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NEW CONCEPTS IN PRESTRESSED CONCRETE PAVEMENT

Neil D. Cable, N.H. Burns,
and B. Frank McCullough

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16. Abstract

Previously conducted research and testing has indicated the superiority of prestressed concrete pavement over conventional concrete pavement in at least three respects:

(1) more efficient use of construction materials;
(2) fewer required joints and less probability of cracking; and
(3) reduced overlay thickness, which not only reduces the required quantity of concrete, but would also be advantageous where clearance is a problem, for example, under bridges.

This report on prestressed concrete pavement (a) thoroughly reviews and summarizes the available literature to ascertain the current state of the art; (b) critically evaluates the design, construction, and performance of several FHWA sponsored projects which were constructed during the 1970s; and (c) provides the details of a design and the associated construction details and procedures based on (a) and (b) to be used in connection with two demonstration projects.

In addition, several other prestressed concrete pavement concepts are introduced and developed in this report. These concepts represent a progression of thought regarding prestressed concrete pavement and address many of the problems encountered on previous projects. Recommendations are given for additional investigation, laboratory and field testing, and analytical studies to further develop the concepts and determine their viability.

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Prestressed Concrete Pavement Design --
Design and Construction of Overlay Applications
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conducted for

Texas State Department of Highways
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The University of Texas at Austin

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PREFACE

This work is a part of Research Project 3-8-84-401, entitled "Prestressed Concrete Pavement Design -- Design and Construction of Overlay Application." The study described was conducted as a part of the overall research program for the Center for Transportation Research, Bureau of Engineering Research of The University of Texas at Austin. The work was sponsored jointly by the Texas Department of Highways and Public Transporation and the Federal Highway Administration under an agreement with The University of Texas at Austin and the Texas Department of Highways and Public Transportation.

Appreciation is expressed to Evelyn Cable for her assistance in editing; to Ahlam Barakat, Michele Mason Sewell, Ruby Stell, and Dion Melton for their assistance in the preparation of the figures; and to all of the other Center for Transportation Research staff members who assisted in the production of the final draft of of this report.

LIST OF REPORTS

Report No. 401-1, "Very Early Post-tensioning of Prestressed Concrete Pavements," by J. Scott O'Brien, Ned H. Burns and B. Frank McCullough, presents the results of tests performed to determine the very early post-tensioning capacity of prestressed concrete pavement slabs, and gives recommendations for a post-tensioning schedule within the first 24 hours after casting.

Report No. 401-2, "New Concepts in Prestressed Concrete Pavement," by Neil D. Cable, N. H. Burns and B. Frank McCullough, presents the following: (a) a review of the available literature to ascertain the current state of the art of prestressed concrete pavement; (b) a critical evaluation of the design, constuction, and performance of several FHWA sponsored prestressed concrete pavement projects which were constructed during the 1970s; and (c) several new prestressed concrete pavement concepts which were developed based on (a) and (b).

ABSTRACT

Previously conducted research and testing has indicated the superiority of prestressed concrete pavement over conventional concrete pavement in at least three respects:

(1) more efficient use of construction materials;
(2) fewer required joints and less probability of cracking; and
(3) reduced overlay thickness which not only reduces the required quantity of concrete, but would also be advantageous where clearance is a problem, for example, under bridges.

This report on prestressed concrete pavement (a) thoroughly reviews and summarizes the available literature to ascertain the current state of the art; (b) critically evaluates the design, construction, and performance of several FHWA sponsored projects which were constructed during the 1970s; and (c) provides the details of a design and the associated construction details and procedures based on (a) and (b) to be used in connection with two demonstration projects.

In addition, several other prestressed concrete pavement concepts are introduced and developed in this report. These concepts represent a progression of thought regarding prestressed concrete pavement and address many of the problems encountered on previous projects. Recommendations are given for additional investigation, laboratory and field testing, and analytical studies to further develop the concepts and determine their viability.

KEYWORDS: Concrete, prestressed concrete, pavements, precast, post-tension, pretension, post-stress.

SUMMARY

The Center for Transportation Research of The University of Texas at Austin was commissioned in 1983, by the State Department of Highways and Public Transportation, to undertake a study of the design and construction of prestressed concrete pavement, with particular emphasis on overlay applications. The culmination of this study is to be a manual for the design and construction of prestressed concrete pavement. The designation given this study was Project 401 and it is under the direction of Dr. B. Frank McCullough and Dr. Ned H. Burns.

This report accomplishes the goals of the first phase of the work plan for Project 401 which were as follows: (a) a thorough review of the available literature to ascertain the current state of the art of prestressed concrete pavement; (b) a critical evaluation of the design, construction, and performance of several FHWA sponsored projects which were constructed during the 1970s; and (c) development of a prestressed concrete design and the associated construction details and procedures based on (a) and (b).

In addition, this report describes the salient features of the prestressed concrete pavement design developed by the Project 401 staff and the anticipated procedure that would be employed in constructing a section of prestressed concrete pavement using this design. However, the specifics of the design for each demonstration project (i.e., site selection, foundation evaluation, and thickness and prestress level determination) are not covered since these are discussed in detail in other reports under this study.

In the course of pursuing the objectives of the first phase of Project 401, several new prestressed concrete pavement concepts were developed by the authors. These concepts represent a progression of thought regarding prestressed concrete pavement and address many of the problems encountered on previous projects. These concepts are introduced in this report. In addition, recommendations are given for additional investigation, laboratory

and field testing, and anlaytical studies to further develop the concepts and determine their viability.

Information from the first stage of Project 401 served as input for the design of two one-mile prestressed concrete pavement overlay sections on Interstate Highway 35 in Texas. These section are located in Cooke and McLennan Counties and were given the designations Project 555 and 556, respectively. Construction of Project 556 is scheduled for late August, 1985. Construction of Project 555 was cancelled since it was felt that it would provide only limited additional research information.

An extensive data collection program is planned in connection with Project 556. This program will include the following aspects:

(a) Typical prestressed concrete pavement slabs will be equipped with electronic and mechanical instrumentation to permit the measurement of concrete and steel strains, slab length changes, deflections, and temperature and moisture gradients along the depth of the slab. This instrumentation will also permit the time dependent variations of these items to be measured.

(b) The performance history of the test section will be monitored by means of condition and riding quality surveys.

(c) Information from (a) and (b) will be presented in a format that will be useful in evaluating the overall performance of the test section and will contribute to an increased understanding of prestressed concrete pavement behavior.

Information from the design, construction and data collection phases of Project 556 will then be fed back into Project 401 where it will serve as the basis for the development of the previously mentioned prestressed concrete pavement design and construction manual.

IMPLEMENTATION STATEMENT

Specific prestressed concrete pavement design recommendations and related construction details and procedures, based on the literature review and the critique of previous FHWA sponsored prestressed concrete pavement projects, are given in this report. These will be immediately implemented in the construction of a demonstration overlay section on U.S. Interstate Highway 35 near Waco, Texas. In addition, several new prestressed concrete pavement concepts were introduced in this report which will help set the direction for future research in the area of prestressed concrete pavement.

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CHAPTER 1. INTRODUCTION

CURRENT INTEREST

> Still 1,500 miles short of completion, the once proud 40,500-mile interstate-highway system will need $33 billion worth of repairs in the next decade. But the Federal Highway Trust Fund, which supported the system throughout the 1960s on ever-burgeoning revenues from the 4-cent-a-gallon Federal gasoline tax, has been sorely depleted with the advent of smaller, more fuel-efficient cars. Conditions are even worse on the larger network of primary and secondary roads. The U.S. Department of Transportation (DOT) estimates that the work needed to keep nonurban highways at current levels will cost more than $500 billion over the next ten years--more than Federal, state and local governments combined spent on all public works in the 1970s (Ref 11).

This quotation from Newsweek, August 2, 1982, describes a new era facing the nation; an era requiring monumental rebuilding and repairing of the highway system and massive expenditures for construction, with dwindling revenues available to pay for this effort. In response to this and other factors, the FHWA has developed the concept of Zero Maintenance Pavements which balances added costs of improvements in design and materials against longer pavement life, reduced maintenance, and increased user benefits. As a result, highway officials are being forced to seek new types of pavement which meet these criteria. One of the new types of pavement currently generating interest and controversy with the general public and the engineering community is prestressed concrete pavement (PCP). Referring to PCP as "new", however, is somewhat misleading, as will be seen later in this report.

Seldom do civil engineering topics, as seemingly mundane as highway pavement, generate as much public interest and controversy as has recently been expressed over the use of PCP. Public awareness of the topic is due almost entirely to the interest taken in it by two well-known, influential individuals: consumer advocate, Ralph Nader, and syndicated columnist, Jack Anderson.

In a July 4, 1983, letter to Elizabeth Dole, Secretary of the Department of Transportation, Mr. Nader charged the Federal Highway Administration (FHWA) with mishandling the potential of PCP (Ref 88). Specifically, Mr. Nader's charges were: (a) the interstate highways are deteriorating too rapidly because of "collusion" between industry and the FHWA to increase business opportunities; (b) design methods have been available for PCP for approximately ten years; (c) the FHWA has been withholding information on PCP; (d) a "coziness" exists between the FHWA and the Portland Cement Association; and (e) a FHWA employee was reprimanded for displaying an urgency to make this pavement type available to the highway designer.

Jack Anderson reiterated and defended Nader's charges in his column of January 27, 1984, and claimed that PCP could save taxpayers billions of dollars. In support of his contentions, Mr. Anderson quoted Fred Lang (an engineer whom Anderson credited with inventing one of the techniques used in prestressing) as saying:

> Everybody can make money by not going to prestressed pavement. The cement industry can make more money. The steel industry can sell more steel. Everybody wins . . . except the taxpayers and the riding public (Ref 7).

Mr. Anderson failed to mention that Mr. Lang holds patents on polyethylene-encased prestressing strand and strand couplers which will probably be used in great quantities if more PCP is constructed. This is not to say that his point might not be valid, however, he is hardly an unbiased observer.

In response to the criticism of the way in which the FHWA has handled the research and experimental development of PCP, Ray Barnhart, Federal Highway Administrator, engaged Dr. B. Frank McCullough, Adnan Abou-Ayyash Centennial Professor and Director of the Center for Transportation Research at The University of Texas at Austin, to review the FHWA's actions and prepare a report. Dr. McCullough's study included a review of literature, interviews with FHWA personnel, interviews with authorities in the pavement field, and an inspection of pavements currently in service. In his report, Dr. McCullough specifically addressed each of the charges made by Mr. Nader. Dr. McCullough's findings are summarized below:

(a) review indicates that the pavement wearout being experienced is due to the end of a design life mandated by law, an increased legal axle load, or traffic expansion greater than projected, rather than a collusion by government agencies with the cement and steel industries to underdesign pavements, and thereby increase sales.

(b) there will not be an extensive application by local governmental agencies of a new design such as prestressed pavement, without a successful trial period of several pavements in the field under various climatic and traffic conditions. The successful ten year plus implementation period of prestressed pavements in four states indicates this pavement type and design is just reaching a viable level.

(c) a logical examination of events over the past ten years indicates that rather than withholding information, the FHWA has been the leading instigator of prestressed concrete pavement activities through their research program in limited areas where they initiate pavement selection. Thus, rather than withholding information, they have actively promoted it, but very little interest has been stirred, due to the state of the economy and limited pavement construction, since 1973.

(d) In summary, a logical examination indicates that an improved product of design that resulted in a thinner pavement on a given

> project would result in a distinct advantage over their competition, thereby increasing sales, in accordance with what is accepted as the "American System." Therefore, if we may make this supposition, that if prestressed concrete pavement were truly the superior product, as hypothesized in Mr. Nader's letter, it would be to the best interest of the portland cement industry of the United States as to press for its use at every conceivable project (Ref 73).

Based on the above findings, Dr. McCullough came to the following conclusions:

> (1) The FHWA has been a 'beacon' in the United States highway field for developing the design and construction criteria for prestressed concrete pavement, and promoting it in an environment where little or no interest was present at the "grass roots" level, i.e., state and local agencies, where pavement selection and design decisions are made.
>
> (2) While prestressed concrete pavement offers an excellent potential as a viable alternative to conventional concrete pavements in the highway system, the performance and state of design knowledge indicates it is not a panacea that corrects all previous problems that have been observed (Ref 73).

Even a cursory review of the available literature is sufficient to convince any reasonable person that all the problems associated with PCP have not been solved and that it is still much too early to commit to any of the design approaches presented thus far. There are still many facets of this complicated subject which are worthy of further investigation and some of them will be explored in this report.

Before proceeding with this report, it is important to establish what is meant by the term "prestressed concrete pavement" and to set forth the meanings of other terms associated with PCP which will be used throughout this report. This is the purpose of the following section.

DEFINITIONS

The Subcommittee on Prestressed Concrete Pavements of the Committee on Rigid Pavement Design defined PCP as follows: "A pavement in which a permanent and essentially horizontal compressive stress has been introduced prior to the application of live load (Ref 30)." This definition is not restricted to any particular means of introducing the compressive stress into the pavement or particular method of construction and many interesting and innovative schemes have been tried on previous projects, some of which are briefly discussed in Chapter 2.

A glossary of terms associated with the subject of PCP is included in the appendix both for convenience and to insure a uniform interpretation of the concepts discussed.

EVALUATION

This section provides a brief overview of the advantages and disadvantages foreseeable with PCP to serve as a further introduction to the topic. The subjects touched on here are dealt with more fully later in this report.

Advantages

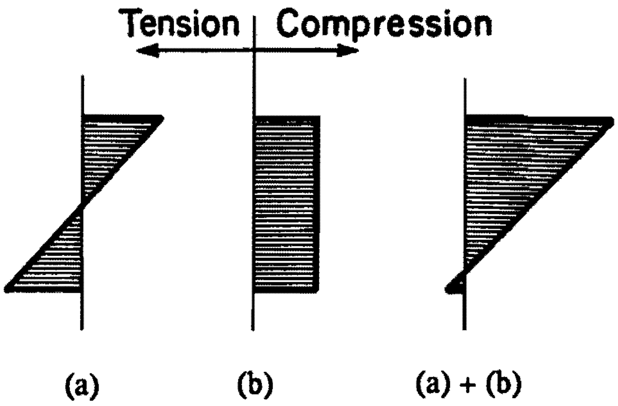
The primary reason for the interest in PCP is that previously conducted research and testing have indicated the potential superiority of PCP over conventional concrete pavement in at least three significant respects:

(1) more efficient use of construction materials;
(2) fewer required joints and less probability of cracking, resulting in less required maintenance and longer pavement life; and
(3) reduced overlay thickness which may be advantageous where clearance is a problem, for instance, under bridges.

Design procedures, such as Westergaard's, for conventional concrete pavement design (reinforced and nonreinforced) are based on restricting stresses to the elastic range of the concrete. In other words, the pavement thickness is determined such that the extreme fiber tensile stress due to applied loads does not exceed the flexural strength of the concrete. With this design approach, the natural advantage of concrete's high compressive strength is not fully utilized to resist stresses due to applied loads, resulting in an inefficient use of construction materials. In addition, the permissible pavement deflection within the elastic range is small due to the brittle nature of concrete and, as a result, the support potential of the subbase and subgrade is not fully utilized.

With PCP, the effective flexural strength of the concrete is increased by the induced compressive stress and is no longer limited merely to the modulus of rupture of concrete. This is illustrated in Fig 1.1. Consequently, the required pavement thickness for a given load would be less than for conventional concrete pavement. However, interest in PCP probably would not be that great if the only structural benefit gained from prestressing was an increase in the concrete elastic range. A much more interesting possibility is that the load-carrying capability is significantly enhanced as PCP enters an elasto-plastic phase of behavior. This was recognized by a number of engineers during the 1950s and 1960s. For example, in a 1961 paper by the Corps of Engineers it was stated:

> If the structural benefits derived from prestressing were limited merely to increasing the stress range for elastic behavior of a rigid pavement, it is doubtful that prestressed pavements, as such, ever would have received serious consideration insofar as adapting this type of pavement to the needs of airfields and highways. Fortunately, prestressing permits the structural behavior of such pavements to be analyzed under concepts completely different from those employed in the familiar Westergaard analyses or other elastic theories applicable to the design of nonreinforced rigid pavements.



(a) Stress distribution across a concrete section due to an applied bending moment
(b) Stress distribution due to a uniform prestress
(a) + (b) Resultant, actual stress distribution showing a stress shift.

Fig 1.1. Stress shift caused by prestressing (Ref 124).

> In addition to providing an increase in the stress range for purely elastic behavior, the presence of the prestress permits the action of the pavement to become essentially elasto-plastic in nature (Ref 113).

The elasto-plastic phase of behavior is characterized by tensile cracking of the lower portion of the pavement as illustrated in Fig 1.2. As shown in Fig 1.3, these cracks serve as momentary or partial plastic hinges under an applied load. After removal of the load, the compressive stress induced by the prestress closes the cracks and the rigidity of the pavement is restored. The load carrying capacity of PCP in this phase of behavior is well in excess of what it would be if stresses were restricted to the elastic range. The ability of PCP to function in this behavior mode is a significant advantage over conventional concrete pavement.

Disadvantages

PCP has its own unique set of design and construction problems which have not been adequately addressed. These problems require additional study before PCP will be generally accepted by those individuals responsible for selecting pavement systems. These problems include, but are not limited to, complexity, special jointing, construction equipment, unfamiliarity, and application of theory. These will be briefly discussed in the following paragraphs.

(1) Complexity. By its very nature, PCP is more complex than conventional concrete pavement. This is obvious from the fact that in addition to most of the same components as conventional concrete pavement, PCP also requires a system for imposing and maintaining permanent horizontal compressive stresses on the pavement. As a result, even though the quantity of materials is reduced with PCP, there is an increase in the number of construction items. For example, one or more of the following items will be required: (a) friction-reducing layers or media; (b) sleeper slabs; (c) placement of tendons and/or conduits; (d) abutments; (e) grouting; and (f) jacking for preliminary and final stressing.

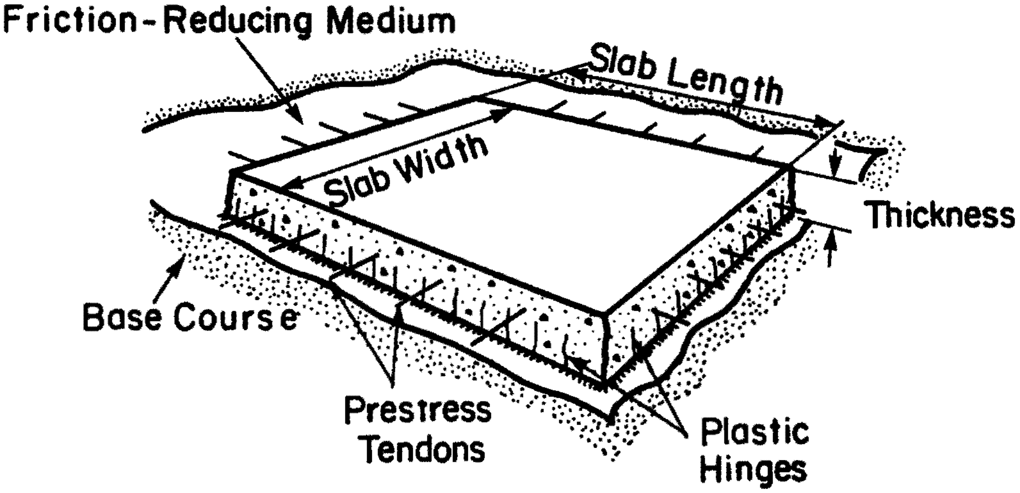


Fig 1.2. Elasto-plastic phase of behavior (Ref 77).

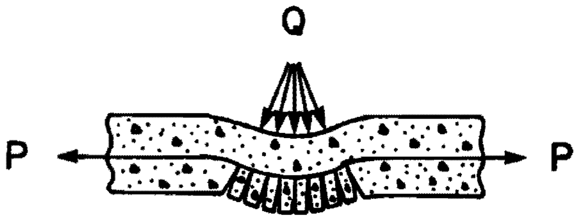


Fig 1.3. Momentary or partial plastic hinge action under an applied load (Ref 77).

(2) Special Jointing. As mentioned in this chapter, one of the important advantages of PCP is that fewer transverse joints are required than with conventional jointed concrete pavement. Most PCP constructed to date has had joints at 300 to 800 ft. intervals versus joint spacing on the order of 15 ft. for nonreinforced, to 60 ft. for reinforced jointed concrete pavement. However, this advantage has drawbacks, primarily due to two factors: (a) the ends of the pavement slabs experience relatively large horizontal movements due to the long pavement slab lengths and (b) the ends of the slabs have a tendency to curl. The two main approaches used to address these factors are: (a) restrain the movements, and (b) accommodate the movements. The first approach requires an elaborate system of abutments and tie-downs. The second approach requires a transverse joint detail, the design of which is relatively complicated from the standpoints of load transfer, sealing requirements, and riding quality.

(3) Construction Equipment. Opportunities for equipment manufacturers to develop innovative modifications of existing equipment (which is currently geared toward conventional pavement construction), or to develop new equipment (which would be better suited to PCP construction) have been virtually ignored. This is primarily due to lack of contractor demand for such equipment. The lack of contractor interest is understandable in light of the fact that PCP has remained such a negligible portion of the total amount of pavement constructed. The small proportion of PCP is partly due to its higher cost which, in turn, is partly due to the lack of proper equipment. A circular pattern emerges which helps explain the lack of equipment development.

(4) Unfamiliarity. The majority of paving contractors in the United States are unfamiliar with prestressed concrete. As a result, a significant program of contractor education is needed so that bids on PCP construction reflect the actual cost of the work rather than being unreasonably high to cover contractor inexperience.

(5) Application of Theory. The performance of previous experimental pretensioned and posttensioned PCPs has demonstrated the validity of the elasto-plastic theory of behavior. However, the lack of a proven and easily used design procedure based on this theory has been a major obstacle to its

application to the design of PCP, and a hindrance to realizing the full potential of PCP.

Poststressed PCPs should, theoretically, behave in accordance with the elasto-plastic theory even though they do not use tendons. However, this has yet to be experimentally confirmed and until it is, it has been recommended that design stresses be limited to the elastic range with this type of PCP, which is a major disadvantage with poststressed PCP.

BACKGROUND OF PROJECT 401

The Center for Transportation Research of The University of Texas at Austin was commissioned in 1983, by the State Department of Highways and Public Transportation, to undertake a study of the design and construction of PCP, with particular emphasis on overlay applications. The culmination of this study is to be a manual for the design and construction of PCP. The designation given this study was Project 401 and it is under the direction of Dr. B. Frank McCullough and Dr. Ned H. Burns.

The first phase of the work plan for Project 401 consisted of the following aspects: (a) a thorough review of the available literature to ascertain the current state of the art of PCP; (b) a critical evaluation of the design, construction, and performance of several FHWA sponsored projects which were constructed during the 1970s; and (c) development of a PCP design and the associated construction details and procedures based on (a) and (b).

Information from the first stage of Project 401 served as input for the design of two one-mile PCP test overlay sections on Interstate Highway 35 in Texas. These sections are located in Cooke and McLennan Counties and were given the designations Project 555 and 556, respectively. Construction of Project 556 is scheduled for late August, 1985. Construction of Project 555 was cancelled since it was felt that it would provide only limited additional research information.

An extensive data collection program is planned in connection with Project 556. This program will include the following aspects:

(a) Typical PCP slabs will be equipped with electronic and mechanical instrumentation to permit the measurement of concrete and steel strains, slab length changes, deflections, and temperature and moisture gradients across the depth of the slab. This instrumentation will also permit the time dependent variations of these items to be measured.

(b) The performance history of the test section will be monitored by means of condition and riding quality surveys.

(c) Information from (a) and (b) will be presented in a format that will be useful in evaluating the overall performance of the test section and will contribute to an increased understanding of PCP behavior.

Information from the design, construction and data collection phases of Project 556 will then be fed back into Project 401 where it will serve as the basis for the development of the previously mentioned PCP design and construction manual.

OBJECTIVE OF THIS REPORT

The objective of this report is to accomplish the goals of the first phase of the work plan for Project 401. The goals are as follows:

(a) thoroughly review the available literature to ascertain the current state of the art of PCP;

(b) critically evaluate the design, construction, and performance of several FHWA sponsored projects which were constructed during the 1970s; and

(c) develop a PCP design and the associated construction details and procedures based on (a) and (b) to be used in connection with two demonstration projects.

This report will describe the salient features of the PCP design developed by the Project 401 staff and the anticipated procedure that would be employed in constructing a section of PCP using this design. However, the specifics of the design for each demonstration project (i.e., site selection, foundation evaluation, and thickness and prestress level determination) will not be covered since these are discussed in detail in reports that are currently under preparation.

In the course of pursuing the objectives of the first phase of Project 401, several new PCP concepts were developed by the authors. These concepts represent a progression of thought regarding PCP and address many of the problems encountered on previous projects. These concepts will be introduced in this report. In addition, recommendations will be given for additional investigation, laboratory and field testing, and analytical studies to further develop the concepts and determine their viability.

SCOPE OF REPORT

The discussion will be primarily directed toward the design and construction of new highway pavements and overlays of existing highway pavements. However, most of the discussion is applicable to airfield pavements as well.

APPROACH AND ORDER OF PRESENTATION

The approach and order of presentation which will be used to accomplish the objectives are as follows:

(1) Chapter 2. This chapter is devoted to a discussion of the three primary methods which have been used to prestress pavement. Each method will be explained; the manner in which they are used to obtain different prestress configurations and the main construction procedures employed in each method will be illustrated; and the problems encountered with their use will be

discussed. This will be followed by a review of the foreign and domestic history of prestressing for airport and highway pavement applications.

(2) Chapter 3. The topics covered in this chapter are (a) factors affecting the design of PCP, and (b) PCP design variables. The factors affecting the design of PCP which will be discussed are as follows: elasto-plastic behavior under loads, load repetition effect, subgrade restraint, temperature curling, moisture warping, prestress losses, and buckling. The design variables which will be covered include foundation strength, pavement thickness, slab length and width, prestress magnitude, tendon spacing, and transverse joints.

(3) Chapter 4. The intent of this chapter is to critically examine the primary aspects of several FHWA sponsored projects which were constructed during the 1970s. This examination is based on the background information provided in Chapters 1, 2, and 3.

(4) Chapter 5. The purpose of this chapter is to introduce several new PCP concepts. Each concept will be discussed in terms of its most important features and the anticipated construction sequence that would be employed in building PCP using the concept. In addition, the characteristics of the new concepts will be compared to determine: (a) the relative ability of each concept to address the problems encountered on previous projects; (b) the relative ability of each concept to effectively utilize the potential of PCP; and (c) what, if any, new problems are created with each concept.

(5) Chapter 6. Recommendations for additional investigation, testing, and analysis necessary to develop the concepts introduced in Chapter 5 and to determine their viability are presented in this chapter.

(6) Chapter 7. This chapter presents a final summary and conclusions.

CHAPTER 2. PRESTRESSING METHODS

Three primary methods have been used to introduce a permanent and essentially horizontal compressive stress: pretensioning, posttensioning, and poststressing. These methods have been employed alone and in various combinations on previous PCP projects to obtain the following prestress configurations:

(1) Longitudinal. Prestress is only applied parallel to the longitudinal axis of the pavement. The pavement may be either unreinforced or reinforced in the transverse direction.

(2) Longitudinal-Transverse. Prestress is applied both parallel and perpendicular to the longitudinal axis of the pavement.

(3) Diagonal. Prestress is applied at an angle to the longitudinal axis of the pavement. Desired prestress levels both parallel and perpendicular to the longitudinal axis of the pavement can be obtained by merely adjusting the angle at which the prestress is applied.

The three prestressing methods (pretensioning, posttensioning, and poststressing) will be explained; the manner in which they are used to obtain the various prestress configurations and the main construction procedures employed in each method will be illustrated; and the problems encountered with their use will be discussed. This will be followed by a brief summary of the history of prestressing for airport and highway pavement applications.

PRETENSIONING

In this method, prestressing tendons (generally wires or strands) are stretched to a predetermined tension and anchored to fixed abutments. (The term "fixed abutments" refers to the fact that the abutments do not significantly yield when subjected to extremely large forces, and not necessarily to the fact that they remain permanently in place, as will be explained later in this section.) The concrete is then cast around the stressed tendons. After the concrete has gained sufficient strength, the jacking pressure is released. The bond between the strands and the concrete prevents the strands from shortening, resulting in transfer of the prestress force to the concrete (mostly by bond near the ends of the slab) without need of special strand anchorage hardware. The compressive stress in the slab is not significantly affected by contraction and creep of the concrete since only a small percentage of the tension in the tendon is relieved.

Two of the pretensioning techniques which have been employed on previous projects are illustrated in Figs 2.1 and 2.2. Two types of fixed abutments have been used in pretensioned PCP construction. The first type is a substantial cast-in-place concrete abutment which transmits force to the subgrade through a combination of soil friction and passive earth pressure. Examples of this type of abutment are shown in Figs 2.3 and 2.4.

The soil friction developed by these abutments is proportional to their weight. Their effective weight includes both the weight of the concrete and the weight of the soil above the potential plane of sliding. This helps explain the configurations of the abutments shown in Figs 2.3 and 2.4. With the abutment shown in Fig 2.3, the masses of earth between the ribs participate in any movement of the abutment. The same is true of the soil mass above the downturned end of the abutment shown in Fig 2.4. In addition, as shown in Fig 2.3, the weight of pretensioning abutments can be relatively easily supplemented to increase the frictional resistance prior to transfer of the prestress to the pavement.

One additional factor should be pointed out in regard to the design of ribbed abutments like the one shown in Fig 2.3. The first ribbed abutments had transverse ribs; however, passive earth pressure on the ribs developed bending in the pavement slab. Thus, longitudinal ribs were added to increase the longitudinal bending strength. In many cases, the transverse ribs were completely eliminated when the longitudinal ribs were cast directly against the vertical earth walls of trenches cut into the ground.

Cast-in-place abutments are expensive, time consuming to construct, and their use is limited to the pretensioning of either one or two

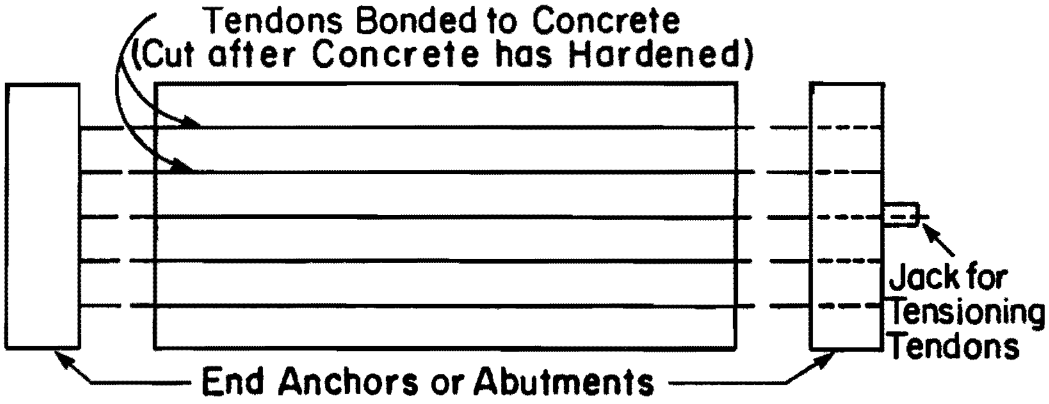


Fig 2.1. Pretensioning (transverse stressing can be accomplished by pretensioning or posttensioning. Ref 30).

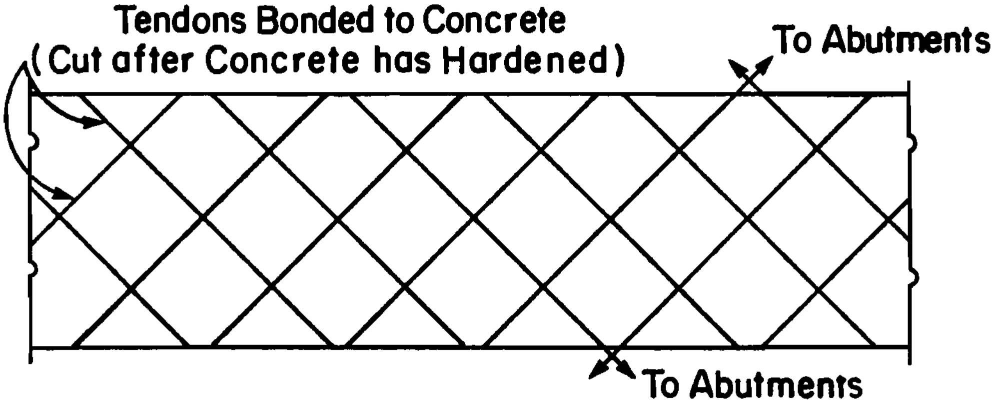


Fig 2.2. Diagonal pretensioning (Ref 30).

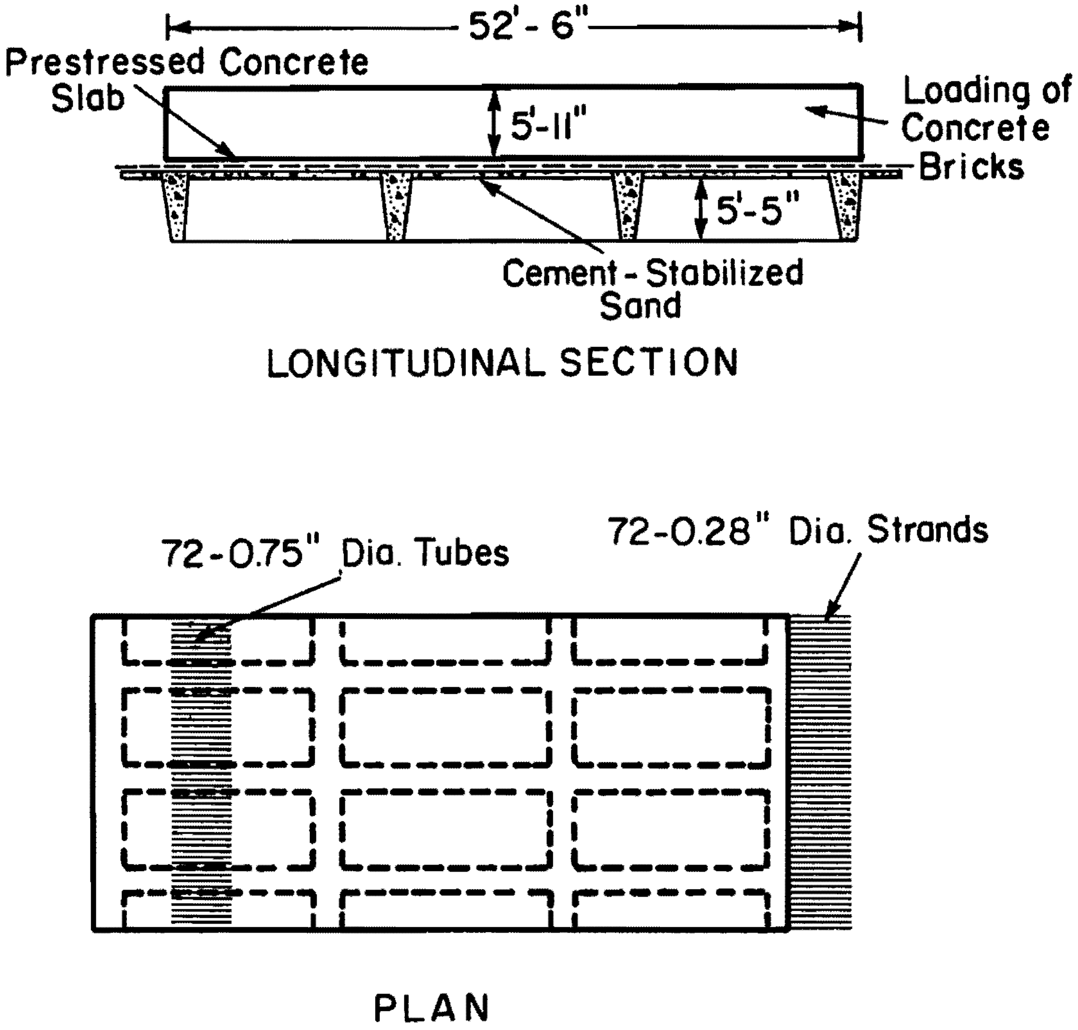


Fig 2.3. Pretensioning abutment for prestressed pavement at Haarlemmermeer, Netherlands (Ref 56).

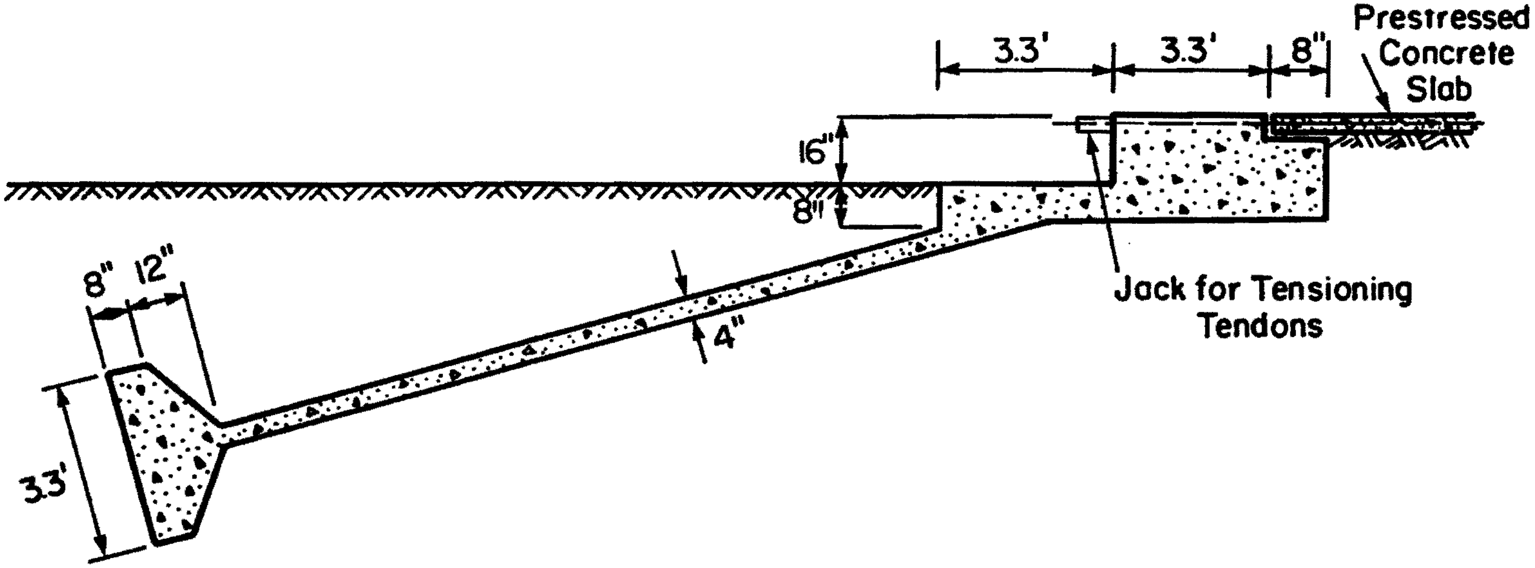


Fig 2.4. Pretensioning abutment for highway pavement at Cesena, Italy (Ref 56).

adjacent pavement slab sections. In addition, with cast-in-place abutments, yielding of the soil during the period between tensioning of the strands and casting of the pavement concrete can cause the strands to lose a large percentage of the prestressing force. These disadvantages led to the development of the second type of abutment, a portable abutment, of which two primary variations have been used.

The first of these variations was used for pavement pretensioned in the longitudinal direction only. With this abutment, pretensioning tendons are stretched between reusable prestressed concrete beams placed at both ends of the pavement section. These beams transmit the force through bending and shear to pipe struts provided parallel to the longitudinal edges of the pavement section. This abutment is shown in Fig 2.5.

The second primary portable abutment variation was used for pavement pretensioned in both the longitudinal and transverse directions. It was developed by Dr. Lev Zetlin for use in the construction of an experimental jet taxiway which he had been commissioned to design by the United States Navy. In a paper presented at the Prestressed Concrete Institute Convention in 1960, Dr. Zetlin explained the basic principle upon which his abutment was based. The following excerpt is from that paper:

> The abutment is based on the simple principle of a closed curve, such as a ring,as shown in [Fig 2.6(a)]. The ring, if subjected to a pair of forces acting across its diagonal, would be extremely flexible, and large bending moments would be set up in it. For example, a 200 ft. dia. ring, subjected to two diametrically opposed forces of 20 kips each distributed over one foot of periphery, would have a maximum bending moment of 637 kips x ft., requiring 70 sq. inches in cross-sectional area of structural steel. On the other hand, if this ring were subjected to hydrostatic pressure of 20 kips per foot over the entire perimeter, as in [Fig 2.6(b)], no bending moments would be set up, but the entire ring would be in compression, with a compressive force of 2000 kips, requiring 100 sq. inches in a cross-sectional area of structural steel for a total force of 12,560 kips as compared with 70 sq.inches in [Fig 2.6(a)], for a total force of 40 kips (Ref 136).

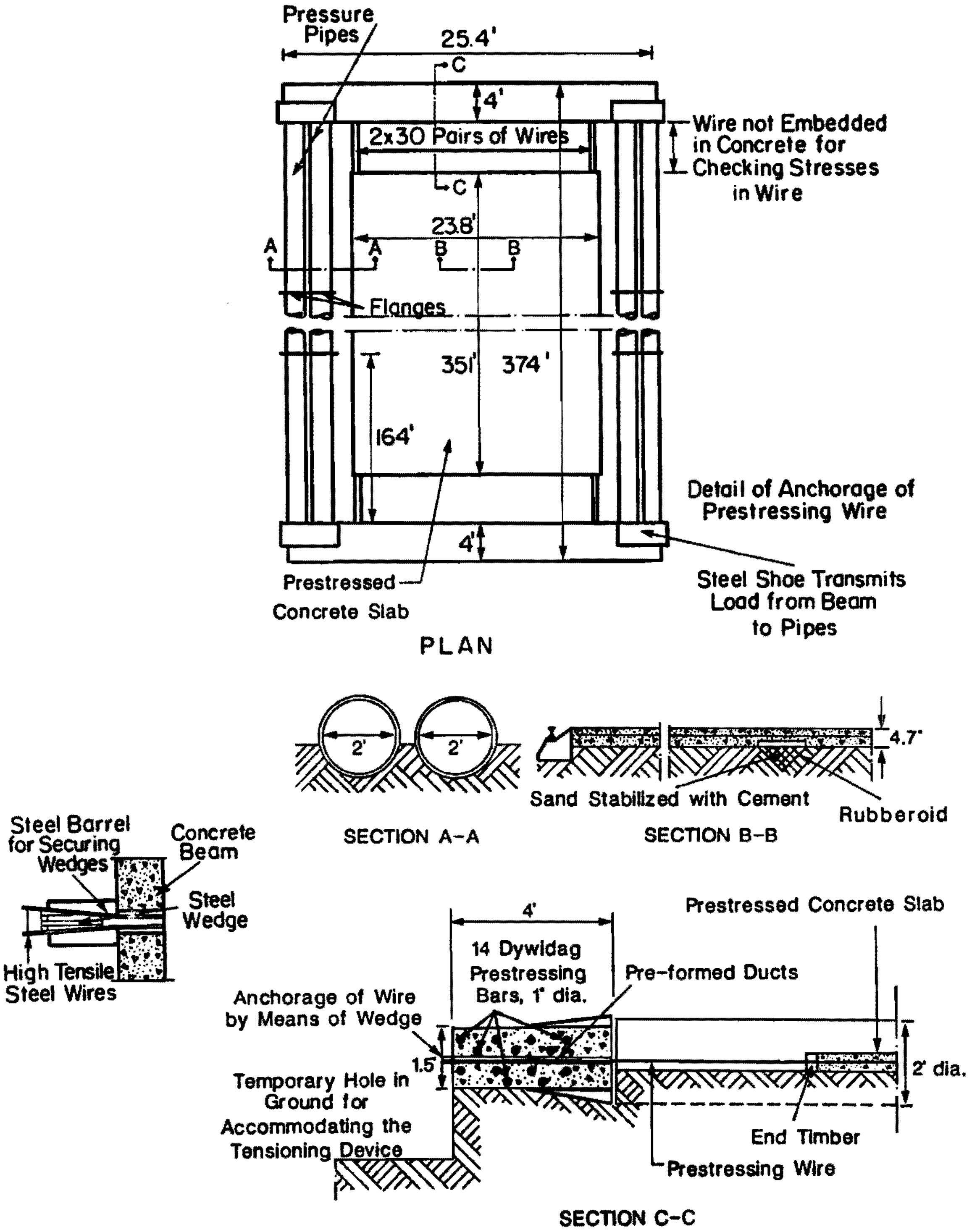


Fig 2.5. Pretensioning frame for prestressed pavement at Leidschendam, Netherlands (Ref 56).

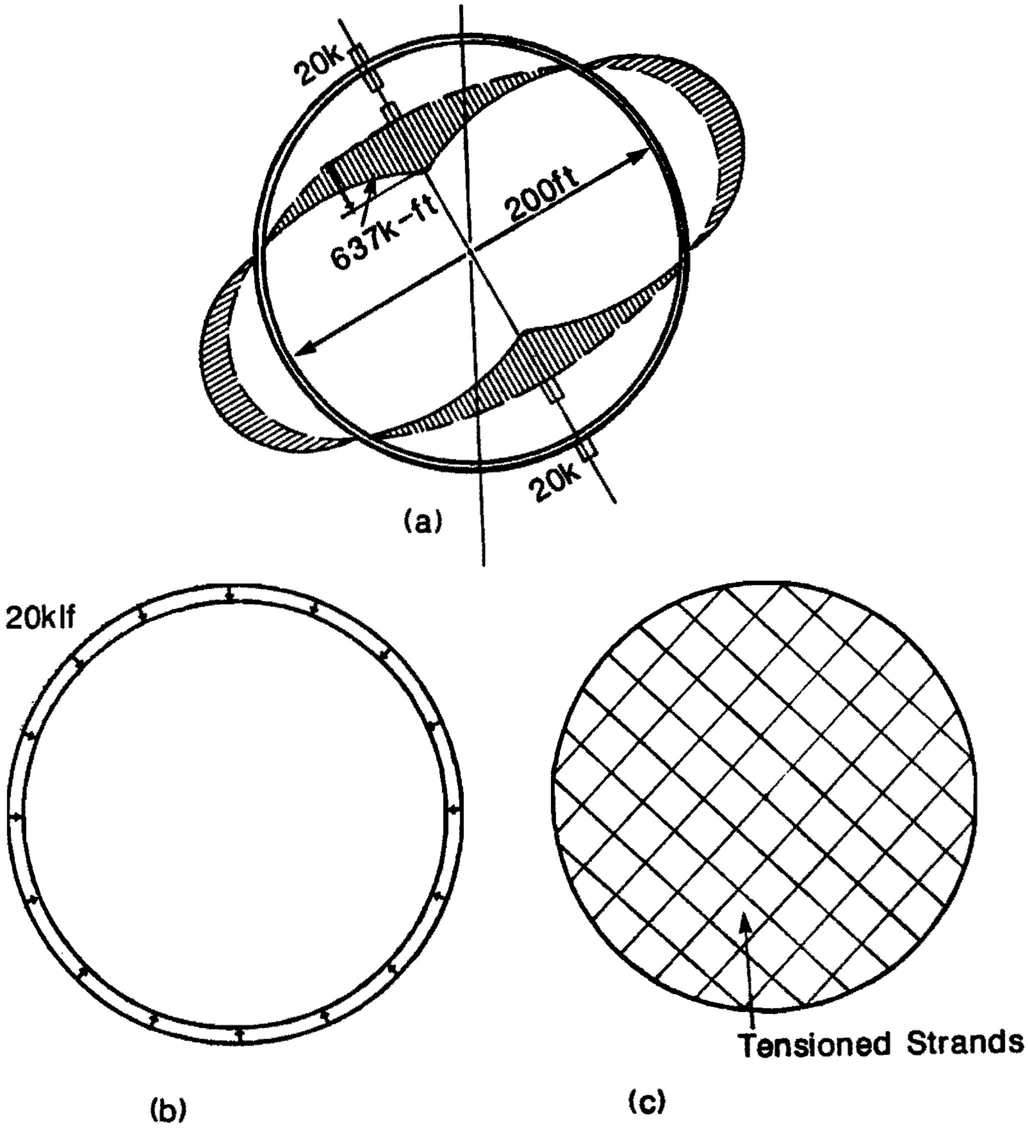
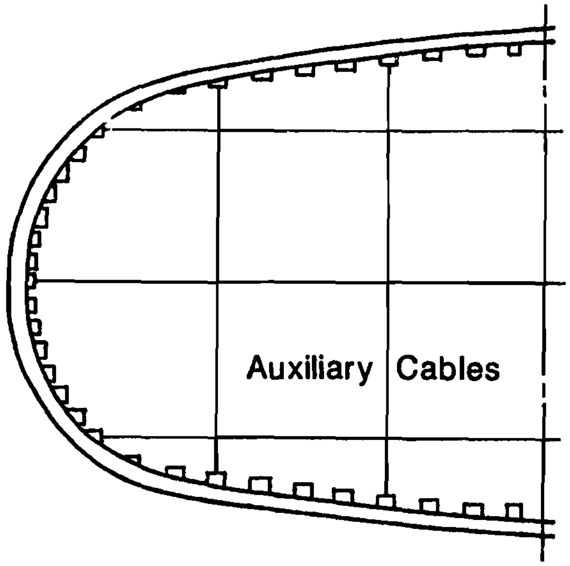


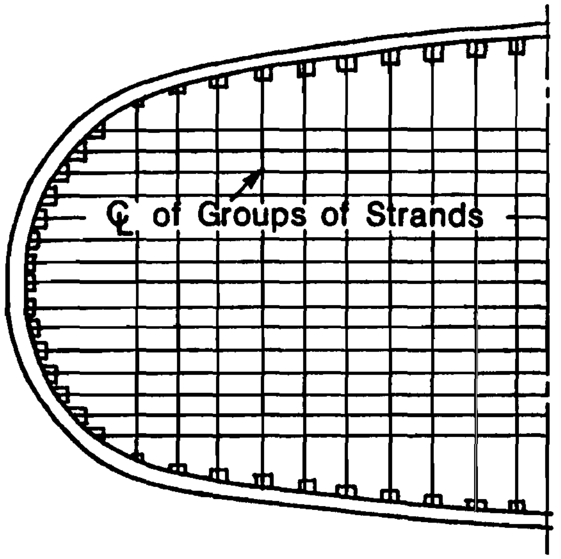
Fig 2.6. Radial force effects on a closed ring (Ref 136).

He then went on to explain how he applied this principle to the design of his portable abutment:

> A state equivalent to hydrostatic compression could be achieved if the ring is criss-crossed by strands in tension, as in [Fig 2.6(c)]. Criss-crossing of strands has an additional advantage in that a ring tied by strands does not buckle in its plane.
>
> The portable abutment that we have developed and shown in [Fig 2.7] is essentially a closed curve, but instead of being a circular ring it has an oval shape. This shape has been adopted since it is more efficient for pavements. In pavements, the required longitudinal prestress is usually higher than the required transverse prestress. Hence, the oval shape.
>
> [Fig 2.7] shows half of the assembled abutment in place. The abutment shown measures 200 ft. x 70 ft., and is composed of assembled elements 10 ft. long each. [Fig 2.7(b)] shows the main prestressing strands. This configuration may be adjusted so that the entire abutment is only in compression. To make sure that the abutment is entirely in compression, as well as to eliminate buckling of the abutment out of its plane, a grid of auxiliary cables, as shown in [Fig 2.7(a)], is attached to the underside of the abutment.
>
> The abutment itself is built of short portable elements, as shown in [Fig 2.8]. This figure shows, also, some cross-sections. In this case the abutments consist of high strength steel channels separated by timber blocking. The separate elements are placed on the ground to form a closed curve as required.
>
> The pretensioning strands in this scheme are in clusters. Each cluster is anchored to a movable anchorage block. Each block has studs passing through the abutment. Jacks grab the studs and pull the blocks with the strands by pushing against the abutment.
>
> When the strands are tensioned--at which point the whole assembly looks like a snow shoe or a tennis racket--the pavement is poured with conventional paving equipment . . . .



(a) Portable abutment forms closed ring which is dimensionally stabilized by auxiliary tension cables.



(b) Groups of pretensioned prestressing strands are held in take-up assemblies attached to anchors.

Fig 2.7. Portable abutment (Ref 136).

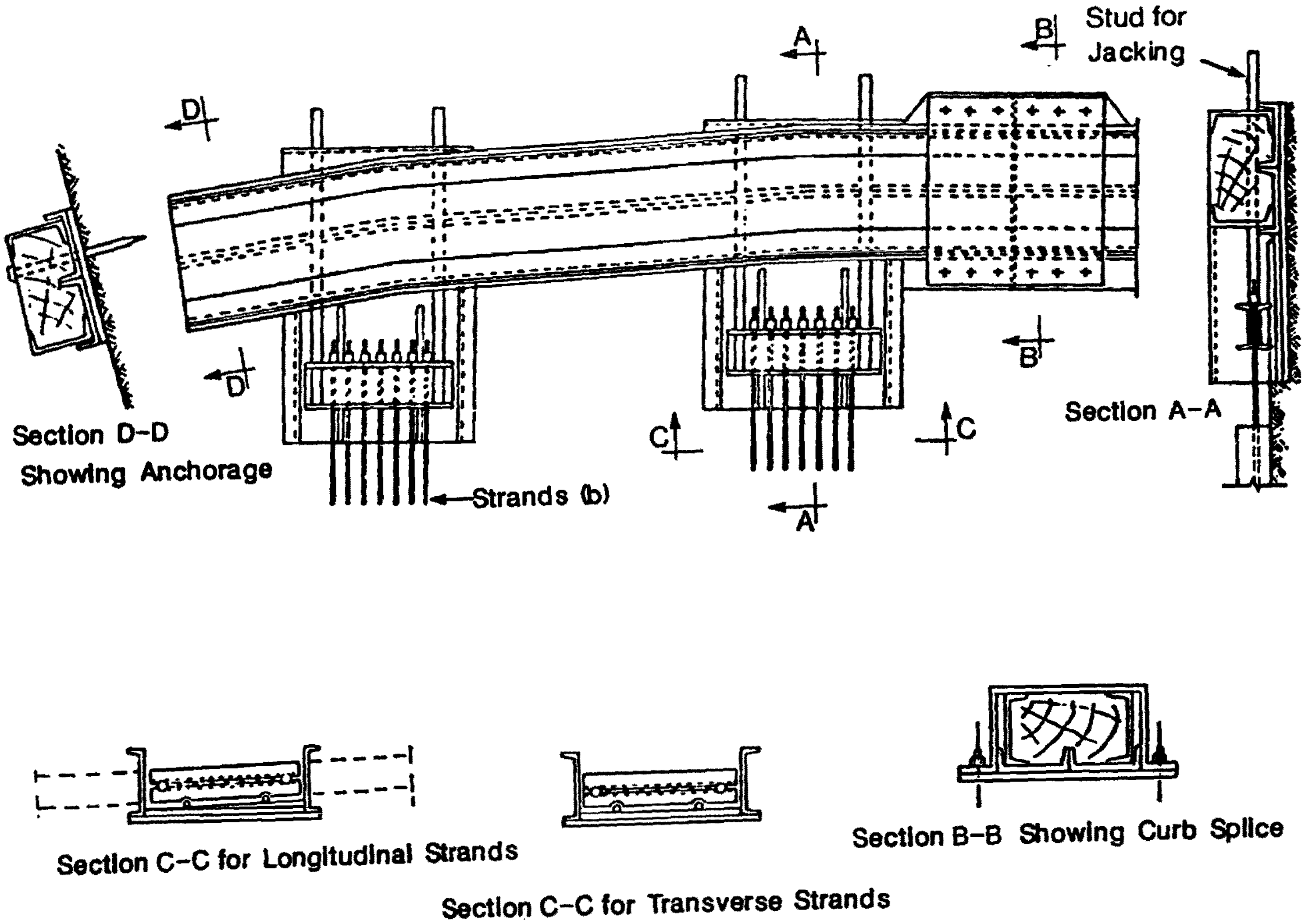


Fig 2.8. Details of portable abutment designed for use on pretensioned, prestressed pavement projects (Ref 136).

> When the pavement has hardened sufficiently, the prestressing strands are burned off and the abutment is ready to be taken apart and moved to another section. The auxiliary strands, which are insignificant relative to the prestressing strands, are left in place, unstressed, under the pavement (Ref 136).

While portable abutments have the advantage of being reusable, they also have some disadvantages. They are expensive and difficult to assemble and disassemble. They also make long pavement slab lengths impractical.

In summary, although pretensioning is a very popular method for the production of precast prestressed concrete elements in a plant facility having permanent, easily reusable casting beds and abutments, the difficulties associated with the use of this method for PCP construction have not been satisfactorily solved. For this reason, interest in the use of pretensioning for PCP construction has not been as great as for other prestressing methods.

POSTTENSIONING

In posttensioned concrete construction, either bonded or unbonded tendons may be used. With bonded tendons, mortar-tight metal tubes or ducts (also called sheaths) are placed in the locations where tendons are required in the final slab prior to casting the slab. The tendons may be preplaced inside the sheath before casting or can be placed after hardening of the concrete. After the concrete has been cast and has attained sufficient strength, the tendons are stressed and anchored at the ends of the pavement slab. The void between each tendon and its duct is filled with a mortar grout which subsequently hardens. Grouting ensures bonding of the tendon to the surrounding concrete, improves the resistance of the slab to cracking, and reduces the risk of corrosion of the steel tendons.

Unbonded tendons, on the other hand, are generally coated with grease, wrapped with waterproof paper, or placed inside a flexible plastic hose, and then placed in the slab forms prior to concrete casting. They remain unbonded throughout their length for the entire service life of the pavement. The tendon force is applied to the slab only at the anchorages. The primary advantage of unbonded tendons is that they eliminate the grouting operation which is required with bonded tendons.

The three primary posttensioning techniques which have been utilized in the past are shown in Figs 2.9, 2.10, and 2.11. One drawback common to the posttensioning techniques shown in Figs 2.9 and 2.10 is that wide gaps must be provided between adjacent slab sections to accommodate stressing operations. Using the technique shown in Fig 2.9, the tendons are stressed by direct jacking of the tendons in the gaps at the boundary of the slab. After application of the jacking force the tendons are anchored in place. Using the technique shown in Fig 2.10, the tendons pass through the gap and are anchored in the opposite ends of the slab. A system of jacks is then used in the gap to force the two slab segments apart, thereby stressing the tendons and inducing compressive stress in the concrete. The drawback of requiring wide gaps between adjacent slab sections associated with both of the previously described techniques is eliminated when diagonal tendons, as illustrated in Fig 2.11, are used because the tensioning apparatus and the anchoring devices can be installed along the longitudinal edges of the slab.

As with pretensioned PCP, the compressive stress in posttensioned PCP is not significantly affected by contraction and creep of the concrete since only a small percentage of the tension in the tendon is relieved.Greater interest has been expressed in posttensioning than in the other prestressing methods for PCP construction primarily because it has proven thus far to be the most effective method for cast-in-place construction requiring stressing on the job site.

POSTSTRESSING

This prestressing method most commonly has been used only in the longitudinal direction of the pavement, with the transverse prestress, if required, being provided by one of the other two methods. Poststressing has usually involved the construction of a series of gap-separated slab

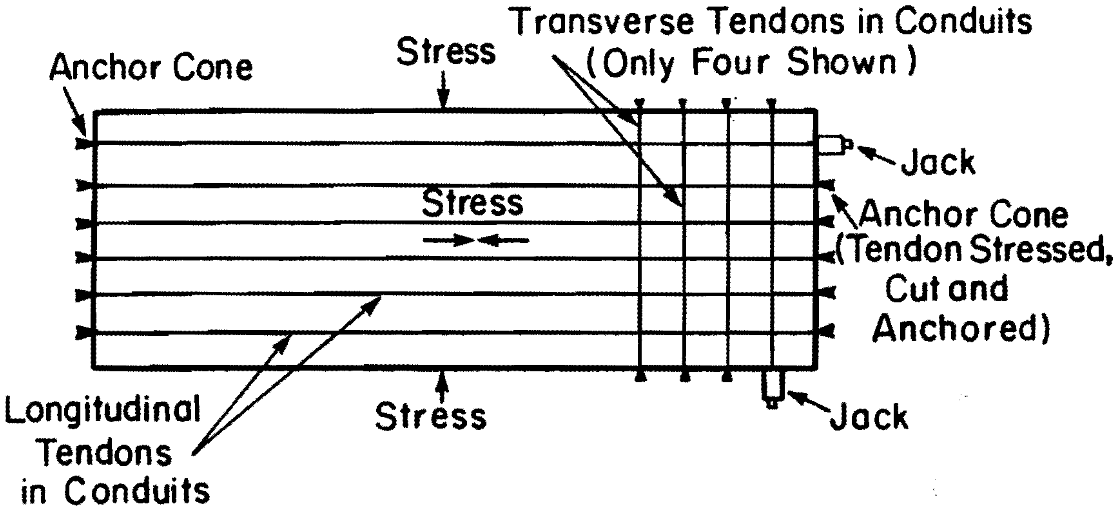


Fig 2.9. Posttensioning with end jacking (Ref 30).

