foreseeable failures due to shear, bending and dowel bearing stress on concrete, and excessive joint movements. The amount of load carried in shear through any dowel can be estimated by considering the legal wheel load (typically considered to be 4,083 KG for a single wheel of a single axle) placed adjacent to the transverse joint and directly over the dowel closest to the pavement edge (Figure 3.14).

The load will be transferred across the joint by all dowels within a certain distance of the applied load – the “radius of relative stiffness,” ℓ, which is calculated as:

$$\boldsymbol{\ell = (E_C h_3/12k\ (1-\mu_2))_{0.25}}$$

Where

E_C = elastic modulus of the concrete (psi),

h = slab thickness,

k = composite modulus of subgrade stiffness (psi/in)

µ = Poisson’s ratio of the concrete.

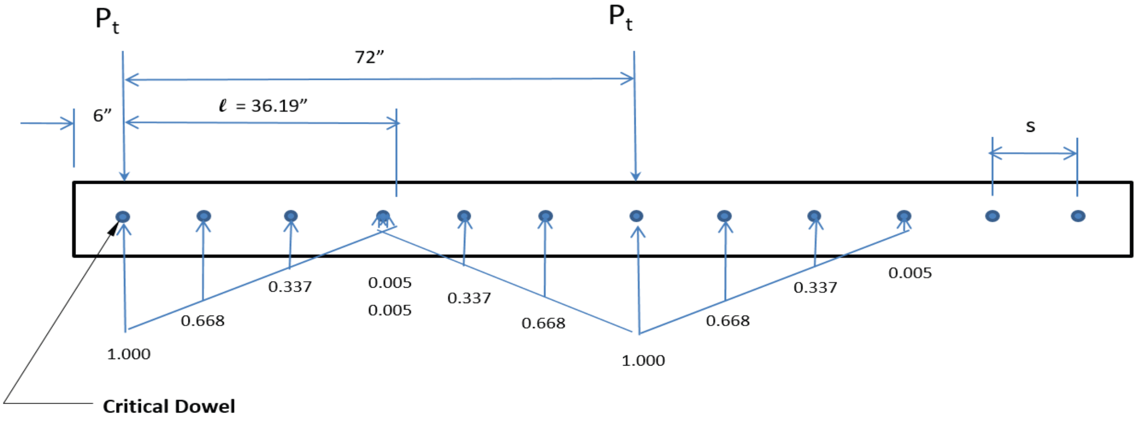


Figure 3.14. Sample computation of individual dowel shear loads within a dowel group. Pt is the transferred wheel load and S is the dowel spacing.

If the dowels are properly anchored or embedded in the concrete and the load is placed directly adjacent to the joint, the dowels will transfer 40% to 45% of the applied load to the adjacent slab, with the rest being carried by the loaded slab and transferred into the foundation. For a 4,083 -KG wheel load, 45% transfer is slightly more than 4,000 lbs. If half of that is carried by the dowel beneath the load, that is approximately 2,000 pounds, and all other dowels will carry less than that. This is a typical paving dowel design load. Bearing stress, σb, can be estimated using the following equations:

$$\sigma b = KPt\ (2+\beta z)/4\beta EdId$$

Where

Pt = transferred load carried by the critical dowel
K = modulus of dowel-concrete interaction
z = joint width at the dowel bar,
Ed = modulus of elasticity of the dowel
Id = moment of inertia of the dowel (πd4/64 for round dowels, where d is the dowel diameter in inches)

$$\beta = (Kd/4EdId)\ 0.25$$

Where:

β = relative stiffness of the dowel embedded in the concrete.
K = modulus of dowel-concrete interaction (typically assumed to be 1,500,000 psi/in),
E_d = modulus of elasticity of the dowel,
Id = moment of inertia of the dowel (πd4/64 for round dowels, where d is the dowel diameter in inches)

3.17 Additional Slab Design Features and Considerations:

3.17.1 Design Criteria for Jointed PCP Systems:

For continuous jointed PCP systems, the following long-term failure manifestations can result:

1. Structural distress:
   a. Slab cracking.

    b. Joint faulting.
    c. Joint salling.

2. Functional distress:
    a. Poor ride quality (smoothness).
    b. Poor surface texture (in terms of surface friction and tire–pavement noise).

The design criteria recommended for CIP JCPs for long-life service are considered applicable to the 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 is given in the table below.

Table 3.3. Recommended Design Criteria for Jointed PCP Systems

Criterion	Value
Structural	
Cracked Slab, percent	25 – 30
Joint Faulting, in	< 0.15
Joint spalling	Minimal
Materials related Distresses	None
Functional	
International Roughness Index, in./mile	150 -160
Surface Texture – Friction	FN (SN) > 35
Surface Texture – Tire-Pavement Noise	No criteria available, but surface should produce accepted level of tire pavement noise

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 if the distress development is acceptable or not and performs additional analysis using a revised pavement structure until an acceptable level of distress development results.

For JCPs, these distresses are considered in the MEPDG:

- Cracking.
- Faulting.
- 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 (as discussed previously).
3. Faulting - 0.15 in.
4. Smoothness (IRI) - 180 in/mi.

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.

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

1. Permanent curl/warp effective temperature difference (built-in curl).
2. Ultimate concrete shrinkage.
3. Contact friction time.

An example of the design of the jointed PCP using the above-listed criteria and design input adjustment is given below:

Project site: xyz

Traffic: Default Level 3 Traffic (equivalent to 100 million ESALs in the design lane)

Design reliability: 90%
Distress limits:
Cracking: 25%
Faulting: 0.15 in.
Smoothness (IRI): 180 in./mile

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: 750 lbf/in2 (5.1 MPa) (28-day)
- Concrete CTE: 5.5 millionth in./in./F
- Built-in Curl: -10°F (-23.3°C)
- Concrete ultimate drying shrinkage (50% of actual)

Layer 2: Permeable granular base

- Thickness: 6 in. (150 mm) 128
- Modulus of elasticity: 15,000 lbf/in2 (103.4 MPa)
- Base Erodability Index: Erosion resistant (Level 3)
- Loss of full friction (age in months): 136

Layer 3: Subgrade (A-5)

- Modulus of elasticity: 8,000 lbf/in2 (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.
- Smoothness: 159 in./in./mile

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/in2. The results of the analysis are given below:

- Cracking: 29.5%
- Faulting: 0.12 in.
- Smoothness: 181 in./in./mile

Table 8.3 provides a comparison of the slab (panel) thickness required for conventional jointed concrete pavements and jointed PCPs for a range of traffic conditions and example design inputs presented above and three types of base/bedding.

Table 3.4. Comparison of MEPDG-Based Designs for a Jointed PCP System for Different Support Conditions

a. With Poor Support Condition (Base Modulus = 15,000 lbf/in2)

Traffic Level, Estimated ESALs	Jointed PCP	CIPJCP
50,000,000	8.5 in	10.0 in
100,000,000	9.5 in	10.5 in
200,000,000	11.5 in	11.0 in

a. With Granular Base (Base Modulus = 30,000 lbf/in2)

Traffic Level, Estimated ESALs	Jointed PCP	CIPJCP
50,000,000	8.5 in	10.0 in
100,000,000	9.5 in	10.5 in
200,000,000	11.5 in	11.0 in

b. With CTB (Base Modulus = 2,000,000 lbf/in2)

Traffic Level, Estimated ESALs	Jointed PCP	CIPJCP
50,000,000	8.5 in	10 in
100,000,000	9.5 in	10.5 in
200,000,000	11.0 in	11.5 in

NOTE: Design Criteria:

Jointed PCP - % Cracking: 25%; Faulting: 0.15 in., Smoothness: 180 in./mi

CIP JCP - % Cracking: 15%; Faulting: 0.15 in., Smoothness: 180 in./mi

3.18 Fabrication Of Modular Rigid Pavement System Panels:

For PCP panel fabrication, the process includes the following:

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

3.18.1 Panel Testing:

Panel testing typically includes the following:

1. Dimensional 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 4.2. These tolerances do not supersede tolerances established by the highway agency for specific projects.

2. Dowel alignment

3. Inspection for panel surface damage or early-age distress check.

4. Pre-tensioning check - strand elongation check to assure that strands are tensioned to the proper load level.

Table 3.5. Geometric Tolerance Requirements (PCI, 2004)

Panel Feature	Tolerance
Length or width	+/- ¼ in.
Thickness	+/- ¼ in.
Squareness of corner - plan view	+/- ¼ in. over 12 in.
Squareness of the sides - 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 pre-tensioning strand	+/- ¼ in.
Blockout dimensions (if applicable)	+/- ¼ in.
Location of lifting inserts	+/- ½ in.

