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16. Abstract

The work plan for the design of the McLennan County prestressed concrete pavement (PCP) overlay consisted of three distinct aspects: (a) a thorough review of the available literature on design of PCP to determine the variables that are relevant to the design of slab length, joint details, thickness and prestress level in the longitudinal and transverse directions, (b) development of models and procedures for accurately predicting the effect of these variables on the elements of the PCP structure, and (c) development of a PCP design based on (a) and (b) to implement in the project. The design of the PCP slabs was also to include recommendations with regard to adequate time of slab placement and application of prestress forces.

The completion of aspects (a) through (c) led to the study of the effect of environfactors on PCP slabs. Environmental variables producing movements, stresses and deflections in the slabs are: (1) changes of temperature and moisture content of the pavement; (2) curling produced by temperature differentials from top to bottom of slabs; and (3) warping produced by top to bottom moisture differentials.

The main objective of this study is to present the development of a model to predict the behavior of long PCP slabs and incorporate the predictions from the model into a design procedure. In this study, the derivation of a model for friction considering its inelastic nature is presented. The working scheme of computer program PSCP1 which incorporates the major findings from this study is also shown. The information generated by the program can be used for designing thickness, prestress level and slab length of the PCP. To check the reliability of themodels inside PSCP1, a comparison of predicted responses from the model is made against responses observed at the McLennan County PCP overlay. A scheme for a design methodology based on design charts and predictions from computer program PSCP1 is finally presented.

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Research Report 401-3

Prestressed Concrete Pavement Design-
Design and Construction of Overlay Applications
Research Project 3-8-84-401

conducted for

Texas State Department of Highways
and Public Transportation

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The University of Texas at Austin

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The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PREFACE

Research Report 401-3, "Behavior of Long Prestressed Pavement Slabs and Design Methodology," is the third report for Research Project 401, "Prestressed Concrete Pavement Design - Design and Construction of Overlay Applications," which is being conducted at the Center for Transportation Research (CTR), The University of Texas at Austin, as part of the Cooperative Highway Research Program sponsored by the Texas State Department of Highways and Public Transportation (SDHPT) and the Federal Highway Administration (FHWA).

The purpose of this report is to present the development of a model to predict the behavior of long prestressed concrete pavement (PCP) slabs and incorporate the predictions from the model into a design procedure. This is accomplished by making, first, a review of the important variables affecting PCP behavior. Then, a model for predicting the stresses in the slab due to subbase frictional resistance is derived. The model derived considers the inelastic nature of the slab-subbase friction forces. The working scheme of computer program PSCP1, which incorporates the major findings from this study, is also described. A comparison of predicted responses from computer program PSCP1 against observed responses at the McLennan County PCP overlay is shown. Finally, some of the possible applications of computer program PSCP1 in connection with the design of several PCP structural elements are described.

The authors are indebted to all members of the CTR staff and professors of the Civil and Mechanical Engineering Departments who participated in the development of this study. Thanks are extended to Lyn Gabbert and Rachel Hinshaw for preparing the drafts of the manuscript. Special acknowledgement is made to the Texas State Department of Highways and Public Transportation personnel for their cooperation, in particular Mr. James L. Brown and Jerry Daleiden (D-8).

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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, Ned 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, construction, 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).

Report No. 401-3, "Behavior of Long Prestressed Pavement Slabs and Design Methodology," by Alberto Mendoza Diaz, Ned H. Burns, and B. Frank McCullough, presents the development of a model to predict the behavior of long prestressed concrete pavement (PCP) slabs and incorporate the predictions from the model into a design procedure.

ABSTRACT

The work plan for the design of the McLennan County prestressed concrete pavement (PCP) overlay consisted of three distinct aspects: (a) a thorough review of the available literature on design of PCP to determine the variables that are relevant to the design of slab length, joint details, thickness and prestress level in the longitudinal and transverse directions, (b) development of models and procedures for accurately predicting the effect of these variables on the elements of the PCP structure, and (c) development of a PCP design based on (a) and (b) to implement in the project. The design of the PCP slabs was also to include recommendations with regard to adequate time of slab placement and application of prestress forces.

The completion of aspects (a) through (c) led to the study of the effect of environmental factors on PCP slabs. Environmental variables producing movements, stresses and deflections in the slabs are:

(1) Changes of temperature and moisture content of the pavement.
(2) Curling produced by temperature differentials from top to bottom of slabs.
(3) Warping produced by top to bottom moisture differentials.

The main objective of this study is to present the development of a model to predict the behavior of long PCP slabs and incorporate the predictions from the model into a design procedure. In this study, the derivation of a model for friction considering its inelastic nature is presented. The working scheme of computer program PSCP1 which incorporates the major findings from this study is also shown. The information generated by the program can be used for designing thickness, prestress level and slab length of the PCP. To check the reliability of the models inside PSCP1, a comparison of predicted responses from the model is made against responses observed at the McLennan County PCP overlay. A scheme for a design methodology based on design charts and predictions from computer program PSCP1 is finally presented.

KEYWORDS: Concrete, overlay, prestressed concrete pavement (PCP), posttensioning, environmental factors, friction, elasticity, inelasticity, temperature change, temperature reversal, curling, warping, stress, deformation, deflection, movement, computer program, regression analysis, design methodology.

SUMMARY

The main objective of this study was to present the development of a model to predict the behavior of long Prestressed Concrete Pavement (PCP) slabs and incorporate the predictions from the model into a design procedure. In this study, the derivation of a model for friction considering its inelastic nature is presented. The working scheme of computer program PSCP1 which incorporates the major findings from this study is also shown. The information generated by the program can be used for designing thickness, prestress level and slab length of the PCP. To check the reliability of the models inside PSCP1, a comparison of predicted responses from the model is made against responses observed at the McLennan County PCP overlay. A scheme for a design methodology based on design charts and predictions from computer program PSCP1 is finally presented.

The study indicated that an elastic design of PCP slabs is not sufficient inasmuch as this method is not sensitive to wheel load repetitions. A fatigue analysis is particularly indispensable for designing pavements of highly trafficked facilities.

The friction forces under rigid pavements resemble elastic forces for small displacements (less than a maximum of 0.02 inch). However, for displacements of a higher magnitude, like those experienced by the long PCP slabs, for daily temperature cycles, the frictional resistance is substantially inelastic. In this case, reversals of slab movement result in reversals of the direction of the friction forces under the slab and changes in the nature of the concrete stresses (tensile to compressive or vice versa).

It is recommended that the design procedure for PCP should be improved by including the beneficial effect of certain environmental factors in resisting wheel loads, e.g., the permanent moisture differential through the slab depth. This permanent moisture differential causes the precompression due to the prestress to concentrate at the bottom of the pavement. The present state of the technology does not allow the designer to incorporate the effects of this factor in the design with sufficient reliability.

Criteria should be developed for evaluating long-term (20 years or more) performance of in-service PCP as related to wheel load repetitions and allowable stresses to use in design.

IMPLEMENTATION STATEMENT

This document is intended to represent a progression of thought regarding the behavior of long PCP slabs.

It is recommended that the programs and design techniques developed in this study be implemented on the procedures currently in use by the Texas State Department of Highways and Public Transportation for the design of rigid pavements and overlays.

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APPENDICES

CHAPTER 1. INTRODUCTION

This chapter provides a background on prestressed concrete pavements (PCP), the development of Project 401 at the Center for Transportation Research (CTR), and the scope and objectives of this study. The information is presented in the following sections: (1) an overview of prestressed pavements, (2) background of CTR Research Projects on PCP, (3) the objectives; and (4) the scope of this study.

OVERVIEW OF PRESTRESSED PAVEMENTS

Definition

The proposed report of ACI Committee 325 (Ref 1) defines prestressed concrete pavement as follows:

> "Prestressed concrete pavements are those which compressive forces have been introduced on the concrete sections during construction, for the purpose of preventing or decreasing tensile stresses in the concrete during service."

Advantages

Some advantages of prestressed pavements over other more conventional types of reinforced pavements include the following (Ref 43):

(1) Important savings in materials are obtained. Stresses in rigid pavements are mainly produced by the combined effect of wheel loads, warping, thermal curling, and frictional drag produced by thermal contraction. The thickness of conventional reinforced pavements is designed based on the maximum flexural stress produced by wheel loads, which should not exceed the concrete flexural strength. For this reason, conventional pavements must be relatively thick to resist flexural tension failure. Additional demands on the tensile strength of the pavement due to friction stresses, warping, and curling are met by

constructing short slabs.

In prestressed pavements, advantage is taken of the fact that concrete is much stronger in compression than in tension. Therefore, precompression is introduced in the pavement to reduce the tension levels. Research on prestressed concrete for pavements has also shown that moisture gradients through the pavement cross section produce a highly favorable prestress distribution with higher precompression at the bottom of the slabs (Ref 2). This higher precompression in the bottom is cumulative with the inherent flexural strength of the concrete, to produce an increase in stress range in the flexural zone. These factors altogether make it possible, using prestressing, to design a thinner pavement with a consequent reduction in the amount of concrete and reinforcing steel.

(2) Improved performance. The thickness of conventional reinforced pavements is designed with little regard for crack prevention and with sufficient bulk to perform during the design period. In order to reduce tensile stresses caused by friction, warping, and curling and to minimize cracking, joints are constructed relatively close together.

With prestressed pavements, the amount of cracking is minimized by the prestress. Then, longer slabs can be built and the number of transverse joints is reduced. The reduction of cracking and the number of joints, which are major causes of distress and failure of the rigid pavements, result in a pavement with high potential for providing a low-maintenance, improved-performance and longer-lasting roadway than conventional concrete pavements.

(3) Increased load carrying capacity. The remarkable increase in load resistance demonstrated by prestressed pavements on load tests (Ref 3), supported with results from actual highway and airport projects (Ref 4),has attracted attention. This increase in load resistance is explained, to a great extent, by the highly favorable prestress distribution obtained as a result of the naturally existing moisture differentials between the top and the bottom of the pavement slabs (Ref 2).

(4) Improved protection to the supporting layers. The elimination of a large percentage of transverse joints and the reduction of cracking in the road surface results in reduction of moisture and generally better protection of the road foundation.

Types of Prestressed Pavements

Past prestressed projects have included two types of slabs: continuous and separate. In the continuous type the stress is applied by using hydraulic jacks between abutments and the slabs to be stressed, or between the slabs themselves. Therefore, the slabs are continuous in the sense that expansion joints are not provided. The use of jacks results in gaps that are subsequently filled. Pavements constructed under this system are also referred to as post-stressed pavements. With the individual type of slabs, the prestress is applied in each slab independently of the other slabs. The stressing is accomplished through the use of high tensile strength cables post-tensioned after the concrete has hardened. The post-tensioning operations can be conveniently done at the slab ends in short gaps left between the long prestressed elements. Subsequently, the gaps are filled with a short filler slab, providing a separate joint at each end of the filler slab. The construction of a nearly one-mile-long experimental highway section in Texas indicates that the post-tensioning of cables can be conveniently done at the center of the slabs in jacking pockets (Ref 4).

With either type of slab, continuous or individual, the pavement may be prestressed in the longitudinal direction only or in both directions. In the individual type, cables for prestressing have been used in a variety of patterns: longitudinal, transverse, and at angles with respect to the center line. The use of transverse prestressing is very important to resisting applied wheel loads, preventing longitudinal pavement cracking, and separating separately placed pavement strips. The use of prestress in both directions is very convenient in highway pavements though conventional reinforcement may be sufficient in the transverse direction. Airport pavements are typically prestressed in both directions because the traffic load stresses are of the same general magnitude in both directions.

Several concepts have been recently introduced by Cable, Burns, et al (Ref 5) regarding the use of prefabricated structural components for PCP. One of the most interesting concepts consists of using a precast joint panel along with slip-forming of the remainder of the slab, similarly to a conventional rigid pavement. The precast joint panel would allow the complicated and critical pavement end sections to be mass produced in a closely controlled factory environment.

History of Prestressed Pavement

The concept of prestressed pavement originated in Europe over 40 years ago, where it found applications in airfields and highways. Prestressed pavements have been investigated in England and France since 1943 (Ref 6). Before 1960, nearly 60 prestressed projects were built, most of them consisting of experimental sections. These projects completed a total of

13 miles of prestressed pavement in highways and 20 miles in airports (Ref 7). One highway and six airport pavements were built in the United States. Slab lengths ranged from 170 ft to 700 ft with an average of 400 ft. The prestressing technique included the continuous and the individual types of slab. Longitudinally applied prestress in individual slabs ranged from 190 to over 700 psi. Transverse prestress was used in one-half of the highway and on all airport projects. It ranged from 0 to over 400 psi in the various slabs. The pavement thicknesses averaged 5 3/4 in. for highways and 6 1/2 in. for airports. During the 1960's, very few prestressed pavements were built in the U.S. whereas in Europe, in contrast, substantial mileages of prestressed runways and taxiways were placed and gave excellent performance. Until the 1960's, achieving a relatively high magnitude of prestress was difficult and expensive, which discouraged the widespread construction of PCP in highways. Design methods were mainly of an empirical nature.

Since the 1960's, several hardware developments and construction practices have favored the use of PCP in the United States. Among these developments are:

(1) The use of plastic-encased, grease-protected, high strength 7-wire strands in structural prestressing.
(2) The use of combined bearings and strand chucks, which permits easy placement of the post-tensioned strand anchors that firmly grip the strand.
(3) The development of low-friction mediums for treatments for use between the subgrade and the pavement that have allowed the slabs to be constructed in lengths up to 800 ft, thus diminishing the prestress reductions due to frictional resistance. Double layers of thin plastic membranes have resulted in friction coefficients of less than 0.2 although these values are difficult to obtain in normal construction.

During the 1970's, new ideas were incorporated on several experimental projects conducted in the USA. These projects include a service road at the Dulles International Airport in Virginia (Ref 8) and three full-scale highway projects in Pennsylvania (Ref 9), Mississippi (Ref 10), and Arizona (Ref 11). Table 1.1 summarizes some of the features of these demonstration programs.

The Portland Cement Association in 1983 developed a computer program called PCP as described in the report FHWA/RD-82/091 (Ref 58) which differs from the program described in the present study in several respects. The program developed herein is called PSCP1 to avoid confusion with the PCA program. The research report FHWA/RD-82/169 describes the performance of prestressed pavements in as observed in four states (Ref 59).

CTR RESEARCH PROJECTS ON PCP

In order to investigate the potential of prestressed pavements, the Texas State Department of Highways and Public Transportation (SDHPT) and the Federal Highway Administration (FHWA) sponsored the planning and design of two prestressed overlay projects, of one mile each, on Interstate Highway 35 in Cooke and McLennan Counties, Texas. The projects were conducted by the Center for Transportation Research of The University of Texas at Austin and were designated Projects 555 and 556, respectively. The work plan for both demonstration projects consisted of four distinct phases: (1) design, (2) construction, (3) monitoring, and (4) reporting. The design step was to encompass the latest procedures in pavement design and technology. Project 556 in Daleiden County was constructed between September and November 1985, whereas the construction of Project 555 was cancelled due to cost; it was considered that it might not provide additional valuable information given its similarity with Project 556.

The development of a design manual for PCP is also being conducted at the CTR under 401. The design manual is to be developed from design recommendations proposed in the literature complemented with the experience gained from the McLennan County Project.

OBJECTIVES OF THE STUDY

The primary objective of this study is to develop several aspects of a rational design procedure for prestressed pavements. The achievement of this study objective requires the following tasks:

(1) Review the available literature on design of PCP to determine the variables that are relevant to the design of slab length, joint details, thickness, and prestress level in longitudinal and transverse directions.

TABLE 1.1. MOST RECENT PRESTRESSED PROJECTS IN USA

PROJECT	VIRGINIA	PENN	MISSISSIPPI	ARIZONA
LOCATION	Dulles	Harrisburg	Brookhaven	Temple
LENGTH	400-760 ft sections	600 ft sections	450 ft sections	400 ft sections
YEAR BUILT	1972	1973	1976	1977
SLAB THICKNESS	6 in	6 in	6 in	6 in
SUBBASE	6 in Cement Treated Agg.	6 in Agg. Bit. Base Course	4 in Hot Mix Bit. Concrete	4 in Lean Concrete

(2) Develop a computer program for accurately predicting the effects of several environmental factors on the pavement structure.

(3) Develop a rational approach for determining the transverse joint spacing.

(4) Develop methods for accurately predicting the post-tensioning stress level at midlength of the slabs.

(5) Develop design procedures which accurately reflect the relationship between level of longitudinal prestress and required pavement thickness.

(6) Develop recommendations with regard to time of placement and application of prestress forces.

(7) Develop a procedure for determining the required level of transverse prestress.

Objectives 3, 4, 5, and 6 represent applications of the computer program. Objective 7 is a particular case of Objective 5 since the design of the transverse prestress follows the same principles as the design of the prestress in the longitudinal direction. The difference is that the frictional resistance is almost negligible in the transverse direction, thus resulting in a slight modification of the design criteria.

SCOPE OF THE STUDY

The design procedure presented in this study considers only the individual type of slabs in which the amount of prestress, except for the effects of subgrade friction, remains nearly constant since expansion is permitted at the joints. In the continuous type of slabs, which require the use of jacks and abutments at the ends, after the jack gaps are filled the slabs cannot expand freely and so the stresses vary with moisture and temperature changes. The result is that it is difficult to predict the amount of initial prestressing necessary to produce the desired residual stress in the concrete.

To achieve the goals of this study, the various chapters described below are presented.

Chapter 2 presents a detailed description of the important variables affecting the design aspects covered in this study.

Chapter 3 presents a discussion of the frictional resistance under rigid pavements that allows subsequent development of mathematical models.

The development of a model that predicts the generation of friction stresses under the temperature variations of the thermal daily cycle is discussed in Chapter 4.

In Chapter 5, some theoretical aspects dealing with the effect of the prestress force on the stress condition and movements of the slab are presented. Shrinkage, creep, and strand relaxation, which are the sources of long term prestress loss, are discussed.

Chapter 6 is devoted to describing the primary features of computer program PSCP1, the meaning of all data, and the input variables, and interpretation of the program output.

Chapter 7 presents a comparison of predictions from PSCP1 against field data recorded at the McLennan County Project.

Several applications of the computer program in connection with the design variables considered in this study are discussed in Chapter 8.

Chapter 9 provides a summary of the main accomplishments of this research, and the conclusions stemming from this study, and makes recommendations for improvements of the design methods by including other relevant effects.

CHAPTER 2. FACTORS TO CONSIDER IN THE DESIGN OF PCP STRUCTURAL ELEMENTS

This chapter presents a brief description of the factors that affect the following elements of a PCP structure: slab length, pavement joints, prestress level, concrete thickness, and prestressing steel. If the variables affecting these elements can be correlated in all possible combinations of their magnitude, duration, and coincidence of occurrence, it would be possible to predict their effects upon the pavement elements and produce an ideal design. First, the factors affecting slab length are described; then, the effect of environmental changes is discussed as they are relevant to the design of thickness and prestress forces.

SLAB LENGTH

Slab length is a function of several variables including expected joint width, prestress applied at the ends of the slabs, subgrade friction restraint, and the desired minimum prestress for the midlength location. However, the governing criterion for selecting the length of PCP slabs is maximum joint width. The joints should not open under extreme conditions more than four inches. If wider joint openings are allowed, a traffic hazard may arise and a problem with the riding quality. Also, the seals may be damaged and eventually pulled out of the joints.

Factors Affecting Joint Movements

The factors that affect the longitudinal movements of the long PCP slabs are

(1) Temperature Changes. These can be classified as

- (a) daily temperature variations, and
- (b) seasonal temperature variations.

