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16. Abstract

As the number of vehicles on America's roadways continues to grow at an unprecedented rate, pavements continue to deteriorate faster and require more frequent replacement. Construction, however, causes traffic delays, which further compound the problem. Traffic delays increase user costs, which are costs incurred by the users of the roadway but are directly caused and attributable to the presence of construction activities. Therefore, a method for expediting pavement construction in order to reduce user costs is needed.

This report describes a method for expediting highway pavement construction through the use of precast concrete panels. Precast concrete panels can be assembled quickly, allowing traffic back onto the pavement almost immediately. This kind of assembly will allow pavement construction to be carried out in overnight or weekend operations, when traffic volumes are low. The result will be a tremendous savings in user costs.

The concept for a precast concrete pavement presented in this report should have the same, if not better, durability as conventional cast-in-place concrete pavements currently being constructed. Also, by incorporating prestressing, it is possible to achieve increased load repetitions and design life, with a significant reduction in pavement thickness over conventional pavements. This is especially important for removal and replacement applications, where pavement thickness is constrained by existing conditions. Although the initial construction costs may at first be higher for a precast pavement, the savings in user costs far outweigh any additional construction costs.

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The Feasibility of Using Precast Concrete Panels to Expedite Highway Pavement Construction

by

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Research Report Number 1517-1

Research Project 9-1517
Feasibility of Precast Slabs in PCC Pavements
conducted for the
Texas Department of Transportation
in cooperation with the
U.S. Department of Transportation
Federal Highway Administration
by the
CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
The University of Texas at Austin

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Implementation Recommendations

This report presents a concept for expediting highway pavement construction through the use of precast concrete panels. Included in this concept are recommendations for panel fabrication, base preparation, panel placement, and prestressing. In addition, basic design tools and procedures are presented.

Implementation of the proposed concept should proceed in a staged process. Preliminary laboratory testing and development of features requiring additional investigation should be carried out prior to actual construction. Small-scale pilot projects should then be constructed to work out construction details and procedures. A larger-scale project should then be constructed in a rural area to further streamline the construction process under actual construction time restrictions. The final stage should be a project constructed in an urban area where there are very stringent construction time restrictions and where issues such as curbs and gutters can be addressed. This staged implementation procedure will allow for development and refinement of the proposed concept with a minimal impact on traffic.

Prepared in cooperation with the Texas Department of Transportation and the
U.S. Department of Transportation, Federal Highway Administration.

Disclaimers

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Chapter 1. Introduction and Background

1.1 BACKGROUND

Precast concrete construction methods have now become feasible alternatives in such applications as buildings and bridges. The primary benefit of precast construction is the speed of construction. Precast elements can be cast in controlled conditions at a precasting yard far in advance of when they will be needed, stockpiled, and transported to the construction site. The structure can then simply be assembled like a puzzle using the precast elements. Allowing time for the concrete to cure before construction progresses, which is a critical operation in terms of operational time and long-term performance, particularly for portland cement concrete pavements, is no longer a factor. The use of precast elements eliminates the operational step and optimizes the curing time.

1.1.1 Current Need/Interest with Regard to Expediting Construction

As the population continues to grow rapidly, so does the number of vehicles on America's roadways. This increasing number of vehicles is beginning to push many roadways far beyond their designed capacity. When a roadway that is near or above capacity is closed for rehabilitation or expansion, major traffic congestion occurs. This congestion results in, among many other things, lost work time and increased fuel consumption. A method for expediting construction/rehabilitation time is, therefore, needed to minimize or even eliminate these effects.

Under these circumstances, and given the success of precast concrete construction in the building and bridge industries, the Federal Highway Administration (FHWA) contracted the Center for Transportation Research (CTR), through the Texas Department of Transportation (TxDOT), to investigate the use of precast concrete technology to expedite pavement construction. Precast panels have been used previously for repair of jointed and continuously reinforced concrete pavements. However, precast concrete construction has seldom been used for large-scale pavement construction. This project was undertaken to develop a concept for using precast methods for large-scale pavement construction.

1.1.2 Problem Statement and Project Objectives

The problem statement for this feasibility project is as follows:

> ***Develop a feasible method for expediting construction of portland cement concrete pavements through the use of precast technology.***

The goal of this project, therefore, was to develop a concept for a precast concrete pavement — one that meets the requirements for expedited construction and that is feasible from the standpoint of design, construction, economics, and durability. The proposed concept should have a design life of 30 or more years to make it comparable to conventional cast-in-place pavements currently being constructed. To meets these objectives, the tasks undertaken as a part of this project were as follows:

1) Determine the current state-of-the-art through a thorough review of available literature and through meetings with professionals in the precast and concrete paving industries.
2) Evaluate potential pavement types.
3) Identify possible concepts for a precast concrete pavement.
4) Perform a feasibility analysis for the identified concepts.
5) Make recommendations for further investigation and future implementation.
6) Make recommendations for performance monitoring of future test pavements.

In addition to these objectives, a secondary objective of this project included knowledge transfer to various parties, including DOTs, academics, and the construction industry, in hopes of fostering further research and development of precast concrete pavement construction techniques.

1.2 PROJECT METHODOLOGY

The methodology for this feasibility project is demonstrated in the flow diagram shown in Figure 1.1. The experience of the researchers and a comprehensive literature review were used to generate ideas and preliminary concepts prior to the first expert panel meeting. These ideas, along with input from the first expert panel, led to the development of the proposed concept. A strategy evaluation was used to further select a pavement type and possible cross-section strategies for the proposed concept. The feasibility of the proposed concept was then evaluated with respect to design, construction, economics, and durability, based on design considerations dictated from the experience of the researchers.

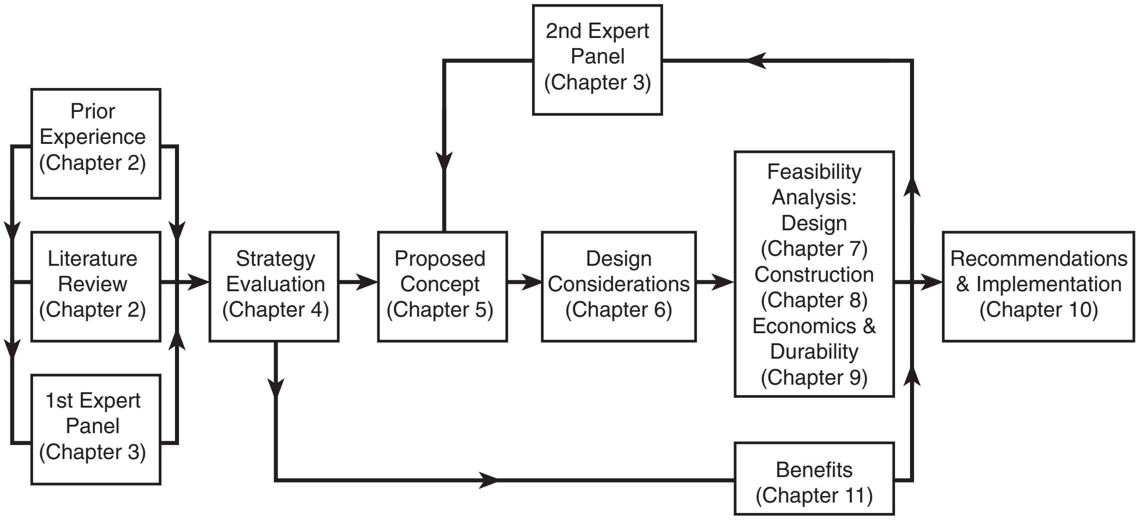


Figure 1.1 *Flow diagram of the precast pavement feasibility project methodology*

After the feasibility analysis was completed, a second expert panel meeting was used to evaluate the proposed concept from a practical point of view — that is, a view based on the opinions of professionals in the precast and concrete pavement industries. The proposed concept was then further refined from the recommendations of the second expert panel. Finally, after refinement of the proposed concept, recommendations for further investigation and recommendations for future implementation were made based primarily on the opinions of the second expert panel.

The benefits of precast concrete construction were realized throughout the project, but primarily through both the strategy evaluation and the feasibility analysis phases. The pavement type, selected from the strategy evaluation, was based on the most efficient pavement type to use for precast concrete pavement construction. As it turns out, this pavement type is really the most efficient for concrete pavement construction in general. The design stage of the feasibility analysis further revealed other advantages of the selected pavement type over conventional pavements.

1.3 SCOPE OF REPORT

This report will focus on the development of a feasible concept for a full-depth precast concrete pavement to be used for newly constructed pavements, overlays of existing pavements, or for pavements being removed and replaced. Issues pertinent to the design, construction, economics, and durability will be discussed. When possible, comparisons will be made to conventional cast-in-place pavements currently constructed in the United States to highlight some of the advantages of precast concrete construction.

1.4 REPORT OBJECTIVES

The objective of this report is to accomplish the goals of the precast pavement feasibility project set forth in Section 1.1.2 in order to provide a foundation for further development of precast pavement concepts for expedited pavement construction. New concepts and ideas for using precast panels to expedite pavement construction will first be presented. These concepts will then be evaluated through a feasibility analysis that will examine feasibility of design, construction, durability, and economics. Recommendations for further investigation and future implementation will also be given. The following is a summary of the remaining chapters contained in this report to meet these objectives:

Chapter 2 presents the findings from relevant literature with regard to precast concrete pavement. These findings include information on previous precast pavements constructed around the world, precast techniques in general, and experiences at the Center for Transportation Research related to this project.

Chapter 3 presents the discussions and recommendations from the two expert panel meetings held at the beginning and at the end of the project. Information obtained from these meetings was crucial for the development and refinement of the proposed concept presented in Chapter 5.

Chapter 4 provides the background for the proposed concepts presented in this project. This background includes an evaluation of current pavement types, as well as the reasons for selecting the pavement type presented in the proposed concept. In addition, possible pavement cross-section strategies for constructing a precast pavement are presented.

Chapter 5 presents the final concept proposed by the researchers for a precast concrete pavement. This concept was developed from the experience of the researchers, from literature related to precast pavements, and from input provided at the expert panel meetings. The proposed concept discusses all aspects of a precast concrete pavement, including fabrication, construction, and pavement finishing.

Chapter 6 presents design considerations for the development of a precast concrete pavement, including factors that affect the design (e.g., temperature and load effects), as well as the design variables (e.g., pavement thickness and magnitude of prestress) that are specific to each project. These design considerations provide the foundation for the feasibility analysis from the standpoint of design and construction.

Chapter 7 is the first of three chapters used to evaluate the feasibility of the concepts presented in Chapter 5. This chapter focuses on the actual design of a typical precast concrete pavement, including the elastic design for fatigue loading and elastic design for environmental stresses and wheel loading. The computer program PSCP2 is presented as an analysis program that can be used for the design of precast concrete pavements. An example design, which resulted in a precast pavement with a design life equivalent to that of a conventional CRC pavement, is presented to demonstrate the usefulness of the PSCP2 program and the advantages of precast pavement.

Chapter 8 evaluates the feasibility of the proposed concept, with a focus on the feasibility of construction. Much of the input for this chapter came from the expert panel meetings and from the experiences of the researchers.

Chapter 9, the final chapter of the feasibility analysis, focuses on both the economics and durability of the proposed concept. Included in the economic analysis is an examination of life cycle costs of a precast concrete pavement. The durability considerations are important for ensuring a high-performance pavement with a design life equivalent to or greater than that of conventional pavements currently being constructed.

Chapter 10 presents recommendations for further investigation and recommendations for possible future implementation. Some of the ideas presented in the proposed concept have not been tested or proved viable and, consequently, need to be further investigated. In addition, a strategy for performance monitoring of a constructed pavement is also presented.

Chapter 11 summarizes both the proposed concept and the benefits of expedited construction through the use of precast techniques. Recommendations are also made for taking the next step in making precast concrete pavements a reality.

Chapter 2. Literature Review

2.1 INTRODUCTION

An essential part of the precast pavement feasibility project was the literature review. The literature review was used in conjunction with the expert panel meetings to determine the current state of the art in the precast and concrete paving industries. It was also used to investigate any previous precast concrete pavements that have been constructed.

There were three main aspects of the literature review. The first was an identification and evaluation of the experience of the Center for Transportation Research (CTR) in this area. This evaluation involved reviewing several reports previously generated by CTR. The second aspect of the literature review was a search for precast concrete pavement literature elsewhere. This search involved not only a computer assisted search, but also input from professionals at the first of two expert panel meetings. A TRIS (computer-assisted) search was first utilized to find published precast experience through a search of a transportation literature database. An Engineering Index (EI) Compendex (computer-assisted) search was then undertaken through The University of Texas library system.

A synthesis of the current state of the art of precast concrete pavement was the final aspect of the literature review. This synthesis required sorting through all of the information obtained from CTR experience and from the computer-assisted searches. What follows is a summary of information from relevant articles/reports obtained from the literature review.

2.2 CTR EXPERIENCE

The Center for Transportation Research at The University of Texas at Austin has been involved in several projects related to precast pavements. This experience proved valuable for the development of a concept for a precast concrete pavement. The most notable of these projects are listed below:

- Cast-in-place prestressed pavement
- Precast bridge decks
- Pavement repair with precast panels
- Bonded concrete overlays
- High-performance concrete
- Polymer/Fast-setting concretes

Aspects of many of these projects were applied to the proposed concept for a precast concrete pavement presented in Chapter 5. Some of these projects are discussed in depth in this chapter and in the appendix.

2.3 PREVIOUS PROJECTS

A very limited amount of information was found on previous precast concrete pavements. Of the available literature, information was found on a precast pavement constructed in South Dakota in the 1960s with an asphaltic concrete overlay, as well as a few precast pavements constructed more recently in Japan. Another project, conducted at CTR in the 1980s, investigated the viability of cast-in-place prestressed pavements, resulting in one such pavement being constructed in McLennan County, Texas, in 1985. Although not a precast pavement, this project provided several useful concepts for a precast pavement. The relevant aspects of each of these projects will be discussed below.

2.3.1 Precast Pavement with AC Overlay in South Dakota

Research by South Dakota State University and the South Dakota Highway Department in the 1960s led to the development of a precast pavement with an asphaltic concrete overlay (Ref 1). The pavement consisted of 6 ft x 24 ft x 4½ in. thick prestressed panels that were placed on a 1½ in. thick sand bedding over an 8 in. granular base. After all the panels were set in place, they were overlaid with 1½ in. of asphaltic concrete. Figure 2.1 shows a cross section of the pavement and slab layout.

The panels were interconnected with "tongue and fork" connections. A steel wedge was used to interlock the tongue and fork. A grout key was cast into the panel edges for grouting the joints after the panels were set in place. Figure 2.2 shows the tongue and fork connections and grout keys. The transverse panel joints were staggered, as shown in Figure 2.1, to provide rigidity in the transverse direction.

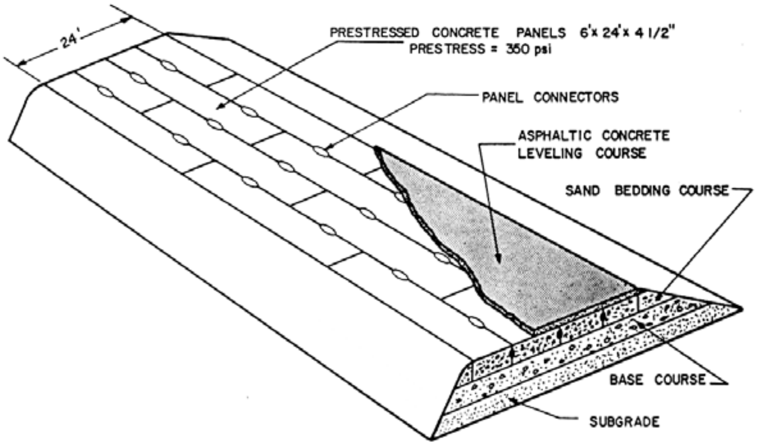


Figure 2.1 *Cross-section and slab layout (Ref 1)*

After favorable performance of the panels in the laboratory involved a 96 ft long, 24 ft wide test section (Figure 2.1) constructed in the driveway of the South Dakota Highway Maintenance building located east of Brookings, South Dakota. In addition, a 1,000 ft test section was constructed on US 14 bypass north of Brookings, South Dakota. For the 1,000 ft section, the original tongue and fork connectors were abandoned in favor of simply casting rebar into the slab for welding in the field. Transverse orientation and longitudinal orientation of the panels were also incorporated (Figure 2.3); the panels were pretensioned to 400 psi, as opposed to the 350 psi used for the original test section.

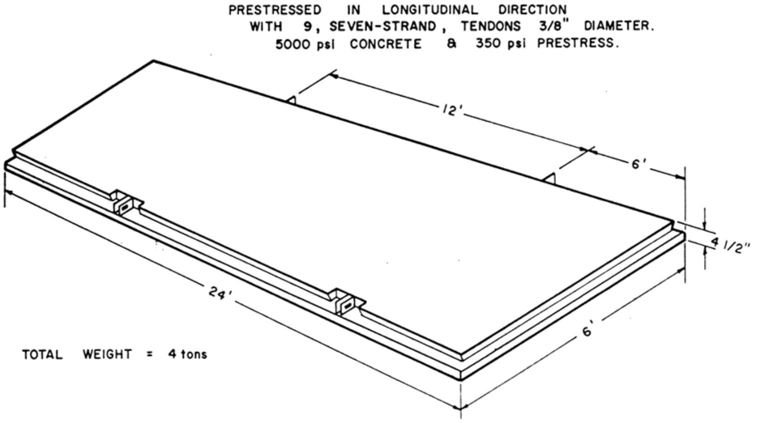


Figure 2.2 *Precast slab with tongue and fork connections (Ref 1)*

One of the main problems experienced with this pavement was the appearance of reflective cracks in the AC overlay only 1 month after the asphalt surface was applied (Ref 2). In addition, it was found to be difficult to insert the steel wedges into the tongue and fork connectors when joining the panels.

In a recent conversation, the South Dakota State University principal investigator for the project stated that, although the pavement is still in place, it has been overlaid with asphalt since it was constructed in the 1960s.

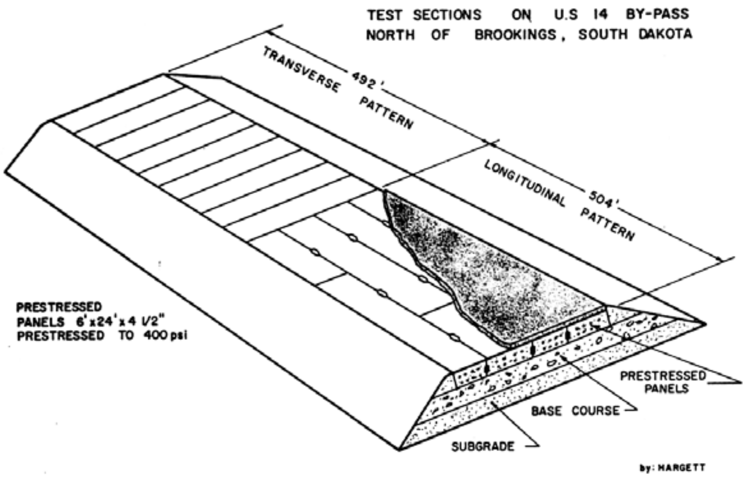


Figure 2.3 *Slab orientation for 1,000 ft test section (Ref 1)*

2.3.2 Precast Pavements in Japan

Research conducted in Japan examined the use of precast concrete panels for pavements (Ref 3). The test pavement consisted of panels of three different sizes. The panel dimensions were 1 m x 2 m (3.3 ft x 6.6 ft), 2 m x 2 m (6.6 ft x 6.6 ft), and 3 m x 2 m (9.8 ft x 6.6 ft). All of the panels were approximately 150 mm (5.9 in.) thick. The panels were placed on mechanically stabilized subbase and were not prestressed either transversely or longitudinally. In addition, there were no load transfer devices incorporated in the joints between the panels. After 1 month of exposure to traffic, neither faulting, cracking, nor excessive joint opening was observed.

Another project in Japan investigated a method for prestressing the joints of precast concrete pavements (Ref 4). The purpose of developing such a joint was to make the joints in precast pavements more continuous, providing a tight fit between panels and complete transmission of the shear loads. The joint detail developed is shown in Figure 2.4.

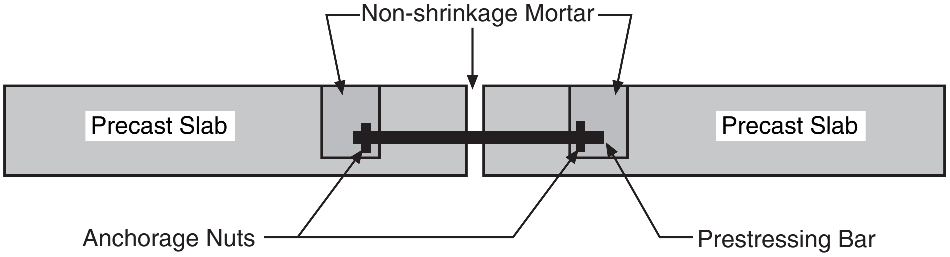
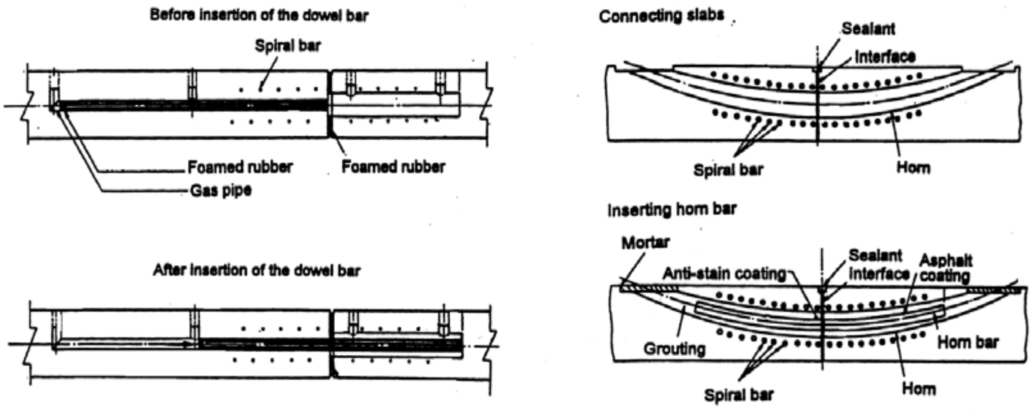


Figure 2.4 *Prestressed joint for precast slabs in Japan*

For this joint, 17 mm (0.67 in.) threaded bars were inserted through holes cast into the slab edges at 50 cm (19.7 in.) intervals. Adjacent slabs were prestressed together by tightening anchorage nuts on either end of the prestressing bar by way of pockets cast into the slab at the bar ends. After the joint was prestressed, the pockets and joint were filled with nonshrinkage mortar. Laboratory testing revealed that this prestressed joint had 3 times the shear resistance of a conventional bar dowel joint. The layout of the actual test section consisted of the slabs set on a vinyl sheet (to reduce base friction) that was placed over a cement-treated base. Testing revealed favorable results, with no faulting of the prestressed joints up to a failure load of 250 kN (28.1 kip). No faulting was observed at the joints of the precast prestressed concrete pavement in situ for 6 months after construction.

A third project in Japan examined the long-term performance of precast prestressed concrete pavements (Ref 5). Seven pavements were examined ranging in size from 170 mm to 200 mm (6.7 to 7.9 in.) thick, 1.3 m to 2 m (4.3 to 6.6 ft) wide, and 4 m to 10 m (13.1 to 32.8 ft) long. The precast panels were prestressed in the longitudinal direction and reinforced with nonprestressed bars in the transverse direction. Two types of dowel bars were used to provide load transfer between panels: straight bars and curved “horn-shaped” bars. Figure 2.5 shows the two different joints used. The panels were laid out in a grid and interconnected with dowel bars, as shown in Figure 2.6. For the straight bar joints (Figure 2.5a), the dowel bars were inserted into a shaft cast into the panel. After the adjoining panel was set in place and leveled, the dowel bars were slid from the first panel into a larger shaft cast in the adjoining panel. The dowel bar was then grouted in place by way of small holes cast into the top of the slab.

For the horn-bar joints (Figure 2.5b), curved slots were cast into the panels. After the panels were set in place, the horn-shaped bars were inserted into the slot to connect the panels. The dowel bars were then grouted in place (filling the slots) and mortar was used to seal the slot openings. For both joint details, spiral reinforcement was cast around the slots for increased bearing strength and support. At the time of the report, the precast pavements examined ranged in age from 9 to 13 years old; the overall pavement performance was reported as quite good.



(a) (b)

Figure 2.5 *Joint details for precast pavements in Japan (Ref 5)*

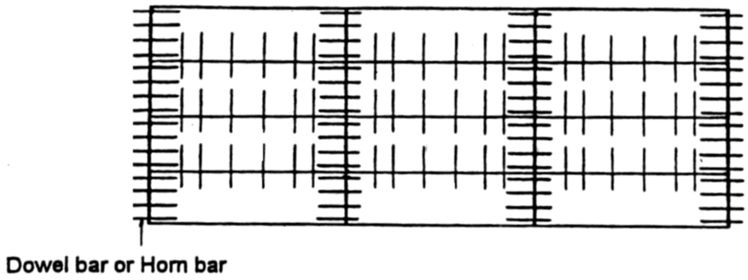


Figure 2.6 *Slab layout for precast pavements in Japan (Ref 5)*

2.3.3 Cast-in-Place Prestressed Pavement in McLennan County, Texas

In the mid-1980s a project was undertaken at the Center for Transportation Research to investigate the practicality of prestressed concrete pavements. Part of this project involved investigating prestressed pavements that had previously been constructed around the world, including four in the United States. This investigation resulted in several new ideas for prestressed pavements, based on the successes and failures of previous projects. Some of the more important ideas, developed during this project, that have possible applications for a precast pavement are discussed below.

Central Stressing

Probably the most significant technique developed for prestressed pavements was central stressing. With this technique, the post-tensioning strands are anchored at the ends of the slab and extend into stressing pockets cast into the pavement, as shown in Figure 2.7. The strands coming from each side of the slab into the stressing pocket are coupled in the pocket with a device similar to that shown in the plan view of a stressing pocket in Figure 2.8.

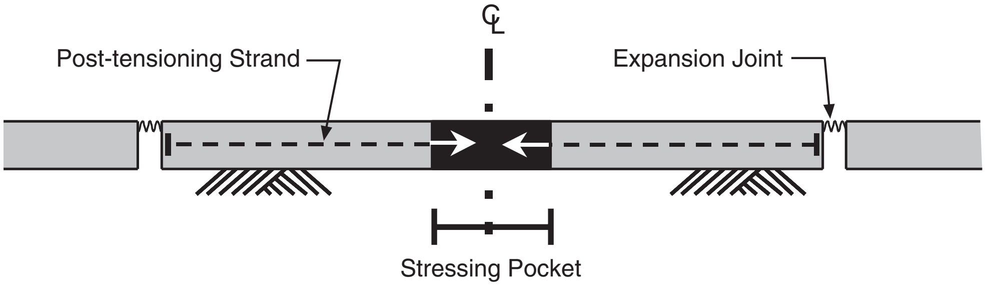


Figure 2.7 *Concept of central stressing*

A stressing ram, similar to that used for post-tensioning circular concrete tanks, is used to stress both strands coming into the pocket at the same time. The stressing pockets are then filled with concrete after stressing is complete. The advantage of using this technique is that access to the end anchorage is not needed in order to post-tension the slab. This technique allows for a more continuous pavement placement operation, avoiding as it does the use of "gap slabs" between prestressed slabs.

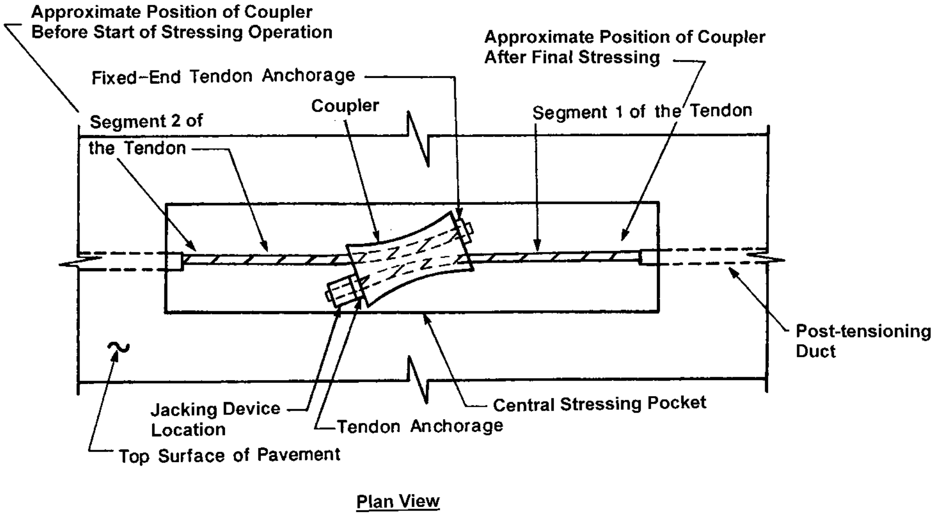


Figure 2.8 *Plan view of central stressing pocket and coupler device (Ref 6)*

Expansion Joint Detail

Expansion joint details represent one of the major problems associated with previous prestressed pavements. Most expansion joints were found to cause faulting of the concrete near the joint, or were simply susceptible to fatigue (Ref 6). The joint detail developed by CTR, shown in Figure 2.9, is a refinement of some of the successful aspects of previous joint details. This joint detail consists of a very stout steel support structure with Nelson deformed bars used to secure the joint to the pavement. A neoprene seal, which can accommodate the joint openings, is used to prevent incompressible material from falling into the joint. Stainless steel-plated dowels, which will not corrode or seize up in the dowel sleeve, are used for load transfer across the joint.

Friction-Reducing Medium

In prestressed pavements, which feature particularly long slabs, a significant amount of expansion and contraction occurs owing to daily and seasonal temperature cycles. The friction between the bottom of the slab and the base material resists these movements, thereby causing tensile stresses in the pavement (during contraction movement). To reduce this frictional resistance, CTR incorporated a friction-reducing membrane placed beneath the slab. Extensive testing revealed that a single layer of polyethylene sheeting was the best membrane material available for meeting the requirements of constructibility, effectiveness, and economics.

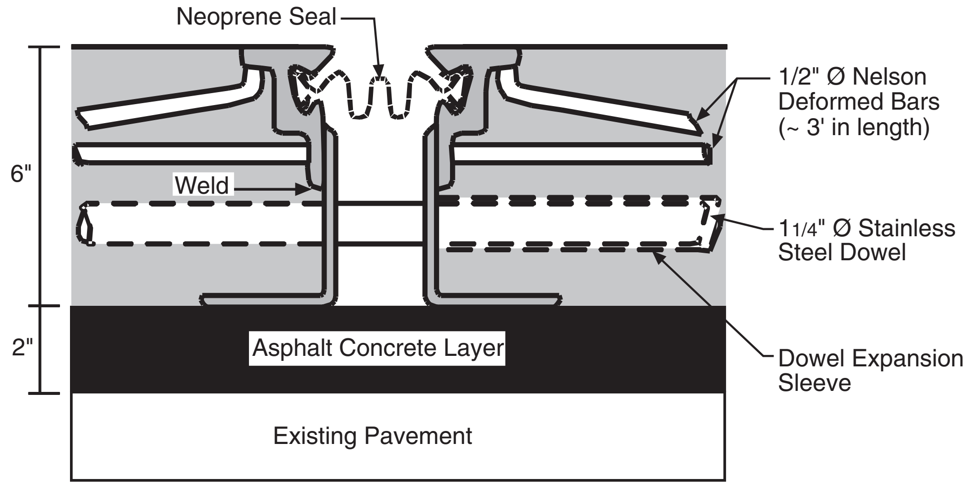


Figure 2.9 *Expansion joint detail developed at CTR for a cast-in-place prestressed pavement (Ref 6)*

Transverse Stressing/Longitudinal Joint

Another major problem with previous prestressed pavements was the lack of transverse prestressing. In all of the pavements constructed in the United States, the lack of transverse prestress led to extensive longitudinal cracking (Ref 6). Therefore, the pavement developed by CTR incorporated looped post-tensioning tendons to provide transverse prestress, as shown in Figure 2.10. This transverse stressing scheme allows for the placement of separate slabs at different times. The transverse strands serve to tie the two slabs together, allowing for a seemingly infinitely wide pavement. The differential movement of the two slabs is accommodated by a tube of crushable material wrapped around the post-tensioning stands at the longitudinal joint to prevent damage to the strands.

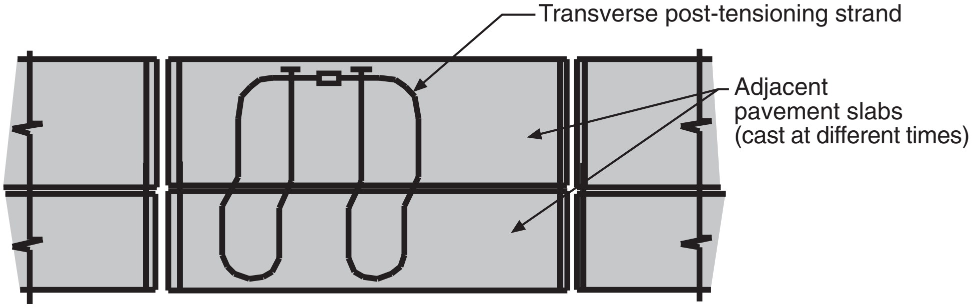


Figure 2.10 *Transverse prestressing scheme for the prestressed pavement developed by CTR (Ref 6)*

PSCP2 Program

A computer program dubbed "PCP1" was developed for analyzing prestressed pavements. This program computes stresses and slab movements for prestressed pavements based on given temperature conditions, support conditions, concrete properties, and steel properties. This program proved valuable for estimating slab movements and for determining the required prestress and maximum allowable slab length in the McLennan County prestressed pavement. PCP1 was later calibrated, using actual data from the McLennan County pavement, and renamed "PSCP2."

Overall, this project revealed many benefits of prestressed pavements. Among these benefits are reduced pavement thickness (only 40–50% of a conventional pavement thickness), fewer joints (slab lengths of up to 440 ft), less maintenance, and enhanced durability (cracks are pulled closed by prestressing). In 1985, a cast-in-place prestressed overlay was constructed on a section of southbound Interstate 35 in McLennan County, Texas. This overlay incorporated all of the ideas that had been generated throughout the project. The pavement was subsequently monitored for several years after construction to investigate the performance of the pavement. Over the 15 years the pavement has now been in service, under very high traffic volumes and truck traffic, it has required only minimal maintenance and shows virtually no signs of distress.

2.4 RELATED LITERATURE

An extensive amount of literature was found on topics related to precast pavements. This literature includes, among many other things, information on precast bridge deck panels, bridge deck joints, raft units, and repair of pavements using precast panels. Most of these topics will be discussed below. However, owing to the quantity of material, additional related literature is included in the appendix. The information included in the appendix is listed below:

- Void effects on pavement life
- Handling and erection of precast panels
- Tolerances for precast panels
- Precast sheet piles
- Precast construction for buildings
- Lightweight concrete

2.4.1 Precast Bridge Deck Panels

An extensive amount of information was found on the use of precast panels for bridge decks. There are significant differences, however, in using precast panels for bridge decks and for pavements, the main difference being that bridge deck panels are usually supported only along the edges, while pavement panels are supported continuously underneath. Despite these differences there is a lot of knowledge and experience from the precast bridge deck practice that can be applied to precast pavements.

Bridge deck panel fabrication techniques, such as match-casting, wherein adjacent panels are cast next to each other, could also be used for precast pavement panels. With this technique, a bond-breaker is applied along the adjoining edge of the panel to keep it from bonding to the adjacent panel. The adjacent panel is then cast using the edge of the previous panel as one side of the form. This technique assures a tight, uniform joint between adjacent panels. This method also allows for precise casting of "tongue and groove" type joints.

Concrete bridge deck panels are usually prestressed during fabrication and/or placement. Some considerations for prestressing include prestress techniques, levels of prestress, and stressing timeframe. Prestressing techniques include pretensioning, post-tensioning, or a combination of both. In general, panels are usually pretensioned in one direction (i.e., longitudinally) during fabrication and post-tensioned in the other direction (i.e., transversely), after they are set in place, via post-tensioning ducts cast into the panels. Levels of prestress for bridge deck slabs vary greatly, depending on the application of the project, the concrete strength, and the prestressing method. Literature on bridge deck panels revealed that prestressing levels vary from 200 to 450 psi, on average, to as much as 1,000 psi (Ref 7).

A research team from the University of Illinois at Chicago performed a field investigation of existing full-depth precast concrete bridge deck panels, from 1993 to 1995, to evaluate the performance of different bridge deck panel configurations throughout ten different states (Ref 8). This project resulted in several conclusions and recommendations for full-depth precast bridge deck construction that should be considered for precast pavement construction. The conclusions and recommendations were as follows:

1) A female-to-female type shear key, similar to that shown in Figure 2.11, should be used between precast panels. This joint should have a ½ in. opening at the bottom to allow for panel irregularities. A foam or polyethylene compression seal can also be used at the bottom of the joint to prevent grout from leaking and to provide flexibility. A tongue-and-groove-type joint, as shown in Figure 2.12, is not practical because of difficulties encountered with the grouting process. A direct contact type joint, or butt joint, is not recommended because it may result in leakage through the joint when the deck panel is under tension.
2) The precast panels should be post-tensioned longitudinally to ensure a tight joint, to keep the joint in compression, and to prevent leakage of the joint.
3) Precast panels should be designed with a sufficient amount of transverse prestress to prevent cracking during handling.
4) An overlay should be used to provide a smooth ride and keep the bridge deck in good condition. The most common overlay used was found to be latex-modified concrete. In addition, a waterproofing membrane system may be used to prevent penetration of water into the joints.

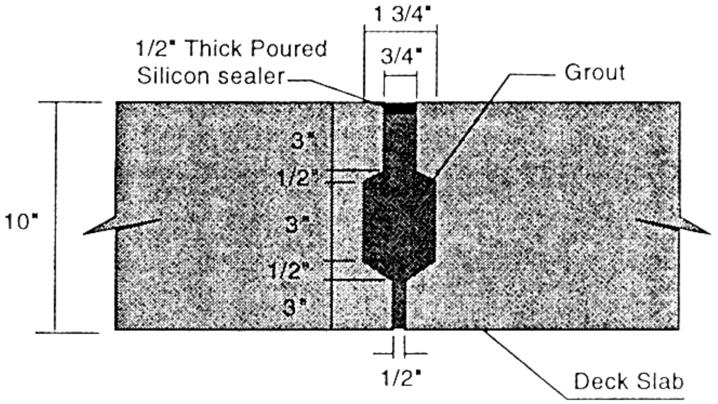


Figure 2.11 *Female-to-female joint for bridge deck panels (Ref 8)*

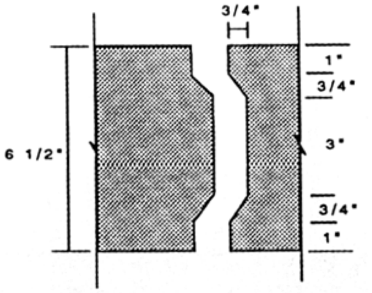


Figure 2.12 *Tongue-and-groove-type joint for bridge deck panels (Ref 7)*

A 1983 report by Martin (Ref 9) on connections for modular precast concrete bridge decks addresses various concepts, details, and problems experienced. This report documents a research project conducted in 1969 at Purdue University on the feasibly of precast, prestressed concrete deck members supported by steel beams. The test specimen consisted of narrow precast, pretensioned planks placed perpendicular to the traffic flow. The planks were interconnected with a tongue and groove joint and post-tensioned longitudinally, as illustrated in Figure 2.13.

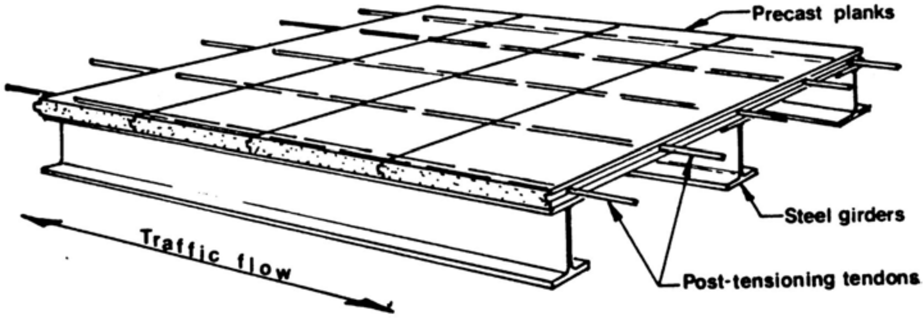


Figure 2.13 *Schematic of Purdue test bridges (Ref 9)*

Three different joint shapes were investigated, as shown in Figure 2.14. The flat joint in Figure 2.14(a) proved to be superior to the other joints. The specimens were post-tensioned to 40 psi and tested with repetitive loads through 2.25 million cycles. The report further mentions that for a tight fit, extremely tight tolerances are required. In the first set of slabs produced, the joints did not fit with sufficient precision and, consequently, severe spalling occurred at the joint after very few loading cycles. To reduce the stress concentrations, a 1/16 in. neoprene sheet was placed in the joint, which seemed to provide nearly full composite action between the deck and the supporting stringers.

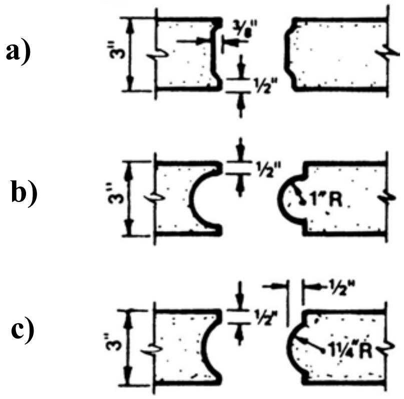


Figure 2.14 *Joint types investigated for Purdue bridges (Ref 9)*

This report further documented a research project on Indiana State Road 140 south of Knightstown. In this project, deck panels 38 ft/4 in. long by 4 ft wide were positioned on steel beams. The panels had keyed joints as shown in Figure 2.15. Problems were encountered as cracks formed, perpendicular to the joints, during post-tensioning of the deck panels. This cracking was attributed to poor joint fit that led to local bending stresses. Upon inspection, irregularities in the width of the joints were found. There were numerous locations where the joint widths were less than 1/8 in., and approximately half of the defective joints were completely closed. A few months after the bridge was opened to traffic, the concrete in the vicinity of the closed joints began to spall. The cause of the joint irregularity was determined to be irregularities in the forms used to cast the slabs.

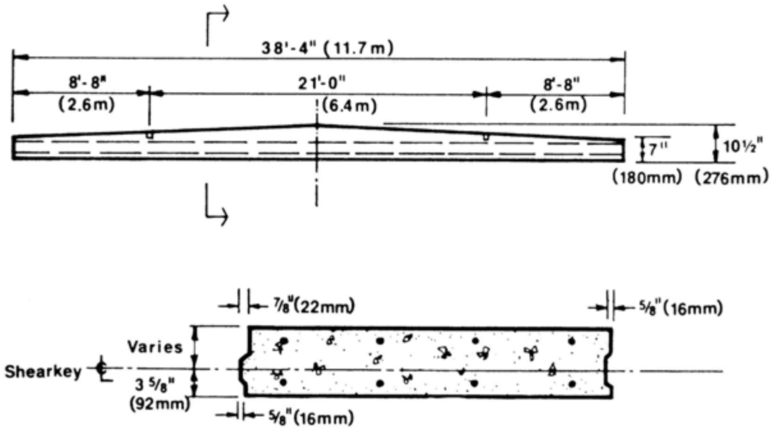


Figure 2.15 *Panel elevation and shear key details, Knightstown Bridge (Ref 9)*

The New York State Department of Transportation used precast deck panels for rehabilitation purposes on the suspension bridge over Rondout Creek near Kingston, New York (Ref 9). The deck panels were 9 ft wide by 24 ft long, with a simple V-shaped male-female joint. No grouting was done except at the connections to the steel stringers. The details of this project can be seen in Figure 2.16. No major problems were reported with these bridge deck panel details.

Martin (Ref 9) summarized the discussion about integral deck bridge connections by stating that "… tongue-and-groove joints have been tried, but an exact fit between units is nearly impossible without match-casting. This is not practical for plant cast products, especially if they are pretensioned."

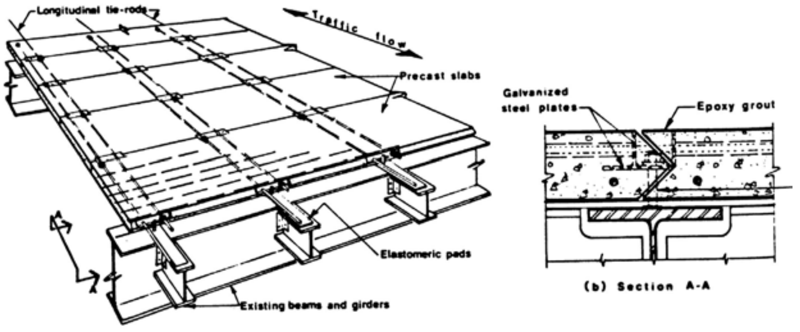


Figure 2.16 *Details used at the Kingston Bridge, New York (Ref 9)*

Although these studies focused on full-depth bridge deck panels, the findings presented will be helpful for the investigation of these aspects as they relate to full-depth precast pavement panels.

2.4.2 Joints for Segmental Bridges

In CTR Research Report 248-1 (Ref 11), the shear strength of joints for precast segmental bridges was investigated. Possible disadvantages in precast segmental construction were identified. Some of the possible disadvantages applicable to the joining of precast panels include:

1) necessity for a high degree of geometry control during fabrication and erection of sections,
2) potential joint weakness owing to a lack of mild steel reinforcement across the joint,
3) temperature and weather limitations regarding the mixing and placing of epoxy joint material, and
4) frequent loading and unloading of segments, with the risk of damage.

Web keys in segmental bridge construction serve two main functions. The first is to align the segments during erection. The second is to transfer the shear force between segments during that period while the epoxy, applied to the joint, is still plastic and acts only as a lubricant.