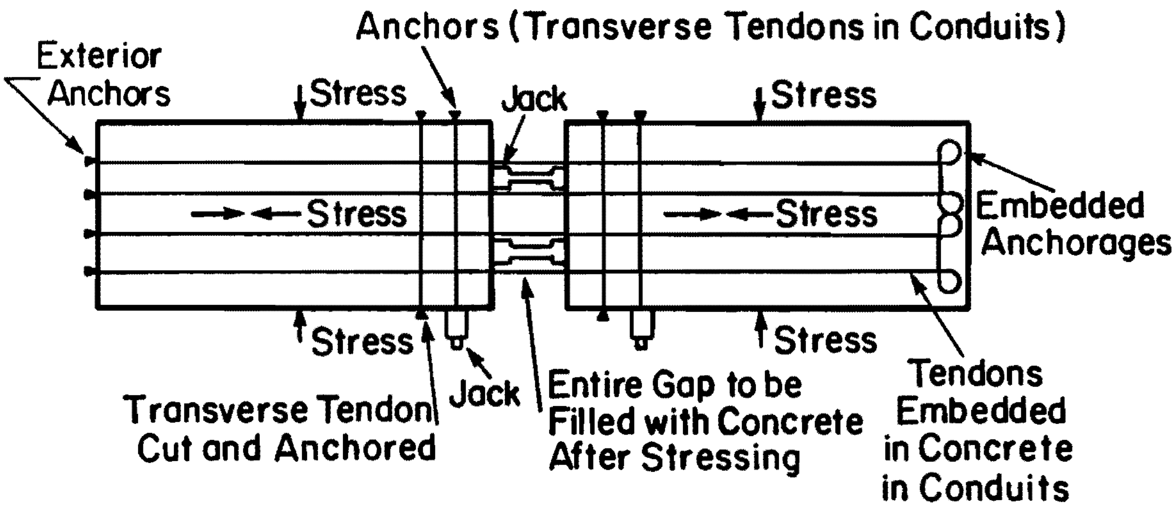


Fig 2.10. Posttensioning with gap jacking (Ref 30).

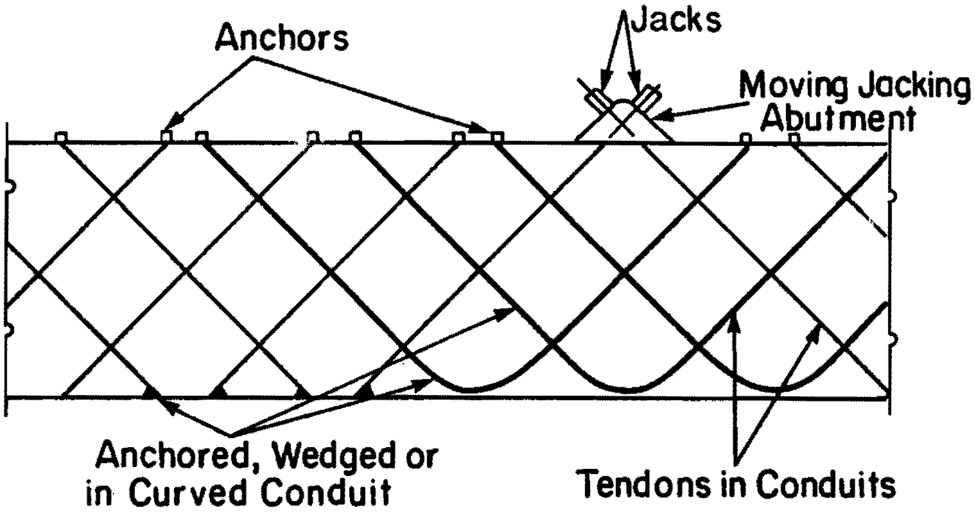


Fig 2.11. Diagonal posttensioning (Ref 30).

segments located between two end abutments. Compressive stress is applied to the slabs by inflating hydraulic jacks inserted in the gaps, thereby forcing the slabs against the abutments. The gaps are filled with concrete after the desired level of compressive stress in the slabs has been attained. This prestressing method is shown in Fig 2.12.

Unlike the abutments for pretensioned PCP, which are required only during the construction period, those for poststressed PCP must transmit thrust to the subgrade throughout the entire service life of the pavement. Two different approaches have been used in the design of abutments for poststressed PCP. In both approaches, the pavement thrust is transmitted to the subgrade through a combination of soil friction and passive earth pressure. However, the approaches differ in the manner in which they respond to differences in the magnitude of the thrust.

In the first approach, fixed abutments are used. As defined earlier in this section in connection with pretensioned PCP, the term "fixed abutments" refers to the fact that the abutments do not significantly yield when subjected to extremely large forces. Examples of fixed abutments used on previous poststressed PCP projects are illustrated in Figs 2.13, 2.14, 2.15, and 2.16.

Problems have been encountered with the use of fixed abutments for poststressed PCP. First, the compressive stress in the pavement can be significantly decreased by small order hygrothermal contraction and/or creep of the concrete. Thus, the compressive stress may be insufficient to enable the slab to carry the working loads. Therefore, the jacking systems which are used often permit reapplication of prestress. Second, small-order hygrothermal expansion may result in very high compressive stresses in the pavement. This can cause at least two major problems. First of all, the highest compressive stresses and, therefore, the maximum pavement thrust is not likely to occur during construction. Thus, the use of temporary supplemental weight on the abutment to increase the soil friction, as is sometimes done for pretensioned PCP abutments (see Fig 2.3), is not possible. As a result, even more substantial and costly abutments are required for

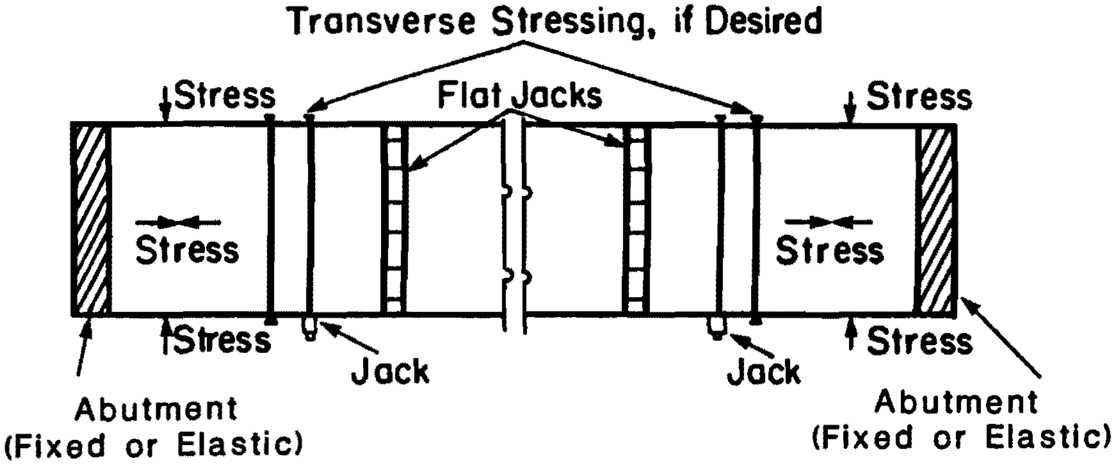


Fig 2.12. Longitudinal poststressing (Ref 30).

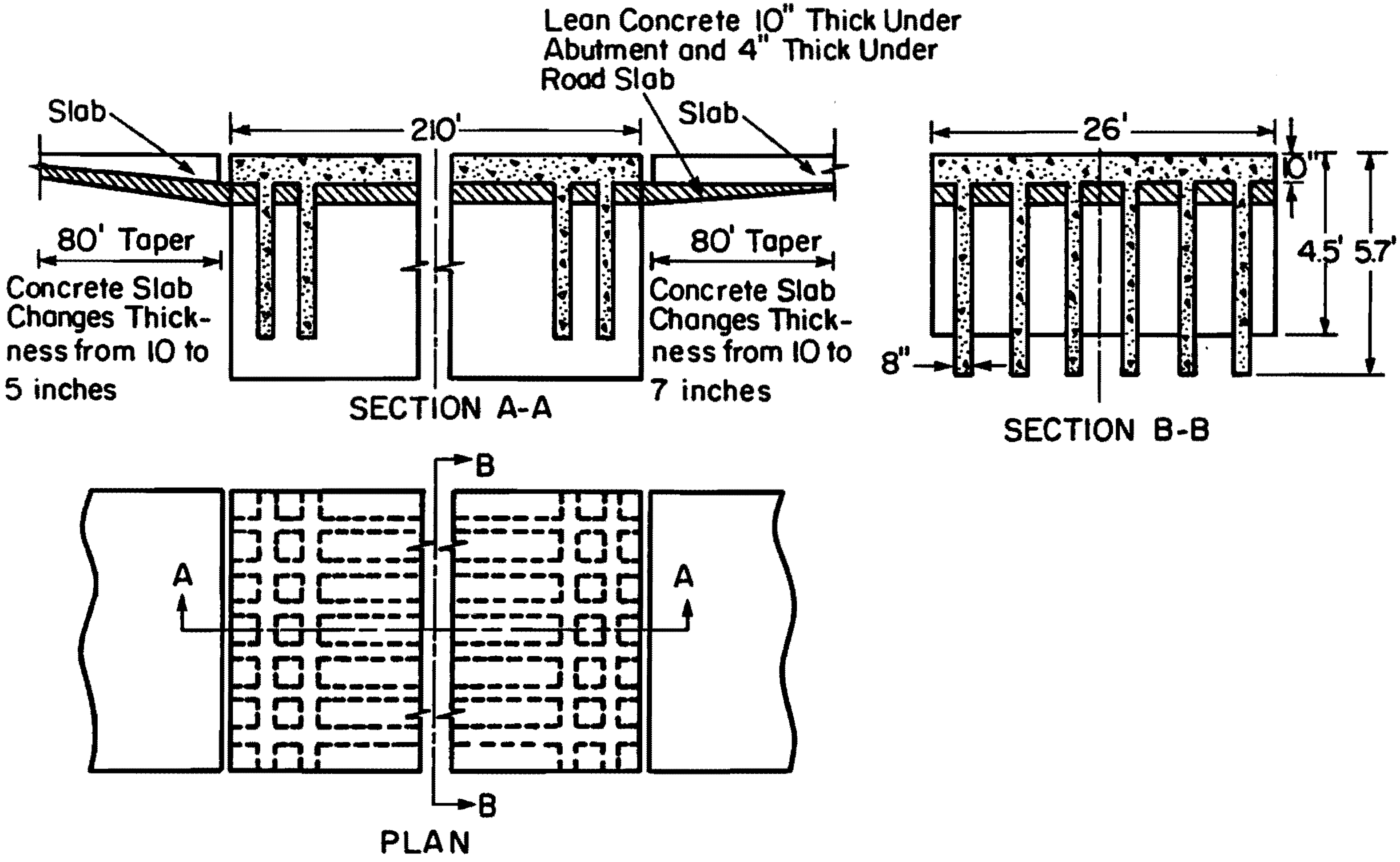


Fig 2.13. Rib soil abutment for prestressed pavement at Winthorpe, England (Ref 56).

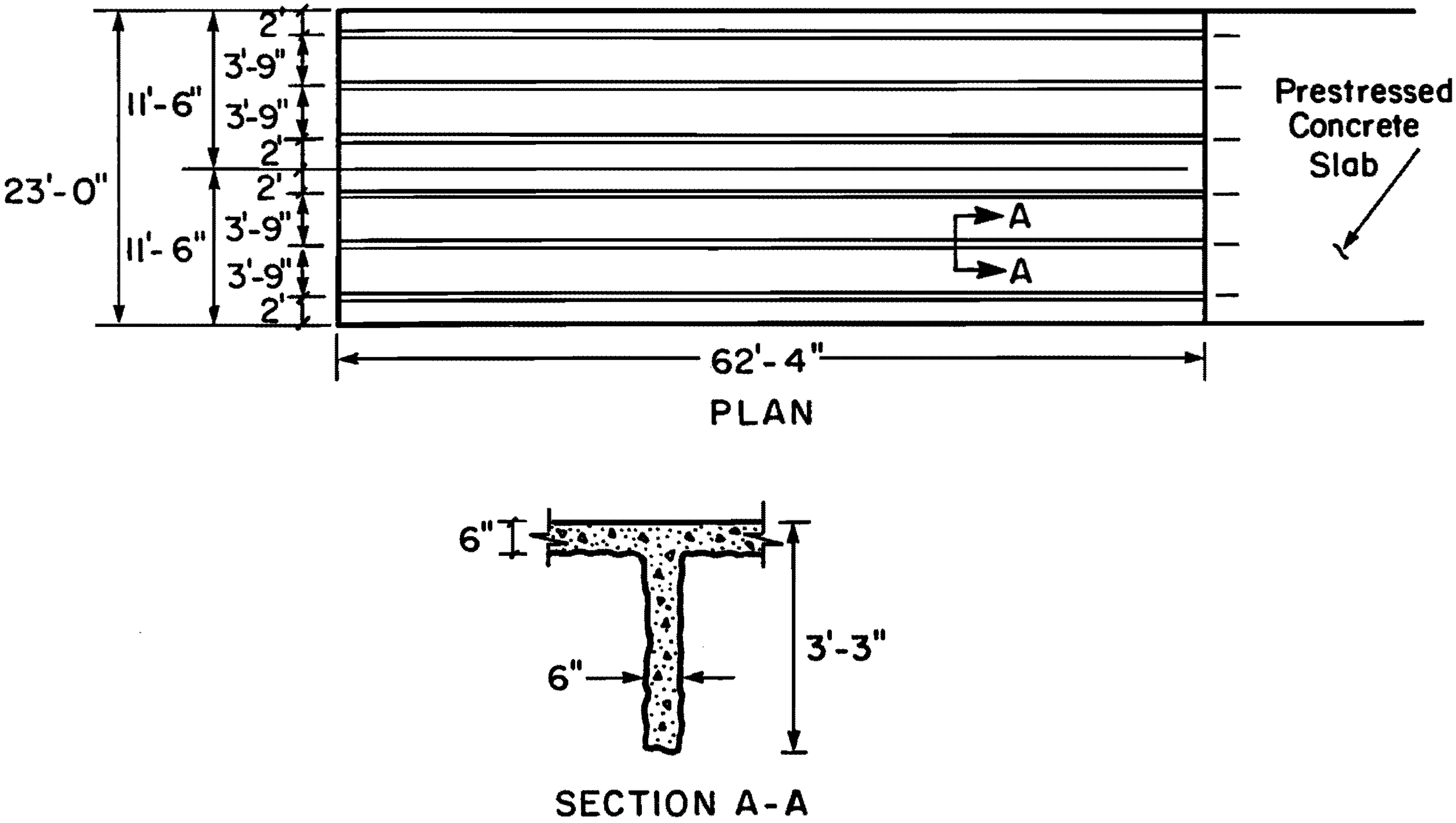


Fig 2.14. Abutment for prestressed pavement at Zwartberg-Meeuwen, Belgium (Ref 56).

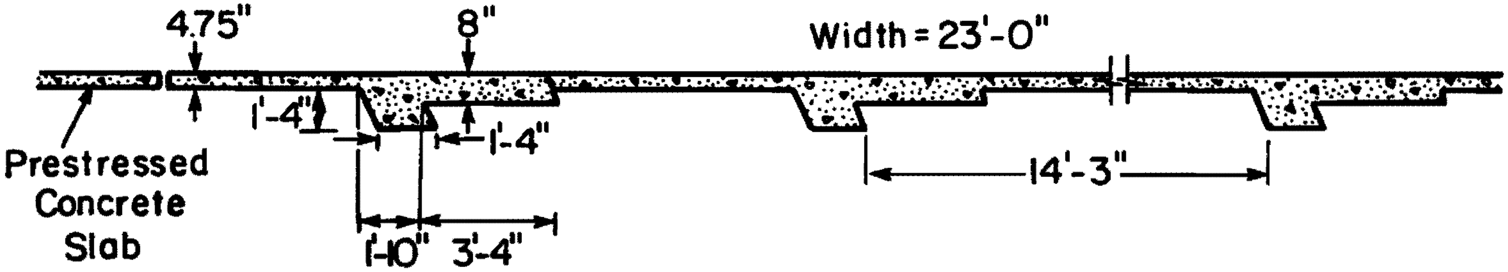


Fig 2.15. Abutment for highway pavement at Bourg-Servas, France (Ref 56).

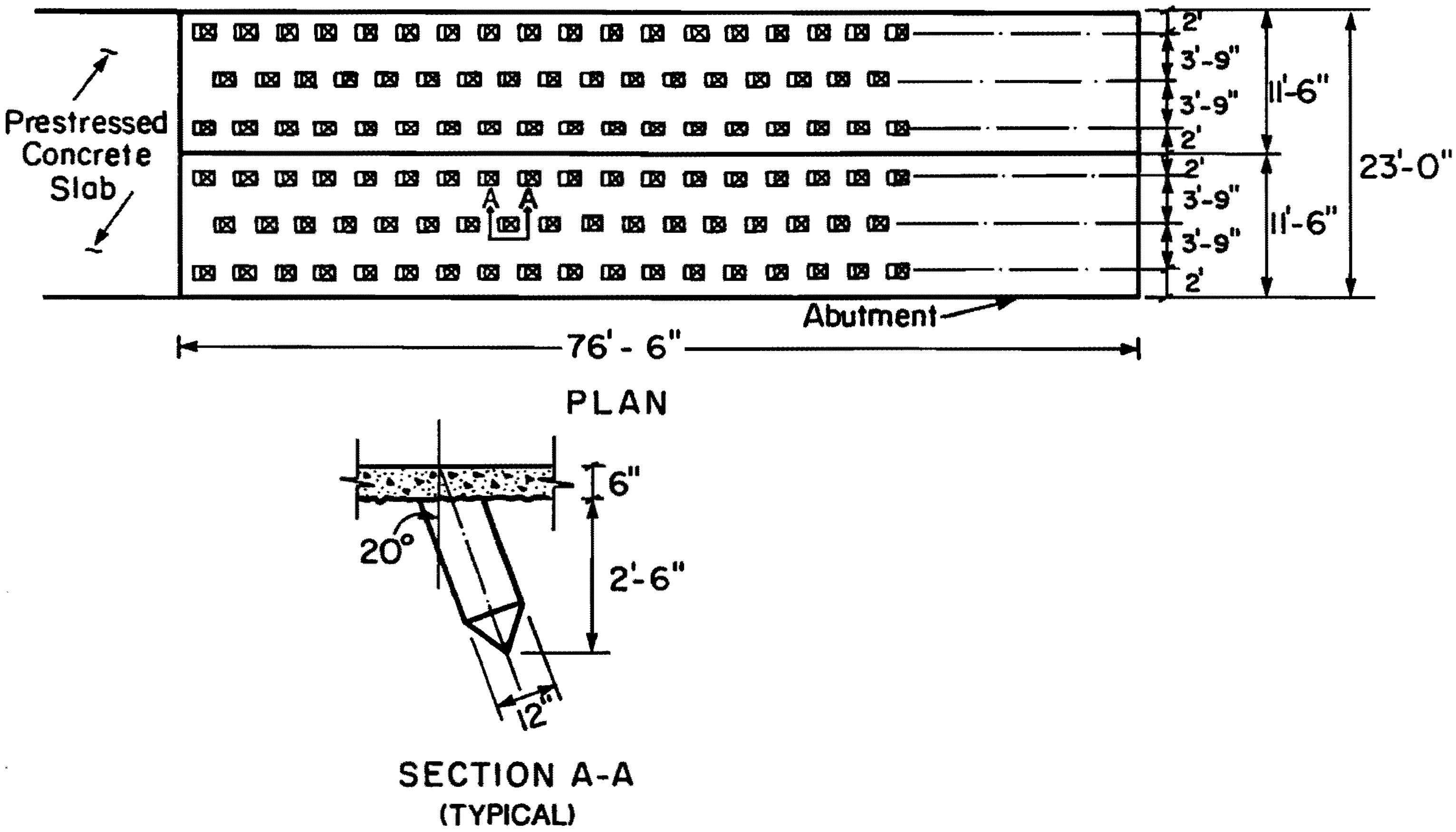


Fig 2.16. Abutment on piles for prestressed pavement at Zwartberg-Meeuwen, Belgium (Refs 56, 131).

poststressed PCP than for pretensioned PCP. Second, since the prestress is produced by external forces, buckling of the slab is conceivable.

The second approach to the design of abutments for poststressed PCP uses abutments designed to react elastically to applied loads in an attempt to avoid the problems inherent in the use of fixed abutments. The abutments used for the runway and taxiway at Maison-Blanche, Algeria are examples of elastic abutments. These abutments consist primarily of a curved concrete slab loaded with 10 feet of earth, as illustrated in Fig 2.17. Rather than being rigidly fixed to these abutments, the ends of the pavement slide over them. The connections between the ends of the pavement and the abutments consist of tendons housed in neoprene sheaths. As shown in Fig 2.17, one end of each tendon is anchored in the end of the pavement and the other is anchored at the far end of the abutment. The tendons remain unbonded after they are tensioned, thus remaining free to move within the ducts and allowing the ends of the poststressed PCP to move back and forth in response to changes in the weather. The tendons act like powerful springs and exert an almost constant, known force against the end of the pavement. Therefore, excessive compressive stresses are prevented from developing in the pavement when it expands. Also, compressive stress is maintained in the pavement when it contracts.

Another method of constructing poststressed PCP, which was investigated, employed self-stressing cement. This cement contains about 15 per cent of an expansive component (primarily calcium sulfoaluminate) which causes the concrete to expand for approximately seven days under moist curing conditions. Preliminary tests of this concrete provided encouraging indications of its potential success in this application. However, the performance of two experimental pavements constructed in California proved to be much less promising. The anticipated results, method of construction, and performance are summarized in the following quote from a report prepared by the Division of Highways, State of California:

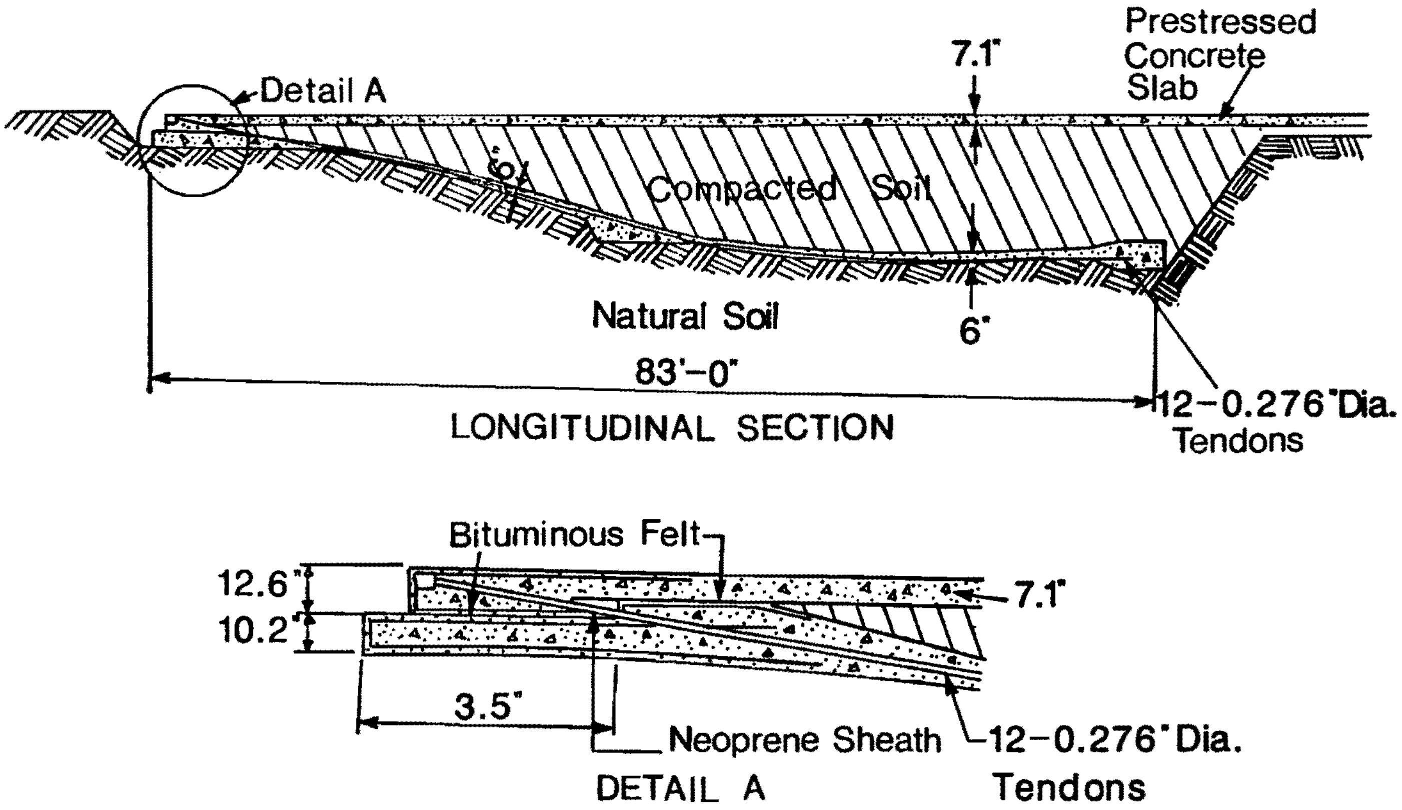


Fig 2.17. Abutment for Maison-Blanche Airport, Algeria (Refs 56, 131).

> The new type concrete appeared to offer the possibility of constructing nonreinforced concrete pavements without joints, which would have few if any transverse cracks. Hopefully, such a pavement, in addition to being essentially crack-free, would provide superior riding qualities by minimizing or eliminating the usual slab curling or warping due to differential drying shrinkage and thermal changes. It was theorized that the monolithic pavement slab expansion would be adequately restrained by subgrade friction in the lateral direction and by a combination of subgrade friction and depressed anchorages in the subgrade near the end of each day's paving in the longitudinal direction. Restraint of expansive forces ideally would build up moderate biaxial compressive stresses in the concrete during the curing period. Then upon drying, instead of the concrete entering a state of tension, the compressive stresses would only be reduced and the normal development of crack-producing tensile stresses would be eliminated. Unfortunately, the performance of these pavement sections has shown no advantage in the use of shrinkage compensated cement in nonreinforced highway construction (Ref 121).

PAST USES OF THE PRIMARY PRESTRESSING METHODS

The principle of prestressing has been widely used in other structural fields, having attained a prominent place in concrete bridge and building construction. However, it still remains a novelty in pavements, despite the fact that the initial investigations into its use occurred at about the same time that use of prestressing for building structures was coming into practice.

The first reported uses of prestressing in concrete pavement construction were in the United States. Approximately 10 miles of highway pavement in Missouri, Michigan and Maryland were constructed between 1937 and 1941 using poststressing. Compressive stress was applied to the pavement at the earliest possible age by means of pneumatic cells located in narrow expansion joints in the pavement. The stress was increased as the concrete gained strength until a level of approximately 200 psi was attained. The stress was removed after the concrete reached maturity. These projects really do not meet the generally accepted definition of PCP since the compressive stress was not permanent, being applied only while the concrete was curing and removed before the pavement was subjected to traffic loads. These projects represent more of an example of stress-cured concrete pavement than of PCP.

Foreign

PCP, as defined earlier, had its origins in Europe during the 1940s. Investigations into its use were first made in England in 1943. The first actual field application was for a runway pavement at Orly Airport in France in 1946 and was based on research done by Eugene Freyssinet, the eminent French engineer and pioneer in prestressed concrete. Additional prestressed concrete airport pavements were constructed during the next fourteen years in Algeria, Austria, Belgium, England, France, Germany, the Netherlands, and New Zealand. The total known length of runway pavement constructed outside of the United States through 1960 was approximately 19 miles.

The first highway applications of prestressed concrete pavement were in France during 1946 to 1949, followed by projects in Britain between 1950 and 1952. These projects employed several different prestressing strand configurations including diagonal, longitudinal, combined longitudinal and transverse. Additional projects followed during the 1950s in Austria, Belgium, France, Germany, Great Britain, Italy, Netherlands, Japan, and Switzerland. The total length of highway pavement constructed outside of the United States through 1960 was approximately 14 miles.

Domestic

As in Europe, the first PCP built in the United States was designed for an airfield. In 1953 the United States Navy, Bureau of Yards and Docks, constructed a 7-inch-thick experimental PCP at Patuxent River Naval Air Station, Maryland. The United States Army Corps of Engineers was also involved in the construction of experimental airfield PCPs during the 1950s. The only nonmilitary airfield PCPs constructed in the United States during the 1950s were two overlay slabs for the San Antonio International Airport which were designed by engineers at the Southwest Research Institute (Refs 31, 63, 64). The total known length of runway PCP constructed in the United States though 1960 was less than two-thirds of a mile. The only additional airfield PCP constructed in the United States after 1960 was an 800 ft. runway segment at Chicago's O'Hare International Airport which was constructed in 1980 (Ref 10).

The first experimental highway PCP project in the United States was built in 1956 in Pittsburgh, Pennsylvania under the sponsorship of Jones and Laughlin Steel Corporation (Ref 85). However, the first operational highway PCP in the United States was not constructed until 1971 near Milford, Delaware and was only 300 feet long.

In 1971 the FHWA, through the joint efforts of the Office of Research and Region 15, placed 3200 feet of 24-foot-wide, 6-inch-thick PCP as part of the permanent airport road network at Dulles International Airport (Ref 105). The pavement was constructed under the FHWA Region 15 Research and Development Demonstration Projects Program. This program was established to accelerate the implementation of research and development results by selecting outstanding research developments, translating them into operating procedures, and demonstrating their advantages to state and federal agencies. The potential advantages of PCP resulted in its early incorporation into this program. Demonstration Project No. 17--Demonstration of Prestressed Concrete Pavement Construction--was, therefore, established to demonstrate that PCP construction is practical and economically competitive with other types of pavements.

Additional goals were to improve design criteria, determine maintenance requirements, obtain construction cost data, stimulate state interest, and provide information for contractors. In addition to these goals, the project had two primary objectives. The first objective was to explore and demonstrate the practicality and economy of utilizing existing prestressing techniques in the construction of large-scale highway paving operations. The second objective was to investigate the behavior of relatively long monolithic concrete pavement slabs with regard to movements and length changes, warping and curling behavior at the ends, and frictional and flexural restraint stresses away from the slab ends.

Since Project No. 17 was to encourage construction of PCPs on major state highway networks, the construction of these additional PCPs was to be within the experimental project framework and in cooperation with the FHWA Offices of Engineering and Highway Operations. The FHWA, through the demonstration project manager and technical advisory committee, was to provide technical advice and assistance to agencies desiring to build experimental installations.

During 1972 the contractor who built the Dulles pavement incorporated 500 feet of PCP, on his own initiative, into a conventional slip-formed mainline pavement he was constructing near Kutztown, Pennsylvania (Ref 53). Although this project was not FHWA sponsored, it did serve as a forerunner to a FHWA funded project which was constructed in the same state.

The Pittsburgh, Milford, Dulles and Kutztown PCP projects were followed by the design and construction of three additional full-scale mainline roadway projects in different parts of the United States, in various climatic areas, and carrying a range of traffic. Like the Dulles project, these projects were built under FHWA Demonstration Projects Program No. 17. They were as follows: Hogestown, Pennsylvania (1973); Brookhaven, Mississippi (1976); and Tempe, Arizona (1977).

Characteristics

In 1963 the Transportation Research Board compiled a compendium of the characteristics of airport and highway PCP projects which had been completed in various parts of the world prior to 1960 (Ref 30). The Portland Cement Association expanded the compendium in 1976 to include the previously discussedMilford, Dulles, Kutztown, and Harrisburg PCP projects (Ref 56). The following summary of the general characteristics of previously constructed PCP projects is based on that compendium. The summary is divided into airport and highway PCPs. Each of these divisions is further subdivided into pretensioned, posttensioned and poststressed PCPs.

(1) Airport Pavements. The compendium lists the 26 known airport PCP projects which had been constructed worldwide as of 1960. The general characteristics of these projects are summarized in Table 2.1.

(2) Highway Pavements. Pretensioned, posttensioned and poststressed highway PCP projects have been constructed in various parts of the world. However, only posttensioned PCP has been built in the United States. The compendium lists the 34 known highway PCP which had been constructed worldwide as of 1960. The general characteristics of these projects are summarized in Table 2.2.

In addition, the four FHWA funded demonstration projects which were built during the 1970s have the following characteristics: (a) slab length varied from 300 to 760 feet; (b) slab thickness was 6 inches on all of the projects; (c) posttensioning was used on all the projects; (d) longitudinal prestress varied from 200 to 331 psi; (e) no transverse or diagonal prestressing was used; and (f) 1/2-inch-diameter or 0.6 in. diameter, 7-wire, stress-relieved steel strands were used. The design, construction, and performance of these four projects is examined in detail in Chapter 4.

SUMMARY

The primary methods which have been used to prestress pavement (i.e., pretensioning, posttensioning, and poststressing) were discussed in this chapter. This discussion included the manner in which these methods have been used to obtain various prestress configurations and the main construction procedures employed in each method. In addition, some of the problems encountered with the use of each method were covered.

As discussed earlier, the performance of experimental pavement sections in California indicated that there is no advantage in the use of expansive cement concretes in nonreinforced poststressed highway construction. However, other research has demonstrated that use of expansive admixtures may

TABLE 2.1. CHARACTERISTICS OF AIRPORT PCP PROJECT CONSTRUCTED PRIOR TO 1960 (REFS 30, 56).

	Prestressing Method		
Characteristic	Pretensioning[a,b]	Posttensioning[c,d]	Poststressing[e,f]
Number of projects using each prestressing method	2	19	5
Slab Length, ft.	65 to 412	80 to 623	343 to 1100
Slab Thickness, in.	4.0 to 6.0	5.5 to 9.0	6.0 to 7.1
Longitudinal Prestress, psi	227 to 310	165 to 570	250 to 550
Transverse Prestress, psi	142 to 310	107 to 570	250 to 550

[a] The PCPs on all but one of the these projects were pretensioned longitudinally and posttensioned transversely. The exception was a Corps of Engineers project in Sharonville, Ohio, where the pavement was pretensioned in both directions with wires.

[b] On a project at Schwechat, Vienna in Austria, longitudinal prestressing was accomplished by pretensioning with strands, then poststressing with flat jacks. Transverse posttensioning with strands was used.

[c] Cables, strands, and steel bars were used for posttensioning.

[d] On several of the projects, precast slabs were posttensioned in place.

[e] On all projects, longitudinal poststressing and transverse posttensioning were used.

[f] On two projects, the pavement consisted of precast slabs that were prestressed together in place.

TABLE 2.2. CHARACTERISTICS OF HIGHWAY PCP PROJECTS CONSTRUCTED PRIOR TO 1960 (REFS 30, 56).

	Prestressing Method		
Characteristic	Pretensioning[a,b]	Posttensioning[c,d]	Poststressing[e]
Number of projects using each prestressing method	3	22	9
Slab Length, ft.	164 to 377	30 to 492	164 to 365
Slab Thickness, in.	3.2 to 4.7	3.35 to 10.0	3.2 to 6.0
Longitudinal Prestress, psi	230 to 384	90 to 654	235 to 1138
Transverse Prestress, psi	0 to 355	13 to 355	0 to 273
Diagonal Prestressing, psi	-	212 to 374	-

[a] Longitudinal and longitudinal-transverse prestress orientations were used.

[b] Wires and strands were used for prestressing.

[c] Longitudinal, longitudinal-transverse, diagonal, and longitudinal-diagonal prestress orientations were used.

[d] Cables, strands or steel bars were used for prestressing.

[e] On four of the projects, the pavement was poststressed longitudinally only and on five of the projects, the pavement was longitudinally poststressed and transversely posttensioned.

have important benefits in reinforced and posttensioned concrete pavement (Refs 89, 107). This will be discussed further in Chapter 6.

This chapter also included a brief summary of the history of prestressing for airport and highway applications.

The next chapter will examine the primary considerations which must be taken into account in designing PCP.

CHAPTER 3. DESIGN CONSIDERATIONS

The design of PCP involves the rational determination of specific values for a number of interdependent variables. This determination should be based on a thorough understanding of the factors affecting the design so that the pavement will be able to withstand the traffic loads and environmental influences to which the pavement will be subjected throughout a specified service life.

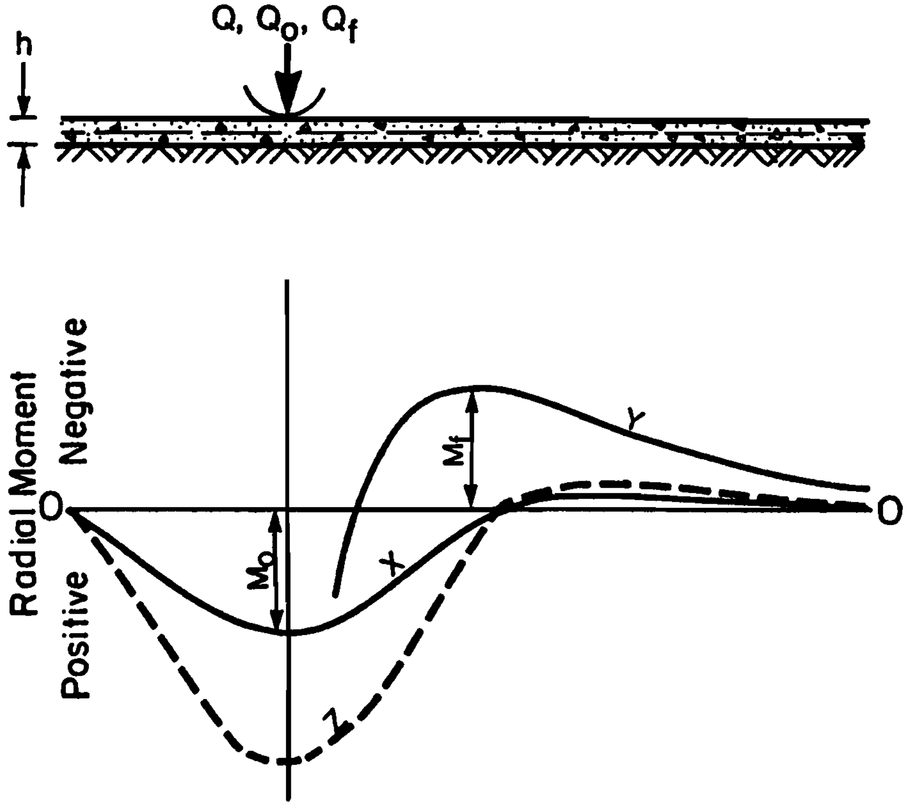
The purpose of this chapter is to provide brief discussions of the main factors affecting the design of PCP and the primary design variables for which specific values are sought during the design process.

FACTORS AFFECTING DESIGN

The main factors affecting the design of PCP include the following: elasto-plastic behavior under loads, load repetition effect, subgrade restraint, temperature curling, moisture warping, prestress losses, and buckling. Each of these factors will be briefly examined in the following sections.

Elasto-Plastic Behavior Under Loads

For stresses in the elastic range, the performance of a PCP slab is similar to that of a conventional concrete slab with the exception that the magnitude of the extreme fiber stress can be increased by an amount equal to the prestress (see Fig 1.1). However, design of PCP based on restricting the stresses solely to the elastic range is generally recognized as unnecessarily conservative. As mentioned, this approach neglects the moment redistribution which occurs with partial plastic hinge formation in the pavement and the resulting potential increase in load-carrying capacity. The redistribution of critical moments is illustrated in Fig 3.1. Curve X in this figure represents the maximum radial moment values for the purely



h = Slab thickness

M_o = Maximum positive moment due to Q_o

M_f = Maximum negative radial moment due to Q_f

Q = Wheel load

Q_o = Maximum load producing elastic behavior

Q_f = Load producing elasto-plastic behavior ($Q_f > Q_o$)

X = Maximum radial moment due to Q_o

Y = Radial moment for elasto-plastic behavior due to Q_f

Z = Hypothetical radial moment equal to X (Q_f / Q_o)

Fig 3.1. Load-Moment Relationships for PCP (Ref 116).

elastic phase of behavior. On this curve the maximum positive moment due to a load of magnitude Q_o is indicated as M_o. As the load is increased, tensile cracking in the bottom of the slab occurs and the resulting radial moments are as indicated by curve Y. The maximum negative radial moment, M_f, caused by load Q_f is indicated on curve Y and is equal to the maximum positive moment, M_o. Further load increases would cause tensile cracking in the top of the slab. Hypothetically, the radial moments would be as indicated by curve Z if the slab continued to behave elastically under load Q_f.

Tentative airfield PCP design procedures have been developed which utilize the relation between the maximum positive elastic moment and the moment associated with the load increase from Q_o to Q_f (Refs 102, 116). These procedures are based on (a) analytical studies, (b) small-scale model tests employing static loads, and (c) data from a very limited number of full-scale accelerated test sections. The validity of these procedures for use in the design of full-scale airfield PCPs remains to be demonstrated.

To the author's knowledge, no similar design procedure presently exists for highway PCPs. However, the airfield design procedure could be modified for use in the design of highway PCPs.

Load Repetition Effect

The small-scale model tests employing static loads, mentioned in the previous section, provided the necessary information for determining the required prestress level for pavements of a given thickness to withstand the single application of given loads. However, prestressed concrete has a fatigue endurance level, like most materials, which is a function of applied stress level and number of load repetitions. The airfield PCP design procedure mentioned in the previous section uses load repetition design factors to account for the differences between the static load tests and the effects of repetitive loads. For a given load, these factors either increase the required prestress level for a given pavement thickness or increase the thickness for a given prestress level, all other pertinent parameters being equal.

Unfortunately, very little performance data were available on which to base the load repetition design factors, simply because there are so few airfield PCPs in service and even fewer that have had enough load repetitions to cause failure.

In fact, the only available data were from a very limited series of full-scale accelerated test sections and small-scale repetitive loading model tests (Ref 116). A considerable unexplained difference in the test results was observed between the full-scale and the small-scale repetitive loading tests. Consequently, conservative load repetition design factors were recommended for use until more definitive data becomes available. This is supported by the observation that little advance warning accompanies the load failure of PCPs, and an underdesigned PCP requires few additional load repetitions to go from showing initial signs of distress to complete failure (Ref 102).

The supporting foundation strength has an influence on the relationship between load repetition and design requirements. The load repetition design factor was observed to be inversely proportional to the foundation strength. However, the relationship is in need of additional study especially where the number of load repetitions is large.

Load repetition design factors are not currently available for highway PCPs. However, if the airfield design procedure is modified for use in the design of highway PCPs, factors for highway design will have to be developed. It is anticipated that the load repetition design factors for highway PCPs will be higher than those for airfields due to the increased traffic volume.

Subgrade Restraint

Differential movement between a pavement slab and the subgrade is resisted by friction. This induces restraint stresses in the pavement. These restraint stresses are additive to the design prestress of a PCP during periods when the pavement is increasing in length and subtractive when the pavement is decreasing in length.

The magnitude of the restraint stresses is a function of the coefficient of subgrade friction and the dimensions of the slab, and is at maximum at the midlength and midwidth of the slab. The maximum value of this stress, for concrete having a unit weight of 144 pcf, is given by the following equation:

$$f_{SR} = \mu L/2 \tag{3.1}$$

where

f_{SR} = maximum subgrade restraint stress, psi;
μ = coefficient of subgrade friction; and
L = length of slab, ft.

Coefficients of subgrade friction of over 4.5 have been measured for slabs placed directly on asphalt and 1.5 for slabs placed directly on granular subbases. PCPs have generally been constructed on some type of friction-reducing layer such as sand and building paper, or sand and polyethylene sheeting. When a friction-reducing layer is provided, the coefficients of subgrade friction usually range from 0.4 to 1.0. Studies by PCA indicate these friction factors may be as high as 1.75 for frozen conditions (Ref 29).

Temperature Curling

Concrete slab curling is caused by temperature gradients across the depth of a slab. The slab curls toward the side with the lower temperature and this curling is resisted by the weight of the slab. Consequently, tensile stresses develop on the side of the slab which has the lower temperature, while compressive stresses develop on the opposite side.

During the daylight hours, the top surface of the pavement is warmer than the bottom and thus, tensile stresses develop at the bottom of the slab. However, this is not the most critical condition for the following two reasons:

(a) As stated, the compressive stress in the pavement increases during the daylight hours due to subgrade restraint of pavement expansion. This counteracts a significant portion of the tensile stresses due to curling.

(b) Cracking of the bottom surface of the slab is permissible and to be expected with an elasto-plastic design approach.

During the night, the temperature gradient is reversed and tensile stresses develop at the top of the slab. This is the most critical design condition for the following three reasons:

(a) As stated, the compressive stress in the pavement decreases during the night due to subgrade restraint of pavement contraction. This effect is additive to the tensile stresses in the top of the slab due to curling.

(b) Upward curling results in loss of support along the pavement edges which, in turn, causes an increase in edge stresses due to traffic loading.

(c) According to the elasto-plastic design approach, failure in a PCP occurs due to tensile cracking in the upper surface of the pavement.

Tentative procedures have been developed for determining the additional prestress which must be added to offset the tensile stresses due to temperature curling (Ref 130).

Moisture Warping

The existence of a moisture gradient in pavements, from relatively dry concrete at the top surface to substantially saturated concrete at the bottom surface, was recognized at least as far back as 1937 (Ref 22). This moisture gradient results in an upward warping of the slab which is resisted by the weight of the slab. Consequently, tensile stresses develop on the top surface of the slab and compressive stresses develop on the bottom.

Moisture warping at least partially offsets the tensile stresses which develop at the bottom surface of a slab due to temperature curling during daylight hours. However, at night it adds to the more critical tensile stresses which develop at the top surface of the slab due to temperature curling and subgrade restraint of slab contraction. No procedure currently exists which permits the seasonal variation in pavement moisture content to be accounted for in the design of PCP. This is because only limited data exists on the variations of moisture content with pavement depth, seasonal changes in moisture content, and the magnitude of the stresses induced by moisture warping. As a result, current practice is to account for its effects empirically based on limited measurements made by two independent researchers (Refs 44, 90).

Prestress Losses

Prestress losses of approximately 15 to 20 percent of the applied prestress force should be expected for a carefully constructed pretensioned or posttensioned PCP. For a poststressed PCP, all of the prestress may be lost unless proper provision is made. These losses must be accounted for in the design of a PCP in order to insure that the required prestress level is maintained over the service life of the pavement.

Factors contributing to loss of prestress include: (a) elastic shortening of the concrete; (b) creep of the concrete; (c) shrinkage of the concrete; (d) relaxation of the stressing tendons; (e) slippage of the stressing tendons in the anchorage devices; (f) friction between the stressing tendons and the enclosing conduits; and (g) hygrothermal contraction of the pavement.

Prestress loss factors a, c, e, and g occur during construction. Prestress losses for pretensioned and posttensioned PCP are generally expressed as a stress loss in the tendons. Therefore, the prestress applied to the pavement by means of the tendons must be increased to counter the stress losses resulting from natural adjustments in the materials during and after construction.

Factors a, b, c, and g contribute to loss of prestress in poststressed PCP. Instead of providing an initially high prestress, some designers of poststressed PCP have provided the ability to reactivate the jacking system during the service life of the pavement in order to apply additional prestress.

Each of the previously listed prestress loss components, and procedures for determining their magnitude, are discussed in the following paragraphs.

(a) Elastic Shortening. Because the concrete shortens when the prestressing force (in full or in part) is applied to it, the tendons already bonded to the concrete shorten simultaneously losing part of their stress. The magnitude of the stress loss is a function of the modular ratio of the prestressing steel and concrete (E_{PS}/E_C), the magnitude of the prestress, and the degree of subgrade restraint. For pretensioned PCP, the stress loss in the steel tendons resulting from elastic shortening of the concrete is given by the following expression:

$$\Delta f_{pES} = (E_{PS}/E_C)(f_{CS} - f_{SR}/2) \tag{3.2}$$

where

Δf_{pES} = stress loss in the tendon, psi;
E_{PS} = modulus of elasticity of the prestressing steel, psi;
E_C = modulus of elasticity of the concrete, psi;
f_{CS} = compressive stress in the concrete, psi; and
f_{SR} = maximum subgrade restraint stress, psi.

Since the loss of stress in the tendons due to elastic shortening is inversely proportional to the modulus of elasticity of the concrete, the magnitude of the loss could be reduced by waiting to apply the prestress until the concrete has gained substantial strength. However, application of prestress at early concrete age is usually desirable in order to prevent shrinkage cracking of the concrete.

In posttensioned PCP, where stretching of one tendon will have little effect on nonimmediate neighboring tendons, an elastic shortening value equal to one quarter that of equivalent pretensioned construction is often used. Of course, there would be no stress loss due to elastic shortening if all the posttensioning tendons could be stressed simultaneously.

In poststressed PCP (which does not use tendons), prestress loss due to elastic shortening is eliminated since the stressing force is simultaneously applied along the entire width of the pavement.

(b) Creep. The continued deformation of many materials when subjected to constant stress or load over considerable lengths of time is referred to as creep. The rate of strain increase is rapid at first, but decreases with time until, after many months, a constant value is approached asymptotically.

Creep strain for concrete has been found experimentally to depend not only on time, but on the mix proportions, humidity, curing conditions, and the age of the concrete when it is first loaded. Creep strain is nearly linearly related to stress intensity.

The stress loss due to creep of the concrete is similar to the loss due to elastic shortening since both are the result of strains induced in the concrete. However, elastic shortening occurs instantaneously upon application of compressive stress, whereas creep is dependent on the length of time the stress is applied. Creep is that portion of the total strain which is in addition to the immediate elastic strain.

Creep, under a constant stress, is proportional to the elastic strain. The ratio of creep to elastic strain has been shown by test to be on the order of 1.33 to 2.0. Tests at age 2 years indicate that creep is generally on the order of 3×10^{-7} to 6×10^{-7} in./in. for each psi of prestress, depending on the modulus of elasticity of the concrete and the strain ratio. However, creep under sustained prestress may continue beyond 2 years, and 1×10^{-6} in./in./psi has been suggested as a conservative end value.

The stress loss in the steel tendons due to creep of the concrete for both pretensioned and posttensioned PCP is given by the following equation:

$$\Delta f_{pCR} = {}_{CR}\, f_{CS}\, E_{PS} \qquad (3.3)$$

where

Δf_{pCR} = stress loss in the tendon, psi;
ε_{CR} = creep strain, in./in.;
f_{CS} = prestress in the concrete, psi; and
E_{PS} = modulus of elasticity of the prestressing steel, psi.

As with elastic shortening, the magnitude of the creep can be reduced by delaying application of the stress until the concrete has gained substantial strength.

(c) Shrinkage. Concrete contains more water than is strictly required by the chemical hydration reaction of the cement. Loss of this excess or "free water" through evaporation leads to gradual shortening of the slab with time, which is described as shrinkage. The steel tendons lose part of their prestress as the slab shortens. This is called shrinkage loss. The evaluation of shrinkage loss as part of the total prestress loss is an important design step.

Shrinkage is dependent on many variables. Most important are the amount of free water, the relative humidity of the environment, the ambient temperature, the type of aggregates used, and the size and shape of the slab. Shrinkage is assumed to be independent of loading and would not take place if the concrete is kept at 100 percent relative humidity. Shrinkage in concrete results primarily from the shrinkage of the paste--the aggregate shrinks very little. Thus, differential internal stresses are created in the structure of concrete leading to compression on the aggregates, and tension in the paste, accompanied by microcracking.

Tests have indicated that the coefficient of length change due to shrinkage may be as small 1×10^{-4} in./in. or as great as 7×10^{-4} in./in. With pretensioned PCP, all of the shrinkage takes place after the tendons are stressed. Tendon shortening on the order of 4×10^{-4} to 5×10^{-4} in./in. can be expected. For posttensioned or poststressed pavement, the shortening may only be on the order of 2×10^{-4} in./in. because at least half of the ultimate shrinkage generally occurs prior to stressing.

The loss of prestress in the tendons due to shrinkage is given by the following equation:

$$\Delta f_{pSH} = \varepsilon_{SH} E_{PS} \tag{3.4}$$

where

Δf_{pSH} = stress loss in the tendons, psi;
ε_{SH} = shrinkage, in./in.; and
E_{PS} = modulus of elasticity of the prestressing steel,psi.

(d) Steel Relaxation. When prestressing steel is stressed to customary levels during initial tensioning and at service loads, it exhibits a property known as relaxation. Relaxation is the loss of tension in a stressed tendon over time when maintained at constant length and temperature. Similar to creep, which describes the change in strain over time at a constant stress, relaxation results from the adaptation of the material to an externally applied constraint. In prestressed concrete members, creep and shrinkage of the concrete, as well as fluctuations in superimposed load, cause changes in tendon length. However, in evaluating loss of steel stress as a result of relaxation, the length may be considered constant.

Relaxation is not a short-lived phenomenon. From available evidence, it appears to continue almost indefinitely, although at a diminishing rate. It must be accounted for in design because it produces significant loss of prestress force.

The amount of relaxation varies depending on the type and grade of steel, but the most significant parameters are time and intensity of the initial stress. Typical relaxation losses for high-strength "stress-relieved" steel range from 0 to 3 percent at an anchorage stress of 0.50 fpu (specified tensile strength of the prestressing tendons); 4 to 6 percent at 0.60 f_{pu}; and 7 to 8 percent at 0.70 f_{pu}.

In the case of pretensioned PCP, the relaxation loss occurring before release (transfer of force to the concrete) should be subtracted from the total relaxation loss predicted for the effective stress at release.

In some cases, relaxation losses have been reduced by prestretching, a technique by which the stress in the steel is increased to a level higher than the intended initial stress, held at that level for a short period of time, and then reduced to the intended initial stress. However, since the practical level of initial stress is about 70 percent of the strength of the steel, it is not feasible to overstress by more than about 15 percent. On the basis of available evidence it appears that prestretching is of little consequence if the prestretching period is limited to only a few minutes.

Special low-relaxation wire and strand are widely available and can be used at little or no price premium. Relaxation loss for low-relaxation wire and strand can be taken to be about 25 percent of the loss for normal wire and strand.

(e) Anchorage Slip. In posttensioned PCP, when the jacking force is released, the steel tension is transferred to the concrete by some type of special anchorage. One commonly used tendon anchorage is shown in Fig 3.2. Inevitably there is a small amount of slip at the anchorages upon transfer, as the wedges seat themselves into the tendons, or as the anchorage hardware deforms. A similar situation is obtained in pretensioning, when the prestressing force is transferred from the jacks to the permanent anchorages of the abutments through strandholding chucks. In either case, anchorage slip loss may be compensated for by overstressing, provided its magnitude is known.

The magnitude of anchorage slip loss will depend on the particular prestressing system or hardware used. The slippage of wires which occurs before they are firmly gripped by friction wedges has been reported to be on the order of 0.1 inch. The reduction in length of the tendons, in the case of direct-bearing anchorages, has been given as 0.03 inch. This value may be reduced to as little as 0.01 inch by the use of shims. Large forces in the end hardware may result in some slippage of the wires where large strands are used. The amount of such slippage will depend on the type of anchorage and

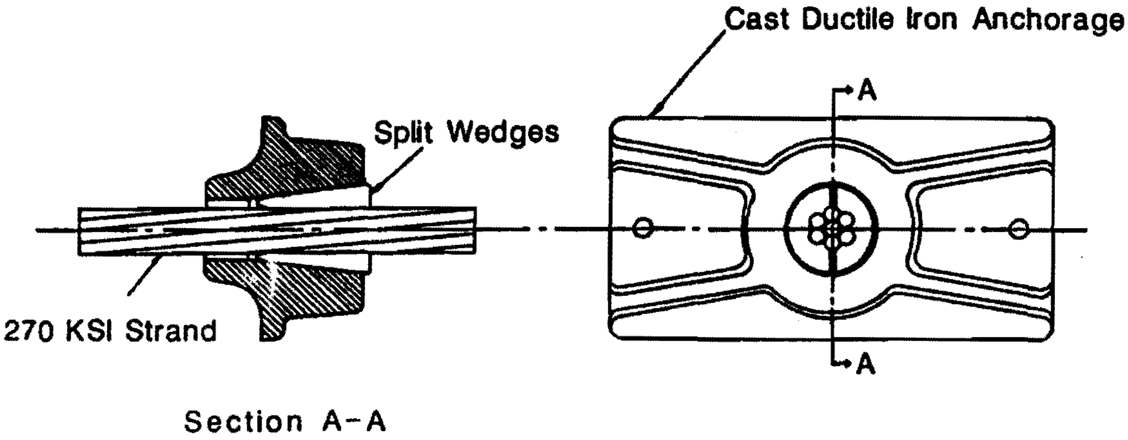


Fig 3.2. Individual tendon anchorage (Ref 108).

size of the strands, and has been reported to be as much as 0.2 inch. The most reliable source of information on anchorage slip loss may be the manufacturer of the specified hardware selected or, better still, laboratory tests of the specific equipment.

Given the amount of slip characteristic of the specified hardware, the anchorage slip loss can easily be calculated from the expression:

$$\Delta f_{pAS} = \Delta L\, E_{PS}/L \tag{3.5}$$

where

$\Delta fpAS$ = stress loss in the tendons, psi;
ΔL = slippage in the anchorage, in.;
E_{PS} = modulus of elasticity of the steel, psi; and
L = length of the tendon, in.

(f) Tendon Friction. For posttensioned PCP, the tendons are usually anchored at one end and stretched with jacks at the other end. Frictional resistance is developed as the steel slides through the duct with the result that the tension at the anchored end is less than the tension at the jack. The total friction loss is the sum of the wobble friction due to unintentional misalignment during construction, and the curvature friction due to the intentional curvature of the tendon which is to accommodate changes in grade of the pavement. Wobble friction loss would be present even if a straight tendon were specified. This is due to the fact that for a theoretically linear tendon, the tendon, or its duct, are never exactly linear, leading to some form of friction. It is a general practice to treat the wobble friction as an additional angular friction instead of a linear one. This leads to the widely accepted formula giving the prestressing tendon force at any point x along the tendon as a function of the prestressing tendon force at the jacking end:

$$P_S = P_X e^{(KL + \mu\alpha)} \qquad (3.6)$$

or, when $(Kl + \mu\alpha)$ is not greater than 0.3, the effect of the friction loss may be computed by

$$P_S = P_X (1 + KL + \mu\alpha) \qquad (3.7)$$

where

P_S = prestressing tendon force at the jacking end, lbs.
P_X = prestressing tendon force at any point x, lbs.
K = wobble friction coefficient per foot of prestressing tendon
L = length of prestressing tendon element from jacking end to any point x, ft.
α = total angular change of prestressing tendon profile in radians from tendon jacking end to any point x.

ACI Committee 343 on Bridge Structures has proposed an extension of the above equations to account for the horizontal angular change α_h of the prestressing steel profile in addition to the vertical angular change α. This extension would allow both horizontal alignment and vertical grade changes to be easily and separately accounted for in the design of PCP by treating the presence of α_h similarly to the presence of α.

The frictional coefficients α and K depend on many factors including the type of prestressing steel (wires, strands, or bars), the type of duct, and the surface conditions of both (rusted, galvanized, etc.).

A range of values recommended by ACI Committee 343 is given in Table 3.1. Recommended average design values can also be found in the AASHTO specifications when experimental data for the materials used are not available.

TABLE 3.1. FRICTION COEFFICIENTS FOR POSTTENSIONING TENDONS (REF 87)

Type of Tendon	Wobble Coefficient, K (Per Foot)	Curvature Coefficient, μ (Per Radian)
Tendons in flexible metal sheathing		
Wire tendons	0.0010-0.0015	0.15-0.25
7-wire strand	0.0005-0.0020	0.15-0.25
High strength bars	0.0001-0.0006	0.08-0.30
Tendons in rigid metal duct		
7-wire strand	0.0002	0.15-0.25
Pregreased tendons		
Wire tendons and 7-wire strand	0.0003-0.0020	0.05-0.15
Mastic-coated tendons		
Wire tendons and 7-wire strand	0.0010-0.0020	0.05-0.15

Temporary over tensioning of the tendons is a common construction practice to compensate for the stress loss due to friction between the tendon and the enclosure. The maximum value of this temporary overstress is limited by the ACI Building Code 318-83 to 0.80 times the specified tensile strength of the prestressing tendons or 0.94 times the specified yield strength of the prestressing tendons, whichever is smaller, but not greater than the maximum value recommended by the manufacturer of the prestressing tendon or anchorages. The stress is then reduced to the maximum value allowed immediately after tendon anchorage, which is 0.70 times the specified tensile strength of the prestressing tendon.

(g) Hygrothermal Contraction. Equation 3.1 can be used to calculate the loss in prestress due to hygrothermal contraction for pretensioned and posttensioned PCP in which tendons are used for prestressing. However, for poststressed PCP, which relies on externally applied prestressing forces, the loss of prestress due to hygrothermal contraction must be determined using the following expression:

$$\Delta f_{CS} = \varepsilon_t E_c t \qquad (3.8)$$

where

Δf_{CS} = compressive stress loss in the concrete, psi;
ε_t = coefficient of thermal expansion for the concrete, in./in./°F;
E_c = modulus of elasticity of the concrete, psi; and
t = temperature change, °F.

Buckling

As previously discussed, pavement expands and contracts in response to hygrothermal changes within the concrete. Although expansion is generally beneficial since it results in increased prestress, there is the possibility of buckling during periods of pavement expansion.

The stressing tendons in pretensioned and posttensioned PCP act to resist buckling and, as a result, the force required to buckle the slab is considerably greater than the compressive force which occurs due to hygrothermal changes. Therefore, buckling is seldom a problem with either of these two types of PCP. Poststressed PCP, on the other hand, has no tendons to help resist buckling due to excessive compressive forces and buckling has been a problem where the joints are fixed by concrete, grout or other type of rigid filler.

The physical properties of the concrete and foundation material, the dimensions of the pavement, the magnitude of the temperature change, and the degree of restraint at the ends of the pavement all have an influence on the buckling of pavement. Additional research is needed in order to obtain a better understanding of the mechanism of pavement buckling by determining the following: (a) the magnitude of the compressive forces induced by various hygrothermal changes; (b) the magnitude of the compressive force necessary to cause slab buckling under different conditions; and (c) the relative effects of daily temperature cycling as compared with long-term seasonal temperature changes.

DESIGN VARIABLES

A thorough understanding of the previously discussed factors is essential before a rational determination of specific values or details for the primary interdependent design variables can be made. These design variables include the following: foundation strength, pavement thickness, slab length and width, prestress magnitude, tendon spacing, and transverse joints. These variables, the factors most directly influencing them, and typical ranges of values used on previous projects are discussed in the following sections.

Foundation Strength

The following relationships between conventional concrete pavement performance and strength of the supporting foundation are well known: (a) the stress in a pavement for a given load is inversely proportional to the strength of the supporting foundation; and (b) the ability of the pavement to withstand repetitive loads is proportional to the strength of the supporting foundation. The relationship between PCP and the strength of the supporting foundation, however, has not been clearly defined.