(2) Moisture Changes. These consist of

(a) concrete shrinkage, and

(b) swelling produced by the change in moisture content in the concrete between seasons of the year (winter as related to spring).

(3) Slab contractions produced by the application of prestress forces. These include

(a) elastic shortening, and

(b) concrete creep under sustained load.

To accomplish the objectives of the study, a procedure to compute joint movements at any time must be developed. In this study, all factors contributing to joint movements are included except concrete swelling, which is a time dependent variable difficult to evaluate. Research by Friberg on prestressed concrete for pavements indicates that the amount of seasonal swelling is independent of the amount of prestress and is not less than 100 microstrains (Ref 2). However, seasonal swelling varies with atmospheric conditions, such as humidity and rainfall, and may also depend on the underlying soil type as well as capillary action and the depth of the water table. Further research is required in this area. Meanwhile, since swelling represents reduction of the joint width, its exclusion provides some degree of conservatism when slab length is selected.

The Effect of the Frictional Resistance

The joint movements of PCP are the result of slab length changes. Length changes of PCP slabs may occur restrained and unrestrained by the friction. Long prestressed and conventionally reinforced pavements have been explored in this respect in recent years. Excellent data on movements have been obtained. In a 1312-foot prestressed pavement in Germany (Ref 12), it was observed that the central portion of the pavement was fully restrained by the friction for daily temperature changes, as illustrated in Fig 2.1. Cashell and Benham (Ref 13) report daily temperature changes restrained by the friction in a 1310-foot continuously reinforced pavement (CRCP), but not for seasonal temperature changes as shown

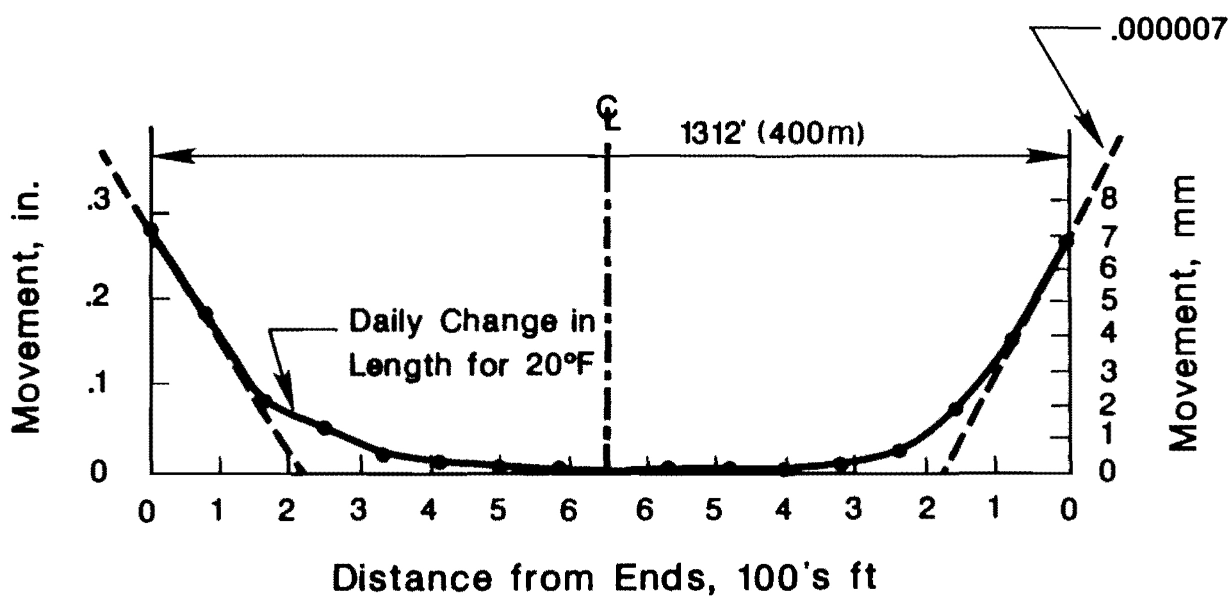


Fig 2.1. Restrained temperature expansion in 1312-feet prestressed slab in Viernheim, Germany, for a 20°F temperature increase from 5:45 AM to 5:25 PM (Ref 12).

in Fig 2.2. The daily movements of the CRCP were smaller than for the prestressed slabs due to the internal relief provided by the cracks of the CRCP. The large and even movements due to seasonal influences in the CRCP corresponded closely to contraction or expansion without frictional resistance.

Summarizing, the slab movements can be classified with respect to the frictional resistance as follows:

(1) Movements partially restrained by the friction. This category includes the movements produced by the daily temperature changes.

(2) Movements unrestrained by the friction. These movements include concrete swelling, shrinkage and creep, and

(3) A third classification type is required for elastic shortening which is diminished by the friction when the prestress force is applied, but which affects the full slab length shortly after prestressing (Ref 43). These movements are, in essence, temporarily restrained movements.

Effect of the Prestressing Technique

In connection with maximum joint opening, the selection of prestressing technique and type of joint plays an important role. The slabs may be prestressed in short gaps left between the slabs, from 6 to 8 feet long, or in blockouts or stressing pockets at the center which are filled with concrete after the prestress force has been applied.

Gap Slabs. If the stressing is done in the gaps, the gaps should be left open for some time period to permit most of the progressive length changes to occur, including elastic shortening, shrinkage, and creep, and then filled with a concrete filler slab. Therefore, the use of gap slabs has the advantage that the increase in width of the joints after placement of the gap concrete is reduced and generally longer slabs can be constructed.

Gap slabs may be constructed in double and single joint configurations. The double joint configuration consists usually of a reinforced slab with two joints, one at each end of the gap slab, as shown in Fig 2.3 (Refs 23 and 60). Since the gap slab is not prestressed, it should be thicker than the PCP. This configuration has the advantage of having less movement at each joint, approximately half the movement of a single joint. The main disadvantage is

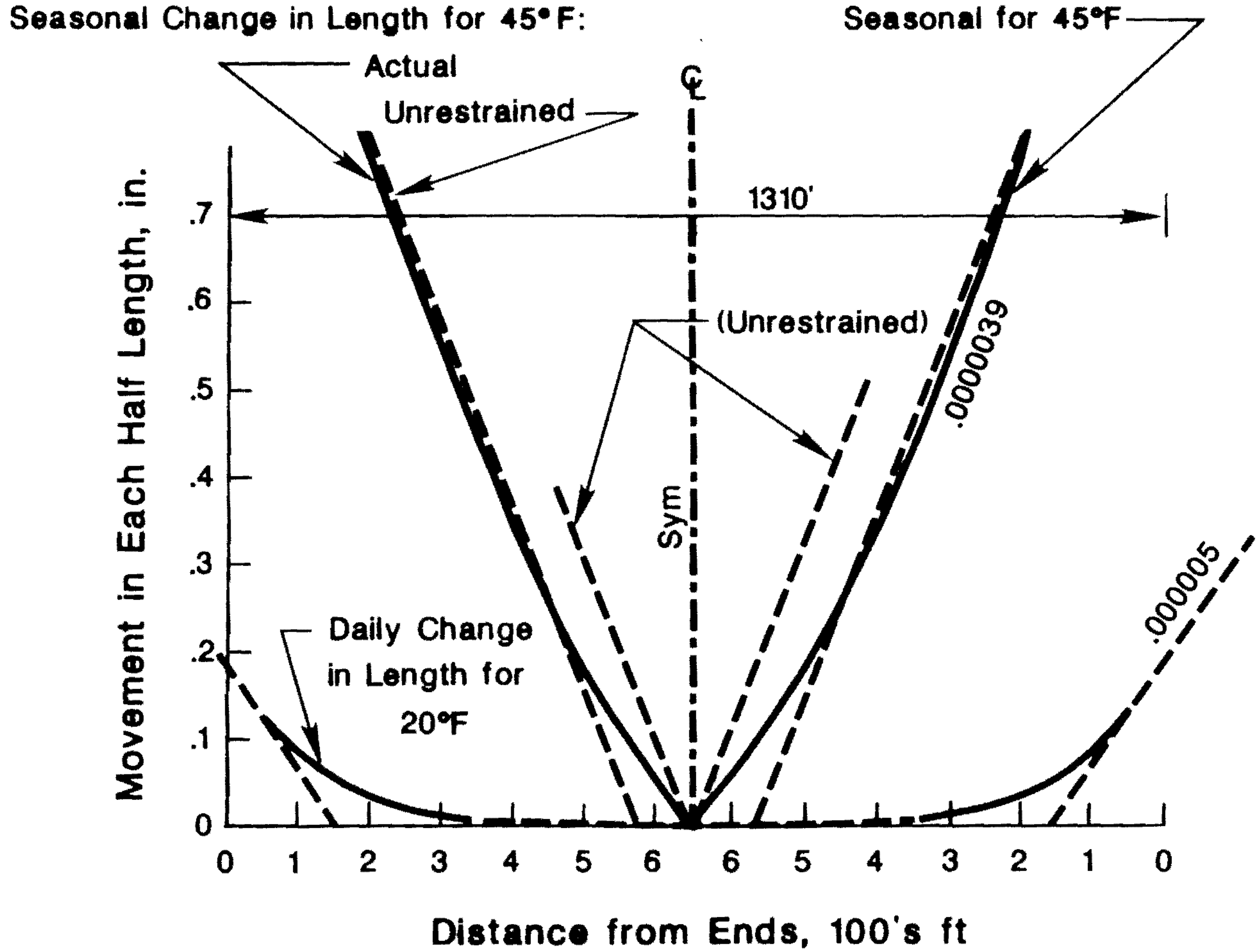


Fig 2.2. Restrained daily expansion and unrestrained seasonal movement for 1310-foot-long CRCP (Ref 13).

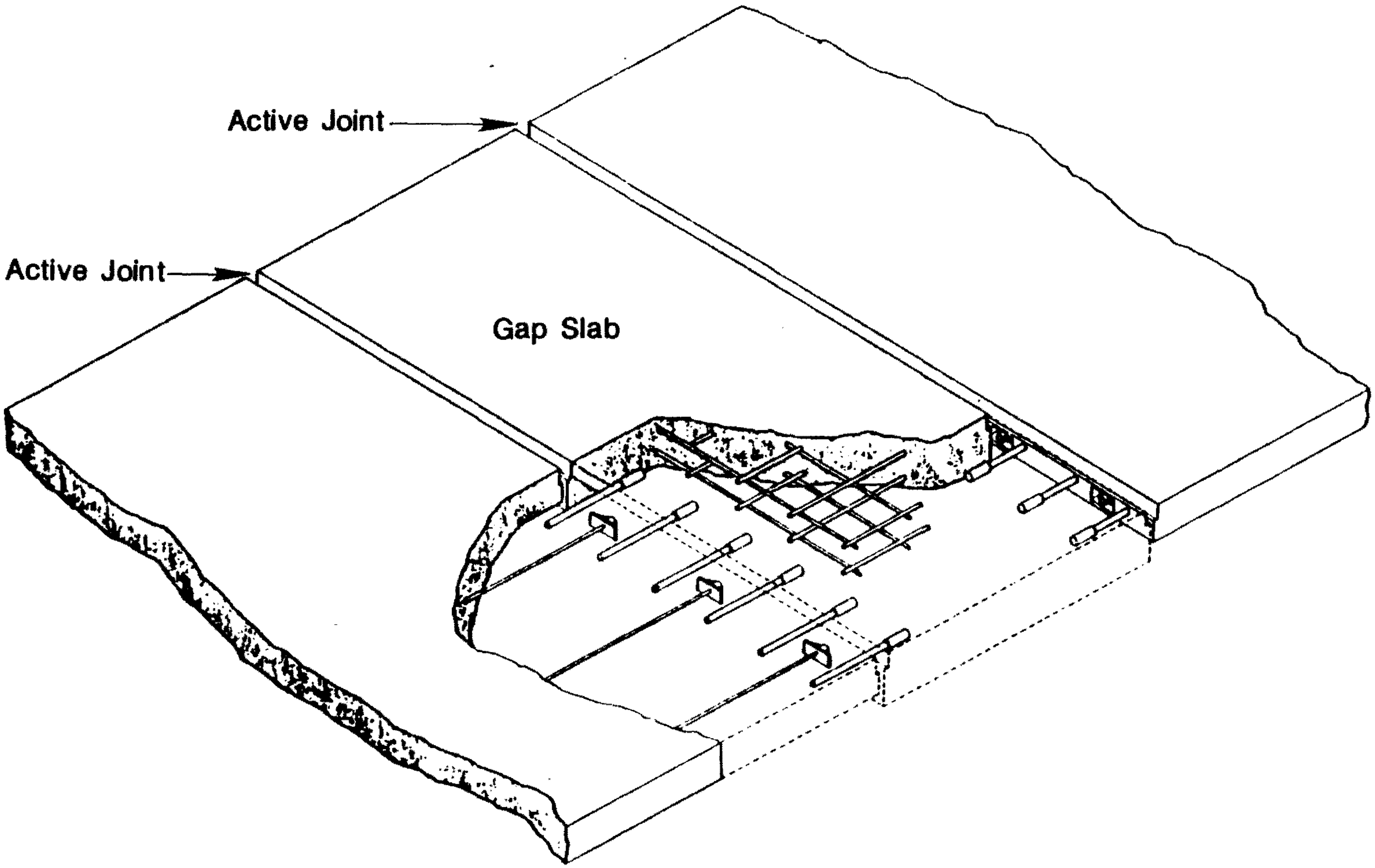


Fig 2.3. Double joint prestressed pavement construction. Reinforced gap slab placed after final post-tensioning of main prestressed slabs (Ref 23).

economics. Since joints are first cost items which require periodic maintenance, both the initial and long term costs associated with a gap slab arrangement having two joints are greater than for a design requiring only a single joint.

Single joint configurations can be obtained for gap slabs if the tendon forces applied to the prestressed slabs are transferred later to permanent anchors in the gap slabs at the joints (see Fig 2.4). The stress transfer process requires special jacks and tensioning provisions at the joint. Since the gap slab is prestressed, it requires less steel. The single joint configuration results in fewer joints but the joints will open approximately twice as much as a single joint with the double joint configuration. For this reason, its use is limited to relatively short slab lengths and concretes with low thermal coefficients.

The Construction Technology Laboratories of the Portland Cement Association (Ref 23) have proposed several designs for double and single joint gap slab arrangements. Two of these are shown in Figs 2.3 and 2.4.

Central Stressing. Since poor gap slab performance (i.e., warping, curling, rocking, etc.) has been observed on several experimental prestressed projects, one of the objectives of Project 401 was to find another method of post-tensioning which would eliminate gap slabs. The most promising alternative was central stressing. Central stressing is a procedure in which the strands are stressed in internal pockets. The concept is illustrated in Fig 2.5. For a series of different schemes of central stressing the reader is referred to a series of field tests conducted near Valley View, Texas, by the staff of CTR Project 401 (Ref 34). The main disadvantage of central stressing in terms of joint openings is that the final joint width will include all the elastic shortening, shrinkage, and creep; therefore, its use is suited to shorter slabs than those that may be obtained if gap slabs are used. This does not mean that central stressing will bring about a larger number of joints than when gap slabs are used since gap slabs require two consecutive joints for each long PCP slab.

JOINT DESIGN

The joint width plays an essential role in the design of the joints of prestressed pavement slabs. The joints of prestressed pavements experience openings which are comparable to the openings of bridge joints. Therefore, the design of the joint should follow the majority of the ACI Committee 504 recommendations (Ref 14). The use of dowels is

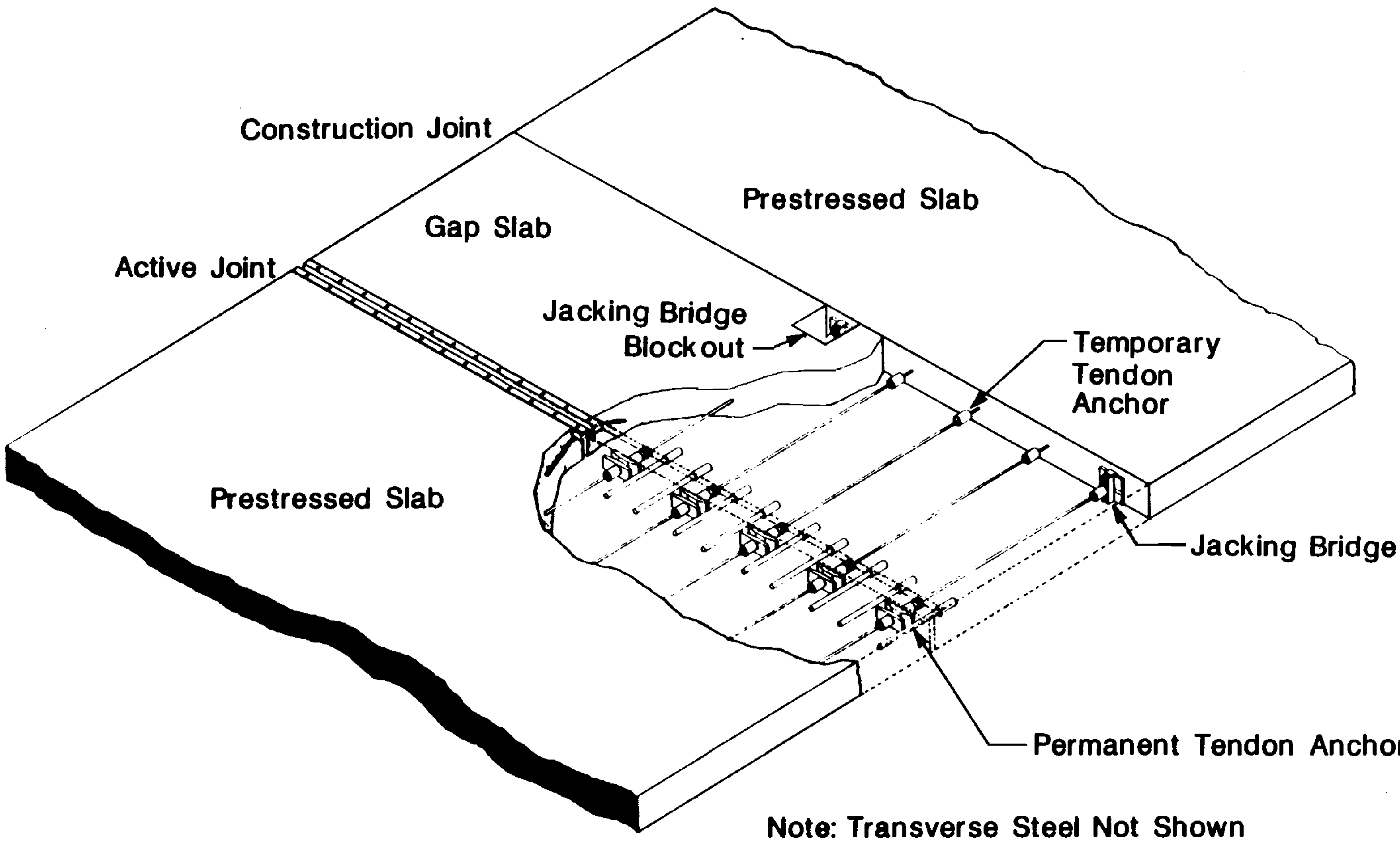
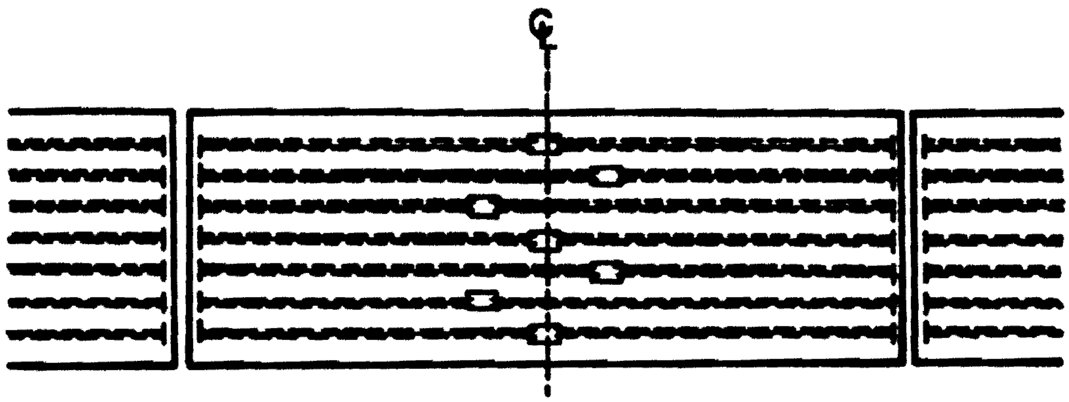
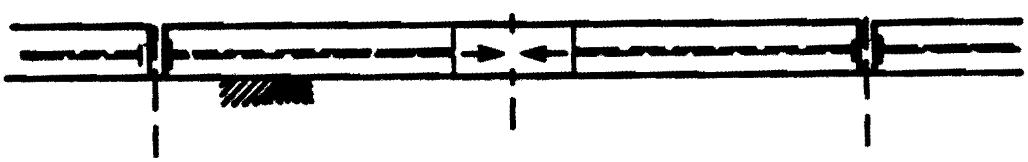


Fig 2.4. Single joint construction of PCP to obtain full-length prestressed slabs (Ref 23).