3.18.2 Embedded Features: Lifting and Jacking Hardware:

PCP panels are typically lifted (from the yard to transport vehicles and from the vehicles to installation) using four lifting anchors that are embedded in each panel at locations that are symmetric with respect to the panel axes and are selected to minimize bending stresses in the slab (Figure 4.15). PCI (2004) provides guidelines for determining concrete bending stresses that result from four-point lifting. Examples of lifting stresses computed for various sizes of panels using the PCI procedures are presented in Table 4.5, which shows that lifting stresses are very small for conventional single panels up to 12 feet wide and up to 15 feet long. Lifting stresses for wider or longer panels can be substantial and may merit the use of pre-tensioned reinforcing strands in the longer panel direction to offset the lifting stresses.

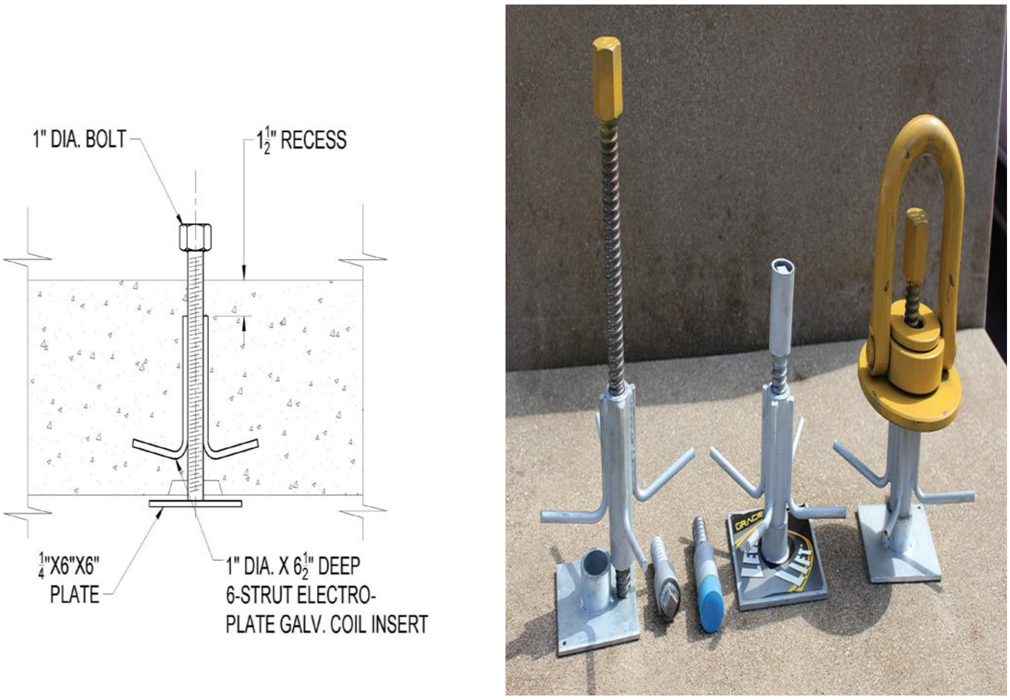


Figure 3.15. Photos and schematic of (from left to right) conventional coil lifting insert, generic lifting/adjusting insert and Gracie-Lift lifting/adjusting device.

Many styles of lifting anchors are available, including conventional threaded coil inserts and some that serve combined functions as both lifting anchor and slab-jack for grout-supported installations (Figure 4.34). Each lifting anchor product and size is rated for the load that can safely be carried for a given stripping strength, slab thickness and edge distance. Lifting anchors that are left in place after use must have sufficient top and bottom cover after installation to ensure they do not corrode and cause surface spalling of the PCP panel and to ensure they do not interfere with future profile grinding of the pavement.

3.18.3 Slab Surface Texture, Color, Patterns:

Concrete pavement surface texture affects both safety (skid resistance or friction number) and tire-pavement noise characteristics. Surface texture requirements for installed PCP panels typically match those required for new CIP pavement construction, although the texture provided during fabrication is often partially or wholly removed by diamond grinding that may be undertaken to restore the overall pavement surface profile. It is also possible to incorporate two-lift paving concepts in precast panels using recycled concrete or other aggregates of lower quality in the lower lifts of the panel while using hard, angular, skid-resistant or uniquely colored aggregate in the top few inches of the panel.

3.18.4 Grout Distribution Systems:

Grout ports and distribution channels that are formed into the PCP panel must be sized and located at positions that ensure the uniform distribution of the selected bedding or hardware grout.

CHAPTER – 4

STUDY AND EVALUATION

4.1 Introduction:

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

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

The assessment approach comprised of three primary zones: momentary results, medium- and long haul results, and effects. The key theories depended on use and execution of PCP innovation just as the effects on movement time and development. These effects included courses of events for street terminations and bypasses just as generally speaking undertaking timetables. Furthermore, FHWA assumed a significant job in planning parts of the theories. The assessment group looked for not exclusively to decide the utilization and results of PCP innovation, yet in addition to separate what job FHWA has played in impelling use and selection.

Three essential information sources were utilized to assess PCP innovation. To start with, the assessment group audited freely accessible data, including FHWA materials, effort, and reports. Second, the assessment group went to introductions at the 94th and 95th Transportation Research Board Annual Meetings, the Finally, the assessment group talked with routine clients of PCP innovation and a subset of concede beneficiaries of SHRP2 Rounds 3 and 6 Implementation Assistance Program. Notwithstanding these formal meetings with State transportation office clients of PCP, the assessment group held various casual discussions with FHWA staff, FHWA temporary workers, and different partners.

Responding to these inquiries will decide how much PCP innovation meets the targets of FHWA's Research and Technology Agenda.(4) Specifically, PCP can be connected to framework destinations 3, 4, and 5:(5)

- Objective 3: Improve the capacity of transportation offices to convey ventures that meet desires for practicality, quality, and cost.
- Objective 4: Reduce client postpone owing to foundation framework execution, support, recovery, and development.
- Objective 5: Improve interstate condition and execution through expanded utilization of plan, materials, development, and support advancements.

Utilizing PCP is an inventive structure and development system that encourages improved support. PCP innovation additionally encourages convenient, top notch extends that can be actualized in high-traffic territories with constrained disturbance. By empowering roadway areas to open the morning after a night of remaking, PCP enables organizations to oversee ventures that meet desires and diminish impacts on clients, not at all like activities that don't utilize PCP. In this manner, PCP innovation is perfect for lessening client delay in high-traffic zones where it is hard to reroute.

Given these hidden destinations, the assessment group built up a diagnostic system dependent on the assessment regions depicted in table 4.1.

Table 4.1. Summary of evaluation framework

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

PCP installation is an innovative practice of using prefabricated concrete panels for pavement and roadway maintenance and rehabilitation. This practice is often utilized in high traffic–volume areas and in variable or moderately inclement weather due to the construction-time and overall travel-time savings that it provides.

4.2 Program Background:

Timeline:

PCP establishment is an imaginative routine with regards to utilizing pre-assembled solid boards for asphalt and roadway upkeep and recovery. This training is frequently used in high traffic– volume regions and in factor or modestly severe climate because of the development time and by and large travel-time reserve funds that it gives. Critical to this assessment, PCP was joined as a SHRP2 venture (Project R05). SHRP2 Project R05 was inside the restoration center region, which focused on "empowering quicker, negligibly problematic, and longer-enduring improvements."(4) Other center territories under SHRP2 included security, unwavering quality, and limit. SHRP2 Project R05 is an essential focal point of this assessment. The movement of PCP in the United States, except for certain ventures that happened before, is as per the following:

- Mid-1990s: FHWA-drove inquire about endeavors started, including improvement of plausibility ponders.

- Early 2000s: Highway and air terminal offices started utilizing PCP innovation, and extra
  FHWA-drove explore was led.

- Mid-2000s: The American Association of State Highway and Transportation Officials
  (AASHTO) Technology Implementation Group (TIG) advanced PCP, and FHW bolstered
  PCP exhibits under the FHWA Highways for LIFE Program.

- Late 2000s: SHRP2 Project R05 work started, and FHWA specialized briefs were delivered.

- Early 2010s: A SHRP2 Project R05 last report was distributed, and the usage program under the task started.

- Mid-2010s: SHRP2 Project R05 granted Lead Adopter and User Incentive stipends to States through the Implementation Assistance Program (IAP) (Rounds 3 and 6).

As exhibited by this course of events, different FHWA-drove look into endeavors, shows, specialized briefings, and innovation refinements have happened in the course of the last 10 to 15 years.