Experimental tests were conducted at The University of Texas at Austin on segmental bridge specimens consisting of combinations of joining methods. Configurations using no key, single-key, and multiple keys, together with either no bonding material (dry) or epoxy in the joint, were evaluated. These joining methods were then compared to the performance of a monolithically constructed joint. Figure 2.17 summarizes the behavior of the different joints considered. From the testing, Kosiki and Breen concluded that the effect of epoxy on performance of precast segmental joints was phenomenal. All three specimens with epoxied joints, including the keyless joint, acted monolithically, carrying loads as high as the monolithic no-joint specimens. It was further recommended that, if nonepoxied joints are to be used, the use of multiple keys improves the overall performance of the joints. However, application of an epoxy bonding agent provides much better total assurance; it is, therefore, highly desirable (Ref 11).

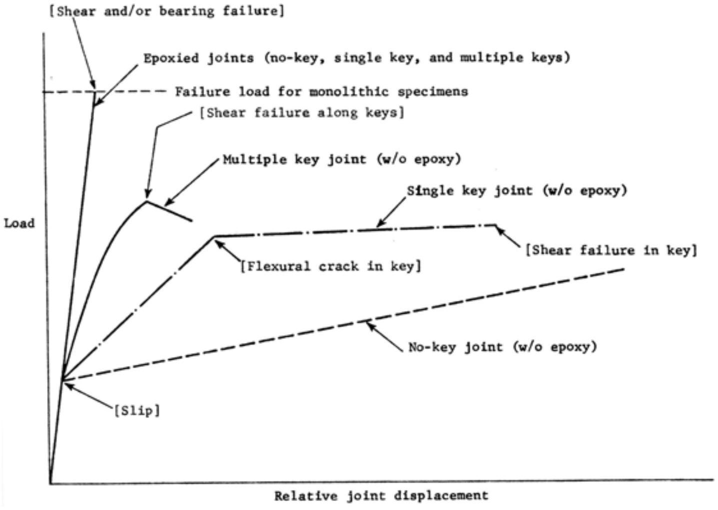
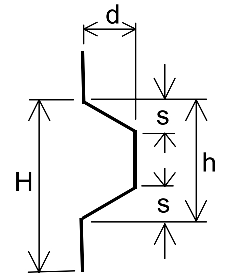


Figure 2.17 *Comparison of behavior of joints (Ref 11)*

A comprehensive literature review of the studies on joints in large precast concrete structures was conducted at the Massachusetts Institute of Technology (Ref 14). A number of conclusions were made from this project. First, under monotonic loading, keyed joints (without adhesive) may be as much as 3 to 4.5 times stronger in ultimate strength than plain joints. Strength is dependent not only on the presence of keys but also on their shape and size. It was shown that for greatest strength, the slope of the key face should be greater than 55° to 60°. It was further recommended that the depth of keys be no less than 0.4 in. and the depth-to-length ratio, d/h (as defined in the diagram of Table 2.1), be greater than 0.125. Examples of multiple key configurations used in three segmental bridges are shown in Table 2.1.

Table 2.1 *Examples of multiple key configurations (Ref 11)*

	**Bridge**	***Long Key***	***Red River***	***Linn Cove***
	Number of keys	9	7-31	12
	h/H	0.60	0.73	0.70
	d/s	2/1	1/1	1.25/1
	d/h	0.32	0.31	0.36

In a paper on the use of precast components (Ref 15), the joint details shown in Figure 2.18 were presented. The combination of a contact joint and a thin concrete-filled joint was shown to provide adaptability to any possible geometry change (vertical/horizontal curves) in the structure. A sealing ring around longitudinal tendons, passing through the precast units, prevents leakage during pressure grouting of the tendons.

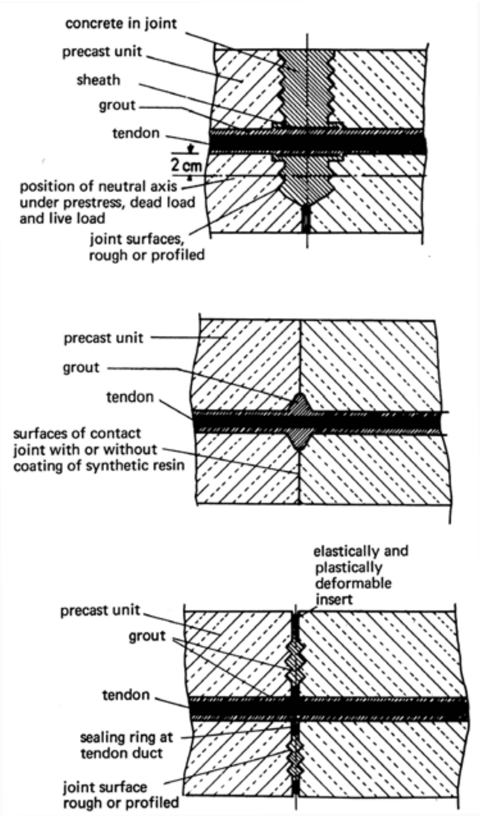


Figure 2.18 *Combinations of various forms of joint construction (Ref 15)*

A large number of precast segmental bridges use an epoxy resin joint material between precast segments. Specifications are provided in the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specification (Ref 10), which pertains to joints in precast segmental bridges. In the AASHTO Guide, cast-in-place concrete, fresh concrete, and epoxy joints between precast units are defined as Type A joints. It is specified that in Type A joints, the prestressing system shall provide a minimum compressive stress of 30 psi and an average stress of 40 psi across the joint until the epoxy has cured. The commentary further states that this temporary stress is required to ensure full bond and to prevent uneven epoxy thickness. Such variations could lead to a systematic accumulation of geometric error.

The commentary to the AASHTO guide (Ref 10) states that the epoxy serves as a lubricant during placement of the segments, prevents water intrusion, provides a seal to prevent crossover during grouting, and provides some tensile strength across the joint. Dry joints are susceptible to freeze-thaw damage and cannot prevent intrusion of water, which may lead to corrosion of internal tendons. If tendons pass through the joints, then the joint detail must have sufficient durability to protect the tendons against corrosion. In CTR Research Report 248-1 (Ref 11), a concern is expressed that "…improper use or choice of the epoxy can be critical with respect to shear strength of the joint." Kashima and Breen (Ref 12) have pointed out that many epoxies furnished as suitable for joining concrete segments in fact are unsuitable. The suitability of specific formulations should be checked using simple tests, but with surface conditions and ambient factors typical of the proposed application.

The epoxy application process must be planned carefully to ensure that all the necessary tasks are completed within a required time frame. The epoxy pot-life serves as a maximum time limit for completion of epoxy measuring and mixing, application of the epoxy to both surfaces of a match-cast joint, joint closure, temporary post-tensioning, and cleaning of the epoxy from the surrounding concrete and equipment. Time studies should be conducted to estimate the necessary manpower and the staging of the various tasks. Bruggeling (Ref 13) describes the function of any bonding agent between precast panels as stated by the AASHTO guide. Bruggeling lists, however, the following requirements to be met by the bonding agent placed between adjacent precast panels (Table 2.2):

Table 2.2 *AASHTO requirements for concrete bonding agents*

Physical Requirements	Mechanical Requirements
Pot life	Compressive strength
Open time	Tensile bending strength
Thixotropy	Shear Strength
Squeezability	Humidity dependence
Bonding qualities	Temperature dependence
Curing speed	
Color	

2.4.3 Raft Units

Bull discusses the use of raft units for precast pavements (Refs 16, 17). Raft units are simply precast concrete panels used primarily for temporary roads, rapid highway repairs, pavements subjected to heavy industrial traffic, airfield construction, or port container terminals. Raft units are usually square, though hexagonal units have been used successfully. Generally, raft units are fairly small in size, usually 2 m x 2 m (6.6 ft x 6.6 ft) and between 75 and 220 mm (3-9 in.) thick, but have been constructed as large as 2.29 m x 10.0 m (7.5 ft x 32.8 ft).

The most common reinforcing method for raft units is steel rebar or wire mesh. Prestressed raft units have been constructed but are generally not cost-effective owing to the additional complexity of fabrication and small size of the units, which reduces the efficiency of prestressing. Raft units are typically fabricated using fiberglass molds and high strength, 60 MPa (8,700 psi), concrete. For general use, such as for temporary roads, raft units are designed for standard axle loads of 80kN (18 kip), but can be designed to accommodate 900 kN (130.5 kip) axle loads. Angle steel is sometimes used around the top edges of raft units and welded to the upper reinforcing layer to minimize damage from impact loading. When angle steel is not used, the edges are typically detailed with an "inverted V-shape," as shown in Figure 2.19. The edge detail shown in Figure 2.19(b) results in a shear path longer than that of Figure 2.19(a), the result being a reduction of spalling at the joint. This edge detail allows for tolerance when placing the panels at a "nose-up" angle, as shown in Figure 2.20.

Raft units are usually set on a mechanically compacted granular subbase, preferably in excess of 250 mm (9.8 in.) thick. No load transfer devices are incorporated in the joints between raft units. Joints are usually not filled or sealed either, as this allows water to percolate and drain through the subbase. When a high riding quality and a smooth finish are desired, the joints can be filled with a fast-curing mortar. Filling the joints, however, inhibits removal and replacement of the unit.

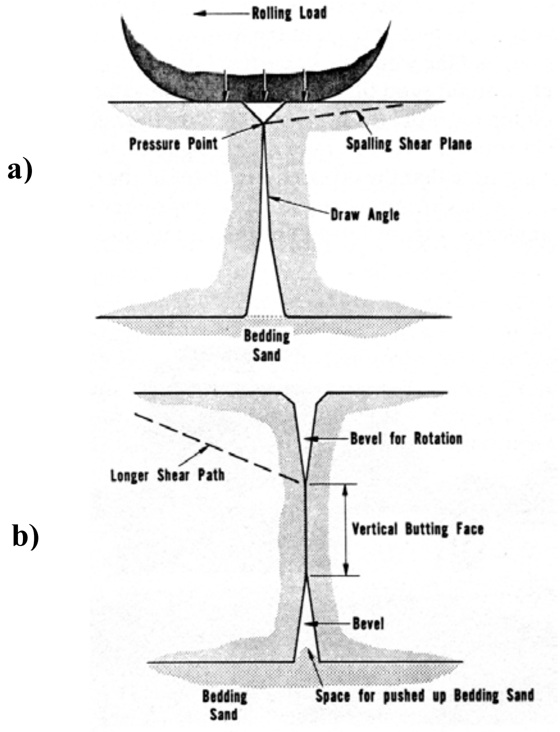


Figure 2.19 *Inverted V-shaped edge detail for raft units (Ref 16)*

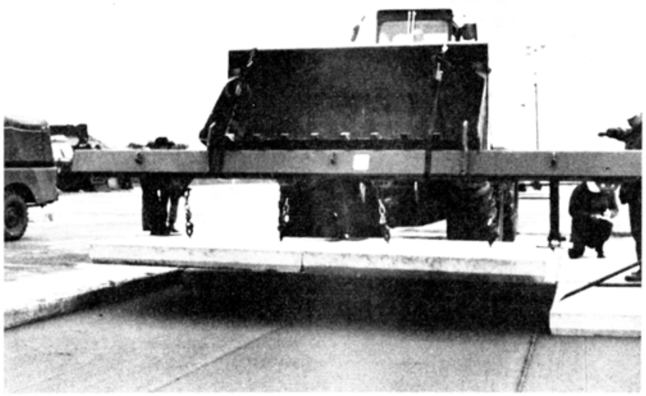


Figure 2.20 Loader placing raft units at a "nose-up" angle (Ref 16)

2.4.4 Sectional Mat Pavement

A sectional mat precast pavement was designed by the U.S. Army Corps of Engineers (ACE) to support military missile carriers (Ref 16). The precast units were designed to be light enough to be carried by a crew of 8–10 men. To accomplish this, lightweight aggregate was used in the concrete mixture and the slabs incorporated a ribbed design, as shown in Figure 2.21. The slabs were approximately 8.9 ft (2.7 m) wide, 11.8 in. (300 mm) long, 5.4 in. (136 mm) thick at the ribs, and 2.7 in. (68 mm) thick between ribs. The slabs were pretensioned transversely during fabrication and post-tensioned together with cable or rod after they were set in place.

Testing the slabs resulted in three failures over the thinned sections of the slabs under the heaviest wheel loads. In addition, some spalling developed a the slab edges; some of the post-tensioning cables and rods lost up to 17% of their prestress under traffic loading. Owing to these problems, the concept was not pursued further by ACE for use as mats for missile carriers. Concepts such as the ribbed design, however, could have promise for reducing the weight of precast slabs for a large-scale pavement.

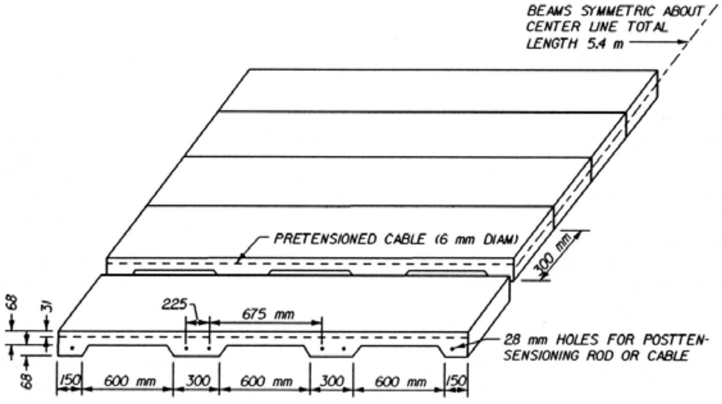


Figure 2.21 Precast sectional mat pavement (Ref 16)

2.4.5 Slab Repair Using Precast Panels

In CTR Research Report 177-15 (Ref 18), the use of precast concrete panels for repair of continuously reinforced concrete pavements (CRCP) is discussed. One of the main purposes for using precast elements is that repairs can be done quickly, thereby reducing lane closures and delays. At the same time, a durable portland cement concrete repair is utilized instead of a less durable asphaltic concrete repair. Precast panels have previously been used successfully for repair of jointed concrete pavements. With a CRC pavement, however, the challenge is maintaining continuity in the reinforcing steel between the existing pavement and the repair area.

The report covers all areas concerning precast repair, including dimensions, fabrication, transportation, preparation of the repair area, installation, and loading of the panels. Recommendations are made in the report for each of these aspects. With respect to a large-scale precast pavement project, it is recommended that:

1) Lifting connections in the panel should not be made more than 1/4 to 1/5 of the total length from the edges of the panel.
2) For panels longer than 7 ft, a bond breaker should be used in the middle of the panel to form a weakened plane so that the concrete fractures before steel stresses become too great.
3) The repair panel should be set on a screeded bed of grout in the repair area.
4) A polymer or fast-setting portland cement concrete should be used in the gaps between the repair panel and the existing pavement.

In a paper by Meyer and McCullough (Ref 19), the actual fabrication and installation of CRCP repair panels along I-30 near Mt. Pleasant, Texas, is discussed. The theory and design procedures presented in the report previously mentioned were used for this project. One of the interesting aspects of this project, which may have applications to a large-scale precast pavement, was the use of leveling beams to set the precast panel to the proper height. With this method, the precast panel is set on a screeded grout bed, slightly higher than the surrounding pavement. Leveling beams are then used to press the panel down so that it is at the same level as the surrounding pavement. This process is illustrated in Figure 2.22.

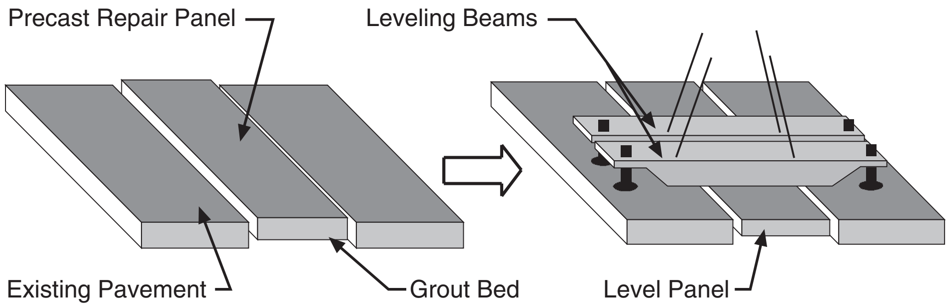


Figure 2.22 *Precast repair panel before and after leveling beams are used to set it into place*

2.5 NEW CONCEPTS

In CTR Research Report 401-2 (Ref 6), a report on new concepts for prestressed concrete pavements, Neil Cable presents some ideas for precast pavements. He discusses the application of some of the techniques developed for cast-in-place prestressed pavements (Section 2.3.3) to precast pavements. One concept proposes the use of full-depth, precast joint panels, central stressing panels, and base panels. These precast elements are shown in Figures 2.23–2.25. All of the panels are pretensioned in the transverse direction and have ducts cast into the slabs in both the transverse and longitudinal directions for post-tensioning adjacent slabs together once they are set in place. After the panels are all set in place and stressing of the post-tensioning tendons is complete, the stressing pockets are filled with a fast-setting concrete.

Figure 2.26 shows the final slab assembly. In actuality there would be several more base panels between the joint panels and central stressing panels than are shown in the figure. The slabs are all set on a single layer of polyethylene sheeting to reduce the prestress losses owing to subbase friction when the slabs are post-tensioned together.

A second concept for precast pavements presented by Neil Cable uses a configuration similar to that shown in Figure 2.26, except that the base panels are not the full depth of the pavement. With this concept, instead of the longitudinal tendons being threaded through ducts in the base panels, the tendons are laid across or set in grooves in the top of the base panels. A bonded concrete overlay is then placed over the base panels and longitudinal tendons. The tendons are then post-tensioned after the overlay has had sufficient time to set.

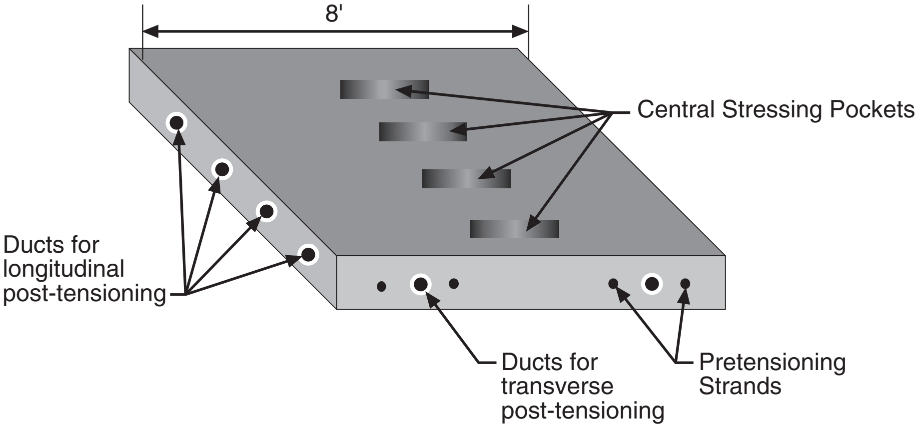


Figure 2.23 *Central stressing panel for precast pavement*

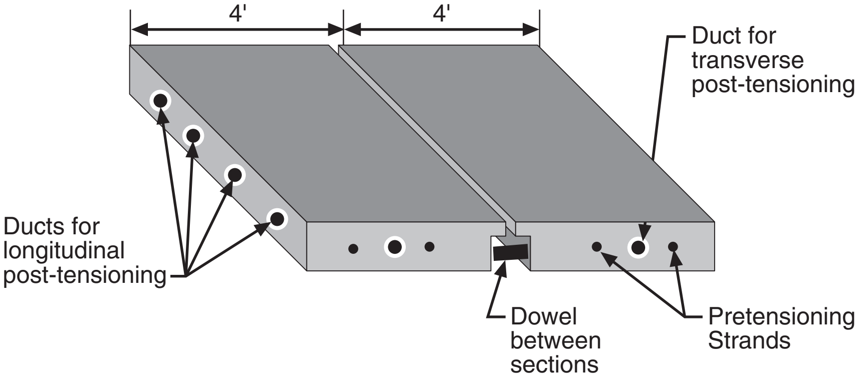


Figure 2.24 *Joint panel for precast pavement*

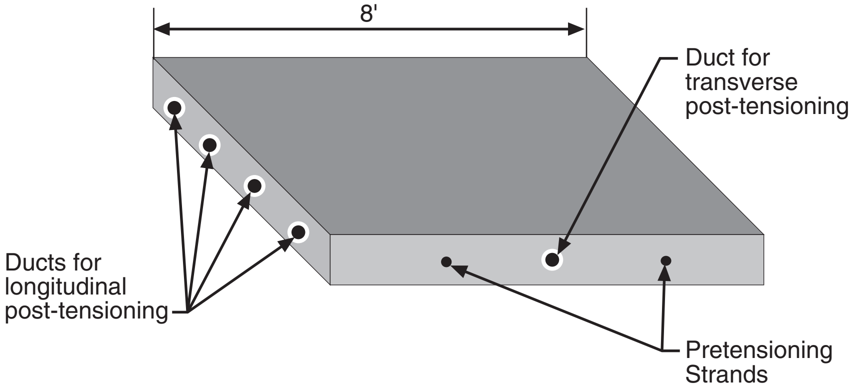


Figure 2.25 *Base panel for precast pavement*

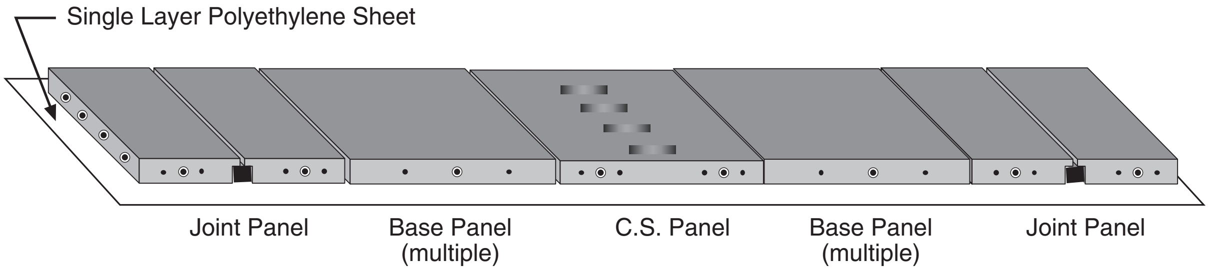


Figure 2.26 *Assembly of panels for precast pavement*

2.6 SUMMARY

The literature review provided an extensive amount of information on the current state of the art in precast pavements and precasting in general. Although there was a very limited amount of information on actual precast pavements, some of the ideas presented, particularly the new concepts described in Section 2.5, and the bridge deck joint details described in Section 2.4, proved very beneficial for the development of a concept for a precast concrete pavement.

Chapter 3. Documentation of Expert Panel Meetings

3.1 INTRODUCTION

Expert panel meetings were held at the beginning and end of the project to both help determine the current state of the art in the precast concrete and concrete paving industries and to generate and refine concepts for a precast concrete pavement. The first expert panel meeting, held at the beginning of the project, primarily provided ideas and recommended areas of further investigation for the development of preliminary concepts. The second expert panel was used to evaluate and refine the original concepts developed by the researchers.

The expert panels were made up of professionals from the precast concrete industry, construction industry, concrete paving industry, and transportation agencies. The panel members represented several regions of the United States. Overall, the panel members had a great degree of experience in their respective fields.

3.2 FIRST EXPERT PANEL

The first expert panel meeting was held on December 15, 1998, at the Hyatt Regency located at Dallas/Fort Worth International Airport. The expert panel consisted of representatives from all fields of the concrete and transportation industry. The purposes of the first expert panel meeting were as follows:

- Determine the current state of the art in precasting and concrete pavement construction.
- Discuss the practicality of various methods proposed by the researchers.
- Discuss feasible techniques for using precast panels in highway construction.
- Recommend areas of further investigation and possible sources of relevant literature.

The feedback from this expert panel was crucial for the development of the proposed concept for a precast concrete pavement. The panel members tended to focus on ideas that would be economically feasible and easily adaptable to current practices.

3.2.1 Panel Members

Of the thirteen members who were invited, seven were able to attend the first expert panel meeting. The members were selected to provide a balance of input from transportation agencies (DOT and FHWA), consultants, contractors, and suppliers — in short, to ensure a feasible final product relevant to all aspects of the transportation industry. The following is a list of those who attended the first expert panel meeting. The “Expert Panel” consists of the various professional members, including the project directors from TxDOT and the Federal Highway Administration. The “Researchers” include the three principal investigators and graduate student researchers from the Center for Transportation Research.

Researchers

- Dr. Frank McCullough
- Dr. Ned Burns
- Dr. David Fowler
- Mr. Anton Schindler
- Mr. David Merritt

Expert Panel

- Mr. Mark Swanlund - FHWA Representative
- Mr. John Dick - Precast / Prestressed Concrete Institute (PCI)
- Mr. Gene Marter - American Concrete Paving Association, (Texas chapter)
- Mr. Burson Patton - Texas Concrete Incorporated
- Mr. Tom D'Arcy - The Consultant Engineers Group
- Mr. Doug Huneycutt - Texas Department of Transportation (TxDOT), (Waco District)
- Mr. Andrew Wimsatt - Texas Department of Transportation (TxDOT), (Dallas District)

3.2.2 Presentation of Scope

The scope of this project is limited to full-depth pavement construction. With this in mind, two variations of a full-depth precast pavement were presented to the expert panel. The first variation is that of full-depth precast panels. With this application, the panels would be constructed to be the full pavement depth, as shown in Figure 3.1. The top surface of the panel would serve as the riding surface.

One advantage of this application is that once the panels are placed in position, traffic can almost immediately be turned onto the pavement. However, problems could be experienced during alignment of adjacent panels.

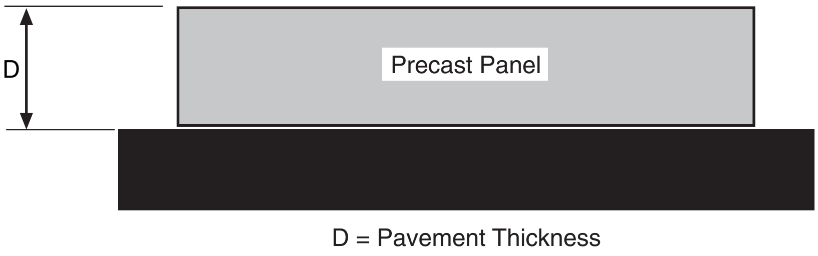


Figure 3.1 *Full-depth panels*

The second variation is precast panels with a bonded concrete overlay. With this application, panels would be constructed to be about 2 in. thinner than the final pavement thickness. The final 2 in. of the pavement would consist of a bonded concrete overlay, as shown in Figure 3.2. The bonded concrete overlay would, thus, provide the final riding surface of the pavement and should provide good riding quality.

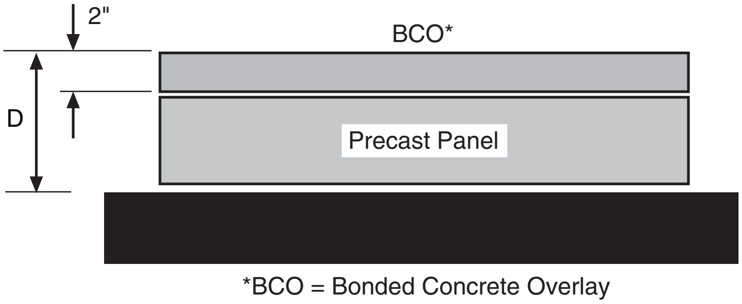


Figure 3.2 *Panels with BCO*

The advantage of this application is that the panels can be placed with less tolerance, as their alignment does not affect the final ride quality. However, a bonded concrete overlay adds an additional operation to the construction process. Additional time will be required to allow the BCO to gain strength before traffic is turned back onto the pavement.

3.2.3 Discussions

The main discussions of the first expert panel meeting were concentrated in three sessions. During the first session the current state of the art was discussed. In the second and third sessions, new concepts were discussed for the two different applications presented above. During each session, certain aspects were discussed as they came up; these discussions are documented below under the appropriate heading.

3.2.3.1 General Discussion

Expediting Pavement Construction

The comment was made that the issue with expediting construction is not necessarily that construction must go from step one to the final step in one uninterrupted operation. Rather, expediting construction can be performed over several (overnight) segments, with traffic allowed back onto the pavement after each segment. If work can be done in pieces, construction is still expedited. Ideally, a weekend closure would be preferable in order to complete the entire job. The next best option is to work only at night, opening the work site to traffic the next morning, and then continuing on the next night. Lane closure at 8:00 p.m. at night and reopening by 6:00 a.m. the next morning would meet these criteria.

Benefits of Expedited Construction

The comment was made that user costs are not yet considered as real agency costs. It was recommended that CTR attempt to quantify potential benefits to construction in terms of direct traffic control cost, as those costs are in fact part of the first costs by which projects are sold. Yet until public agencies accept the fact that user costs are real costs, they are still looking at the (incomplete) first cost. Some agencies are being pressured by the public to reduce delays caused by construction. TxDOT, for example, has recently issued a memorandum stating that the districts can now factor in the average daily cost of interference and inconvenience to the road user by using the A+B bidding method. Contracts are awarded based on the bidder’s contract construction cost (A) and the number of days required to complete the project (B).

General Strategy

One statement made was that the current methods (rules) for concrete paving do not necessary apply to precast — for example, the requirement for not allowing polishing of the aggregate on the surface of the pavement. For precast, it may be economically feasible to cast the panels in two lifts, with the last lift being the riding surface, which has the necessary polishing resistance. Another example is maximum aggregate size. A maximum 2 in. aggregate size is required because it gives better aggregate interlock when joints open up. If post-tensioning is incorporated in a precast pavement, the joints will be prevented from opening up and it may be possible to use smaller aggregate. The focus should be on what is needed for this particular application, and not on trying to shoehorn this new technology into an old paradigm.

Design Strategy

The consensus seemed to be that the recommended concept should start on the safe side and then back off. If corners are cut from the start, and a bad job results, it may be impossible to overcome the poor results. It is better to start with some good jobs, then back off the requirements until a combination is found that works and minimizes costs.

3.2.3.2 Current State of the Art

Panel Size

Beds in precast plants are typically 10 to 12 ft wide. The precasters indicated that 20 ton precast members are shipped on a daily basis. Double-tee sections are commonly shipped in the range of 15 tons. Permitting 12 ft wide panels should not be a problem, but could depend on where the panels have to be transported. The panels may need to be tilted in order to fit them on a truck.

The issue of equipment in the field was also raised. With urban congestion and staged construction, site access and equipment could be a problem. The opinion of the precasters was that most field equipment can handle 20 ton precast members.

Match-Casting

The issue of match-casting the pavement panels was also discussed. If 10 ft wide panels are match-cast, a 20 ft wide bed will be needed, which could be fairly difficult to attain. It was felt the match casting process could be too slow and that the tolerance achieved by a modern precast plant could provide the necessary precision for tight joints between the panels. Tongue-and-groove joints, commonly used for sheet piling, have been used very successfully. Also, if the panels are match-cast, and one of them is damaged somehow, that could delay construction.

The use of epoxy in the joints would help with fitting the panels together and match casting would then probably be unnecessary. Epoxy aids with sealing of the joint and it also develops tensile strength between adjacent panels. The characteristics of modern day epoxies can be tailored to meet various needs.

Joints between Adjacent Panels

A typical joint detail used to join two wall panels was illustrated, as shown in Figure 3.3. It was stated that this joint, or something similar, could perform as well as any monolithic cast-in-place joint. Figure 3.4 shows another concept illustrated for joining flat panels. The use of bars extending out of panels was encouraged, as it aids in establishing continuity. Welded wire fabric used in the panels could also be lapped between adjacent panels. The key is developing a poured concrete or welded connection joint that forces the panels to work together, rather than creating a hinge.

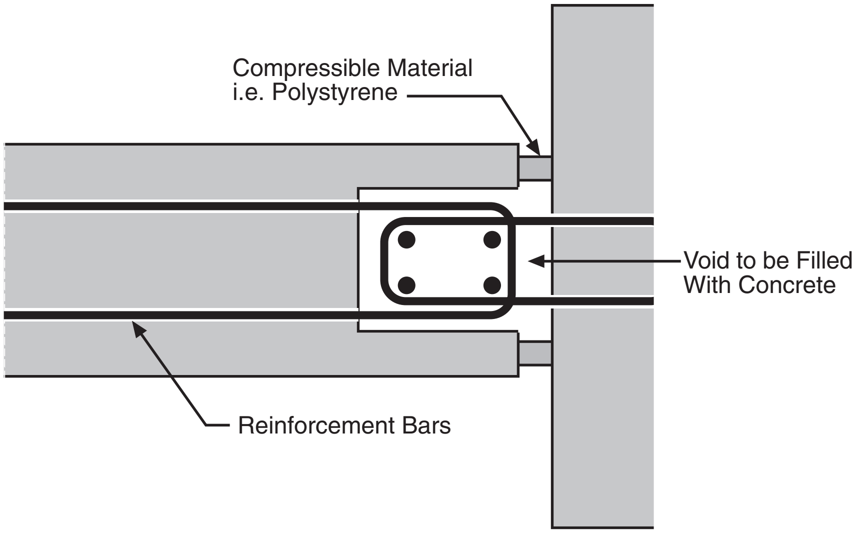


Figure 3.3 *Typical wall-to-wall connection detail*

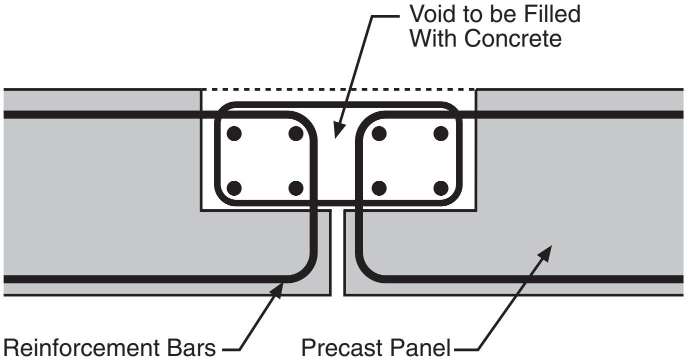


Figure 3.4 *Suggested concept to connect precast panels*

Prestressing

The comment was made that prestressing would probably be very similar to that used in bridge deck panels. Pretensioning could be used for the transverse prestress, and post-tensioning for longitudinal prestress. Typical minimum levels of prestressing in wall panels range from 200–250 psi, which is sufficient to cover stripping, handling, and erection. The panels could also be stressed concentrically so that camber will not be a problem.

Storage/Handling

Various options, such as lift loops, “dog-bones,” and “swift-lifts,” were suggested for handling the panels. Recesses created by these devices can easily be patched with a nonshrink concrete.

The question was raised as to whether it would be possible to drive a transport truck over the assembled panels. This ability could make access easier under situations where working space is limited, owing to the presence of traffic. It was concluded that this might be feasible, provided the panels are supported sufficiently.

Leveling of Panels

The use of shim stacks was recommended for leveling the panels. Enough shim stacks would be needed in order to support the panels sufficiently, particularly if construction vehicles would be passing over them. If the shim stacks are too tall, they can be tack-welded together.

Surface Preparation/Finishing

It was agreed that a macrotexture must be obtained on the riding surface of the panels. A tined finish could be obtained in the prestress plant by simply dragging steel wires through the top surface at the appropriate time.

It was suggested that the panels could be cast face down, with the tined surface then cast-in. This could create a regular pattern, however, which could lead to harmonic problems on the pavement. Irregular patterns were suggested, but the precasters agreed that the surface of the panel would probably be too smooth for highway purposes anyway. Casting the panels face down would also require that the panel be turned over, which could cause handling problems.

For the panel with BCO application, the surface of the panels should be prepared so that sufficient bond can be developed to prevent delamination. A “turf drag” or a rough broomed finish can easily produce the required surface texture.

Concrete Strength/Aggregates

The precast industry produces concrete with very high strengths on a daily basis. The order of concrete strengths required for highway pavements should, therefore, easily be obtained. Less expensive aggregates could be used in the bottom of the panel and more expensive aggregate in the top to achieve the necessary skid and abrasion resistance. This process would permit the use of local, softer fine aggregates and limit the use of the harder fines that are in short supply in many areas. The comment was made that since the implementation of Superpave by the asphalt industry, there has been a change in the usage of fine aggregates, and there are a lot of fines around that can be used, which could even reduce the material cost.

Maximum aggregate in a precast plant is about 1 in., with the average being around ¾ in. Checks will have to be performed to determine whether the smaller aggregates will be a problem, especially since post-tensioning will most likely be incorporated.

Curing Conditions

Typically, in a precast plant, the application of curing compound is followed by a tarp placed over the application. Mat curing is also possible. The expert panel was encouraged by the fact that problems that arise from strength differentials in traditional cast-in-place pavements would not occur in a precast pavement, as improved curing methods can be applied.

Vertical and Horizontal Curves

The issue of vertical and horizontal curves was raised, particularly as to whether any special provisions should be made when curves become too sharp. Provisions could be made to taper the sides of panels if the curves are indeed too sharp to be accommodated by rectangular panels. Whether the panels could be placed along a curve also depends on the joint detail used between the panels. The comment was made that it should not be a problem to skew the side forms for casting “curve-panels.” For interstate applications, the horizontal and vertical curves should be gradual enough not to present a problem, especially if the panel widths are only 12 ft. However, problems could occur with superelevation. Allowance for geometrical eccentricities should also be made when calculating the required post-tensioning. The length of the post-tensioned sections might have to be shortened around curves.

Strand Size

It is likely that 0.6 in. diameter prestressing strands will be used for post-tensioning, as they provide 40% more force per strand compared to 0.5-inch diameter strand. The majority of precast panels are pretensioned with 3/8 in. diameter strands. Half-inch strands are also sometimes used, depending on the panel thickness. The smaller strands have the advantage of having shorter bond lengths.

Unbonded versus Bonded Tendons

Unbonded strands will most likely be used for post-tensioning. This use allows for stressing in multiple stages if needed. The quality of unbonded post-tensioning tendons has greatly been improved, and the Post-tensioning Institute has an excellent specification for unbonded tendons. The possibility that the strands could be bonded to the joint panels, instead of using anchorage, should be considered. One of the advantages of using unbonded tendons is that they can be replaced.

The issue was raised that, with unbonded tendons, an uninformed maintenance worker could be injured when trying to cut into the pavement. There is also concern about damaging the sheathing when stringing the strand through the ducts. Bare strand grouted in the duct might be simpler, with the grout used to seal the voids in the duct and protect the strand. Bare strand would eliminate some of the cost, as bare strand is cheaper than the sheathed strand. In addition, with the bonded strand, cutting the pavement at any location would not result in any danger or loss of prestress. It would also solve the problem of moisture getting into a free duct area, which could cause corrosion problems.

It was also noted that grouting of the bare strands could be done several days after traffic has been allowed back onto the assembled pavement. This would be beneficial for an overnight construction operation. In addition, the grout does not have to be fully cured before traffic is allowed onto the pavement.

Anchorage

It was stated that anchorage is available for 0.5 in. and 0.6 in. diameter strand. If there are exposed end anchorages, however, encapsulation is necessary to prevent corrosion and provide a more durable pavement. It was recommended that the anchorage could be bolted to the steel bearing structure in the expansion joint. This procedure proved very successful in the McLennan County prestressed pavement project in 1985.

3.2.3.3 Full-Depth Panel Application

Size/Orientation

It was felt that the panels should be orientated with the longer dimension of the panel perpendicular to the direction of travel. If the panels were 10 ft wide, for example, this would mean that construction joints would occur every 10 ft, making proper leveling of the panels essential. It may be difficult to have a panel layout where panels are joined longitudinally and transversely.

Minimizing the Panel Weight

It was suggested that lightweight aggregates could be used in the panels. Lightweight aggregates can produce highly durable concrete while greatly reducing the weight of the panels. The advantage of lighter panels is that they will be easier to handle and, more importantly, more panels could be transported per truck. It was also suggested that waffle slabs or panels with thickened edges and thickening along the wheel paths could be used, as this would also reduce the weight of the panels.

Joining of Adjacent Precast Panels

Using tongue-and-groove joints at the panel edges should make panel alignment easier. The tongue-and-groove joint would also aid with load transfer between panels. Tongue-and-groove joints can be formed by the steel side forms on the casting bed, and it is possible to fabricate a panel with a tongue-and-groove detail on all four sides. Care should be taken in detailing the shape of the tongue-and-groove joint, as it was pointed out that thin edges could easily be damaged during handling and installation. The use of a straight V-joint was also suggested.

It was recommended that epoxy be used in the joints where adjacent panels meet. This precautionary provision would prevent water from penetrating into the support layers and would furthermore protect the strands passing through the joints. If epoxy is used between adjacent panels, a clamping force will be required to ensure proper adhesion of the epoxy. This will require a sequential process, whereby each panel is clamped as it is placed in position. An external clamping device could be used to apply the necessary pressure to the joint until the epoxy has cured. It was pointed out that by using epoxied joints on the longitudinal and transverse sides of a panel, temporary stressing would be required in both directions, which could become very complex.

Leveling

During the presentation, two different leveling concepts were presented. The first involved screw levels, whereby the elevation of the panels would be adjusted by a three- or four-point screw level. The second concept used air bags at the corners of the panels to adjust the elevation. With each of these concepts, the pavement would be kept about 0.5 in. off the base surface. After leveling is completed, a thin liquid-like grout would be pumped under the slab to fill the void beneath the slab. The advantage of the air bags is that they could be removed and reused.

The use of shim stacks, as described earlier, was again mentioned as an alternative method of leveling the panels. This method would be simpler and more economical than the two methods described in the preceding paragraph.

Asphalt Leveling Coarse

Concern was expressed about trying to level the panels with any of the proposed leveling devices. This operation could reduce the speed of construction. An inquiry was made as to whether a hot-mix asphalt concrete overlay could be placed with sufficient tolerance such that no leveling devices would be needed. Shims would be required only where the subbase is not sufficiently level. A planer could even be used to smooth out the asphalt layer in areas where it might not be sufficiently level. The asphalt layer could be placed as a separate operation, allowing traffic onto it prior to panel placement. Planing could be performed just prior to placement of the panels.

Grinding Surface of Panels

If, after the panels are assembled, the ride quality is not acceptable, grinding could be used to smooth rough areas. A device similar to the bump-cutting device used on concrete pavements could be used for grinding — meaning that the use of harder coarse aggregates on the top surface should be avoided, as they could be more costly to grind. The grinding process could be performed subsequently to opening the pavement to traffic and only over those areas that require smoothing out.

Prefabricated Ramps to Expedite Lane Opening/Closing to Traffic

After construction is completed for each segment, a prefabricated ramp could be placed at the ends of the slab to provide a transition for traffic moving onto the new pavement. This ramp could easily be removed the next day or weekend when construction commences, and then reused as construction progresses.

Longitudinal Prestress

A sleeved, monostrand could be threaded through an enlarged duct cast into the precast panels for longitudinal post-tensioning. Investigation should be undertaken to determine whether the protective coating around the strand is damaged during the threading process. A special fitting or a trumpeted end might be required where panels are joined.

Construction Rate

The question was posed as to how many panels a contractor could place to be competitive with regular construction. It was stated that this would be dependent on the size of the job and on the location of the project with respect to the precast plant. The production rate achieved in parking structures for double-tee sections is about 20–25 sections per day. For typical double-tee sections of 20 ft x 60 ft, this results in about 24,000 to 30,000 sq ft per day. Pavement panel placement should be competitive with this estimate.

Precast Contractors

The success of a precast pavement will be dependent on the contractors who will be producing the precast panels. Concern was expressed that the level of sophistication involved is probably above the ability of the average highway contractor. The feeling was that the general contractor might want to do his/her own precasting, as this is where most of the profit for this type of project can be achieved.

For this application, however, there might be reasons to prohibit the general contractor from setting up his/her own precasting facility. Durability and long life are essential and can easily be achieved in an established precast plant with a controlled environment, permanent employees, onsite concrete batch plants, and a high level of quality control. These essential qualities probably cannot be achieved by a temporary job-site operation.

3.2.3.4 Additional New Concept

The suggestion was made that products from the company Uretek USA, Inc., could be used for a precast pavement application. Uretek has a process for injecting a two-part expansive urethane beneath pavements to raise the slab through pressure caused by expansion of the urethane. The liquid material has a low viscosity and can spread a significant distance from the point of injection, filling any voids. The urethane material expands in about 10 seconds and cures in about 60 seconds.

Uretek has also developed another system called "stitch-in-time" that is used in pavement repair to provide load transfer across a joint or a crack. With this system, saw cuts 3/8 in. wide and 6 in. deep are made into the pavement, 1½ ft to each side of the joint/crack. A 4 in. wide, flat fiberglass plate is then inserted into the cut. The spaces between the plate and the slot are then filled with sand, which is vibrated in position. The urethane is then injected into the slot, filling the spaces between the sand and completely bonding the fiberglass plate to the slab. This process creates a more uniform load transfer, as compared to a traditional steel dowel.

By applying the stitch-in-time concept to precast pavement panels, post-tensioning would not be needed to tie the panels together. The joints would also be sealed from any water penetration. An expansion joint could also be incorporated using a special joint treatment, whereby the joint is not filled by sand but with rubber particles, which would allow expansion and contraction movement.

Concern was expressed as to how well the fiberglass plate is able to withstand millions of load repetitions under various thermal conditions. It was suggested that a mobile load simulator (MLS) could be used to test such an application under a high number of load repetitions.

3.2.3.5 Panel with BCO Application

The expert panel felt that adding a bonded concrete overlay is not really expediting anything, but rather adding another step, so that it takes more time to construct the pavement. It is not very conducive to expediting construction if a project has two phases.

The consensus seemed to be that a bonded concrete overlay largely defeats the purpose of using precast construction. A BCO requires a paving crew in addition to the workers who are setting panels and post-tensioning. Concern was also expressed about achieving a durable thin overlay without getting delamination, even with well-qualified contractors.

3.2.4 Recommendations and Conclusions

The purpose of the first expert panel meeting was to discuss the issues that should be investigated and addressed during a successful feasibility project for a project of this nature. For this reason, many issues were covered, and some were discussed in more detail than others. In this section, only the most significant recommendations and conclusions gathered from the first expert panel meeting will be summarized.

3.2.4.1 Recommendations for Proposed Concept

Scope of Application

- The addition of a bonded concrete overlay (BCO), in order to obtain a smooth riding surface, is not conducive to expediting construction.
- The full-depth panel application has the best potential for expediting construction. A smooth riding surface should be attainable with this application.

Precast Panels

- Panels should not exceed a weight of 20 tons each, as anything greater could be difficult to handle on site.
- Panel width should be limited to 10–12 ft.
- Match-casting of the panels may be unnecessary and will slow down production.
- A tined surface texture could be provided for the riding surface of the panels.
- Lightweight concrete could be used to minimize the weight of the panels.
- Less expensive aggregates could be used in the bottom of the panel, and more durable, more expensive aggregates in the top.