Although it has been demonstrated by means of both model and full-scale tests that acceptable performance of PCP can be obtained with low-strength foundations (if provisions are taken to prevent pumping), virtually all previous foundations for PCPs have been fairly high-strength, usually 200 pci or higher modulus of subgrade reaction. This is primarily due to an unwillingness of the designers to risk failure of the pavement if it is constructed on a low-strength foundation rather than on a demonstrated need for a high-strength foundation.

Soil cement and bituminous concrete bases have been used to increase the strength of foundations, but the most common method has been the use of a layer of compacted granular material. The thickness of the layer has generally been on the order of 6 to 12 inches, but as little as 4 inches and as much as 18 inches have been used.

Pavement Thickness

Many factors should be taken into account when determining the required thickness of PCP, including foundation strength, concrete strength, magnitude of prestress, and expected traffic loads (magnitude and number of repetitions). In the past, however, highway PCP thickness has been determined more on the basis of providing the minimum allowable concrete cover on the prestressing tendons than on the basis of load-carrying considerations. This procedure has resulted in thicknesses on the order of 40 to 50 percent of equivalent conventional concrete pavement.

Highway PCP thicknesses on previous projects have usually been on the order of 4 to 6 inches, while the usual range for airfields has been 5 to 9 inches. PCPs with thickened edge sections have been used where frequent edge loadings were expected, but uniform thickness has generally been used when predominately interior loads were anticipated.

Slab Length

In this discussion, slab length refers to the distance between active transverse joints and not to the distance between intermediate inactive construction joints, if used.

The two main factors which must be kept in mind when selecting the optimum slab length for PCP are:

(a) The prestress force required to overcome the frictional restraint between the subgrade and the slab, and to provide the desired minimum compressive stress at the midlength of the slab, is proportional to the slab length. The cost associated with providing this prestress force is, in turn, proportional to the magnitude of the required force.

(b) The number of and total cost for transverse joints is inversely proportional to the slab length. (Total cost should include initial cost and maintenance cost over the life of the facility, since transverse joints are the largest maintenance item for a pavement) These joints are discussed in more detail later in this chapter.

Obviously, a compromise must be sought between these two factors. Based on PCP projects built to date, a pavement length on the order of 400 feet appears to strike a reasonable balance between these two constraints. Slabs as long as 760 feet in length have been built in the United States and some over 1,000 feet in length have been built in Europe, however, these are exceptions.

Slab Width

In this discussion, slab width refers to the distance between the two exterior longitudinal free edges of the completed pavement and does not refer to the distance between intermediate inactive longitudinal construction joints.

In many instances it is not feasible to construct the full width of either a new pavement or an overlay on an existing pavement in a single operation and, as a result, the pavement must be constructed in two or more successive, contiguous longitudinal strips. Construction joints must be provided between adjacent pavement strips with this type of construction.

Some of the reasons that this type of construction is necessary are as follows:

(1) Equipment Limitations. Slip-form paving has been shown to be an expeditious and economical method of constructing cast-in-place concrete pavement and bias toward the continued use of this method is likely for the forseeable future. Although machines are available that will pave 36- and 48-foot-wide pavements in one pass, the most common slip-form pavers have a width limitation of 24 feet. Therefore, to permit use of the most commonly available equipment for construction of pavements greater than 24 feet in width, multiple longitudinal strip construction must be allowed.

(2) Accommodate Public Traffic. In many instances it is impossible to completely close a highway section for reconstruction, especially in busy urban areas. In these situations, lanes adjacent to the one undergoing reconstruction often must be kept open to public traffic. After construction of a lane is completed, traffic is diverted to it while the next lane undergoes reconstruction.

(3) Accommodate Construction Traffic. Even in situations where it is feasible to completely prohibit public traffic on a highway section during construction, construction related traffic (i.e., concrete and reinforcement deliveries, finishing operations, etc.) must be accommodated by maintaining an open strip adjacent and parallel to the slip-forming operation. The open

strip is paved after construction traffic can be permitted on the previously placed pavement.

Obviously, multiple longitudinal strip pavement construction is required in many instances. Therefore, a pavement system must be capable of being constructed in this manner in order to be truly viable. However, with PCP construction, problems may occur along the longitudinal joint between the adjacent pavement strips. Special attention must be given to this joint detail to ensure that the second and subsequent pavement lanes are not restrained by the previously placed lanes during longitudinal stressing operations. Provision must also be made to accommodate the transverse posttensioning tendons (if used) where they cross the longitudinal joint.

In addition, load transfer or supplementary structural strengthening must always be considered when longitudinal joints are required. Load transfer may be accomplished by providing keyed, tied, or compression joints. Supplementary structural strengthening may take the form of either thickened slab edges or sleeper slabs (also known as subslabs).

Active longitudinal joints are seldom necessary unless the pavement width exceeds 400 to 500 ft., in which case similar considerations to those for spacing active transverse joints would be applicable.

Magnitude of Prestress

The magnitude of the longitudinal and transverse prestress must be large enough to provide sufficient compressive stress at the midlength and midwidth of the pavement slab during a period of contraction to sustain the momentary plastic hinge action that may occur during the passage of a wheel load. Many factors must be taken into account to assure that the desired prestress level is obtained, including: magnitude of frictional restraint between slab and subgrade, slab thickness, slab length, maximum diurnal temperature fluctuation anticipated during the life of the pavement, pavement curling and warping, foundation conditions, magnitude of expected traffic loads, and number of traffic load repetitions. The problem is further complicated by the fact that many of these factors are interdependent.

On some of the early PCP projects, relatively high prestress levels (over 1,000 psi on some projects in Europe and as much as 700 psi on a project in the United States) were used in order to be certain that sufficient prestress was provided. However, it has been shown by means of small-scale laboratory tests and full-scale field tests that structural benefits do not increase in proportion to increases in the prestress level. Therefore, more recent projects have used prestress levels ranging from 150 to 300 psi longitudinally and from 0 to 200 psi transversely.

Tendon Spacing

The main factors governing tendon spacing are tendon size, magnitude of design prestress, allowable concrete bearing stress at the tendon anchorages, and permissible tensile stress in the tendons. Although bar and stranded cable tendon spacings have varied from a minimum of two to a maximum of eight times the slab thickness, more typically, spacings of two to four times and three to six times the slab thickness have been utilized for the longitudinal and transverse tendons, respectively.

Transverse Joints

The ideal transverse joint would: (a) accommodate the movement of the slab ends; (b) allow compressive forces to be transmitted from slab to slab; (c) carry traffic load without undesirable deflections or stresses at either the joint or slab ends; (d) be composed of materials which are resistant to wear, fatigue, and corrosion caused by traffic, environment, or de-icer chemicals; (e) be sealed against infiltration of water and incompressible material which can contribute to pumping, spalling, and blowups; (f) be drained and self-cleaning (if not sealed), so that little maintenance would be required; (g) have components which could be easily removed and replaced if damaged; (h) have details which are compatible with the prestressing method employed; and (i) be low in cost. In spite of years of research and the efforts of many researchers, engineers, and inventors, the ideal joint has not been found.

Many different transverse joint details have been used on previous PCP projects. Each of these joints may be classified as either free, partial compression, or compression. These basic joint classifications are described in the sections below.

(1) Free Joints. This type of active or working transverse joint is used between either pretensioned or posttensioned slabs, and contains no provision for transmitting compressive forces between slabs. Some form of structural strengthening is generally required with this joint type to permit wheel loads to be adequately carried. This strengthening generally takes the form of load-transfer devices, sleeper slabs, or edge thickening. Two additional factors which must be accounted for in the design of this type of joint are the tendency of PCPs to curl at their edges and the much greater joint width changes experienced with PCP than with conventional concrete pavements. An example of a free joint is shown in Fig 3.3.

(2) Partial Compression Joints. This type of active transverse joint is used with either pretensioned or posttensioned PCP. In cold seasons this type of joint functions as a free joint, but in warm seasons it allows the transmission of compressive forces between adjacent slabs. The same structural strengthening requirement applies to this joint type as for free joints, even though this joint is designed to somewhat restrict the large slab end movements of adjacent slabs. Because relatively high compressive stress is developed with this type of joint, abutments must sometimes be provided at the terminal ends of the pavement to prevent permanent displacement of the pavement. An example of a partial compression joint is shown in Fig 3.4.

(3) Compression Joints. This type of transverse joint may be classified as either an active or inactive (non-working) joint, but in either case, compressive stresses are permanently transferred between adjacent slabs. With working compression joints, either a constant compressive stress or some minimum compressive stress is maintained on the slab ends by means of a system of compressive springs or constant-pressure hydraulic jacking system in the joints.

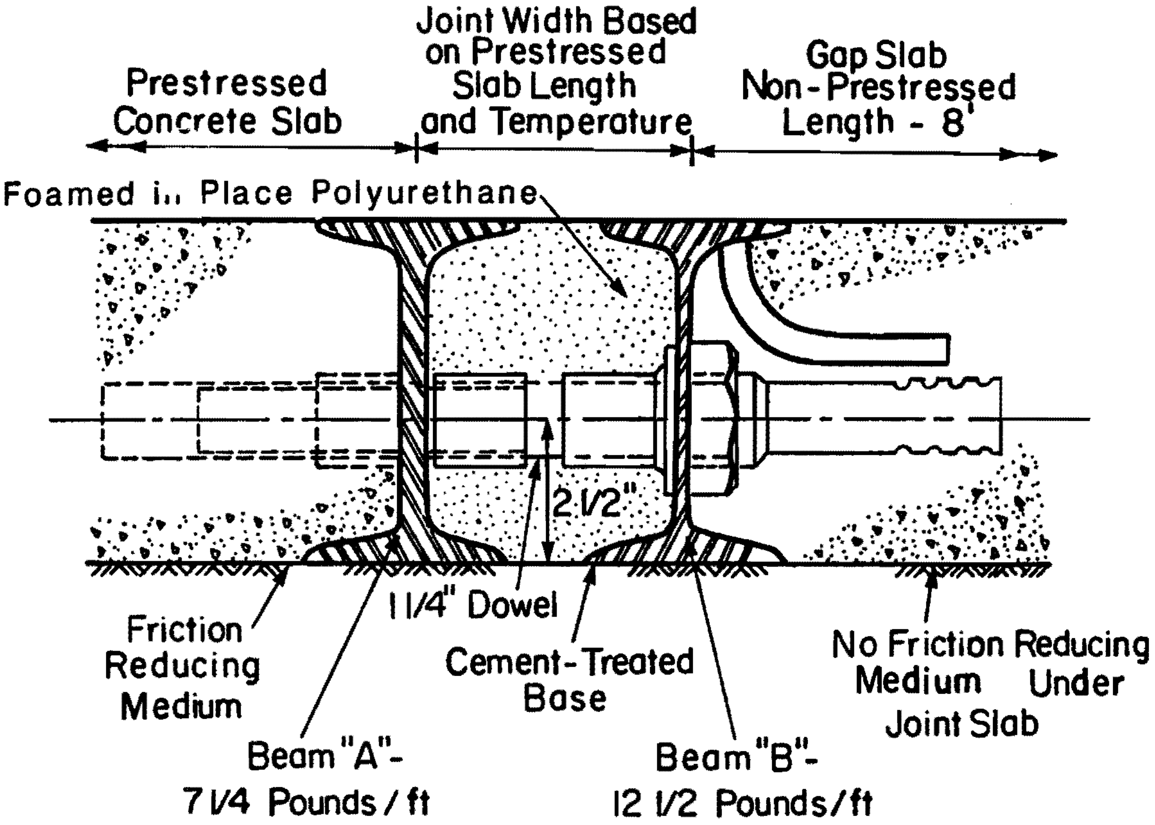


Fig 3.3. Joint detail for prestressed pavement at Dulles International Airport, Virginia (Ref 105).

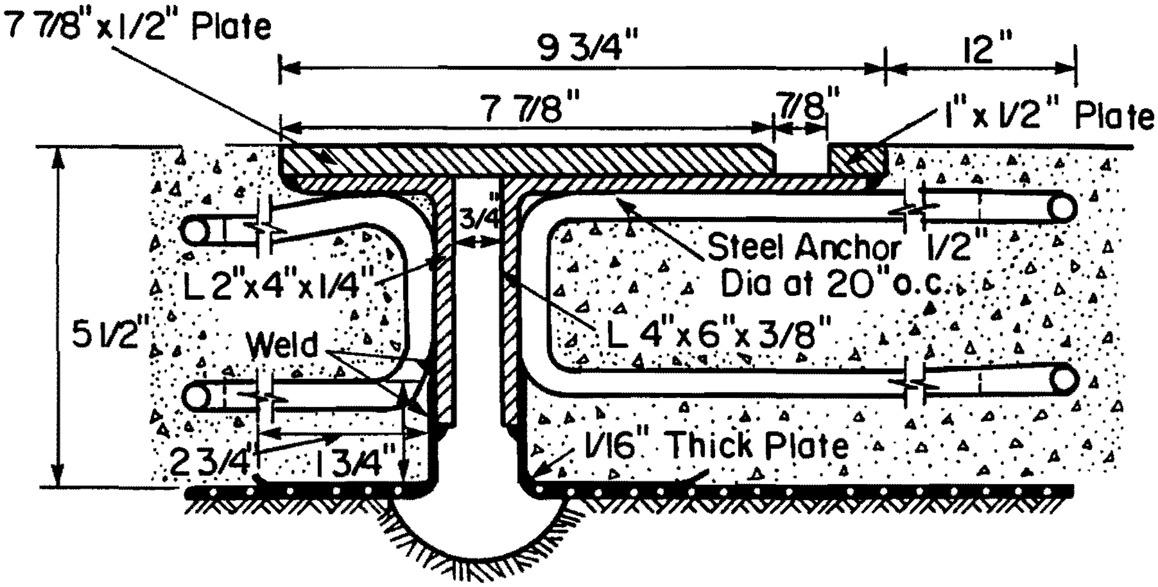


Fig 3.4. Covered joint for airfield pavements in Germany (Ref 56).

As illustrated in Fig 3.5, inactive joints generally contain flat jacks or grout jacks that are used to apply the prestressing force and are then immobilized in place. Some designs permit the reapplication of the jacking force to overcome prestress losses. Another type of inactive joint is formed by continuing the prestressing tendons through a construction joint.

Numerous examples of each type of joint have been tried on previous PCP projects both in Europe and the United States. Although detailed descriptions of these joints are provided in several references, performance information is sketchy. None of the currently available joint details has emerged as clearly superior to all the others. Each has its own set of strengths and weaknesses. At the present time, all of the existing joint details must be regarded as experimental.

SUMMARY

The first objective of this chapter was to provide brief discussions of the primary factors affecting the design of PCP which include elasto-plastic behavior under loads, load repetition effect, subgrade restraint, temperature curling, moisture warping, prestress losses, and buckling. A thorough understanding of these items is essential to be able to design a PCP which will withstand the traffic loads and environmental influences which will act on it throughout a specified service life.

The second objective of this chapter was to provide brief discussions of the primary variables for which specific values or details are sought during the design process. These variables include foundation strength, pavement thickness, slab length and width, prestress magnitude, tendon spacing, and transverse joints. As pointed out earlier in this chapter, these variables are interdependent and, consequently, the determination of specific values for each variable is an iterative process.

One of the primary obstacles to the use of PCP has been the lack of an acceptable design procedure relating the factors affecting the design to the

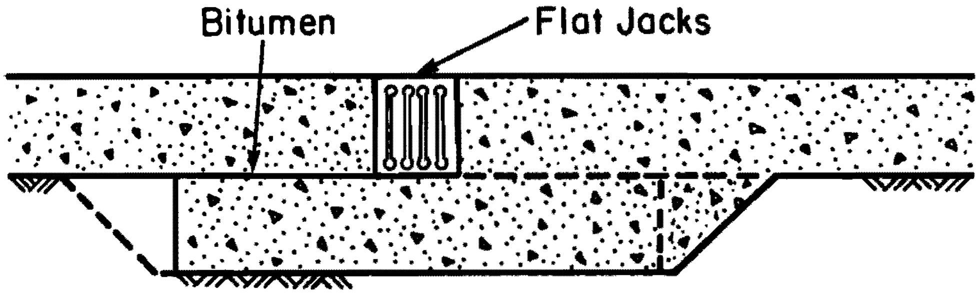


Fig 3.5. Inactive compression joint.

interdependent design variables. Nevertheless, many PCPs have been designed and constructed.

The intent of the next chapter is to critically examine the primary aspects of the four FHWA sponsored PCP projects which were constructed during the 1970s. This examination is based on the background information provided in Chapters 1, 2, and 3.

CHAPTER 4. CRITIQUE OF PREVIOUS FHWA SPONSORED PROJECTS

While the history of PCP and features of PCPs constructed in various parts of the world, including prestressing methods, joint details, and properties of materials, have been documented in previous publications, very little information has been reported on either the relative constructability or performance of the PCP approaches which have been tried. In addition, although some load test information obtained during construction has been reported, procedures and details of these load tests have generally been omitted, thus prohibiting independent analysis of the results. This lack of performance data on previous PCP projects is indeed unfortunate because it severely limits their value as far as improving our understanding of PCP behavior. In addition, evaluation of the relative success of previously tried alternate PCP approaches is rendered virtually impossible by this lack of vital constructability and performance data.

Fortunately, the construction and performance of four projects which were built during the 1970s were monitored somewhat more closely. These projects, sponsored by the FHWA and located in different geographical regions of the United States, constitute the most significant domestic PCP applications during the period from the mid-1960s until the present time. Since the design and construction approach employed on each of these projects is basically the same, they do not allow a comparative examination of alternate approaches. However, the data generated from these projects on constructability and performance, although limited, are extremely valuable and should be critically evaluated.

The primary objective of this chapter is to provide a critique of these projects since, to the author's knowledge, no such independent evaluation has been done. This evaluation is based on the background information on PCP provided in Chapters 1,2, and 3.

DESIGN APPROACH

The necessity of using an elasto-plastic design approach to take advantage of the potential increase in load-carrying capacity provided by the redistribution of moments which occurs with the formation of partial plastic hinges in the pavement has been repeatedly demonstrated both theoretically and experimentally. Articles supporting this approach dominate the technical literature on PCP during the 1950s and early 1960s. In fact, Franco Levi, a well-known French research engineer in the field of PCP, concluded in 1953 that it would be "absurd" to design prestressed pavements strictly in the elastic range (Ref 77). In spite of such strong sentiments about the superiority of the elasto-plastic design approach, many PCPs have been and still are designed on the basis of the elastic theory. This is true of all the FHWA funded demonstration projects constructed to date. In fact, no evidence was found to indicate that the elasto-plastic design approach was even considered on these projects.

BONDED VS. UNBONDED TENDONS

Pavements are often subjected to direct application of de-icer chemicals, which are highly corrosive. One of the primary concerns with the use of unbonded tendons in pavements has been the possibility of corrosion and subsequent loss of prestress. Fortunately, the Post-Tensioning Institute has taken measures to deal with this problem and has recently issued a guide specification for unbonded, single-strand tendons (Ref 4). This specification sets specific guidelines for strand coating materials used to protect against corrosion and/or lubricate the prestressing steel. Guidelines are also established for the strand sheathing materials which are used to provide corrosion protection and prevent bonding between the prestressing steel and the surrounding concrete. With these new specifications, the corrosion of unbonded tendons should become much less of an issue than it has been in the past.

The structural behavior of PCP with unbonded tendons is, however, still very much an issue. In the typical applications encountered in the design of buildings and bridges, the structural behavior of posttensioned concrete using unbonded tendons under service loads is generally considered equivalent to that of either pretensioned or posttensioned concrete using bonded tendons. The decision to use either bonded or unbonded tendons in these cases is generally based on construction convenience and economy. However, as Dr. Lev Zetlin pointed out in a paper presented at the Prestressed Concrete Institute Convention in 1960, the structural behavior of PCP under service loads is fundamentally different than the behavior of a typical prestressed concrete member in a building or bridge (Ref 136). In addition, Dr. Zetlin noted that the structural behavior of PCP is better suited to the use of bonded tendons. A typical edge-supported slab (such as a building floor slab) and a typical PCP will be compared in order to illustrate the differences between the structural behavior of the two and to support the contention that bonded tendons are more desirable for PCP.

The obvious major difference between an edge-supported slab and a PCP is that the former is supported only along its edges, while the latter is supported by a subgrade over its entire area. Not only does this continuous subgrade support develop vertical reaction when vertical loads are applied to the pavement, it also develops horizontal frictional forces at the bottom surface of the pavement in response to horizontal strains in the pavement. These strains are the result of thermal, shrinkage, and creep volumetric changes in the pavement.

The effect of these vertical and horizontal subgrade reactions can be seen by comparing the deformations of an edge supported slab and a PCP when each of the slabs is subjected to a concentrated load at some point in its interior portion as illustrated in Figs 4.1 and 4.2. Under the action of the concentrated load, the suspended floor slab in Fig 4.1 has a continuous curvature. The prestressing forces in this case are acting at the slab edges regardless of whether the tendons are bonded or unbonded

The concentrated load on the PCP, however, would cause local distortions of the pavement in the immediate vicinity of the concentrated load due to the vertical subgrade reaction. This is obvious if the pavement is considered as

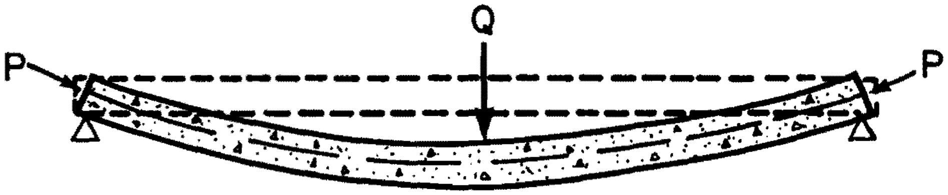


Fig 4.1. Typical edge supported slab (Ref I36).

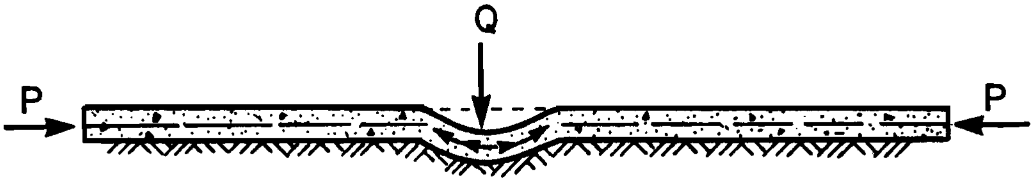


Fig 4.2. Typical PCP (Ref 136).

a plate on a continuous elastic support. In addition, the tendency for the localization of distortions is even greater due to the friction developed by the subgrade on the bottom surface of the pavement.

Under a concentrated load at some point in the interior portion of a PCP having bonded tendons, localized bond stresses would be set up as shown in Fig 4.2. These bond stresses create, in effect, an independently prestressed element inside the prestressed pavement. This is an important contribution of bonded tendons, namely, the potential of developing reliable bond resistance at any point in the pavement.

Another important advantage in using bonded tendons in PCP is with respect to its improved resistance to volumetric changes.

Still another important advantage of bonded tendons in PCP is the improved pavement behavior if it is partially damaged. If a portion of a PCP with bonded tendons--including the edge of the slab where bond or bearing stresses (depending on whether pretensioning or posttensioning is used) are initially concentrated--is destroyed for some reason, the bonded tendons would develop reliable bond stresses in the remaining portions of the pavement. However, if a portion of a PCP with unbonded tendons is destroyed for some reason, the prestress might be lost. Once lost, the prestress might be extremely difficult to restore. This is because the broken unbonded tendons sometimes retract inside the undamaged portion of the pavement and are difficult to retrieve in order to make splice repairs.

Only three of the six PCP slab sections constructed on the Dulles project had bonded tendons. The other three slab sections had unbonded tendons. The slab sections with bonded tendons were constructed by placing the seven-wire strand in 3/4-inch O.D. steel 20-gauge tubing. After posttensioning the tendons, and about a week after the concrete was placed, cement grout was injected through fittings spaced every 100 feet in order to lock the tendons into the slab. The other three slab sections were constructed with pregreased seven-wire strand encased in extruded polypropylene sheathing. The two types of strand enclosures are shown in Fig 4.3.

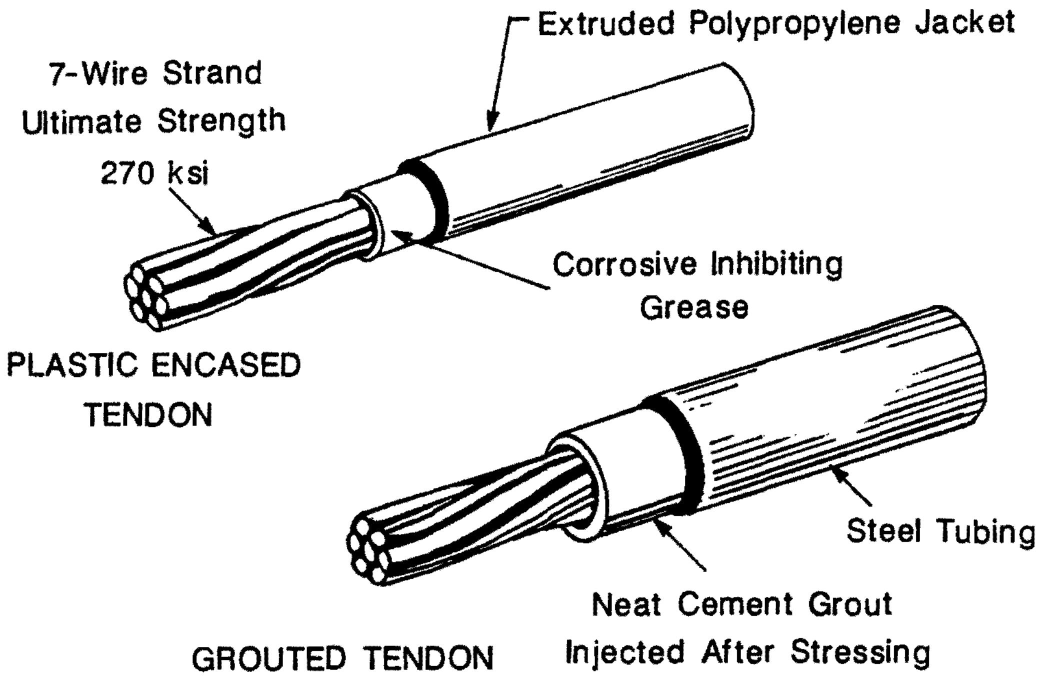


Fig 4.3. Prestress tendons.

Only unbonded tendons similar to those used on the Dulles project were used on the other FHWA sponsored projects. Although not specifically stated in any of the project reports, the most probable reasons for use of this type of tendon were the advantages of construction convenience and economy. Unfortunately, no comparative study of the structural performance of the PCP using bonded tendons versus unbonded tendons was done on the Dulles project. Therefore, it is not known whether the advantages of using unbonded tendons on the subsequent FHWA sponsored projects outweighed the potential disadvantages of using unbonded tendons.

TRANSVERSE PRESTRESS

Tensile stresses due to hygrothermal contraction are usually less in the transverse direction due to the generally narrower pavement dimension in this direction. However, it has been established, both theoretically and experimentally, that the longitudinal and transverse stresses due to applied wheel loads are approximately the same, depending on the wheel footprint.

If an elasto-plastic approach is used for the design of a PCP, transverse prestressing, in addition to longitudinal prestressing, has been shown both theoretically and experimentally to be essential to avoid top-surface cracking when relatively few moving loads greater than those causing bottom-surface cracking are applied repeatedly at interior locations (Ref 26). This need was recognized very early in the development of PCP. In fact, in 1954 the Road Research Laboratory proposed that a minimum transverse prestress of 50 psi be used for narrow pavement slabs and that the use of no transverse prestress be considered only for slabs less than 15 feet in width, where the possibility of longitudinal cracking under overload is an "accepted calculated risk" (Ref 77). Further research, in the form of laboratory model and full-scale PCP testing, resulted in a reduction of the minimum recommended prestress to approximately 30 psi (Ref 26). In addition, the need for transverse prestress was demonstrated by the occurrence of uncontrolled longitudinal cracking, particularly over tendons, on some of the

PCP projects constructed during the 1950s in which only longitudinal prestress was used (Ref 30).

As previously discussed, PCP design based on the elastic theory fails to take advantage of the potential increase in load-carrying capacity provided by the redistribution of moments which occurs with the formation of partial plastic hinges in the pavement. In spite of that fact, many PCPs have been and continue to be designed on the basis of purely elastic behavior. When this approach is used, several options are available for the design of the pavement in the transverse direction.

The first possibility is to prestress the pavement transversely as well as longitudinally as is required when the elasto-plastic design approach is used. This option has the advantage of the pavement remaining crack free in both the longitudinal and transverse directions, but it has the disadvantage of added stressing operations.

The second possibility is to design the pavement transversely as a reinforced concrete pavement. Longitudinal cracking may be acceptable and expected if this option is selected. The purpose of distributed transverse steel reinforcement in this design approach is not to prevent cracking, but rather to hold tightly closed any cracks that may form, thus maintaining the pavement as an integral structural unit.

The third possibility is to design the pavement transversely as an unreinforced concrete pavement. As with the second design option, longitudinal cracking must be acceptable and expected if this option is selected. In fact, as pointed out in the following passage from a 1955 article, longitudinal cracking may be more likely to occur in this type of pavement than in a concrete slab that is unreinforced in both directions:

> In certain conditions the transverse strength of the slab might in fact be less than that of a plain slab, because of the ducts made for the tendons, and longitudinal cracks might occur along the lines of the ducts. That could be overcome, however, by the use of transverse normal reinforcement (Ref 59).

The option of designing the pavement transversely as an unreinforced concrete pavement should be given serious consideration when the following conditions exist: (a) the PCP is designed in accordance with the elastic theory, and (b) the thickness required in the longitudinal direction approaches that necessary for the pavement to function acceptably in the transverse direction as an unreinforced concrete pavement. The required longitudinal pavement thickness is often greater than that strictly needed for design in order to furnish sufficient cover over the longitudinal tendons and for construction convenience.

Longitudinal hinge or warping joints must be used with both the second and third options to prevent the formation of irregular, uncontrolled longitudinal cracks. The type of joint used depends primarily upon the method of placing the concrete slabs. If lane-at-a-time construction is used, keyed joints as shown in Fig 4.4 are often used. The keyed joints should be tied together with tie bars to make certain that the lanes are prevented from separating. This will help assure that the shear key functions properly in transferring loads and preventing joint faulting. Keyed joints are, however, liable to chip off at the joint. If two-lane construction is used, the most convenient type of longitudinal warping joint is the dummy-groove type as shown in Fig 4.5. As with keyed joints, tie bars should also be used with this joint type to make certain that the lanes are prevented from separating in order to maintain aggregate interlock. It is important to note that load transfer across a tied joint is brought about by aggregate interlock. Therefore, the tie bars must be firmly anchored to prevent movement. As a result, either deformed or hooked steel bars or approved connectors are used for tie bars. The groove is generally either mechanically formed, sawed, or formed by placing impregnated fibrous material at the location of the desired joint. The fibrous material is left in the concrete and forms an integral part of the warping joint. In any case, the depth of the grooves should not be less than 1/3 the thickness of the pavement.

For the second and third options, existing, well-established procedures for the design of reinforced or unreinforced concrete pavement would simply be used for the design in the transverse direction.

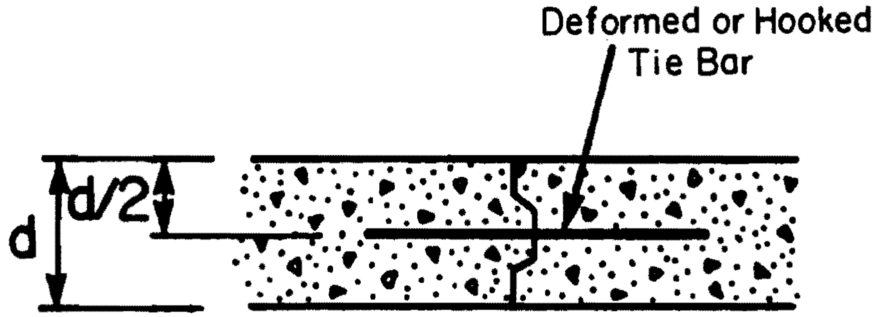


Fig 4.4. Keyed joint (Ref 135).

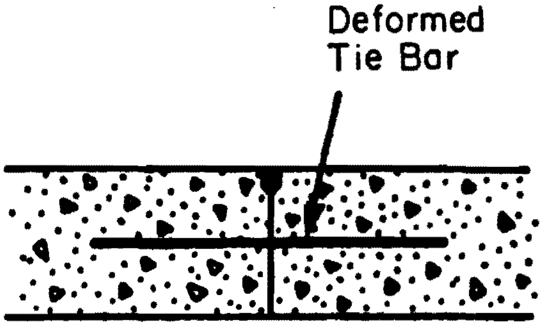


Fig 4.5. Dummy-groove joint (Ref 135).

Regardless of the approach used, careful consideration must be given in the design of a PCP so that equal pavement serviceability is obtained in both directions. This will avoid both unnecessarily high costs due to excessive pavement strength in one direction and premature pavement failures due to insufficient pavement strength in one direction.All of the previously constructed FHWA funded PCP demonstration projects were designed on the basis of the elastic theory. Little discussion of the design of the pavement in the transverse direction is provided in any of the project reports and it appears that this aspect of the design did not receive very much consideration. Varying degrees of longitudinal cracking have been reported on all of the projects except the one in Tempe, Arizona. On the Dulles project transverse steel was provided consisting of either number 3 or 4 bars (depending on the slab section) spaced on 30-inch centers. The transverse steel was terminated near the longitudinal centerline of the pavement and three-foot-long number 4 tie bars, also spaced on 30-inch centers, were provided along the longitudinal centerline of the pavement. In addition, a sawed, longitudinal joint was provided at the centerline of the pavement. It was suggested in the report on the Dulles project that it may be possible to eliminate all transverse steel, except tie bars (Ref 105). This suggestion was based more on conjecture than on actual observation of pavement performance, since it was made in a report that was written in 1972, only a few months after the construction of the project. Although the bases of this suggestion were not given in the report, the probable explanations were that the designers felt that providing tie bars in lieu of transverse steel would result in acceptable pavement performance and, that their method of strand placement would not be feasible if transverse steel were used.

One longitudinal crack about 50 feet long and running about one foot off of the centerline was reported on the Dulles project as of 1981 (Ref 53). It appeared to be a typical uncontrolled longitudinal crack.

Transverse reinforcement was also provided on the 1972 Kutztown, Pennsylvania project (Ref 52). This reinforcement was provided for the entire width of the pavement by providing two 12.5-foot-long number 4 bars every 30 inches along the length of the pavement, lapped 18 inches at the longitudinal centerline. No longitudinal joint was provided. The Kutztown project report reiterated the suggestions made in the Dulles report regarding the elimination of the transverse reinforcement and use of a new strand placement procedure. Since the report on this project was written only months after construction, it is probable that the suggestions were again based on construction expediency rather than actual observed pavement performance. No information is available to date on the performance of the Kutztown project.

On the Hogestown, Pennsylvania project completed in December, 1973, the only transverse reinforcement provided was four-foot-long number 5 tie bars on 48-inch centers along the longitudinal centerline of the pavement. In the conclusions of a report on the project dated two months after the completion of construction, the project engineer for the Pennsylvania Department of Transportation (PennDOT) stated: "Transverse reinforcement steel in prestressed pavement can be eliminated (Ref 13)."

For the first three years of service of the Hogestown PCP, from 1973 to 1976, the winters were mild and without significant frost depth. The winters of 1976-77 and 1977-78 were somewhat more severe and during this time transverse cracks developed in 18 of the 23 PCP slabs and approximately ten longitudinal cracks, varying from 27 to 150 feet in length, appeared in the slabs. A program was undertaken in 1978 to repair the longitudinal cracks. The repair method chosen was to pressure inject all longitudinal cracks with epoxy resin, insert steel tie bars in slots cut across the cracks at selected locations and bond them in place with an epoxy mortar to prevent the cracks from opening or lengthening further. In the conclusions of the report on the investigation and repair of the longitudinal pavement cracking, the same Penn DOT engineer who had authored the previous Hogestown project reports stated:

> The lack of transverse reinforcement in the pavement slabs appears to be an inherent weakness, as there is little to prevent the growth or widening of longitudinal cracks. The use of transverse reinforcement is recommended in future prestressed pavement construction (Ref 12).

The original PCP design for the 1976 FHWA funded project constructed near Brookhaven, Mississippi called for transverse reinforcement consisting of number 4 bars, 23 feet-in-length, spaced at 36-inch centers. These bars were depressed into the concrete by a hydraulic jack assembly located on the rear of the concrete spreader. However, the transverse reinforcement was deleted after the first nine slabs were completed, because it was being displaced as the concrete slid on the polyethylene surface. 36-inch-long, number 4 tie bars, spaced at 36-inch centers, were placed in the remaining 49 slabs. These tie bars were manually inserted into the concrete from a small platform on the front of the slip-form paver. A continuous strip of plastic material was inserted into the concrete along the longitudinal centerline by means of a device attached to the back of the paver. The purpose of this material was to induce cracking along a controlled plane.

A few months after construction of the PCP it was noticed that longitudinal cracks had formed in 15 of the slabs, approximately one foot away from the longitudinal centerline. These cracks were thought to have occurred either because the plastic material was ineffective or because it was installed incorrectly. Consequently, the tie bars (which only extend 15 inches on either side of the longitudinal centerline) are not embedded a full development length on both sides of each longitudinal crack. Whether the tie bars will be effective in preventing separation along these longitudinal cracks and preventing possible faulting due to loss of aggregate interlock for the entire service life of the pavement remains to be seen. There is a possibility that additional longitudinal cracks may form more than 15 inches from the pavement centerline, and there would not be any steel in this area to keep them closed.

In order to evaluate the performance of the demonstration PCPs, the FHWA initiated a study by a panel made up of one research engineer from each of the state highway agencies in Arizona, Mississippi, and Pennsylvania. Also on the panel was the FHWA contract manager who served as an ex officio member and provided input from the Dulles project. After a March, 1981 inspection of the condition of these projects, the panel issued a report which detailed their findings and suggested design guidelines and desirable characteristics for future projects. One of their conclusions was: "Based upon the inspection of the projects in service, no lateral prestress is required (Ref 53)."

The previously discussed reports on the FHWA demonstration projects do not seem to support this conclusion since longitudinal cracking was reported on three of the four projects. In addition, the fact that the longitudinal cracking has not been even worse may very well be attributable to other factors, such as (a) most of the demonstration projects have been subjected to fairly light traffic, (b) two of the projects are in weather zones which are not subject to freeze/thaw, and/or (c) strong base courses were provided on most of the projects. At a very minimum, more study on this subject is warranted before this panel's conclusion is applied to the construction of additional projects.

FRICTION-REDUCING MEDIUMS

A reliable and effective friction-reducing medium is needed for the following reasons: (a) to minimize the subgrade restraint and thereby allow the desired prestress level to be obtained with the minimum amount of posttensioning strand; and (b) to permit the pavement to respond to hygrothermal changes during its service life without inducing excessive tensile stresses in the pavement.

The main requirements for friction-reducing mediums are that they be: (a) efficient in reducing subgrade restraint, (b) practical for road construction, and (c) economical.

Tests have been conducted in both the laboratory and the field on many friction reducing materials. These materials have included sand, building paper, polyethylene sheeting, paraffin wax, oil, asphalts, and combinations of these materials. The following observations were made based on the results of these tests: (a) coefficients of static friction were greater than the coefficients of sliding friction, (b) magnitudes of these coefficients were neither affected by the direction of movement nor by the slab size or weight, (c) the coefficients depend on the textures of the subbase top and slab underside surfaces, and (d) all of the materials require a certain amount of slab movement to overcome the initial restraint. Several of the materials were shown to provide coefficients of friction of less than one. Each of these friction-reducing mediums is discussed in more detail in other references (Refs 18, 78, 81, 125, 126, 127, 133). In addition, tables summarizing the measured coefficients of friction are provided in these same references.

The friction-reducing medium used on nearly all of the pavement slabs on the FHWA funded demonstration projects was a double layer of polyethylene sheeting. However, both the Mississippi and Arizona projects had one slab which was built on a single layer of polyethylene sheeting. In addition, another slab on the Mississippi project was built directly on the prepared subgrade with no friction-reducing medium and, as would be expected, the slab developed relatively uniformly-spaced transverse cracks.

The assumed value of the coefficient of friction used for the design on the Brookhaven, Mississippi project was 0.6 (Ref 5) . This was based on the recommendations of several references (Ref 41). After completion of tendon stressing operations, calculations based on theoretical and measured stresses were done to determine the actual coefficient of friction. Based on these calculations the coefficient of friction was 0.55 with both one and two layers of polyethylene. However, the same method yielded a friction coefficient of 0.72 for the slab placed directly on the hot-mix asphaltic concrete base course with no friction-reducing medium at all. Numerous tests, including one performed by personnel from the Center for Transportation Research of The University of Texas at Austin, have indicated coefficients of friction of well over two for this type of situation. This value (0.72) was even questionable to those performing the calculations on the Brookhaven project, as is obvious from the following quote:

> There appears to be a reasonable doubt concerning the calculated subgrade friction factor of 0.72 psi/ft. as the applied stress for this particular slab was apparently not sufficient to completely close a crack in the slab at midlength (Ref 5).

Actually, the procedure used on the Brookhaven project to calculate all the values appears to be somewhat dubious, and there is no reason to believe that any of the calculated values is more valid than the others.

On the Tempe, Arizona project a design coefficient of friction of 0.5 was used (Ref 86) . The project report stated that this value was selected because they believed that a value of 0.5 could be achieved in the field with reasonable assurance. However, the report did not explain the reason for this assurance.

The main point is that the basis for the previously used coefficient of friction values is somewhat questionable. There are at least as many references that could be quoted in support of the use of higher values as were given to justify the values which were used. Clearly, additional research is needed in the area of friction-reducing mediums in order to establish more reliable design data. This research should also include investigation of various effects (e.g., time, temperature, pressure, abrasion, etc.) on the behavior of various mediums.

Several problems were encountered with the use of the polyethylene sheeting. The first major problem was with the placement of the sheeting. Wind was reported to be one of the most adverse problems. The sheeting tended to billow up and fold over at the edges with only a moderate breeze. On the Hogestown, Pennsylvania project it was reported that when the wind was calm, two men were sufficient to handle the sheeting, whereas, when the wind was strong and gusty, a crew of ten or more men was required (Ref 13) . The paving contractor's comments regarding the construction of this project were included in one of the project reports. One of his major concerns was that a more satisfactory method of laying the polyethylene sheeting be found. This was echoed by the PennDOT highway engineer, who also suggested that specialized placement equipment might be developed.

The second major problem associated with the polyethylene sheeting was in connection with concrete placement. On the Hogestown, Pennsylvania project the placement operation began by unrolling two, overlapping, 12.5-foot-wide rolls of double-layer polyethylene sheeting behind the strand pay-off truck and ahead of the concrete spreader. The spreader used a conveyor to deposit the concrete near the centerline of the pavement and rotating augers to push the concrete toward the edges of the pavement. As the concrete was pushed toward the edges, the polyethylene was pulled along with it. This resulted in a strip up to one foot wide at the centerline of the pavement having no polyethylene sheeting. Rolls of plastic 25-feet-wide would have been more suitable, but were not available.

The third major problem encountered on the Hogestown, Pennsylvania project was that the polyethylene sheeting had a tendency to fold up as it was pushed by the concrete under the spreader. It was feared that these folds would become trapped in the concrete slab, causing potential weak planes. Whether this actually occurred is a matter of speculation, but the problem was never adequately solved.

A similar problem was also encountered on the Tempe, Arizona project (Ref 86). On this project the top layer of polyethylene was reported to have slid over the bottom layer as the paver was moving ahead and it would fold just ahead of the concrete under the spreader. On several occasions this sliding and folding of the top layer was so severe that the paver had to stop so the top layer could be removed. As on the Hogestown project, it was feared that the folds might be trapped in the slabs causing weakened planes and subsequent pavement cracking.

The Brookhaven, Mississippi project also experienced problems with the concrete sliding on the polyethylene sheeting (Ref 5) . As the concrete mix slid on the polyethylene, it also pushed the untied transverse steel which was depressed on top of the longitudinal tendons. Most of the time the transverse steel slid evenly; however, when the concrete began to build up at the slip form paver, it bent the transverse steel into a convex shape. As sufficient concrete accumulated at the convex-shaped steel, it overflowed and created an additional sliding condition. The sliding force of the concrete also tended to move the prestressing tendons laterally. The sliding problems appeared to be aggravated by the 1.5-inch concrete slump, the percentage of large size aggregate (1.5 inch) in the mix, and the frequency of the concrete vibrators (10,000 to 11,000 impulses).

A meeting was held by representatives of the Mississippi State Highway Department (MSHD), the FHWA, and the contractor after the first day's unsuccessful paving operation to discuss these problems. The MSHD Research Committee decided that two layers of polyethylene sheeting must be used and that nothing could be done about it being too slippery. Because 0.75-inch slump had previously been tried and found to cause problems, and problems had been encountered with 1.5-inch slump, it was decided to try a slump on the order of 1 to 1.25 inches. It was decided that nothing could be done about the aggregate size problem since the aggregate being used met the project specification and sufficient aggregate had already been stockpiled for the entire project. Also, as will be described later, it was impossible to tie the transverse steel with the method of strand placement which was being used, so no changes in the placement of transverse steel were recommended at that time.

The contractor made the following modifications to his paving operations: (a) a 1.25-inch slump concrete was used, (b) the vibrating frequency was lowered to approximately 8,000 impulses, and (c) an apron was extended on the lower side of the paving machine for approximately six feet. Although these modifications aided the contractor in increasing both his production and the quality of the paving, they did not stop the sliding of the concrete or the sliding and bending of the transverse steel into a convex shape. In fact some of the transverse bars were exposed at the top surface of the concrete slab. As mentioned, the contractor subsequently deleted the transverse steel and replaced it with tie bars at the center of the pavement.

Three additional points about the friction-reducing medium should also be mentioned. First, in the FHWA initiated performance study of the demonstration projects, one of the conclusions was as follows: "A single layer of polyethylene film may be an adequate subgrade friction-reducing layer for prestressed slabs up to 600 feet long (Ref 53) ." No data was given in support of this statement and, in fact, previous studies have expressed some concern that a single layer of plastic sheeting might be ineffective in the field, because the material is soft and abrades quickly (Ref 126). This statement is probably based more on construction convenience than on pavement performance since insufficient experience with a single layer of polyethylene was obtained on the FHWA sponsored projects to support this conclusion and construction problems were encountered even with the use of a double layer of polyethylene.

The second point has to do with the following statement made in the recommendations section of the report on the FHWA initiated performance study:

> Once prestressing forces are applied, shrinkage has occurred, and low temperatures have contracted the concrete slabs, it appears feasible to eliminate the expansion capability by blocking movement of the slab ends. This type of action would result in the pavement being in a higher state of compression during warmer temperatures and reducing movements occurring at the joints. The Arizona project demonstrated a similar restraining effect from the friction caused by the attached curb and gutter cast later (Ref 53) .

This recommendation may be valid. However, one possibility which is not mentioned in their recommendation must be kept in mind. Although buckling of the slab due to compressive forces induced by the prestressing strands is not a problem, buckling due to externally applied forces can be a problem. In fact, buckling has occurred on some of the poststressed pavement projects constructed in Europe and the United States. If their recommendation is implemented, the pavement design must take this possibility into account.

The third point concerning the friction-reducing medium has to do with another of the recommendations made in the report on the FHWA initiated performance study. The recommendation was as follows:

> Another approach to accomplish reduced slab movement would be to develop a self-destruct friction-reducing layer. The layer would function during the initial shrinkage and stressing period, but then become ineffective and develop increased subgrade friction to retard slab expansion (Ref 53) .

As previously stated, one of the reasons a reliable and effective friction-reducing medium is needed is to permit the pavement to respond to hygrothermal changes during its entire service life without inducing excessive tensile stresses in the pavement. If a self-destruct, friction-reducing layer (such as described above) were used, not only would the slab expansion be retarded but more than likely so would the slab contraction. This would induce excessive tensile stresses in the pavement and uncontrolled cracking would be inevitable.

GAP SLABS

All of the posttensioned PCP projects in the United States consisted of consecutive prestressed slabs separated by short openings to permit the prestressing tendons to be conveniently posttensioned from their ends. It was necessary to stress each tendon from both ends due to the long slab lengths and correspondingly high tendon and subgrade friction forces. Once the posttensioning was applied and most of the progressive length changes had occurred, including all of the elastic shortening and most of the creep, this space was filled with a short reinforced concrete filler slab. Fig 4.6 shows this reinforced "gap" slab between the prestressed elements.

For several reasons, this type of gap slab was not entirely satisfactory. Since joints are a high-first-cost item which require periodic maintenance, both the initial and the long-term costs associated with a gap slab arrangement with two joints are greater than for a gap slab design requiring only a single joint. In addition, poor gap slab performance (i.e., warping, curling, rocking, etc.) was experienced on some of the projects. In fact, replacement of several of the gap slabs on the Dulles project was necessary after only four years of service (Ref 53) .

The gap slab design was modified on the Hogestown, Pennsylvania project to allow movement at only one of the gap slab joints by posttensioning the gap slab to one of the previously stressed pavement segments (Ref 13). This was accomplished by transferring the load from temporary anchors at one end of the previously stressed pavement segments to permanent tendon anchors provided in the gap slab (Fig 4.7). Jacking bridges were provided behind each temporary tendon anchor to permit the release of the load on the

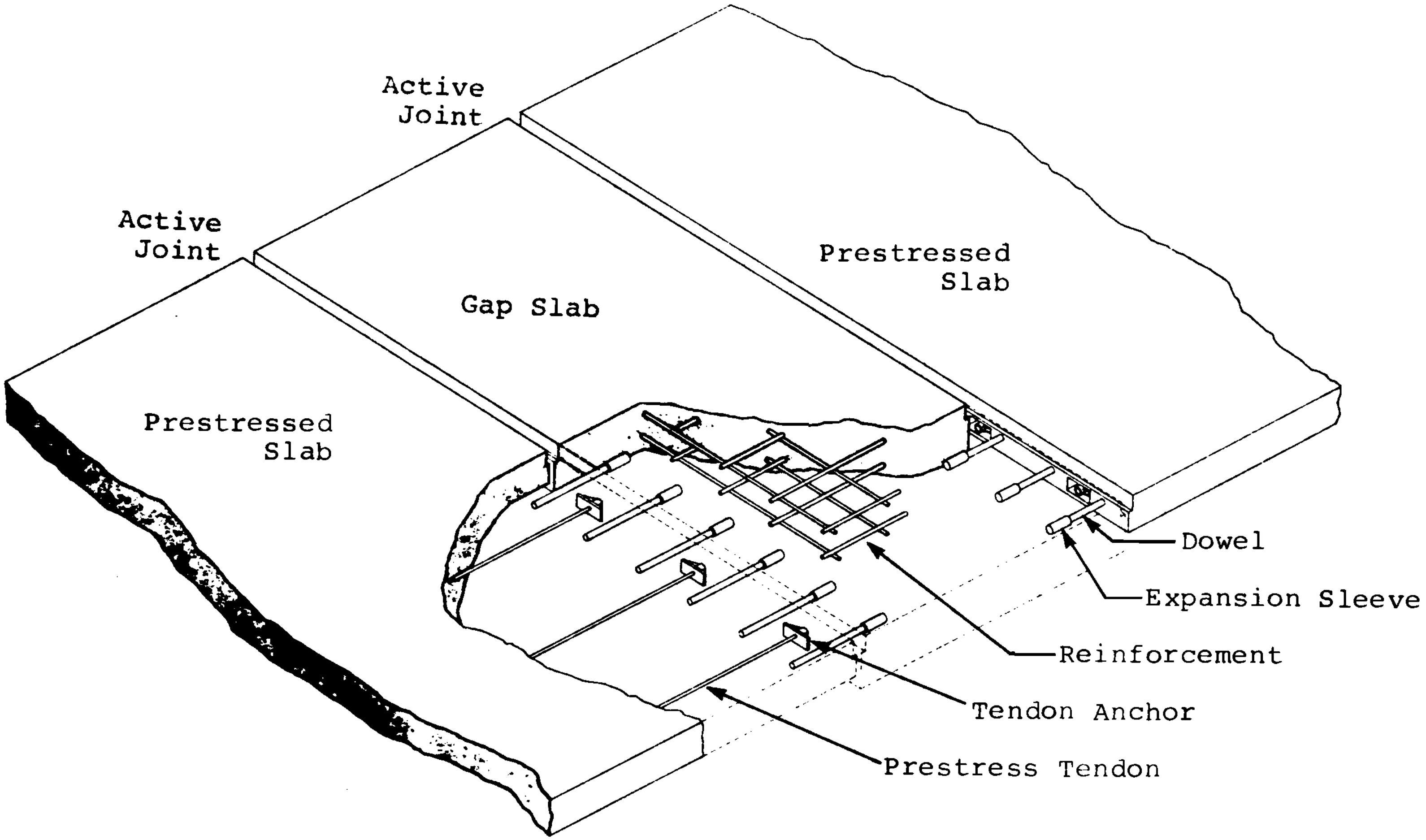


Fig 4.6. Typical detail of gap slab between prestressed slabs (Ref 92).

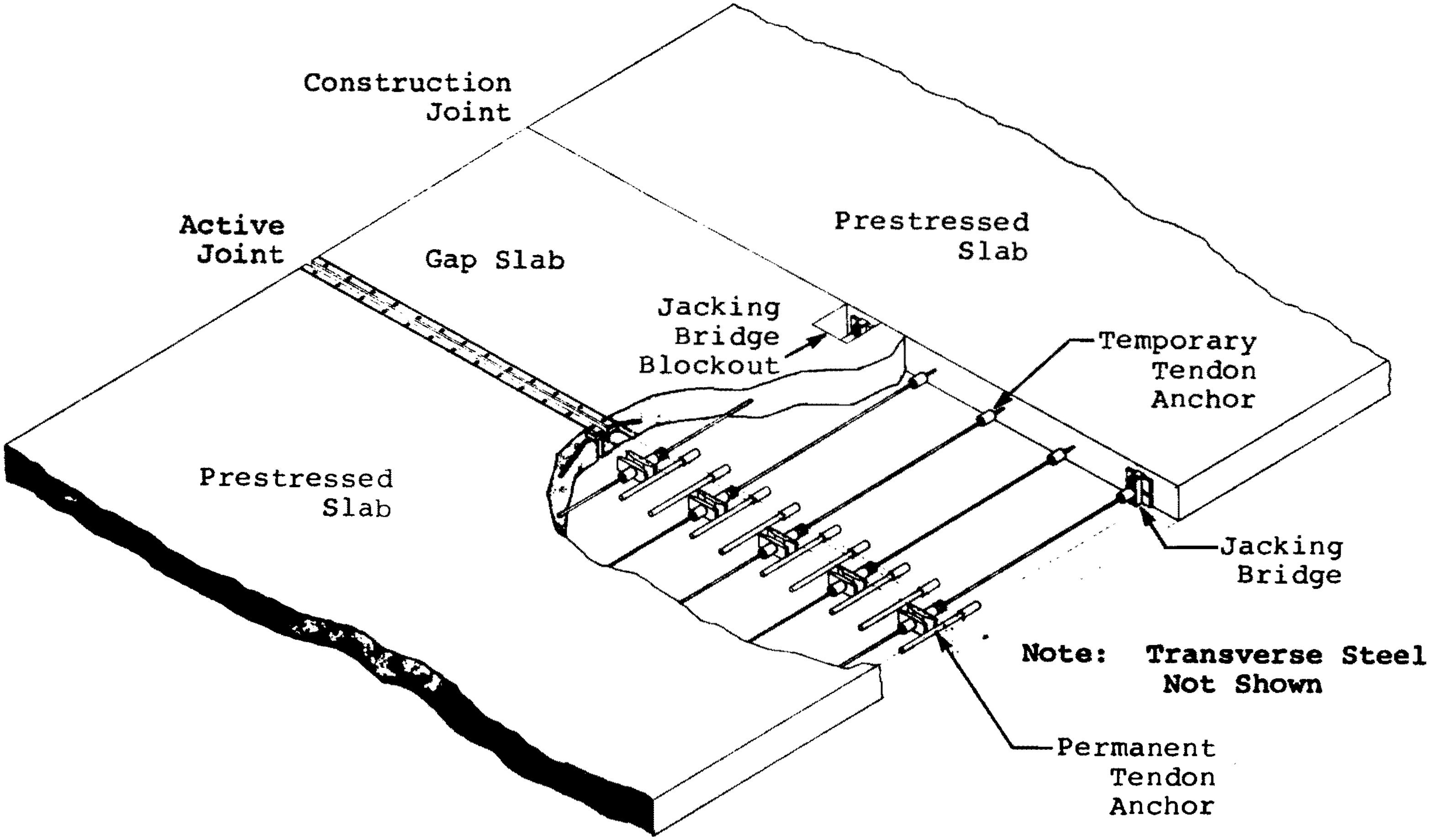


Fig 4.7. Gap slab with one active joint (Ref 92).

temporary anchors. Each of these jacking bridges consisted of two steel bars, one above the strand and one below, which held the temporary tendon anchor a small distance out from the end of the pavement segment. Each tendon extended through the temporary tendon anchor, through the gap area between the previously stressed pavement segments, and terminated at a permanent anchor adjacent to the active joint. A slab blockout was provided around each jacking bridge. After the concrete for the gap slab was cast and had attained sufficient strength, the jacking bridge was cut with a torch. This transferred the strand load from the temporary anchor to the permanent anchor, thus stressing the gap slab.

Several problems occurred in connection with this procedure. The first problem was that adequate consideration had not been given to the relationship between the span of the jacking bridges and the strength of the materials. Although this may seem like a fairly trivial error, it resulted in damage to the end region of the pavement slab and could have easily resulted in more serious consequences. The steel bars which comprised the jacking bridges deflected significantly under the load from final jacking of the tendons. In two cases the bars spread apart and actually slipped from behind the temporary anchors as the jacking bridges deflected. The rapid release of the tendon anchor at full load caused it to snap back against the end of the slab with great force. The first failure resulted in the anchor smashing through the concrete and coming to rest approximately one foot into the slab. The second failure occurred adjacent to the first a few minutes later. Jacking was being done on the first tendon when failure of its jacking bridge occurred, but not on the second tendon. The second failure resulted in the anchor coming to rest against the end of the slab. Flying steel and concrete accompanied both failures, but fortunately no injuries occurred. Although the problem with the jacking bridges was corrected by simply reducing their span length, this example does illustrate that overlooking seemingly minor details can have potentially serious consequences.

A second problem occurred during load transfer as a result of cutting through only the top bar of the jacking bridge. Although this did transfer the load, the uncut bottom bar of the bridge caused the temporary anchor to twist as it moved back, resulting in fracturing of the joint concrete around the anchor. To correct this problem, the welder was instructed to partially sever both the top and bottom bars of the jacking bridge to achieve an even release. Fewer fractures occurred as a result of this procedural change, however, the problem was never completely eliminated.

A third problem was associated with the permanent strand anchors. After cutting the jacking bridges on several of the early joints, the permanent anchors failed to hold, allowing the temporary anchors to move back against the original slab end. It was believed that the permanent anchors had become dislodged during placement and vibration of the gap slab concrete. Precautions were taken during subsequent construction operations to avoid disturbing the permanent anchors and no additional failures were observed.

TENDON PLACEMENT

The importance of applying sufficient preliminary tension to the posttensioning tendons to straighten and hold them in place during concreting operations was recognized even on the very early PCP projects. The tendons need to be straight and securely held in place to assure that the desired compressive stress distribution is obtained on the pavement cross section and that wobble friction losses due to unintentional misalignment of the tendons is minimized. The importance of the preliminary tension on the posttensioning tendons was graphically demonstrated during field tests which were conducted near Valley View, Texas by personnel from the Center for Transportation Research of The University of Texas at Austin (Ref 78). In these tests lateral displacement of unstressed posttensioned strands occurred during concrete placement. The preliminary stress level recommended on one of the early PCP projects was 10,000 psi (Ref 114), however, the actual value which should be used on a given project is a function of several variables, including tendon size, chair spacing, concrete placement technique, etc.

The two types of tendon enclosures used on the Dulles demonstration PCP project were shown in Fig 4.3. All of the tendons were preplaced on chairs and no preliminary tension is reported to have been applied. As the specified low-slump concrete (0.5 inch) was being placed with the slip-form paver, the tendons were pushed forward, producing lateral displacement and some buckling of the tendons. The slump had to be subsequently increased to 2 inches and provisions had to be made to allow for expansion of the tendon in order to be able to construct the pavement. Literature on the project is not clear on what provisions were made to allow for expansion of the tendon.

All of the prestressing tendons on the Kutztown, Pennsylvania PCP project were of the polypropylene encased type (see Fig 4.3). Prefabricated transverse steel assemblies were provided at 2.5-foot centers for the full length of the pavement. Each of these assemblies consisted of a number 4 reinforcing bar with chairs and clips (needed to support the longitudinal prestressing tendons) tack welded to it at each of its intersections with a tendon, as shown in Fig 4.8. Each of the longitudinal tendons was laid in position, snapped into the clips, and its ends inserted into holes in a steel channel section which was provided at the pavement end. A tension of less than one kip was then applied to each tendon to hold it in place and prevent movement during paving.

Three problems were encountered in association with this method of tendon placement. The first problem was that the initial stress of one kip which was applied to hold the tendons in place had been lost by the time the paving was done. This was probably due to a change in temperature.

The second problem was that the clips on the transverse steel assemblies which held the longitudinal prestressing tendons were too tight. Approximately 40 percent of the clips were reported to have cut through the polypropylene jacket, allowing the protective grease to seep out.

The third problem was similar to the one encountered on the Dulles project. When concrete piled up in front of the spreader, the transverse steel assemblies were pushed along with the concrete and displaced as much as six inches.