In view of this work, PCP innovation has achieved the development moment that the innovation will before long be exchanged from FHWA central station to the FHWA Resource Center. The FHWA Resource Center gives, "specialized help, preparing, innovation organization, and interagency participation" by sending Resource Center staff across the nation to direct online classes and workshops.(5) With the exchange, the Resource Center will end up in charge of PCP exceed and will be the essential wellspring of data and experience for States hoping to embrace a PCP venture. The specialized help gave will incorporate addressing questions, sharing accepted procedures, presenting new advancements, and drawing in with States on a coordinated premise through gatherings, instructional meetings, and production improvement. All exercises will help advance the proceeded with use and improvement of PCP innovation.

4.2.1 Project Details:

SHRP2 Project R05 started by examining 16 PCP activities and verified that, while asphalt frameworks are as yet advancing, "admirably planned and well-built PCP frameworks can give high caliber, long haul administration and are regularly a decent decision for quick fix and restoration of existing asphalts." Major expectations from this first period of SHRP2 Project R05 were a lot of rules for determination, structure, creation, and establishment of PCP frameworks just as the advancement of model details.

Alongside the last report, FHWA and its contractual worker built up a showcasing plan for actualizing SHRP2 Project R05. The SHRP2 Project RO5 usage plan concentrated on specialized help, instruction, effort, and research. The arrangement showed that specialized help would be given to a predetermined number of new PCP clients with the objective of relieving any apparent execution dangers. Thruway offices that have gotten specialized help are Alabama, California, Connecticut, Delaware, the District of Columbia, Florida, Hawaii, Indiana, Kansas, Louisiana, New Mexico, Pennsylvania, Texas, Virginia, Washington State, and Wisconsin.

Training and effort concentrated on expanding consciousness of PCP advances, dispersing Errors, and giving preparing to thruway organizations and the PCP contractual worker network. FHWA's temporary worker created preparing modules to help the requirements of parkway offices, focusing on The Highways for LIFE Program looked for exhibits that were durable, inventive, quick to develop, effective, and safe. key plan, materials, and development faculty just as directors and boss designers. Contractual worker network training concentrated on tending to the job of the temporary worker in PCP applications. Throughout SHRP2 Project R05, instruction and preparing effort incorporated the accompanying:

- Twenty-three workshops for highway agencies.
- One industry workshop.
- Three webinars.
- Online search
- Reading general

Finally, the SHRP2 Project R05 implementation plan sought to continuously improve PCP technology through research and development. Efforts included reaching out to other agencies, organizations, and academia to encourage project-level data collection. Eighteen briefings with these other entities have occurred thus far. SHRP2 Project R05 also awarded grants through Rounds 3 and 6 of the IAP. This evaluation focused on the PCP-related projects and activities funded by the IAP awards, projects recently undertaken by routine users of PCP technology, and FHWA activities that promoted PCP. This evaluation was conducted in two phases.

Phase 1

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

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

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

- New Jersey Department of Transportation (NJDOT).

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

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

Phase 2

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

- Alabama Department of Transportation (ALDOT).
- Florida Department of Transportation (FDOT).
- Louisiana Department of Transportation & Development (LaDOTD).
- Pennsylvania Department of Transportation (PennDOT).

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

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

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

4.2.1 Evaluation Design:

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

4.3 Logic Model:

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

4.4 Evaluation Approach and Key Performance Measures:

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

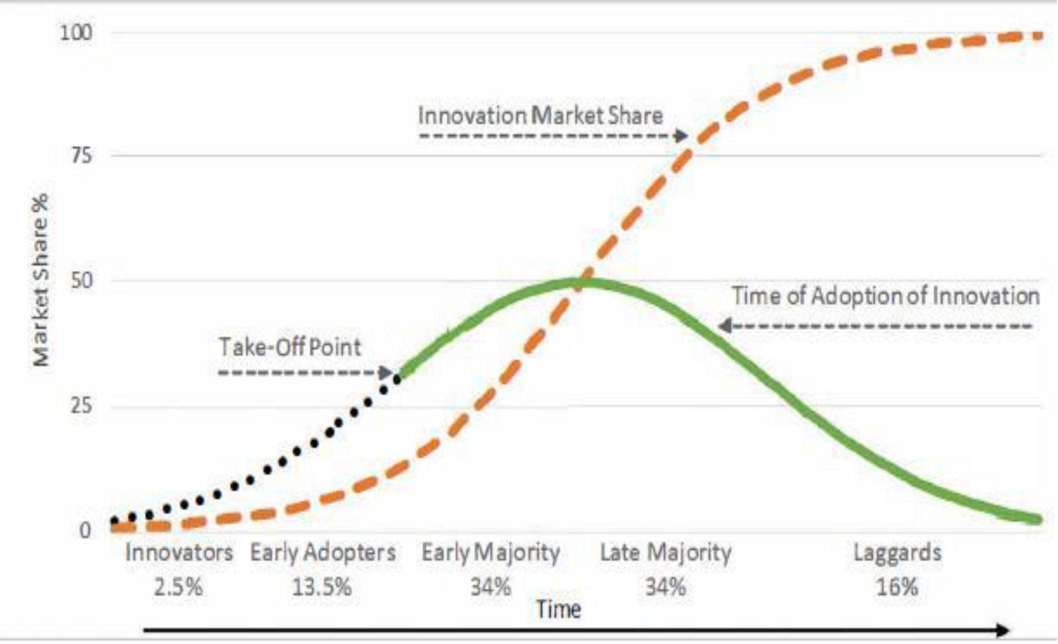
Table 4.2. Evaluation approach.

Evaluation Component	**Key Hypotheses**	**Key performance measures**
Short-term outcomes	PCP technology is being used in a broad range of project types. FHWA/SHRP2 activities contributed to the state of the practice.	• Determine usage of PCP technology. • Determine full range of FHWA activities and the impact they had on States.
Medium-/long-term outcomes	PCP technology leads to more durable pavement repairs and changes to industry practices. FHWA/SHRP2 activities encouraged adoption of PCP	• Compare PCP-project maintenance required against a baseline. • Analyze industry practices.

	technologies.	
Impacts	PCP technology leads to implementation- and travel-time savings compared to conventional rapid hardening–material projects (baseline).	• Compare PCP-project timelines, crew size, and maintenance required compared to a baseline. • Compare itemized PCP-project costs to conventional ready mixed concrete projects.

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

Figure4.1 is an adaptation of a figure generated by the State Government of Victoria, Australia, and shows the standard theory for the adoption of innovation over time. The x-axis represents time but does not have an exact range; the range for this x-axis is better explained as a starting point in time to a later point in time. The time range is flexible for all innovations. Based on the progression of PCP, the evaluation team views PCP as within the early-majority stage as many States have adopted or shown interest in the technology.



Source: Adapted from State Government of Victoria, Australia.

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

Figure 4.1. Line graph. Adoption of innovation over time.

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

In addition to technological diffusion and adoption based on usage and implementation, the key hypotheses incorporated the principles of benefit–cost analysis by comparing the outcomes of PCP usage to a baseline of possible alternatives. These alternatives include traditional ready-mixed concrete as well as high-early-strength concrete. While data for a full benefit–cost analysis were unavailable, the evaluation team made illustrative comparisons using a benefit–cost analytical framework. The comparisons were completed for various known demonstrations and implementations of PCP. The specific benefits and costs assessed are described in more detail in the next chapter. The key hypotheses detailed in table 2 were utilized to address the evaluation areas outlined in table 4.1.

4.5 Primary and Secondary Hypotheses and Key Measures of Effectiveness:

Table 3 describes the full set of secondary hypotheses for each evaluation area as well as the measures of effectiveness used to evaluate the hypotheses.

Table 4.3. Hypotheses and measures of effectiveness by evaluation area.

Evaluation Area	**Secondary Hypothesis**	**Measure of Effectiveness**
Technology diffusion and research	PCP technology is being used for a broad range of applications in a variety of settings.	Determine usage of PCP technology (intersections, road sections, highway sections, bridges, etc.).
Technology diffusion and research	FHWA activities (research, demonstrations, workshops, etc.) contributed to PCP technology development and usage.	Determine contribution FHWA research had on State decision making regarding PCP usage.
Technology diffusion and research	States are aware of and utilize SHRP2 PCP guidelines and technical standards.	Determine level of awareness and usage of guidelines and technical standards.
Costs of PCP	PCP-procurement and -construction costs are greater than those for conventional ready-mixed concrete projects.	On average, costs for materials, equipment, training, installation, and crews are greater for PCP projects compared to conventional ready-mixed concrete projects.
Costs of PCP	Overall PCP-project costs, including maintenance costs over time, are less than those for conventional ready-mixed concrete projects.	On average, costs associated with maintenance, labor time, and travel time are less for PCP projects compared to conventional ready-mixed concrete projects.
Costs of PCP	Use of PCP presents additional installation challenges compared to conventional ready-mixed concrete projects.	On average, PCP projects lead to other disadvantages or challenges compared to conventional ready-mixed concrete projects.
Benefits of PCP	Use of PCP leads to pavement installation time savings (based on ability to install in varying	On average, installation time for PCP projects was less than for

	weather conditions or at night) compared to conventional ready-mixed concrete projects.	conventional ready-mixed concrete projects.
Benefits of PCP	Use of PCP leads to overall travel-time savings (based on no field cure time) compared to conventional ready-mixed concrete projects.	On average, travel time for PCP projects (measured in delays or detours) was less than for conventional ready-mixed concrete projects.
Benefits of PCP	Use of PCP leads to increased durability and longer service life compared to conventional ready-mixed concrete projects.	On average, PCP projects require less maintenance compared to conventional ready-mixed concrete projects.
Benefits of PCP	Use of PCP leads to other advantages, including innovative approaches, compared to conventional ready-mixed concrete projects.	On average, PCP projects lead to other advantages or unique benefits compared to conventional ready-mixed concrete projects.