Joints between Adjacent Panels

- Epoxy should be used in the joints. By using epoxy, the joints will be sealed and tensile strength will be developed between adjacent panels.
- If epoxy is used between panels, a temporary clamping force is required to ensure adhesion of the epoxy.
- Tongue-and-groove type joints could be used. Such a detail will help with load transfer across the joint and with alignment of the panels.

Leveling of Panels

- It may be possible to place the panels on a thin layer of asphaltic concrete so that no additional panel leveling will be required. If needed, a planer could be used to smooth out the AC layer even further.
- The riding surface could be smoothed out by grinding the pavement at the joints. This operation could be done as a separate phase after traffic is turned back onto the pavement.
- If necessary, shim stacks could be used for leveling panels.
- Grout or urethane injection could also be used to level the pavement.

Post-Tensioning

- If unbonded tendons are used, the new Post-Tensioning Institute (PTI) specification on strand protection should be used.
- Bare post-tensioning strands could be used. These strands could be grouted in the ducts in a subsequent operation even after traffic has been allowed back onto the pavement.
- If end anchorages are used, encapsulation of these anchorage devices is highly recommended.

Precast Contractor

- Durability and high quality concrete probably can be attained only in an established precast plant, where a controlled environment, permanent employees, on-site concrete batching plants, and a high level of quality control exist. Therefore, there might be justification not to permit the general contractor from setting up his/her own precasting facility.

3.2.4.2 Recommendations for Further Investigation

During the expert panel meeting, numerous questions and uncertainties were discussed. It was recommended that the following issues be investigated further:

- How well did the precast pavement constructed in South Dakota perform?
- How will unbonded tendons perform if an oversized duct remains ungrouted around it?
- Could smaller aggregates be used in the precast panels, provided that prestressing is applied? Is the use of different aggregate types in the bottom and top of the panel feasible? If grinding is required to improve the ride quality, what type of aggregates will be the most effective to use in the top of the panel?
- What joint detail will be most effective between adjacent precast panels?
- Could an asphalt concrete leveling course be placed to such tolerances that no additional panel leveling is required?
- Which of the various lifting devices that are commercially available to lift and handle panels should be used?
- Could the construction process be done as a one-lane operation?
- Will rectangular panels be able to accommodate horizontal/vertical curves and superelevation?
- To what extent are sheathed strands damaged when they are pulled over long distances through ducts in prefabricated members?
- The use of urethane products and systems marketed by Uretek USA, Inc., should be investigated further.

Many of these issues were resolved prior to the conclusion of the feasibility project. However, some issues will not be resolved until actual implementation is undertaken. This will be discussed further in Chapter 10.

3.3 SECOND EXPERT PANEL

The primary purpose of the second expert panel meeting was to receive input and feedback from the panel members on the proposed concept that the researchers had developed. Input from the second expert panel was used to further refine the proposed concept (presented in Chapter 5).

Issues discussed in the second expert panel meetings primarily revolved around the practicality and constructibility of the proposed concept. Recommendations were made as to how to simplify the fabrication and construction of the proposed concept to make it more appealing to contractors and transportation agencies.

3.3.1 Panel Meetings

The second expert panel meeting was a culmination of several different meetings with various professionals in the precast and concrete paving industries. In each of these meetings, the concepts for a precast pavement that the researchers had developed were presented. The feedback from these meetings provided the researchers with ideas for refinement of the proposed concept and areas for further investigation.

The meetings that were part of the second expert panel were as follows:

- November 18, 1999 – Four-state pooled fund meeting
- December 3, 1999 – Meeting with the TxDOT Austin District Engineer
- December 9, 1999 – Meeting with precast suppliers/consultants

The purpose of the four-state pooled fund meeting was to provide a forum for transportation officials from four different states to discuss common problems and issues with the express intent of developing pooled funded research projects. The four states that participated in this meeting were Texas, California, Minnesota, and Washington. Receiving feedback from researchers and transportation officials from other areas of the country was very important for the development of a precast pavement concept. It is hoped that this concept will be implemented nationwide in the future, especially in states such as California, where expedited construction is a very important issue.

The meeting with Bill Garbade, the district engineer for the TxDOT Austin District, provided feedback on the practicality of construction of the proposed concept. The district engineer is involved in various pavement and bridge construction projects throughout the Austin District.

The meeting with precast suppliers/consultants provided feedback on the ideas the researchers had come up with from the perspective of the precasting industry. Burson Patton is a precast concrete fabricator with Texas Concrete, Inc., which fabricates structural and nonstructural precast elements for buildings, bridges, garages, etc. Tom D'Arcy is a consultant with The Consulting Engineers Group, Inc., which specializes in precast concrete construction. Both have had many years of experience with precast concrete and are aware of the intricacies of precast concrete fabrication and construction.

3.3.2 Discussions

As mentioned previously, the discussions from the second expert panel tended to focus on the actual application and constructibility of the proposed concept. The intent was to refine the proposed concept to make it appealing to contractors and transportation agencies. The discussions from each of the meetings are summarized below.

Four-State Pooled Fund Meeting

The main issue of discussion focused on a removal and replacement option for precast panels. This entails removing part of the existing pavement and replacing it with a new precast pavement that will tie into the existing pavement. This option is useful in areas where full closure to traffic is not permitted and only one or two lanes can be replaced at a time. Discussion centered around the amount of extra width of the existing pavement that would need to be broken out to accommodate the new pavement and the amount of temporary fill concrete needed to fill the gap between the old and new pavements. The cost of using precast pavement for a removal and replacement application was also discussed. Questions were also raised as to how many panels could be placed in one day.

The possibility of using two-way pretensioned precast panels, as opposed to post-tensioning the panels in place, was also discussed. The researchers' response to this issue was that some method for tying all of the panels together is needed, and post-tensioning provides the means for doing this. Two-way pretensioned panels are also difficult to fabricate.

Meeting with the TxDOT District Engineer for the Austin District

The main issues that were discussed in this meeting regarded alternative methods to simplify construction of the proposed concept. Alternatives to using epoxy in the panel joints (as was part of the original concept) were discussed. Applying epoxy has been found to be a cumbersome and time-consuming process in segmental bridge construction. The use of a thin liquid sealant, soaked or injected into the joint after post-tensioning, was suggested.

The possibility of orienting the post-tensioning tendons at an angle, rather than parallel to the length of the pavement, was also discussed. Skewed tendons would eliminate the need for separate transverse and longitudinal prestressing. It would also eliminate the need for the stressing pockets in the middle of the pavement, since the tendon anchorage would be placed along the edges of the pavement.

Concern was expressed over how smooth the finished pavement would be, especially at the panel joints and where the stressing pockets are located. The possibility of diamond-grinding the pavement after placement and post-tensioning was presented as an option. Diamond-grinding the pavement would give the pavement a very smooth and flat riding surface. Diamond-grinding has been used successfully around the United States and has become much more cost-effective in recent years. It may require, however, casting the panels at least 1/8 in. thicker so that they will be flush with the expansion joints after they have been diamond-ground.

The requirements for base preparation when placing a precast pavement under a bridge were also discussed. Because clearance will be an issue when paving under a bridge, it may be necessary to gouge out or rotomill the existing pavement under a bridge to accommodate the thickness of the precast pavement. The researchers noted that it may be possible to use thinner precast panels with increased prestress for applications under a bridge.

The district engineer also recommended that a pilot section be constructed where it will not have adverse effects on traffic if it is not finished as quickly as desired. The possibility of constructing the pilot section on a ramp or a “comfort station” road was suggested so as to expose the pavement to significant traffic, particularly truck traffic.

Meeting with Precast Suppliers/Consultants

As might be expected, the main issues discussed in this meeting regarded the fabrication and assembly of the precast panels. The entire process of placing the asphalt leveling course, placing the polyethylene sheeting, panel placement, post-tensioning, and filling the stressing pockets was deemed to be a great deal of work for an overnight operation. To alleviate the amount of work for one night, the asphalt leveling course could be placed up to a week ahead of the panels. Allowing traffic back onto the asphalt leveling course for a short period of time would not be detrimental to the leveling course. Also, the stressing pockets do not need to be filled the same night either. A steel cover could be placed over the stressing pockets the night the pavement is post-tensioned, and filling the pockets could be done the next night.

Match-casting the panels with discrete keys (which was part of the original proposed concept) was also discussed. The precasters agreed that match-casting is very time consuming and expensive. It would be much cheaper to use a “long line” to cast the panels, with a continuous shear key along the panel edges. With a long line, several panels would be cast end-to-end, as shown in Figure 3.5. The side forms on the long line create a continuous shear key along the edges of the panels. It should be possible to cast the panels to such close tolerances that they will fit together as if they were match-cast.

The precasters estimated that a typical placement rate for double-tee beams in a parking garage is between 20 and 30 pieces per day. If 10 ft wide precast panels were used for the pavement, up to 300 ft of pavement could be placed each night at this rate. If more than one crew were working, however, more could be placed. It would be ideal to have the precast panels on-site ahead of time, instead of hauling them to the site at the time of placement.

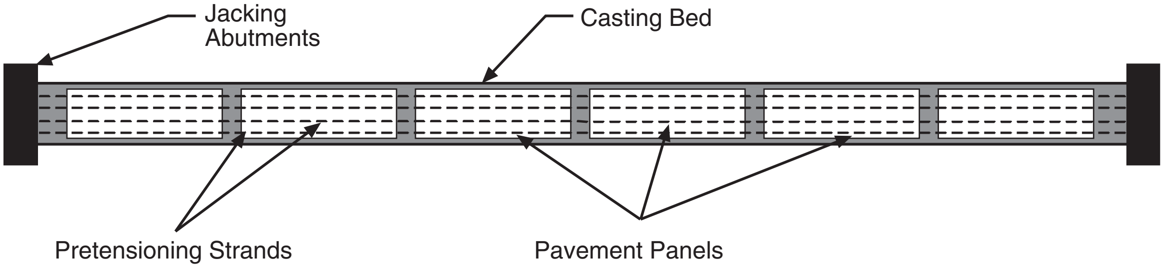


Figure 3.5 *Plan view of a long line casting bed*

The precast consultants felt that vertical curves that must be accommodated by the precast panels are probably gradual enough that the keyed edges could accommodate the slight angle created between the panels. For horizontal curves, the side forms of the precasting bed could be angled to create skewed panel edges.

It was recommended that the transverse prestress be designed for the handling stresses generated when the panels are handled from the ends. A type of lifting device, which clamps onto the keyed panel edges, with a strongback for support, could be used to lift the panels, so that lifting anchors do not have to be cast into the panels. Accommodation of this lifting device will have to be considered when placing the panels in the field.

The precasters agreed that a thin liquid sealant should be used in the panel joints to expedite construction. A small notch could be cast into the panels to receive the sealant material. They recommended the possibility of using keyed ducts to protect the strands crossing the joints, as shown in Figure 3.6. They also recommended the use of ducts with trumpeted or flared ends to make inserting the strands easier where they cross panel joints.

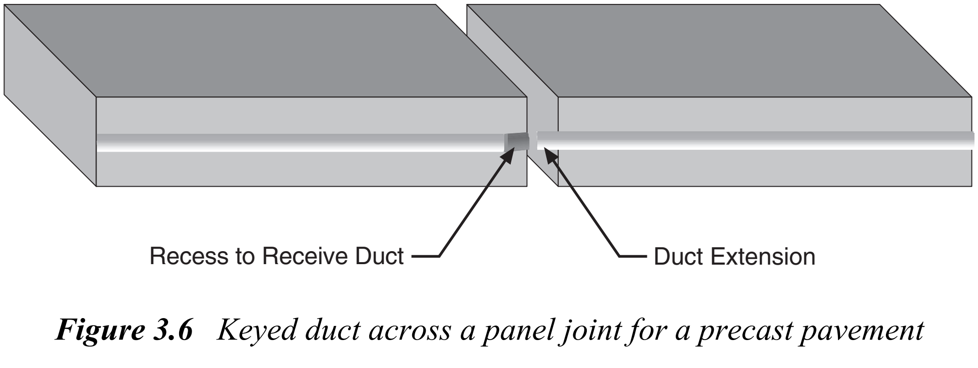


Figure 3.6 *Keyed duct across a panel joint for a precast pavement*

The idea of skewing the tendon ducts was discouraged by the precasters. Skewed ducts would greatly complicate the casting process and would make it difficult to ensure that the ducts are lined up exactly across the panel joints. In addition, pretensioning is necessary for accommodating handling stresses.

3.3.3 Recommendations and Conclusions

Input from the second expert panel was essential for evaluating the proposed concept from a practical standpoint. The information from the second expert panel led to the refinement of the original proposed concept to maximize the efficiency of fabrication and construction of a precast pavement. The significant recommendations for the final proposed concept and recommendations for further investigation from the second expert panel are summarized below.

3.3.3.1 Recommendations for Proposed Concept

Application

- Removal and replacement should be considered as a primary application for precast pavements. Removal and replacement will be useful in areas where full roadway closure is not permitted and in areas where the elevation of the finished pavement cannot be raised owing to overhead clearance problems.

Fabrication

- Long-line fabrication will greatly increase the production rate and decrease the cost of fabrication.
- A continuous shear key along the panel edges will simplify the casting process over using discrete match-cast keys.
- Skewed strand ducts would greatly increase the complexity of fabrication.
- Pretensioning will provide the necessary prestress to withstand handling stresses.
- Ducts with trumpeted or flared ends will make threading post-tensioning tendons through the ducts easier.

Construction

- The shear keys in the panel edges should be able to accommodate vertical curves. The side forms on the casting bed can be angled to accommodate horizontal curves.
- A thin, liquid sealant soaked/injected into the panel joints after post-tensioning will protect the post-tensioning strands from water penetrating the joint. It will also greatly increase the construction rate over applying epoxy to the panel edges. Keyed ducts will provide further protection for the strands.
- Diamond-grinding the pavement, after placement is completed, will ensure a much smoother pavement, particularly at the joints.
- When the pavement is placed in an area where overhead clearance is a problem, either the base/existing pavement can be rotomilled down, or the thickness of the precast pavement can be decreased by increasing the prestress in the pavement.

Implementation

- A pilot section should be constructed before large-scale implementation on a major project. The pilot section should be constructed on a rest area or “comfort station” road where delays in construction will not have adverse effects on traffic. Ramps or weigh station roads will also work for a pilot section but may have construction time restrictions.

3.3.3.2 Recommendations for Further Investigation

There are several issues voiced at the second expert panel meeting that must be investigated further. Most of these issues are not critical for completion of the feasibility project, but, rather, for eventual implementation. These issues are presented below.

- How much additional width/thickness of the existing pavement needs to be broken out to accommodate a precast pavement for a removal and replacement application?
- What is the cost and production rate for a precast pavement?
- What is the cost and benefit of diamond-grinding the finished pavement? What provisions need to be made for accommodating diamond grinding?
- What material would be best for the sealant material? What is the cost and how easily can this material be applied?
- What prestress is required to overcome handling stresses?
- Is it feasible to use keyed ducts to provide protection for the post-tensioning strands?

Many of these issues will not be resolved until a pilot project is undertaken. This pilot project will be discussed further in Chapter 10.

Chapter 4. Evaluation of Strategies

4.1 INTRODUCTION

Before a concept for a precast concrete pavement can be established, a rational evaluation of precast construction strategies will be used to determine the pavement type to be constructed. Four types of precast panels will be evaluated for use in construction. Three of these panel types correspond to pavement types exclusively constructed in the U.S. For each of the four pavement types considered, three construction applications will be considered. The first application is that of a new pavement placed over prepared base material. The second type of construction application is that of an unbonded concrete overlay to be used to overlay an existing pavement requiring rehabilitation. The final construction application is that of removal and replacement. This type of construction entails breaking up and removing the existing pavement and replacing it with a new pavement on the existing subbase.

For each of the three construction applications, the use of full-depth precast panels or partial-depth panels with a bonded concrete overlay (BCO) will be considered. The advantage of using a bonded concrete overlay is that a smooth, controlled riding surface can be attained over the top of the precast panels. This chapter will first evaluate each of these precast concrete pavement strategies with respect to design and construction, narrowing the choices down to a final precast panel type; it will then present a cross-section strategy for determining precast panel sizes.

4.2 PAVEMENT TYPES

There are essentially three types of portland cement concrete pavements commonly constructed in the United States. These pavement types are jointed concrete pavements (JCP), jointed reinforced concrete pavements (JRCP), and continuously reinforced concrete pavements (CRCP). A jointed concrete pavement consists of plain concrete slabs with joints spaced every 15–20 feet. Generally, dowel bars are used for transferring load across the joints. A jointed reinforced concrete pavement is similar to a JCP, the difference being the addition of a mat of reinforcement placed between the joints. This reinforcement allows for longer slab lengths (from 25–100 ft). As with JCP, this type of pavement uses dowel bars across the joints for load transfer. A CRCP is a pavement with an essentially infinite slab length, with reinforcement running continuously along the length of the pavement. The reinforcement in the pavement keeps the cracks, which form in place of joints, at an acceptable width to maximize load transfer and to minimize water entry.

A fourth pavement type, which is seldom constructed in the U.S., is prestressed concrete pavement (PCP). Rather than incorporating standard reinforcing bars, prestressed pavements contain prestressing tendons along the length and width of the slab, which are used to induce a precompressive stress in the pavement. Post-tensioning is generally the method used to introduce this precompressive stress, since it can be performed after the pavement is in place.

In order to select the most efficient pavement type for each application, the following section of this chapter evaluates these precast pavement types with respect to design and construction.

4.3 DESIGN AND CONSTRUCTION

There are several aspects to the design and construction of a precast pavement that will help determine the appropriate pavement type for each construction application. Based on the recommendations from the first expert panel meeting, presented in Chapter 3, the pavement applications that incorporate a bonded concrete overlay were eliminated from consideration. It was decided, based on the opinions of the expert panel, that the use of a bonded concrete overlay would simply slow down the construction process, owing to the additional paving operation. Some of the other factors for precast pavement type selection are discussed below.

Maximize Effective Thickness

When a precast concrete pavement is constructed, there will inevitably be voids beneath the panels. These voids reduce the support provided to the pavement, thereby reducing the life of the pavement under repetitive wheel loading. In order to account for this reduction in support, the thickness of conventional concrete pavements (JCP, JRCP, CRCP) must be increased. A prestressed concrete pavement, however, has the ability to "span" these voids, because of the precompressive stress in the pavement. Rather than increasing the thickness of the panels, the prestress can simply be increased.

Maximize Load Transfer

When cracks in concrete pavements become larger than 0.03–0.04 in., the pavement must rely upon aggregate interlock to provide load transfer. This load transfer ability decreases as the cracks become larger. Reinforcement in the pavement, however, helps to keep cracks from opening excessively. Prestressed reinforcement further helps to not only keep cracks from opening, but actually works to pull cracks closed. The shear friction alone, provided by the precompression in a prestressed pavement, provides optimal load transfer across joints and cracks.

Lifting and Handling

The self-weight of precast panels alone can cause significant bending stresses in the panels when they are handled. These bending stresses, which include dynamic effects, can be large enough to cause cracking. Reinforcement is needed to keep cracks that may form from opening significantly. Clearly, a JCP panel, with no reinforcement, will perform poorly during handling and lifting. JRCP and CRCP panels should be able to withstand the stresses from handling, but more than likely will still experience cracking. PCP panels, on the other hand, can be designed such that no cracking will occur when the panel is handled. Prestressed concrete panels can be pretensioned during fabrication such that handling stresses are accounted for.

Minimize Clearance Problems

When an overlay is placed on an existing pavement, the thickness of the overlay must be considered to minimize overhead clearance problems under bridges and overpasses, especially in urban areas. With conventional pavement types, however, reducing the thickness of the overlay will affect the design life of the pavement. Prestressed concrete pavements, however, allow for the prestress level to be adjusted based on the desired thickness of the overlay. Essentially, the thickness of the overlay can be selected and the prestress level can be tailored to meet the design requirements for the selected pavement thickness.

Continuity of Finished Pavement

The use of conventional precast pavement panels will require a way to provide load transfer at the joints between precast panels. JCP and JRCP normally have dowels at the joints to provide load transfer. It may be difficult to incorporate these dowels into precast panels, however. CRC pavements rely upon continuous reinforcement along the length of the pavement. This arrangement may require splicing the longitudinal reinforcement together somehow to provide continuity in a precast pavement. Load transfer across joints in prestressed concrete pavements, however, is provided through shear friction. The prestressing tendons pull the panels together tightly, providing this load transfer.

Speed of Construction

The design of conventional pavement panels is such that the panels can stand alone, allowing traffic back onto the pavement almost immediately after placement. The strength of a prestressed concrete pavement, however, is reliant upon the prestress provided by post-tensioning after the entire pavement (all precast panels) is in place. This additional post-tensioning operation for a prestressed pavement will significantly reduce the speed of construction of a prestressed concrete pavement.

With these considerations in mind, the researchers constructed a decision matrix to evaluate the different pavement types with respect to design and construction. Table 4.1 shows the evaluation chart used for this purpose. Each pavement type was rated on a scale of 1 to 3, with "1" representing a poor rating, "2" representing a fair rating, and "3" representing an excellent rating. All design and construction considerations were given equal weight, although different weights would not have affected the results.

Based upon this evaluation, PCP has the largest score, and thus the conventional pavement types (JCP, JRCP, and CRCP) are eliminated from consideration for use in a precast concrete pavement. This elimination leaves prestressed concrete pavement as the most feasible method for precast construction. Although PCP rated low with respect to speed of construction, which is one of the most important criterion for this feasibility project, it is believed that the benefits of prestressed concrete panels will far outweigh the additional construction time. Methods for further expediting prestressed construction can be developed later on.

Table 4.1 *Evaluation chart for design and construction considerations for each pavement type*

Design/Construction Consideration	**Pavement Type**			
	JCP	**JRCP**	**CRCP**	**PCP**
Maximize Effective Thickness	1	1	1	3
Maximize Load Transfer	1	1	1	3
Lifting and Handling	1	2	2	3
Minimize Clearance Problems	1	1	1	3
Continuity of Finished Pavement	1	1	1	3
Speed of Construction	3	3	3	1
Total	***8***	***9***	***9***	***16***

The focus of the remainder of this report, therefore, will be on the use of full-depth precast, prestressed concrete panels for pavement construction in new, overlay, and removal and replacement applications.

4.4 CROSS-SECTION STRATEGY

The cross-section strategy will provide a general idea of the required precast panel sizes for pavements of varying widths. From the first expert panel meeting, it was determined that the panels should be oriented transverse to traffic flow to minimize the number of longitudinal joints. Clearly, however, it will not be possible to fabricate precast panels large enough to span the full cross section width of all roadways. It will be necessary to place the pavement in separate “strips” of panels for wider roadways.

Full-width and partial-width construction are both considered. Full-width construction entails placing the entire pavement width before turning traffic back onto the pavement. Partial-width construction implies placing one “strip” of pavement at a time, allowing traffic back onto the pavement after the placement of each strip. These two types of construction will be evaluated for both new or overlay and removal and replacement applications.

Table 4.2 shows possible cross-section strategies for full- and partial-width precast construction. The section (panel) widths were considered for two-lane, three-lane, and four-lane roadways. The lanes were assumed to be 12 ft wide, and the shoulder widths were assumed to be 4 ft for inside shoulders and 10 ft for outside shoulders. It is important that the shoulder be included with its adjacent lane to ensure that traffic will be only on the interior of the precast panels. Edge loading will result in significantly higher stresses in the panels. Therefore, a 22 ft section width corresponds to a 12 ft lane and 10 ft shoulder, while a 16 ft section width corresponds to a 12 ft lane and 4 ft shoulder. A section (panel) width of 38 ft was considered the maximum feasible panel width for transportation and handling purposes.

Partial-width construction is not considered for new or overlay applications. If only one section of the pavement is placed for an overlay application, prior to allowing traffic back onto the pavement, there will be a drop-off from the new pavement down to the existing pavement. For a new pavement, traffic most likely will not be allowed onto the new pavement until the full width of the pavement is constructed.

Table 4.2 *Cross-section strategies for precast pavement construction*

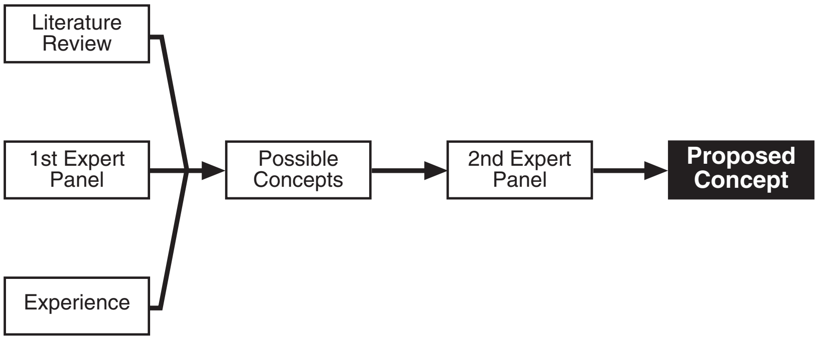
Application	**Type of Construction**					
	Full Width			**Partial Width**		
Number of Lanes	***2***	***3***	***4***	***2***	***3***	***4***
New or Overlay	1 @ 38’	2 @ 25’	2 @ 31’	N/A	N/A	N/A
Removal and Replacement	1 @ 38’	2 @ 25’	2 @ 31’	22’+16’	22’+12’+16’	22’+12’+12’+16’

Based on the cross-sectional strategies and selected pavement type given here, a concept for a precast concrete pavement will be presented in the following chapter. The feasibility of design, construction, economics, and durability will then be evaluated in subsequent chapters.

Chapter 5. Proposed Concept: Full-Depth Panels

5.1 INTRODUCTION

The proposed concept for a precast concrete pavement has evolved from several key aspects of the feasibility project. The flow diagram below demonstrates the evolution of the proposed concept. Possible concepts for a precast concrete pavement were first developed from the literature review (Chapter 2), from the first expert panel meeting (Chapter 3), and from the experiences of the researchers. These possible concepts were then presented to the second expert panel for evaluation. The input from the second expert panel led to a refinement of the original concepts to a final proposed concept.



The proposed concept for a precast concrete pavement focuses on the use of full-depth precast panels. It is believed that a smooth enough riding surface can be obtained with proper alignment of individual panels and with occasional diamond grinding or bump cutting. The pavement will be prestressed so as to maximize the effective thickness of the slabs. The proposed concept consists of base panels, central stressing panels, and joint panels, similar to those items presented in Section 2.5. The panels are placed on a single layer of polyethylene sheeting over an asphalt leveling course. The panels are all pretensioned in the transverse direction during fabrication and will be post-tensioned together in the longitudinal direction after placement. Post-tensioning will not only provide a means for tying the individual panels together, but will also prestress the pavement in the longitudinal direction as well.

The details of this concept will be discussed over the course of this chapter. The discussion includes a description of the panels that will be used, the expansion joint and intermediate joint details, panel assembly process, post-tensioning anchorage and post-tensioning procedures, and base preparation. This concept applies to all of the pavement applications discussed previously, including new pavements, unbonded overlays, and removal and replacement applications.

5.2 PRECAST CONCRETE PANELS

Proper alignment of the individual precast concrete panels is essential for providing a smooth riding surface. The most effective method for ensuring proper alignment appears to be one that uses continuous shear keys cast into the edges of the panels. According to this arrangement, a male shear key will be cast into one side and a female shear key into the opposite side of the panel. These keys will interlock the panels together, such that there is a tight fit and exact vertical alignment between adjacent panels.

All of the panels will be the same length (transverse pavement direction) to simplify the casting and assembly processes. The length of the panels will depend on the application of the pavement, as discussed in Chapter 4. The panel width (longitudinal pavement direction) will depend on the panel type and on the limitations of the fabrication and handling equipment. A panel width of 10 ft will probably be the maximum width owing to precasting bed size and transportation limitations.

Based on experience with prestressed concrete pavements, prestress in the transverse direction is essential. Previously constructed prestressed concrete pavements, which did not have transverse prestressing, experienced extensive longitudinal cracking and premature failure (Ref 6). Transverse prestress will be incorporated by pretensioning the panels in the transverse direction during fabrication.

Ducts for the longitudinal post-tensioning strands will be cast into the panels during fabrication. Tight tolerances on the side forms of the casting bed will ensure that the post-tensioning ducts will line up along the length of the pavement. Single- or multiple-strand ducts may be used for post-tensioning.

5.2.1 Base Panels

Base panels are the “filler” panels between the central stressing panels and joint panels. The number of base panels between the central stressing panel and joint panels will depend on the slab length. Figure 5.1 shows a typical base panel. As described above, the base panels will be pretensioned in the transverse direction during fabrication and will contain ducts for the longitudinal post-tensioning strands. Male and female continuous shear keys will be cast into the edges of the panels to ensure continuity and to provide proper alignment of the panels when they are assembled. The width of the base panels will depend on the application of the pavement and on limitations of the fabrication and handling equipment.

5.2.2 Central Stressing Panels

The central stressing panels will be similar to the base panels, though with the addition of pockets for stressing the post-tensioning tendons, as shown in Figure 5.2. The pockets in the central stressing panel will need to be staggered across the panel, so that the panel will have sufficient rigidity for handling purposes and will not be susceptible to a perforation weakness effect when the slab is post-tensioned. The idea of central stressing is one that was developed for the cast-in-place prestressed pavement constructed in McLennan County and discussed in Chapter 2 (Ref 6). Central stressing allows for the post-tensioning strands to be anchored at the ends of the slab and post-tensioned from pockets at the middle of the slab. The advantage of using this technique is that access to the end anchorage is not needed in order to post-tension the slab. This advantage allows for a more continuous pavement placement operation.

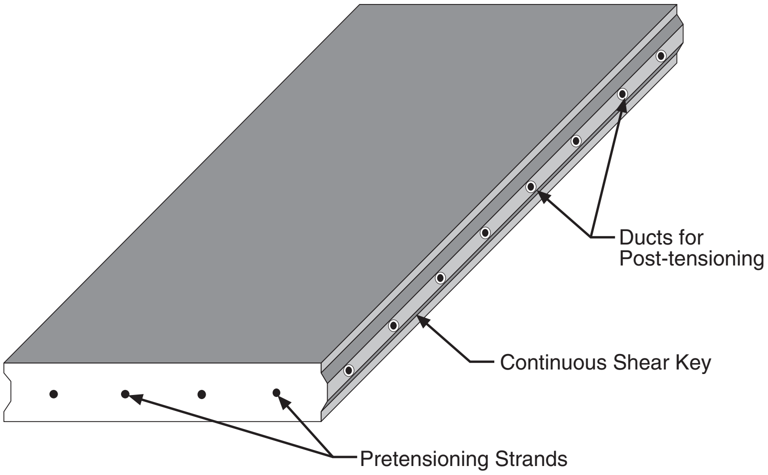


Figure 5.1 *Base panel*

From an investigation of the cast-in-place prestressed pavement project in McLennan County, it was found that pockets with square corners developed cracking as a result of stress concentrations at these corners (Ref 20). For that reason, the pockets in the precast central stressing panels will have rounded corners. It was also found that 48 in. wide pockets were required to accommodate the hydraulic stressing ram. This requirement may necessitate using more than one central stressing panel, so that a perforation weakness effect will not result from such large stressing pockets. The number of pretensioning strands that cross the central stressing pockets should also be minimized.

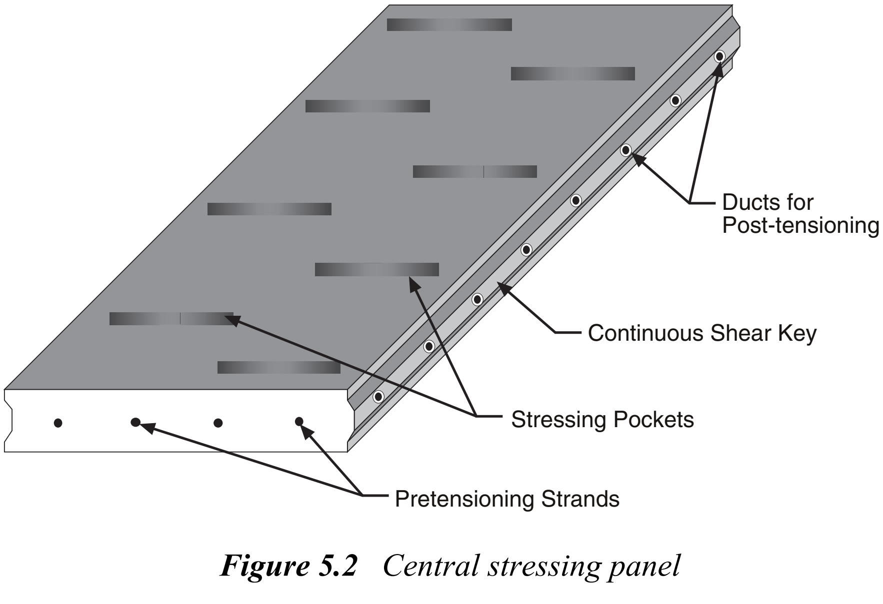


Figure 5.2 *Central stressing panel*

5.2.3 Expansion Joint Panels

The expansion joint panels will contain the actual expansion joint detail and dowels, as well as the anchorage for the post-tensioning tendons. Figure 5.3 shows a typical expansion joint panel. The purpose of the expansion joint is to "absorb" the expansion and contraction movement of the pavement slab caused by daily and seasonal temperature cycles. The joint panels will consist of two separate halves. Each half will be part of the slab on either side of the expansion joint. The expansion joint itself will be tack welded closed — with the dowels in place — during fabrication of the panels to ensure that both halves remain together and the joint remains parallel.

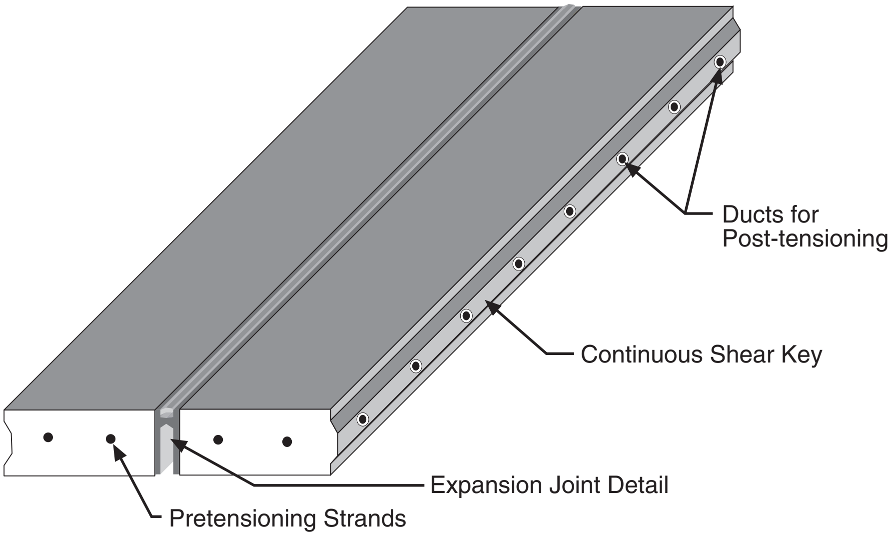


Figure 5.3 *Joint panel*

5.2.4 Panel Assembly

The panels will be placed sequentially, starting with a joint panel at the end of the slab. The base panels will be placed after the joint panel, followed by the central stressing panel(s) at the middle of the slab, additional base panels, and the second joint panel. A typical panel assembly is shown in Figure 5.4. The number of base panels between the joint panels and central stressing panel will depend on the length of the slab and on the width of the panels. The post-tensioning strands will be inserted into the ducts via the central stressing pockets and threaded through the ducts to anchors in the joint panels after all of the panels have been set in place. An optimum width gap will be left between the joint panel and the first base panel so that the strands can be pushed into spring-loaded anchors in the joint panel. The gaps between the panels will be closed as much as possible and the strands will then be post-tensioned from the central stressing pockets. A low-viscosity, liquid sealant will then be soaked or injected into the joints between each of the panels. The pockets in the central stressing panel will then be filled with a fast-setting concrete and the post-tensioning strands will be grouted in the ducts. Finally, if necessary, any uneven areas can be diamond-ground to provide a smooth ride.

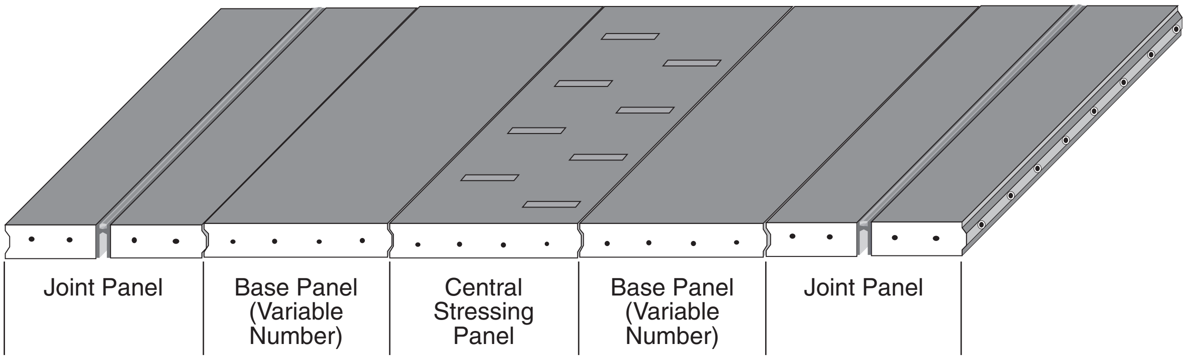


Figure 5.4 *Typical panel assembly*

5.2.5 Coupler Panel (Alternative Concept)

As an alternative to the panel assembly process just described, a coupler panel could be used to assist in anchoring the tendons. Instead of leaving a gap between the joint panel and the first base panel to push the strands into the anchors, a coupler panel, with pockets similar to those in the central stressing panel, could be placed adjacent to the joint panels. Short lengths of the post-tensioning strands could be anchored to the joint panels, prior to assembly, and would extend into the coupler pockets where they would be coupled or spliced to the main strands extending from the central stressing pockets. The strands would then be stressed from the central stressing pockets, as usual. This concept would eliminate the need for a spring-loaded anchor and would allow for the strands to be anchored to the joint panels prior to panel placement, permitting the use of standard post-tensioning anchors. The coupler panel would be similar to the central stressing panel (Figure 5.2). The pockets would have to be only large enough to accommodate the strand coupler and would be staggered across the panel like the central stressing panel.

In a slight modification to this concept, the pockets in the coupler panel would be used to push the strands into the spring-loaded anchors previously mentioned. This method would eliminate the need to leave a gap between the joint panel and adjacent base panel. It would also eliminate the need for a coupler device.

5.2.6 Removal and Replacement

The proposed concept for a removal and replacement application is very similar to that for a new or overlay application. There are some differences, however, in the panels and the panel assembly process. These differences will also apply to new or overlay applications when two or more slabs are used to achieve the full pavement width, as discussed in Chapter 4.

The first difference involves the panels that will be used. For the transverse direction, when two or more slabs are placed next to each other, a method for tying those slabs together is required. To meet this requirement, adjacent slabs will be post-tensioned together via additional post-tensioning ducts cast into the panels in the transverse pavement direction. Post-tensioning strands can then be threaded through these ducts to pull the adjacent slabs together, thereby minimizing the joint width and maximizing load transfer across the longitudinal joint. Figure 5.5 shows a typical panel used in a removal and replacement application. The only difference between the panel shown in Figure 5.5 and the base panel, shown previously in Figure 5.1, is the additional post-tensioning duct for transverse post-tensioning. Most likely, this duct will be a flat duct that can accommodate differential movement and placement offset of adjacent slabs.

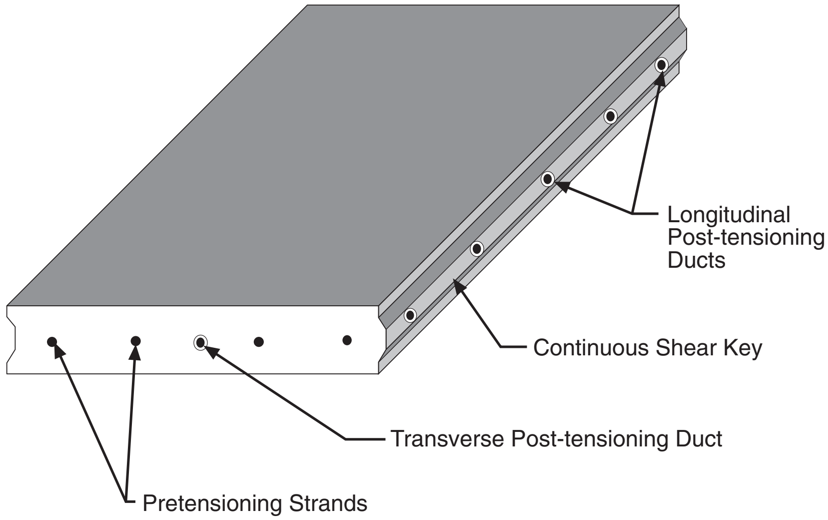


Figure 5.5 *Typical panel for a removal and replacement application*

The other primary difference with a removal and replacement application is the additional post-tensioning process required during the panel assembly. Once an adjacent slab is placed, the slabs will be post-tensioned together using the transverse post-tensioning ducts. To ensure that the ducts will line up between adjacent slabs, any new slabs should be placed from the center out (starting with the central stressing panel[s]), since the center of the slab will not move.

5.3 PAVEMENT JOINT DETAILS

Joints are an integral part of precast pavements. The two types of joints of concern in a precast concrete pavement are the intermediate joints between the individual panels, and the expansion joints at the ends of the slab. The primary purpose of the intermediate joints is to ensure that the assembled precast panels act as a continuous pavement between expansion joints, providing complete load transfer between panels. The expansion joints, on the other hand, are designed to "absorb" the expansion and contraction movements of the pavement.

5.3.1 Joint Requirements

The primary requirement of the intermediate joints between panels is that they ensure that the precast pavement acts as a continuous pavement. This entails that load transfer and a smooth riding surface is provided across these joints

There are several requirements for the expansion joints. The first requirement is that they are able to withstand the expansion and contraction movements of the pavement. The second requirement is that the joints provide adequate load transfer between the slabs on either side of the joint. The expansion joints must also be able to withstand the forces imposed by wheel loads. This requirement will necessitate hardware and a structure that is not susceptible to fatigue; constructibility and economic feasibility must also be maintained.

5.3.2 Joints from Previous Projects

Several different joint details have been developed for previously constructed precast pavements, as described in Chapter 2. One such joint detail, developed in Japan, used straight and "horn-shaped" dowel bars (inserted after the panels are placed) to provide the load transfer between adjacent panels. Another joint detail used in a precast pavement in South Dakota consisted of a tongue and fork type joint. The tongue and fork connectors were cast into the panels and locked together with a steel wedge after the panels were set in place.

Information on expansion joint details from previous projects came from the four cast-in-place prestressed pavements constructed prior to the prestressed pavement in McLennan County, Texas, in 1985 (Ref 6). The information from these previous projects led to the development of an expansion joint detail for the McLennan County project. The final joint detail used for the McLennan County project is shown in Figure 5.6. This joint detail utilizes a steel bearing structure for durability and a neoprene seal to prevent material from falling into the joint. Two rows of ½ in. Nelson deformed anchor bars, approximately 3 ft long, tie the joint structure to the pavement and reduce "rocking" of the joint as traffic passes over it, thereby reducing fatigue on the welds in the joint. The upper and lower anchor bars are alternated over the length of the joint so that there is only one bar every space. Dowel bars provide load transfer across the joint and are plated with stainless steel to prevent corrosion. One of the primary advantages of this joint is that it can be assembled as a single piece, reducing the chance that bars or dowels will be improperly positioned. This joint detail was found to be very constructible and has performed very well under heavy traffic loading (high truck volume) after 15 years in service.

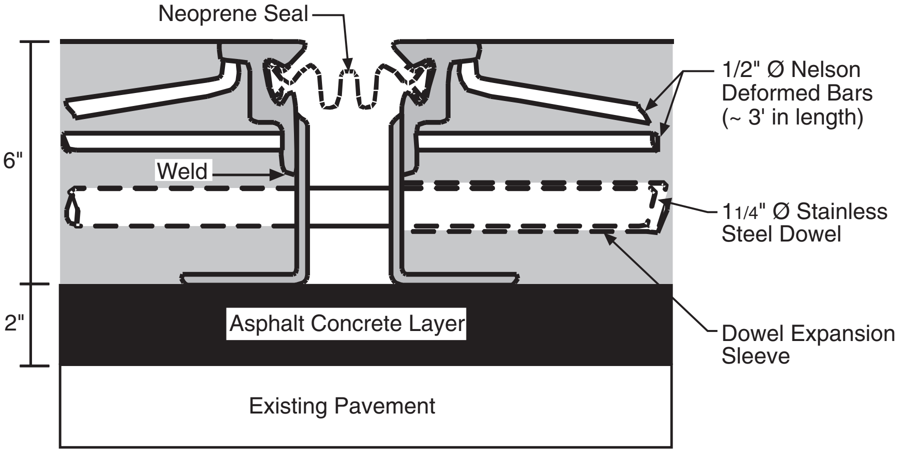


Figure 5.6 *Expansion joint detail for the McLennan County prestressed pavement (Ref 6)*

5.3.3 Expansion Joint Detail

The expansion joint detail used in the McLennan County cast-in-place prestressed pavement (Figure 5.6) has proven to be a very durable joint detail, one that meets the requirements for high-performance pavement. For this reason, the same joint detail is proposed for a precast concrete pavement. The joint detail, which will be prefabricated prior to casting the panels, will be cast into the joint panel during fabrication. The steel flanges at the top of the joint will be tack-welded together, prior to casting the concrete for the joint panel, to ensure that the joint remains parallel during fabrication and placement of the panel. The weld will be removed prior to post-tensioning and once the panel is set in place.

The anchors will be positioned in the joint panel so as not to interfere with the dowels or bars from the joint detail. The anchors will be bolted to the joint structure to ensure that they are correctly positioned during fabrication of the joint panel. This joint detail should be able to accommodate the expected expansion and contraction movements of the pavement slabs while also withstanding repeated wheel loading. In order to ensure good ride quality, however, the joint width design should never exceed 3½–4 in.

5.3.4 Intermediate Panel Joints

The intermediate panel joints will be similar to “dry joints” used extensively in segmental bridge construction. These joints consist of continuous keys cast into the edges of the panels, as shown in Figures 5.1–5.3. A thin liquid sealant will be applied to the joints after assembly and post-tensioning of the panels. This sealant will be soaked or injected into the joints to protect the post-tensioning strands crossing the joints from water penetration.