On the Hogestown, Pennsylvania PCP project, an idea for tendon placement was used which was first suggested in a report on the Dulles project. The idea was described in that report as follows: "Special holding devices into which the strands can be inserted and removed would be used to position the

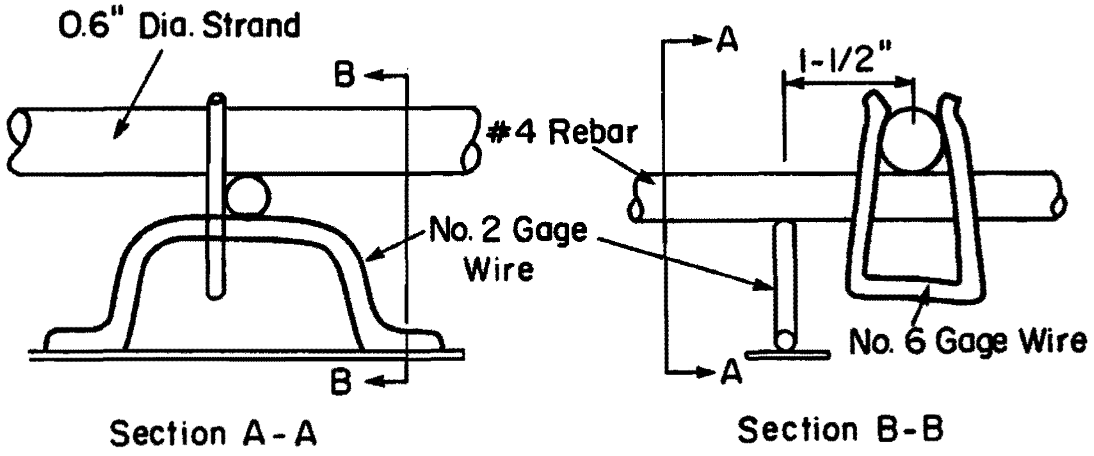


Fig 4.8. Chair and clip detail (Ref 52).

steel strands into the extruded concrete (Ref 105)." The "special holding devices" on the Hogestown project were steel tubes attached to the underside of the spreader machine. Tendon reels were carried ahead of the paving train on a modified flatbed truck from which the tendons were unwound onto the polyethylene sheeting on top of the pavement base course. The tendons were then picked up by the steel tubes attached to the concrete spreader and positioned at the design depth. The remainder of the slip-form paving operation was then done by conventional methods.

A couple of problems were encountered with this placement technique. On at least two occasions the plastic strand enclosure became caught in the placement tube causing it to be damaged or stripped. Where possible, the enclosure was repaired with tape to prevent the concrete from bonding into the strand. Not all of the locations of damaged enclosure were detected and repaired. In at least one instance bonding of the concrete to the tendon was discovered when workmen attempted to apply the final stress to it. On this occasion erratic readings were obtained on the jacking gauge and audible "crackling" sounds emanated from the slab. The full load was not placed on the tendon due to the bonding.

A second problem on the Hogestown project was not discovered until several years after the completion of construction. During the winters of 1976-77 and 1977-78, as mentioned, cracks developed in a majority of the PCP slabs. An investigation was undertaken to determine both the causes of the cracking and appropriate repair measures. In the course of the investigation, a Pachometer was used to measure tendon depths in the longitudinal crack areas. The depth to the centerline of the tendon was found to be 1.5 inches in some locations. This was confirmed by actual measurements in core holes which were drilled to permit epoxy injection of the cracks in the pavement. This depth was substantially less than the design depth to the tendon centerline which was 3.5 inches. Therefore, the question arises of whether the method used on this project can reliably provide the necessary degree of accuracy in the placement of the tendons.

This same tendon placement technique was also used on the Brookhaven project and two problems resulted. First, the transverse steel had to be placed without being tied resulting in the problems with the transverse steel which were described . The second problem was that tendons, especially those along the outside shoulder edge of the slab, were laterally displaced. In fact, one of the tendons was actually exposed along a slab edge as a result of the displacement. It was later necessary to place additional concrete along the slab edge to protect the exposed tendon.

The tendon placement method used on the Tempe, Arizona project was a slightly modified version of the method used on the Hogestown, Pennsylvania and Brookhaven, Mississippi projects. The only modification was that J-bars were attached to the concrete spreader, instead of steel pipes, to position the tendons in the slip-formed pavement.

The modification appears to have been at least partially effective since no problems with damaged strand enclosure, as experienced on the Hogestown project, were reported on the Tempe project. Also, no mention of tendon misplacement is made in the report on the Tempe project. However, the problem of tendon misplacement on the Hogestown project was not discovered until several years after the completion of construction which was, by the way, also after completion of the construction of the both the Brookhaven and Tempe projects. Some tendon misplacement was reported on the Brookhaven project and similar tendon misplacement may have occurred on the Tempe project and simply may not have caused any problems yet. Also, since both the winters and the traffic conditions are less severe at the Brookhaven and Tempe project sites than at the Hogestown site, similar problems due to tendon misplacement may never occur.

TRANSVERSE JOINTS

As discussed earlier, gap slabs were used to provide a work area for posttensioning operations on all four of the previously constructed FHWA sponsored PCP projects. As originally constructed, three of the four projects had active joints at each end of each gap slab. The fourth project was the only one which was originally constructed with only one active transverse joint at each gap slab. Reducing the number of transverse joints per gap slab does cut the total number of required transverse joints in half, which is good both from the standpoints of initial cost and long-term maintenance. However, elimination of one of the joints concentrates all of the movement of the two adjacent slabs at the remaining transverse joint, requiring it to accommodate larger movements.

Different transverse joint details were used on each of the four FHWA sponsored projects. Performance of these various transverse joints was described in the previously mentioned FHWA initiated performance study as "less than satisfactory" (Ref 53). Some of the features of these transverse joints, and the problems encountered with their use, will be described in this section.

The Dulles project (constructed in 1971) used a double I-beam joint at each end of the eight-foot-long gap slab (see Fig 3.3). Black steel dowel bars, 1.25 inches in diameter, were used for load transfer. The space between the I-beams was set in accordance with the prevailing temperature at the time of construction. The opening between the I-beams was filled with foamed-in-place polyurethane.

Performance problems were experienced with some of the joints on this project. In fact, by 1975 (only four years after the construction of the project) the distress was severe enough at several locations to warrant removal and replacement, not only of the joints, but also of the gap slabs. The gap slab concrete had separated from the I-beam at these locations. This problem was attributed to two causes. The first cause was that the black steel dowel bars which were used in the original construction had corroded and frozen. Problems had been anticipated, but stainless steel was not available at the time of construction. The second cause was inadequacies in design details of the steel reinforcement in the gap slab concrete.

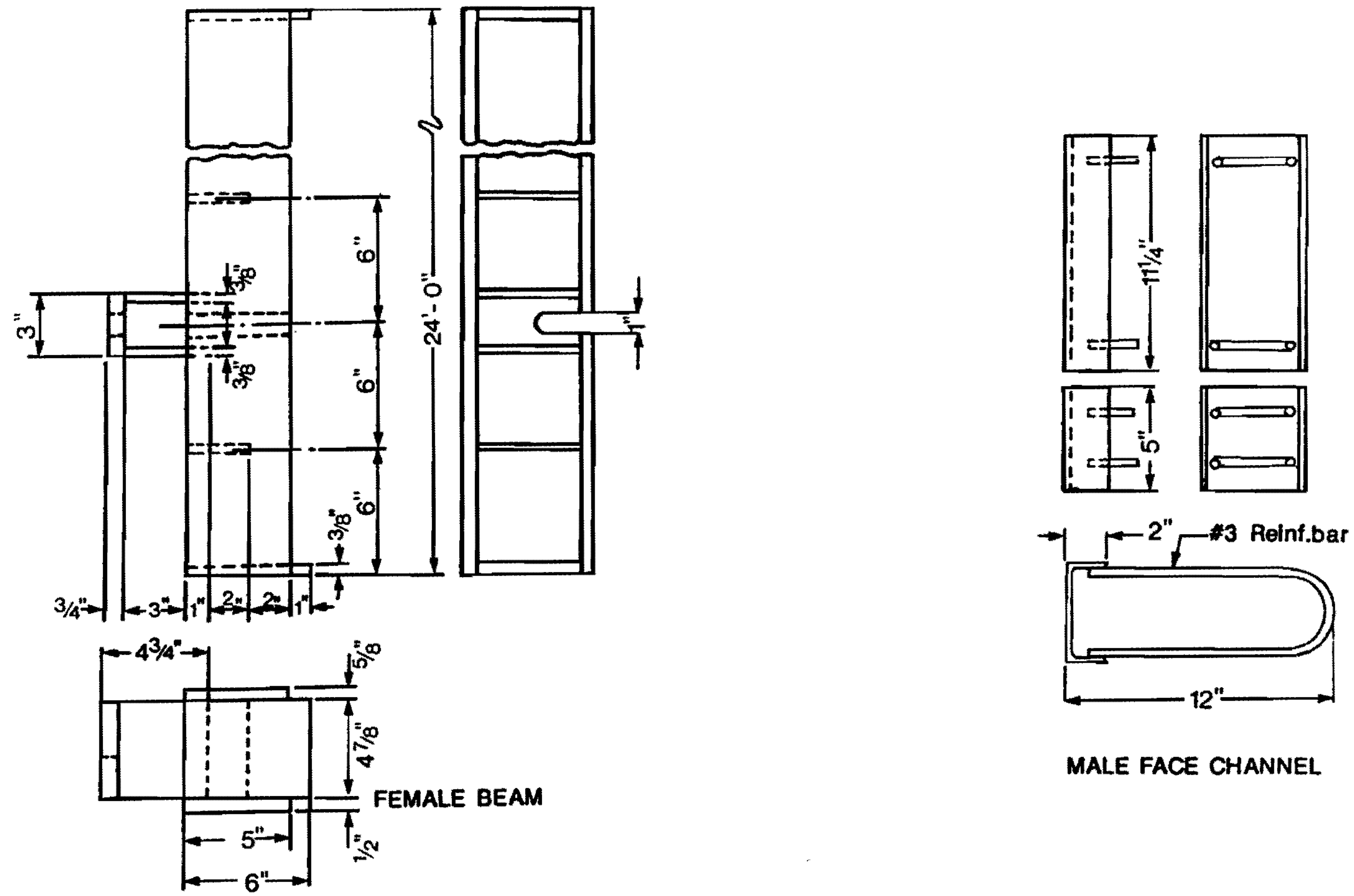
When the gap slabs were replaced, the joint on one side of each gap slab was eliminated and the new gap slab was made integral with the PCP slab on that same side. No details of how these gap slabs were made integral with the existing PCP slabs were given in available reports. The dowels of the remaining joint on the other side of each gap slab were replaced with new stainless steel dowels, and neoprene gland-type seals were substituted for the foamed-in-place polyurethane. The retrofitted joint has an approximately three-inch-wide opening. It is reported to be performing well.

The Hogestown, Pennsylvania project (constructed in 1973) was the only one of the FHWA sponsored projects which was originally constructed with only one active transverse joint at each gap slab. The joint that was used on this project was a patented interlocking beam system, trade named "PAJO", which was a product of Pavement Systems Incorporated. This joint consisted of a female beam placed immediately after the pavement was slipformed and a series of short male beams placed at the time the gap slabs were cast. These two components are shown in Fig 4.9. Anchors pockets were provided in the female beam to receive the PCP tendon anchors. The female beam was securely anchored to the PCP by the stressed tendons. The short male beams were connected to the gap slab concrete by means of U-shaped reinforcing bars which were welded to the beams. Spacers of expanded foam sheeting were placed between each male beam and the female beam to allow for expansion of the slabs. The completed joint is shown in Fig 4.10. This interlocking beam system acted as a load transfer device, eliminating the need for a sleeper slab to reduce stresses and deflections at the slab ends.

By the fall of 1974, major problems had developed with two of the joints. Apparently the male portion of these joints had become tightly wedged into the female portion of the joint. When the temperature dropped, the slabs contracted and the steel welds and tendon anchor pockets were torn loose. Fortunately, Penn DOT maintenance personnel were able to repair the damage. According to the FHWA initiated performance study report, similar distress was observed in March, 1981, at several other joints on this same project.

In addition, a considerable amount of spalling occurred where the joint concrete meets the top plate of the female beam. A hand-tooled edge had been provided at this point to prevent spalling, but apparently the tooled edge was not extended far enough back in the joint concrete. This caused many spalls when the joints closed.

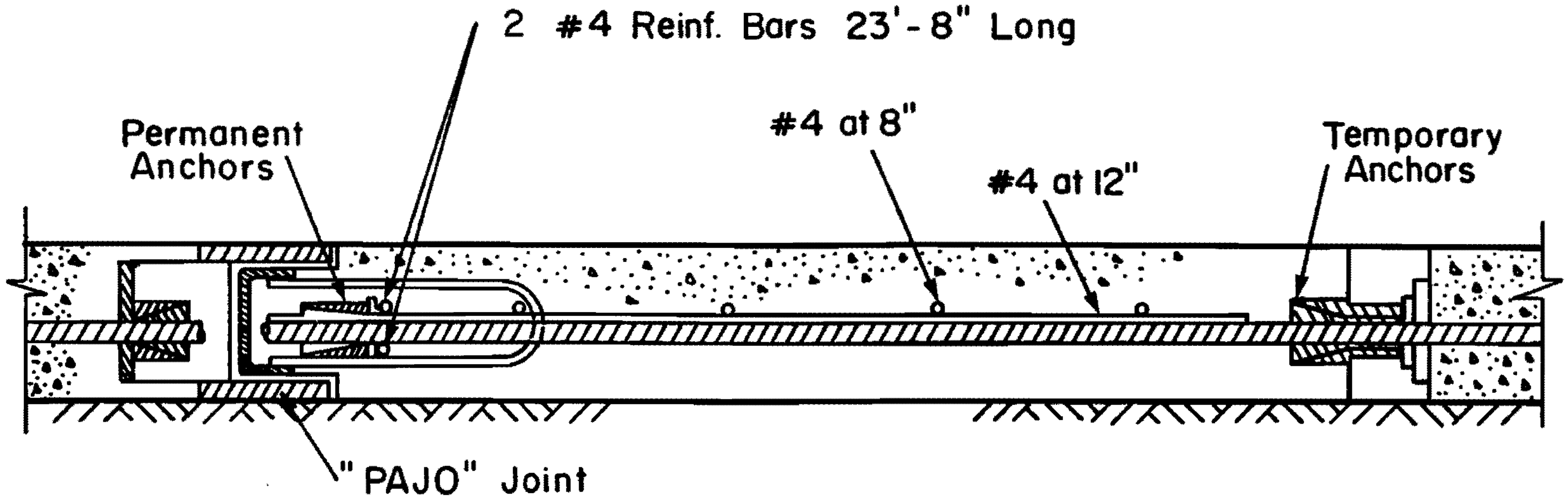
Problems were also experienced with the transverse joints at the terminal ends of the project. The expansion joint material at these locations was compressed to about half its original thickness during the



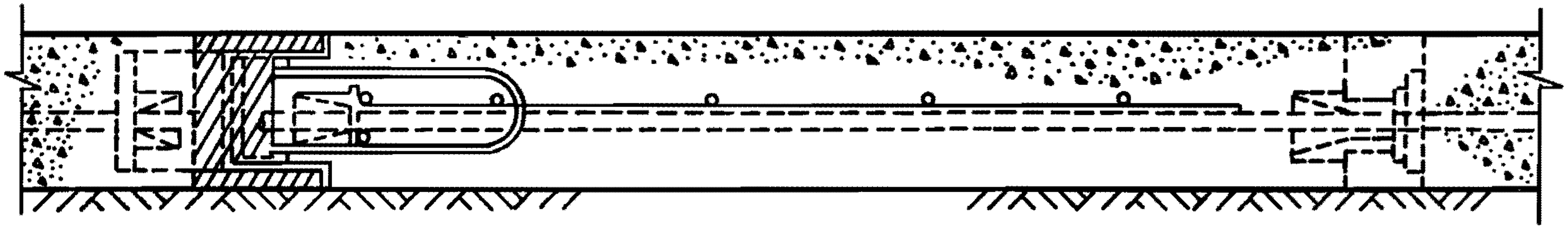
FEMALE BEAM

MALE FACE CHANNEL

Fig 4.9. Details of female beam and male face channel for PAJO joint (Ref 56).



SECTION THROUGH CENTERLINE AT JOINT



SECTION THROUGH VERTICAL MEMBER OF THE FEMALE BEAM

Fig 4.10. Sections through PAJO joint in the pavement at Harrisburg, Pennsylvania (Ref 56).

summer season. In fact, one of the terminal joints closed so tightly during a period of several days of hot temperatures that the short terminal slab provided between the PCP and a bridge approach slab heaved up about 0.5 inch. When the temperature dropped, the terminal slab returned to its normal position. Subsequent contraction of the PCP in colder weather caused these expansion joints to open and a large amount of debris was allowed to enter. After five years, the joints had become filled with debris and the expansion joint material had deteriorated. In addition, there was evidence that the bridge approach slabs were being pushed toward the abutment walls and spalling was occurring at one expansion joint due to excessive pressure caused by closure of the joints during hot weather. As a result, the joints were cleaned and new expansion joint material was installed.

On the Brookhaven, Mississippi project (constructed in 1976) the transverse joints that were provided on both sides of each gap slab were initially set at approximately 1.5 inches wide. This initial joint setting was obtained by providing a 1.5-inch-thick by 3.5-inch-high styrofoam strip. Holes were drilled through the styrofoam strip which permitted it to be slipped over the steel dowel bars and against the slab end (see Fig 4.11). The remaining height of the slab edge was formed with a wood board. Expansion chambers were installed on the exposed ends of the dowels after they had been coated with grease in preparation for the placement of the gap slab concrete. After the gap slab concrete had been cast and the wood form board removed, the sides of the joint were cleaned by sand blasting and two inches of a cold-poured, two component polysulfide material was placed on top of the previously mentioned styrofoam strip.

Within a period of four months after placement, the polysulfide material began to deteriorate. The material was installed during late November, 1976. As the weather warmed during the spring of 1977, the material ballooned above the pavement. Two possible reasons were given to account for this phenomenon. The first reason was that the two component polysulfide material had been improperly mixed. The other reason was that the material had been placed when the joints were wide and when they began to close due to the increasing temperature, the excess material was forced out.

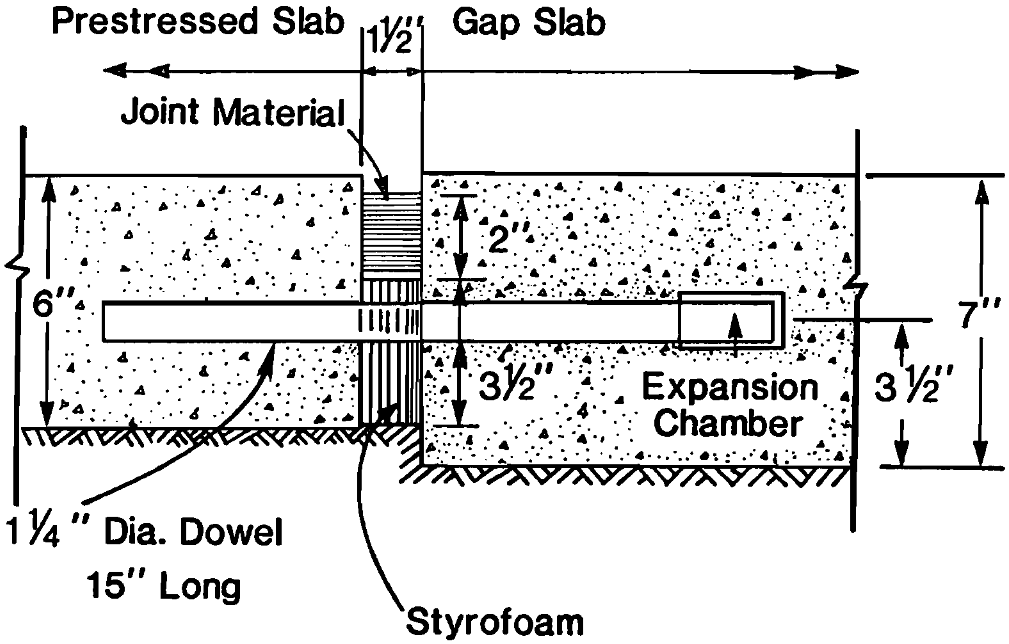


Fig 4.11. Mississippi joint detail (Ref 5).

The polysulfide material was removed from all 116 transverse joints. After removal of the material, the joints were sawed and then sand blasted. Sixteen of these joints were resealed with a cold-poured, two component polyurethane material. Placement of this material was delayed until September, 1977, because it was believed that this was the proper time of year for placing this type of material. The remaining 100 joints were filled with 3.25-inch-wide neoprene compression seals. Placement of these compression seals was delayed until January and February, 1978, when the weather was colder, so that the joints would be open as wide as possible in order to minimize the amount of joint sawing that would be required.

By 1979, the polyurethane joint material had deteriorated. After the joints were again cleaned, they were resealed with a preformed joint material called Evasote. Since then, this material has also been used to replace several of the neoprene compression seals which have not stayed in place. The Evasote material is reported to be performing well and it is planned to eventually replace the material in all the remaining joints with this material.

The transverse joint assembly provided on both sides of each gap slab on the Tempe, Arizona project are shown in Figures 4.12 and 4.13. The steel extrusions used in this joint detail serve a twofold purpose. They act to protect both sides of the joint opening against wear, fractures and edge-spalling due to traffic impact. They also act as a receiver for the neoprene seal which protects against infiltration of water which can cause pumping and prevents intrusion of incompressibles which are potentially damaging to the pavement during periods of pavement expansion. The steel extrusions were secured to both the PCP slabs and the gap slabs with 0.5-inch-diameter by six-inch-long, headed, steel studs. Recesses were formed in the gap slab concrete opposite each strand chuck so that the chucks would not be damaged in the event that the transverse joint closed. Load transfer dowels were also provided to reduce slab deflections under load and to maintain the surface alignment of the adjacent slabs. Stainless steel expansion sleeves were used. In addition, the portion of each dowel bar which is inserted into the expansion sleeve was clad in stainless steel. This was

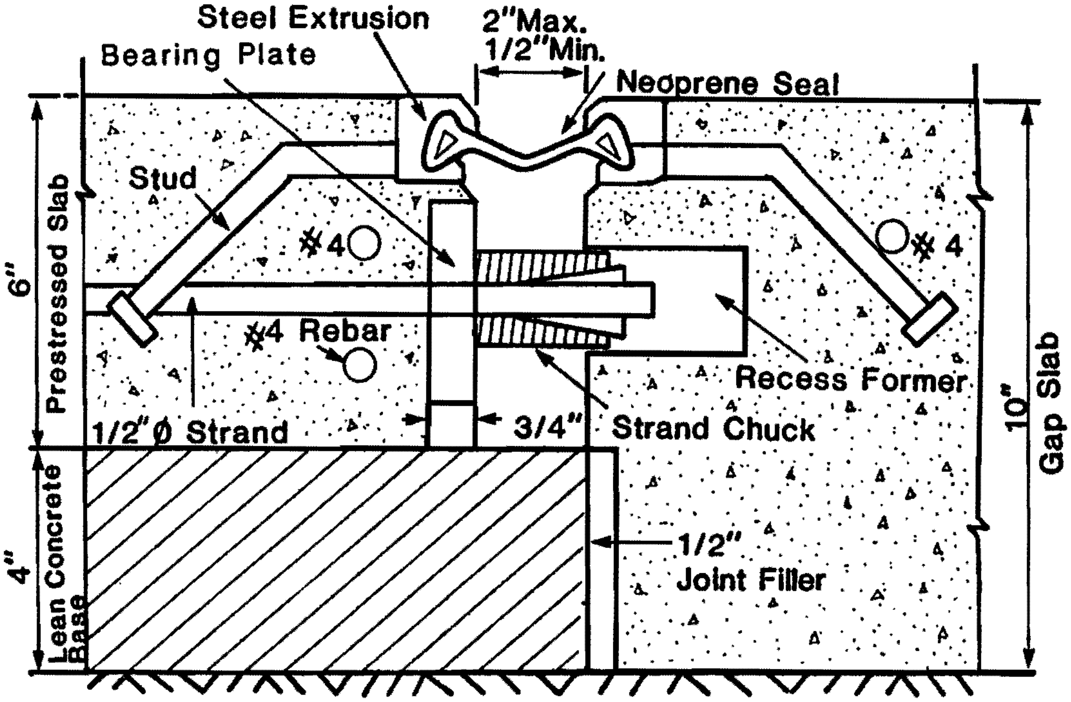


Fig 4.12. Typical joint assembly at strand anchor (Ref 68).

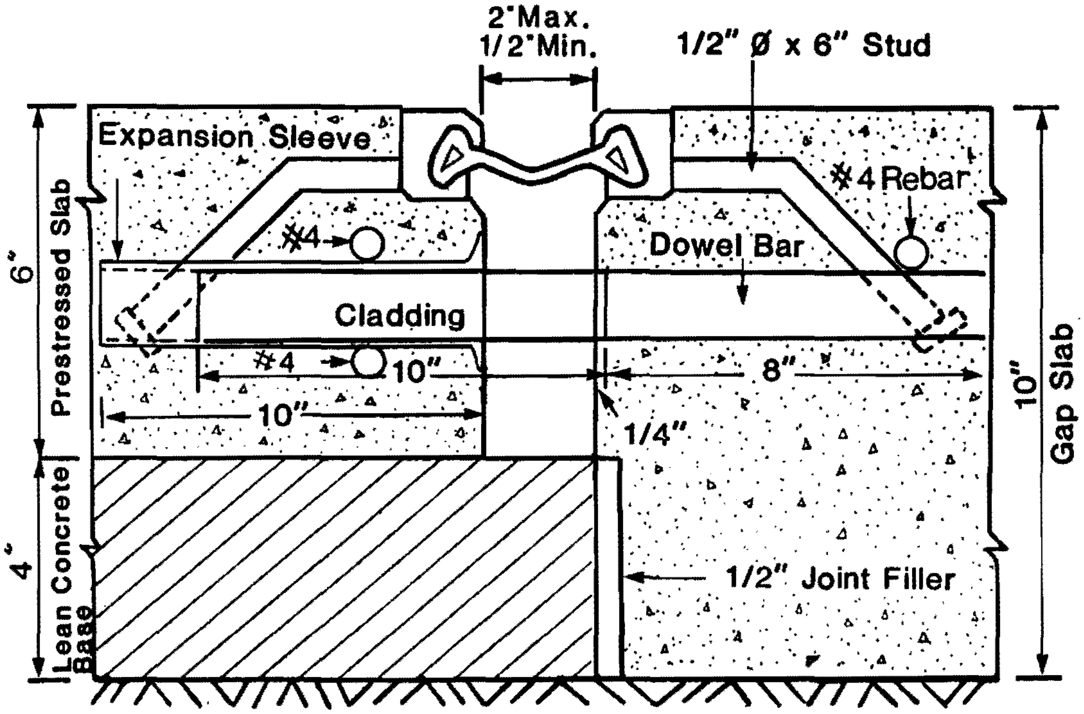


Fig 4.13. Typical joint assembly at load transfer dowels (Ref 68).

done to prevent the dowels from corroding and freezing as had occurred on the Hogestown, Pennsylvania project. Two major problems have been experienced with this joint detail. The first problem was that the welds connecting the headed steel studs to the steel extrusions broke on a significant number of the joints. This problem occurred on both the PCP and the gap slabs. The problem was believed to have been caused by improper consolidation of the concrete at the joint which resulted in lack of support immediately below the steel extrusion. The problem was corrected by rewelding the anchors to the steel extrusion and rebuilding the concrete section with epoxy at the slab ends.

The second problem is that the neoprene strip material has torn at the curb side of the pavement for a distance of 6 to 12 inches on 80 percent of the joints. Replacement of the material had not been necessary as of January, 1984, but it was reported that corrective action will be required at some point in the future.

LONGITUDINAL JOINTS

Longitudinal control joints (also known as hinge or warping joints) are provided in conventional concrete pavement to mitigate the effects of volume change. In monolithically placed conventional concrete pavement, these joints are in the form of sawed or formed grooves on the pavement surface between adjacent lanes to control any possible longitudinal cracking due to volume change. The groove produces a weakened plane in the slab which induces a crack to form at that location and, as a result, formation of undesirable, uncontrolled, longitudinal cracking is inhibited. These joints are generally located between traffic lanes to prevent undue interference with vehicle steering. Either tie bars or continuous transverse reinforcement are required with these joints. As discussed, this type of joint is also necessary in monolithically placed PCP when the pavement is designed in the transverse direction as either reinforced or unreinforced concrete pavement. However, this joint is probably not necessary if the monolithically placed PCP is transversely prestressed. This type of joint was used on all of the FHWA sponsored PCP projects and the problems which were experienced are also reported in this paper.

Longitudinal construction joints, which also act as longitudinal control joints to mitigate the effects of volume change, are another type of longitudinal joint used with conventional concrete pavement. Longitudinal construction joints are used where the required pavement width exceeds the capacity of the paving machine or only a single lane can be taken out of service at a time for repaving. They are also used where concrete shoulders are built in a separate operation from the traffic lanes, and/or other roadways intersect a pavement. This type of joint is equally necessary in the same situations with PCP construction.

Two different types of longitudinal construction joint details, keyed and butt types, are commonly used with conventional concrete pavement. Either type of detail works well in pavements greater than eight inches thick. However, in pavements less than eight inches, the keyed joint may cause construction and performance problems, therefore, the butt joint is generally recommended. In either case, these construction joints should be adequately tied together in order to maintain rigidity between slabs to reduce stress concentrations caused by loading of a free edge. The load carrying capacity of the transverse steel extending through the longitudinal construction joint should be equivalent to the amount of transverse reinforcement determined for the interior of the slab.

Proper design and detailing of longitudinal joints is even more important for PCP than for conventional concrete pavement because: (a) the slab lengths used in PCP construction generally are considerably longer than with conventional concrete pavement construction and, hence, the potential amount of differential longitudinal movement is greater, and (b) it is very important that the longitudinal shortening of a lane of PCP not be restricted by previously placed lanes during curing or stressing, and yet adjacent lanes must still be tied together to maintain rigidity between the slabs in order to reduce stress concentrations caused by loading of a free edge.

Experience was gained with longitudinal construction joints between separately placed concrete shoulder slabs and PCP slabs on at least two of the FHWA sponsored projects. On the Hogestown, Pennsylvania project problems occurred with these joints (Ref 14). A large amount of movement of the PCP slabs in relation to the shoulder slabs occurred near the ends of the PCP slabs. The shearing effect at the longitudinal joints between the PCP slabs and the shoulder slabs caused these joints to become open and unsealed. Sealing of these longitudinal joints was reported to be difficult, if not impossible. In addition, some cracks appeared in the shoulder slab adjacent to the pavement joints as a result of the action of the PCP slabs.

On the Tempe, Arizona project the transverse PCP joint opening was observed to be considerably less at the curb side of the pavement than at the free side of the pavement (Ref 68). This was believed to be because of the restraining friction in the keyed construction joint between the PCP slab and the adjacent 4.5-foot-wide curb and gutter section. Although no problems have been reported yet as a result of this phenomenon, it is conceivable that it could cause binding of the dowel bars. This possibility is discussed in more detail in Chapter 6.

Obviously, the design of the joint between PCP slabs and separately placed reinforced concrete shoulder slabs was not entirely satisfactory on these projects. Moreover, since the PCP slabs on all of the FHWA sponsored projects were placed full width in a single operation, problems which might be encountered with the joint between separately placed longitudinal PCP slab strips did not have to be addressed. However, this situation will eventually have to be addressed and solutions worked out for PCP construction.

CONCRETE COMPACTION

Compacting of the fresh concrete has a critical effect on the final quality of the concrete which is important in virtually any application. However, good compaction is probably more important in prestressed concrete than in other types of concrete construction to insure acceptable in-service performance and to prevent failures during construction due to high compressive stresses induced during tendon stressing operations.

Immediately upon placing, the concrete should be compacted by means of hand tools or vibrators. Such compacting prevents honeycombing, assures close contact with forms and all other embedded items (e.g., reinforcement, tendons, anchorages, joint hardware, etc.), and serves as a partial remedy to possible prior segregation. On all of the FHWA sponsored projects, compaction was by means of vibrators attached to the paver and located between the longitudinal tendons. These vibrators generally had to be raised out of the concrete near the slab ends to clear either temporary bulkheads or joint hardware. Supplemental vibration was usually provided in these areas by means of hand-held units. Both the vibrators attached to the pavers and the hand-held units were of the high-frequency, power-driven variety which are immersed in the concrete.

Problems associated with the concrete compaction were reported on most of the FHWA sponsored projects. In fact, in the report on the FHWA initiated performance study, the following statement was made: "Construction problems were encountered on each of the projects. Tendons and anchors were occasionally lost due to bearing failure during tensioning operations in both Pennsylvania and Mississippi (Ref 53)." This statement does not say that all the bearing failures were due to concrete compaction problems, but it is clear from the individual project reports that some of them were and, in addition, that other problems can be attributed to this same cause.

On the Hogestown, Pennsylvania project several of the permanent tendon anchorages failed to hold. This occurred at random locations. The PennDOT project engineer thought that the anchors might have been dislodged while the joint concrete was being placed and vibrated. Another possible explanation might be that voids existed behind the anchors which caused bearing failures.

On the Brookhaven, Mississippi project it was reported that the concrete at the slab ends was over vibrated. This over vibrating caused the concrete in these areas to flake and produced a rutty appearance.

Problems were also reported on the Tempe, Arizona project. The first problem was discovered on the morning following the concreting of the slabs. During preparations for jacking of the tendons it was discovered that voids due to improperly compacted concrete existed under the bearing plates. Stressing operations were delayed while the voids were repaired with high-early-strength grout.

On another occasion, the corner of a slab end was damaged while applying the jacking force. In this instance the bearing plate and strand anchor buckled because of poor concrete consolidation at the slab end. The area was repaired by chipping away and replacing the damaged concrete.

Improper consolidation of the concrete also occurred in the area beneath the steel extrusion provided at each transverse joint . This was believed to be responsible for the failure of a large number of these extrusions.

CURLING

As discussed, curling in a concrete slab occurs due to a variation in temperature through the slab thickness. This curling induces tensile stresses in the concrete and is most critical when the temperature at the top of the pavement is lower than the temperature at the bottom of the pavement. This phenomenon was observed and recorded on at least two of the FHWA sponsored projects. Measurements of the temperature variations through the slab thickness were made periodically on the Brookhaven, Mississippi project (Refs 5, 6). In addition, vertical elevation measurements were made in conjunction with the concrete temperature measurements to obtain any vertical change along the length and ends of the pavement due to curling. The results of these measurements definitely show that some amount of curling does take place during the day.

Approximately two weeks after the prestressed slabs had been placed on the Tempe, Arizona project, but prior to placement of the gap slabs, it appeared that the slab ends were curling upward (Ref 86). To verify the curling, dial gauges were mounted on iron pins driven into the subgrade adjacent to the slab ends. The gauges were positioned such that their levers rested on the corners of the slabs where the curling was expected to be the greatest. Measurements taken with these gauges showed the total change to be 0.125 inch between maximum downward and upward curl. In addition to this curling, it was stated in a report on the six-year performance of the Tempe project that the gap slab corners were showing "extreme" curling and warping (Ref 68). This curling extended approximately 16 inches from the corner and in some cases was as much as 3/4-inch high.

MISCELLANEOUS

The FHWA sponsored projects emphasized the need for better understanding in at least two major areas. The first is the moisture-temperature-volume relationship of PCP. Improved understanding in this area would permit more accurate estimations of the magnitude of the slab movements in response to temperature and moisture changes. This would allow better predictions of transverse joint opening widths to be made and, as a result, transverse joint materials could be selected to better match the anticipated joint movements. In addition, a better understanding of the moisture-temperature-volume relationship would permit more accurate evaluations of stresses induced by moisture and temperature changes. This would enable the designer to more accurately select the appropriate prestress level to resist these stresses. Finally, a better understanding of the moisture-temperature-volume relationship would aid in determining the level of prestress which must be applied at early concrete age to prevent formation of cracks.

Also emphasized by the FHWA sponsored projects was the importance of a better understanding of the structural behavior of PCP under service and ultimate loads. This would permit better predictions of the load response of the pavement and would provide a better understanding of the relationship between pavement thickness and prestress level. This would enable the designer to select an appropriate pavement thickness and prestress level for a given service life.

SUMMARY

Based on descriptions provided in the literature, the primary emphasis of PCP research undertaken prior to the mid-1960s seems to have been on investigation of alternate design approaches and increased understanding of PCP behavior. Unfortunately, the value of this research was greatly diminished by the lack of constructability and performance information on the resulting full-scale projects.

The PCP research effort required in the future must be broader in scope. What is envisioned is a four-fold approach. First, as with the FHWA sponsored projects, constructability must remain a prime consideration. Second, the basic factors discussed in Chapters I, II, and III must be studied in greater detail to provide a better understanding of PCP behavior. The second phase serves as a basis for the third which would be the development of more rational design techniques. Finally, alternate construction approaches should be investigated which address the problems encountered on previous projects and which are better suited to taking full advantage of the potential benefits offered by PCP.

The purpose of the next chapter is to introduce some promising new concepts which are felt to be worthy of further study. At first inspection the proposed approaches may appear more complex than the FHWA sponsored projects. However, any increased complexity may be due to attempts to address the inadequacies of previously employed approaches and attempts to more effectively utilize the potential of PCP.

CHAPTER 5. NEW CONCEPTS

In the previous chapter, some of the most recent PCP projects were critically evaluated. Based on this discussion, it is obvious that all of the problems associated with PCP have not been solved and it is still much too early to commit to any of the design and construction approaches that have been presented thus far. There is still ample room for innovation and many facets of this complicated subject exist which are worthy of investigation. It is the objective of this chapter to introduce and explore some of them. As will be shown, the ideas on which these concepts are based are not new. Instead, what is "new" is the way in which these ideas are applied to the construction of PCP.

All of the concepts which will be presented in this chapter involve the use of central stressing and/or the use of precast concrete in the construction of PCP. Brief introductions to the use of central stressing and precast concrete will be given to serve as a basis for the discussion of the concepts.

(1) Central Stressing. Central stressing is a technique in which the strands are stressed at internal blockouts or stressing pockets. The idea of central stressing is not new and its origins are uncertain. The technique has been used for some time in posttensioned concrete building construction to stress tendons in slabs where end stressing is not feasible. This technique was also used in June, 1977, and again in September, 1983, to make repairs on the Hogestown, Pennsylvania PCP project (see Fig 5.1). In addition, it was also proposed by Portland Cement Association researchers as a means for prestressing the gap slabs between successive PCP sections (see Fig 5.2). Use of central stressing for new PCP construction instead of gaps between successive PCP slabs was conceived of by the Project 401 staff of the Center for Transportation Research at The University of Texas at Austin.

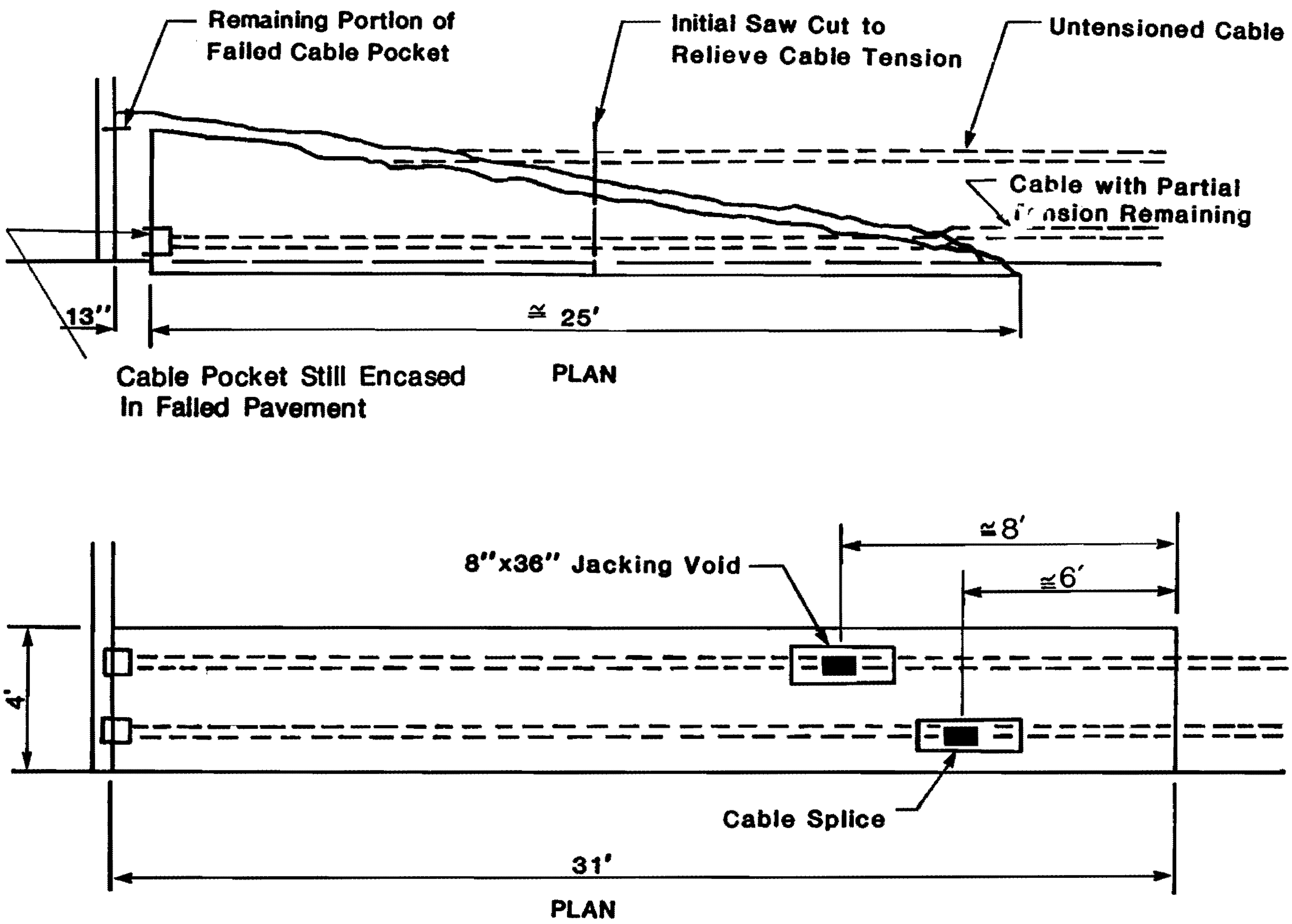


Fig 5.1. Prestressed pavement repair using stressing pockets (Ref 12).

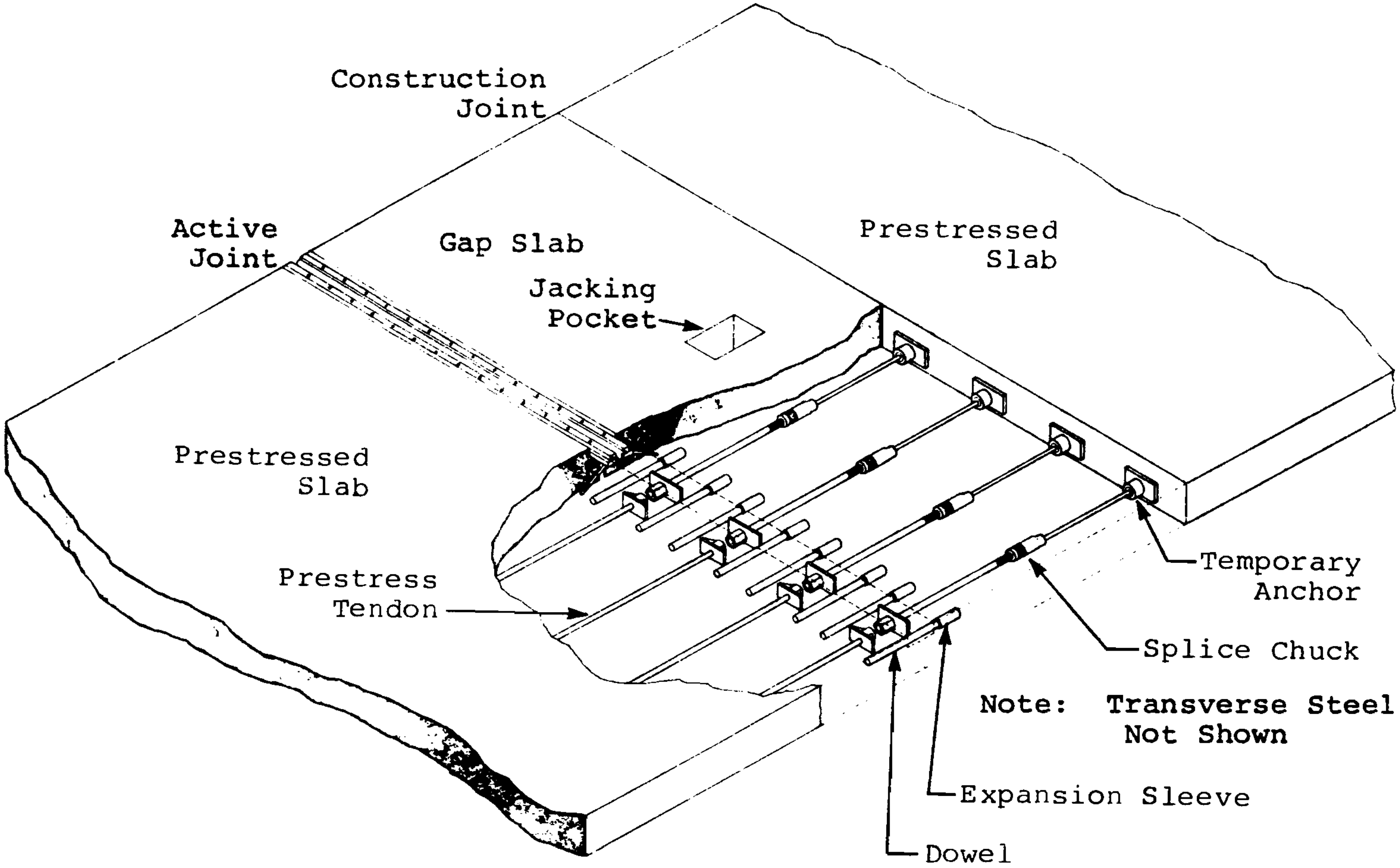


Fig 5.2. Gap slab stressing pockets (Ref 92).

(2) Precast Concrete in PCP Construction. The concept of prefabricating structural components for field placement is a significant departure from conventional pavement construction practices. However, as with central stressing, the idea of using precast concrete in PCP construction is not new. There are approximately six recorded instances of its use. The following brief discussion of a few of these instances is provided as an introduction to the topic and to familiarize the reader with previous experimentation in this area.

(a) France and Great Britain. Precast concrete was used in one of the first field applications of PCP in a 1377-foot-long runway at Orly Airport in France constructed during 1946 and 1947 (Refs 112, 62, 56). This project was based on research done by Eugene Freyssinet, a renowned engineer in the field of prestressed concrete. In 1949, a similar 355-foot-long runway was constructed at the London Airport (Refs 8, 111, 56). Both of these projects were transversely posttensioned and longitudinally poststressed. In each case the runways were composed of 6.5-inch thick precast concrete slabs. On the French project the precast slabs were 3.28 feet square and on the British project they were 2.92 feet square. In both cases, the precast slabs were placed on building paper which, in turn, was placed over a two-inch layer of sand deposited on the leveled ground. Each runway was divided into a number of 45-degree triangles separated by gaps in which small steel rollers were vertically placed as shown in Fig 5.3. Prestressed concrete abutments were placed at each end of each runway and transverse tendons were placed in the joints between the precast slabs. Each tendon was comprised of thirty 0.2-inch hard-drawn steel wires wrapped in bitumen-coated paper. The wires had a yield stress of 200,000 psi. The transverse joints between the precast slabs on one side of a diagonal roller-joint were initially offset one inch from the corresponding joints on the other side in order to cause movement of the triangles when the transverse cables were stretched. Overall longitudinal movement, i.e., elongation of the runway, was prevented by the abutments so that the effect of stretching the tendons tended to produce movement in the direction of the width of the runway. This transverse movement was opposed by the reactions of the adjoining slabs. As

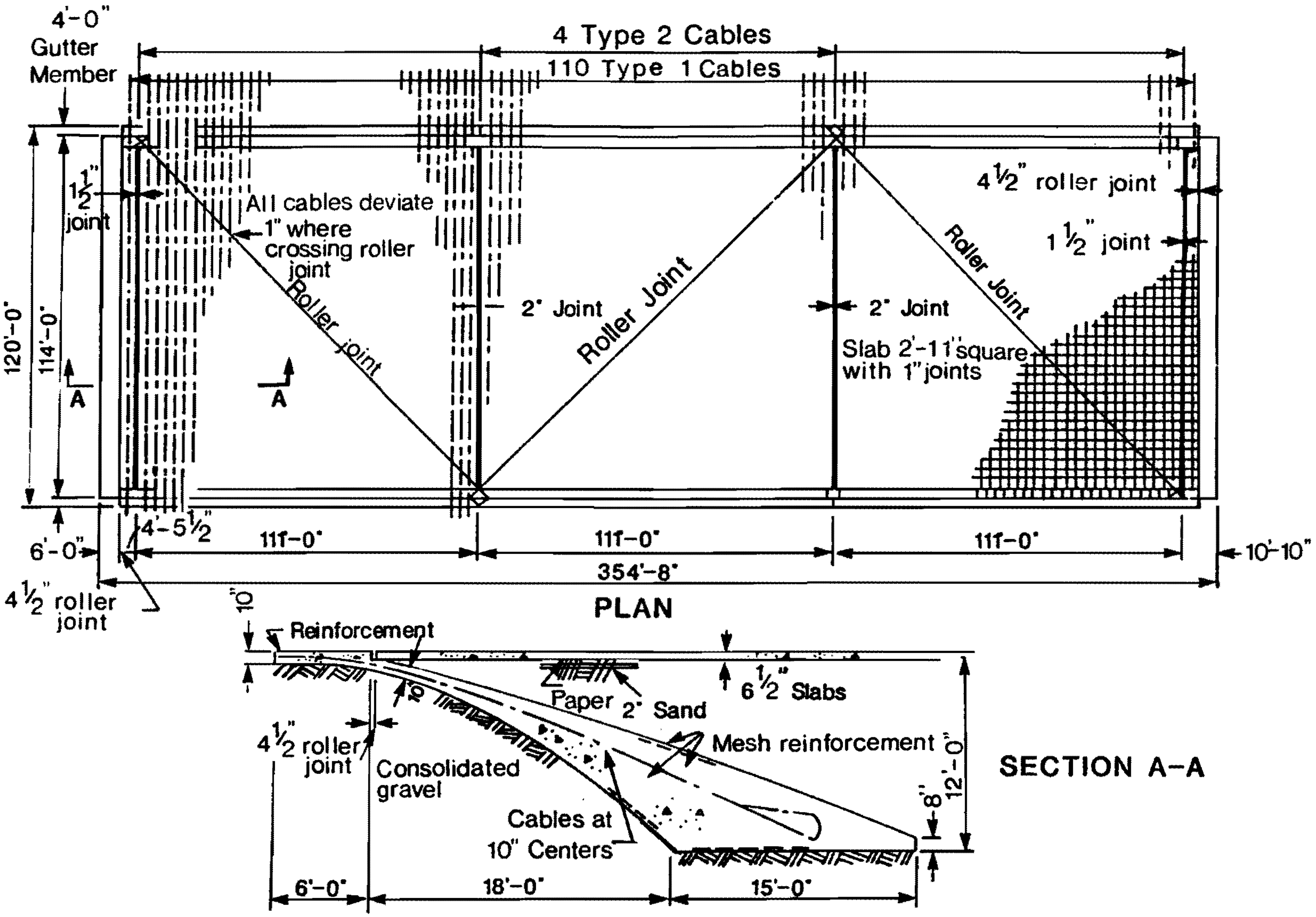


Fig 5.3. Layout of slabs at Orly Runway, France (Ref 56).

a result, a balancing stress was developed in the direction of the longitudinal axis of the runway. The transverse stress was reported to be about 550 psi but the longitudinal stress transmitted to the abutments was less due to friction between the slabs and the ground.

(b) Belgium. Another project in which precast concrete slabs were used was an experimental taxiway at Melsbroek Airport in Belgium, constructed in 1958 (Ref 131). The 1150-foot-long and approximately 75-foot-wide taxiway is composed of precast, prestressed concrete slabs as shown in Fig 5.4. These precast slabs were 39 feet long, 4.08 feet wide and 4 inches thick and were manufactured in a prestressing plant by the long-line process. The prefabricated slabs were placed on a one-foot-thick anti-capillary layer of compacted sand with their long side parallel to the longitudinal center line of the taxiway. Prestressing strands were threaded through transverse ducts in the prefabricated slabs after the joints between adjacent slabs had been filled with mortar. Tensioning these transverse tendons bound the slabs together. After tensioning, the tendons were grouted in place. The prestress level in the pavement was 470 psi in the transverse direction and varied from 620 psi at the midlength to from 810 to 935 psi at the ends in the longitudinal direction.

The transverse joints in adjacent longitudinal rows of precast slabs are staggered. As a result, relative longitudinal movement of any two contiguous slabs in the same longitudinal row is prevented by the slabs in the adjacent rows and by the friction between the rows. This friction is magnified by the normal force on the longitudinal joints resulting from transverse prestressing. Therefore, the transverse joints between contiguous slabs are merely construction joints and not permanent joints, regardless of the pavement length. The prefabricated slabs act together as a monolithic pavement even though longitudinal prestressing is not used to tie them together.

As shown in Fig 5.4, the shape of each prefabricated slab in plan view is a parallelogram. This was done because it was felt that if the slabs were made rectangular, there would not be any prestress across the transverse joints and, consequently, they would not be able to transmit much shear from one slab to the next in the same row. It was believed that if the transverse

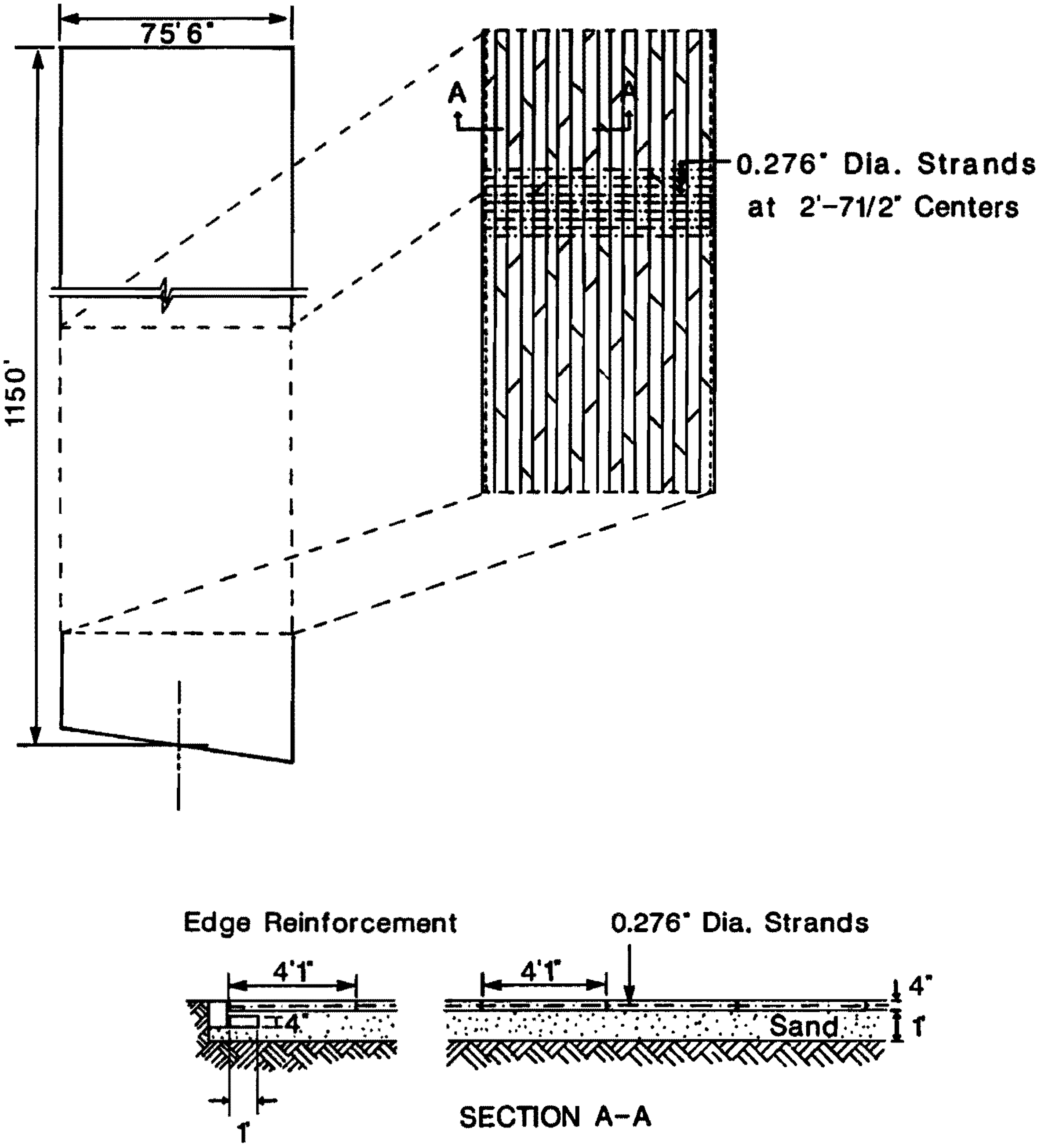


Fig 5.4. Experimental taxiway at Melsbroek Airport, Belgium (Ref 131).

joints slant with respect to the longitudinal joints, the transverse prestressing tendons would press the edges of two contiguous slabs in the same row against the mortar packing, thus preventing differential deflections. Unfortunately, the transverse prestressing did not produce compression in the slanted transverse joints and they had the undesirable effect of locally disturbing the otherwise linear flow of transverse prestress from one edge of the taxiway to the other. However, loading tests indicated that there was no differential deflection between the two sides of these slanted transverse joints even though there was no compression across them.

The pavement was designed for a 45-ton load applied on a 29.5-inch diameter disk located anywhere on the pavement. Test loads of up to 50 tons on the same size disk were successively applied to the pavement in four different locations. Longitudinal and transverse deflection curves were plotted based on the results of the testing. The deflection curves revealed no local weaknesses or discontinuities that might be due to the existence of either the longitudinal or the transverse joints. None of the loading tests caused any visible cracking of the pavement.

(c) United States. The most recent research on the use of precast concrete slabs for pavement construction was conducted in the United States at South Dakota State University (Refs 57, 58). This research was sponsored by the South Dakota Department of Highways in cooperation with the Department of Transportation, Bureau of Public Roads, and was directed toward the development of a more effective means of utilizing the strength of prestressed concrete for highway construction. The pavement that evolved from this research program consisted of precast, prestressed concrete panels which were laid in place on a sand-bedding course. Vertical shearing forces were designed to be transferred to adjacent panels through a grout key. The design included steel connectors to further strengthen the panel joint and prevent lateral movement or separation. The panels were covered with asphaltic concrete which was provided to give a flexible weather-resistant surface course. The advantages of this pavement system were seen to be: (a) prevention of the loss of significant amounts of prestressing force due to subgrade friction; (b) elimination of tensile stresses that develop in concrete slabs during hardening and curing, which result in shrinkage cracks; (c) advantage is taken of quality control inherent in the use of an efficient prestressing plant operation; and (d) construction operations can be kept functioning when confronted with adverse weather conditions.

Two field test sections of this pavement were sponsored by the South Dakota Department of Highways in order to study construction methods, costs, and field performance. The test sections consisted of a 96-foot-long driveway section for the pilot test and a 1000-foot-long section of mainline highway.

The pilot test section was constructed on the driveway of the South Dakota Highway Maintenance Building east of Brookings, South Dakota during September, 1966. In the project, 6-foot-wide, 24-foot-long and 4.5-inch-thick precast panels were used (see Fig 5.5). This size was selected for the following reasons: (a) it was considered the minimum thickness that would provide adequate cover for the prestressing tendons; (b) it provided the necessary rigidity to withstand handling stresses; (c) it utilized the load-carrying capacity of a four-ton crane; and (d) panels of this size could be placed in either a longitudinal or a transverse pattern for the construction of a paved surface 24-feet-wide. The panels were prestressed longitudinally to a level of 350 psi and were reinforced transversely. A longitudinal panel arrangement as shown in Fig 5.6 was used for the following reasons: (a) it was felt that the use of the longitudinal pattern simplified the construction of a pavement with a cross-slope or crown symmetrical about the center line; (b) it was also felt that alternating the transverse panel joints between the outside and inside wheel path offered definite promise of superior riding characteristics as well as an improvement in the structural performance of the pavement. After the panels had been placed on the sand-bedding course, they were seated by applying a limited number of wheel loads. The panels were then interconnected by inserting a wedge through a tongue-and-fork connection, followed by filling grout keys with a high-strength grout (see Fig 5.7).