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

4.6 Evaluation Methodology:

Three primary data sources were used to evaluate PCP technology. First, the evaluation team reviewed publicly available information, including FHWA materials, outreach, and reports. This review included a compilation of known PCP projects to determine a baseline of PCP usage. Second, the evaluation team attended presentations at the 94th and 95th Transportation Research Board Annual Meetings, the 11th International Conference on Concrete Pavements (ICCP), and internally at

FHWA’s Turner-Fairbank Highway Research Center. Last, the evaluation team interviewed routine users of PCP technology and a subset of SHRP2 Rounds 3 and 6 IAP recipients. In addition to these formal interviews with State transportation department users of PCP, numerous informal conversations were held with FHWA staff, FHWA contractors, and other stakeholders. The subsections of this chapter expand upon these three data sources and the hypotheses addressed.

4.7 PCP Documentation:

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

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

4.8 Formal Interviews:

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

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

For phase 2, follow up Interviews provided insight into the activities undertaken and activities the State transportation departments plan to undertake using the User Incentive award. Interviewees described how their States first became aware of SHRP2 funding. For State transportation departments with completed (or nearly completed) projects, the team asked interviewees to discuss potential updates to the contractor-selection process or specifications.

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

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

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

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

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

4.9 Evaluation Findings:

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

4.10 Technology Diffusion and Research:

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

A review of current PCP deployments showed that 27 States have completed projects and several other States are planning to install PCP or exploring the use of the technology. Table 4.5 lists each State by PCP activity level.

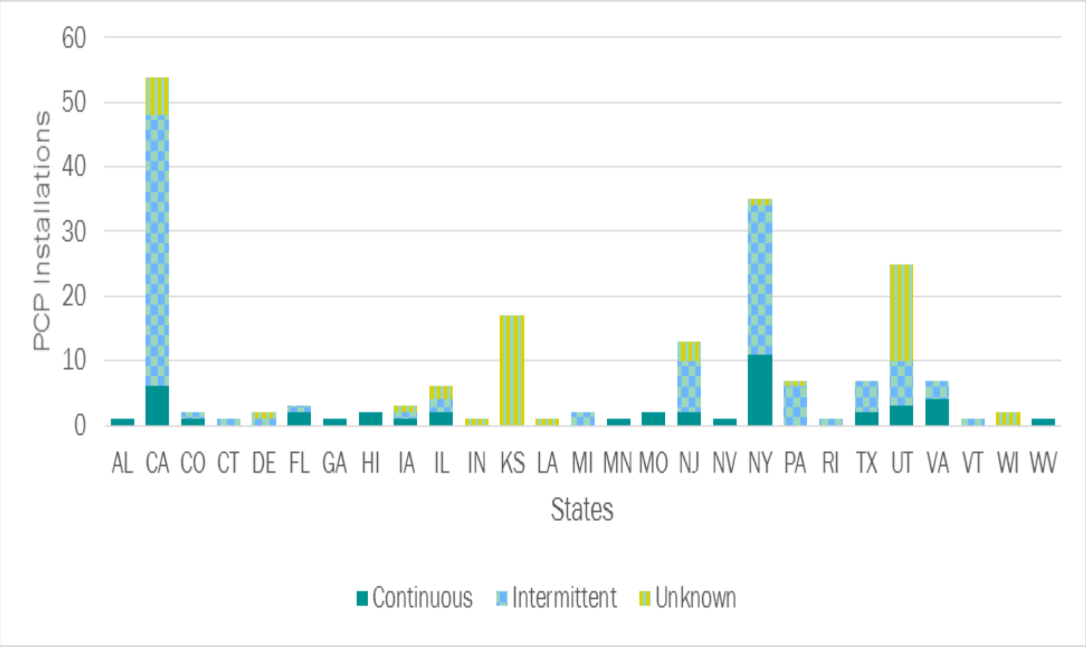
Table 4.5. State PCP activities.

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

During interviews, States mentioned novel uses for precast-concrete panels. For example, ALDOT noted its use of single panels for emergency repairs in high-use areas. Similarly, INDOT expressed interest in using PCP panels for repairs. INDOT noted that, while it has contractors who can pave with traditional methods at the same speed they can pave PCP, these contractors cannot do the same for intermittent patching. Thus, INDOT indicated a desire to devise two systems that its maintenance

team can use: one for intermittent patching and one for long patching. Additionally, PennDOT noted the possibility of using panels with an overlay of asphalt for consistency with Philadelphia's municipal pavement standards. Because the technology is expensive, PennDOT representatives are not sure that applying an overlay (in this case, asphalt) makes sense, but they indicated interest in exploring the technique.

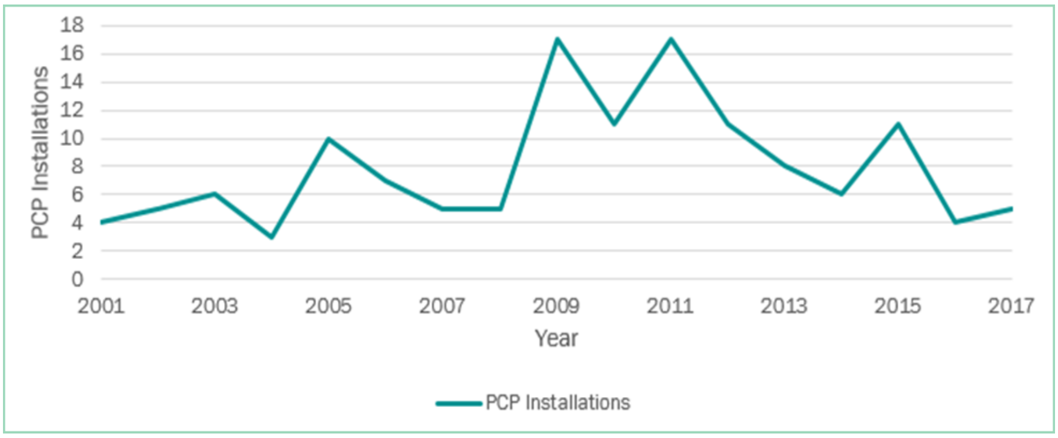
The sizes of PCP projects varied greatly. Some small repair and experimental projects used only a few panels, while projects along longer sections of highway required hundreds of panels. The mean installation size among projects with accurate data was 23,660 square feet. Panel dimensions varied by project and State, though panel depth of 8 to 8¾ inches was most common. State-level use varied significantly, with slightly more than half of all State transportation departments reporting completed installations of PCP, as can be seen in figure 3. Routine-user States (California, New Jersey, New York, and Utah) made up a large portion of total PCP installations nationally. However, several State transportation departments provided reports and feedback to FHWA regarding their trial projects and may not have identified PCP as the technology used in subsequent projects, which may have led to underreporting PCP implementation in this evaluation report.



Source: FHWA.

Figure 4.2. Bar chart. PCP-installation type by State.

As shown in figure 4.2, an initial high point in PCP installations corresponded with FHWA's Highways for LIFE and AASHTO's TIG efforts to promote its use in the mid-2000s. Decline could be the result of a decreased emphasis on PCP usage in State transportation department and FHWA publications or of States using PCP but reporting and promoting successful projects less. In particular, singlepanel emergency repairs that were not part of a larger project are unlikely to be captured by this evaluation report.



Source: FHWA.

Figure 4.3. Line graph. PCP installations by year.

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

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

FHWA has been involved in the promotion and development of PCP applications for nearly 2 decades. Prior to SHRP2, FHWA primarily worked with State transportation departments to fully or partially fund demonstration projects. More recently, FHWA efforts have focused on the SHRP2 Project R05 implementation plan, discussed in previous chapter. Based on the implementation plan, FHWA has produced reports on PCP technology and has provided individual technical assistance to interested States looking to implement PCP. FHWA has also conducted workshops and four ETG meetings, bringing together representatives from State transportation departments, industry, and academia with knowledge and interest in PCP technology. A by-product of FHWA's outreach efforts is the fact that the 2017 ETG meeting had a record attendance of 68 participants—a 209-percent increase over the 2016 meeting (22 participants)—including a large number of first-time attendees.