Alignment of the keys will be ensured through strict tolerances on the casting bed and side forms. The primary purpose of the keys is to aid with alignment of the panels during assembly. However, the keys will also provide some degree of load transfer across the joints, even though the prestress in the pavement provides most of the load transfer.

5.4 BASE PREPARATION

The use of full-depth precast panels requires an efficient method for leveling the panels so that they are properly supported and a smooth ride is provided. Base preparation involves not only providing this support, but also providing a means of reducing the friction between the bottom of the panels and the supporting layer.

5.4.1 Asphalt Leveling Course

A thin (1–2 in.) asphalt leveling course appears to be the most efficient and economical method for ensuring that full-depth precast panels will remain level and be properly supported. The asphalt leveling course can be placed over the existing pavement, in the case of an overlay application, or placed on the subgrade, in the case of a new pavement. If necessary, grinding the leveling course can also be performed to smooth out irregularities.

The asphalt leveling course can be placed well in advance of panel placement. It should not be detrimental to the leveling course if traffic is allowed onto it for up to a week after it is placed. This arrangement will allow for the leveling course to be placed in a single operation for a long section of pavement, rather than just prior to placement of each individual slab.

5.4.2 Polyethylene Sheeting

The purpose of a friction reducing medium is to reduce the prestress losses and the tensile stresses generated in the pavement as a result of the frictional resistance between the slab and supporting layer. Extensive testing of different friction reducing medium, conducted prior to the construction of the cast-in-place prestressed pavement in McLennan County, found a single layer of polyethylene to be a very effective and economical material for reducing the frictional resistance between the slab and supporting layer. The constructibility of this material was demonstrated during construction of the McLennan County prestressed pavement (Ref 20).

The slab-base interface between precast pavement panels and the asphalt leveling course will be different from that of a cast-in-place pavement. Precast panels will have a smooth surface in contact with the leveling course, and will also span small voids, thereby reducing the contact area with the leveling course. These factors will serve to further reduce the friction between the pavement and the leveling course. Push-off tests quantifying these effects should be conducted prior to construction of a precast pavement. However, with the present lack of data on these effects, a friction reducing medium such as polyethylene sheeting should still be used for precast pavement construction. At minimum, the plastic sheeting will serve as a bond breaker between the leveling course and precast panels, allowing the finished pavement to expand and contract with reduced frictional resistance. Additionally, assuming a frictional resistance coefficient similar to that for a cast-in-place pavement will result in a conservative design for precast pavements.

5.5 LONGITUDINAL POST-TENSIONING

Post-tensioning is one of the most important aspects of a precast concrete pavement. Post-tensioning not only ties all of the panels together to form a continuous slab; more importantly, it induces a precompressive stress (prestress) in the concrete. This prestress greatly reduces the required slab thickness and enhances the durability of the pavement. There are several components of post-tensioning that must be considered, including the tendon ducts, tendon anchorage, strand placement procedure, post-tensioning, and grouting. These components will be discussed below.

5.5.1 Tendon Ducts

The tendon ducts provide the conduit or housing for the post-tensioning strands. The ducts will be cast into each of the precast panels during fabrication, as mentioned previously. It is important that the ducts line up exactly between adjacent panels so that the strands can be easily threaded through the ducts after all of the panels are placed. The Post-Tensioning Institute recommends that the duct be at least 1/4-in. larger than the nominal diameter of the strand for single-strand tendons (Ref 22). The ducts must be able to transfer the required bond stresses and should be made of a noncorrosive, preferably plastic, material that will retain shape under the weight of the concrete.

Single- or multiple-strand ducts can be used. Multiple-strand ducts will greatly reduce the number of stressing and grouting operations required. Multiple-strand ducts will require special attention, however, to prevent the strands from crossing or becoming twisted together in the duct when they are inserted.

“Keyed” ducts, similar to those shown in Figure 3.6, will provide additional protection from corrosion of the post-tensioning strands. Keyed ducts will prevent any water penetrating the joint between panels from coming in contact with the post-tensioning strands.

The ducts will have grout inlets or vents, similar to those shown in Figure 5.9, to allow for grouting of the tendons after the strands have been stressed. Grout inlets/vents will be located, at least, at the ends of each slab. At minimum, one vent will be located at the joint panel and one vent will be located near the central stressing pockets. Other vents will be located as needed at intermediate points along the duct to ensure proper grouting.

5.5.2 Tendon Anchorage

The post-tensioning tendons will be anchored to the joint panel using post-tensioning anchorage hardware. One of the ideas brought up during the first expert panel meeting was the possibility of bonding the ends of the post-tensioning strands to the joint panel. This arrangement would eliminate the need for separate anchorage hardware. However, transfer of the prestress from the strand to the concrete occurs over a distance from the end of the tendon referred to as the transfer length, l_t, as shown in Figure 5.7. The American Concrete Institute (ACI) recommends a value of 50 strand diameters for the transfer length (Ref 21). This value corresponds to a transfer length of 30 in. for 0.6 in. diameter post-tensioning strand. Because of this required transfer length, the prestress force transferred to the concrete is built up gradually over the transfer length, as shown in Figure 5.7. Thus, the full prestress force is not acting over the entire width of the joint panel. Having the full prestress force across the entire width of the joint panel is essential, considering the fact that the joint panel takes the most “abuse” under repetitive loading. Accordingly, anchoring the strands through bond is not a very practical method for anchoring tendons.

The use of anchorage hardware will ensure that the full prestress force is applied to the joint panel over the full width. Either a standard post-tensioning anchor or a modified version of standard anchorage can be used. Since there will be very limited, if any, access to the tendon anchorage after the precast panels are set in place, a self-locking or spring-loaded anchor will allow the strands to be inserted blindly into the anchor from some point along the pavement. This spring-loaded anchor, shown in Figure 5.8, is a combination of a standard post-tensioning anchor and a standard pretensioning chuck, commonly used in construction of prestressed concrete beams. This modified anchor has a bearing surface, similar to that of typical post-tensioning anchors, and spring-loaded wedges for gripping the strands, similar to those of typical pretensioning anchors.

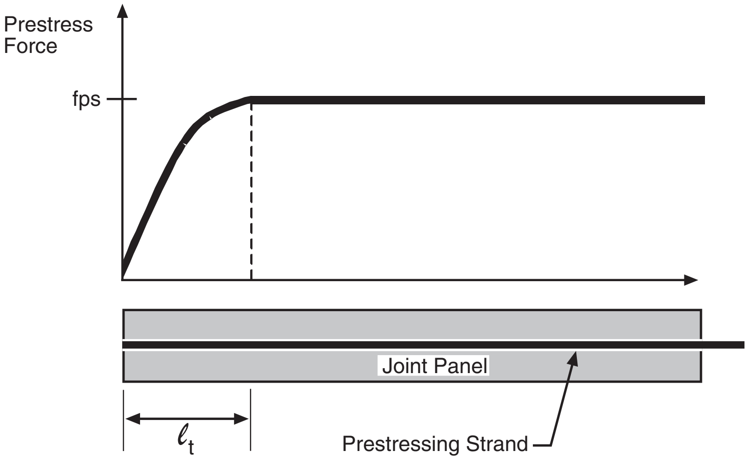


Figure 5.7 *Transfer length for transfer of prestress from the strand to the precast panel*

The modified anchor will be bolted to the bearing plates in the expansion joint to ensure that the anchor is properly positioned and stays in place while the concrete is cast in the joint panel. Bolting the anchor to the bearing plates will also cause the bearing plates to contribute to transferring the prestress to the concrete. A schematic diagram of what the expansion joint detail will look like with the modified anchor is shown in Figure 5.9. The anchors should be spaced such that they to not coincide with the dowel bars in the joint detail (Figure 5.6).

An alternative to using the modified tendon anchor is the use of a standard post-tensioning anchor. With a standard anchor, access to the anchor will be required in order to set the wedges after the strands are inserted. One way to accomplish this will be to anchor a short piece of the strand to the joint panel when the panel is fabricated, as discussed in Section 5.2.5. Like the modified anchor, the standard anchor will be bolted to the bearing plates in the expansion joint. A schematic of this concept is shown in Figure 5.10.

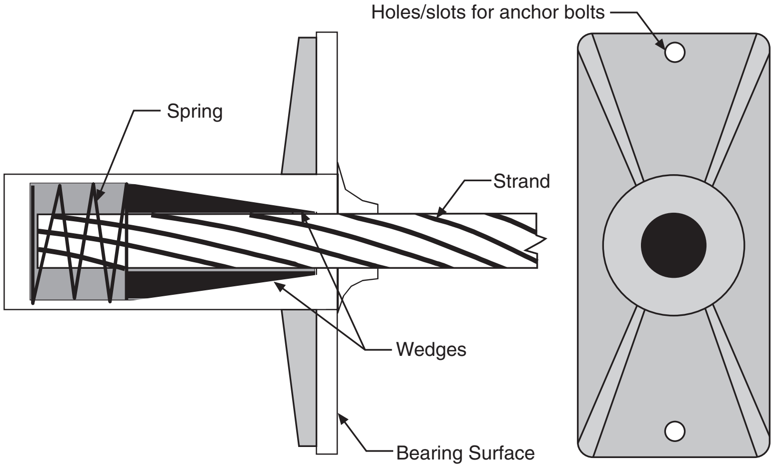


Figure 5.8 Spring-loaded post-tensioning anchor for precast pavements

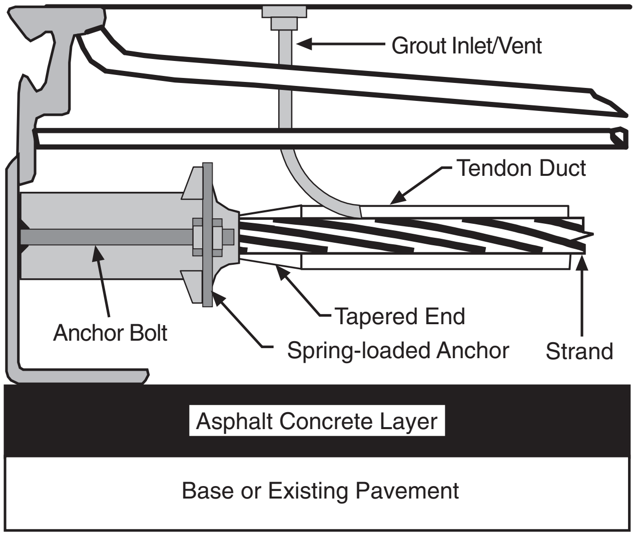


Figure 5.9 Spring-loaded post-tensioning anchor cast into the joint panel

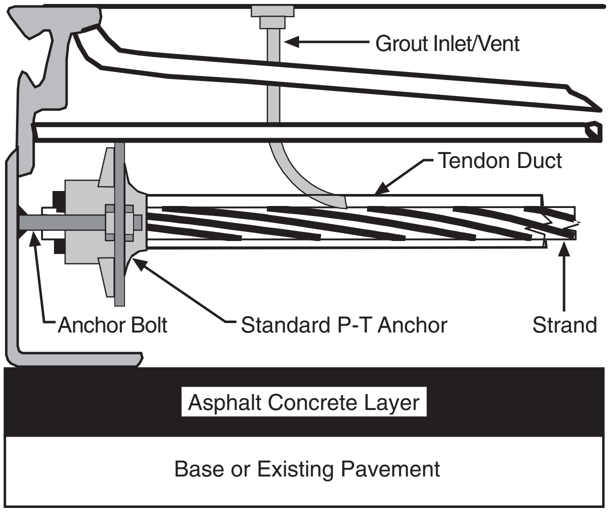


Figure 5.10 *Standard post-tensioning anchor cast into the joint panel*

5.5.3 Strand Placement

Owing to the length of the slabs that will be constructed, strand placement will, most likely, have to be completed after all of the precast panels are in place. The strands will be inserted at the central stressing pockets and threaded through the ducts to the anchorage. It may be necessary to thread a "fish" line (which is attached to the strand) through the ducts prior to inserting the strands so the strands can be pulled, rather than pushed, through the ducts. The procedure for anchoring the strands will be determined by the type of post-tensioning anchorage used.

If the modified anchor is used, the strands will be threaded through the ducts and pushed into the anchors from some point along the pavement section, most likely from the gap left between the joint panel and first base panel, as shown in Figure 5.11, or from pockets in the panel adjacent to the base panel, as shown in Figure 5.12. The tapered duct shown in Figure 5.9 will aid with inserting the strand into the anchor, since pushing the strand into the anchor will be done blindly.

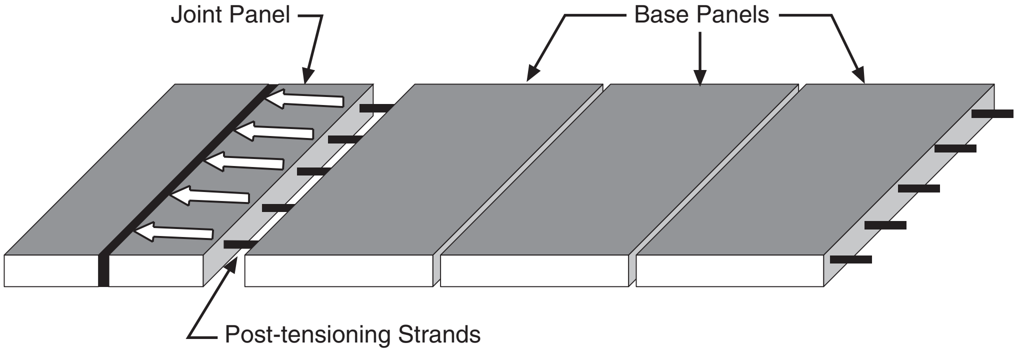


Figure 5.11 *Gap left between joint panel and base panel for inserting strands into the anchors*

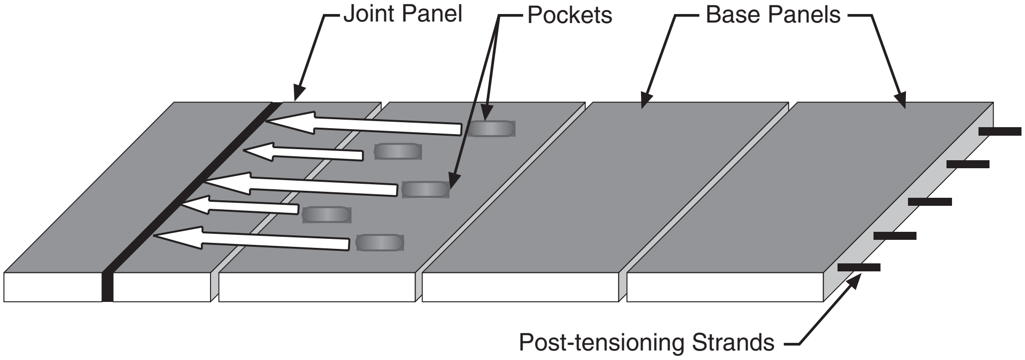


Figure 5.12 *Strands inserted into the anchors from pockets in the base panel*

If the standard post-tensioning anchor is used, short lengths of strand will be anchored to the joint panel during fabrication and will extend into pockets in the coupler panel, as discussed previously. The strands will then be threaded though the ducts from the central stressing pockets to the pockets in the coupler panel, where they will be spliced or coupled to the short lengths of strands. Strand stressing will then be performed in the usual manner.

5.5.4 Post-Tensioning

Post-tensioning must be performed prior to allowing traffic onto the pavement. If the pavement is not post-tensioned prior to exposure to traffic, the pavement will act as a nonprestressed pavement. Because the thickness of the prestressed panels is significantly less than that of an equivalent nonprestressed pavement, failure to post-tension could result in substantial damage to the pavement after only a small amount of exposure.

The post-tensioning strands will be stressed from the central stressing pockets at the center of the pavement slab. A portable hydraulic jacking device, similar to that used for circular tanks and which essentially stresses both strands coming into the central stressing pockets at the same time, may be used for the post-tensioning operation. The full post-tensioning force will be applied after all of the panels are set in place and have been pulled together. Stressing the strands should start with the tendons at the center of the slab and should alternate out to the tendons at the slab edges.

A coupler device, similar to that shown in Figure 5.13, will be used for stressing and coupling the strands in the central stressing pockets. This coupler device grips both strands coming into the pocket simultaneously. The stressing ram is used to pull one of the strands by reacting against the other strand, thus stressing both strands at the same time through the coupler device. This same coupler device can also be used to splice or couple the strands in the coupler pockets; alternatively, standard coupler chucks can be used. After all of the strands have been stressed, the stressing pockets and coupler pockets will be filled with a fast-setting concrete that will have attained to adequate strength by the time traffic is allowed onto the pavement. The pockets do not have to be filled immediately after the panels are post-tensioned; however, it should be possible to place temporary steel cover plates over the pockets until the pockets can be filled at a later time.

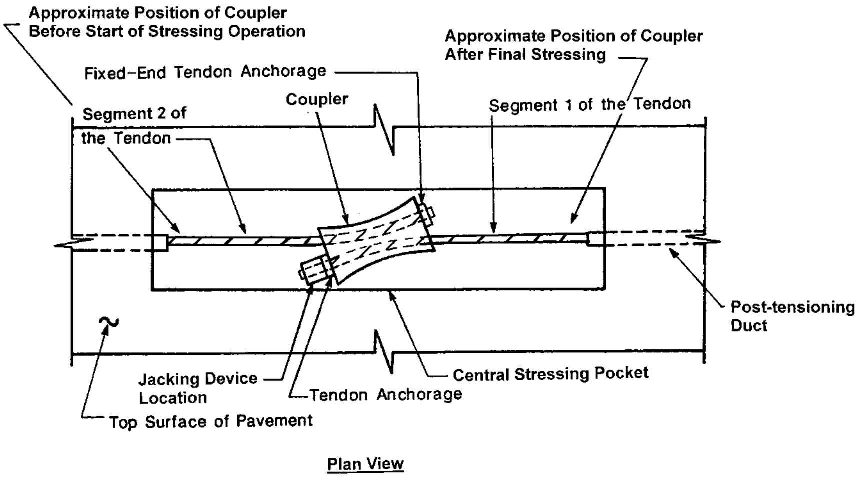


Figure 5.13 *Plan view of a strand coupler used in the central stressing pockets (Ref 6)*

5.6 GROUTING OF TENDONS

After the post-tensioning strands have been stressed, the strands will be grouted in the ducts. Grouting will bond the strands to the pavement, thereby providing continuity between the concrete and the strands, which will greatly reduce, if not eliminate, the amount of nonprestressed reinforcement required in the pavement. In addition, grouted tendons will prevent any damage or significant loss of prestress if a strand is inadvertently cut. Most importantly, however, the grout provides protection from strand corrosion. If grouting is done properly, the grout will provide protection from any water, which penetrates the pavement, from reaching the strands. This protection is especially important at the panel joints, where the duct is not continuous across the joint. The grout will help seal the duct across the joint and will protect the strands.

Grouting, like stressing pocket filling, does not have to be done at the time the strands are post-tensioned. For example, a section of pavement placed and post-tensioned one day does not have to be grouted before traffic is allowed back onto the pavement. The tendons could be grouted during placement of another section on the following day. Grouting does add additional cost and an additional process to the construction of a precast pavement, but the advantages of increased durability and corrosion protection will outweigh the added construction requirements.

Chapter 6. Design Considerations

6.1 INTRODUCTION

There are several design considerations that must be accounted for in order to develop a precast concrete pavement that maximizes performance during its design life. These factors affect both the durability and constructibility of a precast pavement. Durability is critical for ensuring a high-performance pavement that has a design life equivalent to, if not longer than, that of conventional pavements currently being constructed. Constructibility is a critical factor, as expedited construction is the main reason for using precast pavement. The methods used for construction must meet these expedited construction requirements.

Section 6.2 presents factors affecting the design of a precast pavement. These factors will primarily influence the durability of the pavement. In Section 6.3, design variables used to characterize the design factors are discussed. These variables will primarily influence the constructibility of the pavement and will differ for each job.

6.2 FACTORS AFFECTING DESIGN

Factors affecting the design of a precast pavement include design considerations, such as load repetition effects, temperature effects, and site geometry, that must be accounted for in any pavement design. To be considered also are those factors that are critical for prestressed (precast) concrete pavements, such as subgrade restraint, prestress losses, and joint movement. All of these factors should be taken into account, together, in the design of a precast pavement to ensure that the pavement will meet the durability requirements of a high-performance concrete pavement.

6.2.1 Load Repetition Effects

The critical stresses in concrete pavements are tensile stresses, since concrete is inherently weak in tension. Wheel loads cause tensile stresses in the bottom of pavement slabs, as shown in Figure 6.1. The magnitude of the tensile stress depends primarily on the supporting base structure beneath the slab and on the magnitude of the wheel load. Elastic layered theory can be used to determine these tensile stresses, given that the theory takes into account the layered base support structure beneath pavements slabs and the magnitude of wheel loads on the slab.

Wheel load stresses are increased at the edge of slabs owing to the lack of support from surrounding concrete. To account for these higher stresses, the wheel load stresses determined from elastic layered theory, on a semi-infinite slab, must be increased by a critical stress factor (CSF) for the slab edges. For a precast concrete pavement, where paved shoulders are provided, the CSF will be applied only near the end of the slab, at the expansion joint. For the purposes of analysis, a CSF of 1.3 is recommended for precast pavement stress analysis near the expansion joints based upon previous experience of the researchers.

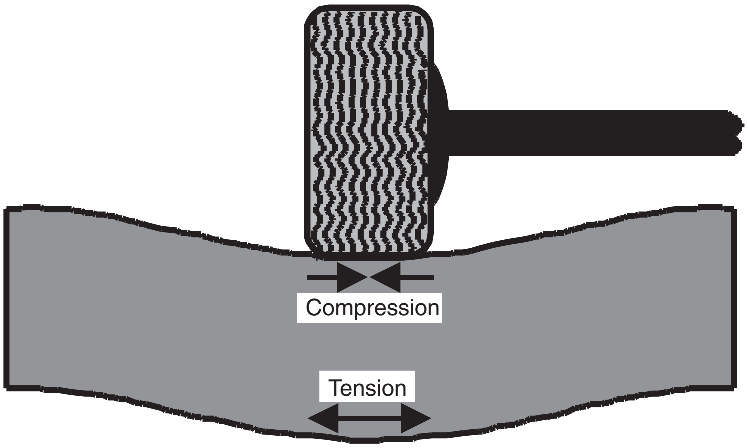


Figure 6.1 *Slab stresses generated from wheel load application*

The continual repetition of wheel loads, especially those from heavy trucks, tends to fatigue concrete pavements over time. Several factors, including the foundation strength and magnitude and number of wheel loads, will dictate the effects of these factors. However, these effects are fairly well understood for conventional concrete pavements, making it possible to design a pavement for a specified life based on given conditions.

To determine wheel load repetition effects, the magnitude and occurrence of various traffic loadings are converted to the total number of passes of the equivalent standard axle loading, usually the equivalent 18-kip single-axle load (ESAL). One of the most difficult aspects of quantifying the effects of load repetitions is predicting the number of ESALs the pavement will experience over its design life. This number is not a constant, as the volume of vehicles has been increasing exponentially on most major roadways each year. Methods do exist, however, for forecasting these numbers.

6.2.2 Temperature Effects

Temperature has a significant effect on any concrete pavement, but particularly on prestressed concrete pavements, where much longer slabs are generally constructed. Of primary concern are two effects of temperature on prestressed concrete pavement: horizontal slab movements (expansion and contraction) and slab curling. Expansion and contraction movements of prestressed pavement slabs are resisted by friction between the bottom of the slab and the base material. This frictional resistance causes stresses in the slab, which can be detrimental to the pavement. Expansion and contraction also affects the expansion joint widths between pavement slabs, which affects the ride quality of the pavement.

Slab curling is caused by temperature gradients across the depth of the slab. When a heat source is acting on the top of the slab (i.e., the sun), the ends of the slab tend to curl downward, as shown in Figure 6.2(a). However, the weight of the slab tends to counteract the curling movement, causing tensile stresses to form in the bottom of the slab. Conversely, when a heat source is acting on the bottom of the slab (i.e., the subbase), the ends of the slab tend to curl upward, as shown in Figure 6.2(b). Again, however, the weight of the slab counteracts the curling movement, causing tensile stresses to form in the top of the slab. The first condition occurs during the warmest part of the daily temperature cycle, usually in the late afternoon. The second condition occurs during the coolest part of the temperature cycle, usually at night and during the early morning hours when the subbase, which acts like a “thermic battery,” is warmer than the surrounding air owing to heat absorbed during the day. Therefore, a thorough analysis of the slab stresses resulting from daily and seasonal temperature cycles is required to ensure that the stresses generated from temperature effects do not exceed limiting values.

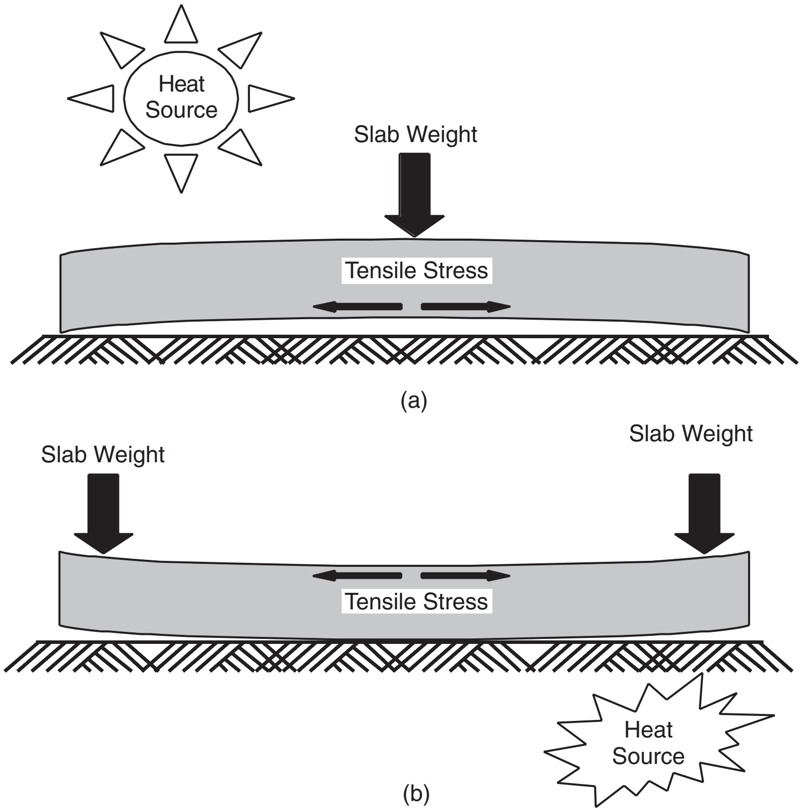


Figure 6.2 *Stresses caused by curling movements of concrete pavement slabs*

One advantage of precast pavement over conventional pavement, with respect to temperature effects, is the fact that construction curl does not need to be accounted for. Construction curl in conventional pavements is due to a temperature gradient over the depth of the pavement at the time of final set. Several factors affect this temperature gradient (and, hence, stresses resulting from construction curl), including ambient temperature at placement, heat of hydration of the cement, and thermal conductivity of the pavement (Ref 48). Each of these factors must be carefully considered with conventional pavement construction so that excessive early-age curling stresses, which can cause premature pavement distresses and significantly decrease pavement life, are not experienced. These factors are particularly critical during “hot weather concreting” and “cold weather concreting.” Because precast panels can be cast in a controlled environment prior to their placement, construction curl is not an issue. This advantage will allow for more flexibility with placement of a precast pavement under extreme hot and cold temperature conditions.

6.2.3 Moisture Effects

Like temperature gradients in pavements, moisture gradients can cause warping-induced stresses in pavements. In general, moisture gradients are such that the bottom of the pavement has a higher moisture content than does the top of the pavement owing to the ease with which moisture can escape from the top surface of the pavement. This moisture gradient will result in curling similar to that shown in Figure 6.2(b), with tensile stresses induced in the top of the slab and compressive stresses induced in the bottom of the slab. For prestressed pavements, this effect is beneficial at mid-slab, where compressive stresses in the bottom of the pavement tend to counteract tensile stresses from frictional slab-base restraint (discussed below) and wheel loading. On the other hand, this effect can be detrimental at the top surface near the ends of the slab, where additional tensile stresses from thermal curling are present during the cooler part of the daily temperature cycle (Ref 49). Owing to the fact that precast panels will generally be able to "dry out" after they have cured and been removed from the casting bed, precast pavements should have very small, if any, moisture gradients over the depth of the pavement. Moisture gradients can further be minimized in precast pavements by ensuring low permeability of the concrete, so that surface moisture (from precipitation) does not migrate too deeply into the pavement, thereby creating a moisture gradient opposite of what was discussed previously. Permeability can be controlled much more closely during fabrication of precast elements than during placement of conventional pavement.

Another consideration, with respect to moisture effects in pavements, is shrinkage. In conventional pavements, rapid moisture loss at early ages can cause shrinkage cracking, which can lead to spalling and premature pavement failure (Ref 48). In cast-in-place prestressed pavements, shrinkage also results in prestress losses, requiring additional initial prestress to account for these effects. In a precast pavement, however, shrinkage occurs during casting and curing of the panels and can be easily controlled using standard curing techniques for precast elements. Additionally, virtually all of the shrinkage will occur in the precast panels prior to setting them in place and post-tensioning. This fact will essentially eliminate any prestress losses caused by shrinkage. Therefore, while moisture effects can be very significant in conventional pavements and cast-in-place pavements, they should have a very minimal effect on precast pavement design.

6.2.4 Subbase Restraint

As mentioned in Section 6.2.2, daily and seasonal temperature cycles cause concrete pavements to expand and contract. These horizontal movements are resisted at the interface of the bottom of the slab and the surface of the subbase. In long, prestressed (precast) pavement slabs, this resistance can be very significant.

The frictional resistance at the subbase interface is the result of three components: bearing, adhesion, and shear (Ref 23). These components are shown in Figure 6.3. Bearing force is the weight of the slab on the subbase. Its direction is dependent on the subbase surface roughness, moisture condition, and temperature. Adhesion is the attraction the slab experiences relative to its subbase. Its magnitude is also dependent on the moisture condition and temperature of the subbase. The shear component is dependent on the rubbing characteristics of the two materials in contact when movement begins. It is also dependent on the magnitude and direction of the bearing component. It is possible for the combined forces of these three components to be such that the frictional restraint at the interface exceeds the internal strength of the subbase layer, resulting in failure of the subbase (Ref 24).

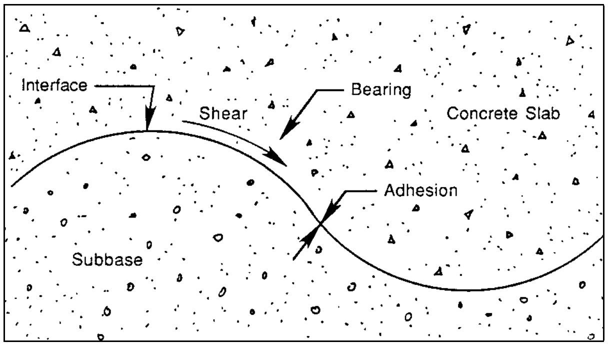


Figure 6.3 *Three components of frictional resistance under concrete pavements (Ref 23)*

Numerous experiments over the years have shown that the relationship between frictional resistance and horizontal slab movement is inelastic (Ref 25). The resistance force versus movement curve for most subbase materials is defined by two major factors: (1) the elastic properties of the material beneath the slab and (2) the condition of the sliding plane and the nature of the materials at the interface. The first factor defines the slope and shape of the curve before sliding. The second defines the peak resistance and the shape of the curve after sliding is reached. This relationship is shown in Figure 6.4.

The relationship between slab movement and subbase resistance can be categorized in three ways:

- **Movements partially restrained by subbase resistance:** movements produced by daily temperature changes
- **Movements unrestrained by subbase resistance:** concrete swelling, shrinkage, and creep
- **Movements temporarily restrained by subbase resistance:** elastic shortening, which is diminished by the friction when the prestress force is applied, but which affects the full slab length shortly after prestressing

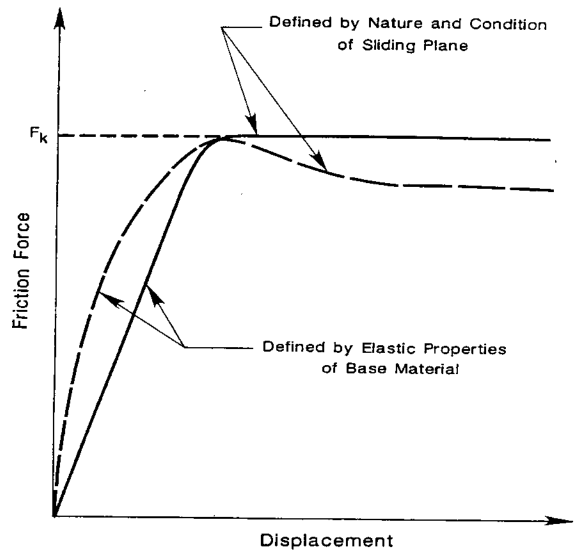
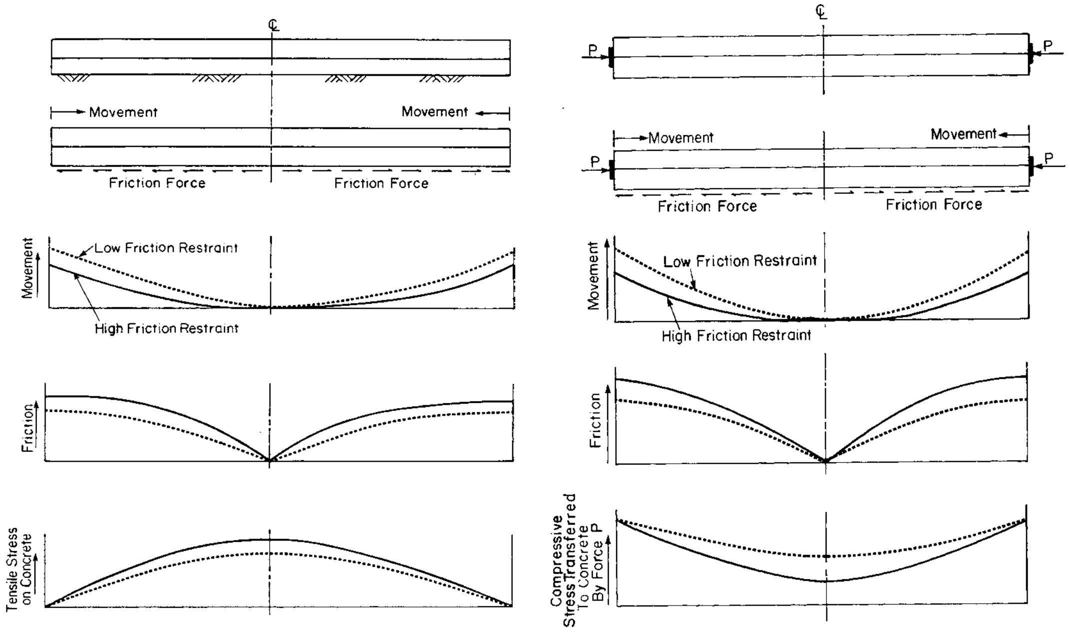


Figure 6.4 *Frictional resistance versus movement for concrete pavements (Ref 25)*

Because long-term movements from seasonal temperature changes occur at minute daily rates, as compared to daily temperature movements, they therefore take place without significant frictional resistance. Frictional resistance to movements from daily temperature changes, however, produces stresses in the slab. Compressive stresses will develop when the slab expands, while tensile stresses will develop when the slab contracts. The latter situation is more critical, as these tensile stresses may be additive to those tensile stresses caused by wheel loads and curling to such an extent that the slab may crack (Ref 25).

Movement of concrete pavement slabs caused by temperature variation decreases from a maximum at the slab ends to zero movement at the center. Likewise, frictional resistance also decreases from a maximum at the ends to zero at the center. The result is tensile stresses (for slab contraction) increasing from zero at the ends to a maximum at the center. This relationship is illustrated in Figure 6.5(a).

In a prestressed (post-tensioned) pavement, frictional resistance has another effect. Frictional resistance causes a decrease in the amount of compressive stress transferred to the concrete from post-tensioning. This effect is illustrated in Figure 6.5(b). The reduction of post-tensioning force along the slab requires that a higher post-tensioning force be applied at the ends of the slab.



(a) (b)

Figure 6.5 Effects of frictional restraint on (a) normal PCCP slab, (b) prestressed PCCP slab (Ref 23)

To reduce the effect of subbase frictional resistance, which causes tensile stresses in the pavement and reduces the amount of prestress transferred to the concrete during post-tensioning, a friction-reducing membrane is placed beneath prestressed pavements to lower the coefficient of friction between the pavement slab and supporting base.

The three main considerations in selecting a friction-reducing medium are the following (Ref 23):

- Efficiency in reducing restraint
- Practicability for road construction
- Economics

Previous research and experience have found a single layer of polyethylene sheeting to be a very practical friction-reducing medium for meeting these requirements. The use of this material will be discussed in more detail in Chapter 8.

An additional consideration, with regard to subgrade restraint, is that the bottom of precast panels will be very smooth, unlike that of a cast-in-place prestressed pavement, in which the concrete conforms to the roughness of the base surface. The precast panels will also be very rigid, spanning small voids in the leveling course, thereby reducing the contact are between the bottom of the slab and supporting layer. These effects will result in a reduction of the shear effect, described previously, at the slab-base interface.

6.2.5 Prestress Losses

Prestress losses are an important consideration in post-tensioned (precast) pavements, as the strength of the pavement relies on the precompression in the concrete from post-tensioning. These losses must be accounted for in order to ensure that the required prestress level is maintained over the length of the slab over the design life of the pavement. Losses of 15 to 20% of the applied prestress force can be expected for a carefully constructed post-tensioned concrete pavement (Ref 6). The factors that contribute to prestress losses include:

- elastic shortening of the concrete
- creep of the concrete (shrinkage is not a factor for precast pavements)
- relaxation of the stressing tendons
- slippage of the stressing tendons in the anchorage
- friction between the stressing tendons and ducts
- frictional resistance between the slab and base material

Extensive testing and experience in the prestressed concrete practice have produced methods to reliably predict the effects of these factors. A detailed discussion of the relationships that have been developed through research and experience for each of these factors can be found elsewhere (Ref 6).

6.2.6 Transverse Prestress

Transverse prestress is an essential component of any prestressed (precast) concrete pavement. An extensive investigation of four prestressed pavements constructed in the United States, prior to the development of the prestressed pavement constructed in McLennan County (Chapter 2), found that a lack of transverse prestress in those pavements resulted in extensive longitudinal cracking after exposure to traffic (Ref 6). Therefore, it is essential that transverse prestress be incorporated in a precast pavement.

Owing to the relatively short width of prestressed pavements (transverse direction), as compared to the length, the effects of prestress losses, particularly subgrade restraint and slab curling, are minimal, as compared to the longitudinal direction. One of the advantages of a precast concrete pavement is that the prestress for the transverse direction can be obtained through pretensioning, during fabrication of the panels. In addition, pretensioning will prevent cracking from occurring during handling of the panels, as mentioned in Chapter 4. In general, the handling stresses will usually govern the magnitude of the required transverse prestress.

6.2.7 Joint Movement

Horizontal slab movements, owing to expansion and contraction of prestressed (precast) concrete pavement slabs caused by daily and seasonal temperature cycles, result in movement of the expansion joints between slabs. These joint movements can become fairly substantial, depending on the length of the slabs. As the slab length increases, so too does the amount of horizontal slab movement (and, hence, the expansion joint movement). In general, the expansion joint width requirements usually govern the permissible slab length.

In order to prevent damage to the expansion joint and the possible crushing of the concrete at the joint, the expansion joints should never be fully closed. Thus, an initial joint opening must be provided when the pavement is constructed. This initial joint width will be different, depending on the design slab length and the time of year that the pavement is constructed. For example, a pavement constructed in the winter will experience more expansion than a pavement constructed in the summer and will consequently require a larger initial joint width during construction. To ensure good ride quality, it is desirable to ensure that the maximum joint width will be less than 4 in. As with the minimum joint width, this maximum joint width will depend on the slab length and time of year when the pavement is constructed.

Expansion and contraction movements are well understood and can be fairly accurately predicted for given conditions. Conditions that affect expansion and contraction movements include the amount of prestress in the pavement, type of friction-reducing medium beneath the slab, coefficient of thermal expansion of the concrete, and the length of the slab. It is essential that these movements be calculated prior to slab construction using given conditions so that the limiting joint width requirements are met.

6.2.8 Site Geometry

Another important design consideration for precast pavements is ensuring that rectangular precast concrete panels will be able to conform to the geometry of a roadway with vertical and horizontal curves. In order to determine the effects of horizontal and vertical curves, the 1994 AASHTO publication, "A Policy on Geometric Design of Highways and Streets," may be used to determine the minimum expected horizontal and vertical curves for a given design speed. The angle created between the adjacent precast panels can then be computed by using geometric relationships, as will be demonstrated in Chapter 7.

6.3 DESIGN VARIABLES

With an understanding of the factors affecting the design of precast concrete pavement, it is now possible to consider the physical design variables that will be part of the actual design. Important design variables that must be considered include foundation strength, pavement thickness, section length, section width, and magnitude of prestress.

6.3.1 Foundation Strength

The relationship between the foundation strength and the performance of conventional concrete pavements is fairly well understood. However, these relationships are not as well known for prestressed concrete pavements owing to the limited number of prestressed pavements — and even fewer precast pavements — that have been constructed. Therefore, the design of a precast concrete pavement will assume the relationships associated with a conventional concrete pavement. Two of these relationships are as follows (Ref 6):

1) The stress in a pavement for a given load is inversely proportional to the strength of the supporting foundation.
2) The ability of the pavement to withstand repetitive loads is proportional to the strength of the supporting foundation.

The first relationship implies that, as the supporting foundation becomes weaker, the stresses generated in the pavement by wheel loads will increase. This action will result in cracking and failure of a pavement on a weaker supporting foundation earlier than it will on a pavement on a stronger supporting foundation. The second relationship implies that a pavement with a weaker supporting foundation will fatigue and eventually fail faster than a pavement with a stronger supporting foundation.

Methods such as cement stabilization have been developed and used extensively for increasing pavement foundation strength. However, since the main purpose of using precast concrete panels is to expedite construction of pavements, it may not be practical to strengthen the existing foundation during precast construction. Fortunately, the prestress level can be adjusted to account for lower foundation strengths.

6.3.2 Pavement Thickness

Thickness of conventional concrete pavements is generally governed by foundation strength, concrete strength, and the number and magnitude of wheel load repetitions. For a prestressed (precast) concrete pavement, however, there is more flexibility with the pavement thickness. In most cases, it is possible to simply select a desired pavement thickness and adjust the amount of prestress in the pavement to meet the design criteria. Although the relationship between foundation strength and pavement performance is not very well understood for prestressed (precast) concrete pavements, these design criteria will be assumed to be the same as that mentioned above, for conventional pavements.

A reasonable limit for precast pavement thickness seems to be a thickness not less than 50 to 60% of the thickness that would be used for a conventional concrete pavement. At the same time, the thickness should be such that sufficient cover is provided for all of the reinforcement and other hardware (such as anchorage) contained in the pavement. As the thickness is reduced, stresses should be evaluated in the lower layers of the pavement structure to ensure that they are at acceptable levels.

6.3.3 Magnitude of Prestress

The magnitude of prestress refers to the prestress force applied to the pavement from pretensioning or post-tensioning. The magnitude of prestress varies along the length of the pavement owing to prestress losses, as described earlier in this chapter. The magnitude of prestress must be such that the compressive stress at all points along the length and width of the pavement is greater than or equal to the minimum compressive stress required to meet the fatigue requirements over the life of the pavement. The fatigue requirements are a function of the number of load repetitions and foundation strength. These requirements will be discussed further in Chapter 7.

The compressive stress at any point along the length of the pavement can be expressed as a critical stress combination, which accounts for the magnitude of the applied prestress, stress generated by applied wheel loads, curling stress resulting from temperature differential over the depth the slab, and friction stress caused by subbase resistance. This critical stress combination is given by Equation 6.1 below:

$$\sigma_{CR} = \sigma_P + \sigma_W + \sigma_C + \sigma_F \tag{6.1}$$

where: σ_{CR} = critical stress combination, (+) = Tension, (-) = Compression

σ_P = effective prestress at the critical location

σ_W = stress generated by applied wheel load

σ_C = curling stress caused by temperature differential through the slab

σ_F = friction stress caused by slab-base interaction

Stresses are different in the top and bottom of the slab, requiring both the top and bottom to be analyzed. Curling stresses are assumed to be equal and opposite (tensile [+] versus compressive [-]) in the top and bottom of the slab. Stresses caused by applied wheel loads are assumed to be tensile (+) in the bottom of the slab, and zero in the top (although compressive stresses would actually be expected). Friction, from slab-base interaction, causes both tensile (+) and compressive (-) stresses, depending on the movement of the slab, and is assumed to be uniform over the pavement depth. Although these stresses vary along the length of the pavement, essentially the only two points at which the stresses must be evaluated are at the ends of the slab and at mid-slab.

6.3.4 Section Length

Section length is the length of the pavement slab between expansion joints. Each section will consist of several precast panels tied together through post-tensioning, as described in Chapter 5. As mentioned earlier in this chapter, the section length will be primarily governed by the expansion joint width requirements. As the section length is increased the amount of slab expansion and contraction (caused by temperature cycles) also increases, causing wider (or narrower) expansion joint widths.

There are several factors to consider with regard to the section length. The first factor is that the cost of the expansion joints is inversely proportional to the slab length. As the slab lengths are decreased, the number of expansion joints, which are a significant cost component of prestressed (precast) concrete pavements, increases. Another factor is that the magnitude of prestress, and hence the cost of prestressing, increases as the section length is increased. In conjunction with this consideration is the fact that as the section length is increased, the maximum expansion joint widths also increase, thereby affecting the ride quality of the pavement. Therefore, a compromise must be sought between economics and quality of the final product, in order to select the optimal section length.

6.3.5 Section Width

Section width refers to the distance between the exterior edges of the finished pavement (transverse direction). Section width is governed by several factors including:

- pavement application
- equipment limitations
- public traffic accommodation

Pavement application refers to the type of pavement that will be constructed. This could be a single-lane or multi-lane pavement. If a one- or two-lane pavement is to be constructed, it may be possible to use precast panels that are the full width of the pavement. If more than two lanes are to be constructed, multiple precast panels may be required to cover the full section width, as described in Chapter 4.