(a) Plan view showing an arrangement of internal pockets in a PCP slab.



(b) Edge view of central stressing in an internal pocket.

Fig 2.5. Concept of central stressing.

essential for load transfer across the joints and to prevent excessive deflections of the thin PCP slabs under heavy weight traffic. Mendoza et al (Ref 4) and Cable et al (Ref 5) presented a review of joint details used with previous PCP projects in the USA, along with the design details for the Texas Project. Also the PCA report FHWA/RD-82/090 "Prestressed Concrete Pavement, Volume 1, Joint Design," (June 1983) is another source of reference for this subject.

EFFECT OF ENVIRONMENTAL CHANGES ON THE PAVEMENT STRUCTURE

Environmental variables cause time dependent variations in the net prestress level longitudinally and vertically in a PCP. Factors producing stresses are

(1) Temperature and moisture stresses due to subbase friction resistance.

(2) Restrained curling produced by temperature differentials from top to bottom of the slabs.

(3) Restrained warping produced by top to bottom moisture differential.

After the prestress forces are applied, long term slab movements may cause significant variations of the prestress level.

Friction Restraint Stresses

As was said earlier, friction restraint stresses are produced in the slab as a result of the daily temperature change movements. Research at the Bureau of Public Roads (Ref 18) established that the frictional resistance is not constant, but increases with slab movement, rapidly at first and then at a decreasing rate with increase in movement until a maximum value is reached. This maximum value corresponds to the force required to produce free sliding (Ref 19) For pavement slabs, the magnitude of the movements produced by a daily temperature cycle depends on the location along the slab length. The movements normally vary from a maximum at the edge to a minimum at the center. Therefore, the maximum friction forces develop at the ends and decrease toward the center. Concrete stresses which are the result of the accumulation of friction forces grow from the end toward the center. Fig

2.6 shows the profiles of movements, friction forces, and concrete stresses which are characteristics of temperature related movements.

Studies by Friberg and Stott (Refs 20 and 21) clearly show the inelastic nature of the friction forces developing beneath long pavement slabs. Reversals of movements result in reversals of friction forces and corresponding concrete stresses. Characteristically, in a daily cycle, two movement and friction resistance reversals take place, a few degrees after the maximum and minimum slabs temperatures occur. Tensile stresses, as shown in Fig 2.6, develop several hours after the afternoon peak, and compressive stresses with opposite profiles than the ones shown in Fig 2.6 develop after the morning minimum temperature. The magnitude of the friction restraint stresses depends primarily on the concrete coefficients of contraction and expansion, the concrete modulus of elasticity, and the friction force versus movement relationship. The tensile stresses are the most important since they result in two unfavorable conditions for the PCP:

(1) Before application of prestress forces, the tensile stresses produced on long slabs, especially during the first night if constructed at high temperatures, may cause premature cracking of the slabs. For this reason, the recommended practice is to apply an initial amount of prestress during the first night to keep tensile stresses below the concrete tensile strength and avoid first night cracking.

(2) After the application of prestress forces, the friction forces arising with temperature drops diminish the prestress applied at the ends to a specific level. After the application of a certain amount of force, the stress level at any section is the super position of the external prestress force on the profile of friction restraint stresses due to daily temperature changes. The final stresses on the concrete are the mirror image of the friction restraint stresses before the prestress force is superimposed. Therefore, it is at the center of the slabs that the frictional restraint reduces the effectiveness of the external prestress more when the temperature drops.

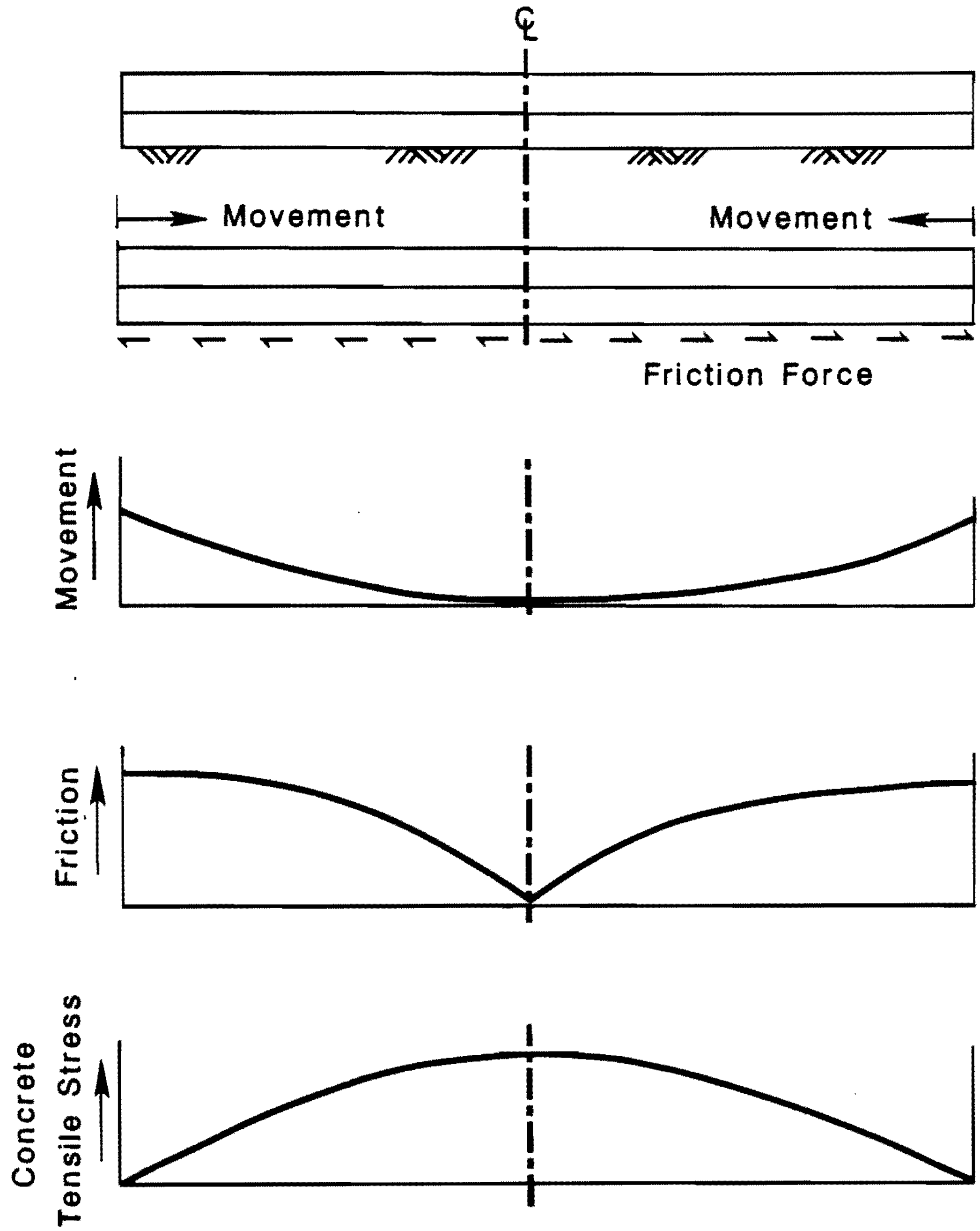


Fig 2.6. Effect of the frictional resistance on movements and stresses in the slab for temperature decreases.

Stresses Due to Temperature Gradient

The curling of panel corners due to fluctuating air temperature and the resulting temperature differential was measured at the AASHO Road Test (Ref 17). However, the occurrence of curling deflections has been recognized since 1935 when Teller and Sutherland (Ref 18) measured the deflections at pavement corners, ends, and edges caused by temperature gradients from top to bottom. Curling occurs because concrete is a relatively slow conductor of heat, and a temperature differential is created by the lag in time required for heat to transfer through the slab. In a typical daily cycle, a pavement slab will curl downward during the day, creating tensile stresses in the bottom, and upward during the night, leading to bottom compressive stresses. These stresses are larger in the slab interior, where the deflections are fully restrained. Also, curling stresses may be larger during the summer months, when air temperature fluctuations are greater.

Stresses Due to Moisture Differential

An important characteristic of concrete pavement evolves from the fact that water evaporates freely from the top surface of the pavement while the bottom surface remains almost saturated. This effect was observed by Friberg in tests with short pavement slabs at Rolla (Ref 2). In these experiments, the slabs showed bottom portions near full saturation, whereas the top portions were at a lower moisture content most of the time. In PCP slabs, this effect is magnified since the movement of water from the bottom upwards is particularly restricted by the membrane sheets on which these slabs are cast (Ref 24). This moisture differential tends to induce warping deformations which are fully restrained by the slab weight in the inner zone of the longer PCP slabs. The warping restraint stresses away from the slab end produce compressive stresses at the bottom, introducing a beneficial factor for the pavement in resisting wheel loads. Although values of moisture differential stresses have been recognized at different concrete ages and climatological seasons and design recommendations have been developed in this regard, these values are not used generally. Moisture differential depends on local environmental conditions, thus becoming difficult to quantify with any degree of reliability. For these reasons, designers do not normally consider warping stresses in the design.

Variations of the Prestress Level

The prestress stresses may fluctuate around some average stress based on initial total elongation of the strands, adjusted for long term concrete length changes and steel stress relaxation. The long term slab movements, which occur without frictional resistance, produce the most significant length variations of the PCP slabs. Therefore, long term slab movements affect the elongation of the strands and the fluctuations of the prestress force. Seasonal temperature variations, shrinkage and creep occurring after application of the post-tensioning force are then the time dependent variables to consider in this case.

Although relaxation of the prestressing steel and the friction between the tendons and their conduits are not environmental variables, they are also factors affecting the prestress level. Steel strand relaxation is a time dependent effect usually greater at the slab ends where the steel stress is higher. The strand friction effects, which cause prestress losses usually referred to as wobble losses. Regardless of the location of initial post-tensioning, the strand friction will not be noticeable in pavement slabs after the first few years (Ref 1). In this study an initial tension plus the close spacing of chairs assures that very little wobble was possible in the tendons. Wobble losses can be minimized by keeping the conduit as straight as possible during construction of the PCP.

Distribution of Prestress

It was noted previously that warping and bottom compressive stresses are the result of moisture differentials between tops and bottoms of PCP slabs. In addition, the difference in moisture results in variations through the slab thickness of the modulus of elasticity and creep of concrete. As a result of these variations, which are time dependent, the precompression applied on the PCP slabs concentrates at the bottom of the pavement. This important characteristic of PCP is rarely considered in the design. Sargious and Ghali (Ref 25) present a method of analysis to calculate the distribution of concrete stresses considering moisture effects. However, the use of this method is limited to the knowledge of certain time dependent parameters related to the concrete properties, such as shrinkage and creep gradients, which are not available in the literature and which can be obtained only by site measurements or field research on actual pavements. The favorable effect of the restrained warping and the distribution of prestress through the pavement depth will be overlooked in this study considering that, if ignored, an additional safety factor in the design is provided.

THICKNESS AND LEVEL OF PRESTRESS

The selection of pavement thickness and the amount of prestressing steel are variables which have to be defined jointly. Sargious proposes the following fundamental equation for designing the thickness and prestress of PCP based on stresses in the elastic range (Refs 15 and 16):

$$f_t + f_p = f_{c+w} + f_F + f_L \qquad (2.1)$$

where

f_{c+w} = restraint stress due to temperature and moisture gradient, i.e., curling and warping;
f_F = restraint stress due to friction;
f_L = flexural stress due to imposed load;
f_t = allowable concrete flexural stress; and
f_p = compression due to prestress.

The use of this equation is found particularly suitable by most designers for its simplicity and because prestressing assures the concrete elastic behavior by raising the stress level against cracking. This equation permits solutions for allowable loads, thickness and level of pavement compressive stress. The prestress levels defined from this equation should be compensated for losses due to shrinkage, creep, relaxation, friction between the conduit and the tendon, seating losses and elastic shortening. For prestressed pavements with long joint spacings and concomitant extensive elongation of the steel tendons, the losses due to seating and elastic shortening are insignificant and may be ignored.

Curling, warping, and friction restraint stresses in Eq 2.1 have already been discussed. Wheel load stresses, allowable concrete flexural stress, and prestress forces are discussed in the following sections.

Wheel Load Stresses

Load stresses in the pavement can be calculated by using the well-known Westergaard equations (Ref 27), one of the computer codes to predict stresses from plate theory (Ref 28), multi-layered elastic theory (Ref 29), or any of the more recently developed finite element programs (Ref 30). The advantage of multi-layered elastic theory and finite element programs is that they can analyze the PCP slabs as a system of layers rather than relying on an adjusted "k" value as required when using the Westergaard equations or the plate theory programs. In the design of PCP for highways, edge loading is the most critical load placement for pavements without concrete shoulders, and interior loading may be considered for pavements in which the PCP extends to the shoulder areas. The critical load for interstate highways may be the maximum allowable 20-kip equivalent single axle load. The critical stress location is the slab midlength where tensile wheel load stresses and environmental stresses are additive.

Allowable Concrete Flexural Stress

The allowable concrete flexural stress in the concrete is the flexural strength divided by a safety factor. Efforts by Klieger (Ref 17) indicate that flexural strength increases rapidly during the first 28 days at which time it reaches 70 percent of its maximum. The maximum strength is reached at approximately 3 months to 1 year, depending on the type of cement used. The 28-day value is suggested for design and can be obtained from the well-known flexural strength test (Ref 26). With respect to safety factors, Report 3 of ACI Committee 325 (Ref 1) suggests 1.5 and 2.0 as reasonable values for secondary and primary highways respectively. The use of statistical data and the application of reliability concepts and confidence levels is another alternative for defining safety factors for design (Ref 47).

Prestress Force in the Longitudinal Direction

In the process of designing thickness and longitudinal prestress force, Eq 2.1 must be solved for the location where, for a certain time of day and season, environmental stresses combined with wheel load stresses result in a critical condition. In highway PCP slabs, the typical conditions to check for design of longitudinal prestress are:

(1) The slab midlength where the prestressed force superimposed on the profile of tensile frictional stresses gives the minimum post-tensioning level. The critical season to check may be the summer when the fluctuations of air temperature are larger. However, this depends on the climatological conditions of the location of the section being designed. The critical time of the day may be between 6 AM and 8 AM when the tensile friction stresses are near their maximum value with a minimum of curling restraint stresses (Ref 31). Also, because the top surface of the pavement is relatively wet at this time of the day, the warping restraint stresses provide the least precompression at the bottom of the slab.

(2) The slab midlength where the maximum tensile stress at the bottom of the slab due to traffic combined with the curling restraint stresses with a minimum of friction restraint stresses create a critical condition between 4 PM and 6 PM during the summer, when the fluctuations of air temperature produce higher curling stresses (Ref 31).

Other criteria that must be satisfied for the elastic design of PCP in the longitudinal direction are:

(1) The post-tensioning force at the slab ends should not exceed an allowable maximum to avoid damage to the concrete near the anchor zone.

(2) The selected thickness of the PCP should result in lower deflections than 0.03 inch to avoid exceeding the capacity of the supporting layer and causing a problem of permanent deformation and creation of voids beneath the pavement under heavy truck traffic (Ref 1). However, this is not a problem with PCP used for overlays of existing rigid pavements given the adequate supporting conditions provided by the existing pavement.

Analysis in the Transverse Direction

In the transverse direction, the frictional resistance is minimum and the condition that should be checked for the design of the transverse prestress is the tensile stress at the bottom of the slab due to traffic combined with the curling restraint stress that creates a critical condition between 2 PM and 4 PM during the summer (Ref 31).

Fatigue Considerations

The argument usually advocated by many researchers of PCP (Refs 15, 16 and 44) to recommend an elastic procedure to design thickness and prestress level over a fatigue approach is that, since PCP is designed for no cracking, the net tensile stress due to wheel loads over the precompression produced by the prestress is relatively small. Hence, it is argued that fatigue is not a major factor in the design. In this study, it will be considered that an elastic approach does not suffice to design PCP slabs, as such a method is not sensitive to wheel load repetitions. Moreover, although the magnitude of the wheel load stresses over the precompression of the prestress is relatively low, their cumulative effect may cause an eventual fatigue failure. A design example presented in Chapter 8 of this report will support clearly this aspect. Finally, it is worth noting that the most innovative design procedures [revised AASHTO method (Ref 47), PCA method of design (Ref 57), etc.] are fatigue oriented.

PRESTRESSING STEEL

For PCP, it is common to use plastic-encased, grease protected, 270-K grade, 7-wire strands with 0.6-inch nominal diameter. The use of low relaxation strands is advisable. The tendons are normally tensioned to an allowable stress of 80 percent of the ultimate strength of the strand and then released back to about 70 percent at the stressing end after the anchoring is finished. The tendons should be stressed from both ends if gap slabs are used to make more efficient use of the strand. For the same reason, in the case of central stressing, nearly equal forces should be applied on both strand segments to each side of the pocket. Therefore, the pocket should be as close as possible to the center of the slab.

SUMMARY

In this chapter, a description of the important variables affecting PCP behavior and several of the design aspects covered in this study have been presented.

The selection of slab length in prestressed pavements is governed by the maximum joint width. The factors that affect joint width are the slab movements due to temperature changes (daily and seasonal), concrete moisture changes (shrinkage and swelling), and contraction induced by the effect of prestress forces (elastic shortening and creep). These movements can be classified as short-term movements (due to daily temperature changes) and long-term movements (due to seasonal temperature variations, concrete swelling, shrinkage and creep). The short-term movements are restrained by the friction. The subbase friction forces and corresponding slab stresses arise exclusively from these movements. The long-term movements occur unrestrained by the friction and, since their magnitude is fairly substantial in the long term, the variations of the prestress level are primarily due to the accumulation of these movements.

The design of thickness and prestress level is based on the prediction of slab stresses. The following factors produce stresses in the slab: (1) subbase friction, (2) temperature gradients through the pavement depth, (3) wheel loads, and (4) the precompression produced by the prestress. Though usually an elastic approach considering these factors is proposed for the thickness and prestress level design of PCP, this method is not sufficient for it is not sensitive to the repetition of wheel load stresses. A fatigue approach is then indispensable for design considering these variables.