The primary observation made as a result of the pilot test was the need to simplify the tongue-and-fork connection. The limited tolerance in the

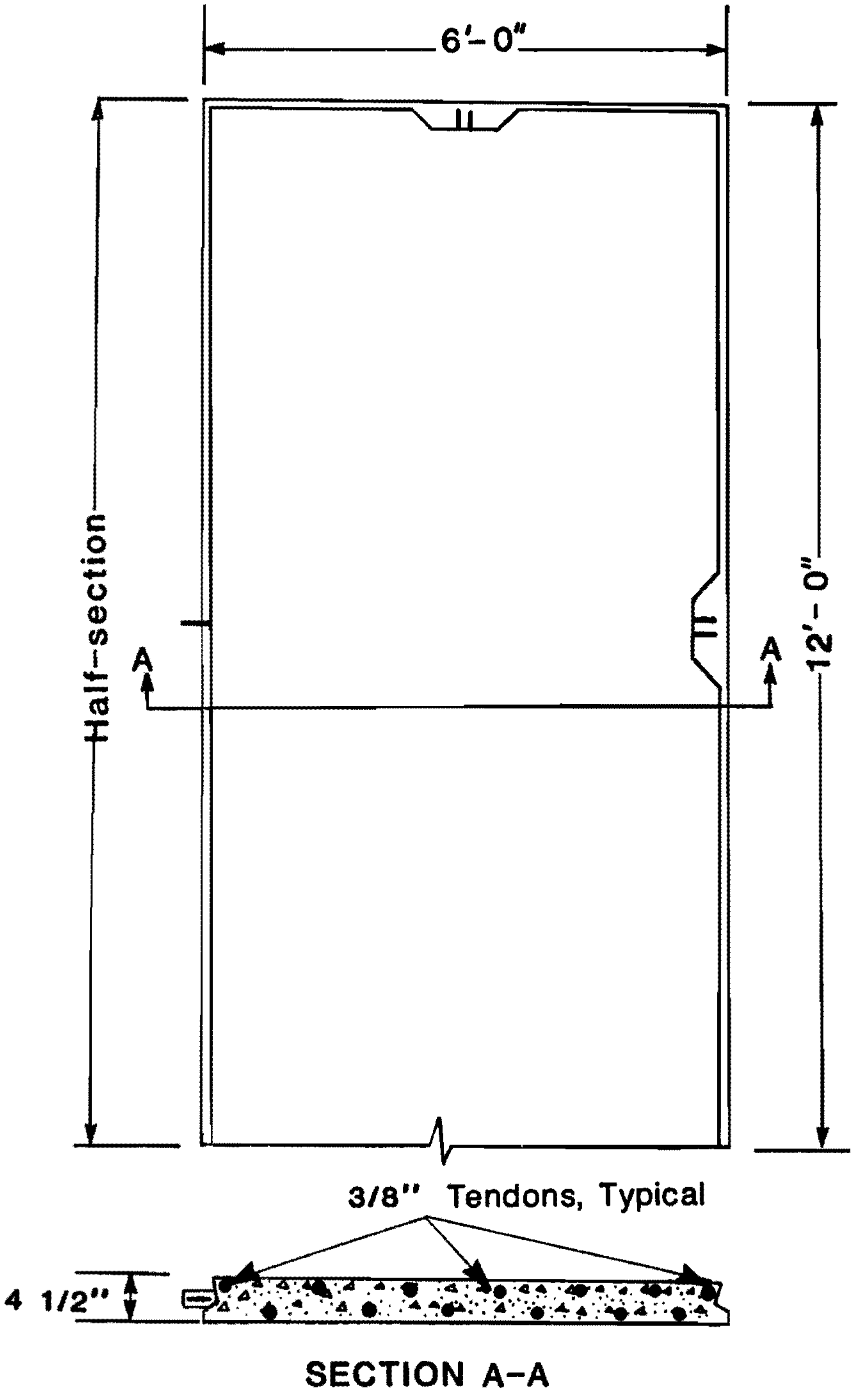


Fig 5.5. Precast panels (Ref 57).

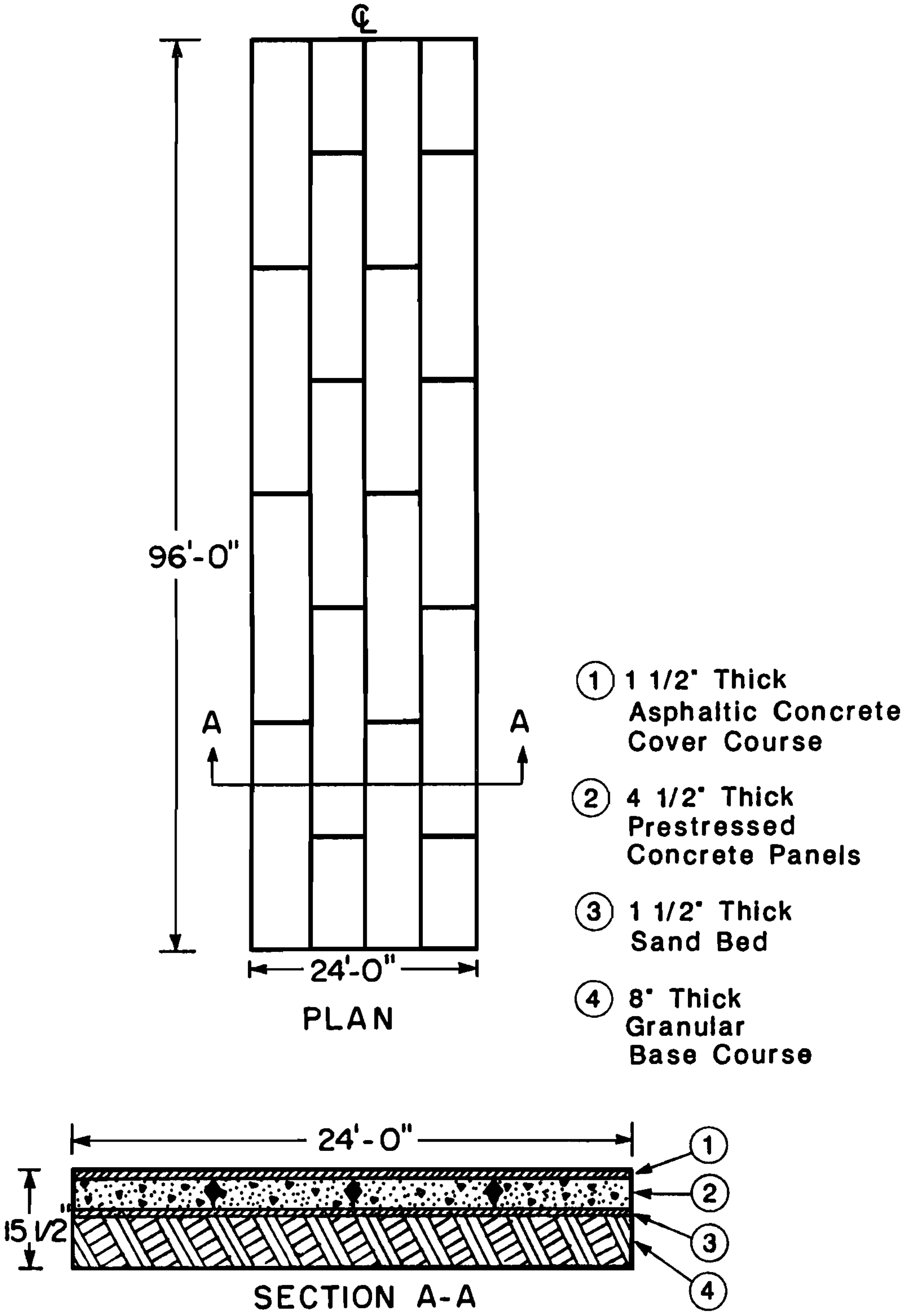


Fig 5.6. Panel arrangement and composite pavement construction (Ref 57).

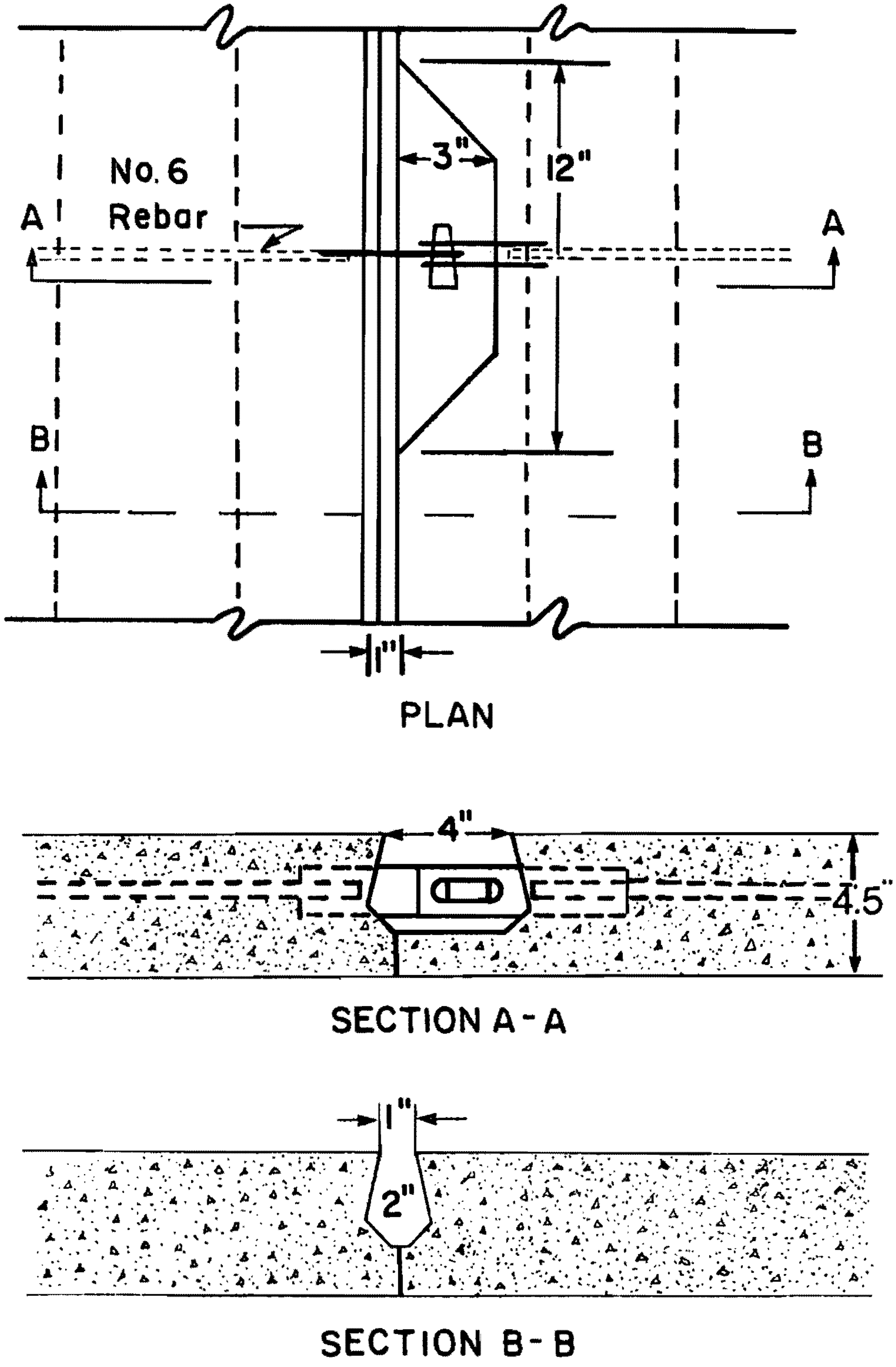


Fig 5.7. Details for tongue-and-fork connection and grout key (Ref 57).

vertical alignment of the slots in the tongue-and-fork connections made it difficult to insert the wedges. It was decided that further consideration should be given to the design of the panel connectors in view of the high material cost and placement problems.

The pilot test section was thought to demonstrate favorable structural performance during the observation period. There were no indications of joint failure or changes in the vertical alignment. However, longitudinal reflection cracks corresponding to the panel joints did appear in the asphalt surface approximately one month after the surface was applied. These cracks were attributed to the "hinge action" of the pavement at the panel joints. In addition, cracks developed along the transverse grout keys due to contraction of the panels at lower temperatures.

For further study of the performance of this type of pavement under typical highway conditions, a 1000-foot-long test section was constructed on the U.S. 14 Bypass north of Brookings, South Dakota, during the summer of 1968. The use of both longitudinal and transverse panel arrangements was included in this test section. Some modifications were made to the pilot test section design. They included increasing the level of longitudinal prestress to 400 psi, abandoning the tongue-and-fork connectors and using connectors which consisted of reinforcing bars which were cast in the panels and welded in the field. No information is available on the performance of this mainline highway field test.

PRESENTATION OF CONCEPTS

The PCP concepts will be presented in the following order: (a) Central Stressing of Slip-Formed Pavement; (b) Precast Joint Panels and Slip-Formed Pavement; (c) Precast Joint Panels, Central Stressing Panels, and Slip-Formed Pavement; (d) Composite Prestressed Concrete Pavement Type I (CPCPI); (e) Composite Prestressed Concrete Pavement Type II (CPCPII); (f) Segmentally Precast Prestressed Concrete Pavement (SPPCP); (f) Continuous Composite Concrete Pavement (CCCP); and (g) Others.

The discussion of each concept will be divided into the following sections:

(1) Description. This section will provide a description of the most important features of the concept.

(2) Construction. In this section, a detailed description will be given of the anticipated sequence that would be employed in the construction of a section of PCP utilizing the concept. Each of the described construction sequences begins with the placement of the friction-reducing medium. It should be kept in mind, however, that major construction activities precede this step. These activities include preparation of the subgrade, placement of subbase course, and placement of base course for new PCP construction and preparation of an existing pavement and placement of a leveling course (usually of asphaltic concrete) for PCP overlay construction. These aspects of the construction sequence will not be discussed in this report for two reasons: (a) these construction activities would be essentially the same for all of the various PCP concepts and would not differ appreciably from similar activities for conventional concrete pavements, and (b) a worthwhile discussion of this topic is beyond the scope of this report.

For the purpose of this discussion it will be assumed that two or more passes of the slip-form paver will be required to construct the full pavement width. Although construction of the full pavement width in one pass eliminates the longitudinal construction joint between adjacent pavement sections and the problems associated with it, full-width construction is often not feasible as discussed. PCP construction using multiple passes of the slip-form paver was not dealt with on the previous FHWA sponsored projects. In order for PCP to be a truly viable option, this type of construction must be examined and problems associated with its use identified and solved.

A detailed comparison of the most important characteristics of the various PCP concepts will be presented after all of the concepts have been introduced.

CONCEPT 1: CENTRAL STRESSING OF SLIP-FORMED PAVEMENT

Description

All of the past FHWA sponsored PCP projects consisted of consecutive slip-formed slabs separated by short openings to permit posttensioning of the prestressing tendons from the slab ends. Due to the long slab lengths and correspondingly high strand and subgrade frictions, it was necessary to stress each strand from both ends. After the posttensioning had been applied and the elastic shortening and most of the creep had occurred, the openings were filled with concrete gap slabs. Some of the problems encountered with the use of gap slabs were discussed in Chapter 4.

One of the objectives identified in the early stages of Project 401 was to attempt to find another method of posttensioning the strands which would eliminate gap slabs and the problems associated with their use, but still permit taking advantage of the slip-form method of pavement construction. The most promising alternative was central stressing. Central stressing, as discussed earlier in this chapter, is a procedure in which the strands are stressed at internal blockouts or stressing pockets. The blockouts are filled with concrete after the posttensioning force has been applied.

Another objective identified in the early stages of Project 401 was to investigate alternate methods for transversely prestressing pavement. It was felt that transverse prestressing is important to resist the applied wheel loads, prevent longitudinal pavement cracking, and prevent possible separation of separately placed pavement lanes or longitudinal pavement strips.

A plan view of the proposed pavement developed by the Project 401 staff is shown in Fig 5.8 and an enlarged plan view of a stressing pocket is shown in Fig 5.9. The advantages and disadvantages of using a looped transverse tendon configuration are discussed. This design was accepted by the Texas State Department of Highways and Public Transportation (SDHPT) for construction of two, one-mile demonstration overlay projects on U.S. Interstate Highway 35. The projects will be located in Cooke and

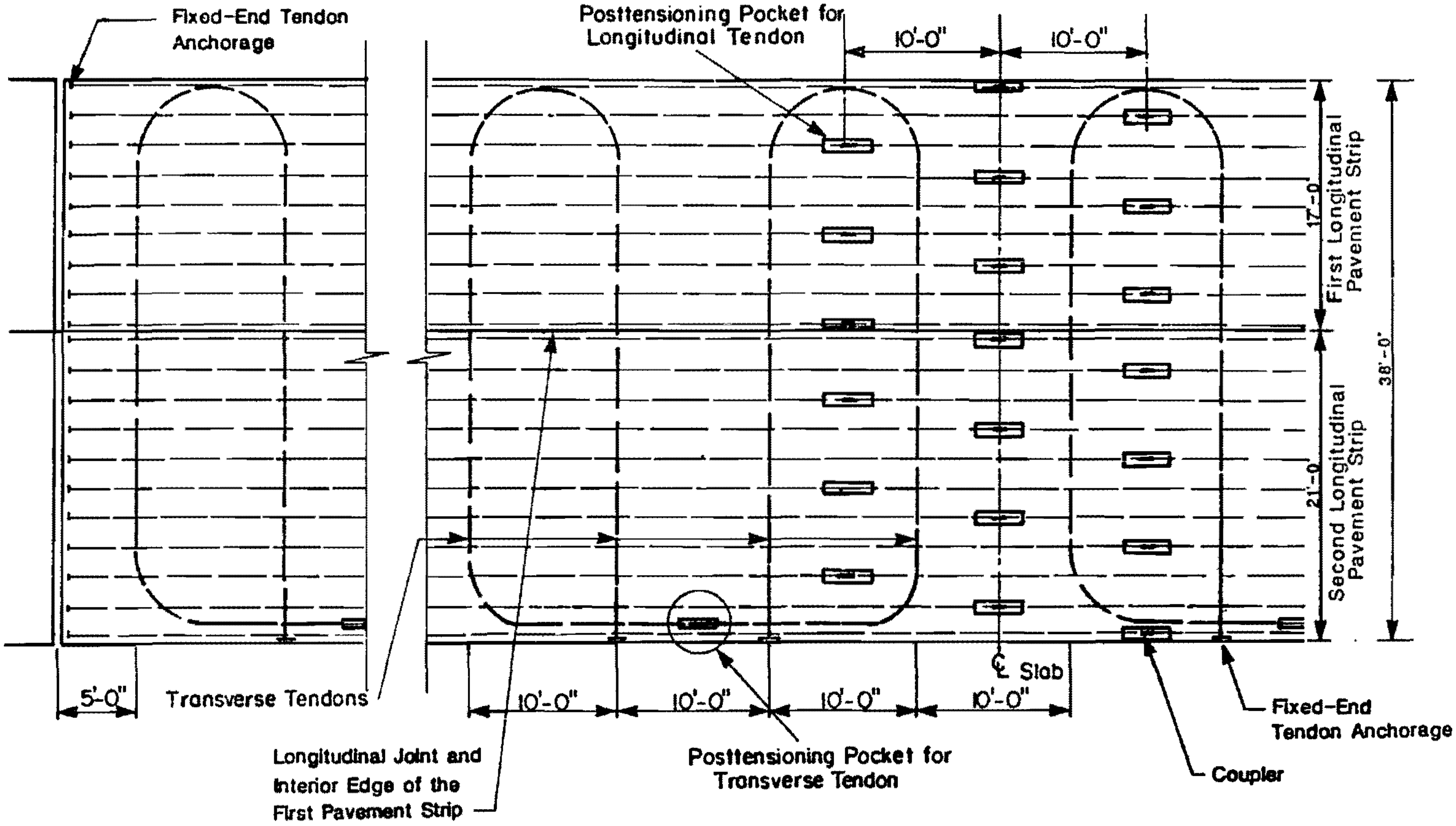


Fig 5.8. Plan view of the proposed pavement developed by the Project 401 staff.

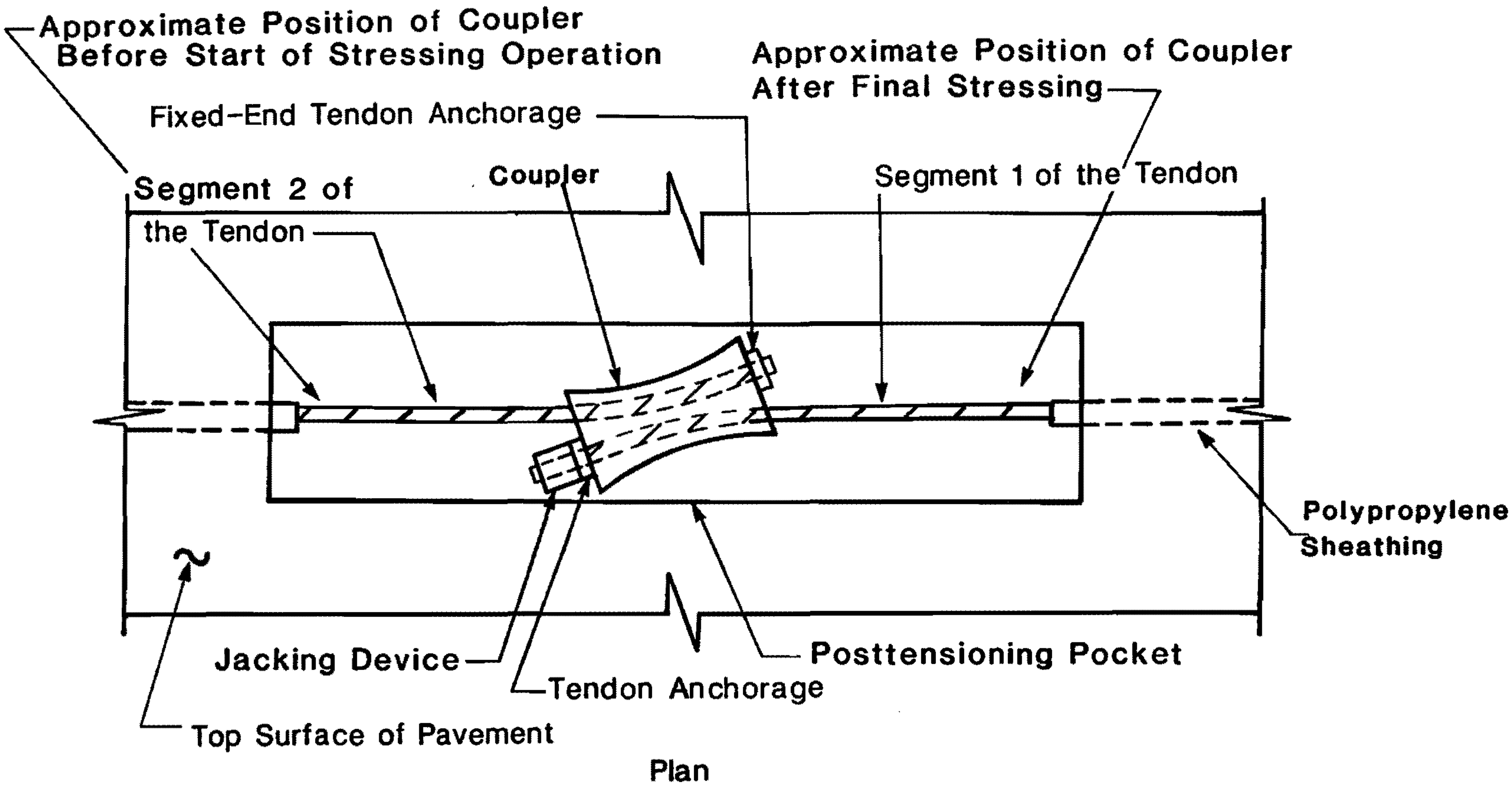


Fig 5.9. Stressing pocket detail.

McLennan Counties. Field testing to obtain additional information related to this approach was conducted near Valley View, Texas by the Project 401 staff (Refs 18, 78, 81).

Construction

Step 1. The first step in the anticipated construction sequence with this pavement concept is placement of the friction-reducing medium for the first longitudinal strip of PCP on: (a) the prepared subgrade for new pavement, or (b) on the leveling course over old pavement in the case of an overlay. Even with the problems encountered on the previous FHWA demonstration projects, a double-layer of polyethylene sheeting is desirable in order to reduce the subgrade drag and thus minimize the number of tendons required to obtain the design prestress level.

The polyethylene should be provided in double-layer rolls so that both layers are placed in a single construction operation. The width of the rolls should preferably be at least one foot wider than the width of the pavement strip under which it is to be placed. This would help insure that the pavement is not placed in direct contact with the base course. If polyethylene sheeting is not available in this width, which was the case on the previous FHWA sponsored projects, narrower width sheeting can be used provided that it is placed in either longitudinal or transverse contiguous strips. In either case, the strips should be lapped and secured together to prevent them from shifting during concrete placement which could cause the concrete to be placed in direct contact with the base course.

As previously mentioned in this report, there is considerable room for innovation in the way of improved techniques or specialized equipment for laying the polyethylene sheeting. Experimentation in this area by the contractor should be encouraged as long as a continuous, unrestrained double-layer of polyethylene is obtained and the quality of the pavement is in no way compromised.

Step 2. After placement, the sheeting should be anchored to the base course with tacked-down sheet metal strips placed along the outside edges to prevent it from being displaced by the wind.

Step 3. Locations of the transverse pavement joints should be determined next. In the case of an overlay, care must be exercised in this step to insure that the transverse pavement joints are not located over joints or cracks in the old pavement. After the locations have been determined, the transverse joint assemblies would be set in place. The transverse joint assembly that was proposed for use with this pavement concept is shown in Fig 5.10. This assembly would be completely fabricated and assembled in the shop including the neoprene seal, dowels, headed studs or deformed bar anchors, and all necessary bolts for attachment of tendon anchorages. Small steel jumper plates would be provided across the top of the joint assembly and tack welded or bolted on each side of the joint opening to keep the joint assembly in a closed configuration. The joint assemblies would be shipped to the job site ready for installation in the pavement and would require no field assembly. After they are set in place, the assemblies must be temporarily secured to the subgrade to prevent them from being inadvertently displaced and so they will be able to withstand the imposed loads caused by placing a small tensile force on the longitudinal tendons to keep them straight during slip-forming of the pavement.

Step 4. Strand chairs should then be placed. Continuous chairs with bottom plates, as shown in Fig 5.11, would be the most logical type of chair to use for this construction. These chairs would be easier to handle and place than individual chairs and the bottom plates would help prevent damage of the polyethylene friction-reducing material. These chairs would be placed across the pavement at a predetermined interval. The interval would be dependent on the amount of tension that could be applied to the longitudinal tendons before the pavement is placed. Of course, the higher the tension, the greater the interval could be between chairs.

Step 5. The next step in the construction of the first PCP strip is laying out the longitudinal tendons. Before they are shipped to the construction site, the longitudinal tendons should be prepared as follows in order to prevent confusion in the field and permit smooth construction operations:

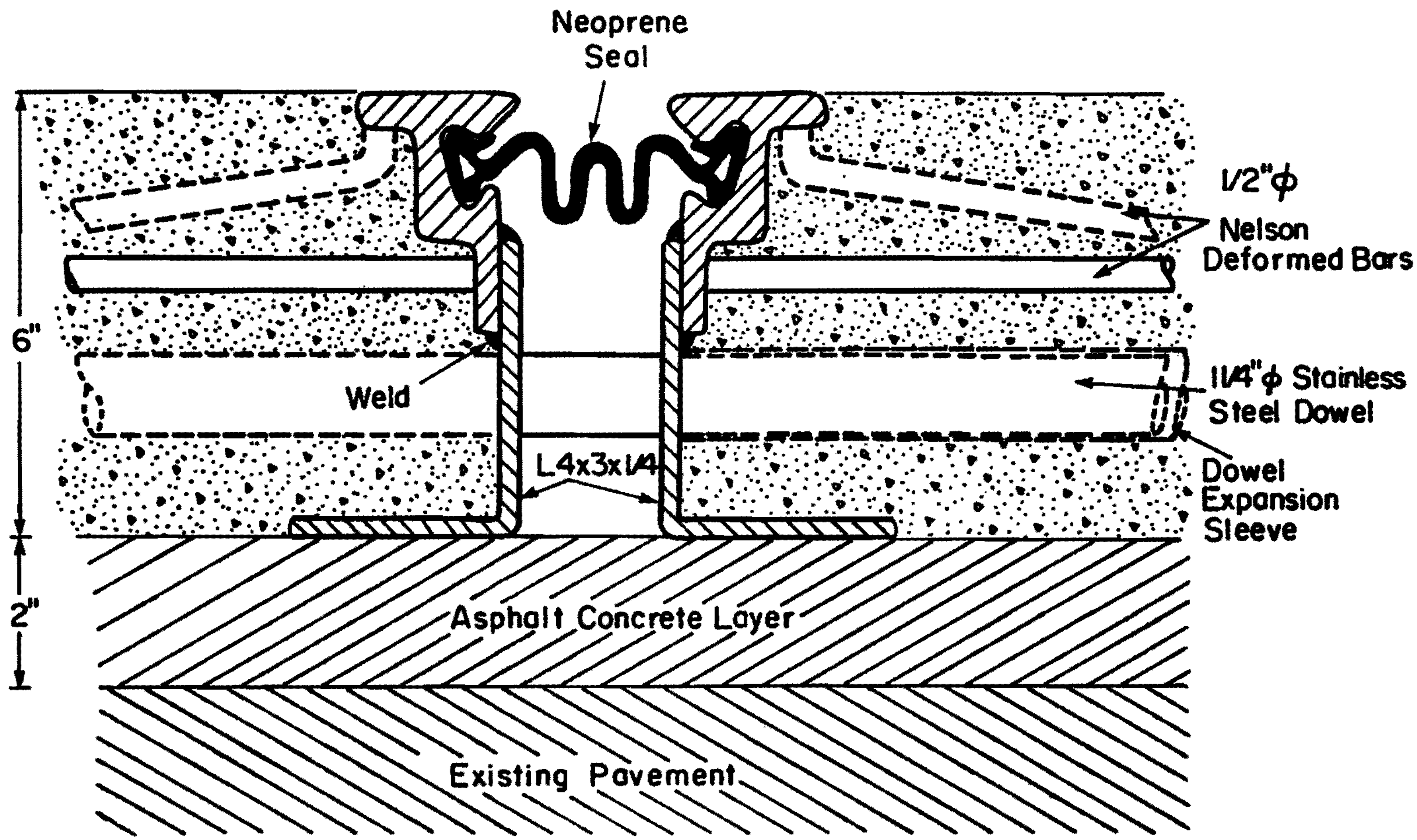


Fig 5.10. Transverse joint assembly (Ref 95).

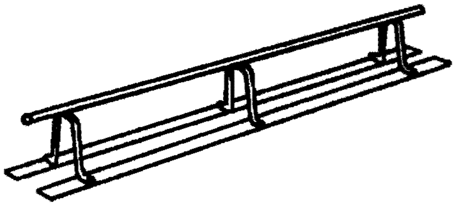


Fig 5.11. Continuous high chair with plate.

(a) They should be cut to the proper lengths. As shown in Fig 5.8 the tendon stressing pockets are staggered. This requires that the tendons be provided in several different lengths. Cutting the tendons to these required lengths is much more efficiently and accurately done in the shop.

(b) Tendon anchorage hardware should be correctly installed in the shop. As discussed in Chapter 4, on some of the previous projects the anchorages were mounted on the tendons in the field. In some cases, they were incorrectly installed and, as a result, they failed to hold. Recovery of the strand ends was often difficult and sometimes impossible.

(c) The polypropylene sheathing should be removed from the end of every tendon which is to be inserted through a coupler. This is a seemingly small task but it is tedious, time consuming, and doesn't belong in the field where it might hold up production.

The most efficient method of longitudinal tendon placement would probably be to have the ends of the two segments of tendon which comprise one complete longitudinal tendon rolled onto a common reel, where the ends of the two tendon segments which are to be inserted through a coupler would be lapped and temporarily wired together. Each reel would be identified with a tag, corresponding to shop drawings, which clearly indicates the tendon's proper location in the pavement slab. This is necessary in order to obtain the desired stagger of the tendon stressing pockets. The anchorage on the leading end of the tendon would then be bolted to the previously placed transverse joint assembly and the reels unwound. As with many other aspects of PCP construction, there is room for innovation in the handling of the tendon reels. On the Hogestown, Pennsylvania project, strand reels were carried on a modified flatbed truck from which they were unwound onto the pavement base course (Ref 13). Other types of special reel handling trailers could easily be developed. At the end of the pavement strip, the ends of each tendon would be bolted to the other transverse joint assembly. The locations of the staggered tendon stressing pockets would then be automatically located.

Step 6. Half forms (or "false" forms as they are sometimes called) are placed along the interior longitudinal edge of the first pavement strip to form the edge of the slab below the level of the transverse tendons and to support the protruding ends of the transverse tendons.

Step 7. The next step in the construction sequence is to lay out and place the looped transverse tendons. These tendons may be laid out in the required looped configuration either at their location in the pavement or in the contractor's yard, transported to the construction site, and set in place. In either case a jig could be used to facilitate layout. In addition, it will probably be necessary to provide light-gauge wire ties in order to maintain the looped tendons in the desired shapes. During placement of the first pavement strip, the portions of each transverse tendon extending outside this strip must be either temporarily coiled or otherwise restricted to a narrow band along the edge of this strip to prevent the protruding transverse tendons from interferring with the passage of the slip-form paver.

Another option would be to provide hollow conduits in the first pavement strip along the desired paths of the transverse tendons. These conduits would terminate at the interior longitudinal pavement edge so nothing would protrude from the first pavement strip to interfere with paving operations. The ends of the conduits would be temporarily capped to prevent intrusion of concrete or other foreign matter such as water or dirt. Before placement of the second pavement strip, the transverse tendons would be threaded through these conduits.

The previously described steps of placing the polyethylene sheeting, locating and setting the transverse joint assemblies, placement of the longitudinal tendons, setting of the half forms along the interior longitudinal edge of the first pavement strip, and placement of the tranverse tendons could be integrated. Two advantages would be gained if this were done. First, the whole construction process would be made more systematic. Second, placement of the tendons on the polyethylene immediately after it is put down will help hold it in place and make it less vulnerable to the wind. This type of construction would favor the use of transverse tendons or hollow conduits laid out in the contractor's yard, transported to the construction site, and set in place.

Step 8. The next step in the construction sequence would be to place the forms for the stressing pockets over the longitudinal tendons where the two segments had been lapped and wired together. The forms should have the following features:

(a) Slots should be provided to permit placement over the longitudinal tendons. Provision should be made for closing the slot below the tendons after the form is in place to prevent intrusion of concrete.

(b) They should have covers which can be closed and secured in place so that no concrete enters the forms during slip-form paving.

(c) They should be slightly shallower in depth than the pavement thickness to prevent them from being disturbed during passage of the slip-form paver.

(d) The forms should be tapered slightly inward toward the bottom. In addition, their exterior surfaces should be oiled. Both of these measures will allow the forms to be removed more easily.

(e) They should be of sturdy, reusable, possibly metal construction.

(f) They should have some provision which would allow them to be temporarily secured to the asphaltic concrete leveling course. This temporary attachment will facilitate aligning the forms and will also prevent them from floating up or otherwise displacing during concrete placement.

Step 9. Next, sufficient tension should be applied to the longitudinal tendons to keep them in straight alignment during concrete placement. The magnitude of the required tension was discussed. This tension might be applied by means of a system of steel springs in the slab blockout forms.

Step 10. After the tensile stress necessary to keep the longitudinal tendons in straight alignment has been applied, the longitudinal and transverse tendons should be tied together at their points of intersection. This will help stabilize the tendon mat and keep the tendons from being displaced during slip-forming of the pavement. Care should be exercised when tying the tendons together to prevent cutting through the polypropylene tendon sheathing as was done on some of the previous FHWA sponsored projects. To help protect against damage to the sheathing, the use of plastic strip ties or nylon reinforced tape in lieu of metal wire ties should be investigated.

Step 11. Concrete placement using a standard slip-form paver may commence after a sufficient number of pavement sections have been prepared (according to the steps described above) so that progress of the slip-form paver is not impeded. Special care must be exercised in placing, vibrating, and finishing the concrete in the vicinity of the transverse pavement joint assemblies and forms for the tendon stressing pockets

Step 12. When the concrete has achieved sufficient compressive strength (approximately 1000 psi), the following items must be removed: stressing pocket forms, anchors used to temporarily secure the transverse joint assemblies to the asphaltic concrete leveling course, steel jumper plates which were provided across the transverse joint assembly opening to keep it in a closed configuration, and the half forms on the interior longitudinal edge of the pavement. The longitudinal tendons would then be sufficiently stressed (in the formed pockets) to prevent shrinkage cracking of the concrete. After the concrete has gained sufficient additional strength, final tensioning of the longitudinal tendons would be done. This would be followed by coating the pocket faces with epoxy bonder and then filling the stressing pockets with concrete. High-early-strength concrete could be used for filling the pockets if it would help to expedite opening the pavement to traffic.

Step 13. Placement of the second pavement strip probably wouldn't occur until after completion of the entire length of the first pavement strip. Depending on the total project length, the intervening length of time between the construction of the two pavements strips could range from several weeks to several months. At the very least, construction of the second pavement strip must wait until traffic can be permitted on the first pavement strip.

Placement of the second pavement strip would proceed in a manner similar to the first with a few exceptions. The polyethylene friction-reducing medium, the transverse joint assemblies, the tendon support chairs, and the longitudinal tendons would be placed as described above.

Step 14. Next, the coiled portions of the transverse tendons which protrude from the first slab strip would be unrolled and made to conform to the configuration shown in the second pavement strip in Fig 5.8. If hollow conduits were provided in the first pavement strip instead of the transverse tendons, then the tendons would be threaded through the conduits.

Step 15. Light tension would be applied to the longitudinal tendons and the longitudinal and transverse tendons would then be tied together as in the first pavement strip.

Step 16. Tendon stressing pocket forms would then be placed over both the longitudinal and transverse tendons at the locations of the tendon laps.

Step 17. Either a strip of polyethylene sheeting or a spray-applied bond breaking compound would then be placed on the interior longitudinal edge of the first pavement strip. This will prevent the second pavement strip from bonding to the first strip and will allow relative movement between the two during longitudinal stressing of the second strip. No half forms would be required on the interior longitudinal edge of the second pavement strip.

Step 18. Next, the concrete of the second pavement strip would be slip-formed in place. After the longitudinal tendons of the second pavement strip have been fully stressed (in two stages as described above), the transverse tendons would be stressed.

Step 19. Construction of the second pavement strip would be completed by filling the tendon stressing pockets with concrete.

CONCEPT 2: PRECAST JOINT PANELS AND SLIP-FORMED PAVEMENT

Description

As implied by its name, precast concrete joint panels are utilized with this PCP concept. The remainder of the pavement would be slip-formed similar to conventional rigid pavement. This concept is illustrated in Figs 5.12, 5.13, 5.14, and 5.15.

The panels would most likely be cast off the job site in a precast plant. However, the contractor could cast the panels in his construction yard near the job site. Whether or not to allow the panels to be cast in the contractor's construction yard would be a decision which must be made by the organization responsible for the design of the pavement system. The decision should be based on whether the contractor could demonstrate that he could maintain an adequate panel production schedule so that the entire pavement construction would not be delayed and also that acceptable quality control could be maintained. In either case, the panels would then be transported to the construction site and set in place.

The precast panels would be provided in pairs, one on each side of every transverse joint. The same type of transverse joint assembly as illustrated in Fig 5.10 would also be used with this PCP concept. Each pair of joint panels would contain an entire transverse joint assembly, including the steel extrusion into which the neoprene seal is inserted, associated headed studs or deformed bar anchors, base angle (if required) to support the steel extrusion, dowels, and dowel expansion sleeves.

Two additional items would be contained in each panel. The first item would be the pockets for stressing the longitudinal pavement tendons and the second item would be a single rigid transverse duct which would be used for posttensioning the precast joint panels together in the first and second pavement strips.

Each individual panel would be prestressed on the casting bed in the precast plant. The level of prestress provided would be sufficient to prevent the panel from cracking due to either lifting and handling of the panel prior to placement in the pavement, or traffic loads after the panel is in its final position in the pavement.

Construction

The construction of this PCP concept would begin with precasting of the joint panels off the job site. Efficient long-line production techniques

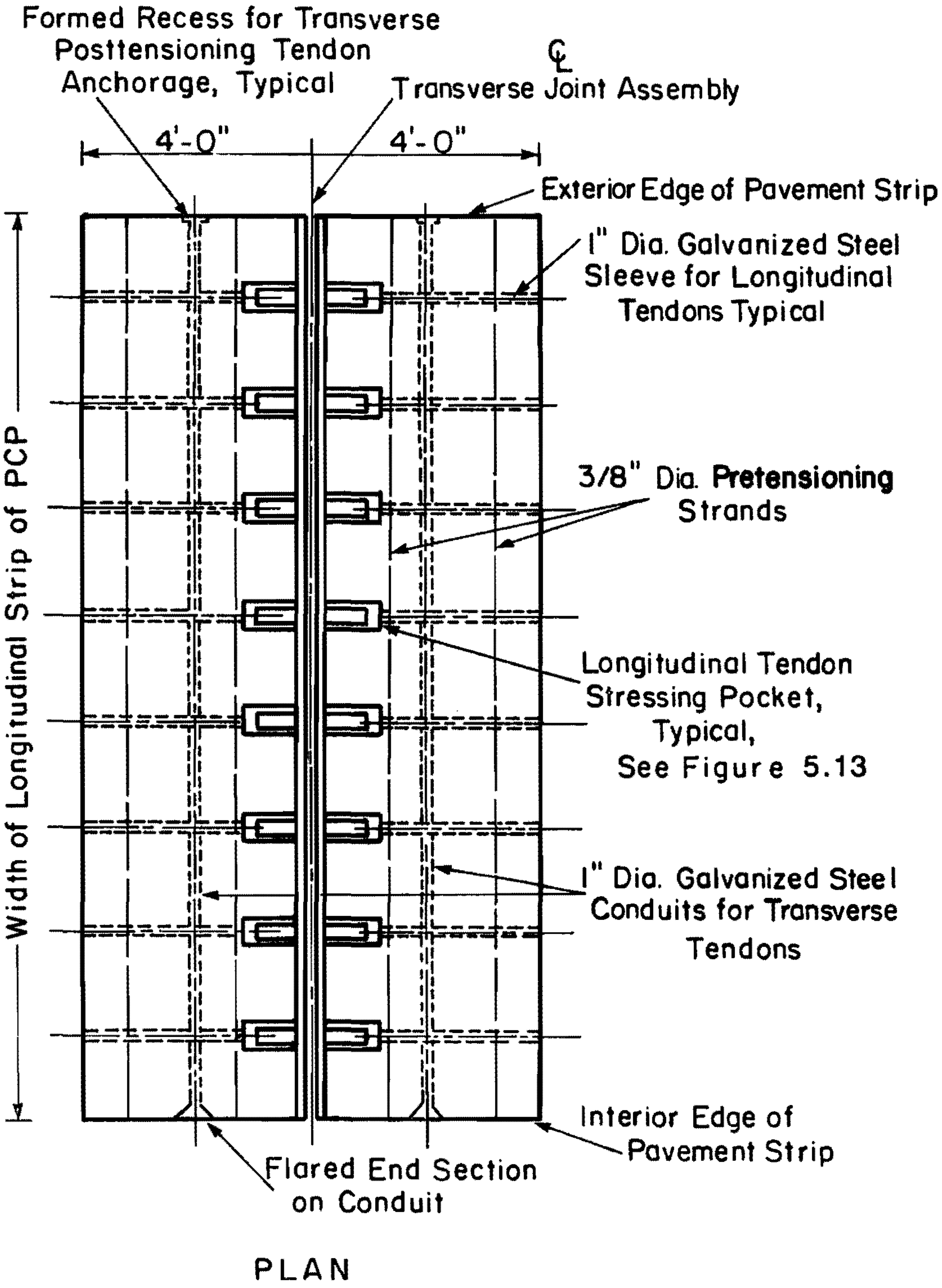


Fig 5.12. Precast joint panels.

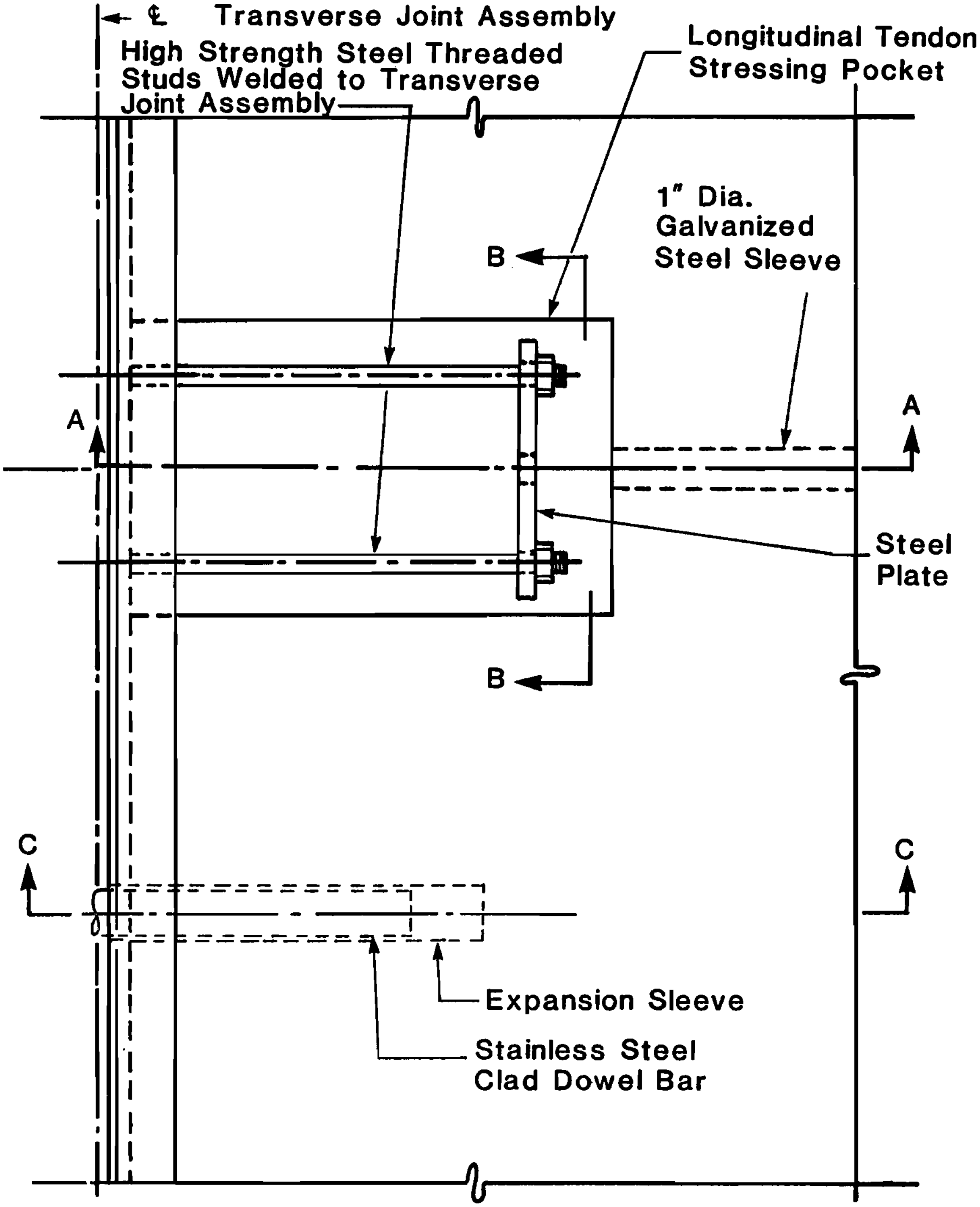


Fig 5.13. Plan view of a tendon stressing pocket.

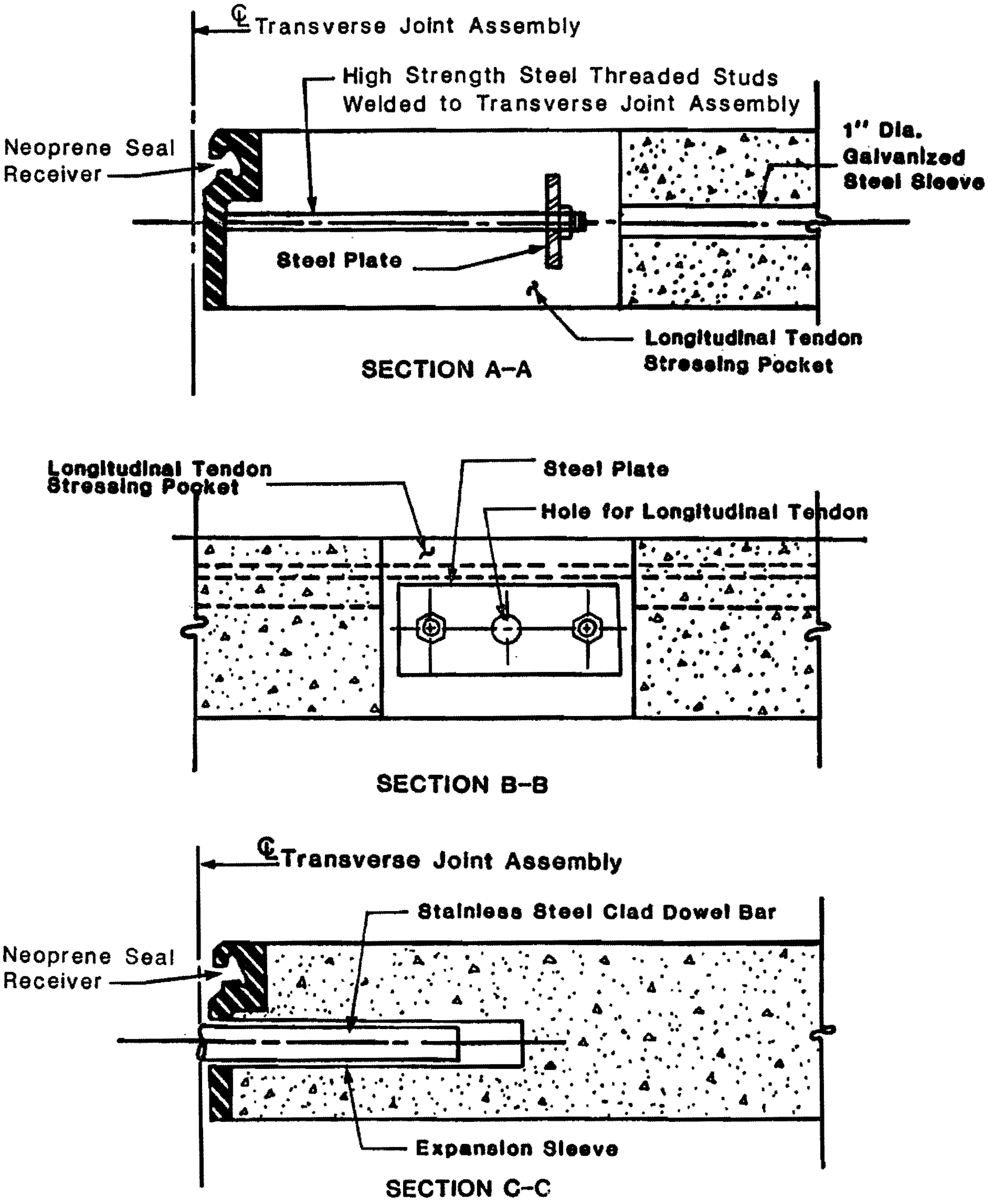


Fig 5.14. Tendon stressing pocket sections.

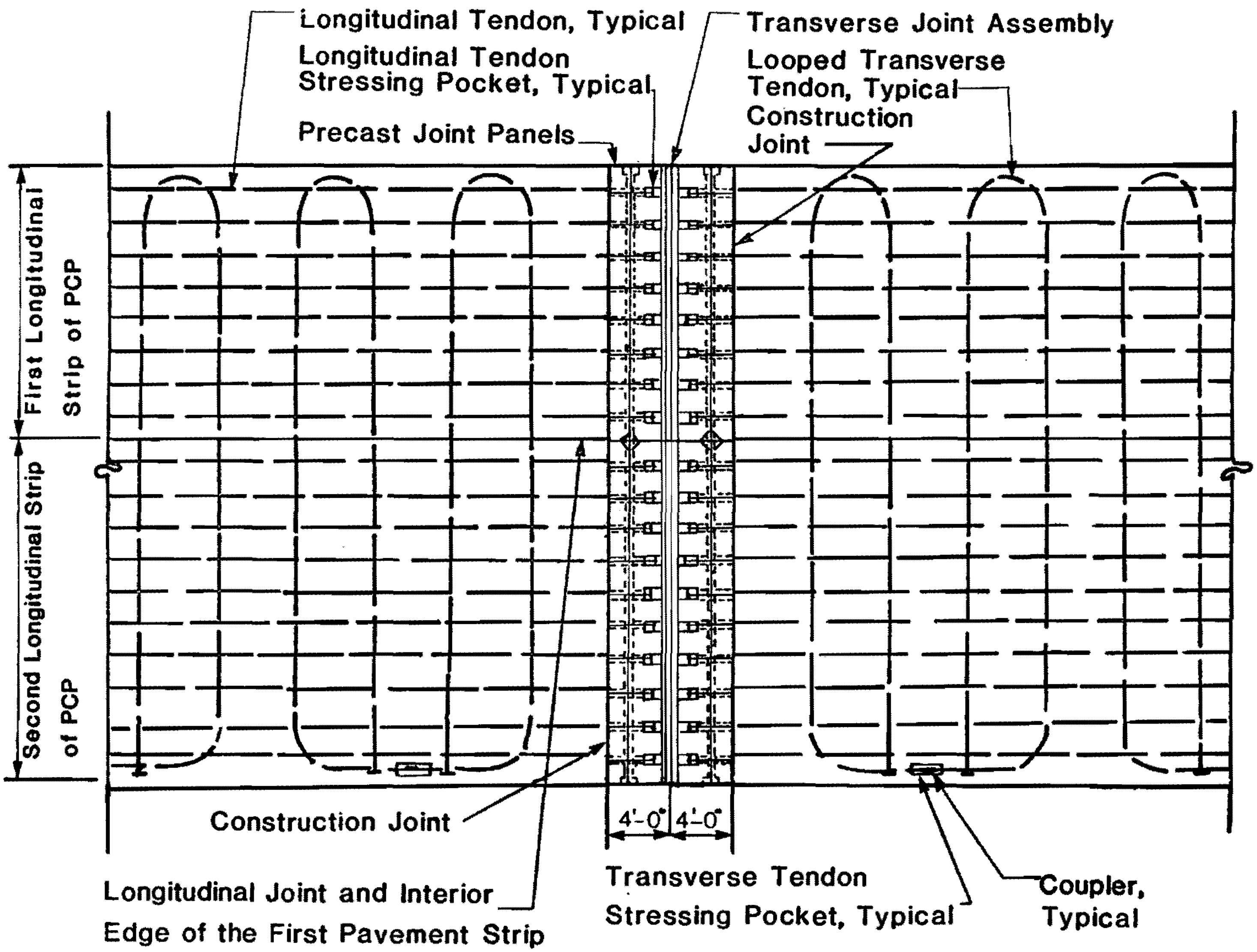


Fig 5.15. Precast joint panels and slip-formed pavement.

would be used which employ casting bed lengths of up to 600 feet where the individual panels are cast end to end. The transverse joint assemblies for each pair of panels would probably be oriented parallel to the length of the casting bed. This would allow all the panels on the casting bed to be prestressed parallel to the transverse joint assemblies in a single tensioning operation. Another reason for orienting the panels in this manner on the casting beds is that few casting beds are wide enough to accommodate the panels with the transverse joint assembly oriented perpendicular to the length of the casting bed.

The panels would not be prestressed in the direction perpendicular to the transverse joint assemblies until after they are placed in the pavement. The joint panels would be kept in matched pairs in order to assure proper alignment of the dowels and dowel expansion sleeves across each transverse joint.

Step 1. As with PCP Concept 1, the first step in the anticipated field construction sequence with this pavement concept is placement of the friction-reducing medium for the first longitudinal strip of PCP on the prepared subgrade for new pavement or on the leveling course over old pavement in the case of an overlay. Again, a double-layer of polyethylene sheeting would probably be used. The methods of placing the sheeting and anchoring it to the base course which were described would be applicable in this case as well.

Step 2. The next step in the construction sequence of this PCP concept is to determine the locations of the transverse pavement joints. In the case of an overlay, care must be exercised to insure that the transverse pavement joints are not located over joints in the old pavement.

Step 3. After the locations have been determined, the precast joint panels are set in place. As stated above, the panels would be cast in pairs with the transverse joint assembly in place. Small steel jumper plates would be provided across the top of the joint assembly to keep the joint assembly in a closed configuration. The joint panels would then be transported to the construction site in matched pairs. Strongbacks would be used for lifting and handling the pairs of panels to prevent any distortion. By handling the panels in pairs, the possibility of inadvertently mixing the matched panels would be eliminated, protruding dowel bars which could be easily damaged during handling of the panel would be avoided, and the awkward reassembly of the joint panels in the field would be eliminated.

Step 4. The next step in the construction sequence is to place the chairs for the longitudinal strands in the slip-formed portion of the pavement. Continuous chairs with bottom plates, as shown in Fig 5.11, would be used. These chairs would be placed across the pavement at a predetermined interval. As before, the interval between chairs would be dependent on the amount of tension that could be applied to the longitudinal tendons before the pavement is placed. This interval could be increased in proportion to the increase in tension in the tendons.

Step 5. Placement of the longitudinal tendons would be the next step in the construction sequence. Before the tendons are shipped to the construction site, they should be prepared as follows:

(a) They should be cut to the proper length. This operation is much more efficiently and accurately done in the shop. Each longitudinal tendon would have to be long enough to extend from the stressing pocket in the joint panel at the start of the pavement section to the stressing pocket in the joint panel at the end of the pavement section.

(b) The polypropylene sheathing should be removed from the ends of each tendon to allow for installation of the anchorages in the field. As with PCP Concept 1, this is a seemingly small task but it is tedious, time consuming, and doesn't belong in the field where it might hold up production.

For each segment of pavement, longitudinal tendon placement begins by inserting the starting ends of the tendons through sleeves into stressing pockets in the precast concrete joint panels at the beginning end of the pavement segment. Stressing anchorages would then be installed on the ends of the tendons in the pockets. All of the longitudinal tendons for the pavement segment would then be simultaneously unrolled. At the end of the pavement segment, the terminal ends of the longitudinal tendons would be inserted through sleeves into the stressing pockets of the joint panel. Stressing anchorages would then be installed on each tendon in the pockets.

Steps 6 through 9 in the construction of the first strip of pavement with this PCP concept are similar to those of the previously discussed concept with some minor variations. These steps and the manner in which they differ (if at all) from those of PCP Concept 1 are as follows:

Step 6. Half forms would be placed along the interior edge of the first pavement strip. Half forms are not needed, however, along the edges of the precast joint panels.

Step 7. Place the looped transverse tendons (or hollow conduits). The first of these looped tendons in each pavement segment would be placed farther from the transverse pavement joints with this PCP concept than with Concept 1 due to the presence of the precast joint panels.

Step 8. Apply sufficient tension to keep the longitudinal tendons in straight alignment during concrete placement. This tension would be applied with a standard stressing jack in the stressing pockets located in the precast joint panels.

Step 9. The longitudinal and transverse tendons would then be tied together at their points of intersection.

All of the previously described construction steps, including placing the polyethylene sheeting, locating and setting the precast concrete joint panels, placement of the longitudinal tendons, setting the half forms along the interior longitudinal edge of the first pavement strip, and placement of the transverse tendons could be integrated. Integration of these construction steps would provide the same advantages as described for the previous PCP concept.

Step 10. After a sufficient number of pavement segments have been prepared (in accordance with the above steps) so that progress of the slip-form paver would not be impeded, concrete placement would begin. Special care must be exercised in the placement, vibrating, and finishing of the concrete at the location where the slip-formed pavement meets the precast concrete joint panels.

Step 11. When the concrete has achieved sufficient compressive strength (approximately 500 psi (Ref 44)), "nail-down pins" which are used to temporarily secure the precast concrete joint panels to the asphaltic concrete leveling course, steel jumper plates which were provided across the transverse joint assembly opening to temporarily keep it in a closed configuration, and half forms on the interior edge of the pavement would all be removed. The longitudinal tendons would then be sufficiently stressed (in the pockets provided in the precast joint panels) to prevent shrinkage cracking of the concrete.

Step 12. After the concrete has gained sufficient additional strength, final stressing of the longitudinal tendons would be done. Due to the long slab lengths and correspondingly high tendon and subgrade frictions, it would be necessary to stress each longitudinal tendon from both ends for both the initial and final stressing. This would be followed by filling the stressing pockets in the precast joint panels with concrete.

Step 13. Placement of the second pavement strip would proceed in a manner similar to the first with a few exceptions. Placement of the polyethylene friction-reducing medium, the precast concrete joint panels, and the longitudinal tendons would be as described above.

After the precast joint panels for the second pavement strip are in place, straight tendons would be threaded through the rigid transverse ducts in the joint panels of the first and second pavement strips. These tendons would not be stressed at this time. This would be followed by uncoiling the portions of the transverse tendons which protrude from the first slab strip and placing them in the proper positions in the second pavement strip. If hollow conduits were provided in the first pavement strip, instead of the transverse tendons, the tendons would be threaded through these conduits.

Step 14. Light tension would be applied to the longitudinal tendons and the longitudinal and transverse tendons would then be tied together similar to the first pavement strip. Stressing pocket forms would then be placed over the transverse tendons at the locations of the tendon laps. These stressing pocket forms were described in detail.

Step 15. The final step before slip-forming the second pavement strip would be to place a strip of polyethylene sheeting or a spray-applied bond breaking compound on the interior longitudinal edge of the first pavement strip. This would prevent the fresh concrete from bonding to the previously placed concrete thus permitting relative movement between the two pavement strips during stressing of the second strip.

Step 16. Next, the concrete of the second pavement strip would be slip-formed in place. Special care would have to be exercised in the placement, vibrating, and finishing of the concrete in the vicinity of the stressing pocket forms for the transverse tendons so tha the forms are not disturbed.

Step 17. After the longitudinal tendons of the second pavement strip have been fully stressed, the transverse tendons (including the ones in the precast joint panels) would be stressed.

Step 18. Construction of the second pavement strip would be completed by filling the tendon stressing pockets with concrete.

CONCEPT 3: PRECAST JOINT PANELS, CENTRAL STRESSING PANELS, AND SLIP-FORMED PAVEMENT

Description

This PCP concept utilizes precast concrete joint panels as described (see Figs 5.12, 5.13, 5.14, and 5.15). In addition, precast concrete stressing panels are also used. These stressing panels would be located at the midlength of each pavement segment and they would contain stressing pockets in which the longitudinal tendons would be jacked (see Figs 5.16 and 5.17). They would also contain a rigid transverse duct which would be used to posttension two adjacent stressing panels together. These panels would also permit the use of couplers for stressing the longitudinal tendons.