Equipment limitations refer to the size of precast panels that can be accommodated. It will be advantageous to use precast panels that are the full width of the pavement, to eliminate longitudinal joints. However, this may result in the use of very large precast panels, and equipment limitations may be encountered during fabrication, transportation, or placement of these panels.

Public traffic accommodation refers to the permissible traffic diversion during construction. For a pavement placed on a roadway that is near or over its design capacity, it may only be possible to divert traffic off of one lane at a time for construction. In this case, the finished pavement would consist of multiple "strips" of precast panels (removal and replacement). If full diversion of traffic is possible, precast panels that cover the full section width should be used.

Additional consideration must be given to the pavement shoulders. If possible, it is desirable to construct a precast pavement in which the shoulders are included in the section width, as discussed in Chapter 4. In this way, traffic will always be on the interior of the precast panels, and the increased stress levels caused by edge loading will not be a concern.

Chapter 7. Feasibility Analysis: Design

7.1 INTRODUCTION

This chapter is the first of three chapters in which the recommended concept presented in Chapter 5 is evaluated. The proposed concept utilizes full-depth, precast concrete panels that are pretensioned in the transverse direction during fabrication, and post-tensioned in the longitudinal direction after they have been set in place on a single layer of polyethylene sheeting over a thin asphalt leveling course. Three types of panels are used between consecutive expansion joints in order to form a continuous slab when they are all post-tensioned together. These panel types consist of joint panels at the ends of the slab, a central stressing panel in the center of the slab, and base panels between the joint and central stressing panels.

Although precast pavement construction will have many advantages over conventional pavement construction, such as speed of construction, increased durability, and reduction in user costs, in order for a precast concrete pavement to truly be a feasible alternative to conventional concrete pavement it must have a design life at least equivalent to that of conventional pavement. Incorporated in this equivalent design is elastic design for fatigue loading, and elastic design for environmental stresses and wheel loads. Ultimately, the pavements must be constructed side-by-side to compare their performance under the same conditions. For now, however, this analysis will show that it is possible to design a precast concrete pavement using accepted design procedures so that the pavement has a design life equivalent to that of a conventional pavement but which requires a significantly reduced pavement thickness.

7.1.1 Equivalent Pavement

The primary basis for developing a precast pavement having a design life equivalent to that of conventional pavements is through the elastic design for fatigue. Fatigue loading design takes into account the effect of repeated load applications on the pavement over its design life. A continuously reinforced concrete (CRC) pavement was selected as the control pavement for comparison. A CRC pavement was selected primarily because CRC pavements are commonly being constructed on major highways, including one designed by CTR currently under construction on I-35 in TxDOT's Waco District. It should be noted, however, that the same procedures can also be used to develop a precast pavement with a design life equivalent to that of a jointed reinforced concrete pavement (JRCP).

The control CRC pavement was designed with the following design parameters, using the existing base conditions along a section of I-35 in the Waco District:

- Design Life: 30 years
- ESAL applications: 127 million
- Concrete tensile strength: 700 psi
- Concrete modulus of elasticity: 4,000 ksi

A design life of 30 years is typical for pavements currently being constructed and is essential for pavements constructed on heavily trafficked roadways. The number of ESAL applications, for the 30 year design life, was determined from regression models developed at CTR for forecasting the expected number of 18-kip ESALs in the design lane, given an expected growth rate (Ref 26). The concrete tensile strength and modulus of elasticity are 28-day values typically used for concrete pavement design.

Based on the design criteria and on the existing base conditions where the pavement is being constructed, a pavement thickness of 14 in. was selected for the control CRC pavement (Ref 27). Under the same design criteria and base conditions, a pavement thickness of 15 in. would be required for a JRCP.

7.1.2 Design Procedure

The first step in the design procedure was to determine the prestress requirements for a precast pavement of varying thickness, based upon the elastic design for fatigue loading. The fatigue loading design criteria were determined from an equation developed by Taute (Ref 28), which relates the number of 18-kip ESALs to the ratio of the concrete flexural strength over the tensile stress at the bottom of the pavement. This relationship will be discussed in more detail in Section 7.2.

The second step in the design procedure was to determine, for a selected pavement thickness and slab length, the prestress force (to be applied from post-tensioning) needed to meet the prestress requirements from fatigue loading, taking into account environmental stresses and wheel loads. This step was carried out for both minimum and maximum expected slab lengths to get an upper and lower bound on the prestress requirements. This step was also performed for various weather (summer versus winter) conditions to determine under which conditions the critical stress combination (Eq. 6.1) would occur.

The third step was to select a slab length to meet the expansion joint width requirements. For a selected slab thickness and corresponding prestress, the length of the slab was varied (between the minimum and maximum expected slab lengths) to determine the minimum and maximum expansion joint widths. From this, an optimal slab length was selected based on the weather condition at the time of placement.

7.2 ELASTIC DESIGN FOR FATIGUE LOADING

For a given slab support structure, the tensile stress generated in the bottom of the pavement by wheel loading will increase as the pavement thickness is decreased. Prestressing, which induces a compressive stress in the concrete, is used counteract this increase in tensile stress. Therefore, as the thickness of the pavement is decreased, the tensile stresses, and hence the required prestress, increase. With this in mind, the basis for the fatigue loading design was to design a precast pavement with the same bottom fiber tensile stress, as compared to the 14 in. thick CRC control pavement.

7.2.1 Slab Support Structure

The tensile stress generated in the bottom of the pavement by wheel loads can be determined through elastic layered theory. Elastic layered theory takes into account the contribution of all supporting layers beneath the pavement based on the thickness, elastic modulus, and Poisson’s ratio of each layer. The slip condition between the pavement and the layer directly beneath the pavement is also taken into account.

The CRC control pavement was designed for the existing conditions of a section of I-35 in McLennan County, Texas. The layer properties for this section were estimated through the backcalculation of the elastic properties of the pavement layers from the deflections measured from a falling weight deflectometer (FWD). For this analysis, the elastic moduli of the subbase layers were based on the results obtained during the backcalculation of the resilient modulus.

The resulting support structure and loading, used for the elastic layered theory analysis of the control CRC pavement, are shown in Figure 7.1. The pavement structure was assumed to be loaded by a 20 kip ESAL with a tire pressure of 125 psi. Two slightly different support structures were analyzed in order to account for the variability in the support conditions where the CRCP control section is being constructed. The difference in the two pavement structures is the elastic modulus of the asphaltic concrete pavement (ACP) layer. A moderate elastic modulus of 1,042 ksi was selected for one analysis, and a low elastic modulus of 780 ksi was selected for the second analysis. The layered structure below the ACP represents the worst conditions that were found where the CRC pavement is being constructed. Such conditions will provide somewhat conservative results.

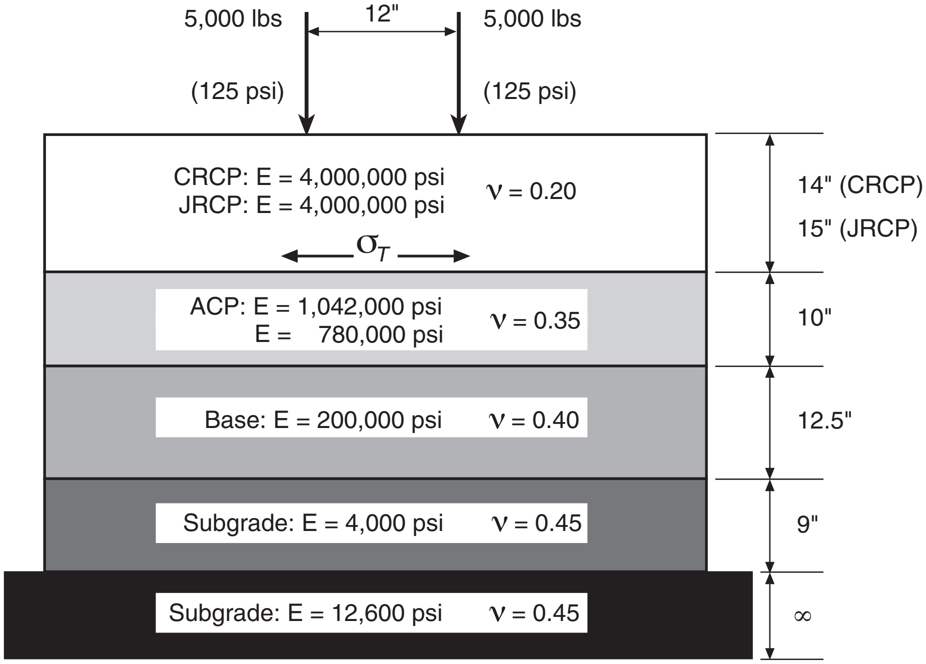


Figure 7.1 *CRC pavement structure analyzed using elastic layered theory*

The tensile stress, σ_T, generated at the bottom of the 14 in. CRC control pavement, for the given support structure and loading, was determined through the use of the elastic layered theory computer program BISAR (Bitumen Structures Analysis in Roads). The stress was computed directly beneath the loads and at the midpoint between the loads to determine the highest stress for the loading condition. The amount of slip between the ACP layer and the CRCP was varied to represent the presence of a friction-reducing membrane between the two layers (for the precast concrete pavement). The different slip conditions analyzed were: frictionless slip, half slip, “1/4 slip” or 75% cohesion, and no slip. Table 7.1 shows the different values for the tensile stress in the bottom of the 14 in. CRC control pavement for these different conditions.

Table 7.1 *Bottom fiber tensile stress (σ_T) at the bottom of the 14 in. CRC pavement for various support conditions*

	Bottom tensile Stress, σ_T (psi)	
Slip Condition	***E_{ACP}=1,042 ksi***	***E_{ACP}=780 ksi***
Frictionless Slip	49.9	51.4
Half Slip	46.2	47.8
1/4 Slip	42.1	44
No Slip	25.8	30.5

The same pavement structure, shown in Figure 7.1, was used to determine the tensile stress at the bottom of an equivalent precast concrete pavement of varying thickness for the same loading conditions. Only the "frictionless slip" condition was analyzed, however, as this was shown to be the critical case from the analysis of the 14 in. control pavement. This analysis will result in somewhat conservative results, as there will always be some amount of friction between the actual pavement and the supporting structure. Figure 7.2 shows the tensile stresses versus pavement thickness that resulted from this analysis. These stresses will be used to determine the prestress requirements for the fatigue loading design.

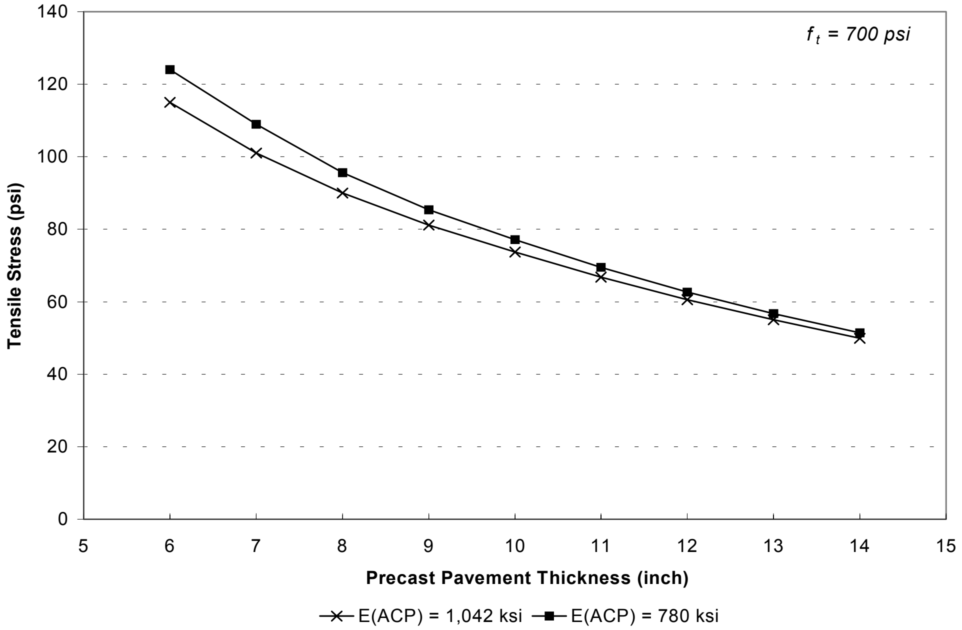


Figure 7.2 *Bottom fiber tensile stress versus precast concrete pavement thickness as determined from elastic layered theory*

7.2.2 Prestress Requirements

The philosophy for the fatigue loading design was to keep the ratio, R_e, of the bottom fiber tensile stress (from layered theory analysis) over the flexural strength equal to that of the control CRC pavement. In keeping this ratio constant, the performance of the pavements under repeated loading should be equal, producing pavements of equivalent life. This methodology is based on the fatigue relationship presented in the following equation (Ref 28):

$$N_{18} = 46{,}000\left(\frac{f}{\sigma_T}\right)^{3.00} \tag{7.1}$$

where: N_{18} = Number of 18-kip ESALs to serviceability failure
f = Concrete flextural strength (psi)
σ_T = Bottom fiber tensile stress from wheel loading

To determine the fatigue stress ratio, R_e, for a precast pavement, the required prestress (σ_{PR}) was subtracted from the bottom fiber tensile stress, obtained from layered theory, as shown below:

$$R_e = \left(\frac{\sigma_T - \sigma_{PR}}{f}\right) \tag{7.2}$$

where: R_e = fatigue stress ratio
f = concrete flexural strength (psi)
σ_T = bottom fiber tensile stress in the precast pavement
σ_{PR} = required prestress (psi)

Using a flexural strength of 700 psi, the required prestress, (σ_{PR}), was backcalculated using the fatigue stress ratio from the CRC control pavement and the tensile stresses, calculated using layered theory, for each precast pavement thickness. The results of this analysis are shown in Figure 7.3 (E_{ACP} = 1,042 ksi) and Figure 7.4 (E_{ACP} = 780 ksi).

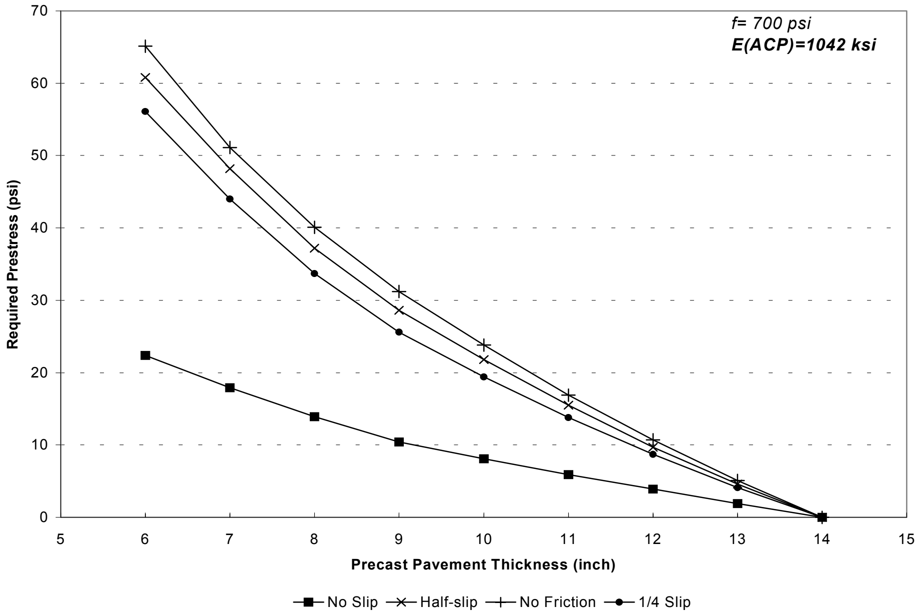


Figure 7.3 *Required prestress for various precast pavement depths for* E_{ACP} *= 1,042 ksi*

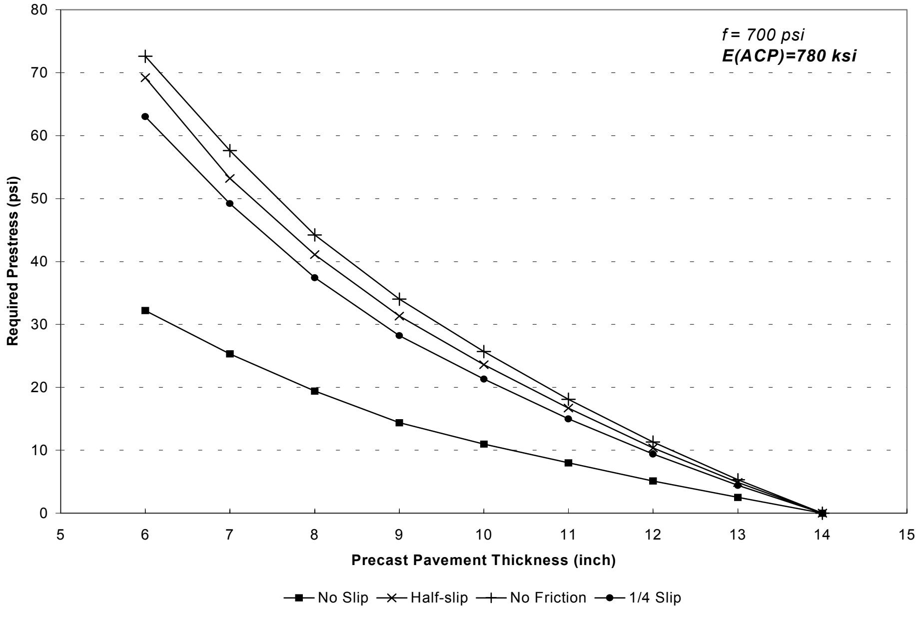


Figure 7.4 *Required prestress for various precast pavement depths for* E_{ACP} *= 780 ksi*

The required prestress (σ_{PR}) shown in Figures 7.3 and 7.4 is, therefore, the minimum compressive stress required at every point along the pavement to produce a precast concrete pavement with a design life equivalent to that of the 14 in. CRC (15 in. JRC) control pavement. The actual applied post-tensioning force, as determined from the elastic design for environmental stresses and wheel loading (discussed below), will be significantly higher than the required prestress (σ_{PR}), however, owing to prestress losses that occur within the pavement.

7.3 ELASTIC DESIGN FOR ENVIRONMENTAL STRESSES AND WHEEL LOADS

Elastic design for environmental stresses and wheel loads deals primarily with design considerations specific to prestressed (precast) concrete pavements. Environmental stress design is used to determine (1) the prestress that must be applied at the ends of the slab during post-tensioning and (2) the section (slab) length for a given pavement thickness. This is accomplished by taking into account prestress losses, curling stresses, stresses generated from slab-base interaction, and expansion joint movement.

A very useful tool for environmental stress design is the computer program PSCP2, which was created specifically for the design of prestressed pavements. The PSCP2 computer program provides a quick and effective method for determining the critical stress combination (Equation 6.1) by taking into account not only concrete and steel properties, but also such external conditions as temperature and slab-base interaction.

7.3.1 PSCP2 Program

Through the use of PSCP2, the pavement thickness, slab length, and required prestress were determined for the equivalent precast concrete pavement using typical temperature conditions, concrete properties, and steel properties. PSCP2 takes into account geometric properties of the pavement, concrete properties, steel properties, slab-base interaction, and daily temperature cycles. The program uses these inputs to determine prestress losses, frictional stresses, curling stresses, and horizontal slab movements.

PSCP2 was used successfully for the design of the cast-in-place prestressed concrete pavement constructed in McLennan County, Texas, in 1985 (Chapter 2). The program was later calibrated using actual data collected from the finished pavement. Because PSCP2 was created for cast-in-place prestressed concrete pavements, however, it was necessary to “trick” the program to take into account the differences of a precast pavement.

7.3.1.1 PSCP2 Inputs

The inputs for the PSCP2 program include geometric properties, concrete properties, steel properties, prestress, slab-base interaction, and daily temperature cycles. Each of these inputs will be described below.

Geometric Properties

The geometric inputs for the PSCP2 program include the slab (section) length (between expansion joints), slab (section) width, and slab thickness.

Concrete Properties

The concrete properties include the coefficient of thermal expansion, the ultimate shrinkage strain, unit weight, Poisson’s ratio, creep coefficient, and age-compressive strength relationship. As mentioned previously, it is necessary to “trick” the program to account for the differences of a precast pavement. This trick can be accomplished by specifying a very low ultimate shrinkage strain and a very high early-age strength (age-compressive strength relationship) to account for the fact that the concrete will already be cured and up to full strength by the time the precast panels are placed.

Steel Properties

The steel properties include the strand cross-sectional area, yield strength, elastic modulus, and thermal coefficient. The spacing of the strands, which dictates the amount of prestress applied to the slab, is also specified. The strand spacing is varied to adjust the amount of prestress in the pavement (to meet the fatigue requirements).

Prestress

The PSCP2 program allows for multiple-stage post-tensioning. This process is essential for cast-in-place prestressed pavements for which it is essential to apply an initial prestress within the first several hours after concrete placement to prevent shrinkage cracking. For a precast concrete pavement, however, only one stage of post-tensioning is required. The program allows for specification of the amount of prestress (per strand) and the number of hours after placement at which the prestress is applied. Prestress is specified by varying the spacing of the post-tensioning strands and the prestress force applied to each strand.

Slab-Base Interaction

The slab-base interaction inputs include the friction-displacement relationship and the stiffness of the slab support. The friction-displacement relationship can be specified as either a linear, multi-linear, or exponential relationship between the coefficient of friction between the slab and the base, and the corresponding displacement.

Analysis Period

The analysis period input specifies the number of days after placement the pavement is to be analyzed. The program automatically analyzes the pavement for the first 24 hours. It also allows for specification of multiple analysis periods beyond the first 24 hours in order to examine the stresses and end movements occurring during the pavement design life. An analysis period near the end of the expected design life should be specified, at minimum.

Temperature

Temperatures are usually specified for the first 24 hours after placement and for any future analysis periods. Mid-depth slab temperature, top-bottom temperature differential, and the time of day are all specified. The concrete setting temperature is also specified. For a precast concrete pavement, the setting temperature will be the temperature of the concrete at the time the precast panels are placed.

Wheel Load Stress

While the wheel load stress is not a direct input into the PSCP2 program, it is essential for determining the critical stress combination in the pavement. Wheel load stresses can be determined from elastic layered theory. These stresses are added to the stresses from the PSCP2 program. Since higher stresses can be expected at the slab edges, a critical stress factor (CSF) should be applied to the wheel load stress at the slab ends, as discussed in Chapter 6.

7.3.1.2 PSCP2 Output

The output from the PSCP2 program gives the stresses and movements for the number of points along the slab specified in the input. For example, if the number of increments specified in the input file was 50, results would be given for 25 points equally spaced from mid-slab to the slab end. For each point, the output gives the horizontal movement, the coefficient of friction, the prestress plus friction stress, curling deflection, and bottom curling stress. Output is given for every hour of the day that a temperature is specified in the input file.

For this analysis, the prestress (from post-tensioning) plus friction stress was assumed to be uniform over the depth of the slab. The top curling stress was assumed to be equal and opposite to the bottom curling stress. These stresses were added to the wheel load stresses to give the critical stress combination (Equation 6.1). Stresses were evaluated at both the top and bottom of the slab, at mid-slab, and at the slab ends. Horizontal movements were evaluated only at the slab ends (at the expansion joints).

7.3.2 PSCP2 Analysis

Fatigue loading design (Section 7.2.2) gave the minimum compressive stress required at every point along the length of the pavement. The results of the fatigue loading design, summarized in Table 7.2, revealed that a 6 in. or 8 in. pavement thickness was attainable from the standpoint of required prestress. Therefore, based on these results and on sound judgment, a preliminary analysis was originally carried out focusing on 6 in. and 8 in. pavement thicknesses and on 240 ft and 440 ft slab lengths. The 240 ft and 440 ft slab lengths were selected because slabs of this length were successfully constructed and monitored for the cast-in-place prestressed pavement in McLennan County.

Table 7.2 *Minimum compressive stress from the fatigue loading design for a typical precast pavement for two different asphalt support layer conditions*

	Minimum Compressive Stress, σ_{PR} (psi)	
Depth	***E_{ACP} = 780 ksi***	***E_{ACP} = 1,042 ksi***
6	72.6	65.1
8	44.2	40.1
10	25.7	23.8
12	11.3	10.7
14	0	0

The preliminary analysis also focused on using two different concrete coefficients of thermal expansion, one corresponding to that of siliceous river gravel and the other corresponding to that of limestone. The final analysis, however, focused on only one thermal coefficient and one pavement thickness. The following inputs were used for these PSCP2 analyses to determine stresses and horizontal end movements, given these analysis parameters.

Geometric Properties

For the preliminary analysis, 6 and 8 in. pavement thicknesses were analyzed for slab lengths of 240 ft and 440 ft. The slab width was set at 38 ft, which corresponds to a typical four-lane interstate pavement width with two 12 ft lanes, a 10 ft outside shoulder, and a 4 ft inside shoulder. For the final analysis, the slab length was varied from 100 ft to 440 ft and slab thickness was set at 8 in.

Concrete Properties

In order to "trick" the PSCP2 program into accounting for the differences of a precast concrete pavement, the age-compressive strength relationship was specified such that the concrete had reached its full compressive strength of 4,000 psi at 0.01 days. The 3, 7, 14, and 28 day compressive strengths were specified at 4,000 psi also. The ultimate shrinkage strain was specified at 0.0001 in./in., which is what might be expected from precast concrete.

Two different values were used for the coefficient of thermal expansion during the preliminary analysis, the first ($\alpha = 9.18 \times 10^{-6}$ in./in./ºF) corresponding to that of a typical siliceous river gravel aggregate and the second ($\alpha = 6.57 \times 10^{-6}$ in./in./ºF) corresponding to that of a typical limestone aggregate. These values, which were obtained from a coarse aggregate project conducted at CTR (Ref 29), correspond to 28 day concrete at 100 ºF and 40% humidity. Since it was decided that limestone aggregate would most likely be used for actual construction, a value of 6×10^{-6} in./in./ºF was used for the final analysis. For the remaining inputs, a value of 150 lb/ft^3 was specified for the unit weight of the concrete, a value of 0.2 was specified for the Poisson's ratio, and a value of 2.1 was specified for the creep coefficient.

Steel Properties

Six-tenths (0.6 in.) diameter strand was specified for the prestressing (post-tensioning) steel, with a corresponding cross-sectional area of 0.216 in.^{2}, a yield strength of 230 ksi, an elastic modulus of 30×10^6 psi, and a thermal coefficient of 7×10^{-6} in./in./ºF.

Prestress

The pavement was assumed to be post-tensioned in the longitudinal direction, in one stage, 6 hours after placement. The strands were assumed to be stressed to 70% of their ultimate strength, corresponding to 189 ksi, which is probably somewhat conservative.

Slab-Base Interaction

Two different values were used for the slab support for the preliminary analysis. Values of 500 psi/in. and 2,000 psi/in. were used, corresponding to weak and moderate slab support, respectively. The preliminary analysis revealed, however, that slab support had no effect on the environmental design stresses or on horizontal movements. Therefore, a single value of 500 psi/in. was used for the final analysis. The slab support value specified for the PSCP2 analysis does not correlate with the slab support values used for the elastic layered theory analysis described previously.

The friction-displacement relationship was assumed to be a linear relationship with a maximum coefficient of friction of 0.2 and corresponding displacement of 0.02 in. at sliding. Although extensive testing has found that the maximum coefficient for slabs placed on a single layer of polyethylene sheeting is around 0.92, the value used for this analysis was obtained from actual measurements of the cast-in-place prestressed pavement in McLennan County. As mentioned previously, the frictional resistance for precast panels will be different than that for cast-in-place pavements, but due to a lack of data on these differences, the values obtained from the McLennan County prestressed pavement were assumed, providing conservative results.

Analysis Period

The precast concrete pavement is expected to have a design life of at least 30 years. At 30 years, the prestress will be at a minimum, owing to relaxation of the post-tensioning strands. Therefore, the number of days after placement for the final analysis was specified at 10,950. In addition, another analysis period at 1 year was specified to ensure that the critical stress combination was not occurring earlier than 30 years. For determining maximum horizontal movements, a third analysis period of 90 days was also specified.

Temperature

Temperature data was specified for the first 24 hour period after placement and for a 24 hour period at the specified final analysis periods (90 days, 1 year, 30 years). The temperature data used in the analysis was actual temperature data collected from the McLennan County prestressed pavement project (Ref 30). Six sets of temperature data were collected for the McLennan County project. From these six sets, one set representing a typical summer condition and one set representing a typical winter condition were selected. The temperature data and the dates on which they were collected are shown in Table 7.3.

Table 7.3 *Temperature data from McLennan County cast-in-place prestressed concrete pavement used for PSCP2 program*

	January 21, 1989 (Winter)			**August 5, 1988 (Summer)**		
Time of Day	***Ambient Temperature***	***Middle Temperature***	***Top/Bottom Differential***	***Ambient Temperature***	***Middle Temperature***	***Top/Bottom Differential***
14:00	53.1	59.0	10.3	98.7	108.8	15.4
16:00	56.3	60.5	4.6	100.9	112.6	10.5
18:00	46.8	55.4	-3.8	94.0	109.2	3.1
20:00	44.4	50.2	-5.3	88.4	102.6	-5.0
22:00	35.1	46.9	-5.6	82.8	96.0	-6.4
0:00	38.5	44.0	-5.6	80.5	92.2	-5.9
2:00	27.4	41.9	-5.6	78.7	89.5	-5.5
4:00	30.0	40.2	-5.4	77.3	87.6	-5.2
6:00	29.9	39.7	-5.5	76.9	84.5	-5.1
8:00	43.9	37.5	-4.1	85.5	84.5	-1.7
10:00	54.5	42.7	5.2	90.8	91.7	8.0
12:00	58.6	52.2	10.8	100.1	101.7	15.3
14:00	58.6	59.9	10.7	102.3	112.0	16.2

For purposes of analysis, four temperature condition cases were considered. For each case, one set of temperature data was specified for the initial 24 hour period after placement, and another set of temperature data was specified for the final analysis periods. The first case considered placement of the pavement in the winter and final analysis period(s) (at 90 days, 1 year, and 30 years), also in the winter. The second case considered placement in the winter and final analysis in the summer. The third case considered placement of the pavement in the summer and final analysis in the summer, while the final case considered placement in the summer and final analysis in the winter. The slabs were assumed to be placed at 2:00 p.m. for all four cases.

The setting temperature, or the temperature of the precast panels at the time of placement, was calculated from a relationship between the ambient temperature and concrete temperature given by (Ref 31):

$$T_C = 20.2 + 0.758 T_A \tag{7.3}$$

where: T_C = concrete temperature (^oF)
T_A = ambient temperature (^oF)

For the temperature sets given above, a setting temperature of 95 ^oF was specified for summer placement and 60.4 ^oF for winter placement.

Wheel Load Stress

The computer program BISAR was used to determine the wheel load stresses resulting from the loading condition shown in Figure 7.1. Table 7.4 summarizes the values obtained for the wheel load stresses for slabs of varying thickness. Although compressive stresses are developed in the top of the pavement as a result of wheel loads, they were assumed to be equal to zero for this analysis in order to ensure a conservative estimate. A critical stress factor (CSF) of 1.3 was applied to the wheel load stresses for evaluating the slab ends, since edge loading results in higher stresses.

Table 7.4 *Wheel load stresses from layered theory for interior slab loads*

	Interior Wheel Load Stress (psi)	
Depth	***E_{ACP} = 780 ksi***	***E_{ACP} = 1,042 ksi***
6	124	115
8	95.6	90.0
10	77.1	73.7
12	62.7	60.6
14	51.4	49.9

7.3.3 Longitudinal Prestress Requirements

The critical stress combination (σ_{CR}) resulting from environmental stress analysis, given by Equation 6.1, must be a compressive stress equal to or greater than the minimum compressive stress (σ_{PR}) from Table 7.2 (from fatigue loading design). The applied prestress component (σ_P), from Equation 6.1, was varied by increasing or decreasing the strand spacing, until this condition was met. The critical stress combination was checked only at two critical locations along the length of the slab — at the ends of the slab and at mid-slab.

The required strand spacing, as determined from this analysis, is shown in Figures 7.5 – 7.8 for 6 in. and 8 in. thick pavements. Figures 7.5 and 7.6 show the required strand spacing for slabs with a thermal coefficient corresponding to siliceous river gravel (SRG) aggregate for the weak and moderate asphalt support layers, respectively. Figures 7.7 and 7.8 show the required strand spacing for slabs with a thermal coefficient corresponding to limestone (LS) aggregate for the weak and moderate asphalt support layers, respectively. As mentioned previously, the analysis was performed for both the 240 ft and 440 ft slab lengths.

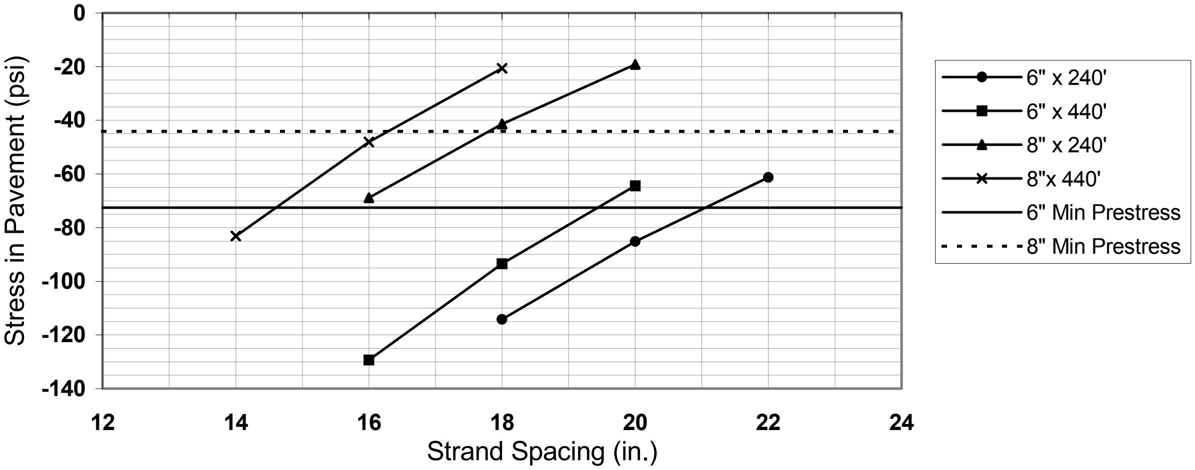


Figure 7.5 Required strand spacing for slabs with siliceous river gravel (SRG) aggregate and weak asphalt support layer (EACP = 780 ksi)

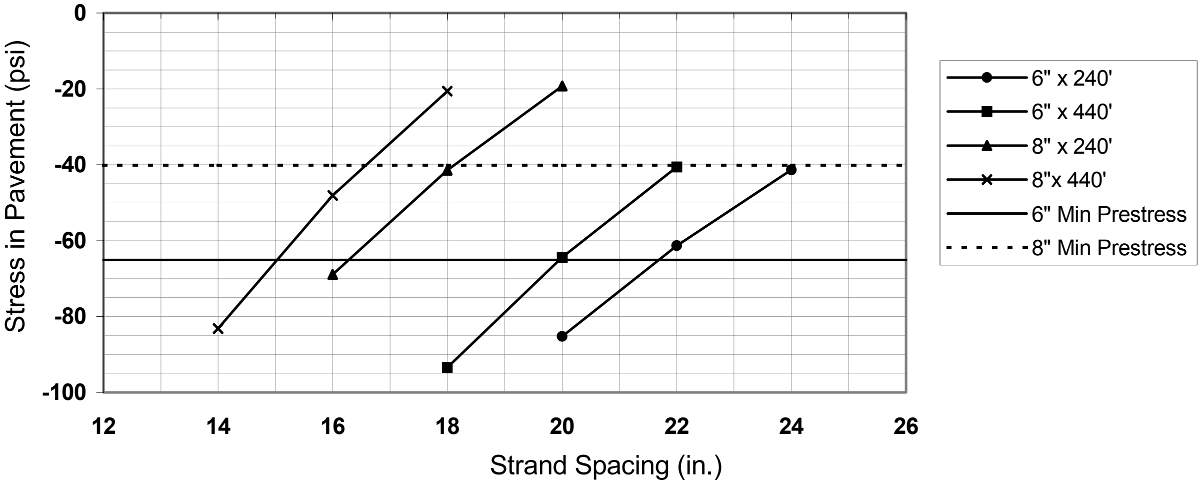


Figure 7.6 Required strand spacing for slabs with siliceous river gravel (SRG) aggregate and moderate asphalt support layer (EACP = 1,042 ksi)

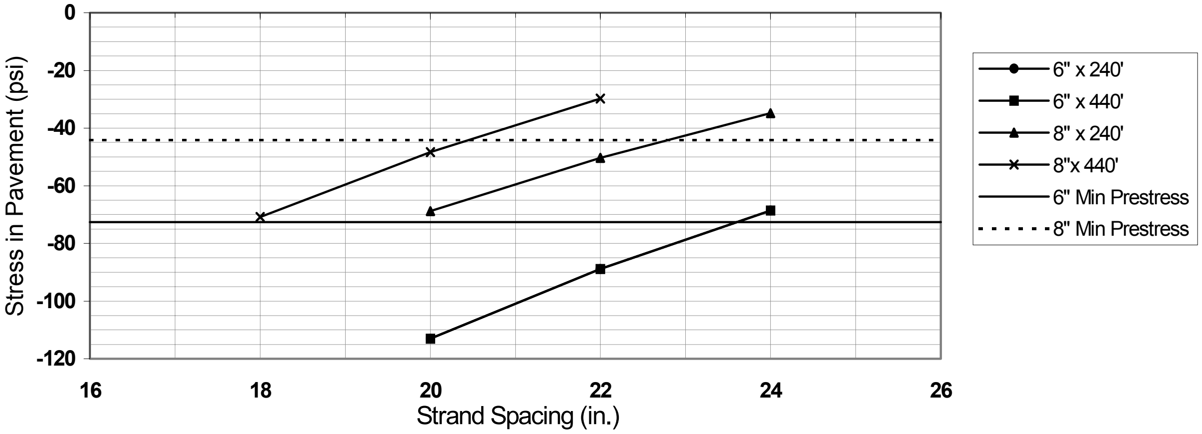


Figure 7.7 *Required strand spacing for slabs with limestone (LS) aggregate and weak asphalt support layer (EACP = 780 ksi)*

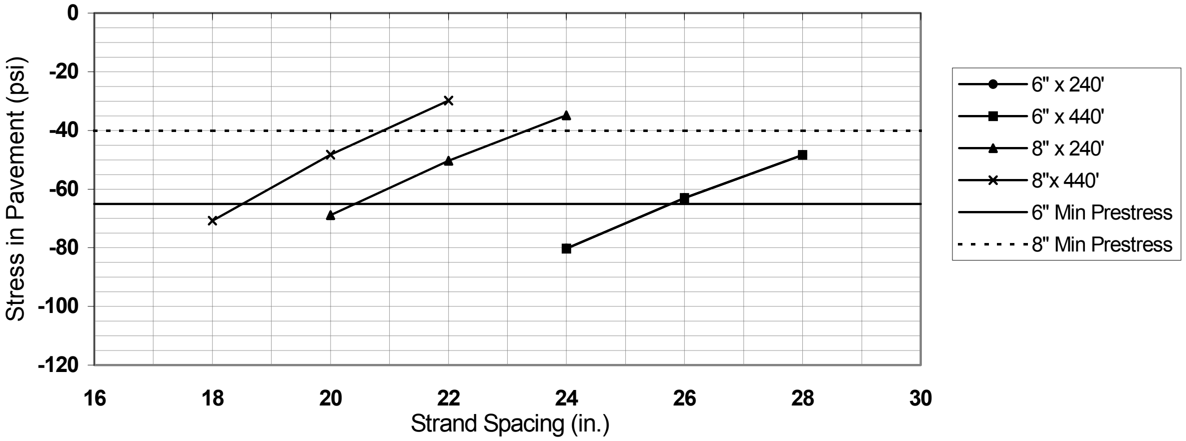


Figure 7.8 Required strand spacing for slabs with limestone (LS) aggregate and moderate asphalt support layer (EACP = 1,042 ksi)

For all slabs with a coefficient of thermal expansion corresponding to siliceous river gravel, the critical stress combination was found to occur at the 30 year (after placement) winter analysis period for slabs placed during the summer. The critical stress occurred in the top of the slab at the mid-slab location at 6:00 a.m. For the 8 in. slabs with a limestone thermal coefficient, the critical stress combination was found to occur at the 30 year winter analysis period for slabs placed in the winter. The critical stress occurred in the top of the slab at mid-slab at 6:00 a.m. For the 6 in. slabs with the limestone thermal coefficient, the critical stress combination occurred at the 30 year summer analysis period for slabs placed in the winter in the bottom of the slab at the slab end at 6:00 p.m.

7.3.4 Transverse Prestress Requirements

Transverse prestress design is necessary for determining the amount of prestress required for pretensioning the precast panels during fabrication. Transverse prestress design was carried out in the same manner, using the PSCP2 program as the longitudinal prestress design. However, because the panels are relatively narrow (38 ft) compared to the slab lengths analyzed (100–440 ft), the frictional stresses and curling stresses are very small. Therefore, only the wheel load stresses, which are tensile in the bottom of the panels, were used to calculate the required transverse prestress. Equation 6.1 was used, as before, to calculate the required applied prestress (σ_P) to meet the minimum compressive stress criteria from the fatigue loading design (σ_{PR}), as given in Table 7.2.

In addition to wheel load stresses, handling stresses must be taken into account in the transverse prestress design. As a worst case scenario, the panels were assumed to be picked up from the short ends of the panel, with two lifting points on each end. This lifting configuration causes significant handling stresses owing to the weight of the panels. The required prestress was determined from the procedure outlined in Section 5.2 of the PCI Design Handbook (Ref 32) for a two-point pick up. The weight of the panel was multiplied by 1.3, to account for additional stripping loads when the panels are stripped from the precasting bed, as per the PCI Design Handbook.

Table 7.5 shows the required transverse prestress determined for elastic design stresses (wheel load and fatigue loading requirements) and the handling stresses for an 8 in. pavement, assuming the panels are 38 ft long (transverse pavement direction) and 10 ft wide (longitudinal pavement direction). As the table shows, for panels of this size, and for the worst case handling configuration, the handling stresses will govern the transverse prestress requirements. The strand spacing in the transverse direction will be determined by the size of strand used and the level to which the strands are pretensioned.

Table 7.5 *Transverse prestress requirements for 38-ft x 10-ft precast panels*

Depth	Required Transverse Prestress (psi)		
	Elastic Design Stresses		*Handling Stresses*
	E_{ACP} = 780 ksi	E_{ACP} = 1,042 ksi	
8	140	130	166

7.3.5 Slab Length/Expansion Joint Movement

For the final analysis, the required strand spacing was determined for an 8 in. slab with a limestone thermal coefficient for slab lengths varying from 100 ft to 440 ft. Based on the required strand spacing, the amount of movement of the ends of the slab was determined for both summer placement and winter placement for the varying slab lengths.

Based on the movement of the slab ends, the minimum and maximum expansion joint widths were determined for the different slab lengths. To calculate the total joint opening, an initial joint opening of 1½ in. (for seal insertion during construction) was added to the joint width from the PSCP2 program. Figures 7.9 and 7.10 show the minimum and maximum joint widths for varying pavement lengths for summer placement of the pavement on the weak and moderate asphalt support layers, respectively. Figures 7.11 and 7.12 show the minimum and maximum joint widths for winter placement of the pavement on weak and moderate asphalt support layers, respectively. The shaded regions in Figures 7.9 through 7.12 represent the required strand (0.6 in. diameter) spacing for the different slab lengths, as determined from Figures 7.7 and 7.8.