CHAPTER 3. NATURE OF THE FRICTIONAL RESISTANCE UNDER RIGID PAVEMENTS

The contraction and expansion movements of short pavement slabs during the daily temperature cycles are not significantly reduced by the frictional resistance. However, in long pavement slabs with fully restrained central portions, the magnitude of the concrete friction restraint stresses is significant. The importance of these stresses in the design of PCP slabs was raised in Chapter 2. In this chapter, a comprehensive discussion is made on the nature of the frictional resistance. A good understanding of this phenomenon is essential for developing mathematical models to simulate the behavior of long PCP slabs.

THE FRICTION FORCE

In classical mechanics, the friction force is defined as the tangential force that develops when two surfaces which are in contact tend to move with respect to each other. The nature of the friction force is not completely known; however, it is assumed to be produced by two factors: (1) molecular attraction and the nature of the surfaces in contact and (2) the irregularities between the surfaces in contact. In a block model, as shown in Fig 3.1, if a horizontal force is applied on the block, the friction force that develops before the block experiences any movement is called static friction force. The friction coefficient corresponding to the maximum static friction force is named static coefficient of friction. The friction force that develops after the maximum static friction force, Fm, is exceeded and the block slides is named the kinetic friction force, Fk.

The friction coefficient that corresponds to the kinetic friction force is named kinetic friction coefficient, and it is lower than the static friction coefficient. Relevant properties of these coefficients are: (1) both coefficients are independent of the normal force, (2) both coefficients depend on the nature of the surfaces in contact and the exact condition of the surfaces, and (3) both coefficients are independent of the area of the surfaces in contact.

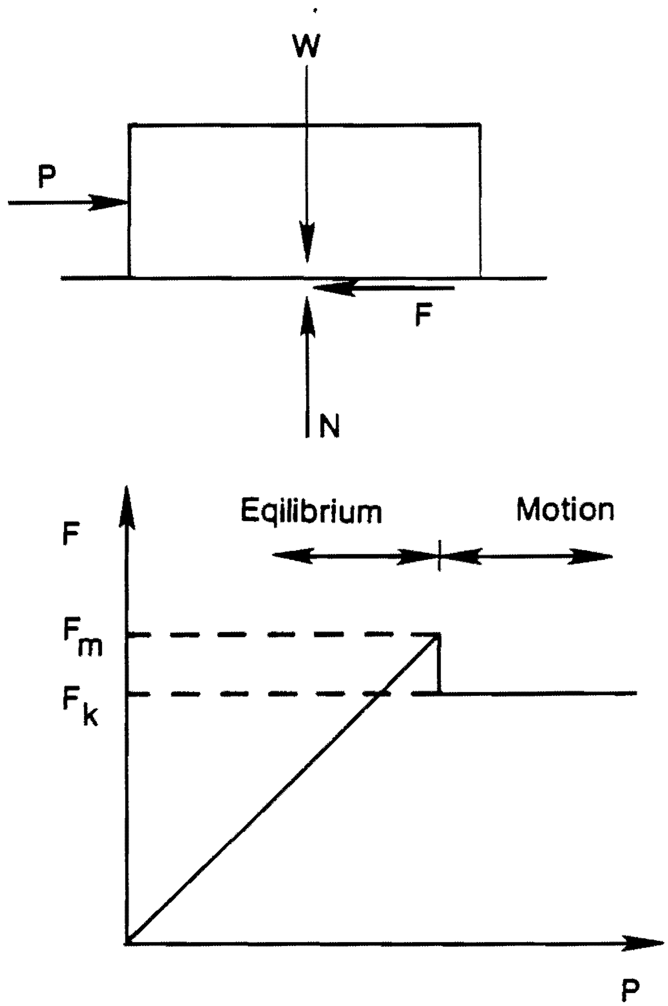


Fig 3.1. Classical friction model.

FEATURES OF SLAB FRICTIONAL RESISTANCE

Studies have been conducted since 1924 to study the nature of the frictional resistance under rigid pavement. Some of the features observed during field tests are presented below.

Goldbeck

Studies conducted in 1924 by the US Bureau of Public Roads (Ref 32) gave the first relevant ideas on the nature of the frictional resistance offered by different materials to horizontal movements of concrete pavement slabs. The following important conclusions may be drawn from these studies:

(1) If a pushing force is exerted on a pavement slab cast under a certain base material, the irregularities between the surfaces in contact act as a grip for the slab when it tends to move. This grip makes shear stresses develop at the surface of the base material and tend to elastically deform it when the slab tends to move. More roughness in the base results in more grip for the slab with a consequent increase of the amount of base material pushed by the slab and, therefore, of the frictional resistance.

(2) The frictional resistance may be greatly reduced in concrete pavements if more slippage of the slab is allowed by the elimination of ridges and depression in the base or if a sand layer is introduced between the base and the pavement.

(3) Secondary observations to the interest of this research, though relevant indeed, are that the frictional resistance is considerable lower when base materials are tested under saturated conditions. This is due to the fact that the water acts as a lubricant, which permits the slabs to slip easier, and because moisture content affects the consistency of most base materials.

After the studies conducted by Goldbeck, a thick layer of sand was introduced under highway pavement slabs. However, in prestressed pavements, the slabs are relatively thin and tend to experience large deformations at edges and joints of the pavement under wheel loads. These deformations may cause voids beneath the pavement and pumping may eventually arise and become a serious problem. This has led highway engineers to study other types of friction relieving materials.

Timms

Relevant results pertaining to the behavior of friction are reported by Timms (Ref 33). His study, conducted by the US Bureau of Public Roads in 1963, consisted of pushing concrete slabs cast on different types of materials. The following conclusions are important :

(1) The friction coefficient is greater when the slabs are pushed initially and decreases for the average of subsequent movements. Figure 3.2 shows this condition for the materials tested.

(2) On release of the thrusting force, the slab tends to return slightly to its original position. This slight return, very small indeed, is a semi-elastic recovery of the base material being tested. This particular feature is also reported by Friberg in tests with 100-foot long slabs (Ref 20).

(3) From Fig 3.2, it is evident that the lowest coefficients of friction are obtained with double layers of polyethylene sheeting, followed by slabs placed on sand bases, granular bases, plastic clays, and emulsified and asphalt sheet layers, in that order consecutively.

Other Field Tests

The results from other field tests that evaluate the properties of particular materials are reported in the literature. Two of these tests are cited herein.

Saudi Arabia Tests. The apron zone of the King Fahd International Airport (KFIA) in Dhahran, Saudi Arabia, was designed by Austin Research Engineers (Ref 31). The severe climatological conditions in Dhahran, where large daily temperature changes are characteristic, required that the merits of different base types be carefully assessed to avoid premature cracking of the pavement. Concrete cylinders 22.5 inches diameter and 16 inches deep were cast and pushed over the following materials:

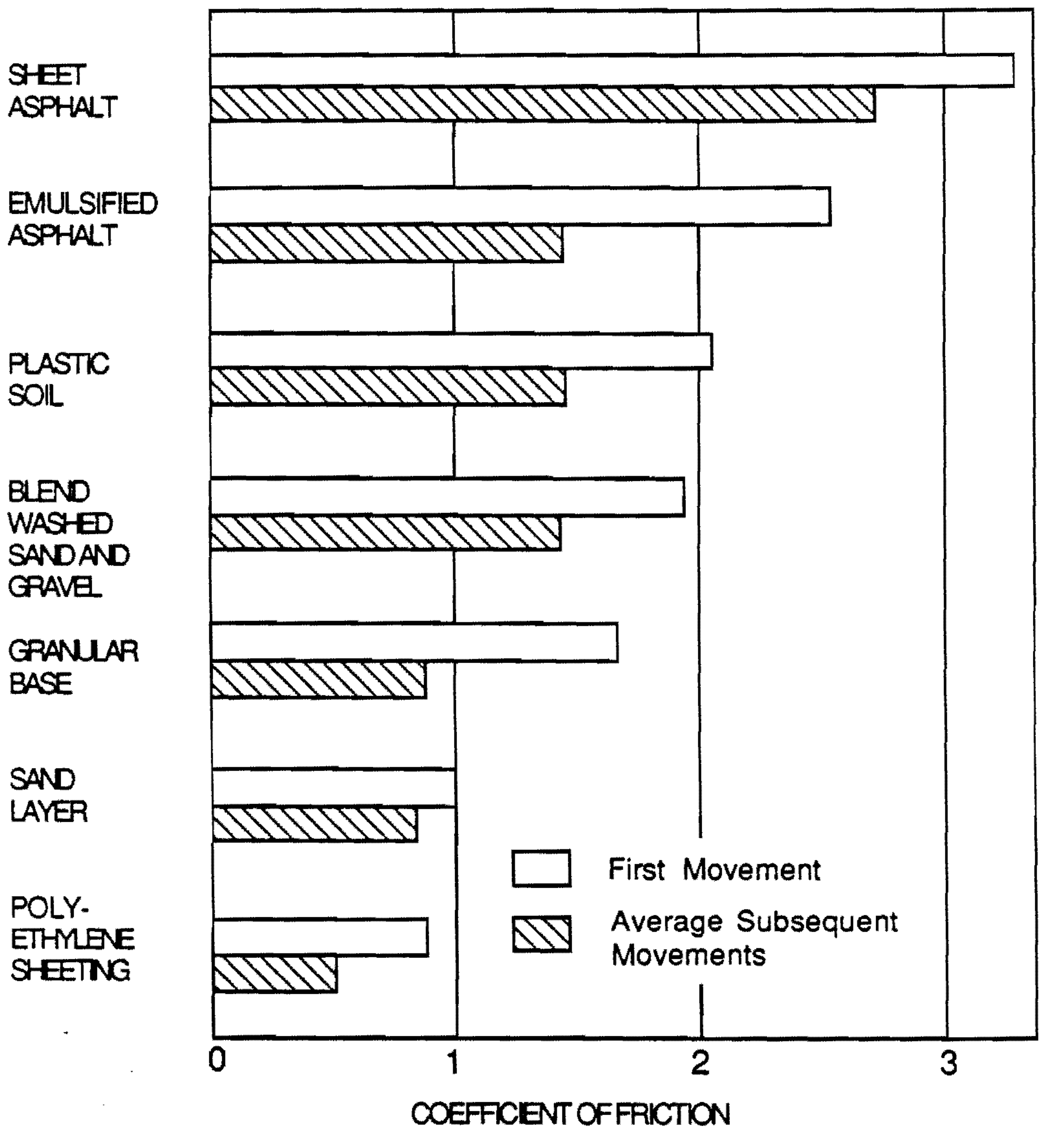


Fig 3.2. Summary of friction coefficients obtain by Timms (Ref 33).

(1) An aggregate base coated with a medium curing asphalt cutback (MC-70).
(2) A fine grade bituminous base course.
(3) One-sheet of visqueen over a bituminous base course.

The testing procedure is described in great detail in Ref 48. The results from these tests are shown in Fig 3.3.

Field Tests at Gainesville, Texas. A series of field tests were conducted by the University of Texas at Austin as part of a program for designing the PCP overlay in McLennan County (Ref 4). In these tests, 6-inch-thick concrete slabs were cast and tested over the following materials:

(1) An asphalt base.
(2) A 6-mil polyethylene sheeting on an asphalt base.
(3) A double layer of 6-mil polyethylene sheeting on an asphalt base.

The testing procedure is described in great detail in Ref 34. The results are in complete agreement with the results obtained in Saudi Arabia and the results reported by Timms for similar materials. Figure 3.4 presents the friction coefficient versus displacement curve for the three conditions analyzed as they will be used for discussion in subsequent chapters of this study.

HYSTERETIC BEHAVIOR

In 1963, Stott (Ref 21) of the Road Research Laboratories of Great Britain presented the results of a comprehensive laboratory investigation. Stott cycled slabs placed on various materials back and forth. The amplitudes of the cycles of movement and the rate of application of the force were varied in the experiment. The materials tested included sand layers, aggregate layers, polyethylene sheetings, and asphalt cements having different nominal penetration values. These tests provide excellent information on friction behavior. Figure 3.5 shows the typical friction force versus movement curve obtained for most materials tested by Stott. Important features of this curve are the following:

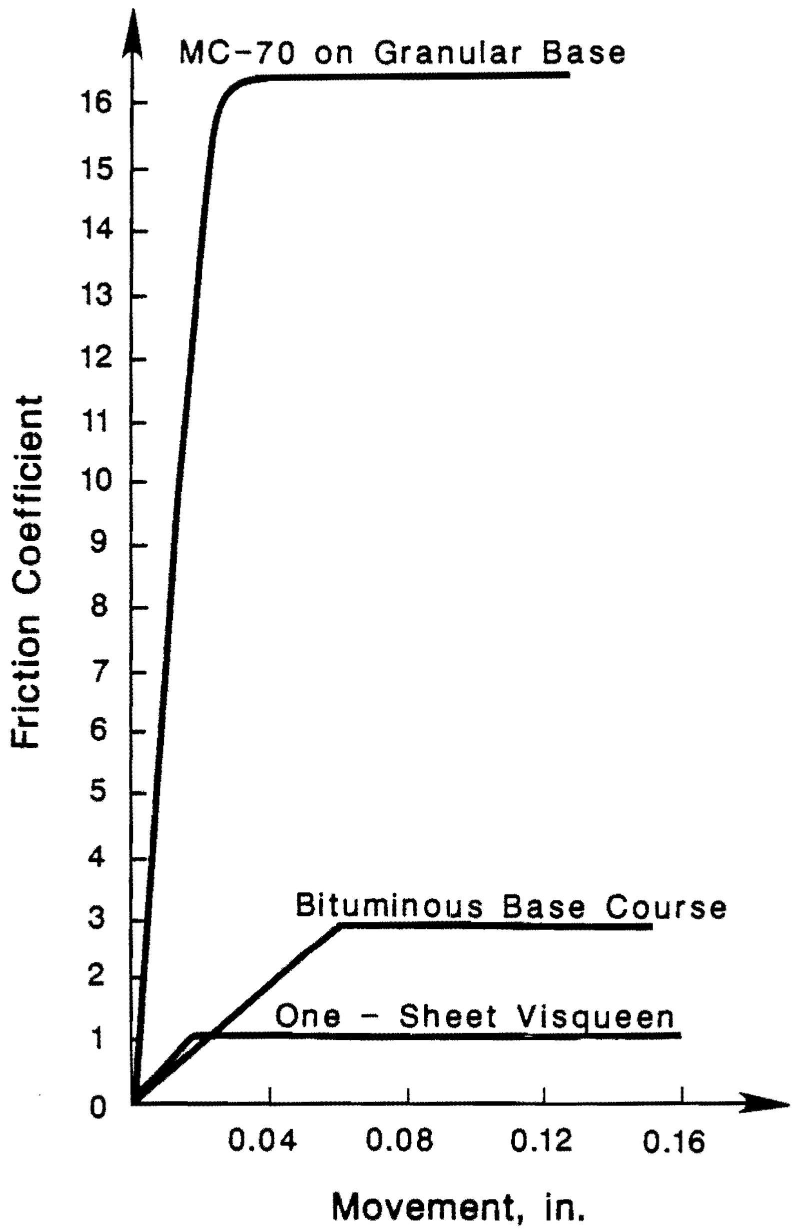


Fig 3.3. Friction coefficient versus movement for materials tested in Saudi Arabia (Ref 31).

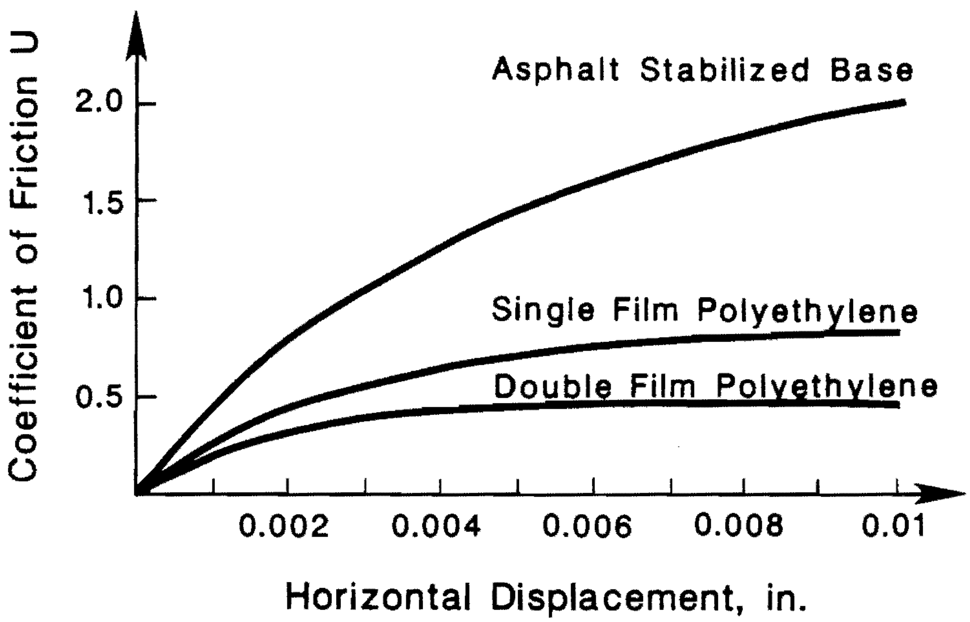


Fig 3.4. Friction coefficient versus displacement for materials tested for the design of the McLennan county overlay (Ref 34).

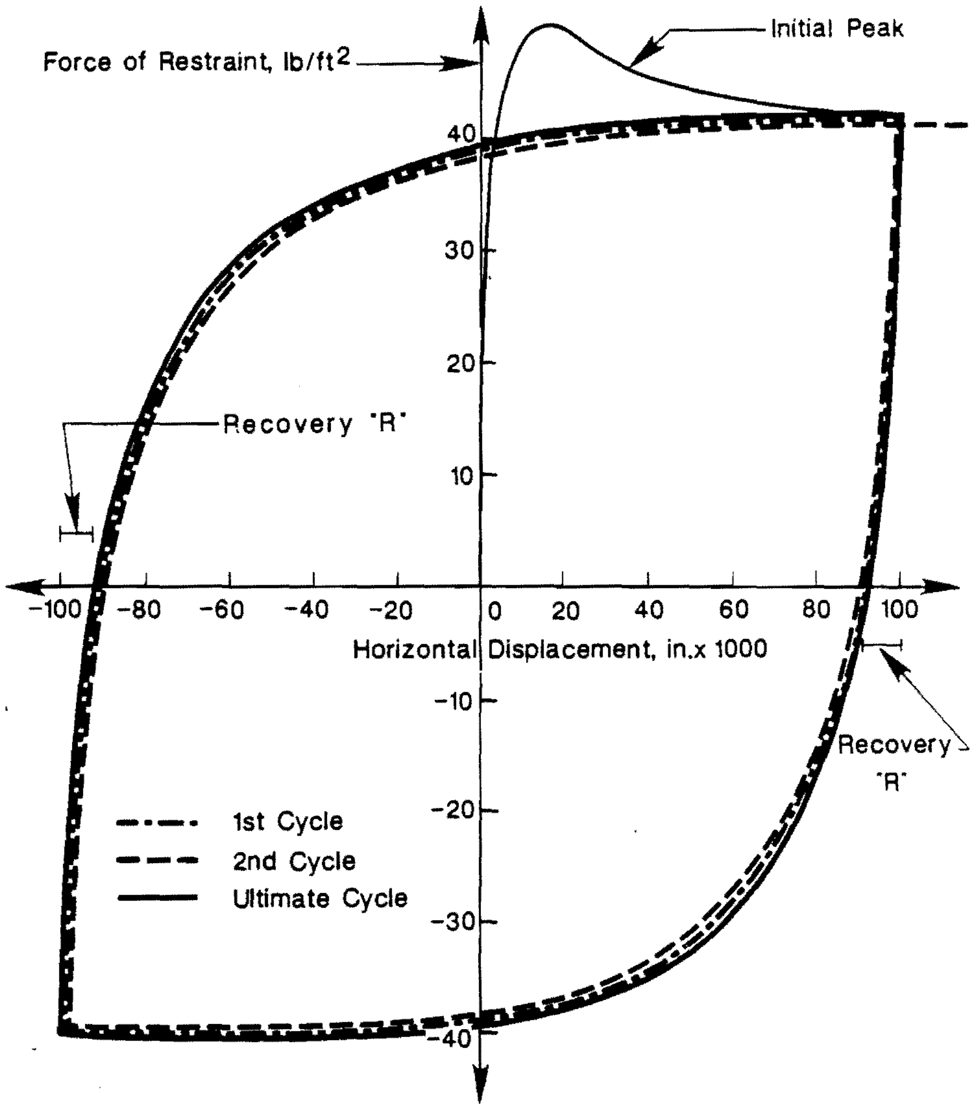


Fig 3.5. Typical force of resistance versus displacement curve that develops under rigid pavement slabs (Ref 21.