All the panels would be cast off the job site either in a precast plant or, if permitted, in the construction yard near the job site. They would then be transported to the job site, where they would be set in place with a truck crane.

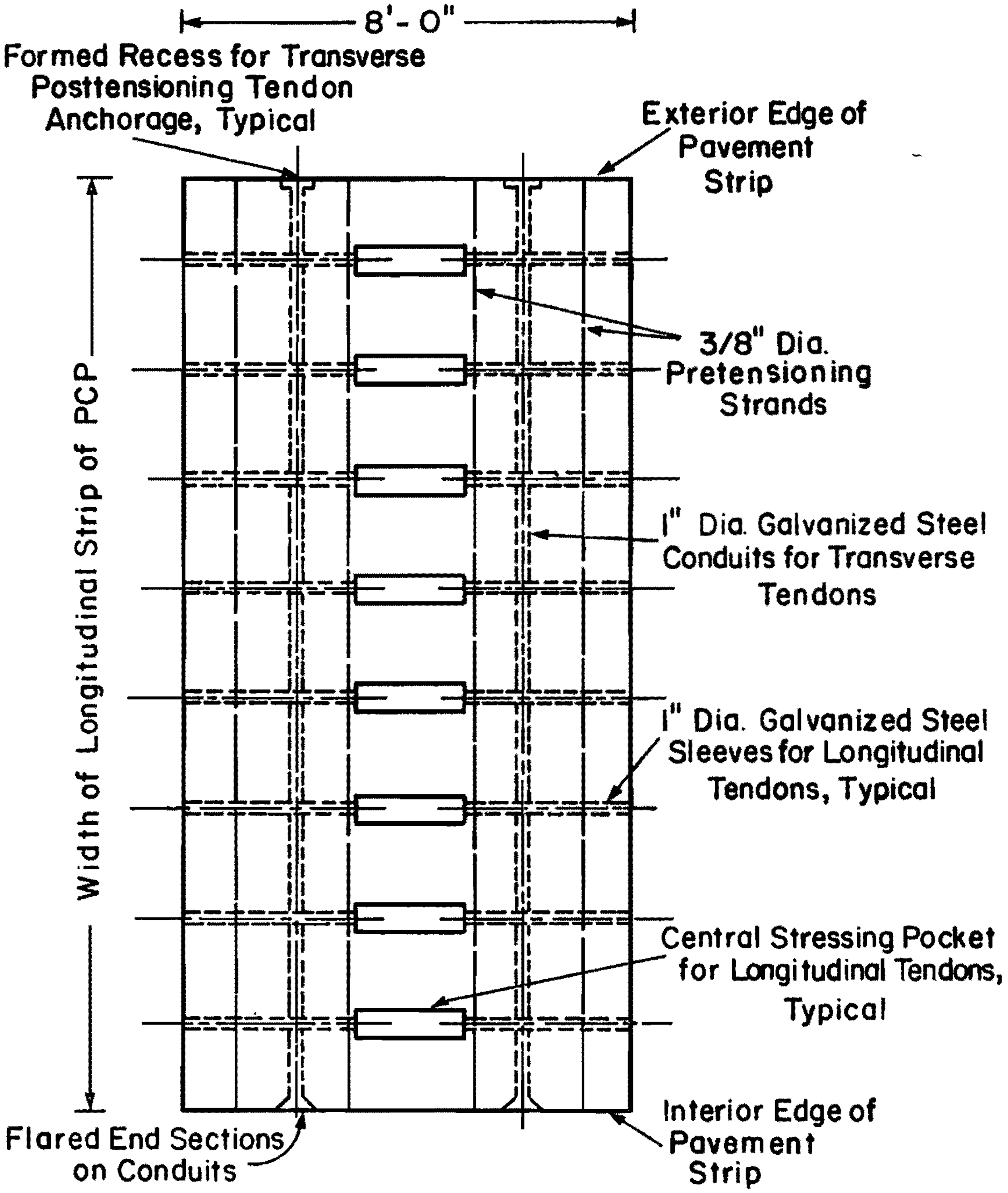


Fig 5.16. Central stressing panel.

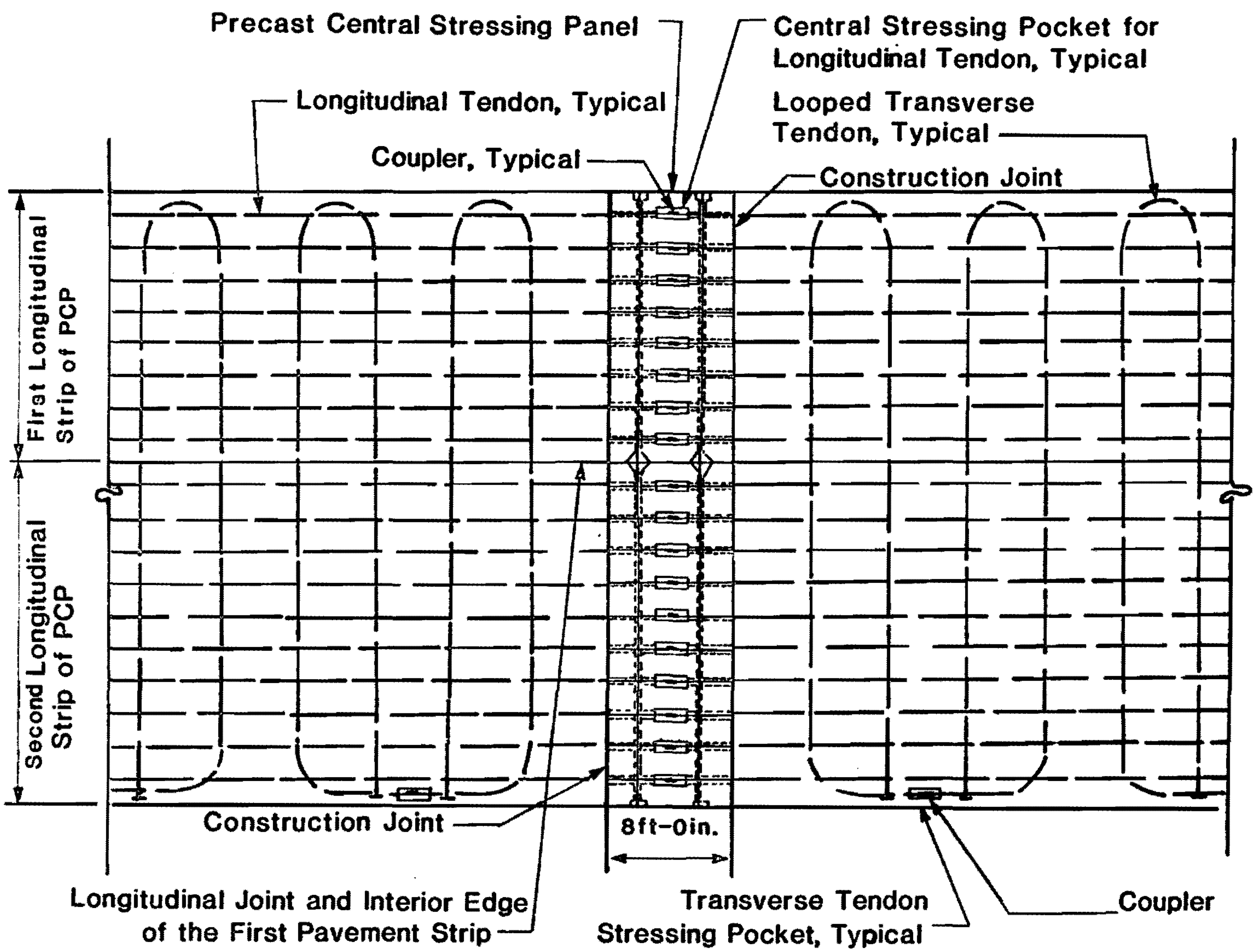


Fig 5.17. Precast joint panels, central stressing panels, and slip-formed pavement.

Construction

As with Concept 2, the construction of this PCP concept would begin with precasting the joint and central stressing panels off the job site. Although these panels could be constructed in the contractor's construction yard near the job site, it would probably be much more efficient to construct them in a precast plant. The joint panels would be oriented on the casting beds with the transverse joint assemblies for each pair of panels parallel to the length of the casting bed. The reasons for this orientation were described. Due to the width limitations of most casting beds the central stressing panels would also be oriented with their longer side parallel to the length of the casting bed.

Step 1. As with both of the previously discussed PCP concepts, the first step in the anticipated field construction sequence with this pavement concept is the placement of the friction-reducing medium for the first longitudinal strip of PCP on the prepared subgrade for new pavement or on the leveling course over old pavement in the case of an overlay. Again, a double-layer of polyethylene sheeting would probably be used. The methods of placing the sheeting and anchoring it to the base course described are applicable in this case.

Step 2. The next step in the construction sequence of this PCP concept would be to determine the locations for the transverse pavement joints and to set the precast joint panels in place. The joint panel pairs would be handled and placed in the same manner as described.

Step 3. Placement of the central stressing panels would then follow. These panels would be placed at the midlength of each pavement segment.

Step 4. The next step in the construction sequence would be to place the chairs for the longitudinal tendons in the portions of each pavement segment between the joint panels and the central stressing panel. Continuous chairs with bottom plates, as shown in Fig 5.11, would also be used in this case. As before, the interval between chairs would be dependent on the amount of tension that could be applied to the longitudinal tendons before the pavement is placed. This interval could be increased in proportion to the increase in tension in the tendons.

<u>Step 5</u>. Placement of the longitudinal tendons would be the next step in the construction sequence. Before the tendons are shipped to the construction site, they should be prepared as follows:

(a) They should be cut to the proper length. The longitudinal tendons would have to be long enough to extend from the tendon anchorage pockets in the joint panels at the end of the pavement section to the stressing pocket in the central stressing panel at the midlength of the pavement section.

(b) The polypropylene sheathing should be removed from the ends of each tendon to allow for installation of the anchorage on the joint panel end and the coupler on the central stressing panel end of each tendon.

For each segment of pavement, longitudinal tendon placement begins by inserting the starting ends of the tendons through sleeves into anchorage pockets in the precast concrete joint panels at the beginning of the pavement segment. The anchorages would then be installed on the end of the tendons in the anchorage pockets. All of the longitudinal tendons for the portion of the pavement segment between the joint panel at one end of the segment and the central stressing panel would then be simultaneously unrolled. At the midlength of the pavement segment, the terminal ends of these longitudinal tendons would be inserted through sleeves into the stressing pockets of the central stressing panel. The same process would be repeated for the other half of the pavement segment. The two overlapping ends of the longitudinal tendons in the stressing pockets in the central stressing panel would then be inserted through couplers.

Steps 6 through 9 in the construction of the first strip of pavement with this PCP concept are similar to those of the previously discussed concepts with some minor variations. These steps and the manner in which they differ (if at all) from those of the previously discussed PCP concepts are as follows:

Step 6. Half forms would be placed along the interior edge of the first pavement strip. Half forms would not be needed, however, along the edges of the precast joint and central stressing panels.

Step 7. With this PCP concept, the first looped tendon (or hollow conduit) in each pavement segment would be placed farther from the transverse pavement joints than with Concept 1, due to the presence of the precast joint panels. In addition, no looped tendon would be required at the midlength of the pavement segment which would be occupied by the central stressing panel.

Step 8. Apply sufficient tension to keep the longitudinal tendons in straight alignment during concrete placement. This tension would be applied with a standard stressing jack in the stressing pockets located in the precast central stressing panels.

Step 9. The longitudinal and transverse tendons would then be tied together at their points of intersection.

Step 10. After a sufficient number of pavement segments have been prepared (in accordance with the above steps) so that progress of the slip-form paver would not be impeded, concrete placement would begin. Special care must be exercised in the placement, vibrating, and finishing of the concrete at the location where the slip-form pavement meets the precast concrete joint and central stressing panels.

Step 11. When the concrete has achieved sufficient compressive strength (approximately 500 psi), "nail-down pins" which are used to temporarily secure the precast concrete joint panels to the asphaltic concrete leveling course, steel jumper plates which were provided across the transverse joint assembly opening to keep it in a closed configuration, and half forms on the interior edge of the pavement would all be removed. The longitudinal tendons would then be sufficiently stressed (in the pockets provided in the precast central stressing panels) to prevent shrinkage cracking of the concrete.

Step 12. After the concrete has gained sufficient additional strength, final stressing of the longitudinal tendons would be done, followed by filling the stressing pockets in the central stressing panels, and the tendon anchorage pockets in the joint panels, with concrete.

Placement of the second pavement strip would proceed in a manner similar to the first with a few exceptions. Placement of the polyethylene friction-reducing medium, the precast concrete joint and central stressing panels, and the longitudinal tendons would be as described above.

Step 13. After the precast joint and central stressing panels for the second pavement strip are in place, straight tendons would be threaded through the rigid transverse ducts in the joint and central stressing panels of the first and second pavement strips. These tendons would not be stressed at this time. The portions of the transverse tendons which protrude from the first slab strip would be uncoiled and placed in the proper positions in the second pavement strip. If hollow conduits were provided in the first pavement strip, instead of the transverse tendons, then the tendons would be threaded through these conduits.

Step 14. Light tension would be applied to the longitudinal tendons and the longitudinal and transverse tendons would then be tied together as in to the first pavement strip.

Step 15. Stressing pocket forms would then be placed over the transverse tendons at the locations of the tendon laps. These stressing pocket forms were described in detail.

Step 16. The final step before slip-forming the second pavement strip would be to place a strip of polyethylene sheeting or a spray-applied bond breaking compound on the interior longitudinal edge of the first pavement strip. This would prevent the fresh concrete from bonding to the previously placed concrete thus permitting relative movement between the two pavement strips during stressing of the second strip.

Step 17. Next, the concrete of the second pavement strip would be slip-formed in place. Special care would have to be exercised in the placement, vibrating, and finishing of the concrete in the vicinity of the stressing pocket forms for the transverse tendons so that the forms are not disturbed.

Step 18. After the longitudinal tendons of the second pavement strip have been fully stressed, the transverse tendons (including the ones in the precast joint and central stressing panels) would be stressed.

Step 19. Construction of the second pavement strip would be completed by filling the tendon stressing and anchorage pockets with concrete.

CONCEPT 4: COMPOSITE PRESTRESSED CONCRETE PAVEMENT TYPE I (CPCPI)

Description

Precast concrete joint panels similar to those used with PCP Concepts 2 and 3 would also be used with this PCP concept (see Figs 5.12, 5.13, and 5.14). These joint panels were described in detail. Central stressing panels similar to those used in PCP Concept 3 could be used with this concept if use of the technique of central stressing is desired (see Fig 5.16).

In addition, still another type of precast panel is involved with this PCP concept. It will be referred to in this section as a "base panel" (for reasons that will become obvious in the following discussion) and is illustrated in Figs 5.18 and 5.19. Like the panels used with the previous concepts, these panels would be cast off the job site. They would be prestressed on the casting beds to compensate for both handling and some in-place stresses. In addition, each base panel would contain a hollow transverse conduit.

All of the various types of precast panels would be transported to the job site where they would be set in place with a truck crane.

Construction

The anticipated techniques for precasting the joint panels and central stressing panels were discussed, respectively. Precasting the base panels would use the same basic procedures described in connection with the other panel types, namely: (a) panels would be cast end to end on long casting beds, (b) panels would be cast with their longer side parallel to the length of the casting bed, and (c) all panels on the casting bed would be prestressed parallel to their longer side in a single tensioning operation.

Step 1. The first step in the anticipated field construction sequence for the first pavement strip would be to unroll enough polyethylene sheeting (on the prepared base course in the case of a new pavement or on the leveling course over an old pavement in the case of an overlay) on which to place the precast concrete joint panel at the starting end of the pavement segment.

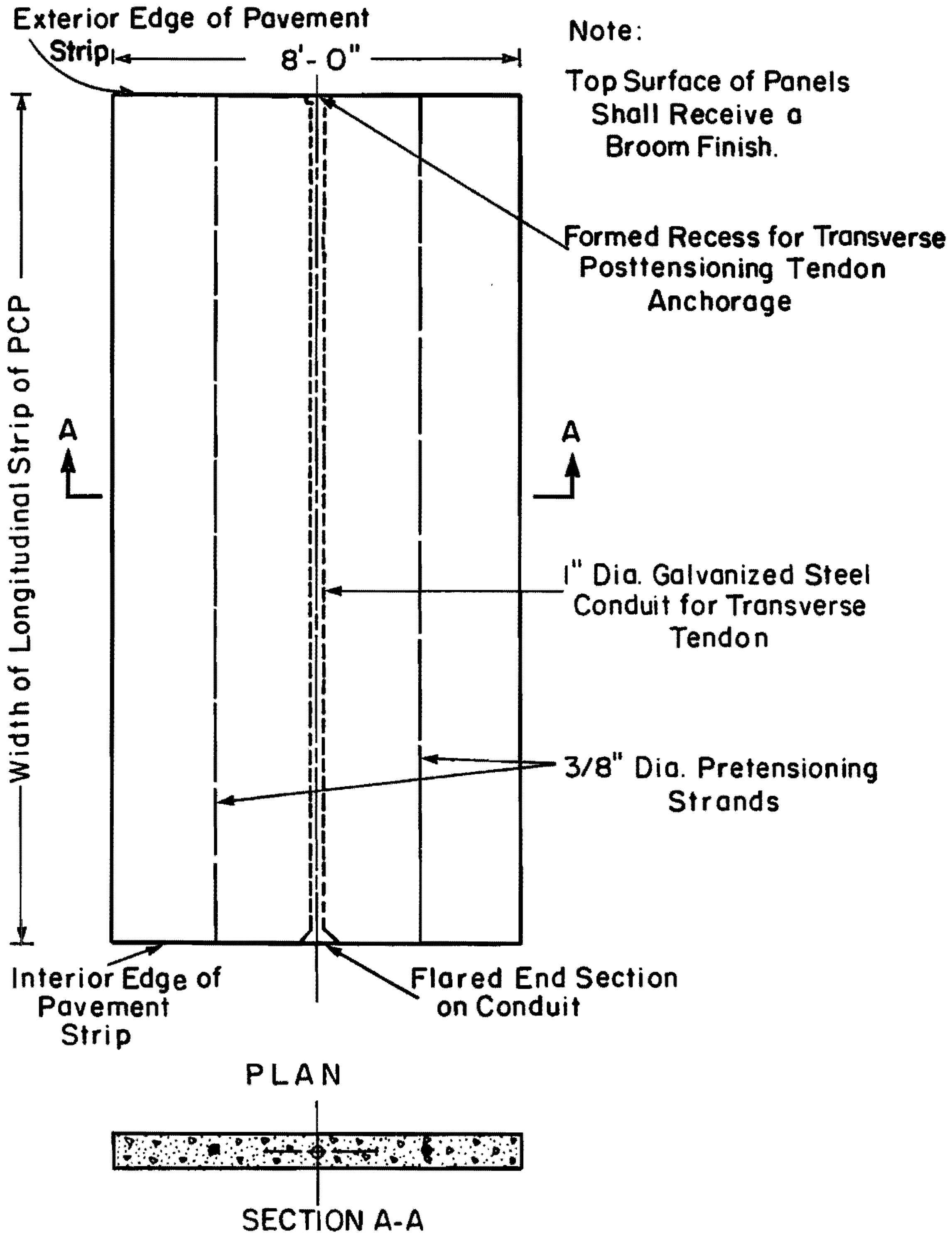


Fig 5.18. CPCPI base panel.

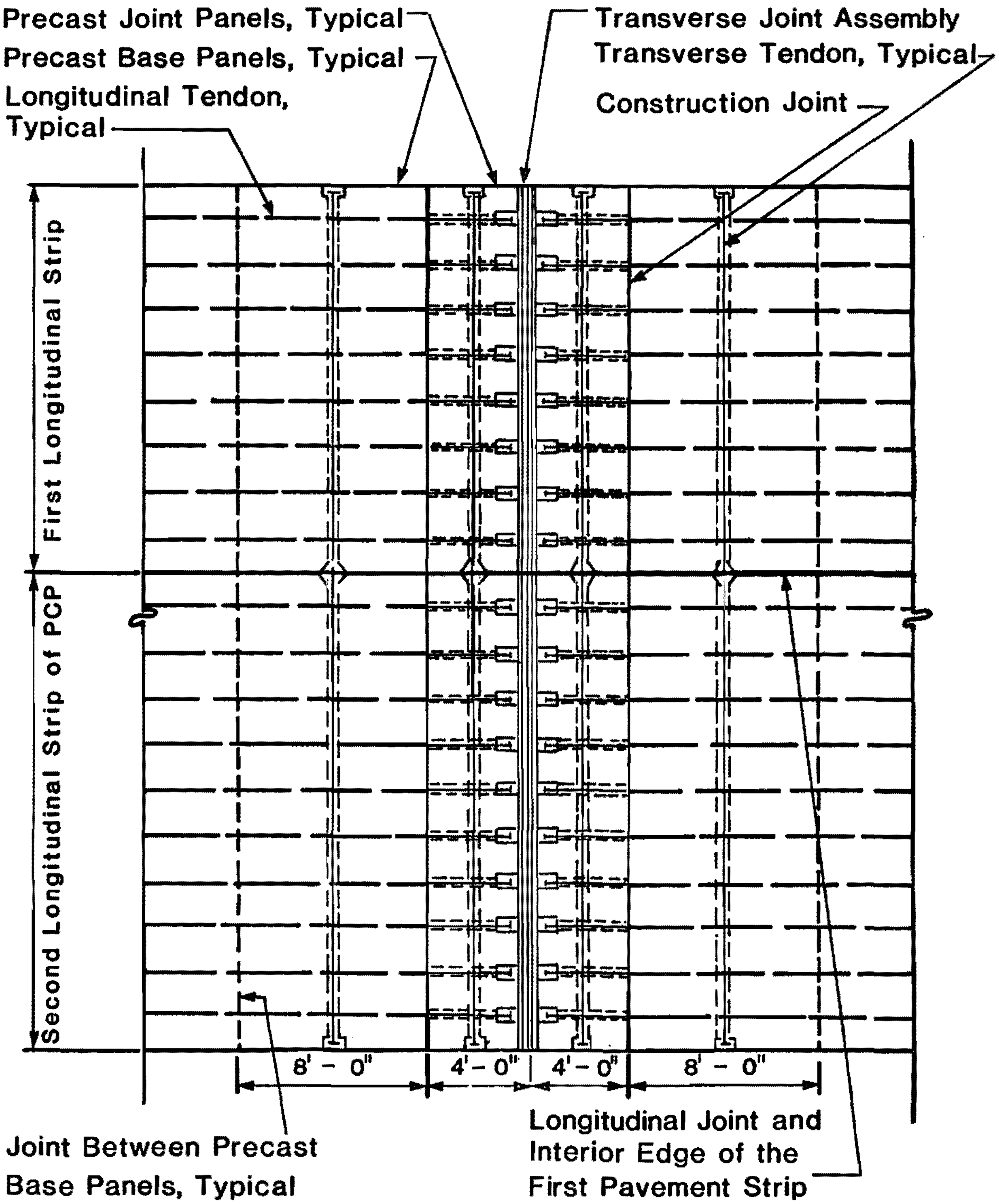


Fig 5.19. Composite prestressed concrete pavement type I (CRCPI).

Step 2. The joint panels would then be set in place and temporarily secured to the subgrade with "nail-down" pins which would help to prevent the inadvertent displacing of the panels during construction.

Step 3. Sufficient additional polyethylene sheeting for the first precast concrete base panel would then be unrolled, and the first base panel set in place, butted against the edge of the joint panel.

The starting ends of the longitudinal tendons would then be inserted through sleeves into the stressing pockets in the precast concrete joint panels at the beginning of the pavement segment, anchorages would be installed on the ends of the longitudinal tendons (in the stressing pockets), and the longitudinal tendons would be unrolled. The sequential process of unrolling the polyethylene sheeting followed by placing additional precast concrete base panels would continue until the terminal end of the pavement segment is reached. At that point the terminal end joint panel would be set in place and the ends of the longitudinal tendons would be inserted through sleeves into the stressing pockets in the joint panel.

If the technique of central stressing is to be used with this PCP concept, the construction process would proceed as described above with a couple of exceptions. First , at the midlength of the pavement segment a central stressing panel would be provided in lieu of one of the base panels. Also, each longitudinal tendon would be only half as long as the pavement segment. After the tendons for the first half of the pavement segment have been fully unrolled, their terminal ends would be inserted through sleeves into the stressing pockets of the central stressing panel. The starting ends of the longitudinal tendons for the second half of the pavement segment would then be inserted through sleeves on the other side of the central stressing panel and coupled to the terminal ends of the tendons from the first half of the pavement segment. The tendons would then be unrolled until the terminal end of the pavement segment is reached, where the ends of these tendons would be inserted through sleeves into anchorage pockets in the precast joint panel.

Step 5. The next step would be to apply sufficient tension to the longitudinal tendons by means of jacking in the stressing pockets in the joint panels (or in the central stressing panel, if used) to keep the tendons in straight alignment during concrete placement with a slip-form paver.

Step 6. After a sufficient number of pavement segments have been prepared (in accordance with the above steps) so that progress of the slip-form paver would not be impeded, placement of the concrete wearing course would begin.

Step 7. After the concrete has achieved sufficient strength (approximately 500 psi), the longitudinal tendons would be tensioned sufficiently to prevent shrinkage cracking of the slip-formed concrete. Final stressing of the longitudinal tendons would be done after sufficient additional strength gain has occurred in the slip-formed concrete.

Step 8. The first pavement strip would then be completed by filing the stressing pockets with concrete.

Step 9. Construction of the second pavement strip would proceed in a manner similar to the first with the exception that the transverse tendons would be inserted through the rigid transverse conduits in contiguous panels as placement of the panels of the second pavement strip proceeds. Transverse conduits and tendons would probably only be required in alternate contiguous panels. This is because each panel would be prestressed at the precast plant and this posttensioning would only be provided to tie the two pavement strips together.

Step 10. After the longitudinal tendons of the second pavement strip have been fully stressed, the transverse tendons would be stressed. The stressing pockets along the exterior longitudinal pavement edges would then be packed with nonshrink grout.

CONCEPT 5: COMPOSITE PRESTRESSED CONCRETE PAVEMENT TYPE II (CPCPII)

Description

Precast concrete joint panels similar to those used in PCP Concepts 2, 3, and 4 would be used for CPCPII. These joint panels were described in detail. Also, central stressing panels similar to those used in PCP Concept 3 could be used with this concept if use of the technique of central stressing is desired (see Fig 5.16).

Base panels, having the following similarities to the ones used for CPCPI, would be used for CPCPII: (a) they would be cast off the job site; (b) they would be prestressed on the casting bed to compensate for both handling and some in-place stresses; (c) they would have a rough top surface finish; and (d) each base panel would contain a hollow transverse conduit. However, the base panels for CPCPII would be different from the ones used for CPCPI in three respects (see Figs 5.20 and 5.21). First, the base panels for CPCPII would be thicker than those for CPCPI. Second, grooves would be provided in the top surface of the panels which would allow the longitudinal tendons to be located at, or slightly below, the centroidal axis of the panels. Third, the edge of the panel would be formed in a manner to permit grouting of the joints between adjacent panels after they are set in place at the job site.

All of the various types of precast panels would be transported to the job site, where they would be set in place with a truck crane.

Construction

The anticipated techniques for precasting the joint, central stressing, and base panels were discussed, respectively. If the casting beds were wide enough, the panels could be cast with their longer side perpendicular to the casting bed and provided with match cast edges.

Most of the initial steps anticipated in the field construction sequence for CPCPII would be the same as for CPCPI with a few exceptions. The first difference is that the joints between the adjacent precast panels would be grouted with high-early-strength grout immediately after each successive panel is set in place. If the panels were match cast, the panel edges could be epoxy-bonded together. Whether or not match cast panels would be provided would depend on several factors, including: (a) the availability of wide casting beds, (b) the additional cost of match cast panels, (c) the increased difficulty in keeping the panels in the correct order, (d) whether

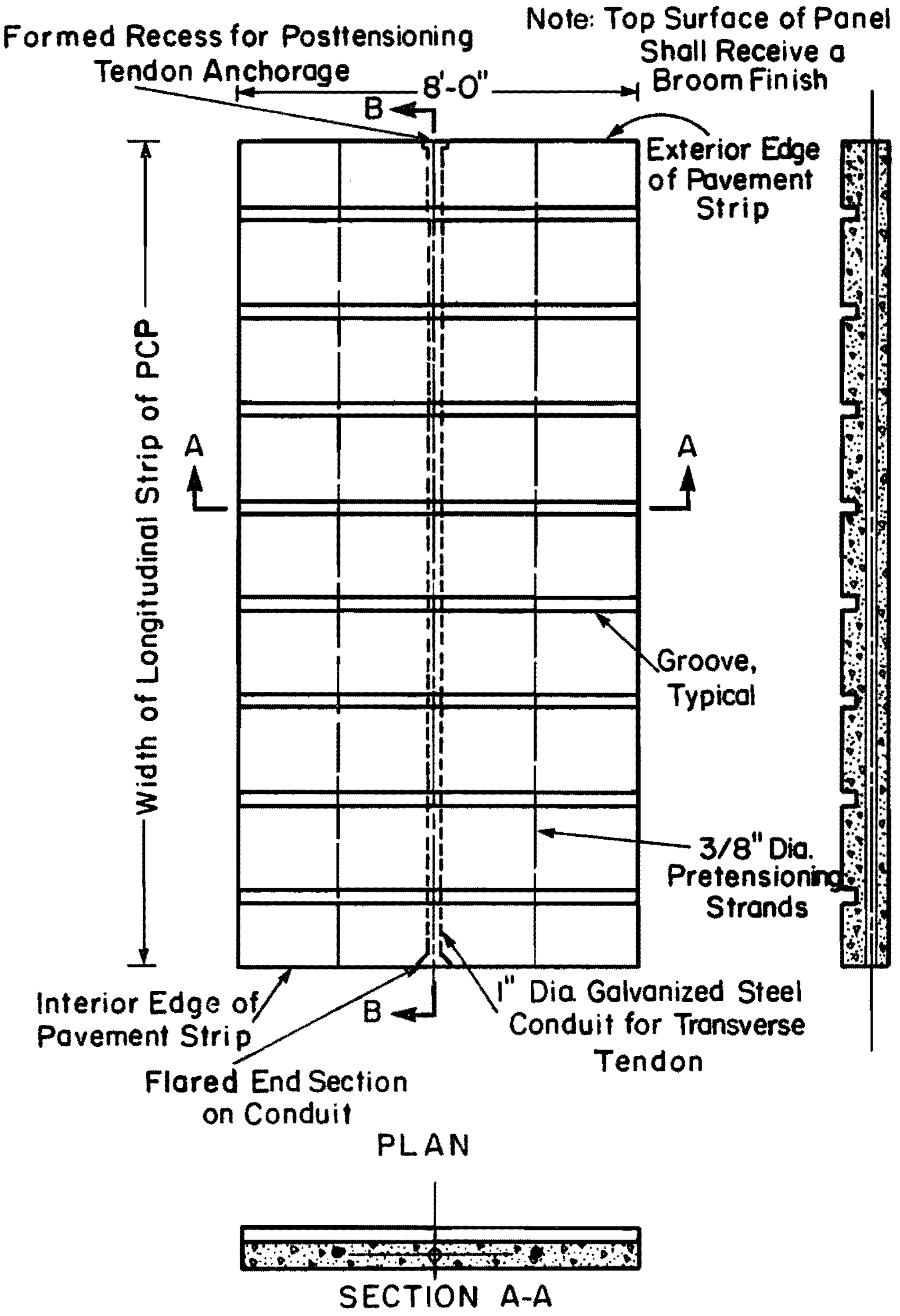


Fig 5.20. CPCPII base panel.

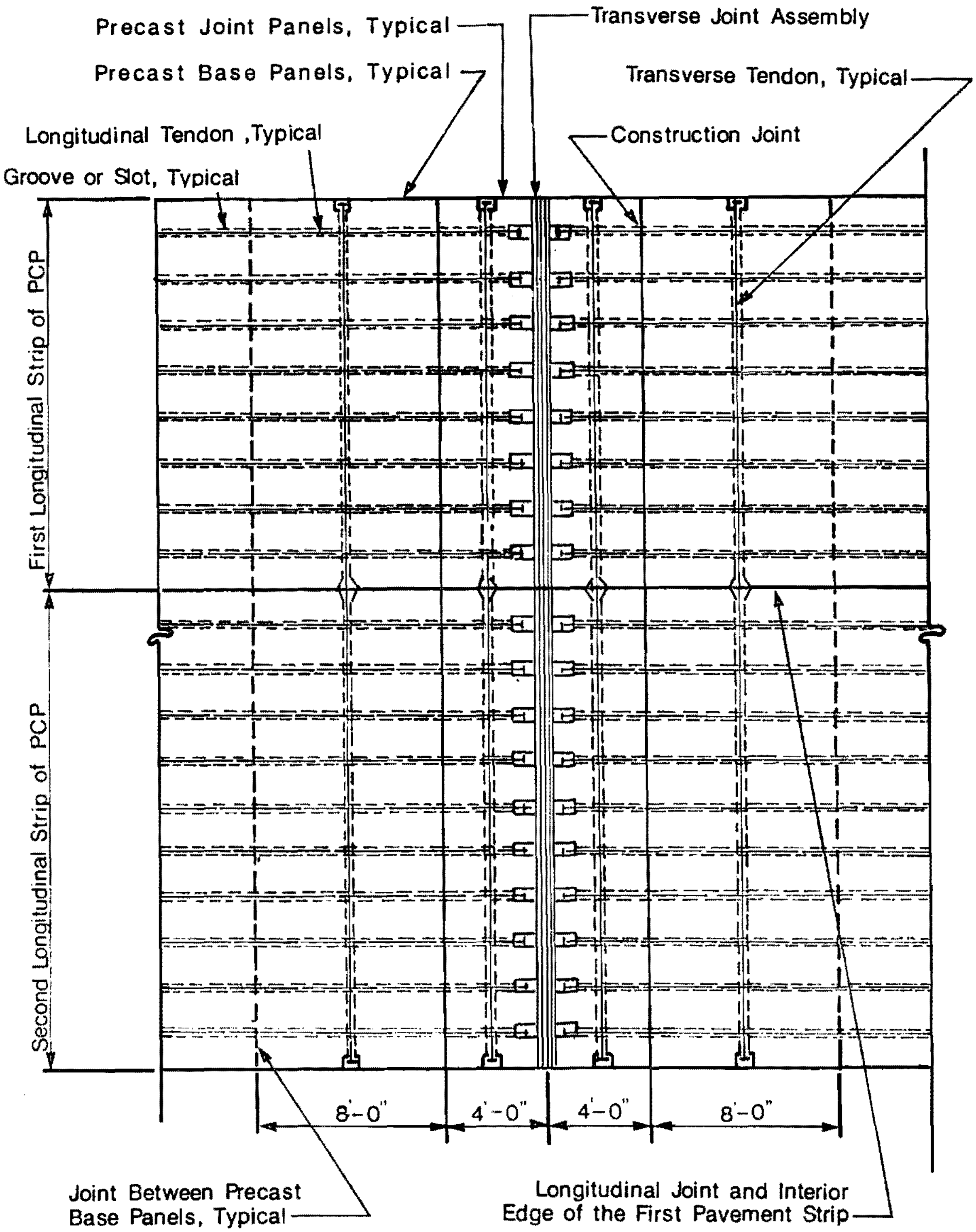


Fig 5.21. Composite prestressed concrete pavement type II (CPCPII).

the panels could be butted together accurately enough in the field to warrant being match cast, and (e) whether epoxy bonding would save enough time and labor in the field over grouting to warrant having match cast panels. The second difference with CPCPII is that after the anchorages are installed on the starting ends of the longitudinal tendons, the tendons would be unrolled in the grooves provided in the top surface of the base panels.

The precast concrete base and joint panels would, in effect, comprise a pretensioning bed. After the grout in the panel joints has gained sufficient strength, the longitudinal tendons would be fully stressed. This might, at first examination, appear to present a hazardous situation since the tendons would not yet be encased in concrete. However, this situation would not be different than regularly encountered in precasting plants and would not be dangerous if proper safety precautions were exercised.

After a sufficient number of pavement segments have been prepared (in accordance with the above steps) so that progress of the slip-form paver would not be impeded, placement of the concrete riding surface would begin. The stressing pockets in the joint panels (and in the central stressing panels, if used) would be filled with concrete at the same time that the concrete riding surface is placed. The progressive shortening of the pavement, especially during the first few days immediately after pavement construction, would result in inducing a compressive stress to the slip-formed concrete riding surface.

Construction of the second pavement strip would follow the same sequence as described above. Transverse prestressing would be done as described for CPCPI.

CONCEPT 6: SEGMENTALLY PRECAST PRESTRESSED CONCRETE PAVEMENT (SPPCP)

Description

Precast concrete joint panels similar to those used in PCP Concepts 2 through 5 would also be used with this concept. These joint panels were described (see Figs 5.12, 5.13, and 5.14). In addition, central stressing panels similar to those used in PCP Concept 3 could be used with this concept if use of the technique of central stressing is desired (see Fig 5.16).

A panel type, referred to in this section as a "full-depth pavement panel" (for reasons that will become obvious in the following discussion), would be used with this PCP concept. This panel is illustrated in Figs 5.22 and 5.23. Like all the panels used with the previous concepts, these panels would also be cast off the job site. They would be prestressed on the casting beds to compensate for both handling and some in-place stresses. In addition, each full-depth panel would contain hollow longitudinal conduits and a single hollow transverse conduit.

All of the various types of precast panels would be transported to the job site, where they would be set in place with a truck crane.

Construction

The anticipated techniques for precasting the joint and central stressing panels were discussed, respectively. Precasting the full-depth pavement panels would use the same basic procedures that were described in connection with the other panel types, namely: (a) panels would be cast end to end on long casting beds, (b) panels would be cast with their longer side parallel to the length of the casting bed, and (c) all panels on the casting bed would be prestressed parallel to their longer side in a single tensioning operation. Like the base panels with CPCPII, the full-depth pavement panels could be cast with their longer side perpendicular to the casting bed if the casting beds were wide enough. If this were done, the panels could have match cast edges. The hollow longitudinal and transverse conduits could be prefabricated into a mat similar to welded wire fabric for ease of handling and placement on the casting bed.

The anticipated field construction sequence for SPPCP would be similar to that for CPCPI and CPCPII with a few exceptions. The first difference would be that the longitudinal tendons for the entire pavement segment would be fed from spools which would remain at the starting end of the pavement segment. The tendons would be pulled through the hollow longitudinal tendons in each full-depth panel as they are set in place. The joints

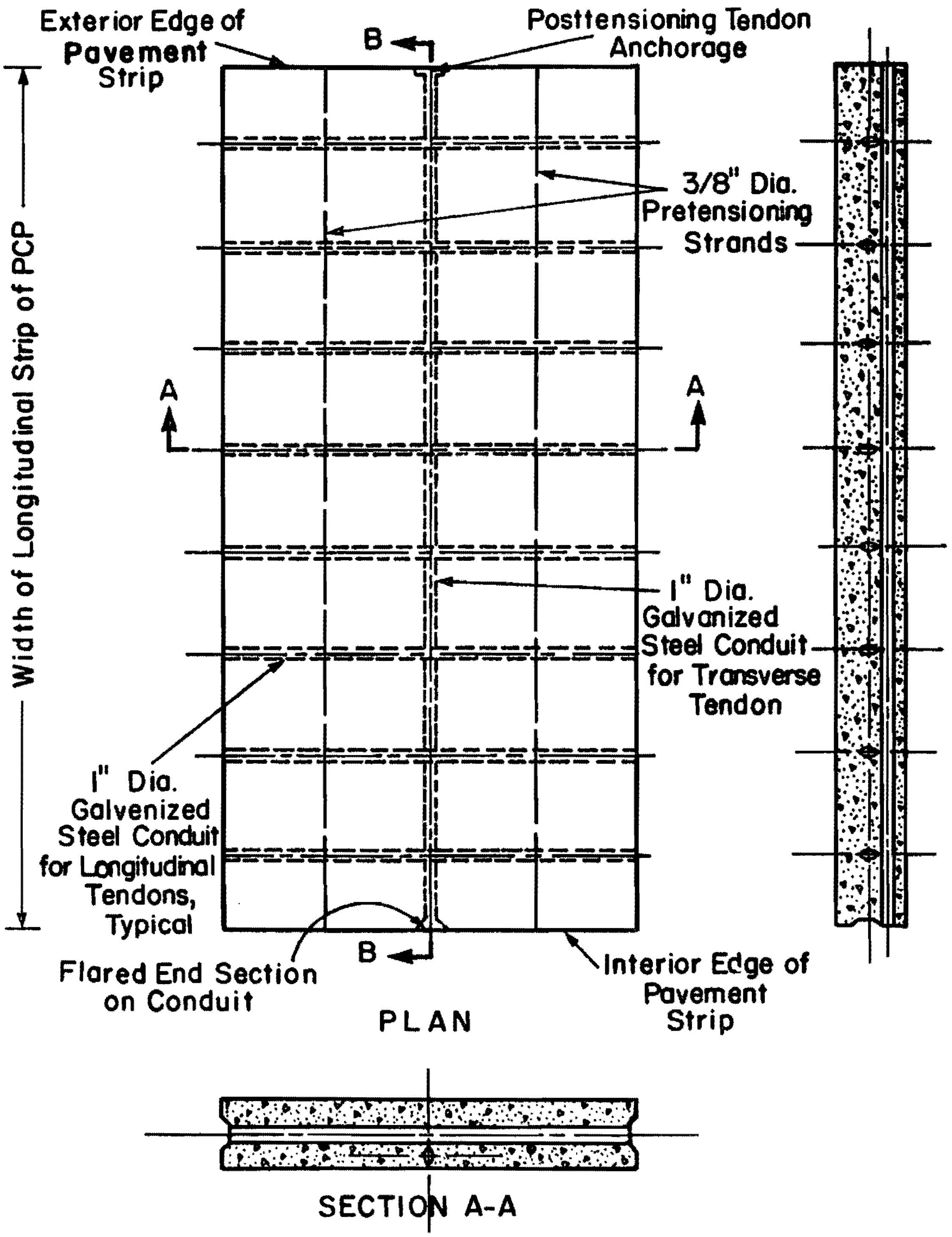


Fig 5.22. Full-depth pavement panel.

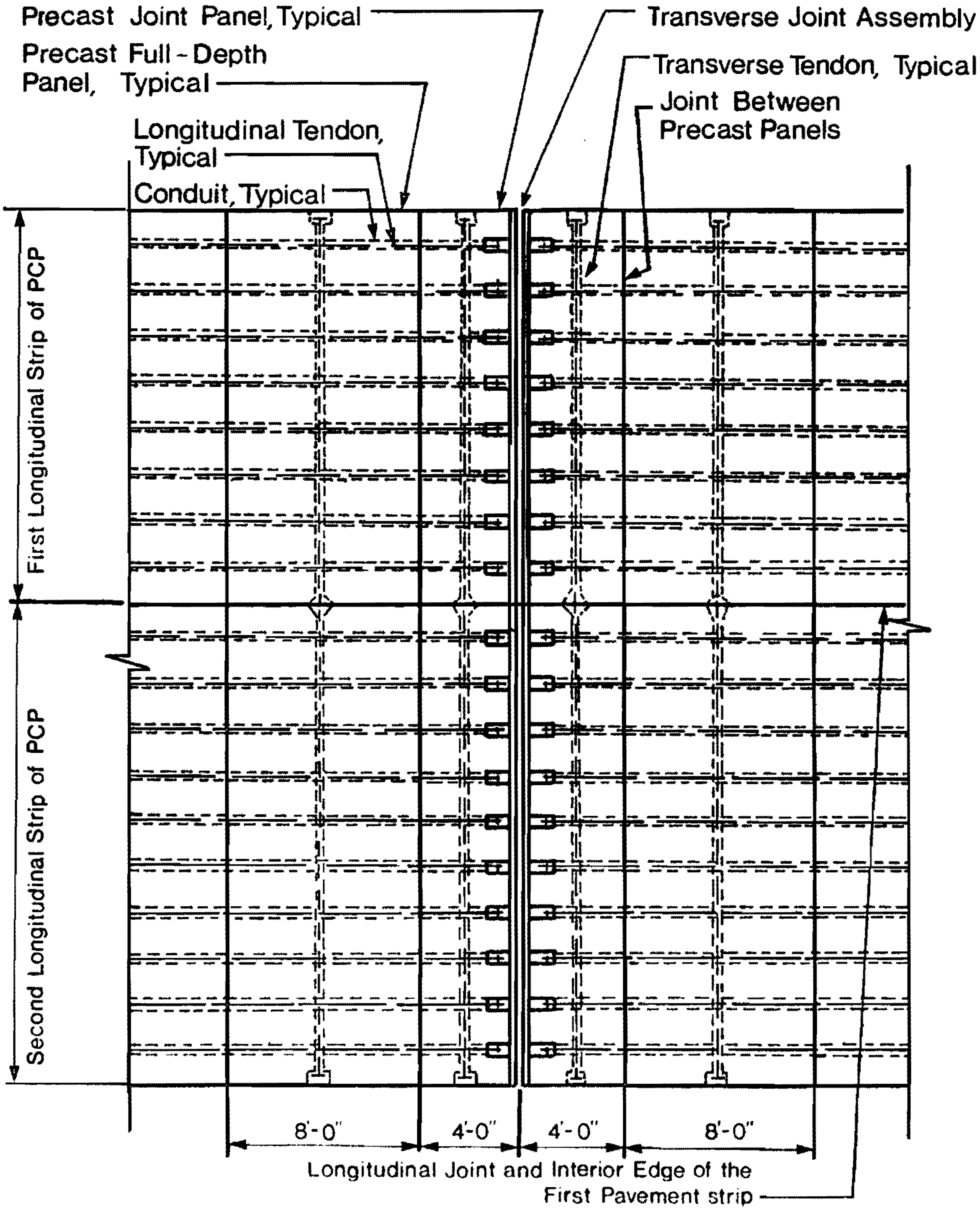


Fig 5.23. Segmentally precast prestressed concrete pavement (SPPCP).

between the adjacent precast panels would be grouted with high early strength grout immediately after each successive panel is set in place. If the panels are match cast, the edges of adjacent full-depth pavement panels would be coated with epoxy rather than grouting the panel joints. This process would continue until the terminal end of the pavement segment is reached. At that point the terminal end joint panel would be set in place and the ends of the longitudinal tendons would be inserted through sleeves into the stressing pockets in the joint panel. Anchorages would then be installed on the ends of each longitudinal tendon.

After the grout in the panel joints has gained sufficient strength, the longitudinal tendons would be fully stressed. The construction of a pavement segment would then be completed by filling the stressing pockets in the joint panels (and in the central stressing panels, if used) with concrete.

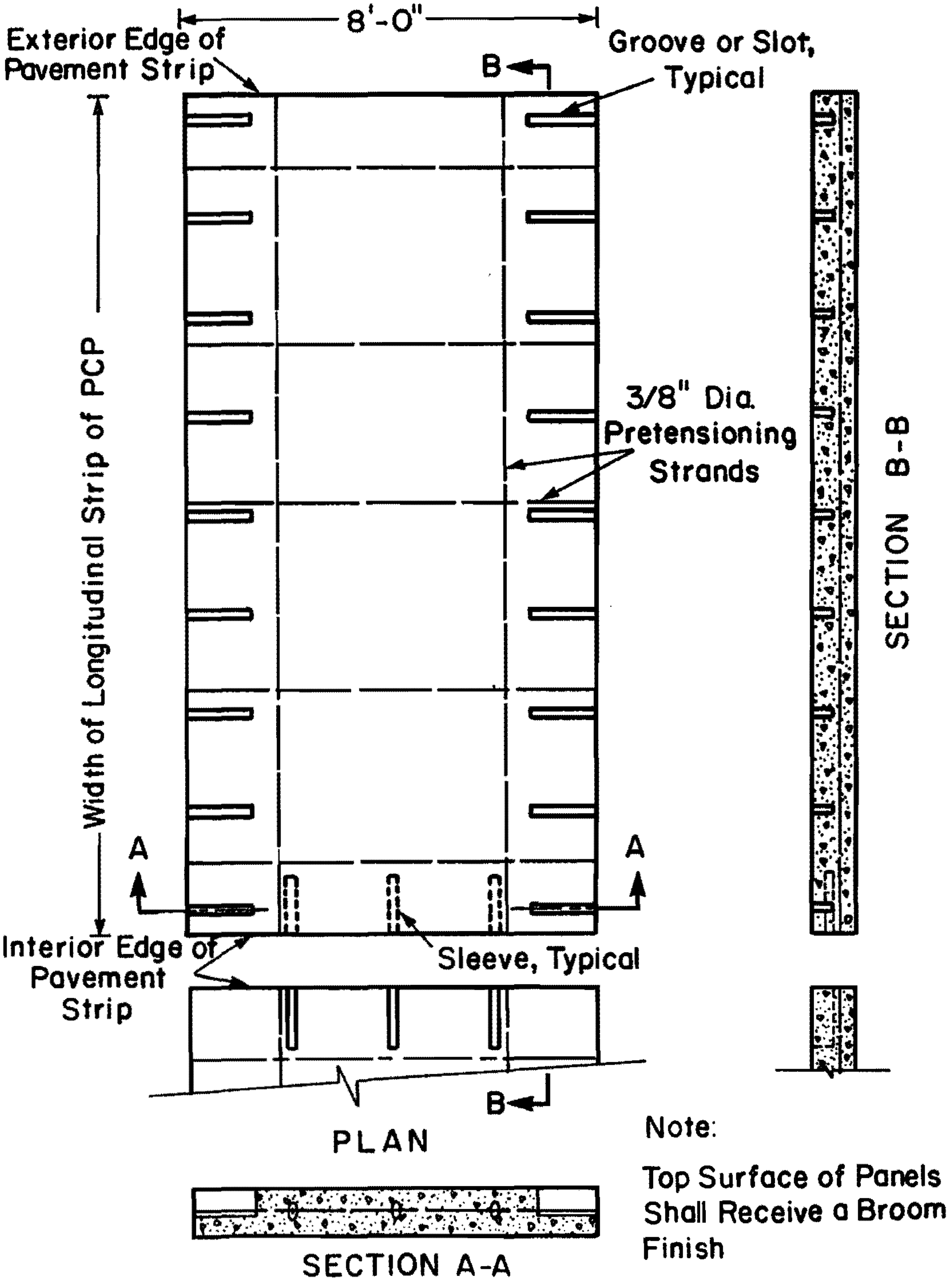
Construction of the second pavement strip would follow the same sequence as described above. Transverse prestressing would be done as described for CPCPI.

CONCEPT 7: CONTINUOUS COMPOSITE CONCRETE PAVEMENT (CCCP)

Description

CCCP is very different from any of the concepts discussed thus far in this report and, in reality, is more similar to the concept of continuously reinforced concrete pavement, as will become apparent in the following discussion.

No joint panels would be used with CCCP because no transverse joints would be required, except where construction joints are required when the paving operation is interrupted or where expansion joints are required, such as at bridges. Only precast concrete base panels (as shown in Figs 5.24 and 5.25) would be used in CCCP construction. These panels would be cast off the job site similar to panels used in the previously discussed concepts. They would be prestressed in both directions on the casting bed to compensate for all handling and in-place stresses. In addition, the panels would



Note:

Top Surface of Panels Shall Receive a Broom Finish

Fig 5.24. CCCP base panel.

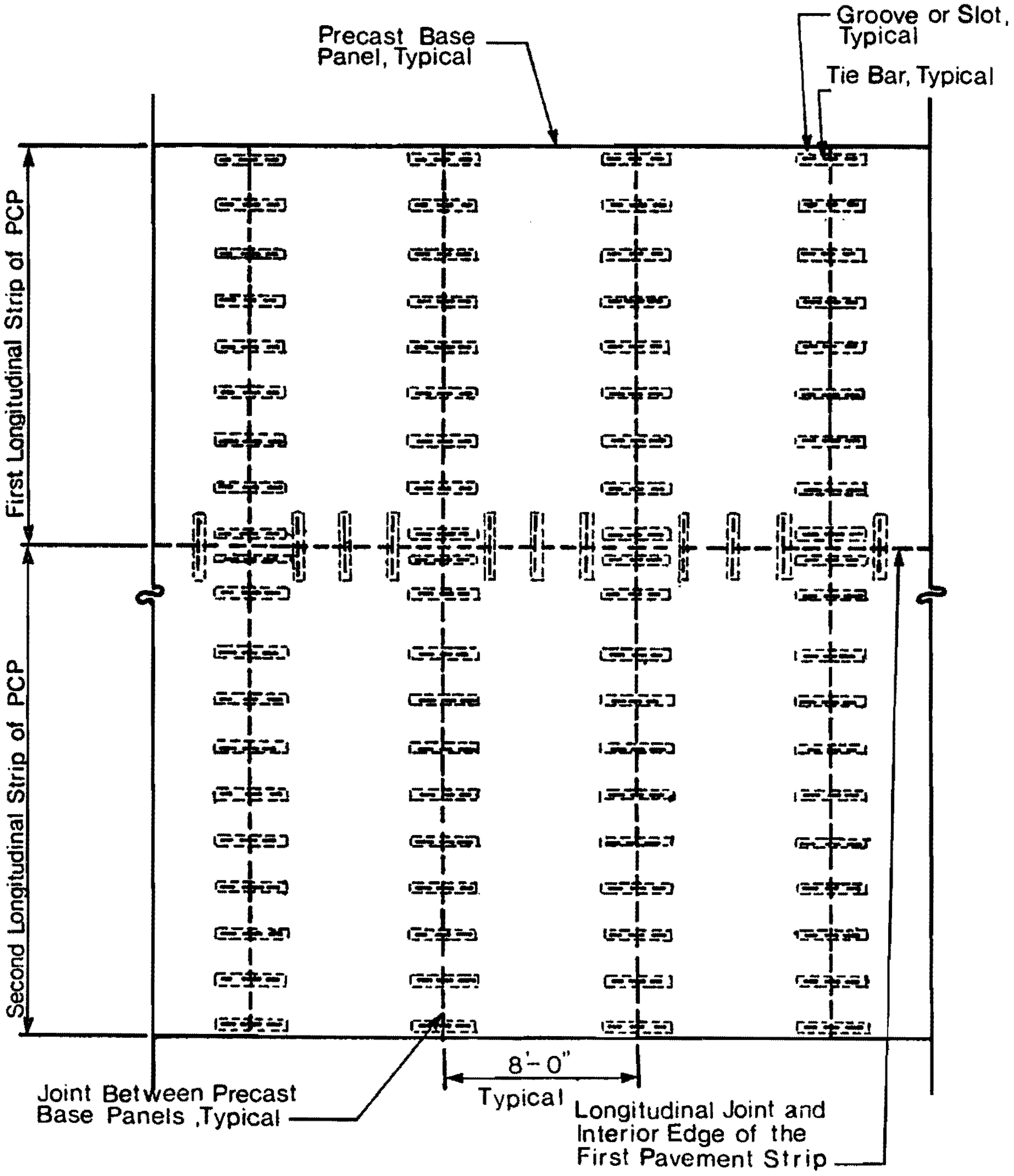


Fig 5.25. Continuous composite concrete pavement (CCCP).

contain grooves or slots which would be perpendicular to the panel edges. These grooves would accommodate tie bars between adjacent panels.

As with all of the previous concepts, the precast concrete panels would be transported to the job site, where they would be set in place with a truck crane.

Construction

The anticipated techniques for precasting the base panels would be the same as discussed for the base panels for CPCPI.

Step 1. The first step in the field construction sequence for the first pavement strip would be to set the precast concrete base panels in place on the prepared subgrade in the case of a new pavement or on the leveling course over old pavement in the case of an overlay.

Step 2. The next step would be to fill the grooves in the pavement surface along the transverse pavement edges with grout. This would be followed immediately by depressing epoxy-coated tie bars in the fresh grout.

An alternative to the use of grooves and tie bars would be to simply lay welded-wire fabric directly on the surface of the precast base panels. The fabric would only have to extend a development length on either side of the joints between adjacent panels.

Step 3. After a sufficient number of base panels have been placed and connected together with tie bars so that the progress of the paver would not be impeded, placement of the riding surface would begin. The riding surface could be either slip-formed concrete or hot-mix asphalt.

Step 4. The placement of the second pavement strip would proceed in a similar manner to that described above with the following exception: tie bars would be placed across the longitudinal joint between the first and second pavement strips in addition to the tie bars provided across the transverse joints between the precast base panels of the second strip.

OTHERS

Numerous other possibilities exist, in addition to those which have been discussed in this chapter, for the use of precast concrete in PCP construction. The purpose of this section is to briefly touch on some of these possibilities without going into as much detail as was done for the previous concepts.

The first possibility is that the precast panels could be oriented with their longer side parallel to the longitudinal axis of the pavement instead of perpendicular to this axis as with all of the previous concepts. In this way panel length would be limited only by transportability. This would minimize the number of transverse joint between consecutive precast panels which might be advantageous in connection with the previously discussed concepts. With long panels it might also become feasible to have segments of unbonded tendons precast in each panel. The tendons would then be coupled between adjacent panels to form continuous longitudinal tendons.

Another very interesting possibility is to use precast hollow-core panels (as shown in Fig 5.26) with the previously discussed PCP concepts. The possible advantages would be: (a) significantly less concrete would be required, (b) the pavement weight would be reduced which would translate to lower friction between the pavement and the subgrade, (c) the reduced precast panel weight would also make the panels easier to handle and transport, and (e) a higher prestress level would be obtained with the same amount of prestressing steel due to the reduction in concrete cross-sectional area. Still another area that should be investigated would be to determine if there are more efficient and effective methods of prestressing the pavement. Some of the more interesting possibilities are discussed in the following paragraphs.

(1) A method for increasing tendon stressing operation efficiency would be to simply develop stressing jacks with long stroke lengths. Standard jacks, as shown in Fig 5.27, have stroke lengths of approximately 8 inches and, consequently, must be reset several times in order to fully stress the longitudinal posttensioning tendons. A jack with a long stroke length would

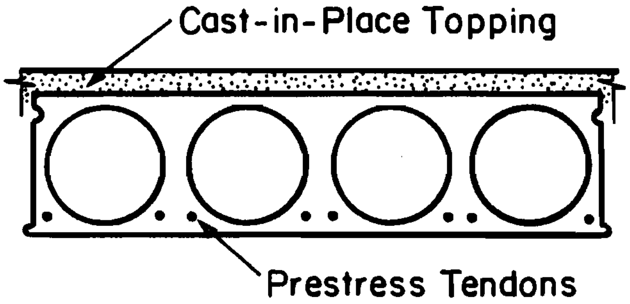


Fig 5.26. Precast hollow-core panels.

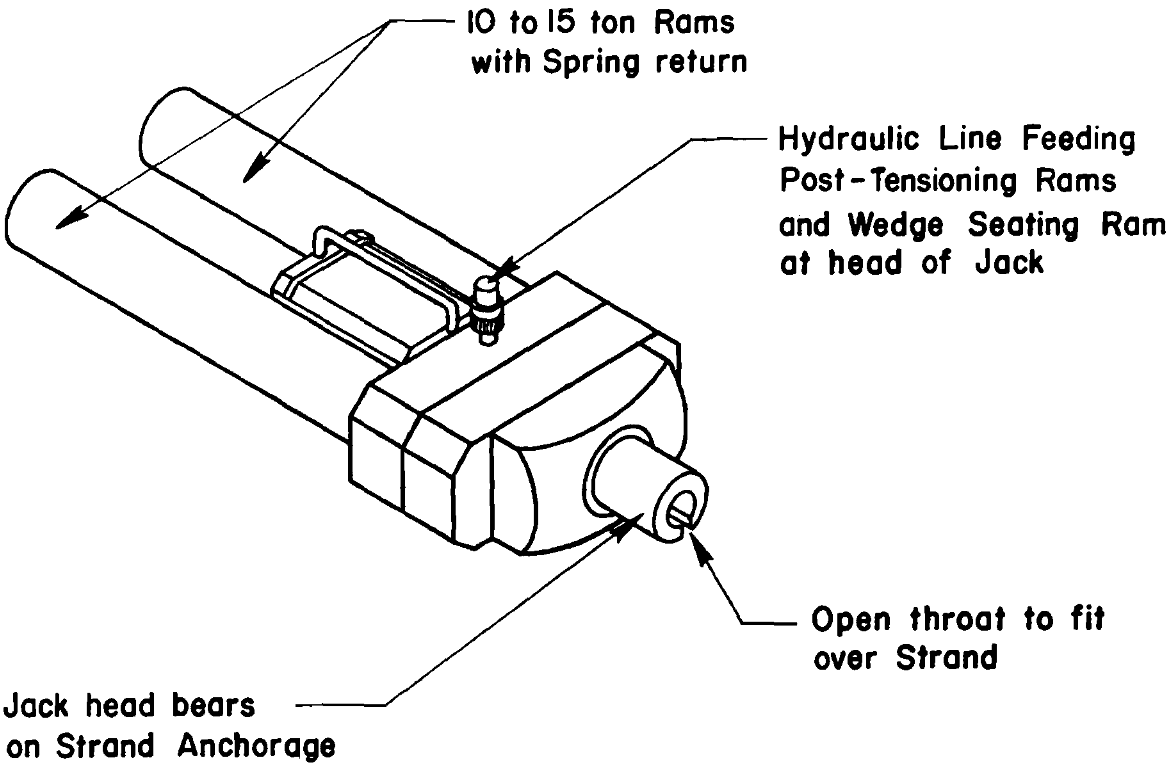


Fig 5.27. Stressing jack (Ref 92).

only have to be reset after completely stressing one tendon and before stressing the next tendon is begun.

(2) A method which might prove to be more effective for longitudinally posttensioning the pavement would be to longitudinally stress each pavement segment in partial lengths rather than attempting to stress the entire segment in one operation. The main advantage of doing this is that the amount of prestress required simply for overcoming subgrade friction could be reduced resulting in a savings in the total required amount of prestressing tendon. One possible way that this might be accomplished, using a concept similar to CPCPII or SPPCP, would be as follows:

(a) As before, the joint panel would be set in place on polyethylene sheeting at the starting end of the pavement segment.