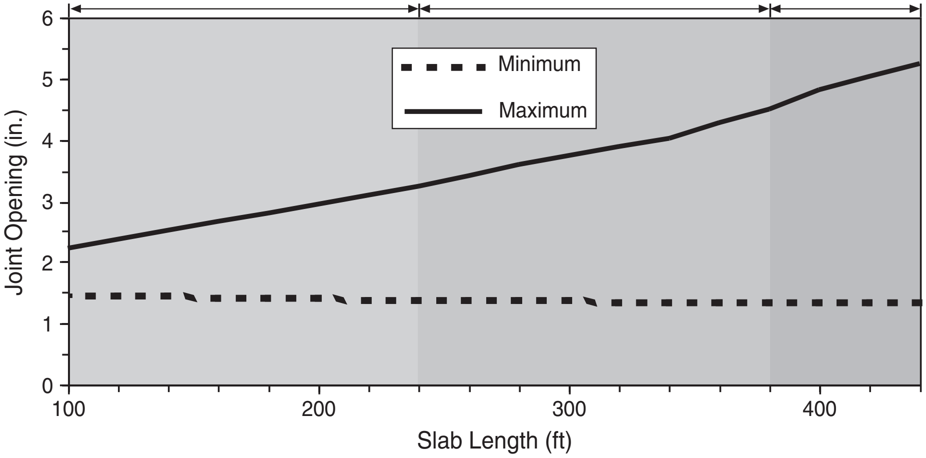


Figure 7.9 *Minimum and maximum joint widths for summer placement on weak asphalt support layer (E_{ACP} = 780 ksi)*

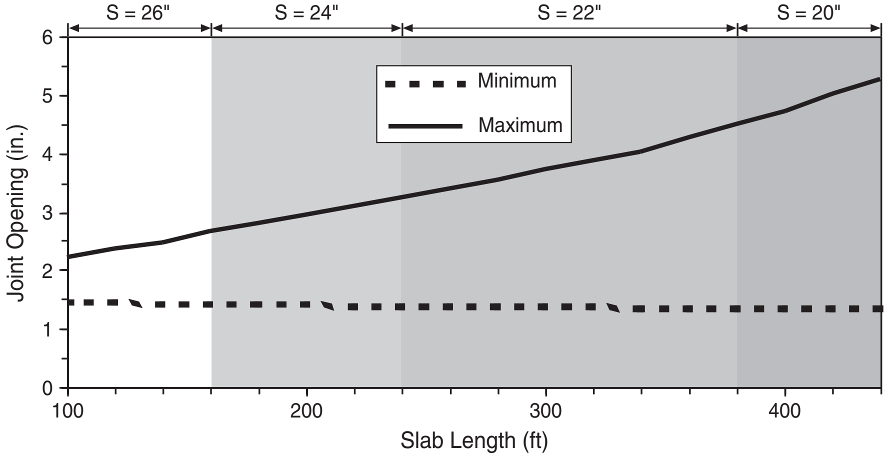


Figure 7.10 *Minimum and maximum joint widths for summer placement on moderate asphalt support layer (E_{ACP} = 1,042 ksi)*

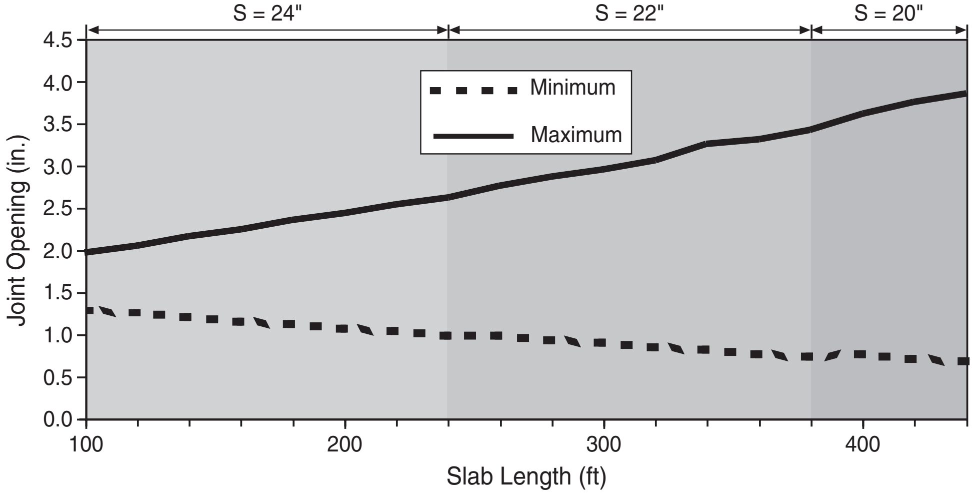


Figure 7.11 *Minimum and maximum joint widths for winter placement on weak asphalt support layer (E_{ACP} = 780 ksi)*

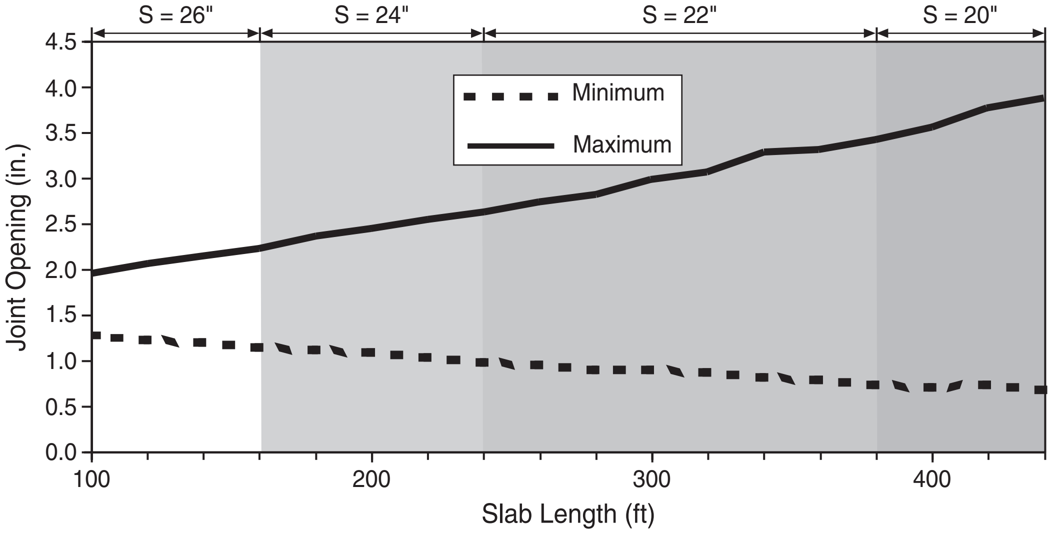


Figure 7.12 *Minimum and maximum joint widths for winter placement on moderate asphalt support layer (E_{ACP} = 1,042 ksi)*

For both summer and winter slab placement, the maximum joint width was found to occur at 8:00 a.m. at the 30 year winter analysis period. For winter pavement placement, the minimum joint width was found to occur at 4:00 p.m. within the first 90 days after placement under summer conditions. For summer pavement placement, the minimum joint width occurred at 2:00 p.m., 12 hours after the pavement was placed. As summer and winter placement represent extreme conditions, placement of the pavement under fall or spring temperature conditions will result in joint widths somewhere between those given by this analysis.

The results of this analysis show that, for an 8 in. limestone aggregate, precast concrete pavement, the expansion joint will never fully close for slab lengths up to 440 ft (with an initial width of 1½ in.). For winter placement of the pavement, there is no restriction on the slab length (up to 440 ft) to meet the maximum joint width requirement of 4 in. For summer placement, however, the slab length should be limited to 340 ft to meet the maximum joint width requirement.

As stated previously, it should be noted that the frictional resistance between the slab and base, which affects the amount of slab movement, will be different for a precast pavement than a cast-in-place pavement. However, due to a lack of data on these differences, the same slab-base interaction was assumed. Push-off tests conducted prior to construction of a precast pavement will help to quantify these differences for future projects.

Chapter 8. Feasibility Analysis: Construction

8.1 INTRODUCTION

This chapter is the second chapter in which the recommended concept, presented in Chapter 5, is evaluated. This chapter focuses on the feasibility of precast concrete pavement construction. Issues discussed include fabrication of the precast panels, installation/placement of the panels, and estimated production rates for pavement placement. Some of the major differences between precast concrete construction and conventional pavement construction become apparent in this analysis.

There are several advantages to precast concrete pavement construction over conventional pavement construction. The most notable advantage is the speed with which a precast concrete pavement can be assembled and exposed to traffic. Although it may not be possible to place as much precast pavement during one day's construction as can be placed using conventional pavement, it will be possible to assemble the pavement piecewise, allowing traffic back onto the pavement between construction sequences. This provides the option of constructing during "off peak" periods, such as at night and on weekends. The primary emphasis in this chapter is the use of a precast pavement for a new pavement or unbonded overlay. In Section 8.7, however, the removal and replacement application is also discussed.

8.2 FABRICATION

Based on discussions with precast consultants, the most effective method for fabrication appears to be through the use of a "long line" process, as described in Chapter 3. There are essentially two options for fabricating the precast concrete panels. The first option is on-site fabrication, whereby the panels are cast at or near the construction site. The second option is off-site fabrication, whereby the panels are cast at an existing precasting plant and transported to the construction site. Each of these options will be discussed in this section.

8.2.1 On-Site Fabrication

On-site fabrication will probably be feasible only for large pavement jobs located in remote areas. On-site fabrication requires setting up a precasting bed at or near the job site. Depending on the size of the precasting bed, this setup may require a large section of land. Land will also be required for storage of the panels after they are cast. The precasting bed itself will require large pretensioning abutments to be constructed (to very strict tolerances). Consideration must also be given to who will supply the concrete. Most likely, it will be necessary to set up a small concrete batch plant on-site to supply the concrete, mainly to ensure that a consistent, proper concrete mixture is used for each pour. Transporting concrete to the site could be very costly, depending on the location of the job site.

Although on-site fabrication seems cost-prohibitive at first, it may actually be more economical, depending on the size and location of the paving job. The more precast panels that are needed, the more the unit-cost of fabricating the panels decreases. Transporting the panels from an existing precasting plant could be very expensive, while on-site fabrication would require the panels to be transported for only very short distances.

8.2.2 Off-Site Fabrication/Transportation to Site

Off-site fabrication may take the form of setting up a precasting yard some distance from the site, or using an existing precasting plant. In either case, a large cost component of off-site fabrication will be cost of transporting the precast concrete panels to the job site, which will increase with the distance the panels are transported. If the size of panels used is such that only one or two panels can be hauled per truck, transportation costs may become substantial. In addition, the size or weight of the panels may require special permits for transportation, which will also increase the transportation cost.

With off-site fabrication (at an existing precasting plant), the cost of setting up the bed will be minimal, unless special provisions, such as new side forms, are needed. In addition, the experience and expertise of the precasters at an existing yard will increase the efficiency of fabrication.

The use of either on-site or off-site fabrication will be job-specific. The determining factor will be the location and size of the paving job. For a large job located in a remote area, on-site fabrication will probably be more economical. For a job located near an existing precast plant, however, off-site fabrication will probably be more economical. A job-specific economic analysis will determine the most cost-effective method for fabrication.

8.3 PAVEMENT PLACEMENT

Pavement placement will follow the sequence described in Section 5.2.4 previously. A 1–2 in. thick asphalt leveling course will first be placed over the existing pavement or subbase. The polyethylene sheeting will then be placed over the asphalt, with some provision for holding it in place. The precast panels will then be placed over the polyethylene sheeting, starting with a joint panel at the end of the slab, followed by the base panels, central stressing panel(s), additional base panels, and a final joint panel at the end.

The post-tensioning strands will then be threaded through the ducts in the panels, starting at the central stressing pockets, to anchors located in the joint panels. The strands will be anchored at the joint panels, and the entire pavement will be post-tensioned from the central stressing pockets. The strands will then be grouted in the ducts and the stressing pockets filled with a fast-setting concrete. Prefabricated ramps can then be placed at the ends of the slab to provide a transition for traffic from the existing pavement onto the new pavement. The feasibility of this construction sequence, as well as some special provisions, will be discussed below.

8.3.1 Asphalt Leveling Course

The asphaltic concrete (AC) leveling course is used to provide a smooth, flat surface for the precast panels to rest on. Any unevenness in the leveling course could cause the panels to sit at awkward angles, thereby creating voids or stress concentrations in the panels. There are primarily two issues associated with using an AC leveling course. The first issue is ensuring that the AC leveling course will be smooth enough that the panels will sit flat on the leveling course. The second issue is determining the magnitude of void volume beneath the panels caused by minor irregularities in the leveling course. Although the panel may sit level on the AC leveling course, minor variances in the asphalt surface may create voids under the panels, which could be detrimental to the pavement.

In consideration of these two issues, profile data for a newly placed asphaltic concrete pavement was analyzed in order to investigate how smooth an asphalt leveling course can be placed (void volume will be discussed in Section 8.6). Profile data was obtained from the Texas Department of Transportation for a 500 ft section of newly placed asphaltic concrete pavement along FM 812 in Austin, Texas. The data was obtained using a van equipped with a laser profiler. The profiler collected data approximately every 5 in. over the 500 ft length. Six passes were made (using two lasers) over the pavement section, generating eleven profiles (one profile repeated), each spaced 1 ft apart. This procedure produced a 10 ft wide by 500 ft long section of pavement for analysis. Figure 8.1 shows a plot of the profile data for the 500 ft section. Each of the eleven lines represents one of the profiles. Attention should be given to the scales on the plot, as the horizontal scale is in feet and the vertical scale is in mils, or thousandths of an inch. The length of the plot, 500 ft, represents the leveling course beneath fifty 10 ft wide panels. To reduce the amount of data to be analyzed, only the first 250 ft of the profile data was analyzed.

The easiest way to evaluate the smoothness of the AC pavement was by visual inspection of the plotted profile data. The data was analyzed in 10 ft segments, representing 10 ft wide panels. Figure 8.2 shows the profile data (eleven profile lines) for a typical 10 ft section. The difference in elevation between the two outermost lines can be attributed to the overall slope of the pavement (for drainage). Considering the scale, however, this difference is only about 400 mils or 0.4 in. The difference in elevation between the ends of the lines can be attributed also to the slope, or grade, of the pavement. There are only a few areas with noticeable irregularities. In particular, between 235 ft and 236 ft, there is a sharp peak. This peak is greatly exaggerated by the scale, however, as it is less than 0.1 in. in height.

Overall, there do not appear to be any major imperfections in this 10 ft section that would compromise the evenness of the leveling course. Visual inspection of the profile data for the rest of the 10 ft sections lead to similar conclusions. Although this pavement is thicker (6 in.) than that which would be used for a leveling course (1–2 in.), this analysis has shown that an AC pavement can be placed that is sufficiently smooth to work as a leveling course for a precast pavement. If obvious imperfections were found in the leveling course, techniques such as diamond-grinding could bring the leveling course to within required tolerances.

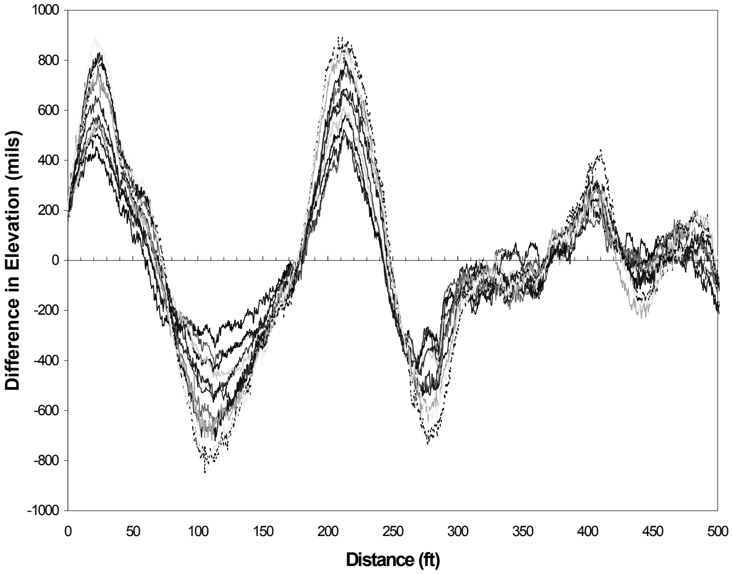


Figure 8.1 *Profile data from a newly placed AC pavement in Austin, Texas*

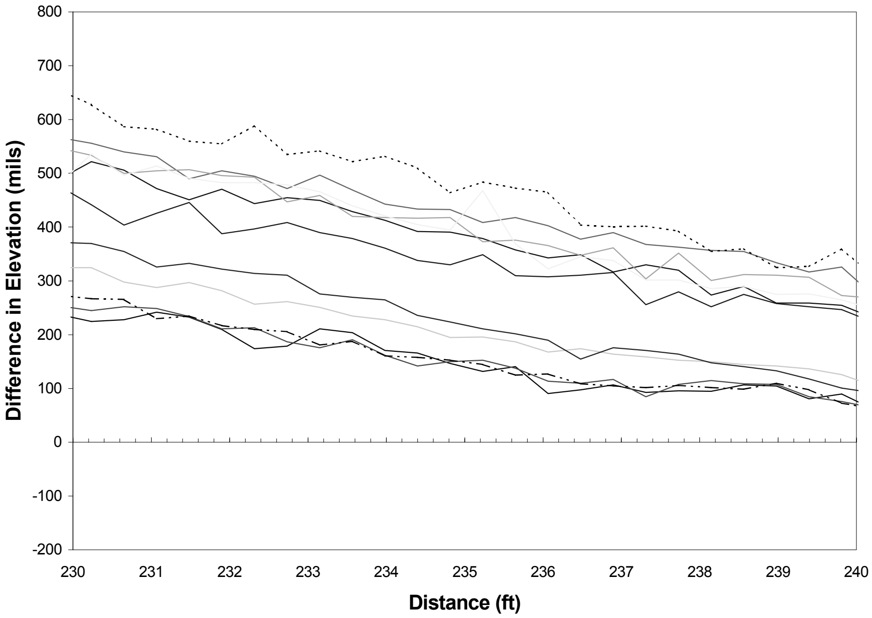


Figure 8.2 *Profile data for a 10-ft-wide section, representing the width of a single precast panel*

8.3.2 Polyethylene Sheeting

Friction-reducing media are used to decrease the amount of frictional resistance occurring between the slab and subbase. The concern for friction is especially important in long, prestressed slabs, where the frictional resistance also reduces the compressive stress transferred to the concrete from post-tensioning.

There are three main considerations for selecting a friction-reducing medium (Ref 23):

- Efficiency in reducing restraint
- Practicability for road construction
- Economics

Extensive research has been conducted over the years on the effects of various types of friction-reducing media. The predominant media that have been investigated include polyethylene sheeting, spray-applied bond breaker, and granular layers. Figure 8.3 shows the relationship between displacement and coefficient of friction obtained from push-off tests performed at The University of Texas at Austin for concrete slabs on three different types of friction-reducing media (Ref 33).

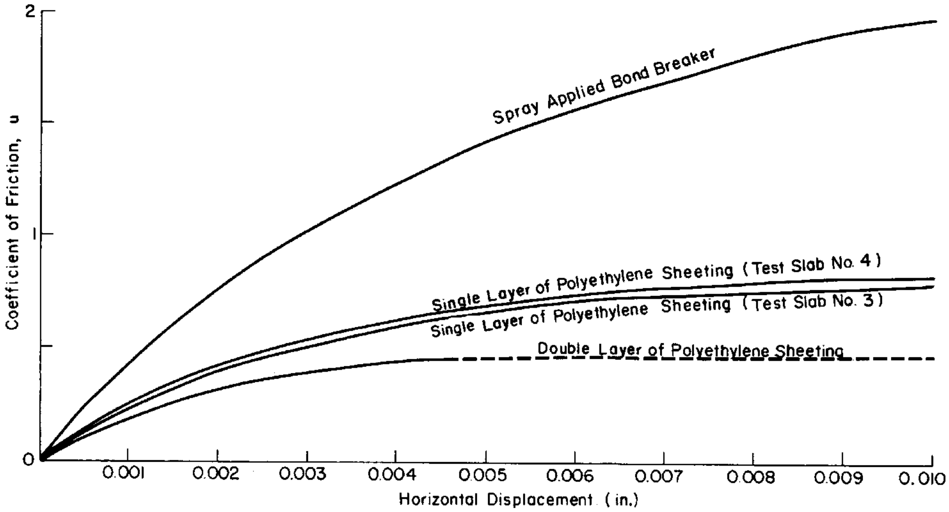


Figure 8.3 *Coefficient of friction versus displacement for three different friction-reducing materials (Ref 33)*

Figure 8.4 shows the results of push-off tests performed by Transtec, Inc., on aircraft pavement slabs in Las Vegas, Nevada. For these tests, a granular material was tested along with other materials.

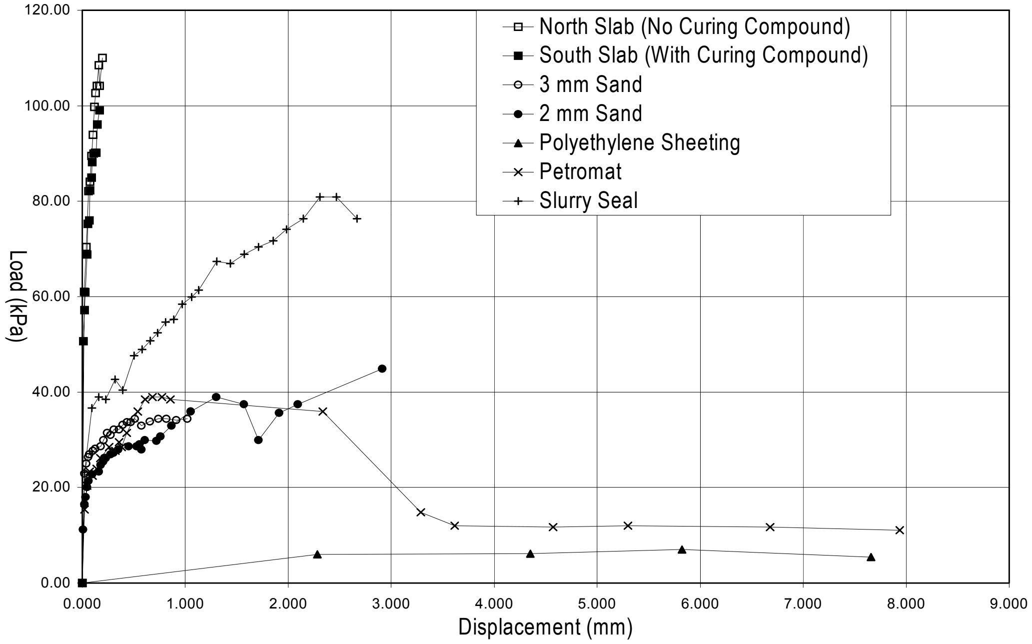


Figure 8.4 *Load-displacement relationship from push-off tests for various friction-reducing media (Ref 24)*

Both of these tests revealed that polyethylene sheeting is the best material for reducing subbase frictional restraint. A single layer of polyethylene sheeting was found to have a maximum coefficient of friction between 0.57 and 0.92 (Ref 33). Tests performed at The University of Texas at Austin showed that a double layer of polyethylene sheeting (maximum coefficient of friction between 0.47 and 0.70) reduced friction more than a single layer did. However, it was felt that a double layer reduced the friction too much. It is desirable to have some friction beneath prestressed pavement slabs to keep expansion joints from opening excessively and to prevent the slabs from sliding transversely off the base material. In addition, previous experience revealed that it was difficult to walk on the surface during construction.

An added benefit of polyethylene sheeting, or virtually any friction-reducing medium, is the prevention of adhesion between the subbase and the bottom of the pavement. This benefit is especially important for pavements whose construction makes use of an asphalt base, as asphalt tends to adhere to concrete.

A single layer of polyethylene sheeting was used successfully beneath the cast-in-place prestressed pavement constructed in McLennan County, Texas, in 1985 (Chapter 2). The polyethylene sheeting proved to be constructible, economical, and effective as a friction-reducing medium (Ref 20). Polyethylene sheeting can be purchased in large rolls and simply rolled out and temporarily pinned down over the leveling course. Based on its success in previous projects, a single layer of polyethylene sheeting should prove viable for use with a precast pavement as well.

8.3.3 Placement of Panels

Placement of the precast panels will follow the sequence presented at the beginning of this section. The panels will, most likely, be lifted off the truck and set in place using a crane. The panels will be handled using either lifting devices embedded in the panels, or using a strong-back with clamps that lock onto the shear keys in the edges of the panels. The latter method eliminates the need to fill holes in the panels, left by the lifting devices, after the panels are in place.

A gap will intentionally be left between the joint panel and its adjacent base panel so that the post-tensioning strands can be pushed into the anchors. Inevitably, there will also be gaps left between each of the other panels when they are set in place, particularly if a strong-back lifting device is used. It will be necessary to close these gaps as much as possible before post-tensioning to minimize the amount of wasted strand. In order to prevent the polyethylene sheeting from bunching up between the panels as they are pulled together, thicker strips of plastic can be placed beneath the panels where they come together.

8.3.4 Installation/Stressing of Post-Tensioning Tendons

As described in Chapter 5, the post-tensioning strands will be threaded through the panels starting at the stressing pockets and terminating at the joint panel. Although ½ in. or 0.6 in. diameter strands are fairly rigid, it may be necessary to pull the strands through the ducts, rather than pushing them from the stressing pockets. This maneuver can be accomplished by first threading wire or rope through the ducts and pulling the strand through. The strand can then be pushed into the self-locking anchor from the gap left between the joint panel and adjacent base panel. As an alternative, a coupler panel can also be used, as described in Chapter 5.

After all of the strands are anchored in the joint panels, they are stressed from the central stressing pockets, as described in Chapter 5. Post-tensioning the pavement will cause the pavement to contract significantly, owing to the gaps between the panels closing up. Because each joint panel is part of two different slabs, the expansion joint will need to be temporarily clamped to prevent it from opening during the stressing operation. Otherwise, when one slab is post-tensioned, it will try to pull the expansion joint open, which is attached to a slab that has already been post-tensioned. With the expansion joint clamped, the slab being post-tensioned will, essentially, contract in one direction, toward the expansion joint.

8.3.5 Mid-Slab Anchor

Once a slab has been post-tensioned, it will be necessary to anchor the center of the slab to the subbase. The purpose of this mid-slab anchor is to restrict movement of the center of the slab so that the slab will expand and contract outward from the center, ensuring uniform expansion joint widths over the length of the pavement. Otherwise, some expansion joints may open up or close more than others.

For the cast-in-place prestressed pavement constructed in McLennan County, Texas, described in Chapter 2, vertical dowel bars were embedded in the supporting layers beneath the prestressed overlay, prior to casting the concrete, to provide the mid-slab anchor. For a precast pavement, it may be possible to drive dowel bars into the supporting layers at the central stressing pockets. When the stressing pockets are filled, the central stressing panel will then be anchored to the subbase. It may even be necessary to use a core drill to drill a small shaft into the subbase layers at the stressing pockets, which will subsequently be filled when the stressing pockets are filled. It is important, however, that the mid-slab anchor is not set (or drilled) until the slab has been post-tensioned. This delay will ensure that the slab is in its final position before being anchored.

8.3.6 Grouting of Post-Tensioning Tendons

After the post-tensioning strands have been threaded through ducts and stressed, they can then either be bonded to the pavement by means of grouting the tendon ducts, or they can be left unbonded. Although leaving the strands unbonded simplifies construction by eliminating the extra grouting process, there is less corrosion protection for the strands, even if greased and polyethylene-sheathed strands are used. Corrosion can cause a strand to eventually lose part or all of its prestress. Another disadvantage of unbonded tendons is the lack of continuity between the steel and concrete, which requires the use of additional nonprestressed reinforcement. There is also the risk of the tendon being inadvertently cut some time during the life of the pavement, which could result in damage to the pavement and which could pose a safety hazard.

The alternative to unbonded tendons is grouting the ducts after the strands have been stressed. Grouting the ducts bonds the strands to the pavement, ensuring continuity between the concrete and the strands, thereby reducing, if not eliminating, the amount of nonprestressed reinforcement required in the pavement. In addition, there will not be any damage or loss of prestress if a tendon is inadvertently cut. Most importantly, however, is the corrosion protection that the grout provides to the strands. If grouting is done properly, the grout will provide protection from water penetrating the concrete and reaching the strands. This protection is especially important at the panel joints, where the duct is not continuous across the joint. The grout will help seal the duct across the joint, thereby protecting the strands.

Grout will be pumped into the tendon ducts through grout inlets near the expansion joint, as shown in Figure 5.10. One or more grout vents will be cast into the pavement, along the length of the slab, to provide an outlet for the displaced air when grout is pumped through the duct.

It is very important that proper procedures be followed for grouting. Proper procedures include the use of the proper grout mixture, materials, and methods for grouting. Improper grouting can result in air voids in the ducts caused by water separation in the grout and by incomplete grouting of the duct. These voids can collect water and contribute to the corrosion of the strands, which cannot be replaced. As there is no easy way to inspect the tendons after the ducts have been grouted, it is important to ensure that the proper procedures be followed during construction.

Neither grouting the tendons nor filling the stressing pockets must be completed before traffic is allowed back onto the pavement. For example, if a section of pavement is placed and post-tensioned one night, traffic could be allowed back onto the pavement the next day. Steel cover plates could simply be used to temporarily cover the stressing pockets. The tendons can then be grouted and the stressing pockets filled during placement of another section on the following night. This practice will serve to further expedite the construction process.

8.3.7 Traffic Control/Temporary Ramps

Traffic control will be determined by the scope of each project. The scope of the project entails the type of pavement to be constructed, such as a new pavement, overlay, or removal and replacement, as well as the time frame allotted for construction. Traffic can be diverted to frontage roads or to opposing lanes of traffic.

A precast pavement can either be constructed piecewise, in separate overnight operations, or all at once. Separate overnight operations will allow traffic back onto the pavement during the daytime, when traffic volumes are higher. For a new or overlay application, temporary precast ramps can be placed at the ends of the precast pavement to provide a transition from the existing pavement to the new pavement. These temporary ramps can be reused as each successive section of pavement is placed.

8.3.8 Ride Quality

Ultimately, an actual determination of ride quality cannot be ascertained until a precast pavement is actually constructed. However, ride quality of a precast pavement should be comparable to that of conventional concrete pavements. Because the panels are cast under controlled conditions, there is a high degree of control over the smoothness and evenness of the precast panels. The continuous shear keys in the edges of the panels will interlock adjacent panels so that tight, flush joints are created. If necessary, uneven areas of the pavement can be diamond-ground smooth using existing techniques and equipment to improve ride quality. Areas that may require diamond-grinding are at the stressing pockets and at panel joints. Any ridges created at the panel joints by the sealant material or misalignment of adjacent panels should be ground smooth.

The expansion joints should not affect the ride quality, as long as the maximum expansion joint width requirements are met. Data collected from the cast-in-place prestressed concrete pavement in McLennan County (Chapter 2) has shown that the expansion joint widths can be predicted accurately using the PSCP2 program for design (Ref 20).

8.3.9 Estimated Production Rates

It is essential that the construction sequence be carefully planned so that a precast pavement can be placed quickly and efficiently. This planning is especially critical when a precast concrete pavement is constructed during an overnight operation. Careful planning entails ensuring that all of the materials and equipment necessary for construction are at the job site before construction begins. These materials include all of the post-tensioning materials and the precast panels themselves.

The actual production rate of a precast pavement will be dependent on how fast the panels can be placed and post-tensioned. The asphalt leveling course can be placed well in advance of panel placement and can be exposed to traffic between nightly construction sequences. It is imperative, however, that the pavement be post-tensioned prior to exposure to traffic.

Based on estimates of production rates for parking garage construction using precast double-tee beams, at least thirty panels can be placed in an 8 hour period. It should be possible to increase this amount, however, so that at least 500–1,000 ft of pavement is placed during a construction sequence. Although this is substantially less than a typical placement rate for conventional pavement (~2,000 ft/day), the savings in user costs (discussed in Section 9.1) associated with overnight pavement placement will far outweigh the additional time required for construction.

One advantage of precast pavement, with respect to actual construction, is that weather conditions will not impact precast pavement placement as they do conventional pavement placement. Precast pavement can be placed under moderate and possibly even heavy precipitation, whereas conventional pavement cannot. Precast pavement placement also will not be inhibited by concreting temperature requirements. For example, in Texas, concrete pavement cannot be placed when the ambient temperature is below 5 ºC (41ºF) and falling or when the concrete temperature is above 35 ºC (95 ºF) (Ref 47). Because the panels will be cast under controlled conditions at a precast yard and set in place after the concrete has already hardened to full or near-full strength, weather conditions will have little effect on a precast pavement when it is placed.

8.4 VERTICAL AND HORIZONTAL CURVES

An important consideration for a precast pavement, brought up during the first expert panel meeting, is whether rectangular concrete panels will be able to conform to the geometry of a highway having sags, crests, and horizontal curves. To investigate this issue, the 1994 AASHTO publication, “A Policy on Geometric Design of Highways and Streets” (Ref 34), was used to determine the maximum expected horizontal and vertical curves. The angle between the adjacent panels, created by these curves, was then computed using geometric relationships.

Vertical curves create gradual transitions from tangent grades. These curves consist of either crest or sag types. The major control for safe operation on crest or sag curves is the provision of ample distances for the design speed and minimum stopping distance. The AASHTO guide recommends the use of a parabolic curve, where the rate of change of grade at successive points on the curve is a constant amount for equal increments of horizontal distance and which equals the algebraic difference between intersection tangent grades divided by the length of curve in meters, or A/L in percent per meter. The constants A and L are shown graphically in Figure 8.5. The reciprocal L/A is the horizontal distance, in meters, required to effect a 1% change in gradient; L/A is, therefore, a measure of curvature, “K.”

The K-value is specified by the AASHTO guide for various highway types and design speeds. The K-values recommended by the AASHTO guide for sag curves are smaller than those required for the crest curves. In the case of sag curves, the length of the curve is limited by the requirement of headlight sight distance. For highway applications, the design speed will, in most cases, be around 120 km/h (75 mph), with corresponding recommended K-value limits of 50 and 73.

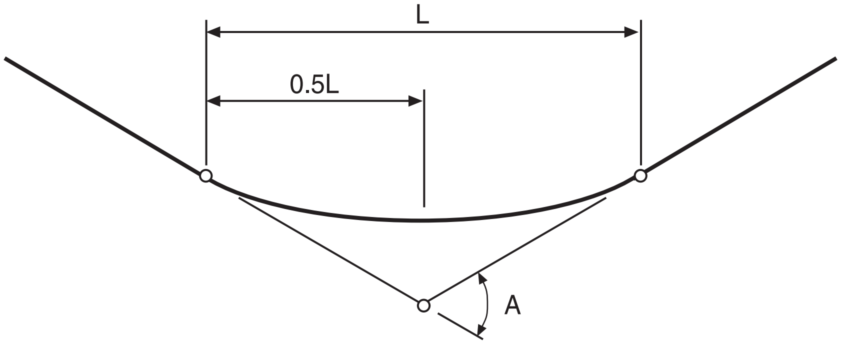


Figure 8.5 *Sag vertical curve*

In order to find the percent change in angle in the parabolic curve over the width of each panel, the panel width (in meters) was divided by the K-value. Depending on the panel thickness, the gap width between panels will vary. For this analysis, a panel thickness of 8 in. was used. The angle created between adjacent panels for the maximum sag curve is shown in Figure 8.6 for varying panel widths. The corresponding gap between adjacent panels, created by this angle, is shown in Figure 8.7.

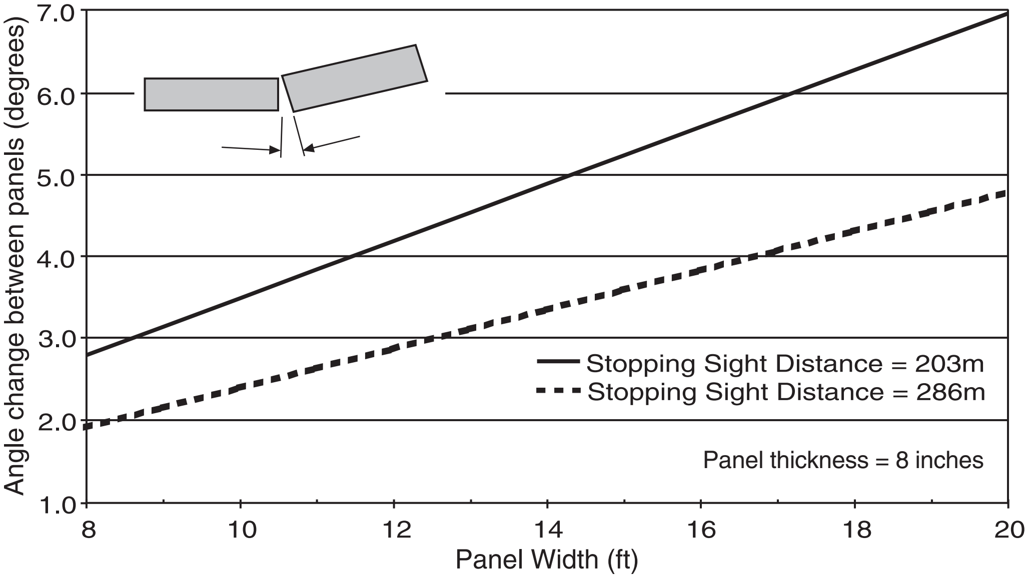


Figure 8.6 *Angle created between adjacent panels on vertical sag curves*

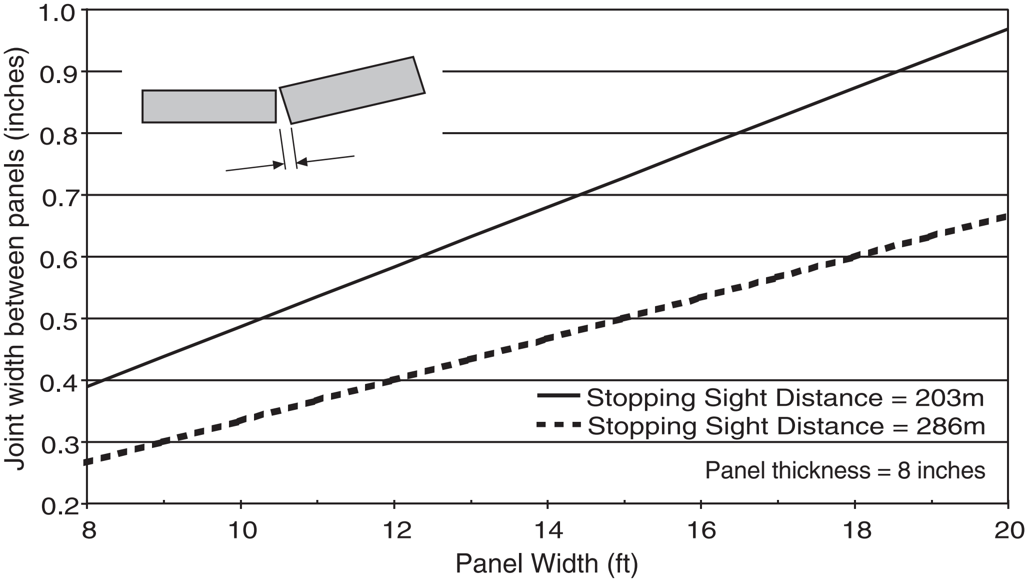


Figure 8.7 *Gap width between adjacent panels on vertical sag curves*

In the design of horizontal curves, it is necessary to establish the relationship between the design speed and curvature, superelevation, and side friction. The AASHTO guide recommends limiting values for the rate of roadway superelevation, *e,* and also for the side friction factor, *f.* Using the maximum superelevation ($e_{\max}$) value with a conservative side friction *(f)* value, a minimum curve radius for various design speeds can be determined. The AASHTO guide lists various minimum radii based on various design speeds, super elevation rates, and side-friction factors. The AASHTO guide recommends a super elevation of 8% as a reasonable value for design, though the maximum that may be used is 12%. Based on this recommended design value for superelevation, on a design speed of 120 km/h, and on a side-friction factor of 0.09, the minimum curve radius (R_0) is given as 665 m.

The minimum curve radius was used to compute the angle and gap width between adjacent panels using geometric relationships. For the purpose of analysis the total panel length was taken as 38 ft, which is probably the largest panel size that will be used. This geometric relationship is illustrated in Figure 8.8.

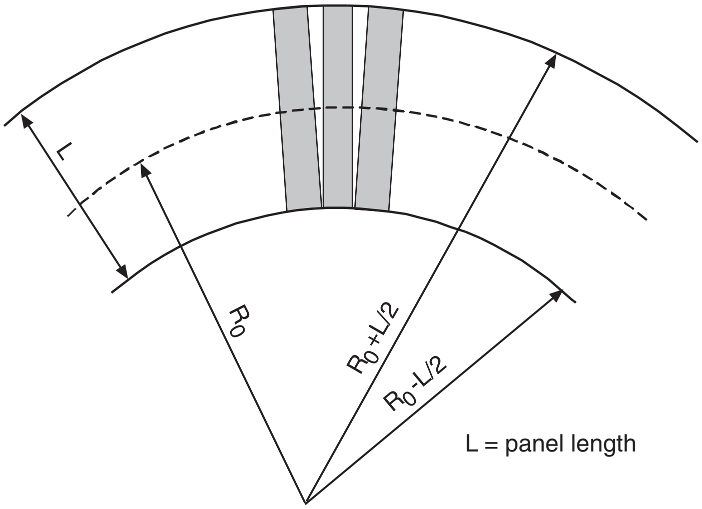


Figure 8.8 *Geometry between panels on horizontal curves*

Figure 8.9 shows the angle created between adjacent panels, for the minimum curvature, for varying panel widths. Figure 8.10 shows the corresponding gap width created by the maximum expected horizontal curve for varying panel widths.

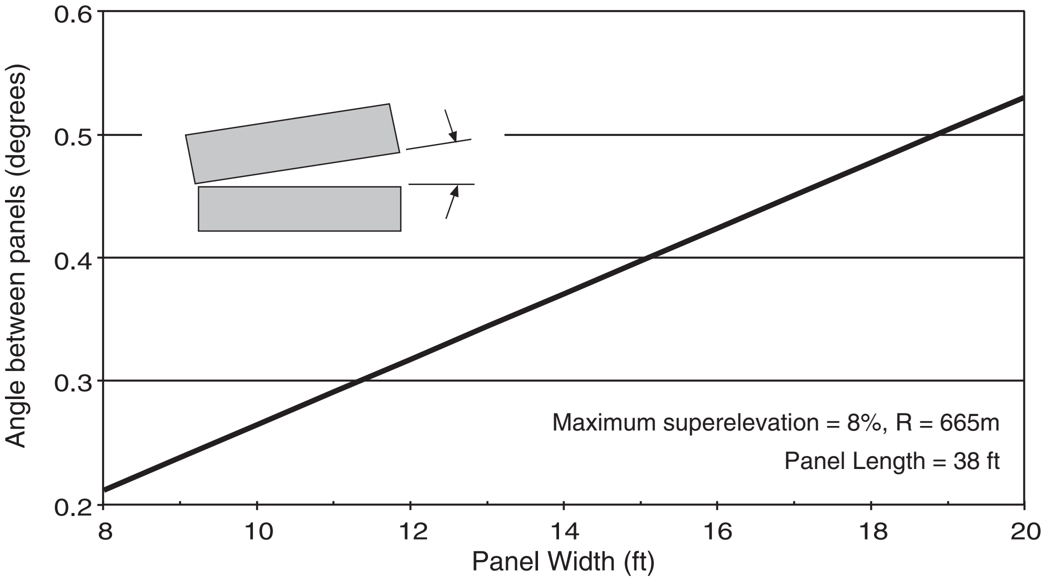


Figure 8.9 *Angle created between adjacent panels on horizontal curves*

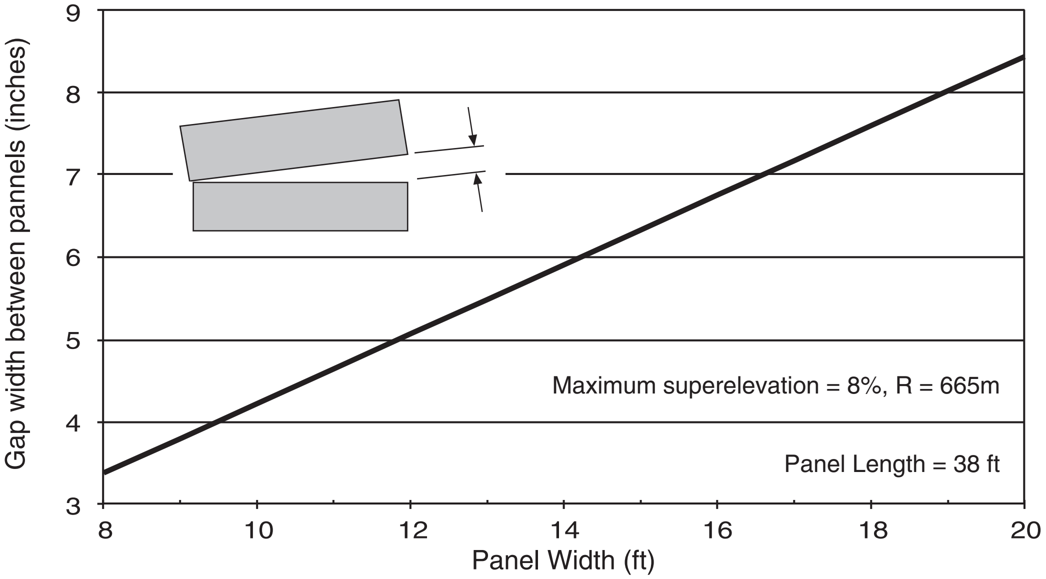


Figure 8.10 *Gap width between adjacent panels on horizontal curves*

This analysis has shown that horizontal and vertical curves can cause significant angles between adjacent rectangular precast panels. For example, with 8 in. thick panels that are 10 ft wide and 38 ft long, a ½ in. gap will be created by a maximum vertical curve and a 4.2 in. gap will be created by the maximum horizontal curve.

Based on the second expert panel meeting with precast consultants, it is believed that precast panels will be able to accommodate these angles. The shear key in the panel edges should be able to accommodate the angle created by vertical curves. For a sag curve, there will simply be a small gap between the panels in the bottom of the pavement. For a crest curve, it may be necessary to fill the gap created in the top of the pavement with a rubberized sealant material, if the gaps are found to be significantly wide. To accommodate the angles created by horizontal curves, the side forms on casting bed can be angled slightly to create panels with slightly tapered sides to accommodate horizontal curves.

The scenarios presented here represent extreme situations and will probably not be encountered in an actual precast concrete pavement. However, this analysis has shown that the angles and gaps created are not extremely large and that measures can be taken to accommodate vertical and horizontal curves.

8.5 CROSS-SLOPE (SUPERELEVATION) CRITERIA

Another consideration for a precast pavement is the possibility of the panels sliding off the base material during construction or gradually over time. The friction-reducing medium greatly decreases the frictional resistance to sliding, which is beneficial for reducing stresses but may result in lateral sliding. To address this issue, the maximum allowable cross slope, before sliding will occur, was calculated. The coefficient of friction beneath the precast panels was assumed to be 0.2, as this was the minimum coefficient of friction determined from the cast-in-place prestressed pavement described in Chapter 2. The following relationship was used to determine the maximum cross-slope angle before sliding:

$$\frac{\mu_S}{FS} = TAN(\theta) \qquad (8.1)$$

where: μ_s = maximum coefficient of friction beneath the precast panels (0.2)
FS = factor of safety, assuming actual coefficient is less than 0.2
θ = cross-slope angle (from horizontal)

Figure 8.11 shows the relationship between the superelevation cross-slope angle and factor of safety. As this figure shows, even with a factor of safety of 4, the permissible cross slope is still nearly 5%. The AASHTO guide for geometric design of highways and streets (Ref 34) recommends a maximum cross slope of 2% for most high-surface-type pavements, and 4% for pavements with three or more lanes that receive intense rainfall. For intermediate surface types, the AASHTO guide recommends a range of cross slope between 1.5% and 3%. These values, which might be expected for a precast pavement application, are all well below the maximum calculated value of 5%, for a safety factor of 4. Therefore, for typical roadway construction, there should not be a problem with the precast panels sliding laterally off the base.