(1) First, the force exhibits a rise until it reaches an initial peak. The friction force that develops along this part of the curve is similar to the classical static friction force. The peak observed in the curve is equivalent to the static friction force from which the static friction coefficient is defined. In this zone of the curve, most materials show a quasi-elastic behavior. If the force that produces the movement is gradually released, the slab tends to return to its original position as the friction force drops to zero.

(2) The friction force that develops after the initial peak is similar to the kinetic friction force of the block model in Fig 3.1. Like the kinetic friction force, this force remains practically constant after sliding, if further displacement of the slab occurs. The displacements that occur after sliding are non-recoverable when the pushing force is removed.

(3) The backward movement "R" observed in Fig 3.5 when the pushing force is removed is a quasi-elastic recovery of the material underneath.

(4) The consecutive application of cycles of displacement produces hysterectic curves. During these cycles, the initial peak is not observed again and it is not possible to establish a boundary between static and kinetic friction forces. However, the resistance force resembles the static friction (with quasi-elastic properties) in the zone where the curve is more vertical and looks like the kinetic friction force where the curve becomes flatter. In this zone of the curve, the slab is sliding and the movements are non-recoverable after removal of the external force.

(5) During the first few cycles of displacement, the maximum force of resistance that develops in each cycle decreases slightly, but at the end it reaches a steady condition. This friction force versus movement curve is probably the one that would be encountered in practice under rigid pavements.

(6) An observation irrelevant to this study though important from the standpoint of material behavior is that asphalt cement sticks to the bottom face of the slab and the resistance force that develops is due to viscous shear through the depth of the material. For this reason, it is independent of slab weight and dependent on: (a) grade, (b) thickness, (c) temperature of the bituminous layer, and (d) rate of movement of the slab.

NATURE OF THE FRICTIONAL RESISTANCE UNDER RIGID PAVEMENTS

The review of tests presented above clearly shows that the relationship between friction forces developing beneath long pavement slabs and horizontal displacements is substantially inelastic.

The resistance force versus movement curve for most base materials placed under road slabs is defined by two factors: (1) the elastic properties of the material beneath the slab, and (2) the condition of the sliding plane and the nature of the materials at the interface. The first defines the slope of the curve before sliding, and the second the maximum or kinetic friction force obtained after the slab slides. Figure 3.6 shows the zones of the curve for each factor.

The interaction of the factors mentioned above is illustrated conceptually in Fig 3.7. If the material beneath the slab is infinitely rigid and does not experience deformations due to friction related shear at the interface, the force versus movement curve may look as illustrated in Fig 3.7(a). This case may correspond to the ideal case of the block of Fig 3.1 in which the "initial" peak has not been drawn because it disappears after a few cycles of displacement. Figure 3.7(b), in turn, shows the curves for two materials having different elastic properties (shear stiffnesses). The sliding plane for the case depicted in Fig 3.7(b) is assumed to have characteristics similar to the one in Fig 3.7(a). The kinetic friction forces F_k are the same in both cases, but the point of sliding is different. Finally, Fig 3.7(c) shows the effect of having two different sliding plane textures for the same base material. This is the case for the rough sliding plane furnished by granular bases with and without a sand layer provided on top of the granular base. This may also be the case for slabs cast on bituminous materials with and without layers of polyethylene sheeting provided at the interface.

Modeling of Friction Forces

The purpose of the previous discussion is to indicate that the friction forces may be considered elastic if sliding does not occur along the slab length. This is the case for plain concrete and conventional reinforced concrete pavements which are typically shorter than 40 feet These slabs develop maximum movements below 0.03 inch under a normal daily cycle and the frictional resistance that builds up is defined by the quasi-elastic properties of the base material.

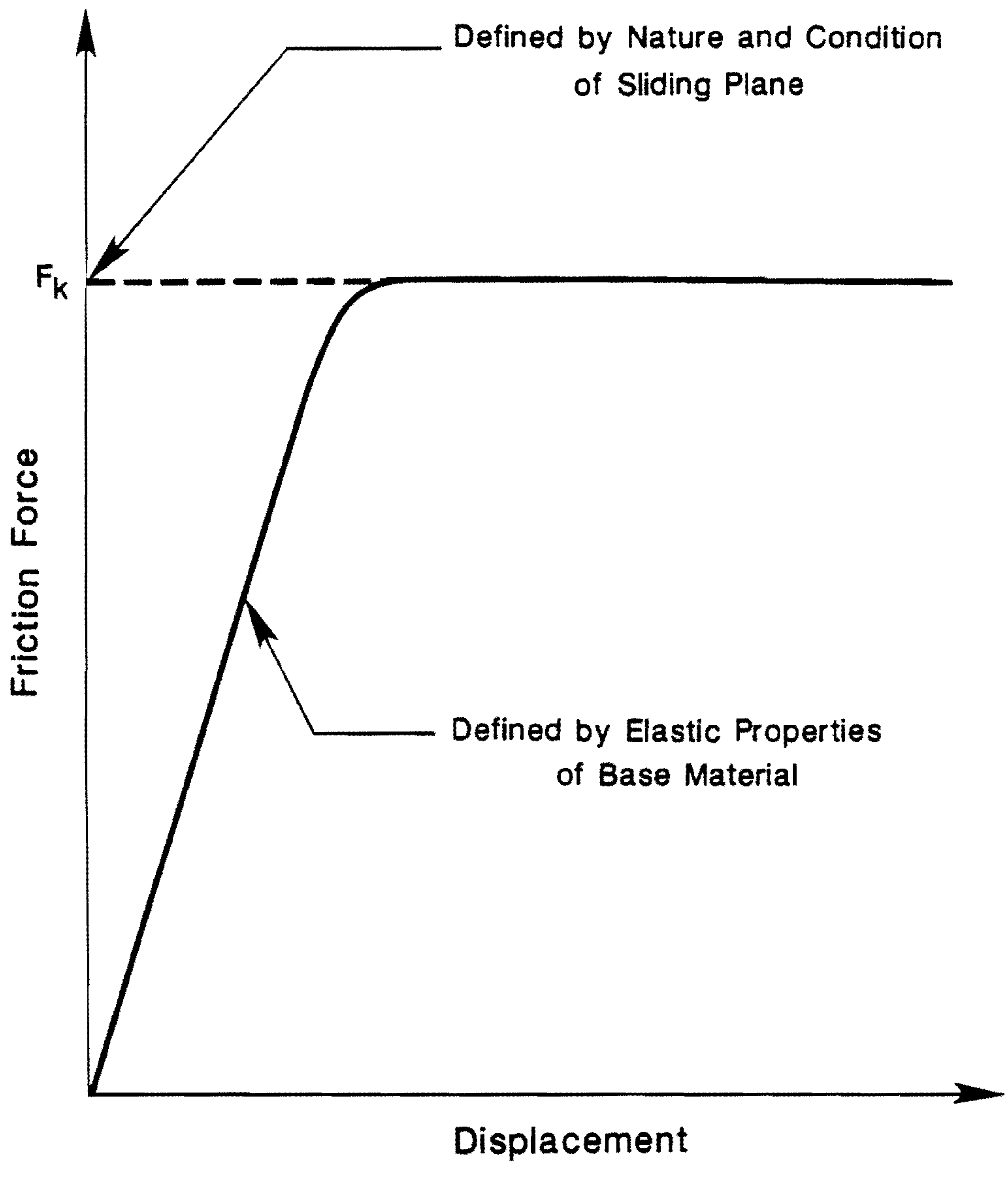
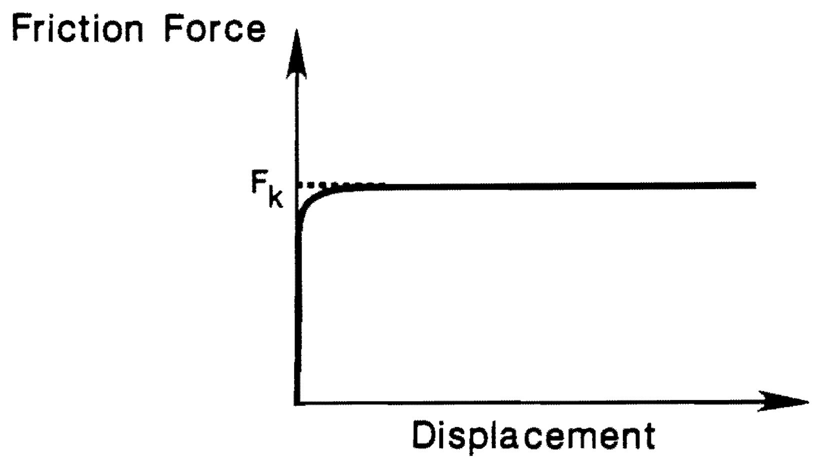
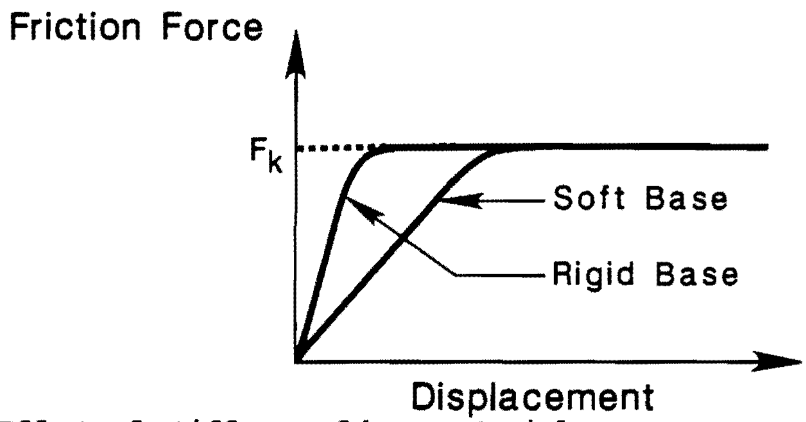


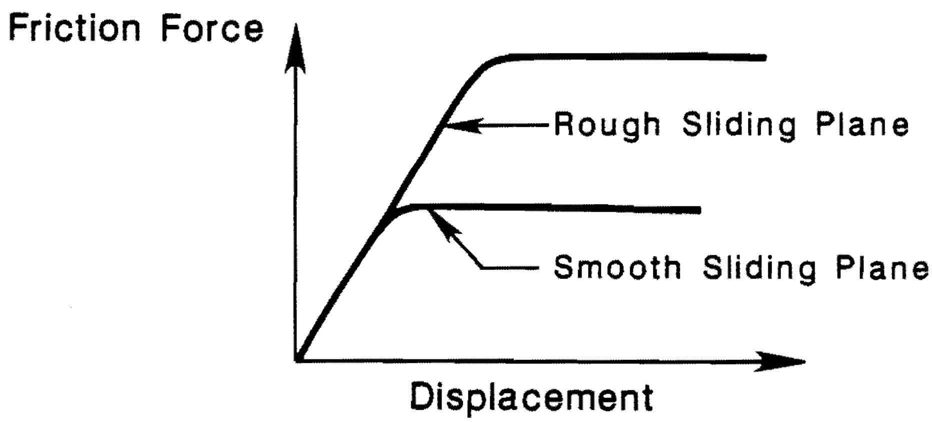
Fig 3.6. Factors affecting the shape of the force versus displacement curve.



a. Force-displacement curve for slab on infinitely rigid base.



b. Effect of stiffness of base material.



c. Effect of texture of the sliding plane.

Fig 3.7. Effect of stiffness of base material and texture of sliding plane on the friction force versus displacement curve.

An elastic system of friction forces, following a force versus movement curve as shown in Fig 3.8, is assumed by McCullough et al (Ref 35) and Rivero Vallejo et al (Ref 36) in developing procedures for the design of continuously reinforced concrete pavements (CRCP) and jointed reinforced concrete pavements (JRCP). However, the need is recognized in both efforts for simulating the real effects to improve the reliability of the prediction methods. In Fig 3.8, friction forces and displacements are drawn as having equal signs. This convention was adopted to obtain uniformity with similar graphs in this chapter. The reader should keep in mind, however, that displacements and friction forces are vectors having opposite directions, as the friction forces always oppose the direction in which the pavement displacements take place.

Some relevant implications in the behavior prediction of assuming elastic friction forces are the following:

(1) The slab will develop compressive stresses whenever the temperature exceeds an initial reference temperature, usually set as the slab curing temperature (Ref 35). At the reference temperature, all the slab points are considered to have zero movements and their behavior can be located at the origin of Fig 3.8. Friction forces and stresses are zero for this initial condition. When the points of the half slab shown in Fig 3.9(a) are located to the right of their initial position, they are assumed to behave in Quadrant 2 in Fig 3.8, thus developing compressive stresses as shown in Fig 3.9(b). This is the case for temperatures higher than the reference temperature. Accordingly, a slab cast at the minimum temperature for the day will develop exclusively compressive stresses during the entire day. Moreover, a slab cast at the minimum temperature of the year will develop compressive stresses during the year only if shrinkage and other sources of slab contraction are ignored.

(2) Figure 3.10 shows an extension of implication (1) for a series of consecutive temperature cycles. For times t_1, t_2, t_3, t_4, and t_5 with equal temperature T_1 above the reference temperature T_0, the slabs will develop the same compressive stresses whether the slab is contracting or expanding. Likewise, equal stresses are obtained for other temperatures representing equal temperature changes with respect to the reference temperature.

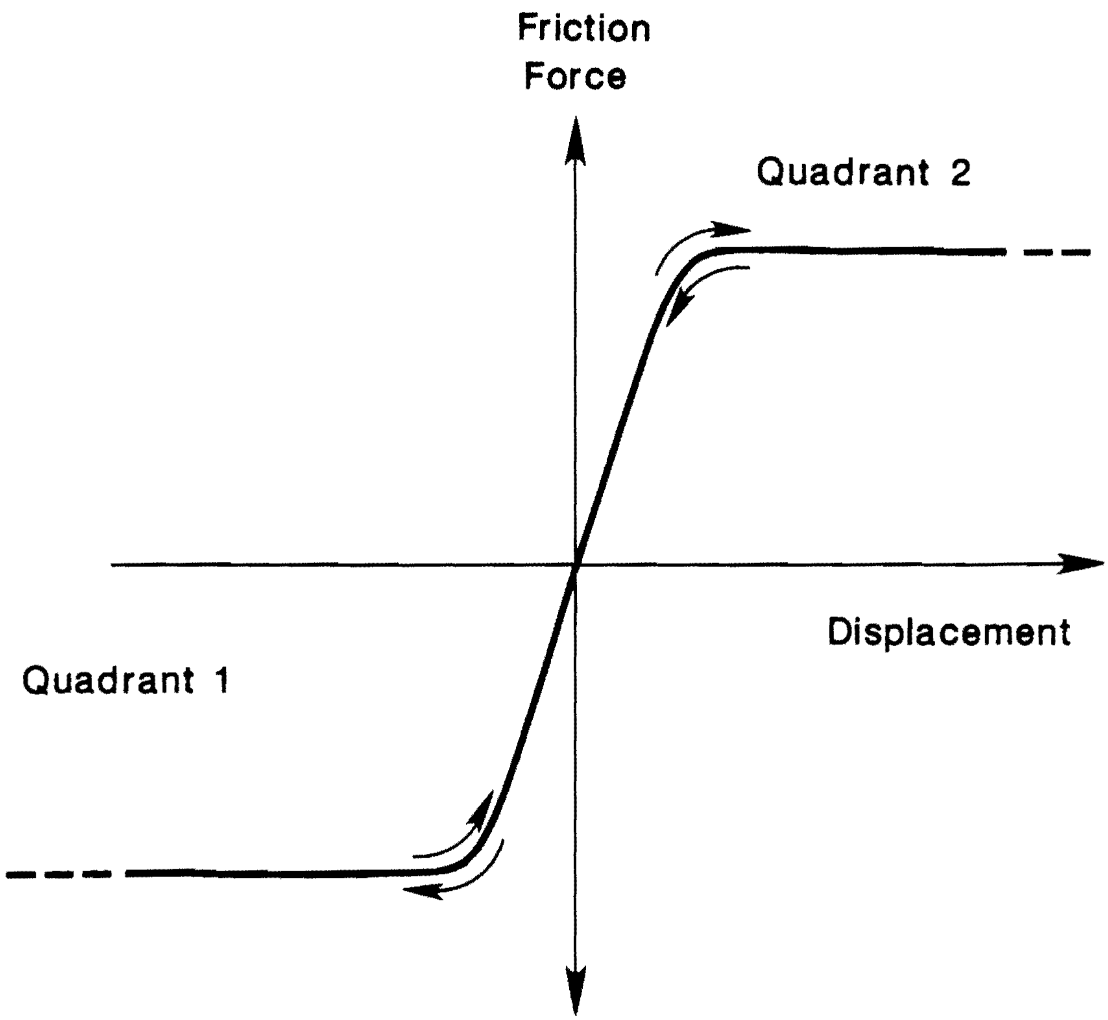
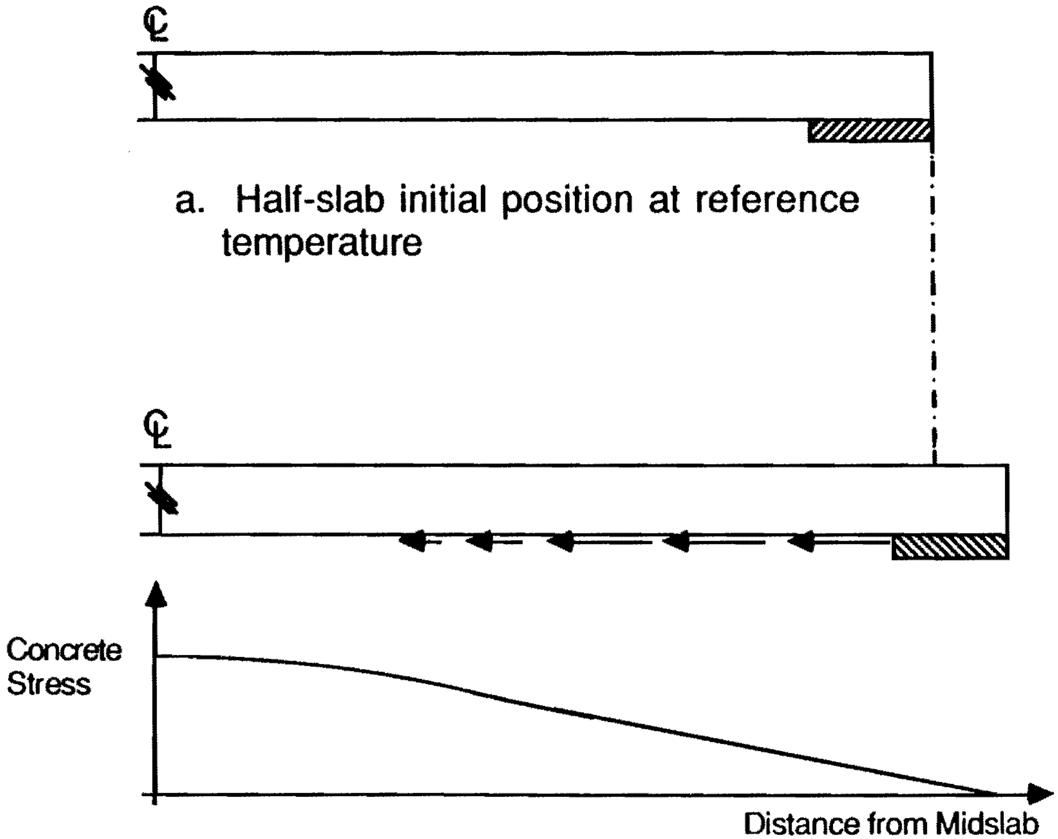


Fig 3.8. Elastic friction force versus displacement curve.



b. Friction forces and concrete stresses whenever the half slab points are displaced to the right of their initial position.