(b) Next, only as many base panels (in the case of CPCPII) or full-depth panels (in the case of SPPCP) would be placed as could be stressed with one full stroke of the stressing jack.

(c) A central stressing panel would be set in place and the partial length of the pavement segment would be stressed.

(d) The next set of base or full-depth pavement panels would be set in place. Again, only as many panels would be placed as could be stressed with one full stroke of the stressing jack.

(e) Another central stressing panel would be set in place and the partial length of the pavement segment would be stressed.

This procedure would be continued until the joint panel at the terminal end of the pavement segment is reached. This approach has some problems, but the potential benefits of this type of approach make it well worth pursuing.

A variation of the above stressing scheme which is worth investigating further is to start construction at the midpoint of each pavement section and work longitudinally outwards in both directions simultaneously toward the transverse pavement joints. This would enable a high level of prestress to be obtained at all points along the pavement section with a reduction in the required amount of prestressing tendon.

(3) Another interesting and possibly very economical alternative method for longitudinally posttensioning the pavement involves the use of a modified approach to central stressing and could be used in conjunction with PCP Concepts 1 through 6. In this method, all of the longitudinal posttensioning tendons would be brought together in a single multitendon, central stressing coupler located at the midlength of the pavement section. This would permit the entire longitudinal prestress force to be applied with a single stressing operation. The coupler would operate in a manner similar to individual tendon couplers in that it would not bear on the concrete. Therefore, no high bearing stresses would be created by prestressing. The prestress force would be transferred to the precast joint panels and then distributed to the pavement in the same manner as before. The multitendon, central stressing coupler could be housed in a precast concrete box which would be located at the midlength of the pavement, with its top surface set flush with the top surface of the pavement. No problems are foreseen if the box extends below the pavement and into the subgrade. In fact, this would be beneficial in preventing the midpoint of the pavement from shifting. The box would be filled with concrete after completion of the stressing operations unless permanent access to the coupler was desired.

COMPARISON OF CONCEPT CHARACTERISTICS

The purpose of this section is to compare the characteristics of each of the seven new PCP concepts to determine: (a) the relative ability of each concept to address the problems encountered on previous projects; (b) the relative ability of each concept to effectively utilize the potential of PCP; and (c) what, if any, new problems are created with each concept. The seven PCP concepts are listed in Table 5.1.

TABLE 5.1. NEW PCP CONCEPTS

PCP Concept Number	PCP Concept Name
1	Central Stressing of Slip-Formed Pavement
2	Precast Joint Panels and Slip-Formed Pavement
3	Precast Joint Panels, Central Stressing Panels, and Slip-Formed Pavement
4	Composite Prestressed Concrete Pavement Type I (CPCPI)
5	Composite Prestressed Concrete Pavement Type II (CPCPII)
6	Segmentally Precast Prestressed Concrete Pavement (SPPCP)
7	Continuous Composite Concrete Pavement (CCCP)

Precast Concrete Panels

Concepts 2 through 6 represent a progressively increasing use of precast concrete panels in the construction of PCP. In addition, Concept 7 also makes extensive use of precast concrete panels. There are several advantages in using precast panels, the most significant being the application of factory methods to an otherwise custom-type industry.

Precasting concrete panels at central plants permits the use and reuse of highly productive automated equipment, weather protection during casting, stabilized experienced labor, concurrent operations removed from the site and from each other, simplification, excellent quality control, and standardization. Excellent quality control is attributable to the greater ease with which high standards (with respect to casting, compaction, curing, etc.) can be enforced in a plant as opposed to in the field and may result in a proportional improvement in the overall pavement quality as the percentage of precast is increased. However, the last item, standardization, is the key to ultimate success in the use of precasting. The industry could eventually develop off-the-shelf paving panels as they have done in the case of single-tees, double-tees, highway girder sections, slabs, and panels for miscellaneous other uses. A catalog similar to the AISC catalog of available steel shapes could ultimately be developed as the various manufacturers coordinate their operations more and more closely.

Precasting can be accomplished at plants as just described or on large jobs, when economic considerations so indicate, a temporary plant could be set up at the job site. This casting yard could be equipped with very sophisticated equipment or may utilize very simple forming and casting procedures.

The casting yard operation used for precasting, whether at a permanent or temporary plant, brings out the best economics in the use of prestressed concrete. The precasting yard lends itself to the economical use of sophisticated tensioning equipment and anchors, high-strength concrete, and accelerated curing. Pretensioning would be used in the production of the precast components. Efficient long-line production techniques with casting bed lengths of up to 600 feet could be used since they would permit a single tensioning operation. This would allow mass production standardized paving panels, complete with stressing pockets and all embedded items including transverse joint assemblies, tendons, lifting inserts, etc. Customizing of the individual panels could easily be accomplished on the casting bed and could include varying the panel lengths as necessary for each pavement strip. Accelerated curing would permit early removal of the elements and daily reuse of the forms (24-hour production cycle).

In planning precast construction, the following aspects must be carefully studied: proximity of precast suppliers, transportation costs, access to site, equipment required to place sections, lifting devices and strength during placing, possibility of on-site precasting, use of standard available sections, simplicity of sections for manufacture, largest pieces manageable, simple but effective jointry, and adequate tolerances.

Provided the designer avoids certain pitfalls, field assembly of the various precast concrete components would be relatively simple and straightforward and would proceed fairly rapidly. The lack of complexity could be a major asset in controlling the overall pavement cost. The four most common pitfalls which must be avoided in using precast concrete are as follows:

(a) Difficulty or impossibility of placing due to size, weight, or site obstructions.
(b) Difficulty of placing due to insufficient tolerance and/or inflexible jointry.
(c) Intricate jointry requiring extensive welding or difficult grouting.
(d) Failure to specify lift procedures and to design for loads that occur during lifting.

Summarizing the advantages of precast concrete, they may include lower costs, quicker construction, early structural strength, less congested construction sites, high quality, optimum use of labor and materials, and relatively easy rejection of imperfect pieces. The disadvantages may include difficult and expensive jointry, transportation costs, weight limitations, and labor jurisdictional problems. Additional advantages and disadvantages attributable to the use of precast concrete are pointed out in the following sections which will compare specific characteristics of the various concepts.

Design Approach

Either the elastic or the elasto-plastic design approaches for PCP could be utilized in the design of any of the concepts introduced in this chapter. However, there are factors which should be considered in selecting the design approach best suited to a particular concept. This section presents a discussion of these factors.

The objective of the elastic design approach for PCP is to find the optimum combination of pavement thickness and prestress level such that the ratio of the tensile stress to the modulus of rupture of the concrete is limited to an acceptable level. This ratio is based on preventing virtually all cracking over the service life of the pavement. With Concept 1, the allowable concrete tensile stress is based on the modulus of rupture of the slip-formed pavement (see Fig 1.1). With Concepts 2 through 6, two conditions must be checked. One is the modulus of rupture of the concrete and the other is the allowable tensile load across the joints between adjacent panels. As demonstrated in segmental bridge construction, tensile strengths in excess of the modulus of rupture of the concrete itself can be developed across properly constructed joints between adjacent precast segments. In addition, tensile stresses across these joints could be avoided altogether by merely providing a high enough prestress level.

Providing joints between precast panels which can transmit tensile stresses, or providing a prestress level high enough that tensile stresses are not developed across the joints could be somewhat expensive. Therefore, the elastic design approach probably favors the concepts which are either totally or mostly comprised of cast-in-place concrete, such as Concepts 1, 2, and 3.

The elasto-plastic design approach is characterized by cracking of the lower portion of the pavement. These cracks serve as momentary or partial plastic hinges under an applied load. After removal of the load, the cracks close due to the compressive stress induced by the prestress and the rigidity of the pavement is restored. It has been demonstrated both theoretically and experimentally that the load carrying capacity of PCP in this phase of behavior is well in excess of what it would be if the stresses were restricted to the elastic range. Concepts 4, 5, and 6, in which precast panels are used, probably are more suited to this design approach because there is no need to develop the tensile continuity across the joint between precast panels as is necessary with the elastic design approach.

The design approach utilized for Concept 7 would be a combination of the design approach used for continuously reinforced pavement and either the elastic or elasto-plastic design approach. The individual panels in this concept would be designed according to the previously discussed elastic or elasto-plastic design approaches and the joints between adjacent panels would be designed using the same approach employed in the design of continuously reinforced concrete pavement.

Bonded vs. Unbonded Tendons

As discussed in Chapter II, use of unbonded tendons offers advantages over bonded tendons in terms of PCP constructability. These advantages are elimination of metal ducts and elimination of grouting operations, both of which are generally necessary with bonded tendons. On the other hand, as pointed out, use of bonded tendons offers three potential advantages over use of unbonded tendons as far as improving the structural performance of PCP. These are: (a) development of reliable bond resistance at any point in the pavement, (b) improved resistance to volumetric change, and (c) improved pavement behavior if partially damaged.

While Concepts 1 through 6 appear to be equally well suited to the use of unbonded tendons, some of these concepts have definite advantages over others in terms of facilitating the use of bonded tendons. For instance, ducts for the transverse tendons would be provided in the precast panels with Concepts 4 and 5. This would result in a significant reduction in the number of metal ducts which would have to be placed in the field (if bonded tendons were desired), compared with Concepts 1, 2, and 3. No field placement of metal ducts would be required with Concept 6 since ducts for both the transverse and longitudinal tendons would be contained in the precast panels.

Another aspect of PCP Concept 5 deserving additional investigation is the possibility of obtaining the structural benefits of bonded longitudinal tendons without the attendant construction disadvantages. The anticipated sequence of steps employed in the construction of a segment of pavement in this manner was discussed. The foreseeable advantages are as follows:

(1) Significant cost savings would be realized due to the following factors: (a) plain prestressing tendons would be used instead of more expensive polypropylene sheathed tendons (also true of Concept 6); (b) no metal ducts would be required; and (c) no separate grouting operations would be necessary.

(2) The longitudinal tendons would be fully stressed before the slip-formed concrete is placed. Therefore, the longitudinal tendons are proof-loaded before being encased in concrete. This is an important advantage of this concept since it would allow a tendon to be easily repaired or replaced if found to be defective at the time of final posttensioning. Repairing or replacing tendons with the other concepts would be much more difficult and in some cases virtually impossible.

(3) Three separate field stressing operations, requiring a substantial amount of labor, would be required for each longitudinal tendon with PCP Concepts 1 through 4. However, with Concept 5, the longitudinal tendons would be fully stressed in a single operation resulting in a significant reduction in required labor and, therefore, pavement cost.

PCP Concept 7 would also have the structural benefits of bonded tendons without the need for metal conduits or grouting operations since only bonded, pretensioned tendons would be used.

Transverse Prestress

As discussed, the designers of the previous FHWA sponsored projects did not believe that transverse stressing was necessary. In fact, some of the designers even felt that transverse reinforcing was unnecessary. However, after review of the available literature on the design and performance of many previous projects, the staff of Project 401 strongly felt that transverse stressing was very important to the successful performance of PCP. Thus, transverse prestressing, utilizing various tendon configurations, is used with all of the PCP concepts introduced in this chapter.

A looped transverse tendons configuration, as shown in Fig 5.8, would be used with PCP Concepts 1, 2, and 3. The first advantage of looped transverse tendons is that they allow transverse stressing of a greater length of the pavement with a single stressing operation than is possible with straight transverse tendons, thus reducing the amount of time required for this operation in the field. The second advantage of looped transverse tendons is that they permit the exterior edges of the pavement strips to be slip-formed without the need for formwork and without interference from protruding tendons.

Unfortunately, there are problems associated with the use of looped transverse tendons. The first problem is that the looped transverse tendons would be difficult to lay out in the field and hold in the desired configuration. The second problem is in preventing the portions of each transverse tendon which protrude from the first pavement strip from interfering with slip-forming operations or becoming damaged while left exposed during the interim period between placement of successive pavement strips. The third problem with the use of looped transverse tendons is that the loops would cause higher prestress losses, thus requiring the use of more tendons to obtain the desired level of transverse prestress.

The first two problems could be avoided by providing rigid hollow conduits in the first pavement strip along the desired paths of the transverse tendons (as mentioned). These conduits would permit the installation of the looped transverse tendons to be delayed until immediately before the second pavement strip is to be placed, thus avoiding both problems.

With PCP Concepts 4, 5, and 6, transverse prestressing would be provided by a combination of pretensioning, which would be done at the precast plant in the production of the precast concrete panels, and posttensioning, which would be done in the field. This combination of pretensioning and posttensioning has the following advantages:

(a) Some pavement design procedures utilize lane distribution factors, recognizing that traffic loads are not the same for all of the lanes of a multi-lane highway. The use of precast prestressed concrete panels would facilitate the incorporation of the concept of lane distribution factors in PCP by permitting the level of transverse prestress for each individual lane to be adjusted in accordance with anticipated differences in traffic volume. This would be done by merely varying the level of pretensioning used in the manufacture of the precast concrete panels.

(b) In the case of multiple longitudinal strip or lane-at-a-time pavement construction, it is very likely that the individual lanes will be subjected to traffic before construction of the entire pavement width is completed. The use of precast pretensioned concrete panels would ensure that each individual lane would have some transverse prestress, in addition to longitudinal prestress, during this initial period of exposure to traffic without the need for transverse posttensioning operations for each lane.

(c) The pavement could be designed such that the transverse flexural strength requirement would be satisfied by either a composite section consisting of precast prestressed concrete panels and cast-in-place concrete wearing course in the case of PCP Concepts 4 and 5 or solely by the precast prestressed concrete panels in the case of PCP Concept 6. This would mean that the only transverse posttensioning that would have to be done in the field would be that amount necessary to prevent the longitudinal pavement strips or lanes from separating which would result in a substantial reduction in the number of required posttensioning operations.

With PCP Concept 7, all flexural strength requirements would be satisfied by a composite section consisting of precast prestressed concrete panels and cast-in-place concrete wearing course. Therefore, the first two advantages listed for PCP Concepts 4, 5, and 6 would also be applicable to this concept. In addition, this concept would have the major advantage of completely eliminating all field posttensioning operations (longitudinal as well as transverse) since precast panel separation would be prevented by the use of epoxy-coated tie bars. This would reduce the field labor requirement and would greatly speed construction.

Friction-Reducing Mediums

As discussed, a double layer of polyethylene sheeting was provided under most of the pavement slabs on the previous FHWA sponsored projects to act as a friction-reducing medium between the slab and the base course. Several significant problems were encountered with the use of this material. These problems were in the following areas: (a) handling and placing the sheeting; (b) maintaining the sheeting in an undamaged condition throughout the construction phase; and (c) preventing the sheeting from causing damage to the pavement during construction. Each of the first six PCP concepts introduced in this chapter will be evaluated in the following paragraphs in terms of its ability to address these problem areas. Of course, the seventh concept is superior to all the others in terms of avoiding the problems associated with polyethylene sheeting since no friction-reducing medium between the pavement and the base course would be used. This would result in greatly simplified construction and major cost savings in materials and labor.

Problem 1. On the previous projects, the sheeting became extremely unwieldy with only moderate breezes. As a result, large crews were required to handle the sheeting and measures were necessary to temporarily secure it in place. With Concepts 1, 2, and 3, the sheeting would be handled and placed in much the same manner as on the previous FHWA sponsored projects. Thus these concepts would not provide any advantages with respect to these problems.

On the other hand, a significant improvement in terms of handling and placing the polyethylene sheeting would be obtained with Concepts 4, 5, and 6. With these concepts, precast panels would be placed on the polyethylene sheeting immediately after short sections of the sheeting have been unrolled. Thus the sheeting would be promptly secured in place, eliminating both the problem of displacement of the sheeting by the wind and the need for temporary measures to secure it in place.

Problem 2. Maintaining the polyethylene sheeting in an undamaged condition throughout the construction phase is important for at least two reasons. First, damage to the sheeting reduces its ability to provide reliable reduction of the friction between the pavement and the base course. This reduction is essential in order to obtain the desired level of prestress in the pavement. Second, the polyethylene sheeting must remain in good condition for the service life of the pavement to allow the pavement to respond to hygrothermal changes without developing excessive tensile stresses.

With Concepts 1, 2, and 3, a number of construction activities (i.e., placement of chairs to support the tendons, placement of longitudinal and transverse tendons, tying tendons together at their points of intersection, placement of forms, etc.) would have to be performed after the polyethylene sheeting has been placed on the prepared base course and before the pavement slab could be placed. The length of time which would be required to accomplish these activities would range from several hours to several days depending on factors such as the weather, available manpower, and the construction sequence employed by the contractor. Due to the fragile nature of the polyethylene sheeting, it would be vulnerable to damage caused by wind and construction-related foot and vehicular traffic throughout this period of exposure. In fact, the possibility of damage caused by construction-related foot traffic may even be somewhat worse with Concepts 1, 2, and 3 than was experienced on the previous FHWA sponsored projects. This is due to the fact that these concepts have more construction activities requiring foot traffic (such as handling and placing transverse tendons and chairs to support the tendons) which must be conducted directly on top of the polyethylene sheeting. Of course, increases in the amount of damage during the construction process would be accompanied by increases in labor and time requirements to make the necessary repairs to the sheeting.

In addition, as learned by the Project 401 staff in the tests conducted near Valley View, Texas (Refs 18, 78, 31), a double layer of polyethylene sheeting is very slick and, as a result, extreme care must be taken when working on it to avoid falls. Therefore, not only is there the probability of damage to the polyethylene sheeting due to construction-related foot traffic, but there is also the very real possibility of injury to the workers caused by falls. This increases the possibility of workers' compensation and employers' liability claims.

Another disadvantage that Concepts 1, 2, and 3 have in common with the previous FHWA sponsored projects is the fact that the pavement would be slip-formed directly on the polyethylene sheeting. This could easily tear or displace the sheeting, as discussed, resulting in the pavement concrete being deposited directly on the base course.

One of the major advantages of Concepts 4, 5, and 6 is that the likelihood of damaging the polyethylene sheeting during construction is greatly diminished because the polyethylene sheeting would be covered and protected by the precast panels immediately after placement. Therefore, the possibility of damage caused by windy conditions would be virtually eliminated. In addition, all construction-related foot traffic would be on top of the precast panels and not directly on the sheeting and, as a result, the possibility of damage to the sheeting and injury to workers due to falls would be avoided.

In addition, the pavement riding surface would be slip-formed on top of the precast panels and not directly on the polyethylene sheeting with Concepts 4 and 5. Thus the possibility of damaging the polyethylene as a result of this activity would be eliminated. With Concept 6, there would not be any possibility of damage caused by slip-forming since no slip-forming would be employed.

Problem 3. Not only does the likelihood exist with Concepts 1, 2, and 3 that the polyethylene sheeting would be damaged as a result of slip-form paving directly on it, but the possibility also exists that the polyethylene sheeting could damage the pavement. As reported on some of the previous FHWA sponsored projects, the polyethylene sheeting has been observed to slide and fold ahead of the slip-form paver and the folds become trapped in the pavement. This could cause weakened planes in the pavement and might have a detrimental effect on its service life.

Again, the pavement riding surface would be slip-formed on top of the precast panels with Concepts 4 and 5. Therefore, virtually no possibility exists with these concepts of having the polyethylene sheeting slide and fold ahead of the slip-form paver or of the folds then becoming trapped in the pavement. Of course, as previously mentioned, no slip-forming would be used with Concept 6 and, therefore, sliding and folding of the sheeting would not even be a consideration.

Gap Slabs vs. Central Stressing

The problems experienced with gap slabs on the previous FHWA sponsored projects were discussed. As stated, one of the primary objectives identified in the early stages of Project 401 was to find a viable alternative to the use of gap slabs for stressing the longitudinal posttensioning tendons. Central stressing was found to be the most promising alternative and it is used in PCP Concepts 1 through 6. Of course, neither gap slabs nor central stressing would be required with PCP Concept 7 since no field posttensioning operations are used. Consequently, all seven PCP concepts are successful in eliminating the need for gap slabs.

In addition to the fact that it eliminates the need for gap slabs, central stressing has the added advantages of centralizing all longitudinal tendon stressing operations and simultaneous application of approximately equal amounts of prestress at each end of the pavement section. However, the use of central stressing is not without its problems--the number and magnitude of which are dependent on the particular PCP concept. For instance, the following problems associated with forming the central stressing pockets for the longitudinal and transverse tendons are foreseeable with PCP Concept 1:

(a) The proper location of the stressing pockets for each longitudinal and transverse tendon must be determined in the field. This is a time consuming, labor intensive task, especially if the prestressing tendons are not cut to the required lengths before being shipped to the job site. (The method described, in which precut tendons are used, may lessen the time and labor required in the field to accomplish this task.)

(b) Another problem is in holding the stressing pocket forms in position during concrete placement. This problem was experienced in the field tests conducted by the Project 401 staff (Ref 78). (A possible method for avoiding this problem was also proposed).

(c) The forms for the tendon stressing pockets might be hit by the bottom conforming screed of the passing slip-form paver. This happened on one occasion with wooden box forms which were used on the Hogestown, Pennsylvania project to form the gap between pavement sections (Ref 13). The forms were torn loose and the concrete had to be removed by hand during placement of the joint.

(d) The vibrators attached to the slip-form paver would have to be positioned to avoid disturbing the stressing pocket blockouts and in doing so may result in poor concrete compaction in the vicinity of the stressing pocket blockouts. However, proper compaction of the concrete in these areas must not be neglected. Therefore, use of hand-held vibrators would probably be required in these areas.

(e) Special attention to finishing of the concrete surface in the vicinity of the stressing pocket blockouts may be required. The possible need for some hand finishing in these areas was indicated in the field tests conducted by the Project 401 staff (Ref 78).

With PCP Concepts 2 and 3, all necessary anchorage and central stressing pockets for the longitudinal tendons would be provided in the precast concrete panels, leaving only the stressing pockets for the looped transverse tendons to be formed in the field. Consequently, there would be a significant reduction in the problems associated with forming these pockets in the field.

As with PCP Concepts 2 and 3, all necessary longitudinal tendon anchorage and central stressing pockets would be provided in the precast concrete panels with PCP Concepts 4, 5, and 6. In addition, straight transverse tendons that would be stressed at the exterior edges of the pavement are used with PCP Concepts 4, 5, and 6. Therefore, none of the previously described problems associated with field forming of stressing pockets would be experienced with these concepts.

One of the disadvantages with the gap slabs used on the previous FHWA sponsored projects was that they require an additional concrete placement operation and curing period after the final stress had been applied to the PCP slabs which slows the entire construction process and delays opening the pavement to traffic. Unfortunately, the use of central stressing pockets is similar to the use of gap slabs in this respect.

Concreting the central stressing pockets may be even more of a problem than for gap slabs because the steps of filling with concrete, vibrating to assure good compaction, striking the surface level, texturing to match, and cleaning the surface of the surrounding pavement of excess concrete and spillage from the concreting operation must be repeated for each stressing pocket (and there would be as many stressing pockets as there are tendons), whereas, for the gap slabs the above steps would only have to be done once for each pavement section.

Another problem associated with the use of central stressing is that it requires the use of tendon couplers (see Fig 5.9). This extra piece of hardware adds to the total cost of the pavement, especially since the coupler that appears to be best suited to PCP construction is a proprietary item. This problem is most significant in connection with PCP Concepts 1 and 3 since these concepts require the use of the most couplers (one for each longitudinal and transverse tendon).

The required number of couplers would be substantially reduced with Concept 2 since they would only be used for the transverse tendons, thus making couplers a much less significant cost item.

Use of couplers with PCP Concepts 4, 5, and 6 would be totally optional. This is a major advantage of these concepts since it would afford the pavement designer flexibility in selecting the most economical method of stressing the tendons.

Prestress Force Transference

The performance of PCP from the time of application of initial prestress through the end of the pavement's service life is significantly influenced by the manner in which the prestress force is transferred from the longitudinal posttensioning tendons to the pavement. The purpose of this section is to show how the methods used for transferring the prestress force with each of the first six PCP concepts influence pavement performance. Of course, transference of the prestress force from the longitudinal tendons to the pavement would not be a consideration with PCP Concept 7 since no field posttensioning operations would be used.

(1) Effects on Application of Initial Prestress. Shrinkage cracking near midlength of the pavement within 24 hours of concrete placement has been a problem on several of the previous FHWA sponsored projects. To prevent this type of cracking it is important to stress the longitudinal tendons as early as possible. The time at which these tendons can be stressed, as well as the magnitude of the stress that can be applied, are functions of the particular PCP concept. For instance, with PCP Concept 1, each individual tendon would have end anchors of the type shown in Fig 3.2 and each of these would bear directly on the immature concrete, thus making the application of early prestress dependent on factors such as anchor bearing area, tendon spacing, and concrete strength. Concrete strength, in turn, is dependent on temperature, humidity, mix design, etc. As a result, some nonprestressed reinforcement may have to be provided in the tendon anchorage zone with PCP Concept 1 to prevent undue delay in application of early stress and to prevent splitting and cracking of the immature concrete.

On the other hand, with PCP Concepts 2 and 3, the prestress force would be transferred from the longitudinal tendons to the mature concrete of the precast joint panels. These panels would, in turn, transfer the force to the immature slip-formed concrete. The stresses caused by the joint panels bearing on the immature slip-formed concrete would be much lower than if the individual strand anchorages bore directly on this concrete, as with Concept 1. Therefore, the longitudinal tendons could be stressed to a higher level with Concepts 2 and 3 while the strength of the slip-formed concrete is still low. This is an important advantage in the prevention of early shrinkage cracking. Care must be exercised, however, to prevent excessive creep of the immature concrete due to the application of compressive stresses which are too high at early concrete ages.

PCP Concept 4 would work in the same manner as 2 and 3 with the exception that the precast joint panels would transfer the prestress force to a composite section consisting of precast base panels and slip-formed concrete wearing course.

Like PCP Concepts 2, 3, and 4, the prestress force with Concepts 5 and 6 would be transferred from the longitudinal tendons to the mature concrete of the precast joint panels. However, unlike Concepts 2, 3, and 4, the precast joint panels would not bear on immature concrete, but rather solely on the precast base panels with Concept 5 and the full-depth pavement panels with Concept 6. Consequently, none of the problems associated with the transfer of prestress force from longitudinal tendons to immature concrete would be experienced with these concepts.

(2) Long-Term Effects. Not only do individual tendon anchors cause problems as far as early stressing, they can also cause long-term problems. The distribution of compressive and tensile stresses at the ends of each pavement section caused by the use of these anchors would be similar to that shown in Fig 5.28. Clearly, the area between tendons is not placed in compression and may, in fact, be subjected to tensile stresses simply by stressing the longitudinal tendons. In addition, the end areas of each pavement section are subjected to higher traffic load stresses than are interior areas of the pavement. These two factors combine to make this area especially vulnerable to damage when individual tendon anchors are used which is the case with PCP Concept 1. Small bolts are to be provided between the tendon anchors and the transverse joint assembly. While the primary purpose of these bolts is to ensure proper positioning of the tendons, they are also intended to transfer some of the prestress force to the joint assembly. Whether they actually will transfer any force remains to be seen.

On the other hand, the method for anchoring the longitudinal tendons which would be used with PCP Concepts 2 through 6 (see Figs 5.12, 5.13, and 5.14) would transfer the entire prestress force to the transverse joint assembly. Therefore, another extremely important advantage of these concepts over Concept 1 is that the critical end regions of each PCP slab would be placed in compression to the very edge of the pavement and no tensile stresses would be induced in the concrete as a result of prestressing. This

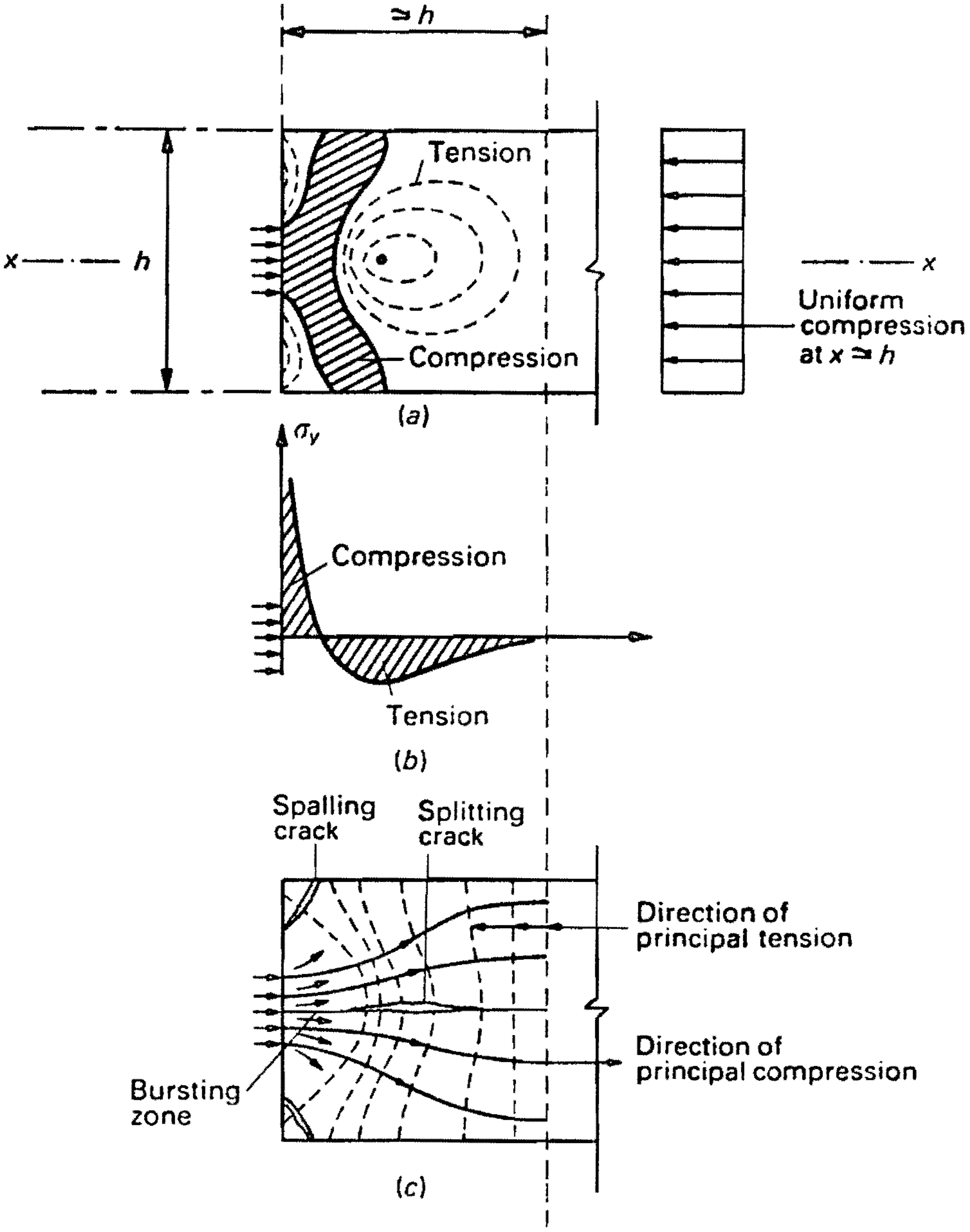


Fig 5.28. Compressive and tensile stresses at the ends of each pavement section (Ref 87).

would result in a decreased likelihood of failure in these regions of the pavement.

Tendon Placement

As discussed, tubes or J-bars attached to the paver were used on most of the previous FHWA sponsored projects to position the longitudinal tendons in the pavement during slip-forming. One of the main advantages of this method was that it eliminated the need to support the longitudinal tendons on chairs during slip-forming. However, use of tubes or J-bars attached to the paver is much less feasible when transverse prestressing (or reinforcing for that matter) is provided. The reasons for this are as follows:

(a) Obviously, use of this method would prevent preplacement of the transverse tendons on top of the longitudinal tendons since they would conflict with passage of the paver. The only other way to place the transverse tendons would be to depress them into the pavement after the paver has passed. This would probably be a difficult operation.

(b) The probability is great that the tubes or the J-bars attached to the paver would snag the transverse tendons if they were located below the longitudinal tendons.

(c) Regardless of whether the transverse tendons are on top of or below the longitudinal tendons, they need to be tied to the longitudinal tendons to prevent them from being displaced by the concrete mass which is pushed ahead of the slip-form paver. This in itself would prevent the tubes or J-bars from sliding along the longitudinal tendons.

For these reasons, the tendons must be supported on chairs during slip-form paving with Concepts 1, 2, and 3. This is a significant disadvantage of these concepts due to the additional material and labor costs associated with this operation.

An important advantage of Concepts 4, 5, and 6 is that no chairs would be necessary to support the tendons. With Concepts 4 and 5, the longitudinal tendons would be placed directly on the surface of the precast concrete base panels and conduits for the transverse tendons would be contained within the precast panels. With Concept 6, conduits for both the longitudinal and transverse tendons would be contained within the precast panels.

Problems associated with field placement of posttensioning tendons would be completely eliminated with Concept 7, since no posttensioning tendons are used with this concept.

Transverse Joints

Another potential problem area with Concept 1 is in holding the transverse joint assembly stationary during the application of the pretension to the longitudinal tendons before the concrete is placed. As discussed, it is important to pretension the longitudinal tendons for two primary reasons: (a) to keep them in straight alignment during concrete placement so that the tendons remain in the desired position in the pavement, and (b) to minimize the amount of wobble friction loss in the tendons. The recommended tension suggested in previous reports is 10,000 psi (Ref 114). It would be extremely difficult (if not impossible) to temporarily secure the transverse joint assembly to the subgrade to resist the force resulting from stressing the longitudinal tendons on only one side of the joint assembly to 10,000 psi. Therefore, the only feasible way of applying this level of tension to the longitudinal tendons before the concrete is placed would be to lock the two halves of the transverse joint assembly together and attempt to apply the pretension to the tendons on both sides of the joint at approximately the same time. Some type of reaction (possibly a heavy piece of machinery) must be provided at the first and last transverse joint assemblies in a run of pavement slabs to resist the unbalanced load at these locations. Temporary attachment of each transverse joint assembly to the subgrade (as discussed would still be necessary to resist the inevitable discrepancies between the loads applied to each side of the assembly.

Placement and consolidation of the concrete in the vicinity of the transverse joint assembly would be another potential problem area with Concept 1. Due to the presence of the joint assembly, the vibrators attached to the slip-form paver must be raised out of the concrete. Thus a region of poorly compacted concrete would be created on either side of the joint assembly. To compensate for this problem, use of hand-held vibrators in this area would probably be required. As discussed, problems of this nature were experienced on some of the previous FHWA sponsored projects and it is likely that similar problems will be encountered with Concept 1.

With Concepts 2 through 6, the transverse joint assemblies would be incorporated into the joint panels at the precasting plant. Therefore, many of the difficulties associated with field placement of these assemblies, and concrete placement and compaction in the vicinity of these assemblies, would be eliminated. This would help prevent some of the transverse joint failures that have been experienced on other PCP projects.

Of course, Concept 7 is superior to all the others in terms of avoiding the problems associated with transverse joints since no active transverse joints would be used with this concept. This would result in greatly simplified construction and major savings in materials and labor both in terms of initial cost and long-term maintenance.

Multiple Longitudinal Strip Construction

The importance of being able to construct a pavement in two or more successive, contiguous, longitudinal strips was discussed in detail. However, as pointed out, all of the PCP slabs on the previous FHWA sponsored project were constructed full width in a single placement operation and, hence, very little experience was gained from these projects in terms of multiple longitudinal strip construction of PCP. What little experience was gained came from the placement of concrete shoulder slabs on at least two of these projects after completion of the construction of the PCP. Using both the reported behavior of the longitudinal joints between these shoulder slabs and the PCPs and intuitive reasoning, some of the problems which may be encountered with multiple longitudinal strip construction of PCP can be envisioned. Four of the most significant problems which are anticipated during construction are as follows: (a) difficulties caused by the use of slip-form paving, (b) undesirable bonding of adjacent longitudinal pavement strips, (c) undesirable dowel action by the transverse tendons where they cross longitudinal construction joints, and (d) lack of transverse posttensioning until after completion of construction of all longitudinal pavement strips. Each of these problems and their implications with respect to the PCP concepts introduced in this chapter will be examined in detail in the following discussion.

Problem 1. As pointed out, slip-form paving is the most popular method for constructing cast-in-place concrete pavement. However, difficulties are anticipated with the use of this technique in connection with multiple longitudinal strip construction with some PCP concepts.

First of all, one of the major advantages with slip-form paving is that the costly and time consuming procedures of placing full-depth longitudinal edge forms, shooting top-of-form elevations, and adjusting the forms to the desired top-of-pavement elevations are eliminated. Unfortunately, the use of transverse posttensioning necessitates the use of some edge forming with PCP Concepts 1, 2, and 3 even if slip-form paving is used.

As discussed, two methods would be available for installation of the transverse tendons for PCP Concepts 1, 2, and 3. The first method would be to place the looped tendons prior to casting the pavement strip. Half forms would be necessary with this method along the longitudinal edge of each pavement strip against which a contiguous pavement strip is to be subsequently placed. These half forms would serve to form the edge of the slab below the level of the protruding transverse tendons and to support the ends of these tendons. Fortunately, the top elevation of these forms would not be as critical as full-depth forms and shooting top-of-form elevations and adjusting the forms to the desired top-of-pavement elevations would not be required.

The second method for installation of the transverse tendons for PCP Concepts 1, 2, and 3 would be to provide hollow conduits in the pavement strip along the desired paths of the transverse tendons through which these tendons would be threaded after casting of the pavement strip. Unfortunately, even if the hollow conduit method is used, half forms along interior longitudinal pavement edges would probably still be required. This is because the tolerance in the alignment of the ends of the conduits which is necessary to allow the slip-form paver to pass without disturbing the conduits would be prohibitively tight and virtually impossible to achieve in the field on a production basis.

Another potential difficulty associated with the first method for installation of the transverse tendons arises from the close tolerances between the passing slip-form paver and the protruding transverse tendons. The hollow conduit option might have a definite advantage in this regard, since there would not be any protruding tendons to interfere with the slip-forming operation.

With PCP Concepts 4 and 5, hollow conduits would be provided in the precast concrete base panels to accommodate the transverse posttensioning tendons and these tendons would not be installed until after construction of all contiguous longitudinal pavement strips. This would provide the following major advantages in connection with multiple longitudinal strip construction of PCP: (a) no longitudinal edge forming would be required; (b) there would be no protruding transverse tendons to interfere with slip-forming of the concrete riding surface; and (c) there would be no prohibitively tight tolerances on the alignment of the ends of the hollow conduits to interfere with passage of the slip-form paver.

With PCP Concept 6, the pavement would be entirely composed of precast concrete panels. Thus, none of the difficulties associated with multiple longitudinal construction using slip-forming would be applicable to this concept.

With PCP Concept 7, either concrete or asphalt wearing surfaces could be used. In either case, no longitudinal edge forming would be required and there would not be anything protruding from the edge of the pavement strips which might interfere with placement of the wearing course.

<u>Problem 2</u>. The second problem, common to PCP Concepts 1 through 5, is that the freshly cast concrete of one pavement strip will bond to adjacent longitudinal pavement strips. This bonding must be prevented during the construction period to permit independent longitudinal movement of each pavement strip. This will allow most of the shortening of each individual pavement strip due to shrinkage, creep, and longitudinal posttensioning to occur without damaging the pavement. In addition, unrestrained longitudinal movement along the joint between adjacent pavement strips will help ensure

that the desired distribution of longitudinal compressive stress is obtained. However, a permanent slip-plane must not be created in the pavement, regardless of the measures employed to temporarily prevent bonding, because the magnitude of the transverse compressive stress may not be sufficient to prevent joint faulting and stress concentrations caused by loading of a free edge.

There are basically three methods which can be used with PCP Concepts 1 through 5 to prevent bonding. In increasing order of effectiveness, these methods are: (a) spray-applied bond breaker, (b) polyethylene sheeting, and (c) a gap or opening between adjacent longitudinal pavement strips. A discussion of each method and the problems associated with its use follows.

The first method is to coat the longitudinal edges of each pavement strip with a spray-applied bond breaker or concrete release agent immediately before casting the adjacent strip. The three problems with this method are as follows:

(a) A continuous, uniform, gap-free film of the spray-applied bond breaker would be difficult to obtain over the entire longitudinal edge of the pavement strip.

(b) Mechanical interlocking across the longitudinal joint caused by surface roughness may prevent differential longitudinal movement from occurring even if the spray-applied bond breaker effectively prevents bonding.

(c) Since the film of bond-breaking material could not be cleaned off the edge of one pavement strip after the adjacent pavement strip is placed, it may create permanent vertical slip-planes at various locations along the longitudinal joint.

The second method of preventing bonding would be to cover the longitudinal edges of each pavement strip with either a single or double layer of polyethylene sheeting immediately before casting the adjacent strip. While this method is more likely to be effective than the first, at least three problems are foreseeable with its use. These problems are as follows:

(a) It would be difficult to cut and shape the polyethylene sheeting to fit around each protruding transverse tendon.

(b) Some mechanical interlocking is likely to occur across the longitudinal joint with the polyethylene sheeting, although probably less than with a spray-applied bond breaker.

(c) The polyethylene sheeting must be removed from the joint after the pavement strips have been longitudinally posttensioned and the majority of the shrinkage and creep have occurred to prevent a permanent vertical slip-plane from being created in the pavement. However, the sheeting may be tightly clamped in place between the two pavement strips and complete removal may prove to be difficult, if not impossible. In addition, even if the sheeting is successfully extracted from the joint, the slab edges may be quite smooth, thus causing permanent vertical slip-planes along the longitudinal joint anyhow.

The third method of preventing bonding would be to provide a gap or opening between adjacent longitudinal pavement strips. Although this method is the most certain of the three to be effective, there are foreseeable problems associated with its use. These problems are as follows:

(a) This method would not permit the longitudinal edges of previously placed pavement strips to be used as forms. Therefore, the length of interior longitudinal pavement edge which must be slip-formed would be greatly increased. As discussed in Problem 1, there are several problems associated with the slip-forming of this pavement edge with some of the PCP concepts.

(b) This method would require a separate concrete placement or grouting operation in order to fill the longitudinal gap between the pavement strips.

Although any of these three methods for temporarily preventing bonding between adjacent pavement strips could be used with PCP Concepts 1 through 5, the most appropriate method in each case is a function of the individual concept characteristics. For example, PCP Concepts 1, 2, and 3 are entirely cast in place, therefore, bonding must be temporarily prevented over the entire surface of the longitudinal edge of each pavement strip. Also, with these PCP concepts the transverse tendons would protrude from the edge of the pavement strip. The spray-applied bond breaker would be the most appropriate method for prevention of bonding for use with these PCP concepts because it could be applied around the protruding transverse tendons without the cutting and shaping that would be required with the polyethylene-sheeting bond breaker. In addition, the spray-applied bond breaker would allow the adjacent pavement strip to be placed in direct contact with the previously placed strip, thus avoiding the problems associated with close tolerances between the slip-form paver and the protruding tendons and the need for a separate concrete placement operation to fill the gap between adjacent pavement strips which would be encountered with this third method.

With PCP Concepts 4 and 5, only the pavement wearing course would be cast in place and, hence, temporary prevention of bonding would only be necessary between the uppermost portion of each pavement strip. Also, the transverse tendons would be contained in the precast concrete panels which is below the level where bonding must be temporarily prevented. Therefore, with these concepts, the polyethylene sheeting bond breaker would be the most appropriate method for prevention of bonding because it would not have to be cut and fit around protruding transverse tendons and it would be more effective than the spray-applied bond breaker. Even the third method of temporarily preventing bonding could be used with these PCP concepts without the problem of close tolerances between the slip-form paver and protruding transverse tendons by simply delaying the installation of the straight transverse tendons until after placement of the slip-formed pavement wearing course. However, the need for a separate concrete placement operation in connection with the use of this method would be less desirable than the polyethylene-sheeting bond breaker.

Bonding between adjacent pavement strips during the construction period would not be a consideration with PCP Concept 6 since no cast-in-place concrete would be used.

Bonding would not be any more of a problem with PCP Concept 7 than it is with conventional concrete pavement because the pavement strips would not be posttensioned, thus independent longitudinal movement of adjacent strips would not be required. In addition, restraint of shrinkage and creep stress caused by bonding across longitudinal joints between pavement strips would not be a problem with this concept since pavement cracking at a regular controlled interval would not be objectionable.

Problem 3. The third problem anticipated with multiple longitudinal strip construction of PCP is that the transverse tendons may act as dowels where they cross the longitudinal joint between adjacent pavement strips. If not prevented, dowel action could restrain the necessary differential longitudinal movement across the joint between adjacent pavement strips and could increase the tendon friction losses by causing the strands to bind in their sheathings where they cross the joint (see Fig 5.29). In fact, damage to the sheathing, or even the strand, could occur as a result of this binding.

There are basically three methods to prevent this dowel action from occurring. In increasing order of effectiveness, these methods are: (a) a sleeve of crushable material around each protruding transverse tendon, (b) a horizontally flared metal conduit section on every transverse tendon on both sides of each longitudinal joint, and (c) a gap or opening between adjacent longitudinal pavement strips. A discussion of each method and the problems associated with its use follows.

The first method is to provide a sleeve of crushable material (i.e., polyurethane foam or corrugated wax impregnated fiberboard tubes) around each protruding transverse tendon as shown in Fig 5.30. This material would provide a void around each tendon which would permit differential longitudinal movement of adjacent pavement strips to occur without damaging either the pavement or the tendons. The following two problems are forseeable with this method:

(a) Placing the crushable material sleeves around each protruding transverse tendon in the field and then securing them in place in some manner (probably with duct tape or metal or plastic ties) to prevent them from being

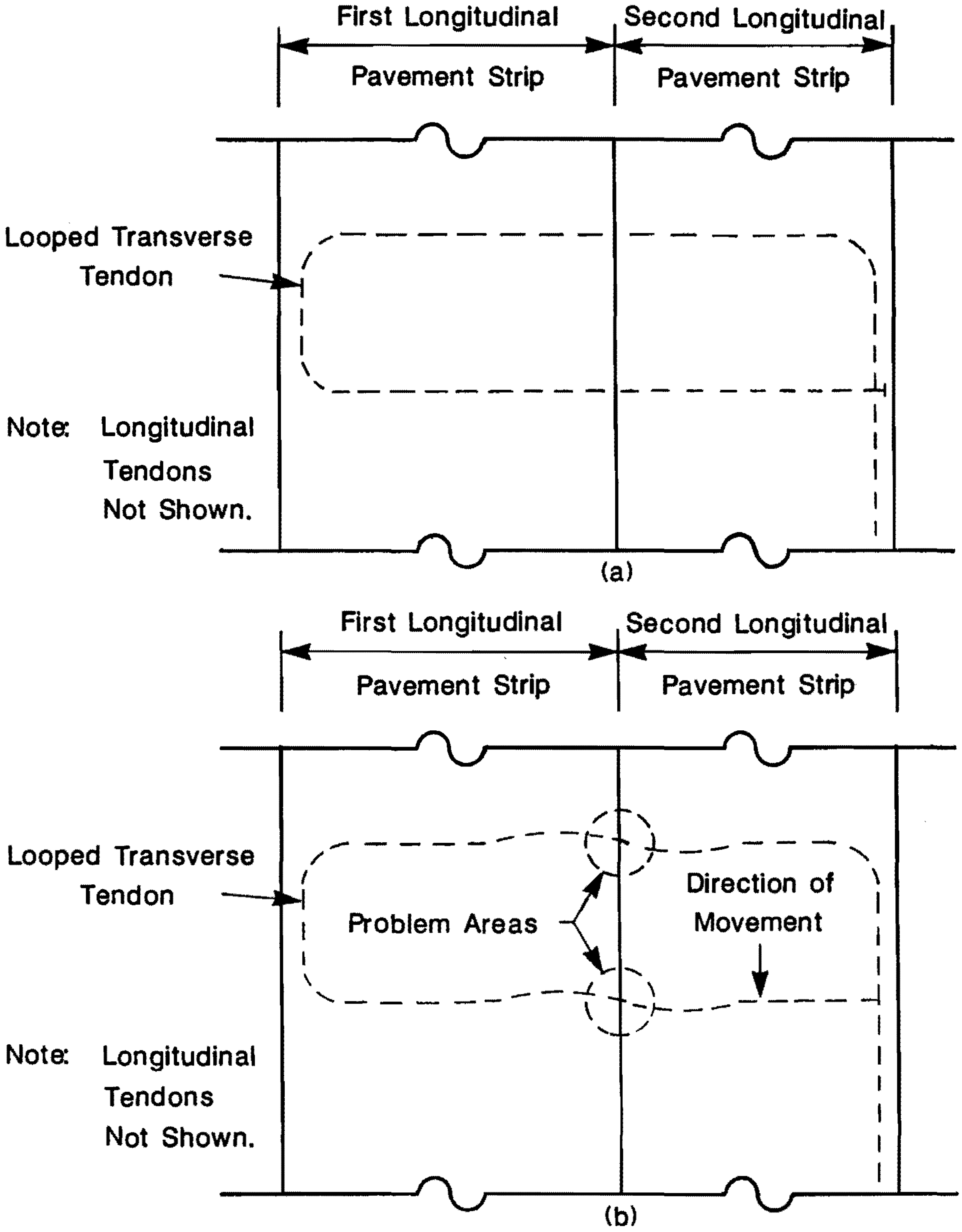
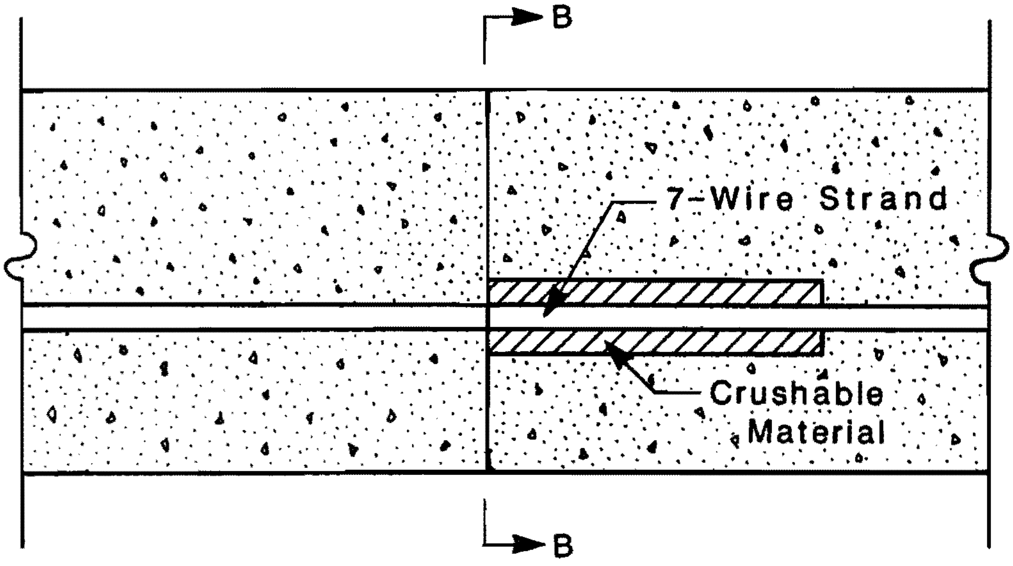
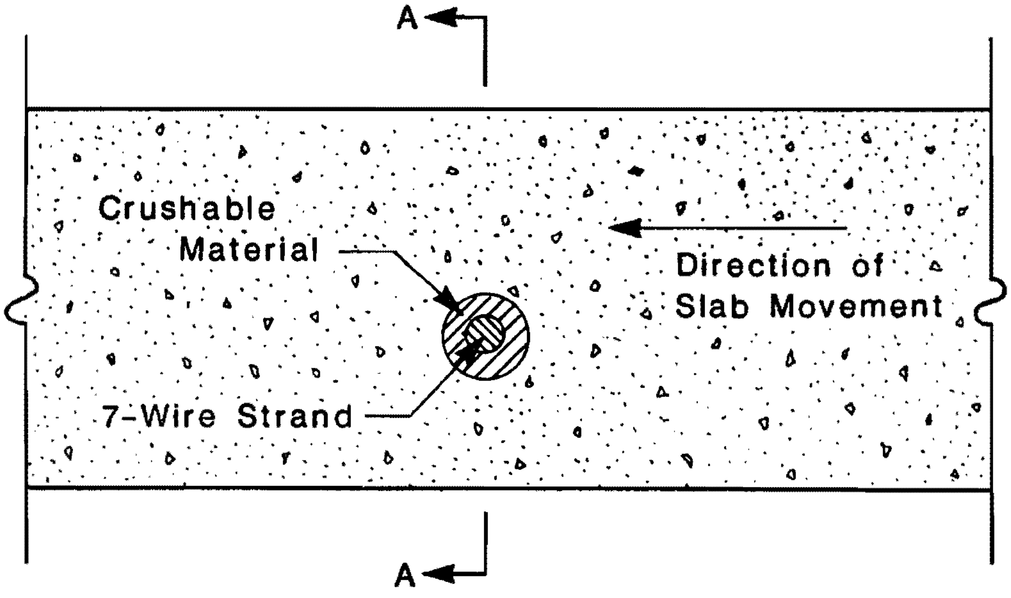


Fig 5.29. Longitudinal pavement joint.



Section A-A



Section B-B

Fig 5.30. Crushable material sleeve.

displaced during concrete placement would be time consuming and labor intensive.

(b) The void which would be formed around each transverse tendon would be permanent. This could cause two problems. First, the void would create localized weakened areas in the pavement which might result in pavement cracking. Second, this permanent void would prevent the dowels from providing the type of dowel action that would be beneficial in preventing relative vertical movement of adjacent pavement strips.

The second method to prevent undesirable dowel action across longitudinal joints during construction is to provide a horizontally flared metal conduit section on every transverse tendon on both sides of each longitudinal joint (see Fig 5.12). This method has the following advantages over the first method:

(a) The horizontally-flared metal conduit sections would permit the necessary differential longitudinal movement to occur across the joints between adjacent pavement strips while still allowing the transverse tendons to provide the type of dowel action that would be beneficial in preventing relative vertical movement of adjacent pavement strips.

(b) The strength of the metal conduit sections would help to offset the reduction in the pavement section caused by providing a void around each transverse tendon.

The following two problems are forseeable with this method:

(a) Placing the horizontally flared metal conduit sections on each transverse tendon in the field and then securing them in place to prevent them from being displaced during concrete placement would be time consuming and labor intensive.

(b) Care must be taken to prevent intrusion of concrete into the flared conduit sections during slip forming.

The third method to prevent undesirable dowel action from occurring across longitudinal joints during construction is to provide a gap or opening between adjacent pavement strips. This method has the advantage that a permanent void is not created around each transverse tendon in the vicinity of each longitudinal joint. However, it would probably be the least desirable method due to the problems associated with its use which were discussed earlier in this section.

Either of the first two methods for preventing undesirable dowel action across longitudinal joints during construction could be used with the looped transverse tendons which are proposed to be used with PCP Concepts 1, 2, and 3. Both methods would permit successive longitudinal pavement strips to be cast directly against preceding strips, thus minimizing the number of longitudinal pavement strip edges where half forms would be required and where difficulties would be encountered with close tolerances between the passing slip-form paver and the protruding transverse tendons.

The second method of preventing undesirable dowel action would be preferrable for use with PCP Concepts 4, 5, and 6 since horizontally-flared end sections could simply be provided on the ends of the metal conduits which are provided in the precast concrete panels as illustrated in Figs 5.17, 5.18, 5.20, and 5.22. This would have the advantage of not requiring a separate installation operation in the field as would be necessary with PCP Concepts 1, 2, and 3.

Problem 4. With PCP Concepts 1, 2, and 3, each pavement strip would only be longitudinally prestressed at the time it is subjected to construction traffic loads since transverse prestressing would not be done until after the construction of all pavement strips. In the case of a multi-lane highway, there might be a considerable time delay before application of the transverse prestress and the pavement strips may be subjected to public traffic during this time in addition to construction traffic. However, with PCP Concepts 4, 5, 6, and 7 all of the various types of precast concrete panels would be transversely prestressed on the casting bed. This prestress, in addition to the longitudinal posttensioning in the field, would better accommodate traffic while subsequent pavement strips are under construction.

Concrete Compaction

The importance of good concrete compaction, and some of the problems encountered on previous projects when it was not obtained, were discussed in detail in Chapter 4. Obtaining proper concrete compaction when using slip-form paving is a matter of some concern, as indicated by the following quote:

> It appears as a somewhat formidable undertaking to thoroughly compact a 24-, 36-, or 48-ft-wide slab of concrete, 6 to 12 in. thick, and shape it to section and profile all with a single machine which is traveling from 6 to 12 ft per minute (Ref 60).

Thorough compaction of the slip-formed concrete would be a much less "formidable undertaking" with PCP Concepts 4, 5, and 7, than with Concepts 1, 2, and 3, because of the greatly reduced depth of cast-in-place concrete necessary with the former set of concepts. This greatly reduced depth of cast-in-place concrete would also permit the slip-forming to proceed at a much faster pace.

With PCP Concept 6, proper compaction of the slip-formed concrete is not a consideration since none would be used.

As pointed out, most of the problems associated with poor concrete compaction occurred in the immediate vicinity of the transverse pavement joints. The use of precast joint panels with PCP Concepts 2 through 6 should reduce the incidence of problems in these areas.

Protection of Tendon Anchorages

On some of the previous FHWA sponsored projects the longitudinal tendon anchorages were exposed in the transverse pavement joints (see Fig 4.12). Two potential problems are forseeable with this arrangement. The first problem is that the anchorages are more vulnerable to corrosion and hence loss of pavement prestress. The second problem is that if the tendon anchors are left exposed in the transverse joint, they are vulnerable to damage caused by closure of the joint in hot weather. However, when central stressing is used, access to the end anchorages is not necessary in order to posttension the tendons. Therefore, the end anchorages would be completely encased in the concrete pavement and, consequently, would not be subject to either of the previously described problems. This would be the case with all of the first six concepts. With the seventh concept, there are no posttensioning tendon anchorages which could be damaged, since only pretensioning is used.

Adverse Construction Conditions

Adverse construction conditions (e.g., hot weather, cold weather, extreme daily temperature fluctuations, precipitation, extremely limited allowable construction time, etc.) can have a significant impact on the construction of site-cast concrete pavement systems. For instance, hot weather may have the following undesirable effects on concrete in the plastic state: (a) increased water demand; (b) increased rate of slump loss and corresponding tendency to add water at the job site; (c) increased rate of setting resulting in greater difficulty with handling, finishing, and curing, and increasing the possibility of cold joints; (d) increased tendency for plastic cracking; and (e) increased difficulty in controlling entrained air content. Undesirable hot weather effects on concrete in the hardened state may include: (a) decreased strength resulting from higher water demand and increased temperature level; (b) increased tendency for drying shrinkage and differential thermal cracking; (c) decreased durability; and (d) decreased uniformity of surface appearance. Likewise, cold weather may have deleterious effects on concrete strength and durability; extreme daily temperature fluctuations may result in pavement cracking before prestress can be applied; and darkness and precipitation may curtail field construction operations, in some cases, for extended periods of time. In addition, busy urban areas where a pavement cannot be taken out of service for extended periods of time may place unrealistic time restraints on the contractor. Measures to alleviate or eliminate the adverse effects of these construction conditions must be well-planned and are generally expensive.

However, the detrimental effects of these adverse construction conditions are reduced as the proportion of precast concrete in the pavement is increased. This is true for at least two reasons. First, production of the various precast components is not severely impaired by adverse conditions since they are manufactured in a controlled environment. Second, adverse conditions (e.g., hot or cold weather) present less of an impediment to field construction operations with precast concrete than with cast-in-place concrete. Obviously then, the more precast that is used, the less the pavement is influenced by adverse conditions. This is illustrated by the following comparison of the seven PCP concepts which were introduced in this chapter.

Concepts 2 and 3 utilize only a minimal amount of precast. Consequently, the additional amount of pavement which can be produced under adverse conditions over concepts in which the pavement is entirely site-cast (such as Concept 1) is minimal. Nonetheless, as pointed out, this small amount of precast is important in terms of minimizing the detrimental effects caused by the adverse condition of extreme daily temperature fluctuations since it enables a larger prestress force to be applied at an earlier concrete age than with Concept 1. This is beneficial in preventing early pavement cracking.

With Concepts 4, 5, and 7, precast concrete comprises a significant portion of the entire pavement. This portion can not only be manufactured, but also can be placed in the field under less than ideal construction conditions.

With Concept 6, virtually the entire pavement can be manufactured and field place under adverse construction conditions since it is almost entirely comprised of precast concrete. In fact, the only cast-in-place concrete that is required is for filling the stressing pockets. In addition, the amount of precast in this concept is extremely valuable in connection with pavement reconstruction in busy urban areas because it minimizes the length of time that the pavement is out of service.

Another important advantage with the PCP concepts in which a large percentage of the pavement is comprised of precast (i.e., Concepts 4 through 7) is that anticipated and unanticipated construction interruptions are much more easily tolerated than with pavement systems that are entirely site-cast. This can be extremely valuable when equipment breakdowns, darkness, or weather changes that prohibit the continuation of any field construction activities are experienced.

Alternate Uses

While the PCP concepts introduced in this chapter were developed with highway pavements in mind, they could also be used in airfield applications with only minor modifications. In addition, some other interesting uses are foreseeable with two of the concepts. For instance, Concept 6 would make an excellent special purpose, temporary, reusable pavement. Several possible applications of this type of pavement are: (a) temporary traffic detours, (b) temporary, quickly constructed, military airfield pavements, and (c) temporary heavy construction work platforms, for instance, on soils with low bearing capacities. In these types of applications the individual precast panels would probably be merely butted together and then prestressed rather than either grouted or epoxy-bonded. This would permit easier disassembly when the pavement is no longer needed.

Pavement damage has less of an adverse impact on PCP Concept 7 than on any of the other concepts for the following two reasons: (a) only bonded tendons are used and (b) the individual precast concrete pieces can be relatively easily removed and replaced. Therefore, if a portion of the pavement is damaged, repairs can be easily made without affecting the remaining pavement. This would be especially valuable for paving situations where access to utilities beneath the pavement might be necessary, as is the case with urban streets, alleys, and parking lots.