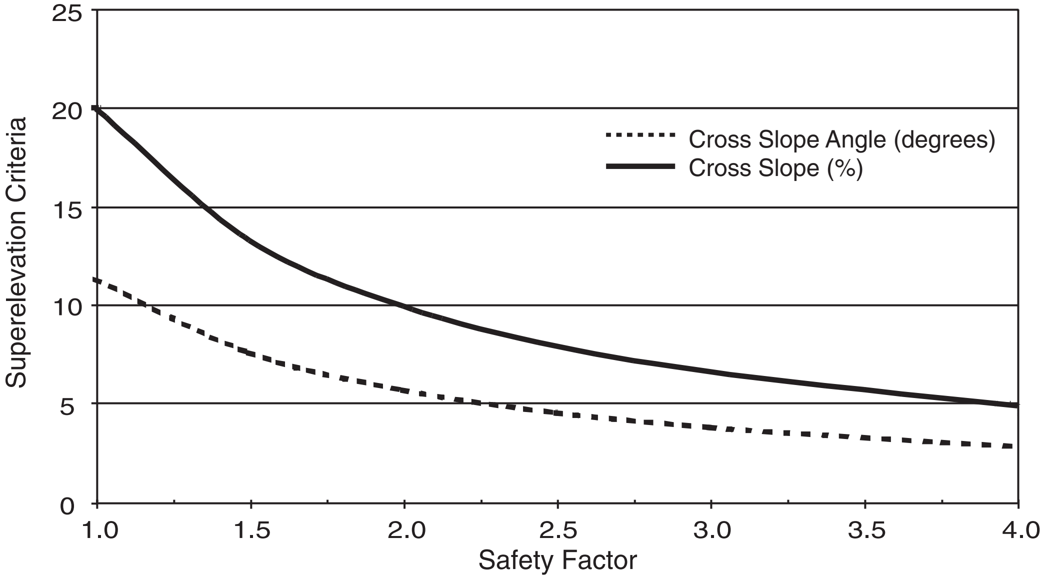


Figure 8.11 *Cross-slope criteria for precast panels assuming a coefficient of friction of 0.2*

8.6 VOIDS BENEATH PAVEMENT

It is inevitable that there will be some degree of unevenness in the asphalt leveling course. This unevenness may cause voids beneath a precast pavement. Because the panels are prestressed, they have the ability to “bridge” these voids, to a certain extent. However, if it is found that there are significantly large voids and/or a significant *number* of voids, these voids will need to be filled so that the panels are properly supported.

To get a general idea of expected void volumes, the profile data presented in Section 8.3.1 was analyzed to determine the approximate volume of voids beneath the section of pavement panels 250 ft long by 10 ft wide. Two different methods were used to fit 10 ft wide rigid "panels" on the profile data to represent precast pavement panels placed on an asphalt leveling course. For both methods the data was divided up into 10 ft segments to match the 10 ft wide panels.

The first method involved finding the least slope between any two data points in the 10 ft section and assuming that the panel would sit at this slope, resting on the high points of the profile. The second method used a trendline, or a best fit line, through the profile data to represent the 10 ft wide panel. Figure 8.12 shows a typical 10 ft segment of profile data with the "panels" superimposed using both methods. The area between the "panel" and the profile was used to determine the volume of voids beneath the pavement. The trendline method provided a lower bound estimate of the actual void area, as the "panels" tended to cut through, rather than rest on top of, the profiles, whereas the least slope method provided an upper bound estimate, as the panels tended to sit on top of the profile data. Adjoining panels were assumed to connect to each other at the ends, as would be expected in the actual pavement.

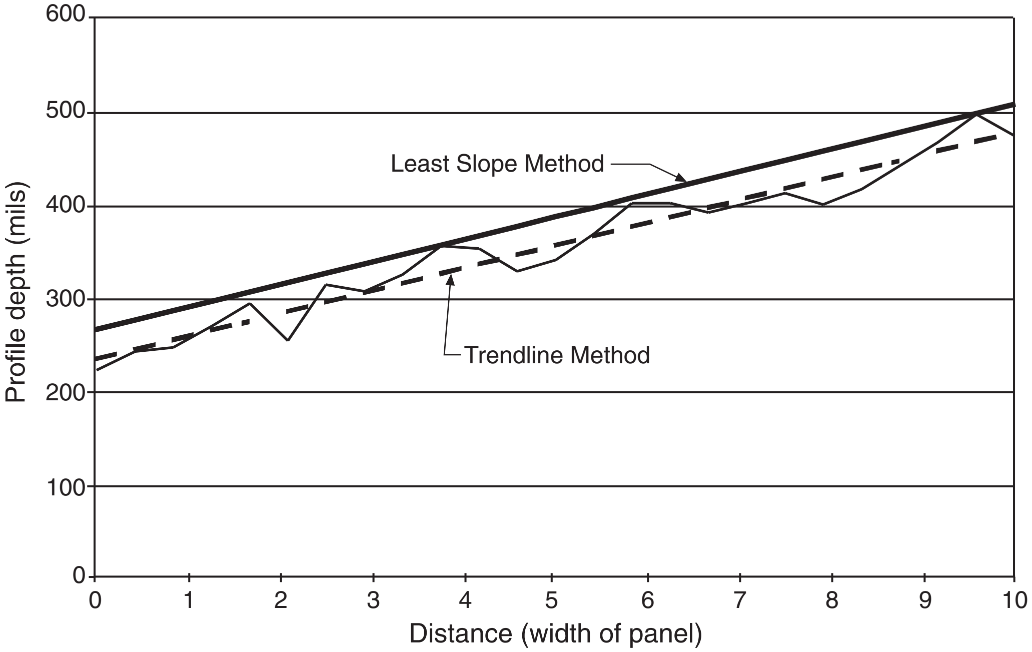


Figure 8.12 *"Panel" superimposed on profile data*

To calculate the volume, the area between the "panel" and the profile was determined, averaged over the eleven profiles, and then multiplied by the 10 ft width. As a check of a reasonable estimate of the void volume, a section of the profile was plotted on paper, and a straight line, representing a panel, was fit over the profile by hand. The area between the "panel" and the profile was then measured and calculated by hand. The area calculated by hand was very close to the value obtained by averaging the values from the two methods mentioned above. Therefore, the volume of voids beneath the pavement was taken as the average of the values found from the least slope and trendline methods.

Upon plotting the "panels" from least slope method superimposed on the profile data, it was found that the voids were significantly overestimated on some parts of the 250 ft section. To obtain a more reliable estimate, each profile was plotted, and the values from any part of the plot clearly in error were thrown out. The new values were then used as the upper bound estimate.

The results from the void volume analysis are shown below in Table 8.1. Void volume was determined for each 10 ft by 10 ft section of pavement for both the least slope and trendline methods. The values were then averaged over the 25 sections (250 ft of profile data) to give an overall average value for a 10 ft by 10 ft section. The values were then added to give the total volume for a 250 ft long by 10 ft wide section. As mentioned previously, the plots for the least slope method were checked and any clearly errant data was thrown out. This value was then averaged with the trendline volume to give an average for a 10 ft by 10 ft section. This value of 0.157 ft^3 is approximately 30% less than the value obtained before data was thrown out (0.228 ft^3) — and probably more reliable.

Table 8.1 *Comparison of calculated volumes*

Volume Determination	Volume (ft^3)
Average for 10 ft x 10 ft (least slope method)	0.409
Average for 10 ft x 10 ft (trendline method)	0.047
Average for 10 ft x 10 ft (average of two methods)	0.228
Total for 10 ft x 250 ft (least slope method)	10.236
Total for 10 ft x 250 ft (trendline method)	1.163
Total for 10 ft x 250 ft (average for two methods)	5.70
Average for 10 ft x 10 ft (after data thrown out)	0.157

This analysis has shown that the volume of voids beneath a precast pavement may be fairly significant. Using the final value (highlighted in Table 8.1) for the void volume beneath a 10 ft by 10 ft segment (0.157 ft^3), a 10 ft by 38 ft panel would average 0.6 ft^3 of voids, while a 250 ft section of panels would average 150 ft^3 of voids. However, this analysis does not show how the voids are distributed. Judging from the smoothness of the profile data, this void volume estimate represents mostly very small voids, which can be bridged by the panels. In essence, this analysis has given a worst case estimate of the void volume.

Void detection may require the use of special techniques, such as ground-penetrating radar. If it is determined that significant voids are present beneath a precast pavement, there are two options for addressing this problem. The first option is to fill the voids using either grout injection or an expansive urethane foam (described in Chapter 3). Either method will require drilling small holes through the pavement, which will require special attention so that the transverse or longitudinal prestressing strands are not affected. The second option is to simply increase the post-tensioning force to account for the increase in stresses caused by the voids.

8.7 REMOVAL AND REPLACEMENT

The construction sequence for a removal and replacement application is essentially the same as that for a new or overlay application, with a few minor differences. Since the finished precast concrete pavement must be level with the existing pavement, the panel thickness (and prestress) must be tailored to match the existing pavement thickness. For example, if an existing 8 in. pavement is removed, either 6 in. panels with a 2 in. asphalt leveling course or 7 in. panels with a 1 in. asphalt leveling course may be used to match the existing pavement thickness.

Once the precast pavement has been placed and post-tensioned, the gap between the new pavement and the existing pavement will be filled with a fast-setting concrete, similar to that used for the stressing pockets. This filler concrete will provide traffic with a transition from the existing pavement to the new pavement. When an adjacent precast pavement slab is placed at a later time, the filler concrete will be broken out along with the pavement being replaced.

In order to tie adjacent pavement slabs together, an additional post-tensioning duct will be cast into each panel in the transverse direction, as described in Chapter 5. This procedure will provide a means for post-tensioning adjacent slabs together, which is essential for keeping the longitudinal joint between the slabs closed and for providing load transfer across the longitudinal joint. Post-tensioning adjacent slabs together can be performed from the edge of the slab using a standard post-tensioning anchorage arrangement. The post-tensioning strands should be left unbonded, so that they can be removed when another slab is added. To ensure that the ducts from adjacent slabs line up, any new slabs should be placed from the center of the slab (central stressing panel first) out to the expansion joints, so that the middle of the slab does not move.

All other aspects of a removal and replacement application will be the same as that for a new or overlay application. The asphalt leveling course, polyethylene sheeting, panel layout, and post-tensioning requirements will be the same as those described in Chapter 5.

Chapter 9. Feasibility Analysis: Economics and Durability

9.1 LIFE CYCLE COST

Life cycle cost analysis is used to quantify the long-term costs of a pavement over its design life. These costs account for the initial quality and strength of design, maintenance and rehabilitation, and the financial impact on the motoring public (Ref 35). The initial quality and strength of design will determine the design life of the pavement. Maintenance and rehabilitation costs will be determined by the durability of the pavement. The financial impact on the motoring public will be determined by, among many other variables, increased fuel consumption and travel-time delays. This latter aspect, often termed *user delay costs,* is where the economic benefits of expedited construction, through the use of precast concrete pavement, will be realized.

Owing to the lack of experience with precast pavements, it is difficult to quantify the maintenance and rehabilitation costs. However, based on the performance of the cast-in-place prestressed concrete pavement in McLennan County, maintenance and rehabilitation costs of a precast pavement should be minimal. For the purposes of analysis, however, maintenance and rehabilitation costs will be assumed to be equivalent to that of a conventional pavement. In addition, since the precast concrete pavement, presented in Chapter 7, was designed for an equivalent design life to a CRCP, the initial quality and strength of design will also be assumed to be the same as that of a conventional pavement.

With these assumptions in mind, user delay costs for precast pavement construction will be compared to those for conventional pavement construction. User costs are, essentially, indirect costs to the users of the roadway. Such costs include those costs associated with traffic delays (e.g., longer commute time and increased fuel consumption). The purpose of precast pavement construction is to minimize, or even eliminate, these traffic delays and, hence, user costs imposed by construction.

Conventional pavements require traffic diversion off of part of or all of a roadway during construction. Diverting traffic reduces the number of lanes open to traffic, thus causing delays when traffic volumes are high. Figure 9.1 shows a typical weekday hourly traffic volume distribution for a roadway very near, or slightly over, capacity during rush-hour periods. The hatched area of the figure represents overcapacity for the roadway (which results in traffic delays). As Figure 9.1 shows, when roadway capacity is reduced as a result of the construction of conventional pavement, the roadway reaches overcapacity during peak traffic times, thereby increasing traffic delays.

The fact that a precast concrete pavement can be placed quickly and exposed to traffic immediately after construction lends it to overnight operations, when traffic volumes are low. Figure 9.2 shows the significant reduction in overcapacity for a precast concrete pavement constructed between 8:00 p.m. and 6:00 a.m. For this type of construction, there will be very minimal, if any, delays owing to construction.

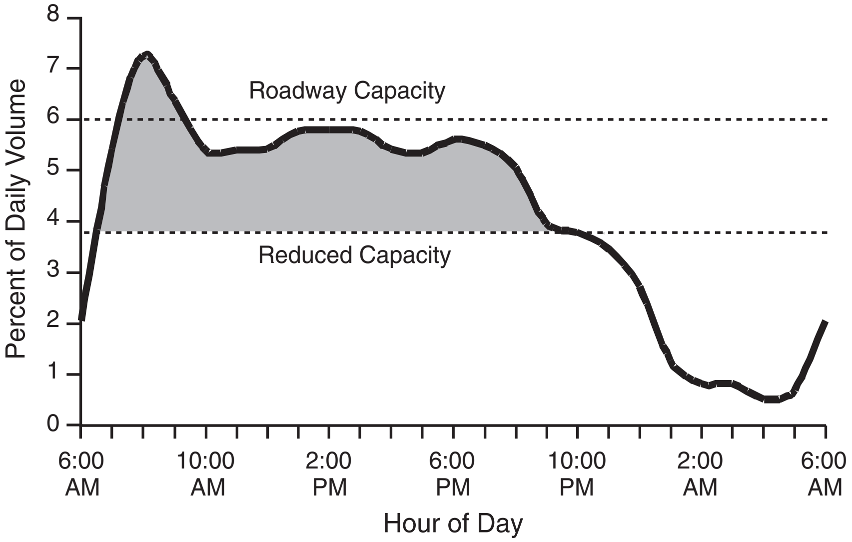


Figure 9.1 *Overcapacity created by conventional pavement construction*

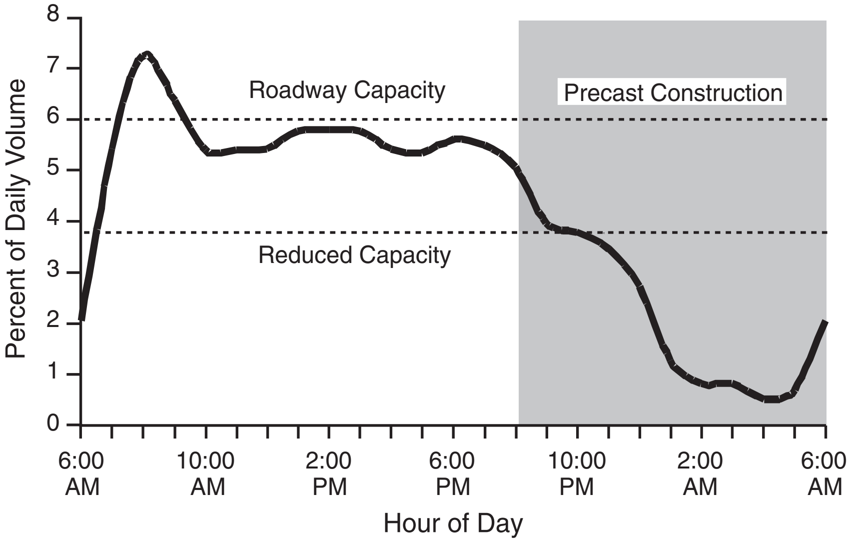


Figure 9.2 *Overcapacity created by overnight precast pavement construction*

In order to quantify the difference in user costs resulting from the reduction in overcapacity through precast construction, the computer program QUEWZ, which was developed by the Texas Transportation Institute (College Station, Texas) and later modified by Transtec, Inc. (Austin, Texas), was used to calculate expected delay time, which can be expressed as a cost to the user in dollars per day (Ref 35).

For the purposes of analysis, the following general assumptions were made:

1) Work zone/project length = 5 miles
2) Four-lane freeway, median separated, with frontage roads
3) ADT = 50,000 – 105,000 vehicles per day (urban principal arterial — Interstate)

4) Vehicle Mix: 25% trucks
5) One side of freeway reconstructed at a time

The 5 mile work zone was chosen as a possible average work zone length for medium-sized projects. The median-separated, four-lane freeway with frontage roads was chosen because it is a type of urban freeway commonly found in Texas. The ADT range of 50,000 – 105,000 vpd (both directions) is a likely range for urban principal arterial interstates in Texas. The vehicle mix of 25% trucks is very common as well, since NAFTA trade with Mexico is increasing the number of heavy trucks traveling on Texas highways.

In addition to those assumptions applicable to both construction methods, certain assumptions were needed for each of the methods. First, for precast construction:

1) Construction during night only
2) Traffic diverted only from 8:00 p.m. to 6:00 a.m.
3) Two traffic diversion strategies:
    - Diversion to opposing lanes (one lane open in each direction)
    - Diversion to frontage road; speed limit on frontage road = 45 mph (one lane open for diverted traffic, two lanes open for opposing traffic)

For conventional concrete pavement construction, only one assumption was needed: Conventional pavement construction will require 24 hour traffic diversion, since the concrete requires time to reach strength before traffic can be allowed back onto the pavement. The actual work might only occur for 10–12 hours a day, but the traffic diversion (one lane open in each direction) must be in place 24 hours a day.

Several runs were made using QUEWZ for varying ADT values and for the three traffic diversion strategies discussed previously. The first run corresponded to using precast construction with one lane open in each direction from 8:00 p.m. to 6:00 a.m. daily. The second run focused on precast construction with traffic diverted to the frontage road, also from 8:00 p.m. to 6:00 a.m. Finally, the third run corresponded to conventional pavement construction, with one lane open in each direction 24 hours a day. Table 9.1 and Figure 9.3 show the results from this analysis. Note the log scale for daily user costs in Figure 9.3.

Table 9.1 *Daily user delay costs for precast and conventional pavement construction*

Construction Method	Precast 1-1	Precast 2-1 (frontage road)	Conventional
User Delay Costs ($/day)			
50,000 vpd	$1,810	$1,670	$383,700
105,000 vpd	$124,500	$63,740	$680,610

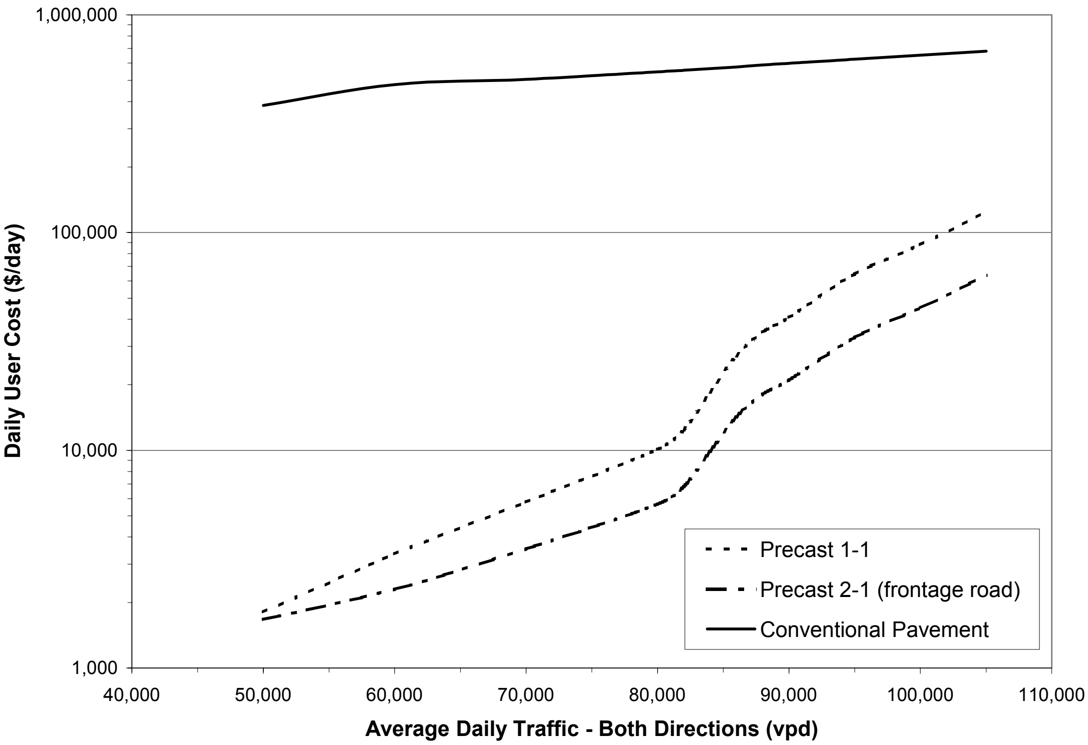


Figure 9.3 *User costs for precast versus conventional pavement construction on an urban principal arterial for varying ADT (Note: Log scale on the ordinate axis)*

Table 9.1 and Figure 9.3 clearly demonstrate that the overnight precast pavement construction process results in a significant reduction in traffic delays, which in turn results in substantially lower user costs. This, again, is a consequence of being able to allow traffic back onto the pavement between construction sequences, when traffic volumes are highest. Although, as mentioned before, it may not be possible to place as much precast pavement as conventional pavement in one day, the savings in user costs are still very substantial. Considering the example presented above, if a placement rate of 2,000 ft per day is assumed for conventional pavement and 500 ft per day for precast pavement, it will take approximately 20 days to place 5 miles of conventional pavement (including an additional 7 days of set time after placement of the final 2,000 ft), and approximately 53 days to place 5 miles of precast pavement. However, as Table 9.2 shows, even under a worst case ADT scenario of 105,000 vehicles per day, the total user costs are still more than twice as much for conventional pavement construction as that for overnight precast pavement construction.

Table 9.2 *Total user delay costs for precast and conventional pavement construction for a 5 mile pavement with an ADT of 105,000 vehicles per day*

Construction Method	Placement Rate	Daily User Cost	Total Construction Time	Total User Cost
Conventional Pavement (CRCP, JRCP)	2,000 ft/day	$680,610	20 days	**$13,612,200**
Precast Pavement	500 ft/day	$124,500	53 days	**$6,598,500**

For a removal and replacement application, it may be necessary to divert traffic over a full weekend, owing to the additional construction time required for removal of the existing pavement. To quantify the user delay costs for this scenario, QUEWZ was again used following the general assumptions given above. However, for this analysis, traffic was only assumed to be diverted to the opposite side of the roadway, providing one lane in each direction. Traffic diversion was assumed to occur from 8:00 p.m. Friday night to 6:00 a.m. Monday morning. Based upon these assumptions, the total user delay cost for weekend construction was found to range from $713,700 (for the entire weekend) for an ADT of 50,000 vehicles per day, to $1,527,540 for an ADT of 105,000 vehicles per day. This delay cost, however, is not dependent on whether precast or conventional (using fast-setting concrete) pavement construction is used. The difference in cost will be realized only through the material and construction costs.

Another consideration with regard to user costs, discussed previously in Section 8.3.9, is the fact that precast pavement placement should not be affected by adverse weather conditions (as are conventional pavement placements). Precast pavement can be placed under moderate precipitation and under extreme temperature conditions that would restrict the placement of conventional pavement. This option will allow for much more flexibility with precast pavement placement and can eliminate construction delays, commonly experienced during conventional pavement placement, caused by inclement weather conditions.

Although the examples presented here are simplified, this analysis has shown that user delay costs resulting from construction can be very substantial, depending on when traffic is diverted. Clearly, overnight construction is desirable, as it greatly reduces any delays caused by overcapacity. Weekend construction, which will result in fairly substantial user delay costs, may be necessary for removal and replacement applications.

9.2 ECONOMIC ANALYSIS

The economic analysis is a comparison of considerations for the overall cost of a precast concrete pavement as compared to the costs of conventional concrete pavements. This analysis includes the initial construction costs as well as the user delay costs resulting from construction, as previously discussed. At this point, it is difficult to quantify other life cycle costs, such as maintenance costs, owing to the lack of experience with precast concrete pavements. It will be assumed that the maintenance costs for a precast pavement are essentially the same as those for conventional pavements with the same design life, even though it is anticipated that a precast concrete pavement will require significantly less maintenance.

It is important for precast concrete pavement to be economically feasible. If the overall cost of a precast concrete pavement is significantly greater than that of a conventional pavement, it will not be practical to construct. Even though it has been shown that there is a significant savings in material (concrete), the initial construction costs for precast pavement will inevitably be higher, owing to the additional cost of the expansion joints and fabrication and transportation, among other costs.

9.2.1 Conventional Pavement Construction

The main advantage of conventional pavement construction is that the methods and materials are fairly standardized and accepted. This increases the amount of pavement that can be placed over the course of one day, while also decreasing the cost of the pavement. Some of the major cost components of conventional pavement construction are listed below:

- reinforcing steel/steel placement
- side forms (for fixed-form paving)
- paving equipment
- joint saw
- dowels (for jointed pavements)
- curing equipment/materials

Conventional concrete pavements require several days or weeks for the concrete to reach sufficient strength for traffic to be allowed back onto it. Because of this, traffic must be diverted 24 hours a day during construction. As shown in Table 9.1, this diversion can result in substantial user delay costs for heavily trafficked roadways. It is possible to use high-early-strength concrete in conventional pavements so that the concrete will reach adequate strength in less than 24 hours. High-early-strength concrete, however, will substantially increase initial construction costs.

9.2.2 Precast Pavement Construction

Precast concrete pavement construction will, invariably, cost more than conventional pavement construction owing to the additional materials and procedures required. Some of the major cost components of precast pavement construction are listed below:

- panel fabrication (pretensioning and keyed edges) and transportation
- pretensioning/post-tensioning steel
- ducts
- post-tensioning anchorage material
- expansion joints
- joint sealant
- grouting tendons
- fast-setting concrete (for stressing pockets)
- asphalt concrete leveling course
- polyethylene sheeting
- handling equipment

Clearly there is a lot more to precast concrete pavement construction compared to conventional concrete pavement construction. The main advantage to precast pavement construction, however, is how quickly traffic can be allowed back onto the pavement. While it may not be possible to place as much precast pavement as conventional pavement over the course of one day, traffic can be turned back onto a precast concrete pavement in between construction sequences. Therefore, it is possible to construct a precast concrete pavement in separate overnight operations, allowing traffic back on the pavement during the day, when traffic volumes are highest.

Precast concrete pavement can also be used for weekend construction operations, as might be required for removal and replacement applications. Although this will result in higher user delay costs, the initial construction cost will be significantly less than a conventional concrete pavement using fast-setting concrete.

9.3 DURABILITY

Durability is essential for ensuring that a pavement will achieve its full design life with minimal life cycle maintenance. Most pavements are constantly subjected to aggressive environments. In particular, pavements in colder regions are subjected to freeze-thaw cycles and to such corrosive agents as deicing salts. Precast (prestressed) concrete pavements are particularly susceptible to aggressive environments owing to the nature of the reinforcement in the pavement.

There are several measures that can be taken to ensure the durability of precast concrete pavements. These measures include using a suitable aggregate and concrete mix, protection of the prestressing steel and anchorage, and using durable expansion joints. These measures will be discussed below.

9.3.1 Concrete/Aggregate

The use of a suitable aggregate and concrete mix can greatly enhance the durability of concrete pavements. Research conducted at the Center for Transportation Research has shown that pavements consisting of concrete with a low ($< 5 \times 10^{6}$ in./in./ºF) coefficient of thermal expansion (COTE) tend be more durable, showing less cracking and overall failures than pavements with a high ($> 5 \times 10^{6}$ in./in./ºF) COTE (Ref 50). Lower COTE concrete reduces the amount of expansion and contraction movement of precast pavement slabs, thereby reducing the stresses generated from frictional resistance to slab (contraction) movements at the slab-base interface.

It is also desirable to use a concrete mix with a very low permeability. Such a mix will prevent chlorides and other corrosive agents from penetrating the concrete and reaching the prestressing steel in the pavement. Low permeability will also reduce moisture gradients in the pavement (moisture gradients can lead to warping, as discussed in Chapter 6). The use of mineral admixtures, such as silica fume or fly ash, in the right proportions will significantly reduce the permeability of concrete. The requirements for water-cementitious materials (which include silica fume and fly ash) should conform to the limits given in Chapter 4 of the ACI Building Code (Ref 21) and Chapter 1 of the PCI Design Manual (Ref 32). These requirements are specific to the exposure conditions of the pavement, which include freeze-thaw exposure, sulfate exposure, and deicing chemical exposure.

Air entrainment will also increase the durability of concrete exposed to freezing and thawing or to deicing chemicals. The requirements for air content should conform to the recommendations of Chapter 4 of the ACI Building Code and Chapter 1 of the PCI Design Manual.

Durability and abrasion resistance of the pavement surface should also be criteria for selecting the aggregate/concrete mix for a precast pavement. As discussed in Section 3.2.3.2, harder fine aggregates, which are in short supply in many areas, could be used at least in the top of the precast panels to provide the necessary abrasion resistance, while local softer aggregates, which are more readily available, could be used in the bottom of the panels. Precasting also allows for the use of smaller aggregates. While larger (2 in.) aggregates are required in conventional pavements to ensure aggregate interlock at cracks and joints, smaller aggregates can be used in precast pavement, as the prestress in the pavement will prevent cracks from opening up. Precasting in a controlled environment allows for this sort of flexibility in varying concrete mixes — a flexibility not possible with conventional pavement.

One inherent advantage of a precast concrete pavement with respect to durability, discussed previously in Chapter 6, is the fact that the precast panels will have a very low moisture gradient over the depth of the panels. This is due to the fact that both sides of the panels will be exposed and allowed to "dry out" after they are stripped from the casting bed. A low moisture gradient will reduce stresses generated in the panels from moisture curling and warping, which can be very significant.

9.3.2 Prestressing

Prestressing strand is made from high strength steel generally specified as Grade 270, meaning a minimum guaranteed breaking stress of 270 ksi. Seven-wire strand is currently used almost exclusively for precast and prestressed concrete structures in the United States (Ref 36). Low relaxation strand has also progressively replaced the use of stress-relieved strand. Prestressing strand is also somewhat flexible, thus facilitating the threading of the post-tensioning strands through the ducts in a precast pavement.

Protection of the prestressing strands and hardware — the anchorage, couplers, and both the pretensioning and post-tensioning strands — is essential for maintaining a durable precast concrete pavement. Protection of reinforcement is primarily provided by embedment in the concrete. A protective film forms on the surface of the steel as a result of the high alkalinity of the cement paste. However, this high alkalinity can be lost in the presence of oxygen, moisture, and chlorides (Ref 32). To protect the steel from these agents, concrete having a low permeability should be used. Corrosion inhibitors can also be added to the concrete mix to reduce or prevent corrosion of embedded metals. In addition, sufficient cover should be provided over the reinforcement. The Precast and Prestressed Concrete Institute provides minimum cover requirements in Section 1.3.4 of the PCI Design Handbook (Ref 32). Epoxy-coated strand and anchorage is also available but can be cost-prohibitive. In particularly aggressive environments, however, the use of epoxy-coated strand may be required.

9.3.3 Joints

Joint durability is critical for prestressed (precast) concrete pavements. Replacing expansion joints can be very costly, particularly when the prestressing tendons are anchored at the expansion joint. The four cast-in-place prestressed concrete pavements projects that were constructed prior to the development of the McLennan County prestressed pavement (Chapter 2) all experienced durability problems with expansion joint details (Ref 6). The expansion joint detail developed for the McLennan County pavement, shown in Chapter 5, was a refinement of some of the ideas borrowed from these previous pavements. At the time of this report, this expansion joint detail has shown virtually no signs of distress after 15 years in service. Minimal maintenance, such as cleaning debris out of the expansion joint, has been the only maintenance required. Based on these observations, this expansion joint detail should perform just as well for a precast concrete pavement.

Using galvanized steel in the expansion joint detail will protect the steel joint from corrosion, particularly when it is used in an aggressive environment. The dowel within the expansion joint should be stainless-steel plated, as shown in Chapter 5. Corrosion could cause the dowels to seize up in the dowel sleeve, preventing the expansion joint from opening or closing.

9.3.4 Grouted Tendons

Grouted tendons have been found to enhance the durability of prestressed concrete structures. Grouting the strands in the ducts ensures continuity between the concrete and steel strands. More importantly, however, grouting provides an additional layer of protection from corrosion. In order for grouting to be effective, proper procedures must be followed, including the use of a suitable grout, proper materials, and sound construction methods.

The requirements for a suitable grout mixture include minimal bleed, good flowability, and minimal expansion and shrinkage. Bleed occurs when water comes out of solution with the grout (owing to the higher density of the grout material), leaving air voids in its place when the water evaporates or seeps out of the duct. Good flowability is important for ensuring that the grout fills the entire duct and completely surrounds the strand. Minimal expansion and shrinkage is important so that the pavement is not damaged by expansion of the grout and air voids are not left from shrinkage of the grout. The grouting material predominantly used for bonded post-tensioning tendons has a water-cement ratio of 0.45 or less, and a combination of mineral and chemical admixtures (Ref 37). The purpose of the admixtures is to tailor the grout to the flowability, bleed, and shrinkage requirements for the job.

Extensive research on grouted post-tensioned tendons was carried out at the Ferguson Structural Engineering Laboratory at The University of Texas at Austin. This research revealed that, for horizontal applications (such as a precast pavement), the optimal grout mixture has a water-cement ratio of 0.35, contains 4 ml/kg of a superplasticizer chemical admixture, and has 30% fly ash mineral admixture (Ref 38). This grout mixture was found to have good flowability characteristics, with low bleed and, essentially, no shrinkage.

Adequate venting is another important factor for grouting. Venting should be provided at the ends of continuous sections of the duct to allow the air displaced by the grout to escape. Grout should continue to be pumped into the duct until there are no visible slugs of air or water ejected from the duct and the efflux time of the ejected grout is no less than the injected grout (Ref 22). This precaution will ensure that all of the air and any water that may have come out of solution has been removed from the duct. Air and water left in the duct tend to create voids that may collect water and contribute to strand corrosion. By following simple, standardized procedures, grouting the post-tensioning tendons should significantly increase the durability of precast concrete pavements.

9.3.5 Anchorage

The proposed post-tensioning anchorage is a modified version of standard post-tensioning anchorage. The durability of the anchorage should be just as good as that of standard post-tensioning anchorage. Protection of the anchorage from corrosion will be provided by embedment in the concrete. If the pavement is placed in a particularly aggressive environment, it may be necessary to use encapsulated anchorage. However, the anchorage is required only to sustain the full prestress force until the strands are grouted in the ducts. After grouting, transfer of prestress to the pavement will be provided by bond between the strand and grout.

Chapter 10. Recommendations for Additional Investigation and Implementation

10.1 INTRODUCTION

Looking to the future, the researchers recommend that implementation be carried out in two phases: preliminary and full-scale implementation. During the preliminary implementation phase, the features requiring additional investigation should be resolved and details worked out in pilot projects. The findings from the preliminary implementation should then be incorporated in the full-scale implementation.

Table 10.1 (at the end of this chapter) summarizes the tasks that must be carried out during each of the implementation phases. Preliminary implementation includes any lab testing, such as that of the self-locking anchor and strand placement (pushing the strands into the anchors), and pilot projects, which will investigate many of the items presented in the following section. Full-scale implementation will apply all of the techniques, tested and refined during preliminary implementation, to large-scale projects in rural and urban areas.

During each of the three implementation projects (pilot, rural, and urban), the design methodology described in Chapter 7 will be applied to determine slab thickness, slab length, prestress levels, and joint details for each of the site-specific projects. In addition, the three different applications (new pavement, unbonded overlay, and removal and replacement) will be examined during each of the implementation projects. As mentioned previously, the majority of the investigation will take place prior to and during the pilot project. However, certain items of investigation, such as void treatment, and performance monitoring, which will be described in Section 10.4, will be considered through both preliminary and full-scale implementation.

10.2 ADDITIONAL INVESTIGATION

Many of the aspects for a precast concrete pavement (presented in Chapter 5) have been tested and proven in previous projects; these aspects include the use of central stressing, polyethylene sheeting, and the expansion joint detail. However, there are several aspects that are only conceptual and should therefore be investigated further. Many of these aspects, discussed in the following sections, are adaptations of existing technology or practice that should be viable for a precast pavement.

10.2.1 Effect of Stressing Pockets on Handling

One of the issues discussed in Chapter 5 was the perforation weakness effect of the stressing pockets on the central stressing panels. This is a concern not only for ensuring that the pavement will not fracture across the stressing pockets when it is post-tensioned, but also for ensuring that the central stressing panels are strong enough for handling. If the pockets are too close together, or if they are not staggered sufficiently, these problems could occur. The possibility of using more than one central stressing panel was mentioned as a possible solution. Ultimately, this issue needs to be investigated further and actually tested in the field to determine an optimum configuration for the stressing pockets and central stressing panel(s).

10.2.2 Panel Alignment and Asphalt-Leveling Course

Keyed panel edges should ensure that the panels are aligned vertically so that a smooth riding surface is provided. Although keyed edges have been used successfully in segmental bridges and bridge deck panels (see Chapter 2), there is no evidence of the use of keyed panel edges for post-tensioned concrete pavements. Therefore, the viability of using keyed panel edges to provide the necessary vertical alignment for a precast pavement should be investigated.

There is also no evidence of the use of an asphalt-leveling course for precast concrete pavements. From the feasibility analysis presented in Chapter 8, however, the use of a thin asphalt-leveling course appears to be a feasible method for providing a smooth and flat surface to place the panels on. Ultimately, the only way to test this idea is through the construction of an actual precast concrete pavement that incorporates an asphalt-leveling course.

10.2.3 Strand Placement/Anchorage

Another aspect of the proposed concept that must be investigated prior to large-scale construction involves the strand placement techniques and the strand anchorage. Threading post-tensioning strands through a long duct (up to 220 ft) may prove to be very difficult. A procedure for either pushing the strands from the central stressing pockets or for pulling the strands from a gap between the joint panel and adjacent base panel should be investigated.

The self-locking strand anchor must also be tested. The proposed anchor already exists, but the details of using this anchor are not yet known. The method for inserting the strands in the anchors should also be tested to ensure that it is efficient and reliable. If an anchor fails to work in an actual pavement, major delays in construction may result. Both anchorage methods, described in Chapter 5, should be investigated during preliminary implementation.

10.2.4 Mid-Slab Anchor/Expansion Joint Clamp

As described in Chapter 8, a mid-slab anchor is needed at or near the central stressing panel(s) to prevent the center of the slab from moving as the pavement expands and contracts. An efficient method for anchoring must be developed prior to construction of a large-scale pavement. Possibilities include driving stakes or dowel bars into the base material at the stressing pockets, or using a core drill to drill a small pile into the base material at the stressing pockets, which would subsequently be filled with concrete when the pockets are filled.

Also, as described in Chapter 8, a method for clamping the expansion joint during post-tensioning must be developed. Such a method would prevent the expansion joint from being pulled open as the individual slabs on either side of the expansion joint are post-tensioned. Possibilities include tack-welding steel plates across the expansion joint or using clamps bolted onto the edges or top of the joint panel on either side of the expansion joint.

10.2.5 Different Aggregates Used in the Panels

Since the panels will be cast in a controlled environment, concrete mixes can be adjusted and proportioned as desired. There are four issues related to the aggregate that should be investigated. These issues are (1) the use of smaller aggregates, (2) the most effective aggregate for skid resistance, (3) the most effective aggregate to use if grinding is required, and (4) the use of lightweight aggregate.

Concrete pavement specifications require that larger coarse aggregate sizes (1–2 in.) be used to provide better aggregate interlock when cracks and joints open up. Since post-tensioning will be incorporated in a precast concrete pavement, however, cracks will not open up as much, if at all, and hence larger aggregate sizes may not be required. Less gradation of the aggregate will reduce the cost of the concrete mix, thus reducing the cost of the pavement. In addition, precast plants typically use only smaller aggregates (less than 1 in.), and may not be equipped to handle larger aggregates.

The type of fine aggregate used affects the skid resistance of a pavement surface. Concrete pavements with softer fine aggregate are susceptible to surface polishing, which greatly reduces skid resistance in wet — and even dry — conditions. Therefore, from the standpoint of skid resistance, a harder fine aggregate is desirable for use in a concrete pavement. A combination of the two aggregates could provide a practical solution. Softer, more readily available fine aggregate could be used in the bottom half of the pavement where skid resistance is not an issue. Harder fine aggregate, which may be limited in supply, could then be used in the top half of the pavement (the riding surface) to provide better skid resistance.

In order to provide a smooth riding surface, grinding the pavement surface may be required. This is typically done using a "bump-cutter" or diamond-grinding machine. The harder the aggregate in the concrete, however, the harder and more expensive it is to grind the pavement. Therefore, it is more desirable to use a softer aggregate in the top of the pavement where grinding is done.

Lightweight aggregate will greatly reduce the weight of the precast panels, which will result in cost savings because more lightweight panels than normal-weight panels can be transported on each truck. This lighter weight may also allow larger panels to be used. Lightweight aggregates have been studied extensively and have proved to be just as durable as normal-weight aggregates. Casting the panels in a controlled environment should provide the necessary quality control required for lightweight concrete. Further investigation of each of these four issues will help determine the most viable solution for the optimum aggregate to be used in a precast pavement.

10.2.6 Performance of Joints

The proposed expansion joint detail has proved to be durable and effective in the cast-in-place prestressed concrete pavement in McLennan County, Texas. The joint has required minimal maintenance over the 15 years it has been in service. The specifications for this joint detail, however, should be investigated for use in a precast concrete pavement. Such a specification should include the length of the Nelson deformed bars, the size of steel angles to be used, the type of dowel bars, and the type of neoprene seal.

In addition to the expansion joints, the intermediate joints should also be investigated, including the type of sealant material for use in the joint, the type of ducts (whether keyed or flared at the joint), and any other provisions, such as a strip of heavier plastic under the joints and accommodation of vertical curves.

10.2.7 Filling Voids with Grout/Urethane Products

The most effective method for filling large voids beneath precast concrete pavements should be investigated. A method for detecting voids, such as ground-penetrating radar, can be used to determine the magnitude of any voids beneath the pavement. From that point, either grout or urethane can be injected to fill those voids. Although grouting is a fairly standard method, expansive urethane foam can be just as effective. Uretek USA, Inc., of Sugar Land, Texas, has developed a controlled and efficient method for injecting an expansive polyurethane foam beneath concrete slabs through a ½ in. diameter hole to fill voids.

10.2.8 Offsetting Voids with Increased Prestress

As described in Chapter 8, the other option for accounting for the effects of voids beneath a precast pavement is to increase the post-tensioning force in the pavement. The amount of increased prestress for various void conditions should be determined during the investigation phase of the project.

10.3 IMPLEMENTATION STRATEGY

As mentioned at the beginning of this chapter, a staged implementation strategy is recommended for the proposed concept. Staged implementation will allow for any problems with the proposed concept to be worked out in smaller, low-profile projects prior to construction of a large-scale, high-profile project. Staged implementation will start with small pilot projects so as to work out the minor details of precast concrete pavement construction. A rural application will then be undertaken to test the concept on a larger scale. Finally, an urban application will provide the ultimate implementation scenario.

10.3.1 Pilot Project

The pilot projects should be small-scale projects used to work out the procedural/assembly details of precast concrete pavement construction. The pilot sections should be constructed in a location where they will have minimal, if any, impact on traffic, such as on frontage roads or rest area/weigh station ramps. Such locations will ensure that any delays in construction owing to unexpected difficulties will not affect the roadway users. The pilot projects will help to fine tune the proposed concept and determine the best way to streamline the construction process to maximize the amount of precast concrete pavement that can be placed.

Any testing, such as that for the strand anchorage, should be completed prior to construction of the pilot sections. The pilot projects will then focus on testing the feasibility of implementing aspects, such as the asphalt-leveling course mentioned in the previous section. Any improvements to the proposed concept should be realized during the pilot projects.

10.3.2 Rural Application

Rural application will be used to apply the proposed concept on a larger scale, incorporating any modifications realized through the pilot projects. The rural application will be a test of how quickly and efficiently a precast concrete pavement can be placed. The application should focus on completing pavement placement under a time constraint, such as an overnight operation. Because the pavement will be constructed in a rural area, however, traffic disruptions caused by unexpected problems will be minimized.

10.3.3 Urban Application

Urban application will be the final and most challenging test of precast concrete pavement implementation. The urban application should be constructed at an intersection or on a major arterial roadway where traffic disruptions cannot occur during peak traffic times. From the pilot project and the rural application, the physical details and construction sequence should be worked out. The focus will be on resolving issues associated with urban pavements, such as incorporating curb and gutter, manholes, and tying into existing pavements. Some of these issues may also be investigated on a smaller scale during the pilot projects.

10.4 PERFORMANCE MONITORING

Performance monitoring will provide information on how an actual precast concrete pavement behaves in comparison to behavior predicted by computer modeling during the design phase. There are several aspects that must be monitored, including environmental and behavioral variables. These aspects will be described below.

Fabrication Conditions

Fabrication conditions will affect the quality of the precast concrete panels. Conditions that should be monitored include concrete strength (at removal from forms and at 28 days), casting/curing conditions (temperature, humidity, method for curing), applied prestress, and storage conditions.

Temperature

Ambient temperature will have an effect on the expansion and contraction movements of the pavement. Ambient temperature should be monitored at the time of placement and at any other time slab movement is measured. Pavement temperature at the bottom, top, and mid-depth should also be monitored. Pavement temperature differentials will affect curling movements and stresses in the pavement.

Horizontal Slab Movement/Joint Width

Joint widths should be continually monitored at construction and over the life of the pavement to determine the amount of horizontal slab movement (expansion and contraction). Several locations along the length of the slab should also be monitored for horizontal movement. Slab movement and joint widths should be monitored at various times of the day (and night) and during various seasons (summer and winter).

Vertical Slab Movement (Curling)

Vertical slab movements should be monitored to determine the magnitude of any curling movements. Vertical slab movements essentially need to be checked only at the ends of the slabs, at the expansion joints. Like the joint widths, vertical movement should be checked at various times of the day during various seasons.

Cracking/Distresses

Any cracking or obvious distresses, such a spalling, should be recorded and carefully monitored. The width and length of any cracks should be continually monitored, particularly if they develop soon after placement. Weaker areas, particularly around the stressing pockets and at the joints, should be constantly checked.

Joints

Expansion joints should be continually monitored to ensure that there are no signs of distress and that the joints are behaving properly. The neoprene seal and the cavity below the seal should be checked regularly for debris trapped in the joint. The intermediate joints should also be checked to ensure that the sealant material remains intact and properly seals the joints.

Performance monitoring, according to the variables just discussed, will provide information for calibrating the models used for design, as well as information on the durability of the proposed concept. Precast concrete pavements should be monitored closely during construction and over the first several months after construction. Monitoring should continue over the design life of the pavement, though to a lesser extent.