Fig 3.9. Development of compressive stresses provided that the half-slab points are displaced to the right of their initial position. System of elastic friction forces.

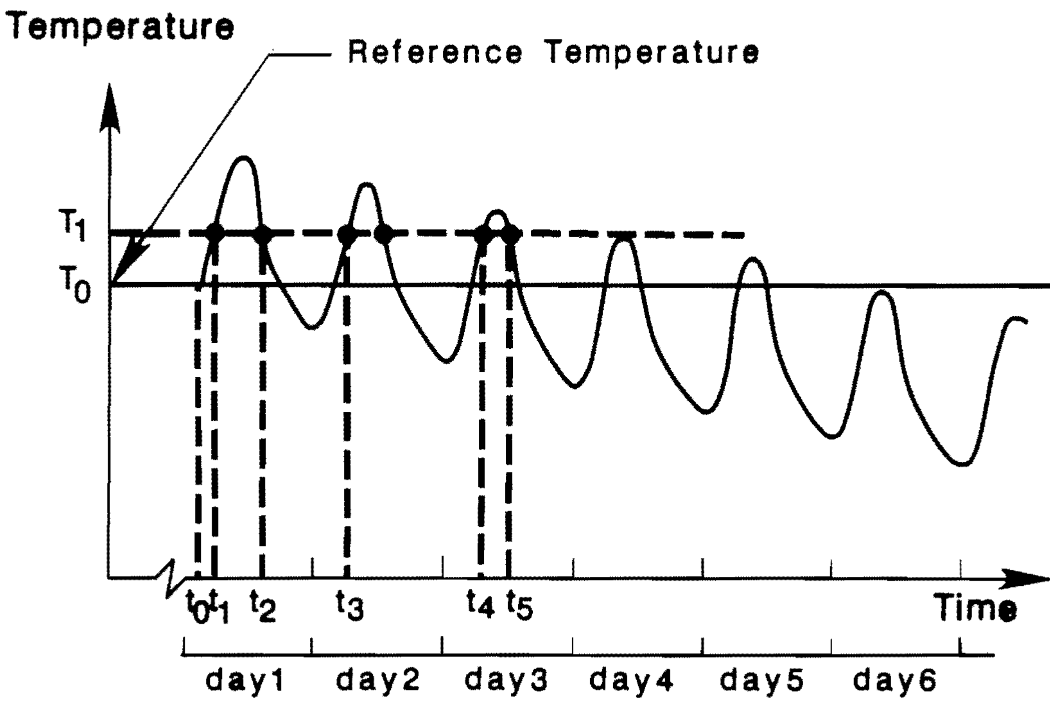


Fig 3.10. At times t_1, t_2, t_3, t_4, and t_5, when the same temperature T_1 is reached, the same slab compressive stresses will be obtained if elastic friction forces are assumed.

(3) Shrinkage and other sources of long term longitudinal movement do not occur without frictional resistance but accumulate on a daily rate basis, resulting eventually in the maximum friction forces and concrete restraint stresses. This mechanism is illustrated in Fig 3.11. If the slab starts contracting from the maximum temperature of the day, point A in Fig 3.11 moves from its initial position, Z_{A0}, to position Z_{A1} after the maximum contraction of the day. The part of the movement Z_{A1} due to the temperature drop is Z_{AT1} whereas the rest of it is produced by shrinkage and other sources of long term contraction. If the temperature increases to the maximum again, point A moves to position Z_{A2} following the same path along the curve. The point does not return to its initial position Z_{A0} because a small portion of long term movement has occurred. If long term movements did not occur, point A would move between positions Z_{A0} and Z_{A1} indefinitely.

However, the accumulation of shrinkage, etc., along with the movements due to the daily thermal cycle results in shifts of point A along the curve between positions Z_{An-1} and Z_{An} several days after the start of this process. Thus, point A reaches the maximum or kinetic friction force F_k. This concept was demonstrated for a single point; however, a similar behavior would be observed for the rest of the slab points if elastic friction forces are assumed.

For the case of the long PCP slabs, a substantial portion of the slab works in the sliding range due to movements produced by the daily cycle. The inelasticity of the frictional resistance and the significant sliding of the slab points make reversals of temperature, producing reversals of movements exceeding 0.01 to 0.02 inch, result in reversals of frictional resistance. This is particularly true if friction reducing materials are used beneath the slab.

The following are the implications from assuming an inelastic system of friction forces beneath the slab:

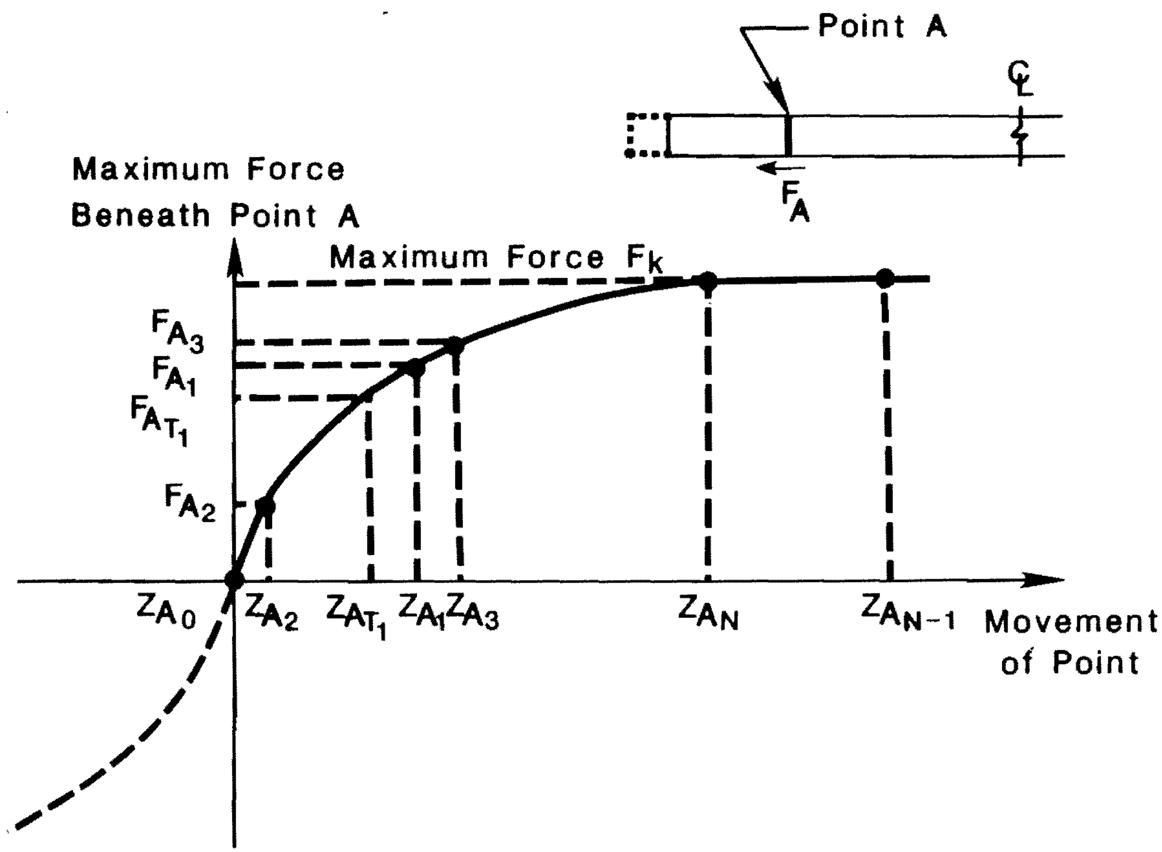


Fig 3.11. Eventual build-up of maximum friction forces under assumption of elastic system of friction forces.

(1) A slab cast at the minimum temperature of the day will develop compressive stresses during the part of the temperature cycle at which the temperature increases above the set temperature. A few hours after the peak temperature, the reversal of frictional resistance causes the build-up of slab tensile stresses.

(2) The long term sources of longitudinal movement, occurring at small daily rates in comparison to the daily contraction and expansion, takes place without frictional resistance and practically does not cause stresses in the concrete slab. As reported in Chapter 2, this behavior type was observed by Cashell and Benham (Ref 13) in experiments with a 1310-foot-long continuously reinforced concrete pavement. This behavior can be explained based on the mechanism shown in Fig 3.12. If the slab starts contracting from the maximum temperature of the day, point A in Fig 3.12 will move from its initial position Z_{A0} to Z_{A1} for the maximum contraction of the day. The part of the movement Z_{A1} due to the temperature drop is Z_{AT1}; the rest of it is produced by the small portion of long term movement occurring during the day. This portion of movement does not cause a significant increment in the friction force (from F_{AT1} to F_{A1}). If the temperature rises to the maximum again, point A moves to position Z_{A2}, reducing the force F_{A1} and increasing the friction force F_{A2} in the opposite direction. The point does not come back to Z_{A0} because a portion of long term contraction has occurred. Z_{A2} is the new initial position for the movements of the next cycle. For the next day cycle, the portion of long term movement occurring during the day causes a small increment of friction force again, but the effect is not cumulative with the force increment of the previous cycle which had already dissipated when the slab movements reversed. Therefore, Point A like the rest of the points of the slab will shift following this mechanism without significant build-up of friction forces from the long term movements.

This analysis substantiates and justifies the need for developing a model that considers the inelasticity of the friction forces to determine movements and stresses developed during a daily cycle in long concrete slabs. Figure 3.13 illustrates the type of friction force versus

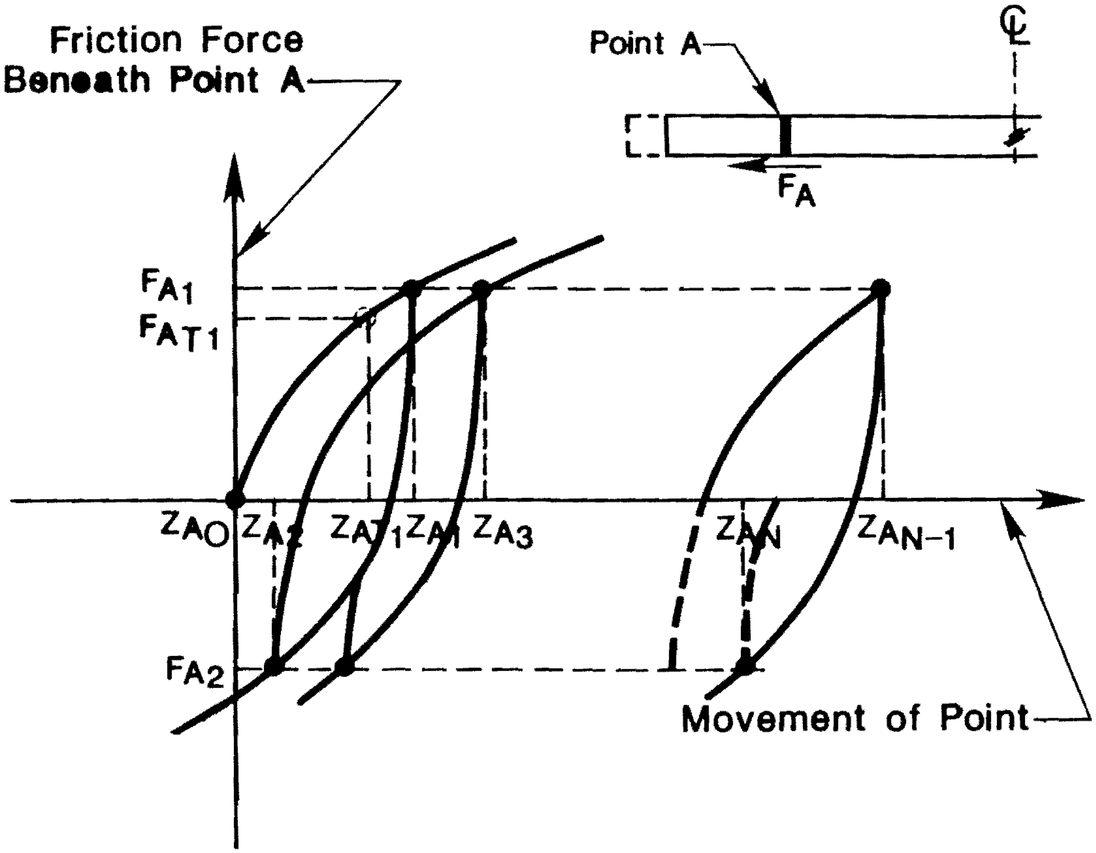


Fig 3.12. Shifting of point A without frictional resistance for long-term movements if an inelastic system of friction forces is assumed.

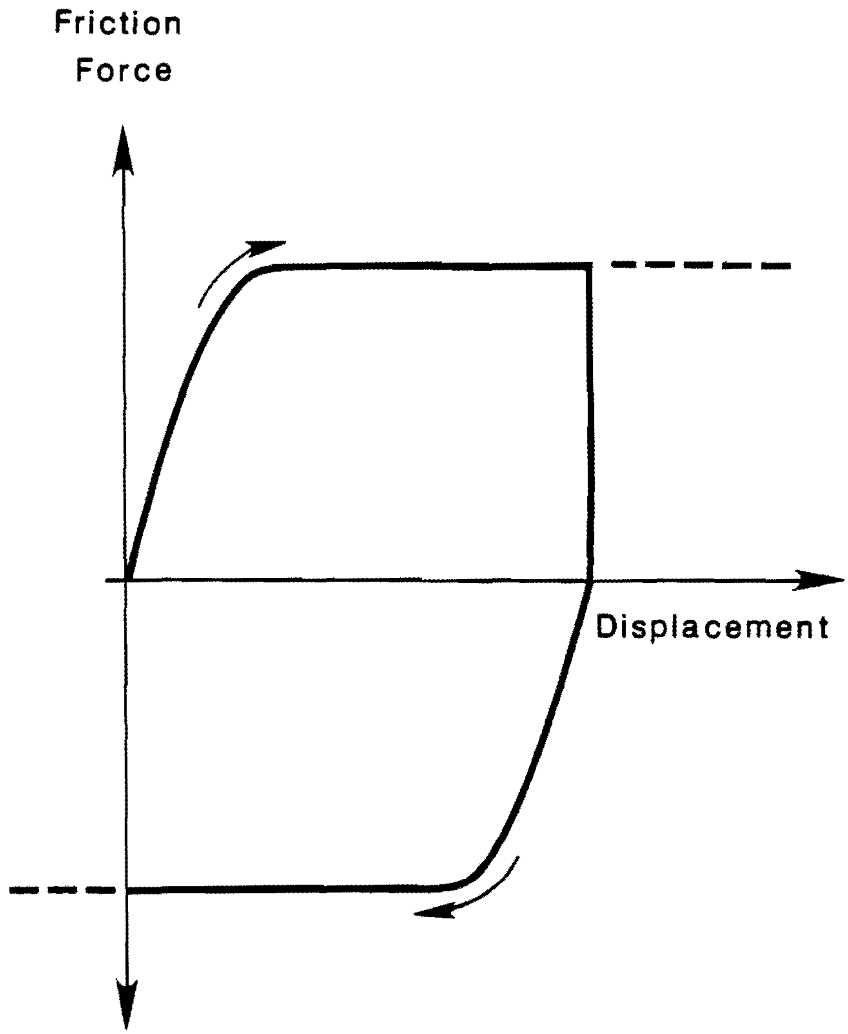


Fig 3.13. Friction force versus displacement curve assumed in this study.

movement curve assumed in this study. Since the elastic recovery that takes place when the forces inducing slab movements are removed is typically small for most materials used under rigid slabs, this can be neglected. A slightly conservative prediction of movements and stresses would then be obtained.

SUMMARY

In this chapter is a comprehensive discussion of the nature of the frictional resistance under rigid pavements. From a review of field and laboratory tests, it is observed that the frictional resistance is substantially inelastic with long slabs. The friction forces have, then, to be modeled elastically in the case of the long slabs of PCP, for a substantial portion of the slab works within the sliding zone for the movements of the daily thermal cycle. For the short slabs of the jointed pavements the friction forces can be modeled as elastic forces, as the slab movements due to the daily temperature variations do not exceed the sliding movement (near 0.02 in.).

If inelastic friction forces are assumed, reversals of slab movement result in reversals of the direction of the friction forces. Accordingly, a slab cast at the minimum temperature of the day will develop compressive stresses only during the part of the day when the temperature increases. A few hours after reaching the peak temperature, the slab movement reversal causes a friction force reversal and the build-up of tensile stresses in the slab. This behavior type cannot be predicted if the friction forces are modeled elastically.

Another relevant implication of assuming inelastic friction forces is that the long term sources of longitudinal movement (shrinkage, creep, etc.), occurring at small daily rates (as opposed to the contraction and expansion movements of the daily cycle, which are fairly substantial) occur practically without frictional resistance and do not cause concrete stresses. This behavior could not be predicted if the friction forces were assumed to be elastic. If elastic friction forces are assumed, the long term movements, usually representing contractions, accumulate on a daily rate basis resulting in an eventual build-up of maximum friction forces and slab stresses.

CHAPTER 4. PROBLEM STATEMENT AND MODEL FOR FRICTION

Due to its nature, the prediction of movements and stresses as a function of time for a PCP slab is a highly complex problem. However, it is greatly simplified by assuming that the slab will remain uncracked during its entire life. As indicated in Chapter 2, PCP slabs are designed elastically for non-cracking, an assumption carried throughout this study.