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

During phase 1 and 2 interviews, State transportation departments frequently identified FHWA involvement as beneficial to the design, specification, and construction phases of projects. States often mentioned FHWA's contractor as being a valuable resource for developing and modifying specifications as well as providing more general one-on-one support for State transportation department representatives as the project progressed through the construction phase. Participants reported that site visits and the personal attention of FHWA's contractor gave those working on the project confidence that the project was progressing as it should. Specifically, when difficulties arose, the people working on the project had an experienced resource to help mitigate those challenges. Funding from FHWA for demonstration projects directly affected the number of installations nationwide, and programming has helped States learn about and develop skills for the implementation of PCP technology.

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

The initial hypothesis, in this instance, was found to be largely correct. FHWA activities and resources have proven useful to States in promoting usage of PCP and, in turn, have furthered the technological development of PCP implementations. Hypothesis: States are aware of and use SHRP2 PCP guidelines and technical standards.

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

As discussed earlier in this section, PCP is a new technology, with limited documentation of best practices. Additionally, a significant portion of the innovation in the PCP realm has been undertaken by private industry, where firms have begun to market proprietary systems to interested agencies and transportation departments. Proprietary systems can be difficult for States and contractors to learn and use; these challenges can slow adoption of otherwise useful or beneficial technologies like PCP. The publication of the R05 final report collected much of the publicly available knowledge on PCP design, fabrication, and installation in one accessible location, and the accompanying marketing and distribution of the report sought to address challenges to PCP adoption. Every State interviewed reported utilizing the R05 final report extensively in developing and designing PCP installations. Of routine users and Round 3 IAP recipients, five of seven interviewees specifically cited the R05 final report as the most useful resource produced by FHWA thus far. While some noted that the information in R05 was becoming out of date at the time of the interview, it remained the best collection of information on PCP and had helped the development and spread of PCP.

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

The initial hypothesis was correct in part. In interviews, State transportation departments expressed a strong awareness of SHRP2 materials and commented on their usefulness. While most interviews were conducted with SHRP2-grant recipients, multiple routine users (who began use of PCP before SHRP2) cited R05 as a significant resource for them and noted that SHRP2 implementation activities had furthered their thinking on the subject. For example, UDOT specifically noted its participation in the SHRP2 Project R05 ETG, which provided opportunities to learn from other practitioners and facilitated site visits to observe demonstrations

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

However, in interviews, multiple State transportation departments described developing or starting to develop a generic specification following the publication of the SHRP2 materials. Specifically, most States that received SHPR2 Round 6 IAP User Incentive funding are using that funding to develop their own installation specifications or to update and train staff on existing specifications. However, those States did not specifically mention the use of SHRP2 technical demonstrations as a resource. All interviewees mentioned consulting with FHWA's contractor and other FHWA and SHRP2 resources in their processes. One State noted that the specifications were the least helpful of the resources published and that it would rely on the R05 authors in development of its projects and specifications. The DDOT indicated it needed to develop its own specifications due to its use of unique pavement technology on roadways. INDOT indicated it was required to develop specifications stamped by an Indiana Professional Engineer. In addition, approximately half the interviewees indicated they used or had originally developed specifications related to a proprietary PCP system.

4.11 Costs of PCP:

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

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

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

Caltrans compared PCP to high-early-strength concrete as those are the two options best suited for short working windows. While the initial cost of installation for high-early-strength concrete was estimated to be roughly half the cost of PCP several years ago, the industry is evolving.

Based on the increased use of PCP in recent years, the agency now generally views the cost of PCP as two-thirds the cost of high-early-strength concrete in that district. This difference leads to the broader point that specific costs vary based on location and project size. Similarly, Caltrans noted that costs of various PCP-system types vary. Precast, pretensioned concrete pavement is viewed as the most expensive, followed by precast, jointed concrete pavement, followed by individual precast-slab replacement. Depending on project size and the type of PCP used, the comparison to possible alternatives in terms of costs will fluctuate. NJDOT reported average costs of approximately $525 per square yard for CIP-concrete installation, compared to $625 per square yard for PCP. In New Jersey, the average expected performance of CIP concrete is 8 years, compared to 20 years for PCP. As a result, when including maintenance and repair costs, overall lifecycle costs for CIP concrete exceed PCP costs.

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

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

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

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

As described earlier in this section, less detail was provided by interviewees regarding conventional ready-mixed or CIP-concrete solutions. Instead, more information was provided regarding high-early strength concrete as a viable alternative. Given the particular project types, using PCP led to lower project costs compared to high-early-strength concrete. This finding was particularly evident when considering expected service life and the need for additional maintenance or repairs over time.

CIP concrete repairs were viewed as having higher lifecycle costs compared to PCP in addition to leading to lengthy road closures that, in many cases, are not feasible given the configuration or the traffic volume of the site. All agencies with which the evaluation team spoke noted that PCP has a longer expected service life than high-early-strength concrete and CIP concrete, leading to notably lower costs for future maintenance and repair. Considering performance and all relevant cost factors, as we views PCP as two times more beneficial than CIP concrete. This view is largely based on the fact that the lifecycle costs for PCP are significantly lower compared to high-early-strength concrete and CIP concrete. we has found that PCP will last for 20 to 50 years compared to 1 to 15 years for CIP concrete repairs. The agency also noted that PCP has failed in less than 1 percent of cases where it has been installed, leading to increased confidence in the repairs being performed. It is clear that the reduced maintenance cost associated with PCP makes it cost beneficial from an installation and repair perspective.

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

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

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

Given that PCP remains a relatively new technology in the United States, many of the implementations, in recent years, have been conducted by agencies using PCP for the first time. It was evident that the majority of the well-attended session was interested in learning more about undertaking and implementing PCP, rather than refining existing practices. As a result, based on the limited knowledge of and experience working with PCP, a learning curve exists that can include unexpected costs, particularly on the part of contractors who do not have pre casting expertise. This topic was discussed at the 2014 ETG meeting, where participants concluded that this learning curve led to higher risk and costs. As experience increases, it is expected that risk and cost will decrease. Based on this assumption, all 4 of the SHRP2 Round 3 IAP awardees conducted trial installations with a small number of panels (ranging from 4 to 30) before beginning full construction. Additionally, all agencies, including the routine users interviewed, noted that resources were spent determining specifications and refining which methods of PCP to use.

As a result, contractors need to invest in different machinery and employee training, which can lead to higher overall project costs. UDOT noted similar costs associated with learning how to use PCP, stating that PCP requires a higher level of initial design and verification than standard concretes used for intermittent repairs. When designing PCP specifications for an implementation, participants at the 2014 ETG meeting noted a fear of lawsuits and violation of intellectual property as there are a number of proprietary systems already in place. This concern could hinder implementation. Along these lines, when implemented, PCP requires more attention to inspection and workmanship, and a more conscientious and skilled (i.e., trained) workforce.

During the Leavenworth, KS, implementation, panel fabrication began 96 days prior to construction, which lasted approximately 30 days. While some lead time was built in for the panels to reach a certain level of strength prior to installation, experience could lead to a more condensed timeline and potential cost savings. TxDOT noted that several panels were damaged during handling at the project site, resulting in corner spalls, and several panels were not aligned within the specified tolerances and needed to be redone.

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

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

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

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

4.12 Benefits of PCP:

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

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

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

During one PCP-project installation in Mobile, contractors installed six test panels prior to the area being hit by a hurricane. The hurricane temporarily shut the project down as resources were diverted to recovery efforts. However, evacuation traffic was able to be routed through the project intersection because the PCP panels were installed, unlike projects using other concrete options, which require road closures for the concrete to cure and dry. Due to the evacuation, the project area experienced an unexpected and significant increase in traffic volumes. Being that PCP panels were used rather than typical repair techniques, there were no construction-related materials blocking traffic, no new safety hazards were created by partially completed repair work, and both lanes were completely open. ALDOT was particularly impressed with the flexibility of the project installation; the project area could be reopened mid repair to accommodate hurricane traffic and remaining repairs could be completed at a later date after the recovery was underway.