Table 10.1 *Summary of investigation for the staged implementation strategy*

	Investigation Item	**Preliminary Implementation**		**Full-scale Implementation**	
		Lab Testing	***Pilot Projects***	***Rural Project***	***Urban Project***
	Slab Length		✔	✔	✔
	Prestress Level		✔	✔	✔
	Joint Details		✔	✔	✔
Investigation	*Effect of Stressing Pockets*		✔		
	Panel Alignment		✔		
	AC Leveling Course		✔		
	Self-locking Anchor	✔	✔		
	Strand Placement	✔	✔		
	Mid-slab Anchor		✔		
	Expansion Joint Clamp		✔		
	Aggregates		✔		
	Filling Voids/ Adding Prestress		✔	✔	✔
	Performance Monitoring		✔	✔	✔
Application	*New or Overlay*		✔	✔	✔
	Removal & Replacement		✔	✔	✔

Chapter 11. Conclusions and Recommendations

11.1 SUMMARY

This feasibility project has demonstrated that it is possible to expedite the construction of portland cement concrete pavements through the use of precast concrete panels. While the construction process is quite different from that of conventional pavements, the concepts should be easily adaptable to current practices. The following is a summary of the important aspects of a precast concrete pavement presented in preceding chapters.

In Chapter 2, the results of the literature review were presented. The literature review proved very beneficial for examining previous precast pavements constructed around the world, and for determining the current state of the art in the precast industry. Some of the concepts from the literature, particularly from the cast-in-place prestressed pavement constructed in McLennan County, Texas, were incorporated in the final proposed concept. The literature should also be beneficial for future implementation.

Chapter 3 presented the significant findings and recommendations from the two expert panel meetings. These meetings were very beneficial for generating and refining the proposed concept to make it practical for construction and appealing to contractors and transportation agencies.

Chapter 4 discussed and evaluated the different pavement types that could be used for precast concrete pavement construction. The pavement types were evaluated on the basis of design and constructibility. In addition, cross-section strategies for each of three common applications (new pavements, unbonded overlays, and removal and replacement) were also presented.

In Chapter 5, the proposed concept for a precast concrete pavement was presented. The concept consists of base panels, joint panels, and central stressing panels placed on a thin asphalt-leveling course with a single layer of polyethylene sheeting provided as a friction-reducing medium. The panels have continuous shear keys cast into the edges to aid with alignment of the panels during assembly. The panels are all pretensioned during fabrication in the transverse direction, and post-tensioned together in the longitudinal direction, after they are all set in place. The post-tensioning strands are inserted through the stressing pockets and threaded through ducts to self-locking, post-tensioning anchors embedded in the joint panels. The pavement is post-tensioned from the stressing pockets, which are subsequently filled with fast-setting concrete. The post-tensioning ducts are then grouted to bond the strands to the pavement.

In Chapter 6, design considerations for a precast concrete pavement were discussed. The design considerations include factors affecting the design, such as load repetitions, subgrade restraint, prestress losses, and joint movement, as well as design variables, such as foundation strength, pavement thickness, and magnitude of prestress. The design variables are adjusted to accommodate the factors affecting design, which will be job-specific.

Chapter 7 presented a feasibility analysis for design. For the sake of comparison, a precast concrete pavement was designed for a design life equivalent to that of a conventional CRC pavement. From the design analysis, it was found that an 8 in. precast concrete pavement can be designed to be equivalent to a 14 in. thick CRCP (15 in. JRCP), which is a significant savings in concrete. The computer program PSCP2 was introduced as a design/analysis tool for precast concrete pavements. Based on the example design, it was determined that expansion joints can be spaced up to 440 ft for winter pavement placement, and up to 340 ft for summer pavement placement, in order to meet the expansion joint width requirements.

In Chapter 8, the feasibility of construction of the proposed concept was discussed. Feasibility of construction is very important for gaining acceptance among contractors and transportation agencies. This chapter evaluated the feasibility of some of the proposed methods for construction, such as the use of an asphalt-leveling course and polyethylene sheeting. Issues raised during the expert panel meetings, such as accommodation of horizontal and vertical curves, were also discussed.

Chapter 9 focused on the feasibility of the proposed concept from the standpoint of economics and durability. It is important that precast concrete pavement construction be economically feasible, as compared to conventional concrete pavement construction, with comparable, if not enhanced, durability characteristics. The feasibility analysis showed that the major economic advantage of precast pavement construction will be realized through savings in user costs. Since precast concrete pavements can be exposed to traffic almost immediately after placement, they can be constructed in short segments, minimizing the effects on traffic. In addition, the high degree of quality control that can be achieved with precast concrete panels will ensure outstanding durability of the pavement.

In Chapter 10, recommendations for additional investigation and implementation were presented. Several aspects of the proposed concept, such as the self-locking strand anchor and the asphalt-leveling course will need to be investigated further through actual implementation of the proposed concept. A staged implementation strategy was recommended as the most effective method for achieving this. Staged implementation involves first conducting laboratory tests and constructing pilot sections, where any details or possible problems can be worked out without having an impact on the motoring public. A rural section will then be constructed to implement the proposed concept on a larger scale, under actual construction time constraints. Finally, an urban project will provide the ultimate test of the speed, efficiency, and adaptability of precast construction.

11.2 CONCLUSIONS

This project has demonstrated that the construction of a precast pavements is feasible and provides numerous benefits.

11.2.1 Feasibility

The project objectives set forth in Chapter 1 ensured a thorough feasibility analysis of precast concrete pavement construction. As revealed through the literature review, many of the aspects of the proposed concept, such as the keyed panel joints, expansion joint details, and post-tensioning, have been used successfully in the past and should also prove viable for precast pavement. From the expert panel meetings, feasible techniques for panel fabrication and construction were incorporated into the proposed concept. Such incorporation will ensure that the proposed concept meets the expedited construction requirements and will be easily adaptable to existing precasting and pavement construction techniques.

Based on the evaluation of different pavement types, prestressed concrete panels were determined to be the most practical pavement type to use for precast pavement construction. Prestressing greatly reduces the required thickness of the pavement and enhances the durability of the pavement, which is particularly important for handling considerations and pavement applications in areas where overhead clearance is restricted.

The feasibility analysis for design revealed that a precast pavement can be designed to have a design life equivalent to that of conventional pavements, with a significant savings in pavement thickness. The feasibility analysis for construction reveled feasible methods for rapid construction, such as the use of an asphalt leveling course, as well as solutions for job-specific considerations, such as site geometry.

Finally, the feasibility analysis for economics and durability showed the economic advantages of a precast pavement, such as reduced user costs, as well as advantages in terms of durability, which have been proven through prior experience with prestressed pavements. Further investigation, future implementation, and performance monitoring will, ultimately, demonstrate the feasibility of the proposed concept, as discussed in Chapter 10.

11.2.2 Benefits of Precast Pavement Construction

The most obvious benefit of precast concrete pavement construction, the attraction to which is the reason this project was originally undertaken, is the speed of construction. By using precast panels, additional time is not required to allow the concrete to cure before traffic can be allowed back onto the pavement. This quick opening to traffic allows for precast concrete pavements to be placed during separate (overnight or weekend) operations. Construction can take place when traffic volumes are low, while the pavement will be open to traffic when traffic volumes are higher.

The economic benefits of precast construction will be realized through savings in user costs. As was demonstrated in Chapter 9, by limiting construction to an overnight time frame, user delay costs are significantly reduced (from approximately $680,610/day to $124,500/day for the example presented). Although it may not be possible to place as much precast pavement as conventional pavement in a daily operation, the user cost savings far outweigh the additional time needed for construction.

The proposed concept has many aspects that are favorable for separate overnight construction operations. First, the asphalt leveling course can be placed well in advance of the precast panels, allowing traffic onto the leveling course prior to panel placement. Second, the post-tensioning tendons do not have to be grouted before traffic is allowed back onto the pavement. Grouting can be done at a later time, during a subsequent operation. The stressing pockets, also, do not have to be filled before traffic is allowed onto the pavement. Finally, the use of prefabricated ramps will provide an efficient method for transitioning traffic onto the new pavement from the existing pavement.

Other major advantages of precast construction include increased slab lengths (fewer joints), material savings (less concrete and reinforcement), and increased durability. The cast-in-place prestressed concrete pavement in McLennan County, Texas, which formed the basis for many of the aspects of the proposed precast pavement concept, is evidence of these advantages. The McLennan County pavement had expansion joints spaced at only 240 ft and 440 ft. The thickness of the pavement was only 6 in., as compared to 14 in. CRC pavements currently constructed in the same region. Also, the pavement, which has been in place for nearly 15 years, shows virtually no signs of distress.

Precast concrete pavements can be used for any application where expedited construction is required. They can be used for new pavement applications, for unbonded overlay applications, and for removal and replacement applications. The ability to place several adjacent slabs at different times and tie them together through post-tensioning makes precast concrete pavement ideal for applications where only one or two lanes can be replaced at a time, such as is the case in a removal and replacement application.

11.3 RECOMMENDATIONS

The proposed concept should meet the requirements for expedited pavement construction. The feasibility of precast concrete pavement construction, however, will ultimately only be realized through actual implementation. Further development of some of the conceptual ideas should also be completed prior to actual implementation. As discussed in Chapter 10, a staged implementation strategy is recommended. This strategy allows for small-scale implementation at first (to work out the minor details), followed by larger-scale implementation, and ultimately, urban implementation, which will present the greatest challenges to precast pavement construction.

As implementation proceeds, the proposed concept will continually be refined. Since the purpose of using precast concrete pavement is to expedite construction, it is important to streamline the production and placement processes as much as possible to increase efficiency. In the end, a simple concept, which is appealing to contractors and transportation agencies, is desirable. A concept that is easily adaptable to existing techniques, but yet not restricted by current practices, will ensure the viability of precast concrete pavements.

Appendix

Additional Topics from Literature Review

A.1 VOID EFFECTS ON PAVEMENT LIFE

CTR Research Report 249-3 (Ref 39) describes an investigation into the effects of voids beneath concrete pavement slabs on the life of pavements. When voids are present, the pavement must span the voids, causing a significant increase in pavement stresses. These increased stress levels reduce the fatigue life of pavements considerably. In this project, slab stresses were determined through analytical techniques for three different void size conditions. Using these stresses, the fatigue life under these conditions was computed using the following fatigue equation developed for Texas (Ref 28).

$$N = 46{,}000\left(\frac{f}{s}\right)^{3.0} \tag{A.1}$$

where: N = number of load applications to failure
f = flexural strength of concrete (psi)
s = stress in the concrete (psi)

The parameters for the project are shown in Table A.1. These conditions pertain to conventional concrete pavements. Under conditions where prestressing is applied to the slab, the pavement fatigue life should be less affected by the presence of voids. In Figure A.1, the results of this project show that increasing void size results in a significant pavement life reduction.

Table A.1 *Summary of parameter values used in the project*

	Parameter	Value(s)
1)	Slab size	24 ft x 12 ft
2)	Void size	2 ft x 6 ft 4 ft x 12 ft 6 ft x 18 ft
3)	Pavement thickness	8 in, 10 in, 12 in
4)	K-value	100 pci, 300 pci
5)	Wheel load	18-kip single axle with dual tire 32-kip tandem axle
6)	Load position	0.5 ft from edge 1.5 ft from edge 2.5 ft from edge
7)	Concrete: Modulus of Elasticity	5,000 ksi
8)	Poisson’s ratio	0.20
9)	Concrete: Flexural strength	650 psi

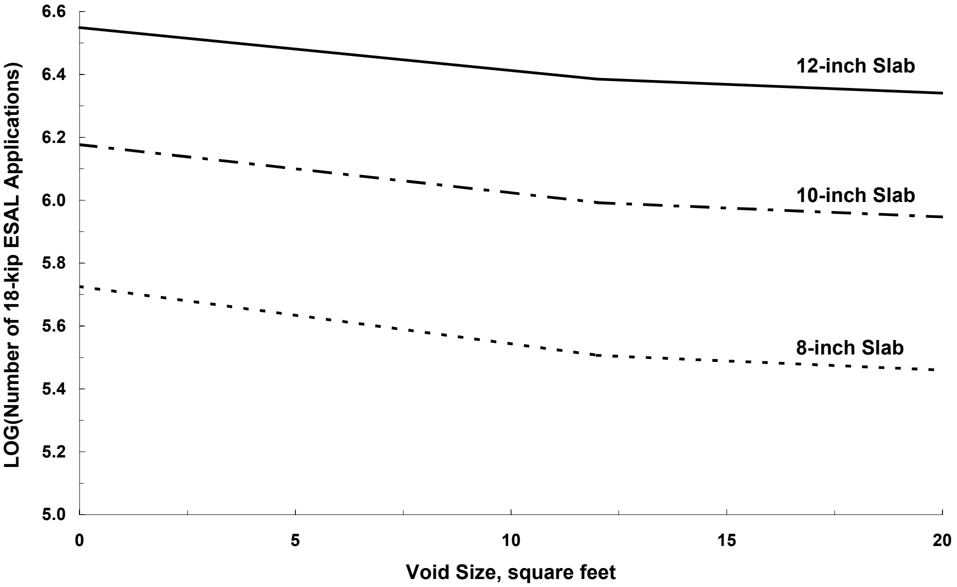


Figure A.1 *Effect of void size on fatigue life of pavement (Ref 39)*

When precast slabs are used for pavements, there is a high probability that voids will be present under the slab after it is in place. These voids could be caused by:

(a) unevenness in the support layer
(b) unevenness in the precast concrete panels
(c) misalignment between adjacent precast concrete panels requiring adjustment of panel elevation
(d) presence of unwanted debris beneath the precast panels

Depending on the supporting layers beneath the precast concrete panels, the amount of prestress applied to the pavement, and the method used to level the panels, the reduction in pavement fatigue life caused by the presence of voids should be less severe than that for conventional pavements.

A.2 HANDLING AND ERECTION OF PRECAST PANELS

Waddell (Ref 40) describes very detailed guidelines for handling and erection of precast concrete elements. He discusses various lifting hardware, such as that shown in Figures A.2 and A.3. Note that each item consists of two parts: (1) the anchor that remains embedded in the concrete and (2) the attachment element that is bolted into the anchor.

The single insert (Figure A.2a) is the most widely used insert and is adapted for use with the swivel lifting plate (Figure A.2c). For unusually large panels or heavy panels, angle lifting plates (Figure A.2b) are used with double inserts (Figure A.2e). Another lifting unit is shown in Figure A.2f. With this device, the plastic sleeve and cap attached to the insert are removed just before making the lift. A bushing on the lifting hardware fits into the hole left by the plastic sleeve and a steel locking hook engages the insert. The hardware is then adjusted by hand, and the crane hook is attached to the bail to make the lift. The lifting hardware on all of these units is reusable, and the insert holes can be filled with mortar.

Waddell further recommends that inserts be sized to set back 3/8 in. from the top face of the panel. The Precast Concrete Institute (PCI) Handbook (Ref 41) also warns against the thread connector protruding from the face, as this could possibly be damaged during handling.

One of the simplest anchorage elements consists of a spiral or threaded unit embedded in the concrete, as shown in Figure A.3. This element forms a "nut" into which a special bolt can be threaded. To increase the pullout resistance of the anchor, a wire loop is welded to the coil (Figure A.3), thus increasing the depth of embedment. The loop may be single or multiple, straight or flared. Some are designed with a loop through which a short bar of reinforcing steel can be inserted.

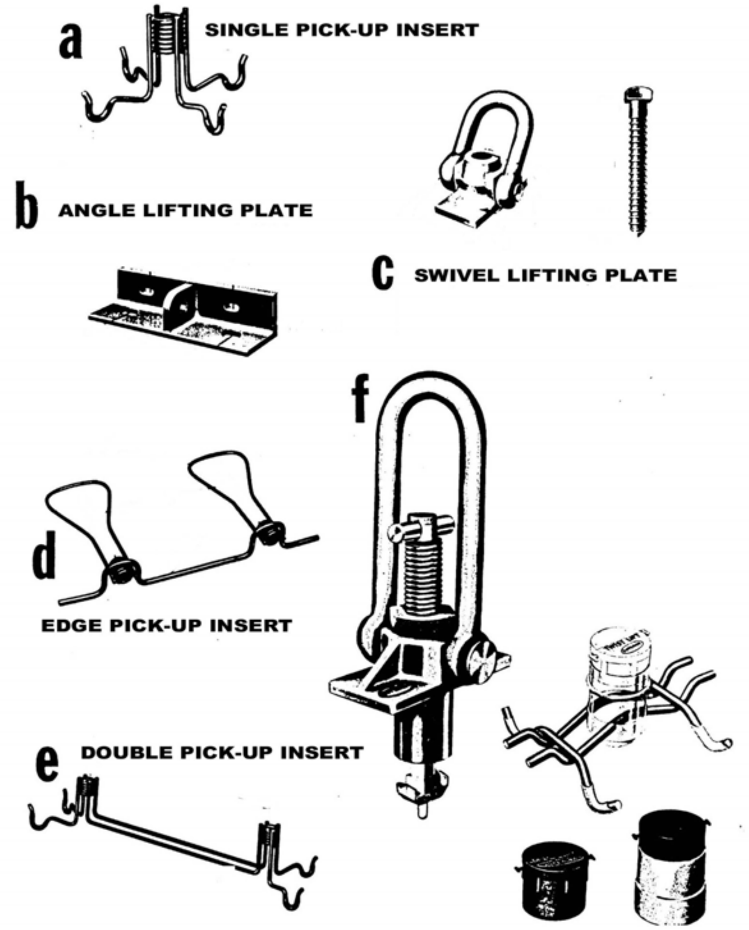


Figure A.2 *Several basic items of lifting hardware for precast panels (Ref 40)*

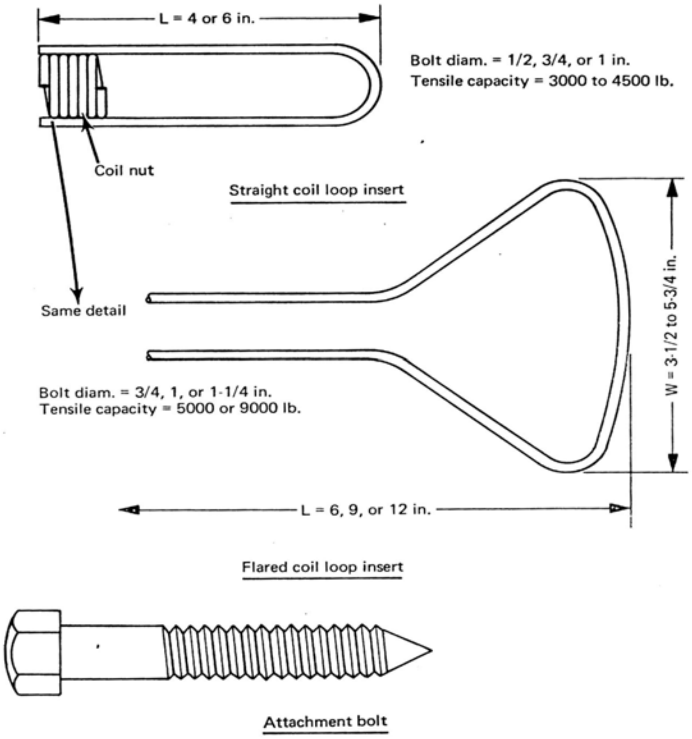


Figure A.3 *Straight coil loop insert, flared coil loop insert, and attachment bolt (Ref 40)*

Selection of the correct insert depends on a number of factors associated with the type, weight, configuration, thickness, and strength of the precast member. It is recommended that the insert selection be based on the manufacturer's recommendations and on an engineering analysis of the proposed installation. Many conditions of loading should be considered, depending on the type of handling operation involved. It is also recommended that the strength, as controlled by the steel, can be taken from manufactures' catalogs. The PCI Handbook (Ref 41) contains design tables for inserts such as those shown in Figure A.3.

Waddell (Ref 40) also presents vacuum lifting devices, as shown in Figure A.4, that have been used to successfully handle flat precast elements. One advantage of vacuum lifters is the reduction in handling time. It takes only a few seconds to attach or release the lifter. Also, the panel is not disfigured by holes for inserts that have to be patched later. A fail-safe period of an hour is built into the equipment in case of power failures.

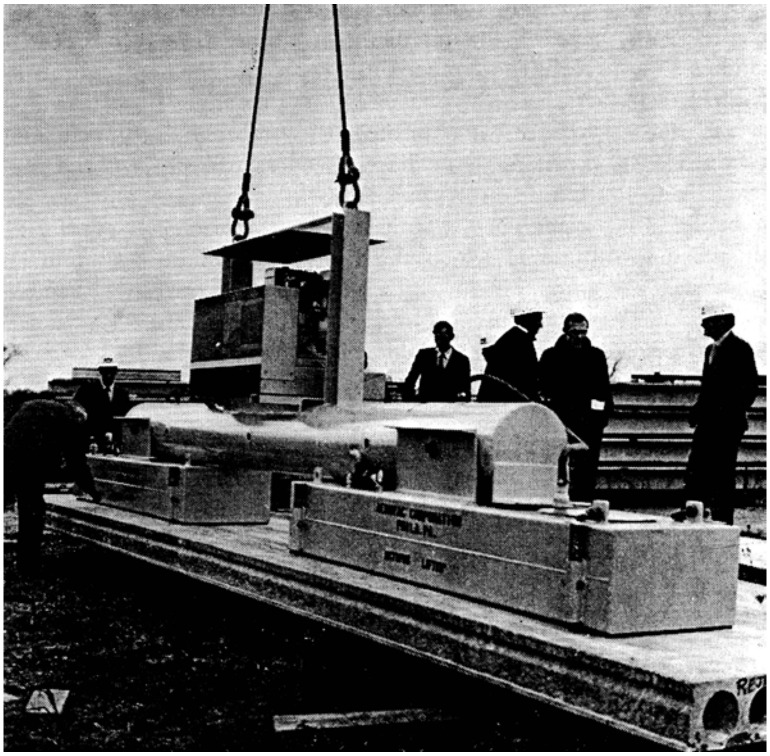


Figure A.4 *Vacuum lifters come in a variety of sizes and capacities and are adaptable to a variety of precast units (Ref 40)*

Waddell (Ref 40) also addresses issues regarding the transportation of precast concrete members. It is recommended that the loading of any type of unit be done in a way that provides adequate support and cushioning to minimize damage while the unit is in transit. Adequate padding must be provided between chains, cables, or ropes and the members to prevent chipping or other damage, especially around edges and corners. Most precast panels can be supported by an A-frame positioned on the bed of a truck, trailer, or rail car to hold the panels in nearly vertical position, with the panels loaded in such a manner to minimize the weight of one unit bearing on another. The use of an A-frame to support a panel is shown in Figure A.5.

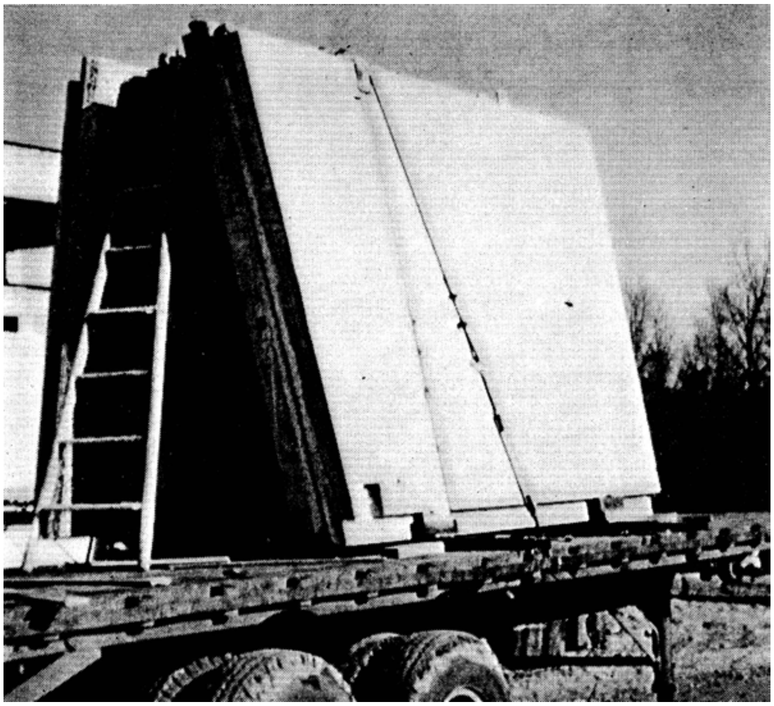


Figure A.5 *A center A-frame supports flat panels (Ref 40)*

A.3 TOLERANCES FOR PRECAST PANELS

Guidelines for tolerances for precast and prestressed concrete elements are provided in the PCI Design Handbook (Ref 41). It is stated that these tolerances are established by economics, practical production, erection, and interfacing connections. Tolerances must be used as guidelines for acceptability and not as limits for rejection.

Positioning of Tendons

It is common practice to use 5/8 in. diameter holes in end dividers (bulkheads or headers) for 3/8 in. to ½ in. diameter strands, since it is costly to switch end dividers for different strand diameters. Thus, better accuracy is achieved when using larger diameter strands. The PCI Handbook recommends that individual tendons be positioned within ±1/4 in. of the design position.

Warping and Bowing

Warping and bowing tolerances affect panel edge match up during placement. The PCI Handbook defines warping as "… a variation from plane in which the corners of the panel do not fall within the same plane." Panel warping is illustrated in Figure A.6. The PCI warping tolerance is given as 1/16 in. per ft from the nearest adjacent corner.

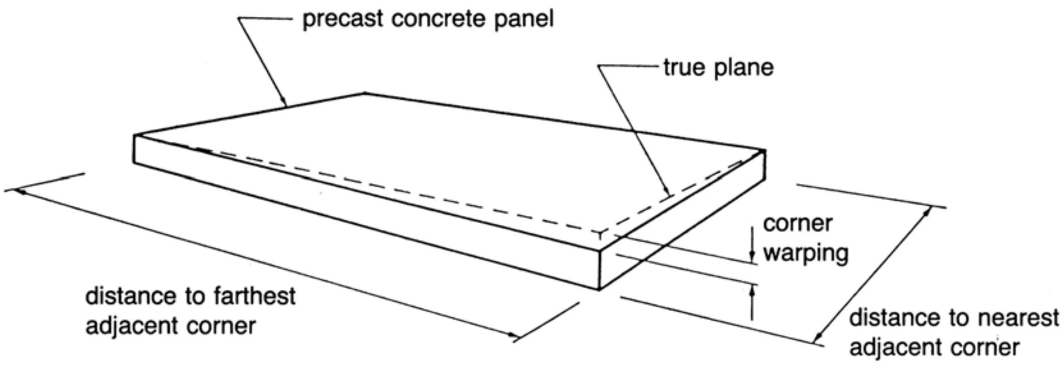


Figure A.6 *Corner warping as defined by PCI (Ref 41)*

Bowing differs from warping in that two opposite edges of a panel may fall in the same plane, but the portion between is out of plane, as shown in Figure A.7. The PCI bowing tolerance is L/360, where L is the length of bow. The maximum tolerance on differential bowing between panels of the same design is ½ in.

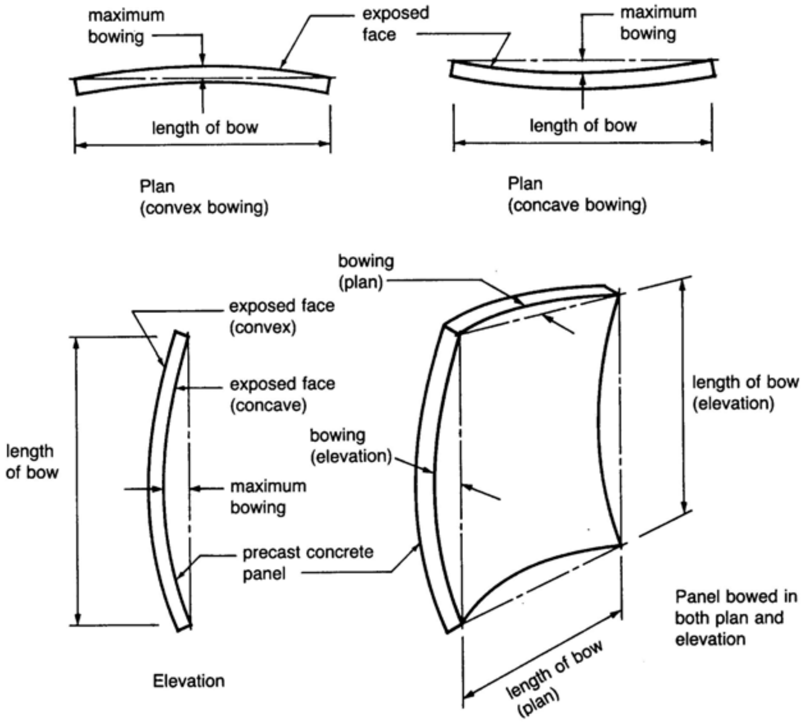


Figure A.7 *Bowing as defined by PCI (Ref 41)*

It is further recommended that the effects of differential temperature and moisture absorption between the inside and outside of a panel, along with prestress eccentricity, be considered in design of the panel and its connections to minimize bowing and warping. Pre-erection storage might also affect warping and bowing. Because thin panels are more likely to bow, tolerances should be more liberal (Ref 41). Table A.2 gives the thickness, related to panel dimensions, for which the given warping and bowing tolerances should apply. It is stated that more rigid tolerances can be set, but this could lead to significant increases in cost and should not therefore be specified unless absolutely necessary.

Table A.2 *Minimum thickness (in.) for use of normal bowing and warping tolerances (Ref 41)*

	Panel length (ft)							
Panel width (ft)	***8***	***10***	***12***	***16***	***20***	***24***	***28***	***32***
4	3	4	4	5	5	6	6	7
6	3	4	4	5	6	6	6	7
8	4	5	5	6	6	7	7	8
10	5	5	6	6	7	7	8	8

A.4 SHEET PILES

For concrete sheet piles, many variations of interlocking joint details have been developed and successfully used. Figure A.8 shows typical cross sections used for prestressed concrete sheet piles (Ref 42). These joints provide both structural strength and sand-and-water tightness. With no epoxy in the joint, the ordinary tongue-and-groove interlock transmits shear but no tension. A polyethylene interlock embedded in the concrete, as shown in Figure A.9, acts as a water-stop.

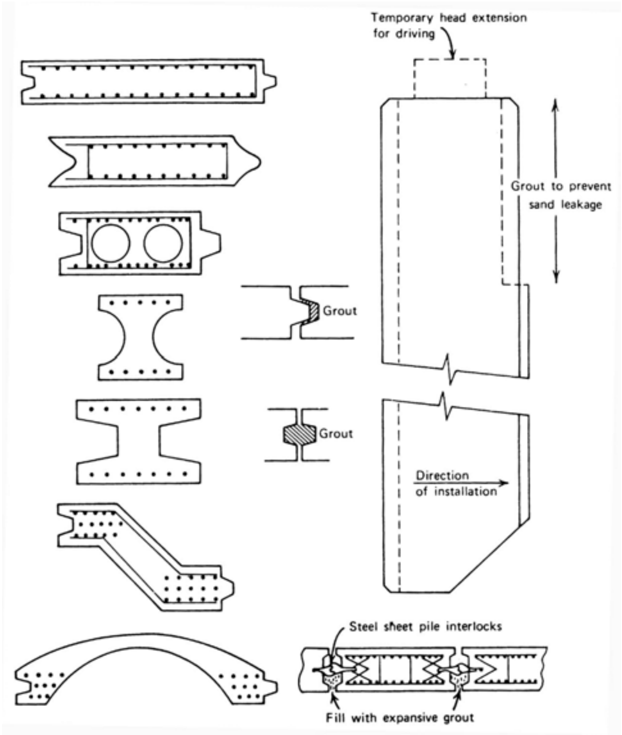
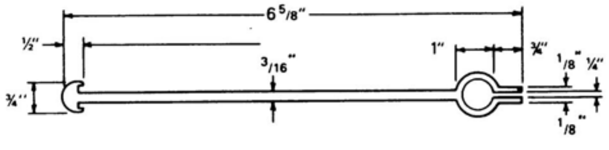


Figure A.8 *Typical cross sections used for prestressed concrete sheet piles (Ref 42)*



Cross section of plastic interlock

Figure A.9 *Polyethylene interlock for prestressed sheet piles (Ref 42)*

A.5 PRECAST CONSTRUCTION FOR BUILDINGS

A paper by Franz (Ref 43) documents experimental findings from tests on different connections to obtain continuity between precast segments. Figure A.10 shows a recommended looped bar detail. The testing procedure involved loading the specimens in pure bending up to yielding of the bars. It did not involve repetitive loading or investigation of fatigue characteristics for the joints. The following conclusions were drawn from the tests:

1) ***Overlap:*** If $Ø_s$ is made less than 14Ø, more of the tension force has to be transferred by bond in the straight side of the loop. This means that the overlap of the bars must be increased. A simple rule of thumb is that when diminishing the diameter $Ø_s$ below 14Ø, add the difference to the overlap length, as shown in Figure A.10.

2) ***Concrete Cover:*** The loops must be far enough, at least 5Ø, from the edges. If the concrete cover to the outer loop is less than this, then failure could occur owing to spalling of the top cover.
3) ***Provision of Lateral Reinforcement:*** The effect of the lateral tensile stresses is evident in the splitting of the outer concrete zone and the cracking of the slabs. To withstand these tensile forces, lateral reinforcement should be provided. The reinforcement, however, will not come into action before the cracks are already visible and, therefore, will not substantially reduce the rotation at the joint. The recommended lateral reinforcement layout is also shown in Figure A.10.

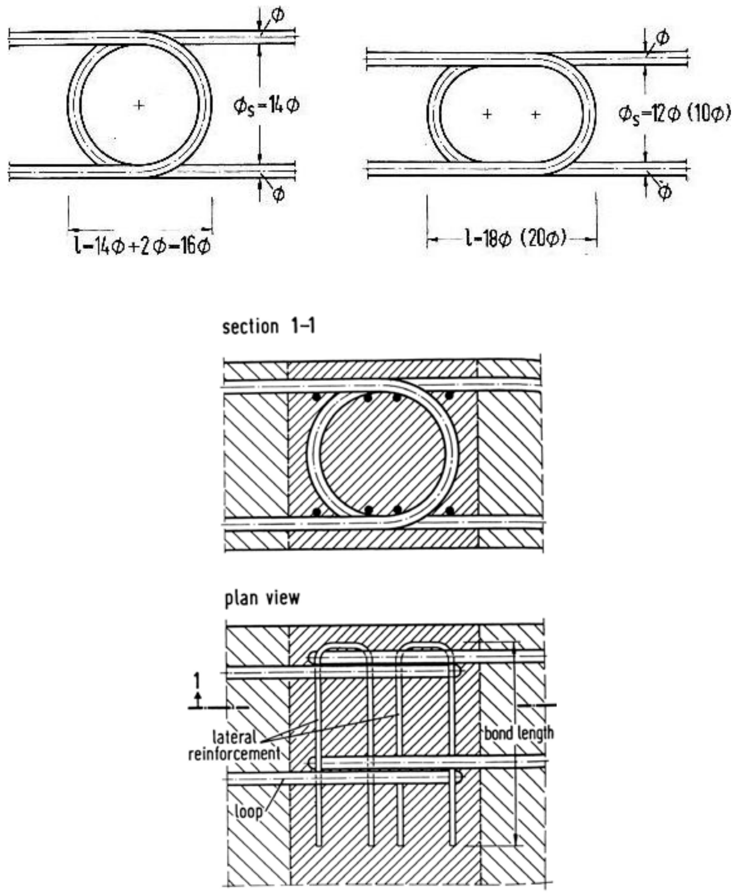


Figure A.10 *Recommended joint type to connect precast panels (Ref 43)*

An article by Despeyroux (Ref 44) presents the detail, shown in Figure A.11, used to join wall panels. It is stated that this detail successfully provides continuity between two panels. Despeyroux recommends the use of indentations (see Figure A.11), as they reduce sliding between panels and provide a better key.

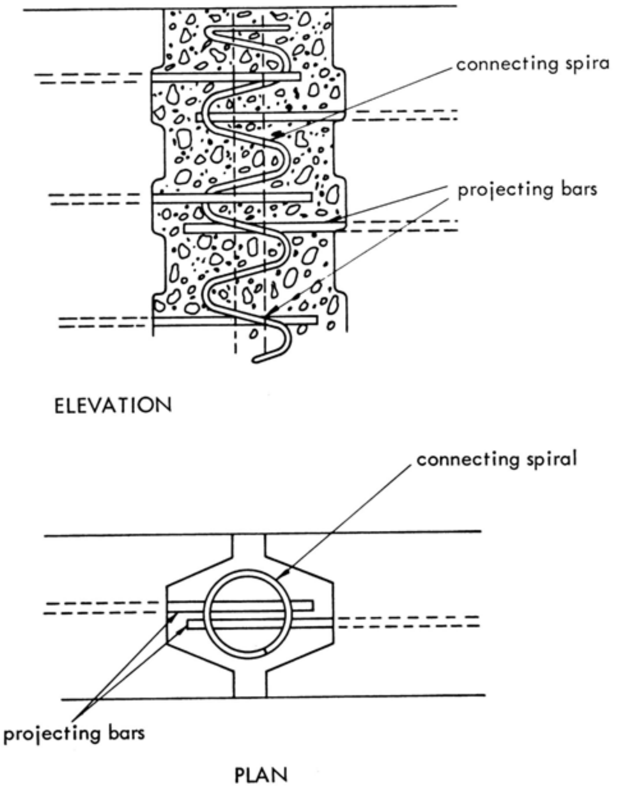
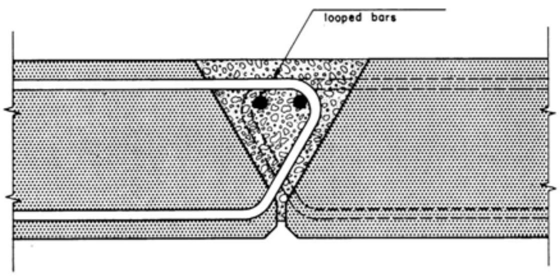
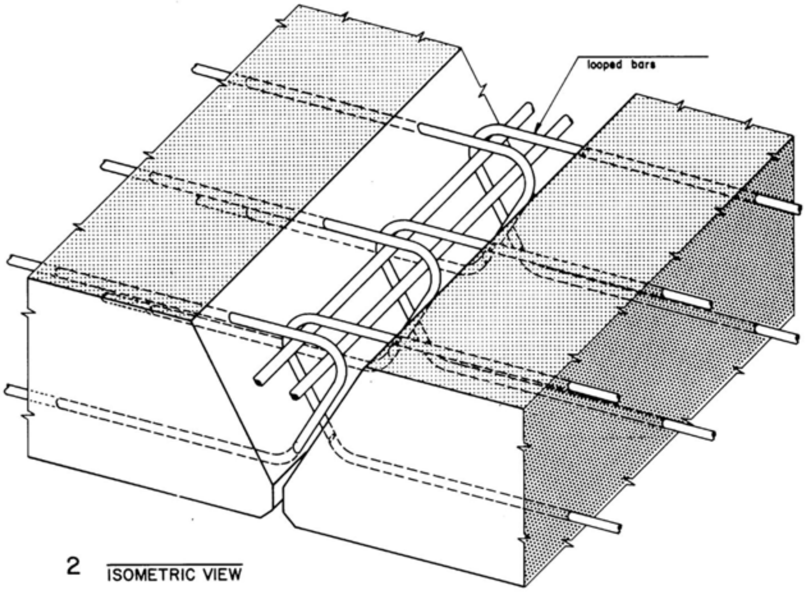


Figure A.11 *Vertical joints between panels with auxiliary spiral (Ref 44)*

In a publication on structural connection details for precast concrete elements (Ref 45), the detail in Figure A.12 is presented for connecting adjacent floor units. In this connection, the sides of the floor panels have large chamfers from which looped reinforcing bars protrude, overlapping those of the adjoining panel. Reinforcement bars are then inserted through the loops, along the full length of the joint, around which concrete is then cast. It is noted that, depending on the design of the looped splice connections and the quality of the in-situ concrete, the connection is able to transmit large compressive and tensile forces, large horizontal and vertical shear forces, and a fairly large negative and fairly small positive moment.



1 SECTION



2 ISOMETRIC VIEW

Figure A.12 *Floor unit to floor unit connection by looped bars (Ref 45)*

An article by Munch-Peterson (Ref 46) discusses details of connections between hollow core floor panels. The proposed connection between floor-to-wall panels is shown in Figure A.13.

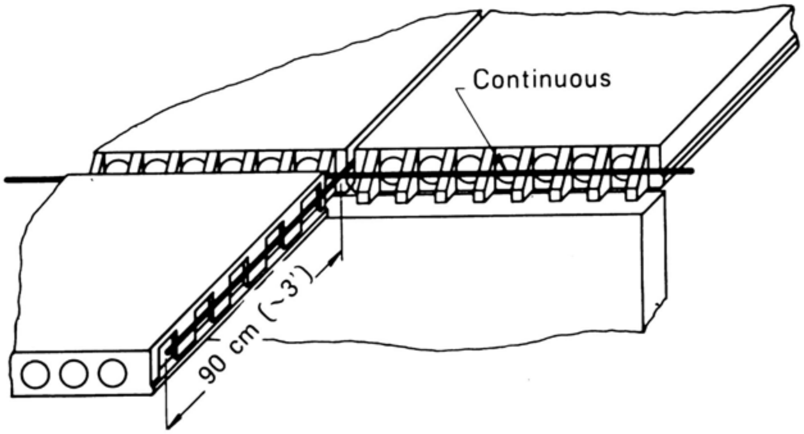


Figure A.13 *Floor-to-wall joint (Ref 46)*

The PCI Handbook (Ref 41) presents the groove joint details shown in Figure A.14. These grooved joints are continuous and usually filled with grout. It is recommended that the minimum groove dimension be 1½ in. deep and 3 in. wide. The PCI Handbook addresses methods to design the capacity of such keyed connections. The capacity of such a connection can be limited by:

(a) cracking of grout concrete parallel to joint,
(b) diagonal cracking across joints,
(c) crushing of key edges or joint concrete at key edges, or
(d) slippage along contact area.

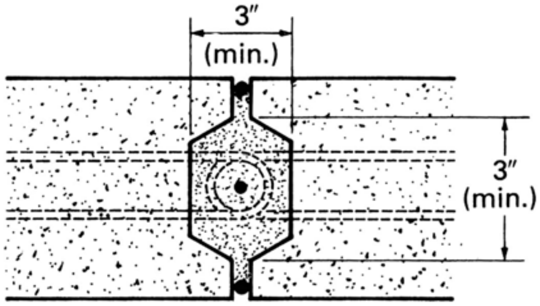
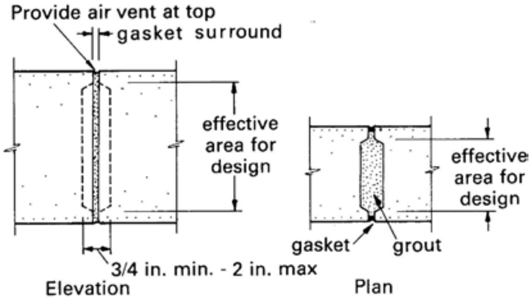
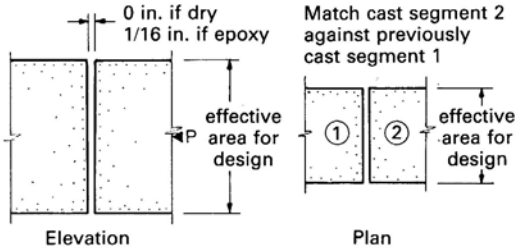


Figure A.14 *Grooved joint connections (Ref 41)*

Figure A.15 illustrates the types of joints recommended by the PCI Handbook for segmental precast construction. Two types of joints are defined: "open," designed to permit completion by a field-placed grout, or "closed," designed such that the joint is either dry or bonded by a thin layer of adhesive.



(a) OPEN JOINT



(b) CLOSED JOINT

For epoxy joints, apply a temporary prestress of 50 psi immediately after application of epoxy.

Figure A.15 *Joint details for segmental construction (Ref 41)*

Open joints (PCI Handbook, 1985)

The individual segments are separated by an amount sufficient to place (usually by pressure) a grout mix, though not more than about 2 in. Prior to placing the segments, the joint surface is thoroughly cleaned and wire brushed or sandblasted. The perimeter of the joints is sealed with a gasket, which is compressed by use of come-alongs or by a small amount of prestress. Gaskets are also provided around the post-tensioning elements to prevent leakage into the ducts, which would block passage of the tendons.

Closed Joint (PCI Handbook, 1985)

If a closed joint is used, the segment is usually “match-cast,” meaning each segment is cast against its previously cast neighbor. A bond breaker is applied to the joint during casting. Thus, the connecting surfaces fit each other accurately, so that little or no filling material is needed at the joint. The sharpness of the line of the assembled construction depends mainly on the accuracy of the manufacture of the segments. Match cast elements are usually joined by coating the abutting surfaces with a thin layer of epoxy adhesive and then using the post-tensioning to draw the elements together and to hold them in position.

Surface preparation of closed joints is extremely important. The joints should be sound and clean, free from all traces of release agents, curing compound, laitance, oil, dirt, and loose concrete. A small piece of foreign material in a joint, or a slightly imperfect alignment, will frequently cause the concrete to spall around the edges of the contact area of a closed joint. Consequently, care in joint preparation and segment alignment cannot be overemphasized.

A.6 LIGHTWEIGHT CONCRETE

Gerwick (Ref 42) addresses the application of prestressing techniques for highways. With regard to the use of lightweight aggregates, he comments that, because a major portion of the stresses in prestressed slabs is due to temperature, it is obvious that a concrete with a lower thermal response would be desirable. Expanded shale, slate, and clay aggregates (lightweight aggregates) have a reduced thermal response and provide better insulation so that the lower surface of the slab, in contact with the subgrade, is not subjected to as great a variance, particularly the short-term variances, which are the most troublesome. However, most lightweight aggregate, when used in pavements, is subject to “plucking” erosion under traffic. Strains caused by temperature are transformed to stress in direct proportion to the modulus of elasticity. A concrete, such as lightweight concrete with a low modulus of elasticity, can reduce temperature stresses by up to 30%.

Gerwick states that prestressed lightweight-aggregate concrete for pavements has the following advantages:

1) lower modulus of elasticity,
2) better insulating qualities,
3) reduced thermal response,
4) better skid resistance, and
5) improved durability under deicing salts.

The use of lightweight aggregate would also reduce the weight of the precast concrete panels, which would make handling, transportation, and placement of the panels easier.

An article by Despeyroux (Ref 44) also addresses the use of lightweight concrete in order to reduce the weight of precast members. Regarding the use of lightweight aggregates, it was stated that various structural problems present themselves because of the following factors:

(a) Shrinkage is 50 to 60% greater than that of ordinary concretes.
(b) Creep is likewise 50 to 60% greater than that of ordinary concretes.

Because of the shrinkage, it may be necessary to specify rather longer periods of storage (maturing) in the storage yard before the components are allowed to be used.

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