Alternate Materials and Methods

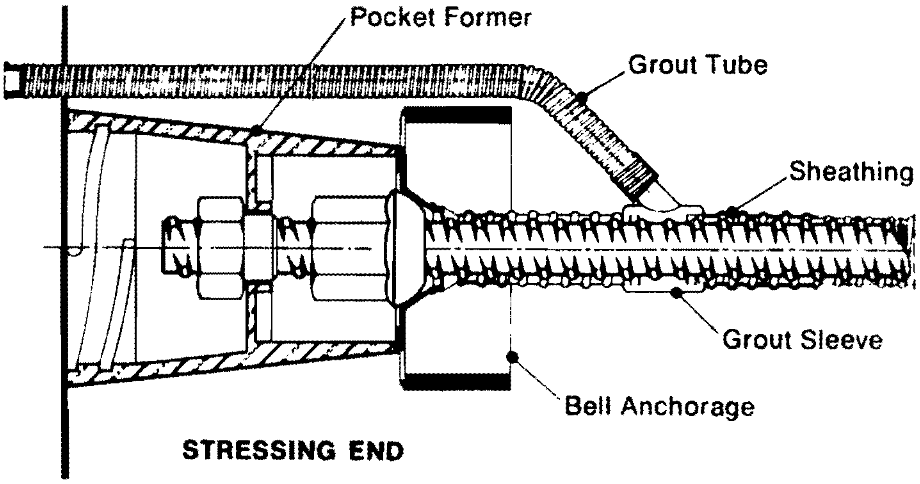
As a general rule, cost savings can be realized when the contractor is given latitude in the selection of materials and methods since this promotes competitive bidding. Therefore, concepts which permit alternate materials or methods to be used may have important economic advantages. For instance, straight transverse posttensioning tendons are used with PCP Concepts 4, 5, and 6. Therefore, high-strength bars, as shown in Fig 5.31, could be substituted for strand and this might encourage competitive bidding on this material. In addition, with Concept 5, the longitudinal tendons are fully tensioned before the wearing course is placed. This situation might also allow coupled, high-strength bars to be used as an alternate to strand.

Concepts which permit alternate tendon stressing systems to be used are another example of how cost savings may be obtained by allowing leeway in the selection of materials and methods. As discussed, PCP Concepts 4, 5, and 6 offer the greatest flexibility as far as selection of the method for stressing the tendons. With these concepts, either central stressing or end stressing (without the need for gaps between successive PCP pavement sections) can be used with equal ease. This would permit the pavement designer or the contractor to weigh the cost of the tendon couplers required with central stressing against the cost of the additional stressing operations required with end stressing and select the most economical stressing system.

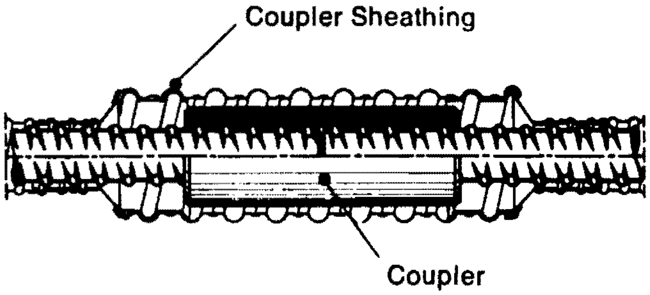
Another instance in which alternate materials could be used is in connection with PCP Concept 7. With this concept, either concrete or asphalt could be used for the wearing course. This would allow competitive bidding for these materials which would help decrease the total pavement cost.

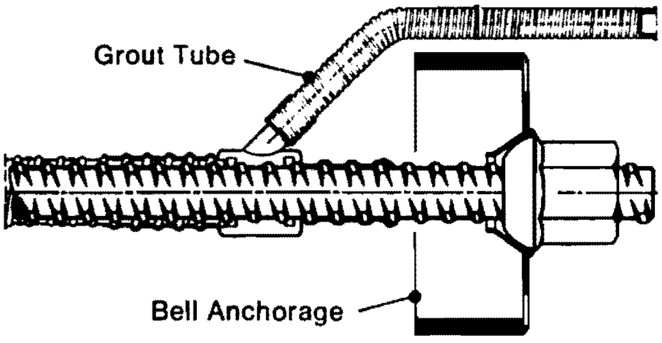
Unfamiliarity

One disadvantage shared by all of the PCP concepts introduced in this chapter is their novelty. Unfamiliarity on the part of organizations responsible for selecting pavement systems often results in reluctance to use new concepts. In addition, unfamiliarity on the part of contractors often results in high bids (at least on the initial projects in which new concepts are used) to protect against unanticipated problems. After contractors become familiar with the construction techniques involved, their bids more realistically reflect the actual cost of constructing pavement using new concepts. Only then can valid comparisons be made between the cost of



STRESSING END





FIXED END

Fig 5.31. High-strength bars (Ref 108).

pavements based on new concepts and the cost of pavements based on more conventional concepts. Table 5.2 summarizes the key points and provides a concise comparison of the concepts.

SUMMARY

The purpose of this chapter was to introduce seven new PCP concepts which were as follows: (a) Central Stressing of Slip-Formed Pavement; (b) Precast Joint Panels and Slip-Formed Pavement; (c) Precast Joint Panels, Central Stressing Panels, and Slip-Formed Pavement; (d) Composite Prestressed Concrete Pavement Type I (GPCPI); (e) Composite Prestressed Pavement Type II (CPCPII); (f) Segmentally Precast Prestressed Concrete Pavement (SPPCP); and (g) Continuous Composite Concrete Pavement (CCCP).

The introduction to each new concept included descriptions of its most important features and discussions of the anticipated sequence that would be employed in the construction of a section of PCP utilizing the concept. In addition, the characteristics of the seven new PCP concepts were compared to determine: (a) the relative ability of each concept to address the problems encountered on previous projects; (b) the relative ability of each concept to effectively utilize the potential of PCP; and (c) what, if any, new problems are created with each concept.

No attempt was made to select the best concept because each has its own strengths and weaknesses and different situations may favor the use of one concept over another. Additional testing is needed to further develop the concepts and determine their viability. The purpose of the next chapter is to determine what additional investigation and testing is necessary.

TABLE 5.2. COMPARISON OF PCP CONCEPT CHARACTERISTICS

CHARACTERISTIC (SECT. NO.)	PCP CONCEPT NUMBER						
	1	2	3	4	5	6	7
Precast Concrete Panels (5.10.1)							
- Utilization of high quality, mass produced, precast, prestressed concrete panels:							
(a) Significant				X	X	X	X
(b) Less significant		X	X				
(c) None used	X						
- Relative importance of the fact that the precast panels must be transported to the job site:							
(a) Significant				X	X	X	X
(b) Less significant		X	X				
(c) Not a factor	X						
Design Approach (5.10.2)							
(a) Elastic design approach	X	X	X				
(b) Elasto-plastic design approach				X	X	X	
(c) Combined elastic and elasto-plastic design approach							X
Bonded vs. Unbonded Tendons (5.10.3)							
- Suited to the use of unbonded tendons	X	X	X	X	X	X	NA*
- Relative difficulty associated with the use of bonded tendons							
(a) Significant	X	X	X				
(b) Less significant				X			
(c) Least significant					X	X	X

(CONTINUED)

TABLE 5.2. (CONTINUED)

CHARACTERISTIC (SECT. NO.)	PCP CONCEPT NUMBER 1	2	3	4	5	6	7
- Number of posttensioning operations required for each longitudinal tendon:							NA
(a) One					X	X	
(b) Three	X	X	X	X			
- Less expensive unsheathed posttensioning strands could be used					X	X	
Transverse Prestress (5.10.4)							
- Difficulties associated with laying out and holding the transverse tendons in a looped configuration	X	X	X				
- Pavement transversely prestressed before being subjected to construction traffic				X	X	X	X
- Transverse prestress level in adjacent lanes can be varied in accordance with the anticipated traffic volumes				X	X	X	X
- Eliminate all posttensioning operations in the field							X
Friction-Reducing Mediums (5.10.5)							
- Relative difficulty associated with handling and placing polyethylene sheeting:							
(a) Significant	X	X	X				
(b) Less significant				X	X	X	
(c) None							X
- Construction operations (i.e., setting tendon chairs, placing tendons, and slipforming pavement) would be conducted in direct contact with polyethylene sheeting	X	X	X				

(CONTINUED)

TABLE 5.2. (CONTINUED)

CHARACTERISTIC (SECT. NO.)	PCP CONCEPT NUMBER						
	1	2	3	4	5	6	7
- Polyethylene sheeting would be protected from construction operations				X	X	X	
- Eliminate the need for polyethylene sheeting							X
Gap Slabs vs. Central Stressing (5.10.6)							
- Elimination of gap slabs	X	X	X	X	X	X	X
- Number of tendon stressing pockets which must be formed in the field:							
(a) Greatest	X						
(b) Minimal		X	X				
(c) None				X	X	X	X
- Couplers for posttensioning tendons:							
(a) Required	X		X				
(b) Optional				X	X	X	
(c) None used		X					X
- An additional concrete placement operation is required to fill the stressing pockets after completion of final posttensioning operations	X	X	X	X		X	NA
Prestress Force Transference (5.10.7)							
- Level of compressive stress which can be applied by posttensioning at early concrete age is dependent on:							NA
(a) Concrete strength	X	X	X	X	X	X	
(b) Tendon anchorage size	X						
(c) Tendon spacing	X						

(CONTINUED)

TABLE 5.2. (CONTINUED)

	PCP CONCEPT NUMBER						
CHARACTERISTIC (SECT. NO.)	1	2	3	4	5	6	7
- Application of initial prestress force:							NA
(a) Prestress force transferred from tendons to immature concrete via individual tendon anchorages, thus limiting the amount of prestress that can be applied at early concrete age	X						
(b) Prestress force transferred from tendons to precast joint panels and then to the immature concrete, allowing greater initial prestress force to be applied at early concrete age		X	X	X	X	X	
- Possible long-term problems due to tensile stresses at the end of each pavement section caused by prestressing							
(a) Possible	X						
(b) Significantly decreased likelihood		X	X	X	X	X	
(c) No likelihood							X
Tendon Placement (5.10.8)							
- Chairs required to support tendons during slip-forming	X	X	X				
- No chairs required to support tendons during slip-forming				X	X	X	X
Transverse Joints (5.10.9)							
- Relative difficulty associated with holding the transverse joint assembly stationary while applying tension to the longitudinal tendons before the pavement concrete is placed:							NA

(CONTINUED)

TABLE 5.2. (CONTINUED)

CHARACTERISTIC (SECT. NO.)	PCP CONCEPT NUMBER 1	2	3	4	5	6	7
(a) Significant	X						
(b) Less significant		X	X				
(c) None				X	X	X	X
- Difficulties associated with concrete placement and consolidation in the vicinity of the transverse joint assembly in the field	X						
Multiple Longitudinal Strip Construction (5.10.10)							
- Problems associated with transverse tendons protruding from the first pavement strip	X	X	X				
- Concrete formwork required along the interior edge of the first pavement strip	X	X	X				
Concrete Compaction (5.10.11)							
- Reduced difficulty in obtaining good compaction of slip-formed concrete because of reduced cast-in-place concrete depth				X	X	NA	X
Protection of Tendon Anchorages (5.10.12)							
- Tendon anchorages completely encased and protected in the concrete pavement	X	X	X	X	X	X	X
Adverse Construction Conditions (5.10.13)							
- Reduction in required quantity of cast-in-place concrete which reduces vulnerability to adverse construction conditions:							
(a) Significant				X	X	X	X
(b) Less significant		X	X				
(c) None	X						

(CONTINUED)

TABLE 5.2. (CONTINUED)

CHARACTERISTIC (SECT. NO.)	PCP CONCEPT NUMBER						
	1	2	3	4	5	6	7
- Problems associated with stopping construction at intermediate points:							
(a) Significant	X	X	X				
(b) Less significant				X	X	X	X
- Possibility of being able to quickly open the pavement to traffic						X	X
Alternate Uses (5.10.14)							
- Possibility of being used for a special purpose, temporary, reusable pavement						X	
- Damaged sections easily repaired							X
Alternate Materials and Methods (5.10.15)							
- In addition to strand, high-strength bars can be used for transverse posttensioning				X	X	X	
- Possibility of using high-strength bars for longitudinal posttensioning					X		
- Couplers for posttensioning tendons:							
(a) Required	X		X				
(b) Optional				X	X	X	
(c) None used		X					X
- Possibility of using alternate wearing course materials							X
Unfamiliarity (5.10.16)							
- Organizations responsible for selecting							

(CONTINUED)

TABLE 5.2. (CONTINUED)

CHARACTERISTIC (SECT. NO.)	PCP CONCEPT NUMBER 1	2	3	4	5	6	7
pavement systems are unfamiliar with the concept	X	X	X	X	X	X	X
- Paving contractors unfamiliar with the concept	X	X	X	X	X	X	X

*NA = Not Applicable

CHAPTER 6. RECOMMENDATIONS FOR ADDITIONAL INVESTIGATION TESTING, AND ANALYSIS

The purpose of the previous chapter was to introduce and briefly examine several new PCP concepts from the standpoints of constructibility and relative advantages and disadvantages. However, thorough testing and analysis is required of any new concept in order to further develop the ideas and demonstrate their viability. Therefore, the next logical step in the development of the concepts introduced in Chapter 5 would be to determine what additional investigation and testing are required. If the concepts prove viable, mathematical models based on these investigations and tests could be developed to predict pavement behavior. These mathematical models could be used, in turn, to develop rational design procedures which would facilitate the use of the concepts.

The purpose of this chapter is to provide recommendations for additional investigation, testing, and analysis which are necessary to further develop the concepts introduced in Chapter 5 and determine their viability.

PRECAST CONCRETE PANEL/BASE COURSE INTERFACE

There are several factors in connection with the precast concrete panel/base course interface which have a significant impact on the behavior and performance of the PCP concepts discussed in the previous chapter. The effects of most of these factors are difficult, if not impossible, to accurately gauge by intuition and they require additional investigation and testing in order to evaluate their influence.

Friction-Reducing Mediums

The importance of an effective and reliable friction-reducing medium at the interface between the pavement and the base course has already been discussed in some detail earlier in this report. The subject of friction-reducing mediums is important regardless of whether or not precast concrete panels are used. The main requirements for friction-reducing mediums are: (a) efficiency in reducing restraint, (b) practicability for road construction, and (c) low cost.

The most frequently used medium on previous FHWA sponsored projects was a double sheet of polyethylene. The Project 401 staff proposed that this medium be used on the PCP demonstration projects for the Texas SDHPT for lack of a better alternative. However, the ability of this medium to adequately fulfill the main requirements of a friction-reducing medium (listed above) is somewhat dubious. With regard to the first requirement, tests have shown that the double layer of polyethylene sheeting will provide a fairly low coefficient of friction if installed properly, at least on a short-term basis. However, virtually nothing is known about the long-term behavior of the material. In fact, some preliminary tests conducted by the Project 401 staff indicate that the friction-reducing properties for two layers of this medium may deteriorate with time (Ref 81). This conclusion is in agreement with tests on various friction-reducing materials carried out in the early 1960s in Britain. The report on those tests states:

> It was observed with both types of polyethylene that the material was soft and abraded quickly, e.g., in sliding over sand. A sliding layer of polyethylene might quickly become ineffective, therefore, unless it were protected by sandwiching it between sheets of paper (Ref 126).

Deterioration of this material would have a serious adverse effect on the behavior of a PCP.

The second main requirement for a friction-reducing medium is its practicability for road construction. With all of the construction related problems that have been encountered with its use, the double layer of polyethylene sheeting can hardly be considered ideal from this point of view.

The last of the primary requirements for a friction-reducing medium is low cost. This is an important factor because it affects the overall economy of PCP. The double layer of polyethylene sheeting does meet this requirement. However, the fact that it is economical hardly justifies its use when compliance with the other requirements is questionable.

Therefore, one especially important area of further investigation and testing would be in the area of friction-reducing mediums. This investigation should begin with a thorough review of all of the available literature on the subject to determine the state of the art, eliminate alternate mediums which have already been tested and shown to be unsatisfactory, provide leads on other possibilities, and provide information on successful and unsuccessful test procedures which have been employed in the past, which in itself could be very valuable and time saving.

After completion of the literature review, a test program should be undertaken. Tests should be conducted on the mediums which are determined by the literature review to be most promising, and on mediums not previously considered. For instance, a great amount of research and development has recently occurred in the area of reinforced and unreinforced elastomeric membranes. Some of these materials might be suitable as friction-reducing mediums. These test should simulate the amplitudes and rates of slab movement which occur in a road slab under diurnal temperature variations. In addition, these tests should go beyond merely determining the medium's efficiency in reducing restraint. They should also determine the effects of age, temperature, abrasion caused by various materials (sand, crushed stone, asphalt, concrete, etc.), and reactivity with various materials on the friction-reducing medium (i.e., does the material deteriorate in contact with asphalt). In addition, each medium's practicability for road construction should be studied in detail.

On the basis of these tests, mathematical relationships could be developed between the properties of the friction-reducing mediums and the variables involved. This information would be extremely beneficial in assuring that the mediums reliably perform their critical function throughout the service life of the pavement. In addition, this information would also help determine if there is any merit in attempting to match the type of friction-reducing medium used with the anticipated movement. This might allow use of less expensive mediums for short pavement sections or for the portions of long pavement sections where the movement would be minimal (the midportion) and reserve the higher quality mediums for the end portions of the pavement section where large movements are expected.

Another factor which must be considered with friction-reducing mediums is that using precast panels may improve the performance of the medium or may even eliminate the need for it in some cases. This is due to two factors. First, most precasting beds are fabricated from steel. Therefore, the bottom sides of panels precast on these beds are generally extremely smooth. This smoothness should help to reduce friction between the pavement and the subgrade. Second, the panels are placed, as opposed to being cast on the subgrade. The tests conducted in Britain in the early 1960s indicate that this second factor may result in a reduction in friction and may eliminate the need for a friction-reducing medium, especially when a granular base course is provided (Ref 127). The potential benefits of using precast panels definitely warrant their inclusion in any investigation of friction- reducing mediums.

Contact Uniformity

Another very important factor needing additional investigation is the uniformity of contact between the precast concrete panels and the base course. First of all, analyses should be done to determine the stresses in the pavement caused by support discontinuities. This is a fairly complicated problem which should take several factors into account in order to be meaningful. One of these factors is that under an applied load the bearing stress on high points of the base course, in the vicinity of a void, would be high. This high-bearing stress would cause the material to flow or redistribute, thus eliminating the void. Of course, the degree to which this occurs is dependent on the type of base-course material.

Another factor to consider is that prestressing extends the elastic range of the pavement. Therefore, the PCP can deflect more under load than conventional rigid pavement without being damaged, and is less vulnerable to damage as a result of small voids in the base course.

Still another factor to keep in mind is that voids in the base course may form even with cast-in-place pavements. Voids are caused by unequal base course compaction or impact loads which cause differential settlement. Therefore, the performance of a pavement in which precast is used may not be significantly different in this respect to one that is entirely cast in place.

Tests should be conducted on all the commonly employed base course materials in order to determine what, if any, special measures need to be taken when they are used with precast concrete. For instance, the tests might indicate that a particular asphalt mix or method of placement produces a superior leveling course. Information could also be obtained from these tests on the relative abilities of various base course materials to flow or redistribute to compensate for irregularities in the surface of the base course.

Uniformity of contact between the pavement and the subgrade can also be improved by the use of undersealing. Undersealing (also known as sub-sealing or highway grouting) is the process of mixing and pumping a thin grout composed of cement, fly ash, and water into the voids beneath a slab to create an incompressible filler material. Use of this process could be facilitated by casting grouting sleeves into each precast panel. The use of undersealing in connection with precast concrete panels should be further investigated.

Foundation Strength

Tests should be conducted to determine the effect that varying the foundation strength has on the required pavement thickness and prestress level. The mathematical relationship developed from the data gathered would then provide a more rational basis for the design of a PCP for given foundation conditions. They would also help determine the necessary strength which must be provided in the base and subbase courses in order to use a PCP of given thickness and prestress level.

WEARING COURSE

Most of the concepts introduced in the previous chapter utilize a concrete wearing course which is slip formed in place after placement of the precast panels. This wearing course is another area of the proposed concepts which is in need of study. One of the first things to be determined is what minimum thickness of wearing course should be used. This must be examined from the standpoint of both placement and durability. The second item which should be studied is the bond between the wearing course and the precast panels. Third, the effect of applying prestress in plane to a composite section should be examined. Specifically, the questions of how the compressive force distributes between the precast panels and the wearing course due to the differences in the maturity of the concrete and how this affects the early stressing of the pavement should be studied. Fourth, the behavior of the composite section under load should be examined.

A considerable amount of research has recently been done on the subject of thin-bonded overlays. This research should be reviewed to determine what, if any, aspects of it would be applicable to the design of wearing courses for PCP.

With PCP Concept 6, no separately placed wearing course would be used. Therefore, it would be very important that the top surfaces of adjacent precast panels match in order to assure a smooth riding surface for the finished pavement. Testing is needed to determine the magnitude of difficulty that this presents.

JOINTS BETWEEN PRECAST PANELS

The question arises with most of the previously introduced concepts of how to handle the joints between adjacent precast panels. Several possible approaches exist for treatment of this interface, some of which may be better suited to one concept than another.

The preceding chapter simply gave an overview of the various PCP concepts and did not get into the specifics of alternate joint types.

However, it is necessary to give a brief discussion of some of the most promising joint types. This will help to better visualize their construction and the additional research required to determine joint behavior in the completed pavement, thus aiding in selection of the appropriate joint for each PCP concept. Most of the following discussion is based on the recommendations of the PCI Committee on Segmental Construction (Ref 106). The primary emphasis of their work was placed on bridge construction. Undoubtedly, therefore, modifications of these joint recommendations will be required as more is learned about segmental pavement construction.

(1) Cast-In-Place Joints. The minimum width of a joint of this type must allow access so that the joint concrete can be thoroughly vibrated. In addition, the width of a joint must allow access for coupling of conduits or welding of reinforcement, depending on the particular PCP concept. The width of this type of joint should not be less than about 3 inches.

The compressive strength of the joint concrete at a specified age should be equal to the strength of the concrete in the adjacent precast panels. High-early-strength portland cement may be used. Aggregate size should be selected to ensure maximum compaction.

(2) Dry-Packed Joints. Concrete mortar for dry-packed joints should have the following characteristics: compressive strength equal to the concrete in the adjacent precast panels, or at least 4000 psi; thoroughly mixed; zero slump; and 3/16-inch maximum aggregate size. Mortar should be rammed into place using a heavy hammer and a wood ram.

The width of dry-packed joints should not exceed approximately 2.5 inches. Mortar should be introduced into the joint in small batches of approximately 10 pounds each. Each batch must be thoroughly tamped and packed before placement of the next batch.

(3) Grouted Joints. The compressive strength of the grout at a specified age should equal the concrete in the adjacent panels, or at least 4000 psi. Nonmetallic grout mixes should be used because of the exposure to the weather.

Grouted joints should not exceed approximately 2 inches in width. This type of joint may be made with either gravity or pressure methods. In either case, provisions must be made to contain the grout.

When gravity grouting methods are employed, rodding or tamping should be used to consolidate the grout to assure that the joint is completely filled. In addition, the grout should consist of approximately one part of cement, one-third part of clean sand passing a number 16 mesh screen, and a water-reducing agent which preferably minimizes sedimentation. The total water content should be kept as low as practical.

Pressure grouting of joints requires both equipment in good condition and adequate preparation. The joint must be tightly sealed in order to sustain the pressure. Pressure grouting is particularly effective when forms or gaskets can be easily used. Formwork must be vented at the top. The vent should be closed at the conclusion of the grouting operation, and the pressure increased to a minimum of 15 psi at the vent. Twenty-four hours after grouting, the vent should be opened and filled if sedimentation has occurred.

(4) Epoxy-Bonded Joints. It is particularly important with epoxy-bonded joints that the adjacent surfaces are solid, clean, and free of dust and grease. Therefore, all remnants of formwork oil, grease, soap, talcum powder, etc., must be removed by thorough washing or sandblasting.

The adhesive should be applied in a uniform thickness to both surfaces. No epoxy mix must be allowed to enter the tendon ducts. The tubes must be checked after the segments are joined to be sure they are not blocked by the adhesive. Some posttensioning must be applied within the "open time" of the adhesive. A small quantity of the adhesive will extrude from the joint when pressure is applied if the correct amount of adhesive has been used. It has been recommended that a minimum pressure of 30 psi be applied to the joint.

(5) Metal Joints. Metal joints in the form of mating pairs of steel plates which are welded together, or pin connected metal hinges, could be used. However, these are classified more as connections than as typical joints between precast elements in segmental construction.

(6) Dry Joints. It is particularly important with dry joints that the joint faces be very smooth and accurate. This is necessary to prevent both the occurrence of high local stresses and the possibility of breaking pieces of concrete off during stressing.

This type of joint has the following main advantages over the previously discussed joints: (a) no grouting, epoxy bonding, or welding operations are required; and (b) it permits easy disassembly of temporary pavements.

The disadvantages of this type of joint are: (a) increased difficulty in obtaining the necessary joint accuracy and smoothness; (b) the joint cannot transmit tensile stresses; (c) vertical slip can occur; and (d) water can penetrate into the joints. Only testing will determine whether these disadvantages can be overcome. For instance, it may be possible to prevent vertical slip across the joints by the use of mechanical keying. In addition, the penetration of water into the joints may be prevented by the use of gaskets.

In conclusion, the suitability of one joint over another can only be determined by subjecting the joints to a series of tests, the first set being for joint constructability. The purpose of the constructability tests would be to determine the relative difficulty associated with field construction of each joint type. The second set of tests would be to determine the bending stiffness provided by the various joint configurations. The third set of tests would consider joint fatigue, which would demonstrate the ability of each joint to sustain repetitive loading. The fourth set of tests would be for joint overload to determine the ultimate strength of each joint. The fifth set of tests would be to determine the permissible horizontal and vertical panel misalignment for each panel joint type and each PCP concept. Some types of panel joints and PCP concepts require much closer tolerances than others. All of these tests would provide a better understanding of the basic modes of joint failure and would aid in the development of a mathematical model of the behavior of the pavement, which, in turn, would help in the development of a more rational design approach.

TRANSVERSE PAVEMENT JOINTS

The ideal transverse pavement joint has been described as follows:

> The ideal joint is one that provides load transfer with stress reducing properties at all times under adverse conditions so that faulting will not occur; one that can be sealed against water and incompressible material which cause pumping, spalling and blowups; one in which the sealant has no tendency to pile up and produce surface irregularity; also, one that will resist curling so that riding quality will not be impaired (Ref 69).

Unfortunately, in spite of years of research and the efforts of many researchers, engineers, and inventors, the ideal joint has not been found. Although the ideal joint may never be found, this is still a very important area which is in need of a great deal more research. Research in this area is even more important in connection with PCP than with conventional concrete pavement because of the larger horizontal movements that the transverse joints for PCP must be capable of accommodating.

An especially important aspect of the design of transverse joints for PCP which is in need of research is the design of load transfer devices, such as dowel bars and supplementary structural strengthening methods such as the use of sleeper slabs. Design procedures for dowel bars for conventional rigid pavement are well established and take into account stresses resulting from shear, bending, and bearing. However, significantly wider joint openings are encountered with PCP which will undoubtedly have an effect on the relative magnitude and importance of the stresses due to shear, bending, and bearing, thereby, requiring a reexamination of the design procedures.

In the design of dowel bars for conventional rigid pavement, the simplifying assumptions are made that the dowel bars are perfectly aligned and free to move. These assumptions are fairly reasonable for the relatively small joint movements that occur with these pavements. However, these simplifying assumptions may not be reasonable with the magnitude of the joint openings which are anticipated with PCP. Improper alignment or lack of lubrication may cause the dowels to freeze, with the result that joint spalls may occur. Variations in the size of the joint opening across the width of the pavement may be caused by non-uniform subgrade restraint or, as experienced on the Hogestown, Pennsylvania, and Tempe, Arizona, projects, restraining friction between the pavement slab and separately place concrete shoulder slabs. This can be a problem even for conventional rigid pavements with their relatively small joint movements. However, it could be disastrous with the anticipated large joint movements associated with PCP, resulting in binding of the dowel bars.

Sleeper slabs are another effective means for controlling deflection of the ends of pavement slabs and preventing faulting. In addition they can be provided with connections which permit differential horizontal movement of the pavement and sleeper slabs and yet will resist curling of the pavement slab so that riding quality will not be impaired.

Research is needed to better understand the behavior of sleeper slabs and thus be able to more rationally determine the required size and stiffness for a given set of conditions (i.e., foundation strength, pavement thickness, load repetitions, etc.). In addition, investigation should be made into the different types of connections which will reliably allow differential horizontal movement between the pavement and sleeper slabs for the life of the pavement. Also, different types of surface treatments which would provide a low coefficient of friction between the pavement and sleeper slabs and thus permit unrestrained horizontal movement of the pavement should be investigated.

TRANSPORTING THE PRECAST CONCRETE PANELS

One of the aspects of using precast concrete panels which needs additional investigation is transporting of the panels to the job site. Some of the important factors which should be included in an investigation are as follows:

(1) Distance from the precast plant to the job site. The cost of transporting the panels would probably be insignificant if the job site is fairly close to the precast plant. On the other hand, this cost might be considerably more for remote job sites. However, transporting precast members (bridge girders, bridge deck panels, single and double tees, utility vaults, manholes, pipe, etc.) appreciable distances is no longer that unusual. The amount that transporting the panels would add to the cost of each individual panel would undoubtedly be dependent on the size of the order. For a large job, the cost per panel for transporting might be relatively small.

(2) Size and weight of the precast panels. The maximum permissible panel dimensions must not exceed the limitations imposed by governing regulations for transporting on highways by truck. In addition, regulations also govern the permissible truck weights, which would control the number of panels that can be transported in a single load.

(3) Use of a temporary precast plant near the job site. Another factor influencing the importance of transporting the panels is whether the contractor is permitted and elects to precast the panels in a temporary plant near the job site. If this is done, then transporting the panels would probably not be a significant problem since they would only have to be moved from the yard to the job site.

This investigation would help establish the maximum permissible panel dimensions and economical haul distances. This information would enable cost comparisons to be made between pavement systems which employ varying amounts of precast and pavement systems which are entirely site cast.

PCP SLAB LENGTH CHANGES

As mentioned, the magnitude of the slab length changes which occur with PCP are much greater than those experienced with conventional pavements, primarily due to the much shorter distance between joints or cracks with conventional concrete pavements. These large magnitude length changes are responsible for several problems associated with the design of PCP, the most significant of which are determining the amount of movement that must be accommodated by the transverse joints between successive slabs and the effect that these movements have on the magnitude and distribution of stresses in the slab. Length changes in pavement slabs have been categorized as either cyclical (alternating expansion and contraction) or progressive (contraction only). Cyclical length changes occur throughout the life of the pavement in response to the continuous hygrothermal fluctuations in the concrete. Cyclical length changes are further classified, according to the time period over which they occur, as either daily or seasonal. Progressive length changes, a large portion of which occur early in the pavement's life, are caused by creep, shrinkage, and elastic shortening of the concrete. The influence that each type of length change has on PCP performance and the research needs associated with each type are briefly discussed in the following paragraphs.

(1) Daily Cyclic Length Changes. A 40°F daily temperature cycle (20°F above to 20°F below the average daily temperature) would seldom be exceeded in slabs of the thicknesses used in PCP. In addition, measurements of daily movement at points along continuously reinforced concrete pavements (in lieu of reliable data for PCPs) indicate a coefficient of thermal expansion of approximately 5×10^{-6} in. per in. per oF for daily length changes. As discussed, the optimum PCP slab length appears at this time to be on the order of 400 feet long. Using these values in an equation developed by Friberg (Ref 2) yields a maximum daily length change of 0.8 inch or a daily change in transverse joint width of 0.8 inch between successive PCP slabs. Transverse joints capable of accommodating movements of this magnitude can be designed fairly easily. Therefore, daily length changes, by themselves, are not a critical factor in the design of these joints.

However, daily length changes have a major influence on the magnitude and distribution of compressive stresses in PCP. Observations indicate that these length changes are resisted by friction between the slab and the subgrade and that this resistance is proportional to the magnitude of the length changes. The average stress on any section would then be the prestress plus the restraint stress for expanding slabs, and the prestress less the restraint stress for slabs in an equivalent state of contraction.

The additional compressive stress due to pavement expansion is beneficial, unless it becomes so great that buckling becomes a concern. However, the loss of compressive stress due to pavement contraction is harmful and, at its worst, results in the minimum mid-length effective prestress which is a critical design condition.

A twofold research effort is needed to obtain a better understanding of the effects that daily length changes have on the magnitude and distribution of stresses in PCP. First, the daily variations in length of a number of full-scale PCP slabs should be measured. This would permit the determination of reliable coefficients of thermal expansion for daily length changes. This information will in turn permit more accurate predictions of these length changes to be made. Second, daily stress level fluctuations should be monitored for these same PCP slabs. The correlation between stress level fluctuations and length changes could then be more accurately established.

(2) Seasonal Cyclic Length Changes. A 60°F seasonal change in the average daily temperature would be exceeded only in climates with extreme annual temperature fluctuations. In addition, measurements of seasonal movements at points along continuously reinforced concrete pavements (again, in lieu of reliable data for PCPs) indicate a coefficient of thermal expansion of approximately 4×10^{-6} in. per in. per °F for seasonal length changes. These values translate into a seasonal change in length of 1.15 inches for a 400-foot-long PCP or a seasonal change in transverse joint width of 1.15 inches between successive 400-foot-long PCP slabs. This length change takes place over many days with only minute cumulative differences from one day to the next, which are insignificant compared to the previously discussed diurnal length fluctuations. Observations indicate that these cumulative seasonal length changes occur virtually without frictional restraint. In addition, their total magnitude is small (approximately 3 percent) relative to the elongation of the longtiudinal tendons due to posttensioning (approximately 38 inches for a 400-foot-long slab).

Consequently, seasonal length changes are not an important factor in terms of the magnitude and distribution of stresses in PCP.

The importance of seasonal length changes lies in their influence on the design of transverse joints for PCP. Seasonal length changes cause cumulative forward and subsequent backward movements of the position of the slab ends about which the diurnal fluctuations occur. An accurate knowledge of the magnitude of these movements is critical in setting the initial width of the transverse joints at the time of construction. This initial width is a function of the time of year that construction take place. It is important in order to obtain joints that do not become too wide in winter which may adversely affect ride quality, create hazardous conditions for snow plows, tax the holding strength of joint seals, and cause high stresses in the dowel bars. In addition, it is important in order to obtain joints that do not remain closed for extended periods in the summer, which may damage the joint seals or possibly even the concrete in the vicinity of the joints.

Three areas of research are needed in connection with the seasonal cyclic length changes. First, the seasonal variations in length of a number of full-scale PCP slabs should be measured. This would permit the determination of reliable coefficients of thermal expansion for seasonal length changes. Second, seasonal variations in the concrete moisture content should be studied to more fully understand the interplay between them and seasonal length changes. Third, the composite cyclic length changes, daily plus seasonal, should be further investigated to provide a better understanding of their interaction.

(3) Progressive Length Changes. As previously stated, progressive length changes are caused by creep, shrinkage, and elastic shortening. Each of these causes will be briefly discussed in the following paragraphs.

As with other prestressed concrete structures, creep of PCP occurs throughout its life. Using a conservative end value for creep strain of 1×10^{-6} in per in. per psi, and an average prestress of 225 psi, the total shortening of a 400-foot-long PCP slab due to creep would be approximately 1.1 inches. Roughly 25 percent of this amount takes place within the first 2 weeks after application of prestress, another 25 percent within 2 to 3 months, another 25 percent within 1 year, and the remaining 25 percent in the course of many years.

Concrete used in structures which are totally protected from the weather may continue to experience drying shrinkage throughout the life of the structure. Concrete used in pavements, on the other hand, undergoes an initial period of drying shrinkage, followed by alternating periods of shrinking and swelling in response to the prevailing weather and subgrade moisture conditions. Only the slab shortening due to the initial period of drying shrinkage can be classified as a progressive length change. Observations indicate that this shortening is on the order of 0.05 inch per 100 feet of slab length. Thus, the total shortening of a 400-foot-long PCP slab due to shrinkage would be approximately 0.20 inch.

Creep and shrinkage shortening occur virtually unrestrained by subgrade friction due to the extended time period over which they take place. In addition, the magnitude of the creep and shrinkage shortening is only a small portion of the elongation of the tendons due to prestressing (approximately 3.5 percent for a 400-foot-long slab with an average prestress of 225 psi). Therefore, these progressive length change causes do not have a significant influence on the magnitude and distribution of stresses in PCP.

The phenomenon of elastic shortening is significantly different for PCP than for most other prestressed concrete structures. With most prestressed concrete structures, elastic shortening occurs virtually instantaneously upon application of the prestress force. However, the elastic shortening of a PCP is restrained by friction between the slab and the subgrade. As a result, the effective prestress on any section away from the point of application would temporarily be decreased by the amount of frictional restraint induced by slab shortening under prestress, making the slab more vulnerable to midlength cracking at early age. After some daily temperature cycles, the elastic shortening would be complete and no reduction in effective prestress attributable to restraint of elastic shortening would remain. Thus, while elastic shortening has a significant short-term effect on the magnitude and distribution of prestress in a PCP, its long-term effect, similar to that of creep and shrinkage, is negligible.

The total progressive length change due to creep, shrinkage, and elastic shortening for a 400-foot-long PCP slab with an average prestress level of 225 psi is approximately 1.7 inches. This length change is relatively insignificant in respect to its long-term effect on the magnitude and distribution of stresses in a PCP. It may or may not be significant in terms of the design of transverse joints between successive PCP sections, depending on the method used to tension the longitudinal tendons.

If gaps are used, they can be left open for some period of time after the application of full prestress, thus permitting a significant portion of the progressive length changes to occur before the transverse joint assemblies are placed and the gap concrete is cast. This reduces the magnitude of the opening widths which is important in preventing joints that become too wide in winter which can cause problems of the types described earlier in this section.

When central pockets are used for stressing the longitudinal tendons, the transverse joint assemblies are placed at the same time that the entire pavement is cast. Therefore, these joints must accommodate all of the progressive length changes.

This appears, at first inspection, to be a significant disadvantage with the use of central pockets versus the use of gaps for stressing the longitudinal tendons. However, it may not be. When gaps are used, the transverse joints must be placed with an initial opening to prevent the joints from remaining closed for extended periods in the summer which could damage the joint seals or possibly even the concrete in the vicinity of the joints. Whether or not this initial joint opening is significantly less than would be produced by the progressive length changes when central stressing pockets are used remains to be seen. This area, as well as the whole topic of progressive length changes, is definitely in need of additional research.

In summary, improved understanding of the causes and effects of the PCP slab length changes would be helpful in the following areas: (a) permit better predictions of transverse joint opening widths to be made, thus enabling transverse joint materials to be selected to better match the anticipated joint movements; (b) allow more accurate evaluations of stresses induced by temperature and moisture changes, thus enabling a more accurate determination of the appropriate prestress level to resist these stresses; and (c) aid in determining the level of prestress which must be applied at early concrete age to prevent formation of cracks.

STRESS DISTRIBUTION IN THE TENDON ANCHORAGE ZONE

One of the primary concerns in the design of a successful posttensioning system is the problem of transferring the large prestress force to the structure over a small local anchorage zone. Previous researchers have identified two important tensile stress fields within the anchorage zone. The first is the bursting stress field which is located along the line of loading, normal to it, and away from the point of loading. The second is the spalling stress field which is located along the loading surface, parallel to it, and away from the point of loading. Another important stress in the anchorage zone is the compressive bearing stress immediately under the anchor. These stresses are illustrated in Fig 5.28. Previous research has improved our understanding of the role that each of these stresses play in the behavior of the anchorage zone of prestressed girders and has enabled more positive prediction of cracking loads (Ref 123). However, additional study of this topic is needed in connection with PCP design. This study should begin with a thorough review of the literature to determine the current state of the art and investigate the applicability of previously performed research to PCP design. Some of the factors which should be included in this study are anchor configuration, anchor spacing, concrete strength, pavement thickness, and effect of reinforcement in the anchorage zone.

In PCP design the anchorage zone stress problem is aggrevated by the need to apply prestress at early concrete ages to avoid the formation of cracks due to hygrothermal changes and concrete creep. The degree of aggrevation is dependent on the particular concept employed. Concepts such as Concept 1 or the one utilized on the previous FHWA sponsored projects, where the tendon anchor bears directly on the immature concrete, are especially affected by the problem of anchorage zone stresses.

EXPANSIVE CEMENT CONCRETES

As discussed, the performance of experimental pavement sections in California indicated that there is no advantage in the use of expansive cement concretes in nonreinforced poststressed highway construction. However, research conducted in Japan in 1968 demonstrated that use of an expansive admixture may have important benefits in reinforced and posttensioned concrete pavement (Ref 89).

In the case of reinforced concrete pavement it was shown that use of expansive cement concrete makes it possible to introduce compressive self-stresses in the pavement due to restraint of expansion. The results of the research conducted in Japan are as follows:

(a) self-stresses exist only due to restraint of expansion by the reinforcement for pavement sections less than 130 feet from a free end;

(b) self-stresses exist due to subgrade frictions in addition to reinforcement for pavement sections beyond 130 feet from a free end;

(c) higher self-stresses which are obtained during initial stages decrease with time but a certain level of permanent self-stress remains.

Initial and permanent compressive self-stresses of 300 psi and 150 psi, respectively, were measured in the central zones of pavements more than 470 feet in length. These compressive self-stresses are effective in preventing pavement cracking.

In 1971 two taxiways were constructed at Love Field in Dallas, Texas, using reinforced concrete containing expansive cement (Ref 107). While no actual stress measurements were taken, the good performance of the pavement tends to support the research done earlier in Japan.

In the case of PCP, research indicates that 300 psi compressive self-stress could be introduced at the center of the pavement by the suitable use of expansive admixture without mechanical prestressing. This value would make it unnecessary to induce preliminary prestressing, thus reducing the severity of the posttensioning tendon anchorage zone problems discussed. These self-stresses could possibly compensate for the loss of prestress due to subgrade friction, if mechanical prestress was introduced before the loss of self-stress due to restraint by subgrade friction. These research results suggest the possibilities of reducing the quantity of prestressing tendons and increasing the distance between active transverse joints.

The potential benefits with the use of expansive cement concretes are significant and well worth pursuing. However, there are drawbacks to its use. Research conducted in California indicates that concrete made with shrinkage compensated cement has an extremely low resistance to sulfate attack (Ref 121). Whether this problem can be overcome or whether it will render expansive cement concretes unsuitable for use in highway construction remains to be proven.

Clearly, additional research in the use of expansive cement concretes in connection with reinforced and prestressed concrete pavements is warranted.

STRESS DISTRIBUTION ALONG PCP SLABS

Achieving and then maintaining the proper distribution of stresses along a PCP is essential to the assurance of satisfactory performance throughout its service life. The ability to do this would definitely be enhanced by field measurements of stress distribution along several full-scale PCP slabs of various designs under diverse environmental and traffic load conditions, at different stages of their service lives. These field measurements would provide valuable data which would enable the determination of the following: (a) effectiveness of alternate prestressing techniques; (b) viability of alternate PCP concepts; (c) ability of various design procedures to accurately reflect the load/deflection response of the pavement structure; (d) effectiveness of various friction-reducing mediums; (e) effects on the distribution of stresses caused by broken tendons; and (e) level of prestress required to prevent the pavement from cracking at early age and throughout its service life.

PAVEMENT CRACKS

Another very important subject where additional research would be especially beneficial in connection with PCP is pavement cracks. There are several aspects of this subject which need to be examined in detail. First, the mechanisms involved in the formation of pavement cracks, both before and after application of prestress, should be studied. A better understanding of these mechanisms will aid the designer in determining appropriate measures to avoid their occurrence. Second, load transfer across cracks in PCP should be studied from the standpoints of both flexure and shear. Third, the behavior of cracks subjected to repetitive loads should be studied. One especially important aspect of this behavior, which should be closely observed, is the amount of pavement spalling due to pavement cracking. Fourth, the infiltration of water through cracks in PCP should be studied.

Information obtained regarding the load transfer, repetitive load behavior, and infiltration of water aspects of PCP cracks would aid in more rational determination of the actual deleterious effects of cracks in PCP. It may be found that prestress keeps the cracks so tightly closed that these aspects of PCP cracks are not as serious as with conventional rigid pavement. If this were true it would make it much less urgent to apply prestress to the concrete at very early ages. In addition, it may be found that the cracks which may form between adjacent precast concrete panels would not present any difficulties.

The significance of cracks in PCP should be studied in relation to the following considerations:

(a) When cracks are opened by wheel loads or restrained warping, the cracks will close up again when the load is removed or the warping reduced. The slab will thus be restored to approximately its original section modulus.

(b) Because the tensile component of the moment of resistance is created by the prestressing force, the cracked section will transmit bending moments fairly efficiently, although, since both positive and negative moments occur in pavements, it is not possible to place the steel in the most efficient position.

(c) The prestress gives the section a higher shear strength.

(d) Since the opposite sides of cracks are held together by the prestress, even in badly cracked sections, shear can be transmitted by effective aggregate interlock and friction in the plane of the crack.

In short, cracks in PCP do not reduce the efficiency of the section as much as in a conventional concrete pavement, and recovery on removal of load is nearly complete.

SUMMARY

The purpose of this chapter has been to provide recommendations for additional investigation, testing, and analysis necessary to further develop the concepts introduced in Chapter 5 , and to determine their viability. There are many other topics, in addition to the ones discussed in this chapter, where further research would be extremely beneficial. For instance, production costs and erection problems, as well as curling and warping due to temperature and moisture gradients across the depth of the pavement warrant additional research. Still other topics will undoubtedly become apparent as these PCP concepts are developed.

CHAPTER 7. SUMMARY AND CONCLUSIONS

SUMMARY

The main points of each chapter of this report are briefly summarized in the following sections.

Chapter 1

As discussed in Chapter 1, construction of this nation's interstate highway system was started prior to 1964, and the majority (approximately 80 percent) was completed by 1971. The Interstate Act of 1956 mandated that the system have a twenty-year design life. Consequently, some of the system has already come to the end of its design life. The majority of the remaining portion of the system will come to the end of its design life during the next decade. As a result, we are now entering a period which will see a major increase in highway reconstruction and a search for new pavement systems which will, hopefully, have the advantages of requiring less material and virtually no maintenance over their design life. This search is responsible for sparking renewed interest in PCP.

In addition, as pointed out in Chapter 1, some very influential (although nontechnical) people have asserted that the only reason that PCP has not come into widespread use is because of collusion between the FHWA and the concrete industry. They charge that not only do design procedures now exist for PCP, but that they have been in existence for some time. In addition, they claim that PCP is far superior to all other currently used pavements both in terms of reductions in material requirements and for in-service performance. However, these assertions are simply not supported by the facts.

In response to the assertion of collusion, a well-respected authority in the field of transportation conducted an independent review of the FHWA's handling of PCP. His findings were summarized in Chapter 1. This review revealed that the FHWA has taken a very active role in the development of PCP and the promotion of its use. In addition, this review also pointed out the illogical nature of the charge that the concrete industry would even attempt to suppress the development of PCP. Why would the concrete industry suppress technology that would give them clear superiority over other competitive pavement materials? It may be true that the industry might sell less concrete per project but that reduction would be more than offset by the increase in the number of projects.

This chapter also presented a brief evaluation of the advantages and disadvantages foreseeable with PCP to serve as a further introduction to the topic.

Additional topics covered in this chapter included the background of Project 401 and the specific objectives, scope, approach, and order of presentation of this report.

Chapter 2

The primary objective of this chapter was a detailed review of the three primary methods used to prestress pavement which are pretensioning, posttensioning, and poststressing. Each method was explained; the manner in which each method is used to obtain various prestress configurations (i.e., longitudinal, longitudinal-transverse, and diagonal) and the main construction procedures employed with each method were illustrated; and the problems encountered with the use of each method were discussed. This was followed by a review of the foreign and domestic history of prestressing for airport and highway pavement applications.

Chapter 3

Chapter 3 pointed out that the design of PCP involves the rational determination of specific values for a number of interdependent variables. This determination should be based on a thorough understanding of the factors affecting the design so that the pavement will be able to withstand the traffic loads and environmental influences to which it will be subjected throughout a specified service life.

The purpose of Chapter 3 was to provide brief discussions of the main factors affecting the design of PCP (i.e., elasto-plastic behavior under loads, load repetition effect, subgrade restraint, temperature curling, moisture warping, prestress losses, and buckling) and the primary variables for which specific values are sought during the design process (i.e., foundation strength, pavement thickness, slab length and width, prestress magnitude, tendon spacing, and transverse joints).

Chapter 4

The purpose of Chapter 4 was to provide a critique of the design, construction, and performance of the four FHWA sponsored projects which were constructed during the 1970s. No comparative design or cost studies of conventional rigid pavement versus PCP were reported in connection with any of these projects. Therefore, reductions in material requirements remain merely conjecture. Furthermore, the primary design variables on most of these projects were selected empirically rather than analytically. For example, the decision to eliminate transverse reinforcement was based on ease of construction rather than demonstrated lack of need. Some of the most significant problems encountered, both during construction and in service, were discussed in detail in Chapter 4. Needless to say, none of these projects produced maintenance-free pavements. In fact, it is uncertain at this point whether these pavements have demonstrated clear superiority over comparable conventional rigid pavements under similar conditions.

Chapter 5

It is obvious from the critique in Chapter 4 that all of the problems associated with PCP have not been solved and it is still much too early to commit to any of the design and construction approaches presented thus far. The objective of Chapter 5 was to introduce several new concepts which represent a progression of thought regarding PCP and which address the problems encountered on previous PCP projects.

Concept 1, central stressing of slip-formed pavement (developed by the Project 401 staff for the demonstration projects), resembles the approach employed in the previous FHWA sponsored projects with a few significant changes, the most noteworthy being the provision of transverse prestressing and elimination of the need for gap slabs by the addition of tendon stressing pockets.

In Concept 2, precast concrete joint panels were introduced which would be used in connection with slip-formed paving. These joint panels would serve two primary purposes. First, they would allow the complicated and critical pavement end sections to be mass produced in a closely controlled factory environment. Second, tendon stressing pockets would be precast in the panels, thus eliminating the tedious operation of constructing them in the field.

Concept 3 differs from Concept 2 only in that precast central stressing panels are provided. These panels would provide prefabricated stressing pockets near the midlength of each pavement segment which simplifies the stressing operations.

Concept 4 is called Composite Prestressed Concrete Pavement Type I (CPCPI). CPCPI utilizes precast joint panels similar to Concepts 2 and 3. Use of central stressing panels as described in Concept 2 would be optional. In addition, precast concrete base panels would be used.

Concept 5 is called Composite Prestressed Concrete Pavement Type II (CPCPII). CPCPII differs from CPCPI in that:

(1) The base panels for CPCPII would be different from those for CPCPI in the following respects: (a) considerably thicker; (b) contain grooves in their top surface which would allow the field-placed longitudinal tendons to be located at, or slightly below, the centroidal axis of the panels; and (c) have panel edges formed in a manner to permit grouting of the joints between adjacent panels after they are set in place at the job site.

(2) Unsheathed longitudinal tendons would be used with CPCPII.

(3) With CPCPII, the longitudinal tendons would be fully stressed in a single operation.

The precast concrete base and joint panels would, in effect, comprise a pretensioning bed. After the grout in the panel joints has gained sufficient strength, the longitudinal tendons would be fully stressed. The pavement construction would be completed by placement of the riding surface on top of the base panels by means of a slip-form paver.

Concept 6 is called Segmentally Precast Prestressed Concrete Pavement (SPPCP). This concept is similar to CPCPI and CPCPII but with one major difference. With SPPCP, full-depth pavement panels are substituted for the base panels that were used in both of the previous concepts.

Concept 7 is Continuous Composite Concrete Pavement (CCCP). CCCP represents a rather significant departure from all of the preceding concepts. In fact, its only resemblance to the previous concepts is in its use of precast, prestressed concrete panels. CCCP is actually more similar to the concept of continuously reinforced concrete pavement (CRCP). Like CRCP, the objective of CCCP would not be to prevent transverse cracking of the pavement, but instead to prevent random uncontrolled cracking. CCCP would achieve this by the use of precast, prestressed concrete base panels which are interconnected by reinforcing bars and covered with either a concrete or asphalt wearing course. Cracking of the completed pavement would occur at the joints between adjacent panels. The crack spacing would be great enough to prevent punchouts and yet small enough to control the magnitude of the crack width, thus preventing spalling and water infiltration through the pavement.

Chapter 6

Before acceptance and application of virtually any new concept, it must be subjected to thorough testing and analysis. Therefore, the next logical step in the development of the PCP concepts introduced in Chapter 5 is to determine what additional investigations and testing are required to demonstrate the viability of the concepts. The purpose of Chapter 6 was to suggest some of the main areas where additional research would be especially beneficial, such as: precast concrete panel/base course interface, wearing course, joints between precast panels, transporting the precast concrete panels, PCP slab length changes, transverse pavement joints, stress distribution in the tendon anchorage zone, expansive cement concretes, stress distribution along PCP slabs, and pavement cracks.

Some of these proposed areas of research are primarily applicable to the concepts introduced in Chapter 5. However, most of them would provide information that would be beneficial regardless of the PCP approach employed.

CONCLUSIONS

This report accomplished the objectives of the first phase of Project 401, which were as follows:

(a) thoroughly review the available literature to ascertain the current state of the art of PCP;
(b) critically evaluate the design, construction, and performance of several FHWA sponsored projects which were constructed during the 1970s; and
(c) develop a PCP design and the associated construction details and procedures based on (a) and (b) to be used in connection with two demonstration projects.

In the course of pursuing the objectives of the first phase of Project 401, several new PCP concepts were developed by the author. These concepts represent a progression of thought regarding PCP and address many of the problems encountered on previous projects. These concepts were introduced in this report. In addition, recommendations were given for additional investigation, laboratory and field testing, and analytical studies to further develop the concepts and determine their viability.

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APPENDIX A

GLOSSARY OF TERMS RELATED TO PRESTRESSED CONCRETE PAVEMENTS (REFS 4, 30, 56, 66)

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Abutments. External reactions used in pretensioning tendons and poststressing externally prernally prestressed pavements.

Adhesive. A bonding material used in joints.

Anchorage. The means by which the prestressing force is transmitted from the prestressing steel to the concrete.

Blowup. A pavement failure due to high eccentric compressive stresses that force the slab upward from its at-grade position. This is generally associated with rapid stress increase due to increase in concrete temperature.

Bonded Tendons. Tendons in which the prestressing steel is permanently bonded to the concrete to which they are applying their prestressing forces.

Buckling. A failure condition resulting from the development of compressive forces of sufficient magnitude to cause an interior portion of a slab to move upward from its original position.

Coating. Material used to protect against corrosion and/or lubricate the prestressing steel.

Coefficient of Subgrade Reaction. See Modulus of Subgrade Reaction.

Concrete Consolidation. A method of compacting plastic concrete by rodding or vibration.

Conduits. Passages in the concrete (such as tubes, pipes, or channels) for encasing the tendons of a posttensioned pavement.

Contraction of Prestressed Pavement. Shortening of the length of pavement slab due to drying shrinkage, temperature decrease, elastic shortening, or creep.

Couplers. Hardware to transmit the prestressing force from one partial length prestressing tendon to another.

Creep. A contraction or shortening of the pavement under the sustained horizontal compressive stress. In pretensioned and posttensioned systems this action merely results in an increase in joint opening and the accompanying loss in net prestress is not significant. In poststressed systems the action tends to relieve the induced compressive stress, thus requiring a reapplication of pressure at the boundary of the slab to maintain the design prestress.

Curling. Pavement profile change due to temperature gradient. Prestressed pavements have a definite tendency to curl. For this reason many of the experimental pavements which have been constructed have been designed with end tie-downs to prevent this action.

Design Prestress. The compressive stress remaining in the concrete, after deduction of anticipated prestress losses, to meet the requirements for traffic loadings, subgrade restraint, and restrained temperature warping.

Dowel. A load transfer device embedded in a concrete pavement to provide shear or load transfer across a joint. Round steel bars are generally used. One end of the bar is not bonded to allow slab end movements.

Drainage. The control of water accumulation in pavement subbases and subgrades.

Drying Shrinkage. Volumetric contraction of the concrete due to drying or loss of free water.

Eccentricity. Distance from the mid-depth of the slab to the center of the tendons in pretensioned and posttensioned systems.

Elastic Shortening. A reduction of prestressed concrete pavement length when compressive stress is applied.

Externally Prestressed Concrete Pavement. A concrete pavement that requires an external reaction system to preserve horizontal compressive stress in the pavement slab.

Final Prestress. The horizontal compressive stress imposed on the concrete after substantial strength gain. This is generally applied after a specified compressive strength has been attained.

Flexural Strength. See Modulus of Rupture.

Friction-Reducing Layer. Material placed immediately below the prestressed pavement to reduce slab-subbase interface friction.

Frost Action. The action of freezing, thawing and associated movement of water to the freezing surface.

Grout. A mixture of cement, sand, and water with or without admixtures.

Grouting. A method of filling the conduit void spaces with cement mortar to provide bond between the posttensioned tendon and the concrete.

Initial Prestress. The horizontal compressive stress imposed at an early age on the concrete pavement. This is generally applied to prevent early drying shrinkage cracking of the pavement.

Internally Prestressed Concrete Pavement. A concrete pavement that is prestressed with tendons and does not require permanent external reactions.

Jacks. Devices used to apply tension to tendons or compressive horizontal stresses to concrete pavements.

Joint. The junction of two adjacent slabs interrupting the continuity of the pavement.

Joint Faulting. This defect is an abrupt change in elevation at a joint and may be due in part to: (a) the displacement of underlying soil, or (b) soil densification under repeated loads. It is important to note that the lack of adequate load transfer across a joint will also result in joint faulting.

Modulus of Elasticity. The ratio of normal stress to strain. For concrete the secant modulus may be used. The secant modulus of elasticity is the ratio of stress to strain defined by the chord between origin and a point on the stress-strain curve.

Modulus of Rupture. Concrete flexural strength determined from the breaking stress of a concrete beam tested in third point loading.

Modulus of Subgrade Reaction. A measure of the subgrade support equal to the unit load on a 30-in. diameter plate required to obtain a deflection of 0.05 in., divided by 0.05 in.

Moisture Gradient. The variation of moisture content in the vertical dimension of the pavement cross-section.

Net Prestress. The lowest level of compressive stress in the concrete to meet the requirements for traffic loadings.

Poststressing. A method of prestressing wherein compressive stress is is imposed on a concrete member without the use of tendons after the concrete has gained sufficient strength to withstand the applied forces.

Posttensioning. A method of prestressing wherein compressive stress is imposed after concrete has gained sufficient strength to withstand the applied forces.

Preliminary Stressing. See Initial Prestress.

Prestressed Concrete Pavement (PCP). A concrete pavement in which a permanent and essentially horizontal compressive stress has been induced prior to the application of live load.

Prestress Loss. Reduction in the initially applied horizontal compressive stress due to creep, elastic shortening, shrinkage, relaxation, and friction losses.

Pretensioning. A method of prestressing wherein the tendons are stressed prior to casting concrete around the tendons. The concrete is then cured to gain the required bond strength prior to releasing tendons from reaction system.

Pumping. The ejection of water and/or soil from below pavements through joint, cracks and/or edges due to moving loads.

Relaxation of Tendons. See Stress Relaxation.

Rigid Pavement. A Portland Cement concrete pavement.

Sheathing. Enclosure around the posttensioning steel to provide corrosion protection and to eliminate bond between the steel and the surrounding concrete.

Slab. A monolithic section of concrete pavement bounded by joints and edges.

Slab Length. The distance between transverse pavement joints.

Sleeper Slab. A concrete slab placed beneath joints and ends of adjoining slabs to provide support for slab ends and/or the joint hardware.

Slip-Form Pavers. Slip-form pavers perform the functions of spreading, vibrating, striking off, consolidating, and finishing the pavement to the prescribed cross section and profile with a minimum of handwork required for an acceptable riding surface. The name "slip-form" is derived from the fact that the side forms of the machine, which vary from 16 to 48 feet in length, slide forward with the paver and leave the slab edges unsupported.

Soil Consolidation. The gradual reduction of a fine grained soil mass under sustained load due to squeezing out of water from the void spaces. The load is initially carried by the pore water and is gradually transferred to the soil structure.

Stabilized Subbase. A compacted layer of granular soils, gravel or crushed stone mixed with Portland Cement, bitumen or lime prior to compaction, placed on the subgrade below the pavement.

Stress Relaxation. The irreversible inelastic elongation of steel under tensile stress, that results in tendon lengthening and reduction of tendon stress.

Subbase. A compacted layer of high quality material with good bearing strength and/or permeability placed over the subgrade. Stabilized or untreated compacted subbases are generally used below concrete pavements.

Subbase Friction. The resistance to sliding movement of a concrete pavement over the subbase.

Subslab. See Sleeper Slab.

Swelling. Volumetric expansion of the concrete due to gain of moisture content.

Temperature Gradient. The variation of temperature in the vertical dimension of the pavement cross-section.

Tendons. Tensile members used to impose and maintain horizontal compressive forces on the concrete pavement. Tendons are generally embedded in the concrete pavement, and consist of steel wire, bar, or strand.

Tendon Friction Losses. The difference between the load applied on the tendon and the load on the tendon a distance away from the point of load application due to friction between tendon and conduit. This is generally divided into wobble and curvature tendon losses.

Tie Bar. A deformed steel reinforcing bar embedded in a concrete pavement at a joint to hold slabs together. Usually used in longitudinal joints separating paving lanes.

Unbonded Tendons. Tendons in which the prestressing steel is permanently free to move relative to the concrete to which they are applying their prestressing forces.

Warping. Pavement profile change due to moisture gradient.

Zero Maintenance Pavement. A pavement designed and constructed so that it performs for at least 20 years without structural maintenance at the required level of serviceability.