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

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

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

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

NJDOT noted that a significant advantage of PCP is the quick return to traffic, opening the roadway in the morning and allowing for morning peak traffic to proceed uninterrupted without lane closures. Similarly, NYSDOT noted that its interest in PCP arose from a desire to decrease closure times and reduce the impact that construction had on travel times and congestion. Given these impacts, the agency noted that the decision to use PCP versus its alternatives is based on how long the agency can reasonably close the road without causing significant delays. There is not a specific traffic volume cutoff point, and the decision depends instead on the construction area itself. For example, PCP is used in cases where congestion will be significant and detours or other mitigations are not sufficient. UDOT also noted the advantages of driver-time savings and having an emphasis on the maintenance of traffic when speaking more broadly about the benefits of PCP. The agency stated that, if a lane closure would have a significant impact on delays, then PCP is considered as it allows for shorter delays. If closing a lane will provide minimal or no delays, the agency prefers traditional methods, and this preference emphasizes the belief that PCP is useful for minimizing travel-time delays.

PCP does not have a specific cutoff for traffic volumes that would lead them to use PCP. Instead, the agency looks at traffic windows on the given section of roadway to determine the effect delays would have on the system as a whole. This mindset emphasizes overall traffic flow and travel times for network users. In some cases, the general commitment to maintain traffic flow, reduce travel-time delays, and reopen the roadway to traffic for the morning peak was written into the contracts by the State transportation departments. For KDOT, a $2,000 penalty was owed by the contractor for each day past 30 days of lane closures (on each of the three sections of the project).

As access to the fort is critical, closing this section of roadway was not an option. Finally, TxDOT chose PCP for the intersection between State Highway 97 and State Highway 72, in part, because the detour in the rural area would be lengthy and lead to a significant travel-time increase for roadway users, many of which are commercial trucks. Based on these circumstances, potential negative economic impacts exist as well.

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

Using PCP allows for overnight closures and construction that can be completed prior to the morning peak, reopening the roadway to traffic. Utilizing PCP takes into consideration medium-term terminations and development that can be finished preceding the morning crest, reviving the roadway to traffic. This capacity prompts a noteworthy decrease in movement times contrasted with choices that would keep the roadway shut amid pinnacle periods. Reviving the roadway decreases clog by taking into account extra volume. This advantage is critical in regions where volume and blockage are as of now high even without roadway terminations. These movement time investment funds are an essential piece of utilizing PCP, and therefore, State transportation offices frequently compose punishments into their agreements if the temporary worker is postponed in reviving the roadway. Furthermore, PCP diminishes travel time by relieving the requirement for critical makeshift routes. Shutting certain crossing points or extension approaches, as kept away from in Texas and Kansas, individually, would expect drivers to occupy their courses essentially and increment travel times likewise. Speculation: Use of PCP prompts expanded strength and longer administration life contrasted with an ordinary prepared blended solid venture (benchmark). As portrayed in area 4.2 in regards to support costs after some time, PCP gives fundamentally longer administration life contrasted with high-early-quality cement and is like customary CIP concrete in toughness.

Caltrans noticed that PCP gives prevalent execution and essentially longer administration life contrasted with high-early-quality cement. This experience is established by the way that the organization utilizes lifecycle cost examination to contrast elective undertaking costs with deference with execution. With a normal administration life of more than 40 years for PCP, the innovation performs well under this investigation regarding fixes. This administration life is in accordance with customary portland bond concrete and ordinary solid, which is assessed to most recent 40 years, and as an unmistakable difference to the way that, in Caltrans' understanding, high-early-quality cement has an administration life as low as a half year. PCP is more predictable than high-early-quality cement. The office essentially utilizes high-early-quality cement for 5-to 7-year fixes, which are for the most part seen as littler fixes. The agency expects PCP repairs to last at least 10 to 15 years and, in some cases, up to 40 years, comparable to the industry standard for conventional concrete.

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

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

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

The assessment group recognized a few advantages identified with PCP that were not initially depicted in the assessment plan. Most remarkably, these advantages incorporate the capacity to reuse boards for fix purposes. Caltrans introduces boards for transient fixes before full-profundity restorations of roadways. The organization at that point rescues, stores, and reinstalls those boards. This gives extra support reserve funds dependent on the way that PCP is more solid than its options.

ALDOT has started building up the utilization of pre-assembled PCP boards for support fixes in high rush hour gridlock territories of Birmingham. Furthermore, PCP gives chances to other interesting advancements with potential advantages. In particular, amid a meeting, Caltrans revealed that it is dealing with an undertaking that would install sun powered boards inside PCP boards. The boards would be introduced at a rest stop, and the sun oriented vitality caught would be utilized to control the rest zone. While the utilizations of this innovation might be constrained, PCP gives the adaptability to investigate and additionally create it.

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

Three interviewees showed that their offices were utilizing or wanted to utilize single boards for roadway fixes. Per INDOT, at any rate two different States (not met) had frameworks set up for quick, irregular fixing utilizing boards. This advancement permits State transportation offices to make quick fixes utilizing prior boards. Also, some enthusiasm for reusing boards was referenced, however this has not been investigated adequately to survey possibility.

Notwithstanding fast fixes and improved toughness, PCP gives various different advantages. These incorporate creative upkeep strategies and potential for one of a kind applications, for example, asphalt boards with inserted sunlight based (solar panel) boards.

Example of designing a panel which size 4×3.5

Given data:

Design wheel load (P) = 7000 kg
Contact pressure (p) = 7.5 kg/cm^2
Elastic modulus of pavement (E) = 3×10^5 kg/cm^2
Poisons ratio (μ) = 0.15
Thermal coefficient of cc per degree centigrade = 1×10^{-5}
Flexural strength of cc = 45 kg/ cm^2
Modulus of base course = 30 kg/ cm^2

Solve:

Assume thickness (h) = 28 cm.

Radius of relative stiffness (l) =

$$l = \left[\frac{Eh^3}{12k(1-\mu^2)}\right]^{0.25}$$

$$l = \left[\frac{3\times10^5\times28^3}{12\times30\times(1-0.15^2)}\right]^{0.25}$$

$$l = 65.78\ cm$$

Radius of circular load (a) =

$$a = \sqrt{\frac{P}{p\pi}}$$

$$a = \sqrt{\frac{7000}{7.5\times\pi}}$$

a = 17.24 cm

Ratio a/h = 17.24/28 = 0.167 [less than 1.724]

So,

$$b = \sqrt{1.6a^2+h^2} - 0.675h$$

$$b = \sqrt{1.6\times17.24^2+28^2} - 0.675\times28$$

$$b = 16.6\ \text{cm}$$

Ratio l/b = 65.78/16.6 = 3.965 cm

Now edge load stress as per tellers and Sutherland –

$$s_e = 0.526\times\frac{P}{h^2}\times(1+0.54\mu)\times[4\log_{10}(l/b)+\text{log10b} - 0.4048\ ]$$

$$s_e = 0.526\times\frac{7000}{28^2}\times(1+0.54\times0.15)\times[4\log_{10}(3.965)+\log10(16.6) - 0.4048\ ]$$

$$s_e = 16.38\ \mathrm{kg/cm2}$$

Temp. Different for slab thickness = (16.2+16.8)/2 = 16.5^0C
So L_x/l = 400/65.77 = 6.96 m
From Bradbury chart C_x = 0.92
Warping stress at edge

$$(Ste) = \frac{\mathrm{Cx} \times E \times e \times t}{2}$$

$$(Ste) = \frac{0.92 \times 3 \times 105 \times 1 \times 10 - 5 \times 16.5}{2}$$

$$(Ste) = 22.77\ \mathrm{kg/cm2}$$

Total flexural stress at edge = Load stress + warping stress at edge
16.38 + 22.77
= 39.15 kg/cm2

Factor of safety (FOS) = flexural strength/total stress
= 45/39.15
= 1.14

As the FOS is in the acceptable range for rigid pavement, the design thickness of 28 cm may be adopted.

Corner load stress by kelley's eqn.

$$s_c = \frac{3p}{h^2}\left[1 - \left(\frac{a\sqrt{2}}{l}\right)^{1\cdot 2}\right]$$

$$s_c = \frac{3 \times 7000}{28^2}\left[1 - \left(\frac{17.24\sqrt{2}}{65.77}\right)^{1\cdot 2}\right]$$

$$s_c = 19.34\ \mathrm{kg/cm2}$$

Temperature difference during night = 60% of 16.5 = 9.9^0C
Warping stress at corner during night (S_{tc})

$$s_{tc} = \frac{E \times e \times t}{3(1-\mu)} \times \frac{\sqrt{a}}{l}$$

$$s_{tc} = \frac{3 \times 10^5 \times 1 \times 10^{-5} \times 9.9}{3(1-0.15)} \times \frac{\sqrt{17.24}}{65.77}$$

$$s_{tc} = 5.97\ \mathrm{kg/cm2}$$

Total corner load stress = corner load stress + corner warping stress at top at night
= 19.34 + 5.57

= 25.3 kg/cm^2

This value is less than the total edge load stress so the thickness 28 cm is adopted.