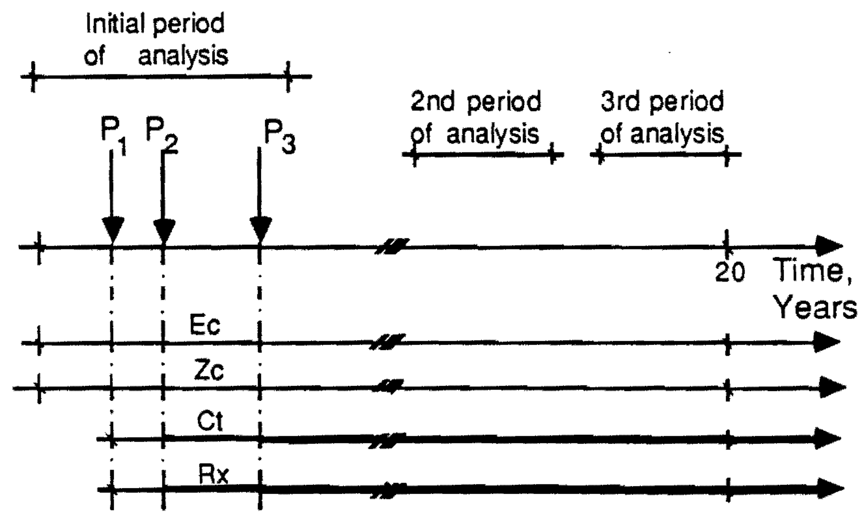
The inelastic modeling of friction forces requires a time incremental approach to be adopted for predicting pavement responses during daily temperature cycles occurring at specific periods of the pavement life. A time incremental approach is required, because the state of stresses and deformations in the slab at a specific time is dependent on the slab condition during the previous time increment.

The fundamental phenomenon to model in this research is stated in the following section.

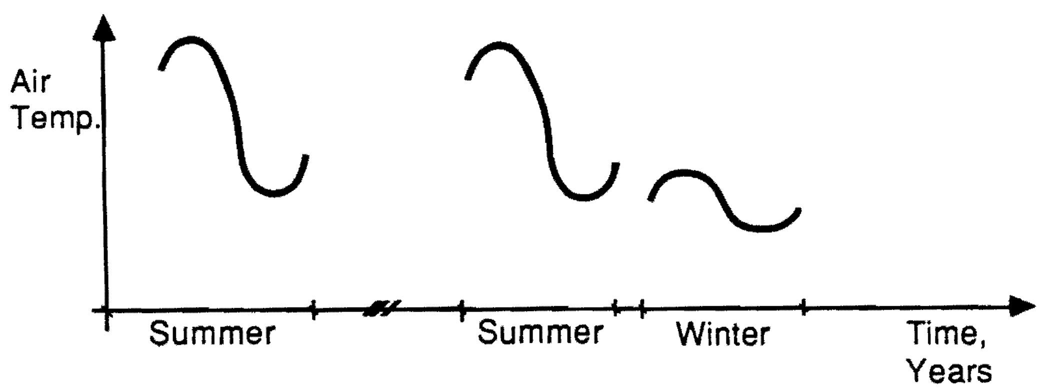
PROBLEM STATEMENT

Environmental factors are assumed in this study to start to affect the pavement structure at the setting hour. The setting hour is defined herein as the reference time from which the concrete can be considered to have gained enough plasticity to act as a semi-rigid body. McCullough, Abou-Ayyash et al (Ref 35) assume that this reference time takes place five hours after slab casting, in the design of continuously reinforced concrete pavements (CRCP). This study develops a procedure for predicting the state of deformations and stresses in the structure due to environmental factors (temperature, moisture, etc.) and prestress forces at specific periods after the setting time.

A scheme illustrating the scope of the problem and the variables considered in this analysis is presented in Fig 4.1. Temperature changes and shrinkage Z_c tend to cause slab movements after the setting time (t_o) which induce friction forces and related stresses. Curling deformations and stresses start occurring at time t_o as a result of vertical gradients through the pavement depth. Concrete modulus of elasticity, E_c, is a time dependent property which starts building at the setting time t_o. Elastic shortening, creep, and strand relaxation start affecting the pavement structure after the first amount of prestress force P_1 is applied, and they increase in magnitude with additional increments of the prestress force P_2, P_3, etc.



(a) Factors affecting the pavement structure during its design life.



(b) Change of climatic conditions between seasons.

Fig 4.1. Conceptual scheme illustrating the probelm and variables considered in this study.

The magnitudes of movements, stresses and deformations vary depending on prevailing climatological conditions. The variation of climatological conditions is represented in Fig 4.1(b) by shifts and changes in the shape of air temperature cycles between seasons.

Simulations of three periods has been found to be particularly important for the design of the pavement elements considered in this study:

(1) From slab setting until all post-tensioning stages have been completed -- The simulation of this initial period permits one to analyze the movement and stress mechanism during the first hours of life of the PCP, including the effects of the application of prestress forces.

(2) A 24-hour interval during the PCP design life when most prestress losses have occurred and at the season when the fluctuations of ambient temperature are largest (commonly the summer) -- The analysis of this period allows one to obtain the critical stress combination produced by the factors considered in this study. This critical combination is essential in the design of the PCP thickness and prestress level.

(3) A 24-hour interval during the PCP design life when the effects of the time-dependent variables (shrinkage, creep, relaxation, etc.) have mostly occurred -The analysis of this period allows evaluation of maximum joint opening and minimum prestress level after losses. These variables are relevant for designing slab length, pavement joints, and strand spacing.

The periods of analysis considered herein are illustrated in Figs 4.1(a) and 4.1(b). Estimates of the following aspects, as a function of time, are required for each period:

(1) Friction stresses and prestress. Only friction stresses if prestress forces are not applied by the time of analysis.

(2) Cumulative slab movements since the setting time, and

(3) Curling deformations and stresses.

General Assumptions

In order to solve the problem stated previously, several assumptions which simplify the analysis but do not invalidate the model are necessary. The following premises will be assumed then:

(1) For the initial period of predictions, after prestress forces are applied, the slab movements occur unrestrained by the prestress. Likewise, movements occurring during this period do not cause significant variations of the prestress level. This assumption permits exclusion from the analysis of a compatibility relationship between concrete and steel deformations. Prestress forces are assumed to be applied instantaneously, thus only temporarily affecting the friction forces, and then they remain constant until the end of the analysis period. The validity of this assumption is discussed later in Chapter 5.

(2) For the second and subsequent periods of predictions, it is assumed that friction forces develop as a result of the movements due to daily temperature changes and independently of prestress forces and long term movements. Likewise, the prestress level is assumed to be significantly affected by long term movements but unaffected by daily slab movements. If the development of friction forces and the prestress level variations are assumed to occur independently, both mechanisms can be modeled separately and the slab responses superimposed for computation of final movements and stresses. This assumption is valid several hours after the prestress force is applied. Immediately after post-tensioning, the sequence of friction force development due to temperature changes is temporarily perturbated by the sudden contraction produced by the external prestress force. In this time interval, an independence of occurrence cannot be assumed.

(3) For all analysis periods, curling stresses occur independently of other mechanisms causing stresses in the structure. Then, responses from a curling model can be superimposed to the responses from other models for computation of final movements and stresses.

The assumptions stated above permit the analysis of pavement behavior through three independent models: a model for friction, a curling model and a model, to account for the time dependence of the prestress level. The primary contribution of this study is modeling the friction mechanism assuming inelastic forces. The model for curling was adopted from the literature (Ref 42) and implemented in this approach. The remainder of this chapter is devoted to presenting the principles of the friction model.

FRICTION MODEL

In a temperature daily cycle, rigid pavement slabs experience two reversals of movement. These reversals occur at the maximum and minimum temperatures of the cycle. Away from these maximum or minimum temperatures, temperature changes cause contraction or expansion movements and tensile or compressive stresses along the slab length. After the afternoon peak movement reversal, the slab shortens as the concrete temperature steadily decreases. A profile of tensile stresses due to frictional restraint is presented in Fig 4.2. A similar situation, in the opposite direction, with compressive stresses rather than tensile, occurs after the morning minimum temperature reversal. In both cases, the slab segments closer to the ends (Zone 3 in Fig 4.2) are the ones that accumulate lower restraint stresses. The central portion (Zone 1) is typically fully restrained in long slabs and, therefore, develops a constant stress. The first submodel for the thermal cycle should simulate exclusive contraction or expansion movements and stresses developing along the entire slab.

The inelastic nature of the frictional resistance causes the movement reversals taking place at the peak or the trough of the thermal cycle to also result in reversals of frictional resistance. Likewise, these reversals of frictional resistance cause slab reversals of concrete stress. The movement direction changes occur first near the slab ends where the friction restraint stresses accumulated up to the peak or the trough are lower. During this transition stage, the slab develops tensile and compressive stresses at the same time in different locations. The dashed line in Fig 4.3 illustrates the stress condition at the morning minimum temperature, and the continuous line the condition after the temperature has increased a few degrees above the minimum. It is possible to complete the cycle of movement and stress predictions if a second submodel simulates the mechanism during these movement reversal intervals.

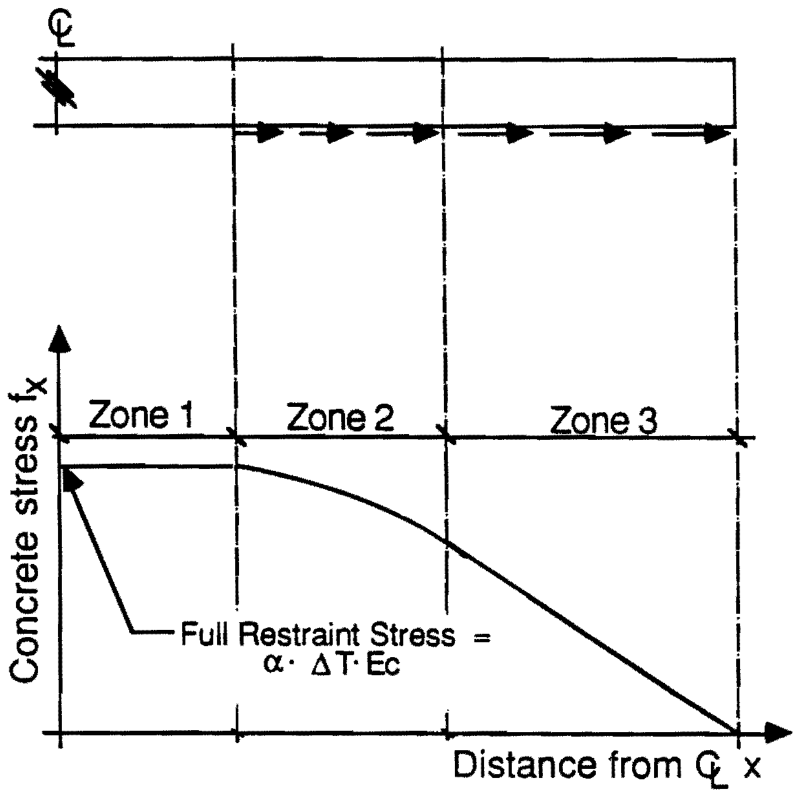


Fig 4.2. Friction forces and tensile concrete stresses arising after temperature peak. Submodel 1 of friction model.

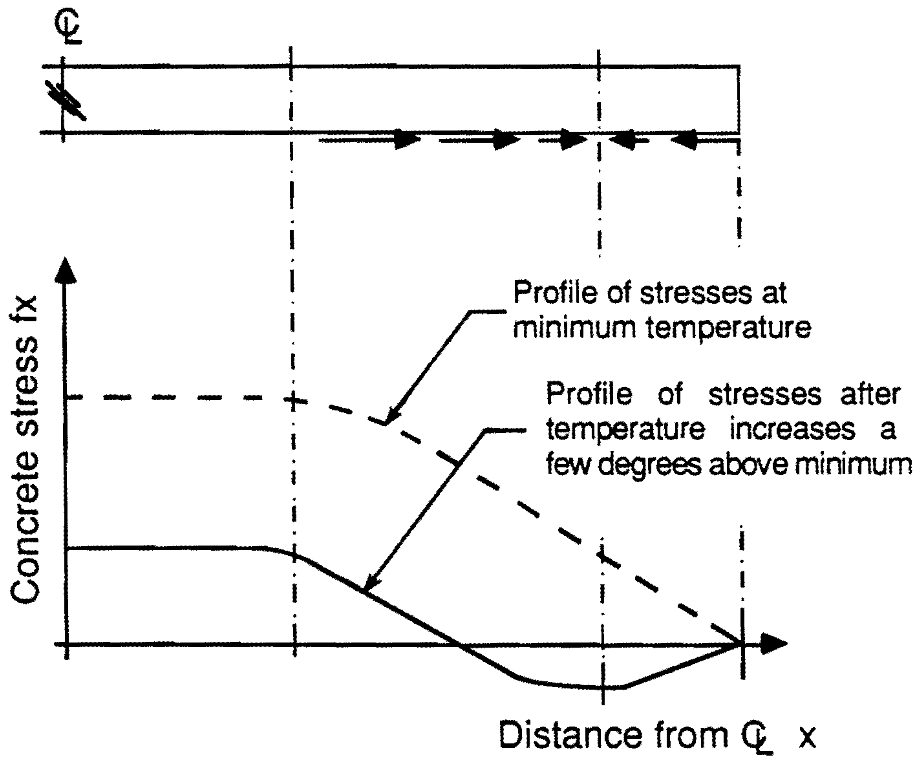


Fig 4.3. Friction forces and profile of concrete stresses for temperature reversal taking place immediately after minimum temperature of the thermal cycle. Submodel 2 of friction model.

Assumptions of the Model

The following assumptions are made in the derivation presented herein:

(1) Concrete is a homogeneous, linearly elastic material. The slab is a solid body without discontinuities, such as cracking.

(2) The frictional resistance produced by dowels, tie bars, and lanes adjacent to the slab longitudinal movements is neglected.

(3) The friction coefficient versus displacement relationship which caracterizes the frictional resistance under the slabs is of the type shown in Fig 3.13 in Chapter 3.

(4) The temperature variations considered in this analysis are those occurring at the slab mid-depth. The friction stresses that develop will be considered as evenly distributed on the cross section. As a result of this assumption, a one-dimensional analysis of an axial structural member is applicable.

(5) The redistribution of the slab weight due to curling and warping that affects the friction forces developing beneath the slab is neglected.

(6) The effect of concrete creep before application of prestress forces is also neglected.

(7) Symmetry of conditions with respect to the geometric center of the slabs is assumed. Therefore, the analysis will be limited to the half slab length with the geometric center being fixed.

(8) The origin for slab length X in the longitudinal direction is at the midslab. Friction forces are positive in the positive X direction. Movements in the positive X direction are also positive. Friction forces and movements are always of opposite signs. Tensile stresses in the concrete are positive. Mid-depth temperature changes are positive if they represent temperature increments at a given time, with respect to an earlier time considered.

Submodel for Contraction and Expansion

The well-known finite difference technique will be applied for solution of the problem stated herein. Therefore, it is necessary that the slab be divided into small elements for analysis.

In order to facilitate the reader's understanding of this derivation, an initial stressless condition will be assumed. Then, for a temperature change ΔT with respect to the reference temperature, all the slab elements tend to experience the same unit deformation $\varepsilon_X = \alpha \bullet \Delta T$ in the X direction (see Fig 4.4), where α is the concrete coefficient of thermal contraction and expansion.

In the sequence of the occurrence of thermal cycles, an initial stressless condtion may be assumed only for movements and stresses occurring between the setting time and the first temperature reversal. For temperature changes after temperature reversals, the slab elements start reversing the movement from an initial stress condition which is different for each slab element. In this case, the elements tend to experience different unit deformations ε_X. Therefore, it is required that the principles presented herein be extended to cover this situation. A detailed discussion of this aspect is provided in subsequent sections of this chapter.

If a temperature change ΔT occurs with respect to the setting temperature T_o (Fig 4.4 exemplifies a temperature drop), an element of length dX located a distance X from the midslab, as shown in Fig 4.4(a), tends to develop a strain equal to $\alpha \bullet \Delta T$. Part of this strain may be restrained by the frictional resistance, and the remainder of it occurs as a unit deformation. The part of the strain restrained by the friction produces a stress in the concrete. Hence, friction forces develop beneath the slab to balance the stress or force in the concrete. The equilibrium of forces in the slab segment to the right of the element considered can be written as

$$F_X = \int_X^{L/2} U_x \bullet \gamma \bullet D \bullet dx \qquad (4.1)$$

This equation represents the equilibrium condition for a section located a distance X from the center of the slab and is a function of the friction coefficient U_x developed below the elements dx located to the right of section X [see Fig 4.4(b)]. γ and D in Eq 4.1 are the concrete unit weight and the slab thickness respectively.

Equation 4.1 can be transformed to the stress equation

$$F_X = \int_X^{L/2} U_x \bullet \gamma \bullet dx \qquad (4.2)$$

If f_X is the resisting frictional stress at the distance X from the midslab and Z_X is the corresponding slab movement, then the deformation dZ_X of the length element dX is

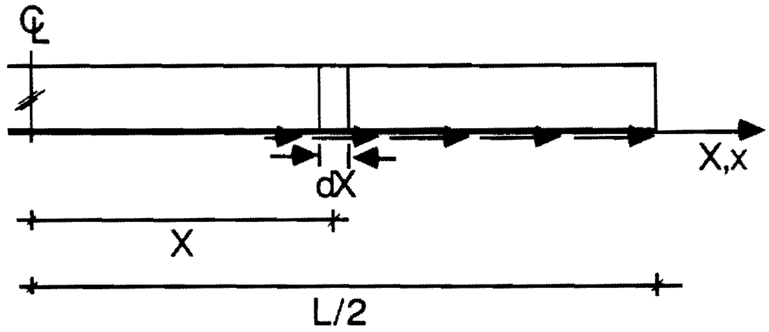
$$dZ_X = \underbrace{\alpha \cdot \Delta T \cdot dX}_{\text{free deformation}} + \underbrace{(f_X/E_c)\, dX}_{\text{part of deformation restrained by the friction}} \qquad (4.3)$$

Therefore, the unit deformation at point X is

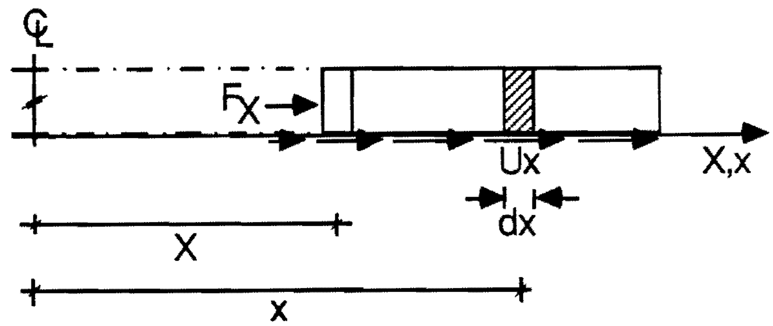
$$dZ_X/dX = \alpha \bullet \Delta T + f_X/E_C \qquad (4.4)$$

Obviously, in this equation the value of the term f_X/E_c cannot be greater than the negative value of the term $\alpha \bullet \Delta T$, since the restrained strain cannot be greater than the deformation per unit length produced by the temperature change. Therefore,

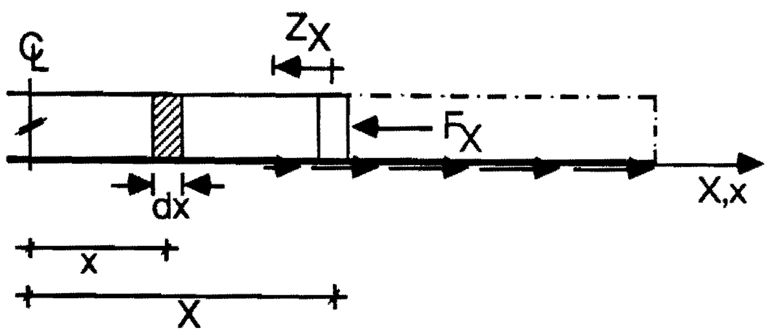
$$f_X/E_C \leq -\alpha \bullet \Delta T \qquad (4.5)$$



(a) Location of considered element dX.



(b) Accumulation of friction forces beneath elements to the right of section X.



(c) Movement of point X evaluated from the strain of elements to the left of section X.

Fig 4.4. Submodel 1 of friction model.