Calculation of steel bar reinforcement:

Area of steel bar = 3.5×2×0.28
= 1.96 m
= 1.96 × 10^{-3}×100×100
= 16.9 m^2
Area of one steel bar = $\pi \times r^2$
= $\pi \times 5^2$
= 78.53
No of steel bar = 16.9/0.7853 = 21.5
Spacing = 350/22 = 16 cm

Dia of bar 10mm
c/c distance = 0.15 cm
No. of main bar = (4/0.15)+1 = 27

No of DB = (3.5/0.15)+1 = 24

Main bar length = 27×3.5 = 94m

DB length = 24×4 = 96 m

Total length of bar = 94+96 = 190m

Unit weight of steel bar = D^2/162.162
10^2/162.162
= 0.61 kg/m
Total weight of steel = L × unit weight of steel
190× 0.61
Total weight of steel = 116 kg per layer

We provide two layers so 116+116 =232 kg weight of steel is used

Total weight of hook = 4×0.5966 = 2.38kg

Total weight of steel we used 232+2.38 = 234.38 kg

Concrete quantity = L×B×h = 4×3.5×0.38 = 3.92m^3

4.13 RATE ANALYSIS OF CAST IN PLACE CONCRETE PAVEMENT AND PRECAST CONCRETE PAVEMENT:

4.13.1 CAST IN PLACE CONCRETE PAVEMENT:

Cement Concrete Pavement				

Construction of un-reinforced, dowel jointed, plain cement concrete pavement over a prepared sub base with 43 grade cement @ 400 kg per cum, coarse and fine aggregate conforming to IS 383, maximum size of coarse aggregate not exceeding 25 mm, mixed in a batching and mixing plant as per approved mix design, transported to site, laid with a fixed form or slip form paver, spread, compacted and finished in a continuous operation including provision of contraction, expansion, construction and longitudinal joints, joint filler, separation membrane, sealant primer, joint sealant, debonding strip, dowel bar, tie rod, admixtures as approved, curing compound, finishing to lines and grades as per drawing				
Unit = cum				
Taking output = 1050 cum (2415 tone)				
a) Labour				
Mate	Day	2.000	260.00	520.00
Mazdoor skilled	Day	15.000	450.00	6750.00
Mazdoor	Day	35.000	350.00	12250.00
b) Machinery				
Road Sweeper @ 1250 sqm per hour	Hour	2.800	300.00	840.00
Front end loader 1 cum bucket capacity	Hour	18.000	800.00	14400.00
Cement concrete batch mix plant @ 175 cum per hour (effective output)	Hour	6.000	10000.00	60000.00
Electric generator 250 KVA	Hour	6.000	450.00	2700.00
Slip form paver with	Hour	6.000	13000.00	78000.00

electronic sensor				
Water tanker6 KL capacity	Hour	36.000	15.60	561.60
Transit truck agitator 5 cum capacity.	tonne.km	2415x50	3.20	386400.00
Add 10 per cent of cost of carriage to cover cost of loading and unloading				38640.00
Concrete joint cutting machine .	Hour	12.000	250.00	3000.00
Texturing machine .	Hour	12.000	260.00	3120.00
total				587661.00
85% OF TOTAL COST				499511.85
			SAY	**1087172.85**
c) Material				
Crushed stone coarse aggregates of 25mm and 12.5mm nominal size @ 0.90 cum/cum of concrete conforming to clause 602.2.4. .	Cum	945.000	2697.00	2548665.00
Sand as per IS: 383 and conforming to clause 602.2.4 @ 0.45 cum/cum of concrete	Cum	473.000	1764.00	834372.00
Cement 43 grade @ 400 kg/cum of concrete	Tonne	414.000	5000.00	2070000.00
32 mm mild steel dowel bars of grade S 240	Tonne	9.450	52000.00	491400.00
16 mm deformed steel tie bars of grade S 415	Tonne	1.170	52000.00	60840.00
Separation Membrane of impermeable plastic sheeting 125 micron thick	Sqm	3675.000	25.00	91875.00
Pre moulded Joint filler, 25 mm thick for expansion joint.	sqm	16.330	75.00	1224.75
Joint sealant	Kg	875.000	400.00	350000.00
Sealant primer	Kg	116.670	125.00	14583.75
Plastic sheath,1.25 mm thick for dowel bars	Sqm	46.670	300.00	14001.00
Curing compound	Liter	1850.000	700.00	1295000.00

Super plastisizer admixture IS marked as per 9103-1999 @ 0.5 per cent by weight of cement	Kg	2070.000	12.50	25875.00
Cost of water	KL	216.000	50.00	10800.00
Add 1 per cent of material for cost of miscellaneous materials like tarpauline, Hessian cloth, metal cap, cotton / compressible sponge and cradle for dowel bars, work bridges for men to approach concrete surface without walking over it, cutting blades and bites, minor equipments like scabbling machine, threads, ropes, guide wires and any other unforeseen items.				78086.37
d) 10% Overhead charges @ input on (a+b+c)	8993415.72			899341.57
e) 10% Contractor's profit @ input on (a+b+c+d)	9873737.29			987373.73
Cost for 1050cum = a+b+c+d+e				10880131.02
Rate per cum = (a+b+c+d+e)/1050				10362.03
			Say	***10362.00***

4.13.2 PRECAST CONCRETE PAVEMENT:

Description	**unit**	**Rate**	**Quantity**	**Total coat**

Providing and position precast reinforcement cement concrete pavement unit square or rectangular as per design and shape of the pavement in 1:1½:3 (1 cement: 1½ coarse sand : 3 graded stone aggregate 10 mm nominal size) including flush or deep ruled pointing at joint in cement mortar 1:2 (1 cement : 2 Fine sand), marking necessary holes of required size of carrying through service lines etc., Dowel bar and providing steel hooks for lifting etc, from work in precasting, handling, hoisting, centering and creation complete for all pavement panels but excluding cost of reinforcement.	cum	15292.75	3.92	59,945
10mm of steel bar for reinforcement	Per kg	52	230	12960
Total cost	₹			**71905**

4.14 RATE COMPARISON BETWEEN PRECAST PAVEMENT AND CAST IN PLACE CONCRETE PAVEMENT:

DATA ASSUMPTION
ANALYSIS PERIOD = 40 YEAR
MAINTINENCE COST = 20 %

SR NO		**PRECAST CONCRETE PAVEMENT**	**CAST IN PLACE PAVEMENT**
1.	COST OF PAVEMENT PER KM FOR 40 YR	3,59,52,500	4,06,19,040
2.	20% MAINTINENCE COST (2,03,09,520) BEFORE 20 YR	NILL	40,61,904
3.	20% MAINTINENCE COST (2,03,09,520) BEFORE 40 YR	7190500	40,61,904
	TOTAL COST	4,31,43,000	4,87,42,848

Total saving is 1.11% per kilometer

Benefits of Choosing an Established System:

One of the major benefits of choosing an established system is that time may be saved during system evaluation for other projects. For example, system fabrication and installation instructions already prepared and proven to work for previous trial installations may not need to be developed again unless changes are being proposed. Another benefit of using an established system is that the system designer is typically available to provide support during the trial installation and subsequent submittal, fabrication, installation and inspection processes. This greatly facilitates the approval process at the beginning of the project (when pressure to start installation may be the greatest) and subsequent training of installation and inspection personnel at the project site.

CHAPTER – 5

CONCLUSION

5.1 General:

PCP panels are easily adaptable for more Roadway patches or lanes replacement which are most commonly made Precast pavement installation till today. Recent changes Dowell enables regular additions in load transfers Pre-installed pavement and existing
Sidewalks Traveled on existing concrete roadways on an essential basis Without traffic-crippled restrictions, which are often Changing the same highways using traditional CIP Methods. As the use and adoption of PCP technology continues to grow, the job FHWA has played in the innovation's advancement and the advantages and expenses of PCP establishments have turned out to be clear. As far as the dispersion of R&T, the assessment group found that FHWA and SHRP2 productions, subsidizing, and programming added to the advancement and utilization of PCP in a variety of settings. FHWA exercises have

given direction to various States that have utilized the office's materials. Like other solid techniques, PCP costs differ dependent on various variables, including venture measure and geographic area. Expenses for PCP or CIP cement can fluctuate fundamentally inside each State, let alone around the nation. In view of this cost variety, the various application types and PCP frameworks being used, and the presence of choices, for example, high-early-quality solid, it is hard to definitely extrapolate the expense of PCP contrasted with regular prepared blended cement. To do as such, the assessment group talked with routine clients of the innovation and assessed a few explicit undertakings. All in all, societal expenses for PCP are not as much as expenses for CIP and conventional solid arrangements. This cost distinction is especially evident when contrasting PCP with high-early-quality solid, which is comparable as far as establishment times and expenses; be that as it may, PCP performs better and is increasingly sturdy after some time.

Regardless of being cost advantageous from a societal viewpoint, PCP leads to different one of a kind costs that are not induced by conventional strategies. New clients, specifically, experience an expectation to absorb information that can prompt expanded costs when endeavoring to receive and actualize PCP out of the blue.

These expenses deflect reception; be that as it may, as organizations become progressively comfortable and experienced with PCP, these costs will decrease, and the advantages will be completely figured it out. Alongside expanded execution and solidness, the key advantage of utilizing PCP innovation is its establishment adaptability. By permitting medium-term terminations and opening the roadway for the morning crest, PCP limits arrange effects and blockage and encourages proficient fixes or development in touchy territories, for example, connect methodologies or regions where get to can't be restricted. Also, utilizing PCP can prompt creative or one of a kind practices on a framework level, for example, versatile support in which precast sections are reused and reused dependent on future development plans.

Because of these discoveries, we assist & prescribes that FHWA keep on advocating PCP innovation and report institutional information without underwriting specific frameworks even as it changes the obligation of PCP advancement to the Resource Center. Also, the assessment group suggests that potential adopters and clients of PCP create and keep up their own institutional learning. While endeavoring imaginative methods, potential adopters ought to consider the pertinence of PCP and lead test preliminaries. These activities will make establishments increasingly productive and increment quality, giving better task results. As the expectation to absorb information decreases and task results improve, PCP will keep on picking up consideration, and utilization and appropriation will increment.

Generally speaking, we observed FHWA's endeavors to be to a great extent fruitful and contributory to the improvement and reception of PCP innovation. FHWA has directed starting exploration and models and has helped the utilization of the innovation. In its proceeded with endeavors, FHWA has encouraged and received beginning use in a few States. PCP is a successful and productive approach to lead roadway upkeep, fixes, and reproduction. Advantages most surpass costs in high volume regions or exceptional roadway segments that would prompt critical alternate routes whenever shut for significant lots of time.

5.2 Future Scope of precast concrete pavement:

1. Solar Power-generating Pavement Panels.
2. Battery-charging Roadway Panels.
3. Precast Panels for Industrial Use.

Solar Power-generating Pavement Panels:

Solar power generation is generally perceived as a sustainable way to harvest energy from the sun. As such, generating power from photovoltaic panels mounted on roofs or specially designed supports arranged in field-sized arrays has gained popularity over the last few decades. However, effective energy-harvesting farms may require acres of costly land that must be exclusively devoted to that purpose for as long as they are kept in service. Recent efforts to develop multipurpose energy-harvesting areas have focused on using committed areas such as bikeways, parking lots, driveways and even roadways as a strategy to save the cost of land devoted only to that purpose.

Battery-charging Roadway Panels:

In our country in future the increasing use of electric vehicles and other countries has resulted in a need for efficient and rapid recharging of the batteries that power them. Most recharging facilities are plug-in stations located at homes, offices or other convenient locations. A charge at a home-based, 120-volt charging location typically takes one hour per 25 miles of charge or up to 10 hours for a complete recharge. Special, high-speed charging stations may completely recharge a battery in as little as one hour, but these require a cord, power source receptacle and a timeframe during which the vehicle is unusable.

Precast Panels for Industrial Use:

Most industrial operations can be shut down long enough for floors, aprons, building approaches, driveways and other traffic-intensive throughways to be replaced by casting concrete in place. However, there are occasions when precast panels are extremely beneficial in industrial applications due to time constraints or other conditions.

REFERENCES

1. AASHTO (American Association of State Highway and Transportation Officials). 1998. Supplement to the AASHTO Guide for Design of Pavement Structures. Part II, Rigid Pavement Design & Rigid Pavement Joint Design. Washington, DC: AASHTO.
2. Alwehaidah, N., and B. Russell. 2013. "Refinement of Precast, Post-tensioned Concrete Pavement Technology." In The PCI Convention and National Bridge Conference: Proceedings, September 21–24, 2013, Grapevine, Texas. Chicago, IL: PCI. CD-ROM.
3. David Merritt, Frank McCullough Ned Burns. ''Precast Prestressed Concrete Pavement'' Pilot Project near Georgetown, Texas Article, Jan 2003, Transportation Research Record Journal of the Transportation Research Board.
4. Ameen Ibn Zafir 2017 ''Analysis of Prestressed Precast Concrete Pavement Article *in* Materials today: proceedings 4(9):9713-9717 · January 2017.
5. Nantung, T.E., Fimansjah, J., Suwarto, E., Hidayat, H. M., 2010. Design and Construction of Precast Prestressed Concrete Pavement in Indonesia, Transportation Research Board Business Office, Washington, DC 20001.
6. Shiraz Tayabji Load Transfer Systems for Jointed Precast Concrete Pavement Technical Report October 2015 *with* 295 Reads DOI: 10.13140/RG.2.1.3286.9207 Report number: FHWA-HIF-16-008, Affiliation: Applied Research Associates.
7. Y. Jung, T. J. Freeman, and D. G. Zollinger. Guidelines for Routine Maintenance of Concrete Pavement. Research Report 5821-1. Texas Transportation Institute, Texas A&M University, July 2016

8. Tayabji, S., Ye, D., and Buch, N., (2012), *Precast Concrete Pavement Technology*, SHRP 2 Report S2-R05-RR-1, Transportation Research Board of the National Academies, Washington, D.C.
9. Priddy L P, Bly P G and Flintsch G W 2012 Review of Precast Portland Cement Concrete Panel Technologies for Use in Expedient Portland Cement Concrete Airfield Pavement Repairs TRB Annual meeting paper No 13-2956
10. Khazanovich, L. and Ioannides, A.M. (1993), "Finite Element Analysis of Slabs-On-Grade Using Improved Subgrade Soil Models," Proceedings, ASCE Specialty Conference 'Airport Pavement Innovations--Theory to Practice,' Waterways Experiment Station, Vicksburg, MS, September 8-10, pp. 16-30.
11. Merritt, D. K., McCullough, F. B., Burns, N. H. (2002), "Construction and Preliminary Monitoring of the Georgetown, Texas Precast Prestressed Concrete Pavement", Report No. FHWA/TX-03-1517-01-IMP-1, Texas Department of Transportation, Austin, Texas.
12. Merritt D, McCullough, B. F., Burns, N. H., and Schindler, A. K. (2000); "*The Feasibility of Using Precast Concrete Panels to Expedite Highway Pavement Construction*" Report FHWA/TX-01/1517-1, Texas Department of Transportation, Austin, Texas. Merritt, D. K., Rogers, R. B.,
13. Rasmussen, R. O. (2008), "Construction of a Precast Prestressed Concrete Pavement Demonstration Project on Interstate 57 near Sikeston, Missouri", Draft Report No. FHWA-RD-08-XXXX, U.S. Department of Transportation, Federal Highway Administration, January 2008
14. PCI (2004), PCI Design Handbook--Precast and Prestressed Concrete, 6th Edition, Precast/Prestressed Concrete Institute, Chicago, IL.
15. PCI (2012), State-of-the-Art Report on Precast Concrete Pavements, Report No. PP-05-12, First Edition, Precast/Prestressed Concrete Institute, Chicago, IL.
16. Smith, K., D. Harrington, L. Pierce, P. Ram, and K. Smith. 2014. *Concrete Pavement Preservation Guide. Second Edition*. FHWA Publication No. FHWA-HIF-14-014. National Concrete Pavement Technology Center, Institute for Transportation, Iowa State University, Ames, IA. http://www.cptechcenter.org/technicallibrary/documents/preservation_guide_2nd_ed_508_final.pdf.
17. Smith, P. J. 2011. "Replacement of Bridge Approach Slabs and Super-Structure In Two Consecutive Weekends, Rt. 46 Over Broad St., Clifton, NJ." *Proceedings of*

the 2011 Precast/ Prestressed Concrete Institute 57th Annual Convention and National Bridge Conference. Precast/Prestressed Concrete Institute, Chicago, IL.

18. Snyder, M. B. 2011. *Guide to Dowel Load Transfer Systems for Jointed Concrete Roadway Pavements*. National Concrete Pavement Technology Center, Institute for Transportation, Iowa State University, Ames, IA.
19. Rao, S., H.T. Yu, and M.I. Darter. 1999. The Longevity and Performance of Diamond-Ground Pavements. Research and Development Bulletin RD118. Portland Cement Association, Skokie, IL.
20. Tayabji, S. and S. Lim (eds.). 2006. Proceedings of the International Conference on Long-Life Concrete Pavements. Federal Highway Administration, Washington, D.C.
21. Tayabji, S.D., D. Ye, and N. Buch. 2013. Precast Concrete Pavement Technology. SHRP-2 Report S2-R05-RR-1. Transportation Research Board, Washington, D.C.