Correspondingly, the movement Z_X is:

$$Z_X = \int_0^X \alpha \bullet \Delta T \bullet dx + (f_x/E_c)dx \qquad (4.6)$$

Herein, the term f_X represents the resisting frictional stress of the elements to the left of point X [see Fig 4.4(c)]. Eq 4.6 gives the movement of the concrete at any point X along the slab.

The last condition that allows a solution for movements, stresses, and friction forces along the slab is the friction coefficient versus displacement relationship F. The coefficient of friction below each element dx may be expressed as

$$U_X = F(Z_X) \text{ if } Z_X \geq 0 \qquad (4.7a)$$

or,

$$U_X = -F(Z_X) \quad \text{if } Z_X > 0 \qquad (4.7b)$$

By solving simultaneously Eqs 4.2, 4.6, and 4.7 subject to restriction 4.5, the profiles of movements, concrete stresses, and friction forces can be determined. Since the nature of the problem is nonlinear, because of the friction coefficients, the integrals in Eqs 4.2 and 4.6 have to be evaluated numerically. Therefore, the slab length must be divided into discrete elements to compute movements of the nodes bounding the elements and the average restraint stresses of the elements.

Successive Approximation Procedure (SAP). The procedure suggested for determining movements, stresses, and friction forces consists of solving iteratively Eqs 4.2, 4.6, and 4.7 subject to restriction 4.5. A detailed flow chart of the procedure is presented in Fig 4.5. The procedure is based on determining successive profiles of movements, friction forces, and restraint stresses, starting from an initial unrestrained condition. Profiles of movements between any two consecutive iterations should be compared for convergence according to a

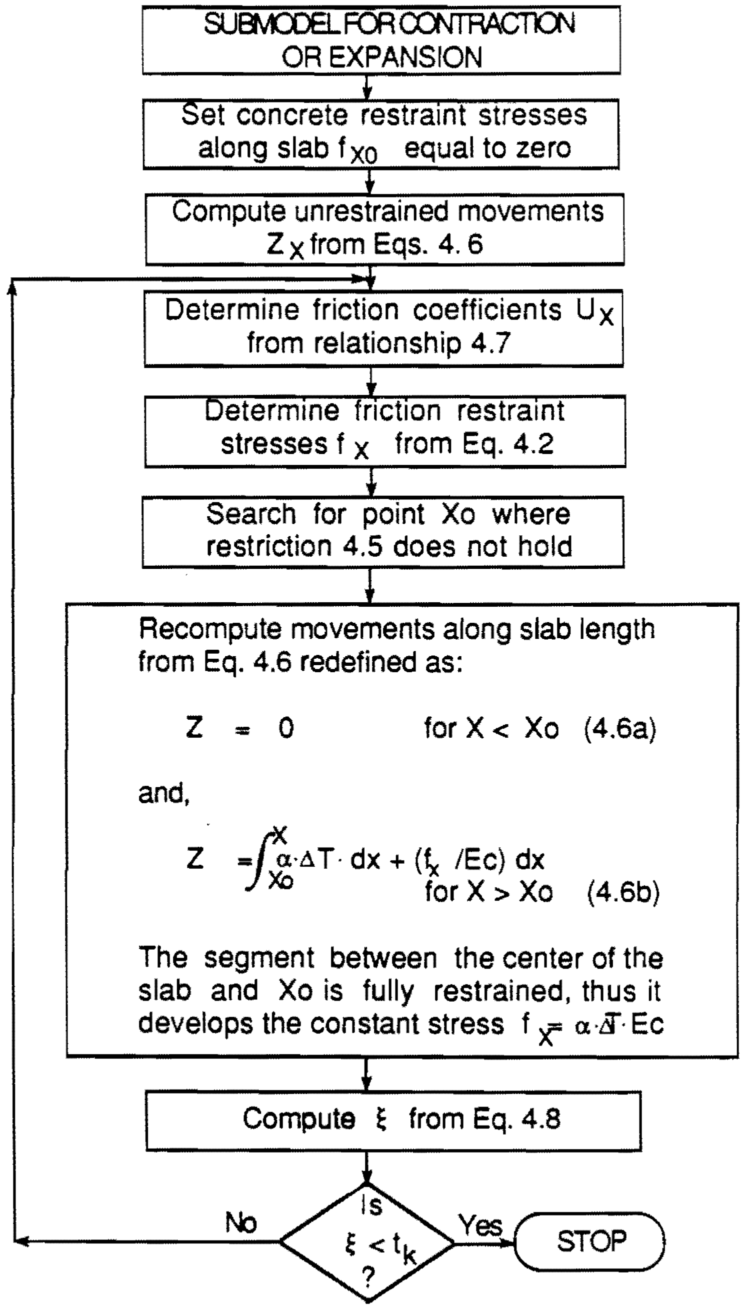


Fig 4.5. Flowchart of successive approximation procedure (SAP) for submodel 1 of friction model.

specific criterion. A recommended convergence criterion for checking relative closeness between successive iterations is based on the following ratio, ξ, which should be less than a desired tolerance level (Ref 49):

$$\xi = \sqrt{\frac{\sum_{\forall\ nodes} \Delta Z_{X_i}^2}{\sum_{\forall\ nodes} \Delta Z_{X_i}}} \leq t_k \qquad (4.8)$$

where

ΔZ_{X_i} = change of evaluated movement of node at coordinate X between two successive iterations,

Z_{X_i} = evaluated movement of node at coordinate X at iteration i,

t_k = tolerance level, and

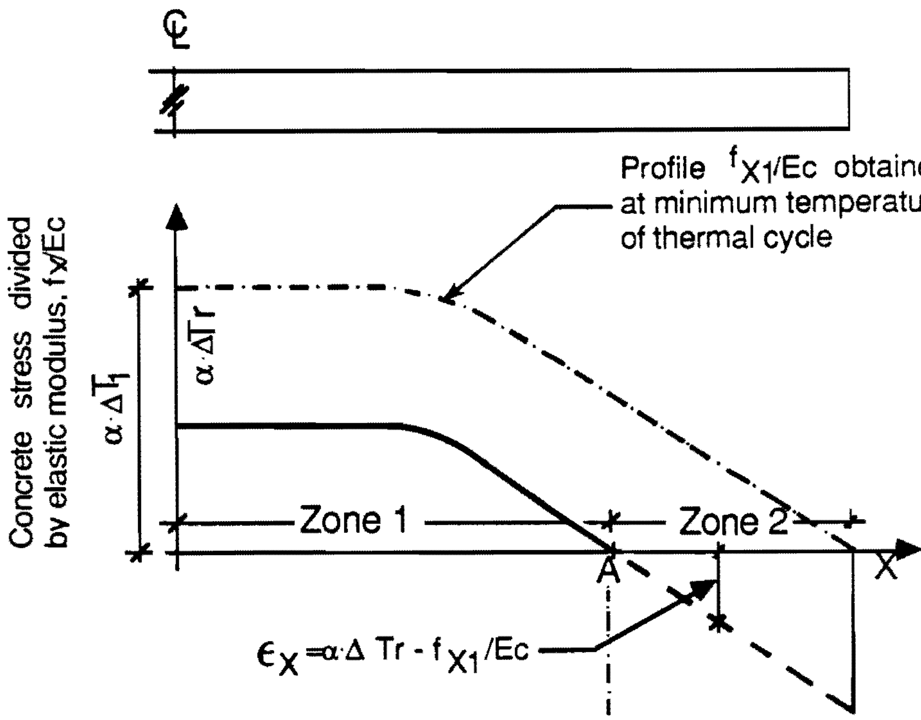
V nodes = (symbol V means "for all").

Submodel for Movement Reversal Intervals

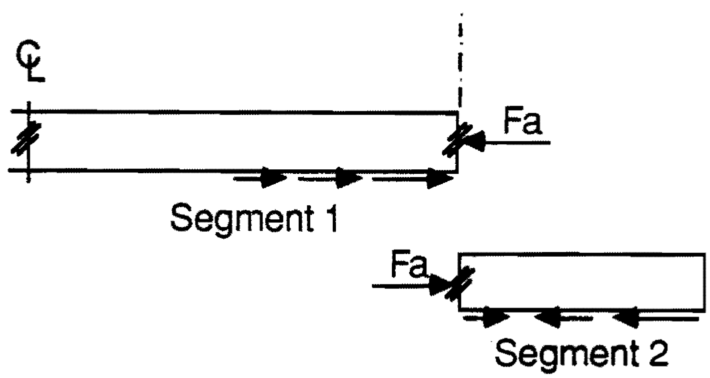
The development shown in this section after the first temperature reversal is illustrated for the minimum temperature of the day. The same analysis would be valid for a reversal occurring at the peak temperature.

The profiles of tensile stresses and movements obtained at the minimum temperature of the cycle after a ΔT_1 drop with respect to the setting temperature are considered those shown with dotted lines as f_{X1} and Z_{X1} in Figs 4.6(a) and 4.7 respectively. For the purpose of illustrating more clearly subsequent steps in the derivation of this submodel, Fig 4.6(a) shows the term f_{X1}/E_c instead of the profiles of stresses f_{X1}. These profiles represent the new "initial" condition for computation of further movements and stresses after the reversal.

Just beyond the trough of the cycle, the next temperature variations change from temperature drops to temperature increases. Due to this reversal of temperature variations,



(a) Relief of internal stress in slab.



(b) Split of slab half in two segments for analysis.

Fig 4.6. Mechanism considered for analysis of intervals of movement reversal. Submodel 2 of friction model.

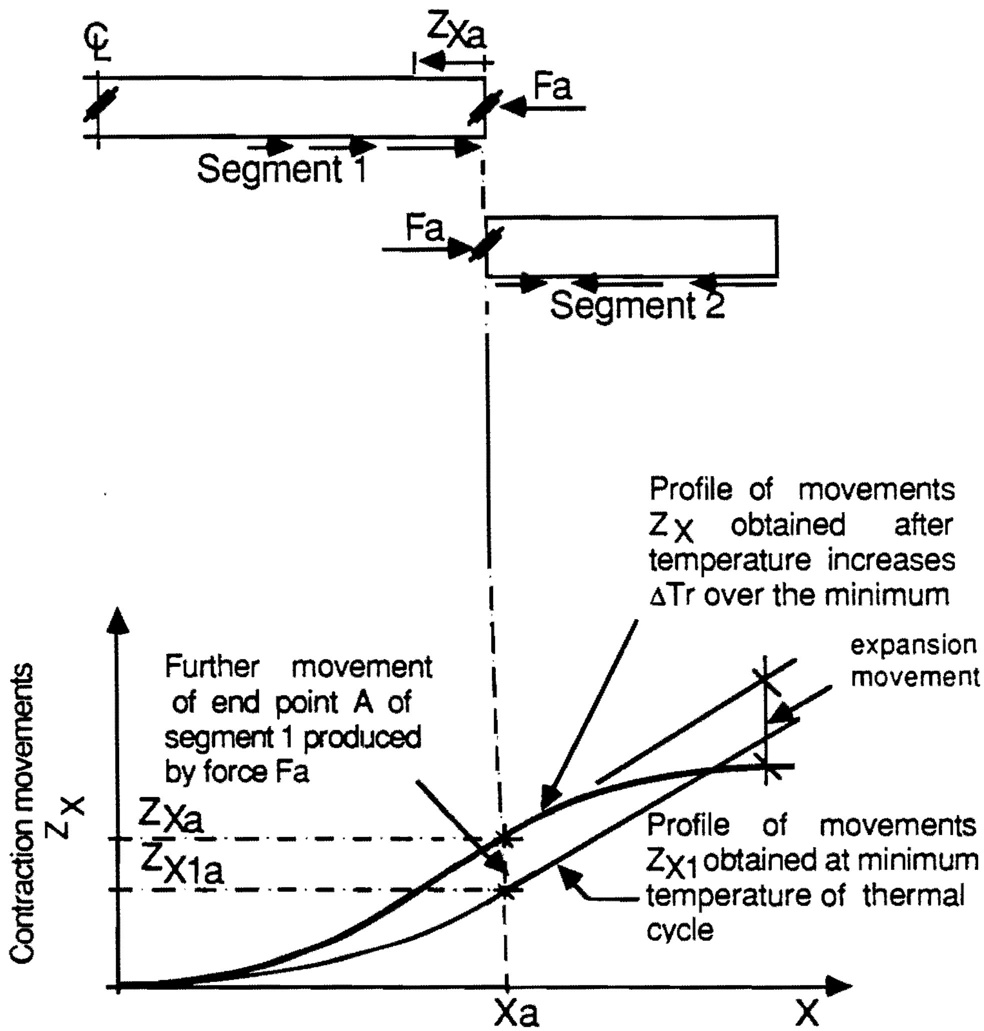


Fig 4.7. Variation of the profile of movements at interval of movement reversal.

the elements of the slab are assumed to relieve the restraint stresses first, and then to experience expansion deformations. The elements that first experience the movement reversal are those at the slab ends with lower restraint stresses accumulated from the contraction stage. This situation is illustrated in Fig 4.6(a). Following a temperature increase equal to ΔT_r with respect to the minimum, the elements to the left of point A [Zone 1 in Fig 4.6(a)] relieve part of the tensile stress f_{X1} accumulated up to the trough. The part of restraint strain relieved by these elements is equal to $\alpha \bullet \Delta T_r$ [see Fig 4.6(a)]. The elements to the right of point A (Zone 2) relieve totally the restraint stress f_{X1} and then tend to develop the expansion unit deformation $\varepsilon_X = (\alpha \bullet \Delta T_r - f_{X1}/E_c)$ [dashed line in Fig 4.6(a)]. Following the friction force versus movements curve in Fig 3.13 in Chapter 3, the elements to the right of point A (Zone 2) start developing friction forces in the opposite direction as soon as they reverse movement.

For the purpose of modeling this transition stage, the half slab should be analyzed by dividing it in two segments. Segment 1 in Fig 4.6(b) is to be analyzed subject to the net temperature change $(\Delta T_1 + \Delta T_r)$ from the setting temperature plus the internal force F_a acting at the end of the segment. ΔT_1 representing a temperature drop is negative in this derivation. The force F_a is the internal reaction that segment 2 communicates to segment 1 when it tends to expand. This reaction force allows the equilibrium of segment 2. If the effect of the internal force F_a on segment 1 is neglected, the elements of segment 1 should relieve the tensile stress without experiencing further movements with respect to the "initial" position Z_{X1}. This situation arises as a result of neglecting the elastic recovery in the typical friction force versus displacement curve. However, the internal force F_a shifts the movement profile of segment 1 from Z_{X1} to Z_X, as illustrated in Fig 4.7.

Segment 2 should be analyzed considering that its elements tend to develop the expansion unit deformation:

$$\varepsilon_X = (\alpha \bullet \Delta T_r - f_{X1}/E_c) \tag{4.9}$$

The analysis of both segments should follow the principles of submodel 1 based on Eqs 4.1 through 4.7. However, some of the expressions should be modified slightly. For segment

1, the stress equation Eq 4.2 should include the internal force F_a acting at the end of the segment:

$$f_X = F_a/D + \int_0^X U_x \bullet \gamma \bullet dx \qquad (4.10)$$

Equation 4.6 should be restated as:

$$Z_X = \int_0^X \alpha \bullet (\Delta T_1 + \Delta T_r)\ dx + (f_X/E_C)\, dx \qquad (4.11)$$

For segment 2, the movement of the end point A of segment 1 due to the internal force F_a [term $(Z_{Xa} - Z_{X1a})$ in Eq 4.13 below] plus the expansion movements experienced by segment 2 (integral in Eq 4.13) should be added to the initial contraction movement Z_{X1} to obtain the net movement Z_X with respect to the zero movement condition at the setting time (reference time). Therefore, Eq 4.6 should be redefined as

$$Z_X = Z_{X1} + Z_{Xr} \qquad (4.12)$$

where

$$Z_{Xr} = (Z_{Xa} - Z_{X1}) + \int_{Xa}^{X} \varepsilon_x\, dx + (f_x/E_C)\, dx \qquad (4.13)$$

and,

ε_X = expansion strain of the elements between point A and the point X considered within segment 2 (defined by Eq 4.9),

f_x = concrete stress of the points between point A and point X,

Z_{Xa} = movement of end point A of segment 1 evaluated from Eq 4.11 (see Fig 4.7),

Z_{X1a} = "initial" contraction movement of end point A of segment 1 (see Fig 4.7), and

Z_{Xr} = expansion reversal experienced by the points of segment 2 starting from the initial contraction Z_{X1} (see Fig 4.7).

The term f_x in Eq 4.13 should be evaluated from the following expression:

$$f_x = \int_x^{L/2} U_{xr} \bullet \gamma \bullet dx \qquad (4.14)$$

where the friction coefficients U_{xr} should be determined from relationship 4.7 as a function of the reversal Z_{xr}:

$$U_{xr} = F(Z_{xr}) \quad \text{if} \quad Z_{xr} <= 0 \qquad (4.15a)$$

or,

$$U_{xr} = -F(Z_{xr}) \quad \text{if} \quad Z_{xr} > 0 \qquad (4.15b)$$

Iterative Solution. Due to the nature of the development presented above, a numerical iterative technique ideal to solve for movements, stresses and friction forces along the slab. First, for the specific amount of temperature reversal ΔT_r, the coordinate X_a which defines the length of each segment should be defined. The iterative procedure starts at this point and consists of applying the successive iterative procedure (SAP) proposed for submodel 1 consecutively on both segments. When applying SAP to the solution of each segment, the mathematical expressions corresponding to each segment should be substituted as indicated above. In order to facilitates the reader's understanding of the procedure, a flow chart of the solution scheme is presented in Fig 4.8. By applying SAP on segment 2, an estimate of the reaction force F_a should be obtained, which if input immediately into the SAP procedure for segment 1 allows an estimate of the movement Z_{Xa} of point A to be determined. A consecutive sequence of applications of SAP to segments 2 and 1 completes one iteration. The last estimate of Z_{Xa} in any iteration permits to recompute F_a by applying SAP on segment 1 again. In each iteration, the profiles of movement Z_X of the slab half (which is the profile of movements of both segments put together) should tend to converge. The same convergence criterion as for the first submodel is applicable to this submodel. Profiles of movements, friction coefficients, and stresses along the slab are obtained after convergence is reached.

Incremental Approach and First Temperature Cycle

It is obvious that the solution for a complete temperature daily cycle can be achieved by combining the solutions presented earlier for the part of contraction and expansion and for the intervals of movement reversal.

Following a time incremental approach, the application of submodel 1 permits solution for the first temperature variations, at specific time increments (2-hour increments in Computer Program PSCP1 to be described later), starting at the setting hour if the predicted cycle is the first cycle. The volumetric strains ε_x to be input in the procedure should be determined with respect to the setting temperature for the first time increment and, then, increased or decreased (depending on the nature of the temperature change) with respect to the temperature of the last time increment considered.

After the first temperature reversal, part 2 of the model is applicable. The initial conditions for stresses and movements in this case are those obtained by the time of the reversal. This part of the model continues to apply for the next time increments until the movement reversal interval is completed and the stresses in the slab become of one nature again, either tensile or compressive. Then, the first submodel is applicable again. However, the term $\varepsilon_X = (\alpha \bullet \Delta T_r - f_{X1}/E_c)$, which is variable for each element, should replace the constant term $\alpha \bullet T$ in Eqs 4.3 to 4.6 of the first submodel.

Fig 4.9(a) illustrates the shape of the profiles obtained for a daily temperature cycle every four hours, in a 240-ft. slab, for a setting hour around 8 AM, near the minimum temperature of the cycle. These profiles were obtained from computer program PSCP1, whose main features will be addressed in Chapter 6, for a daily temperature variation of 35°F

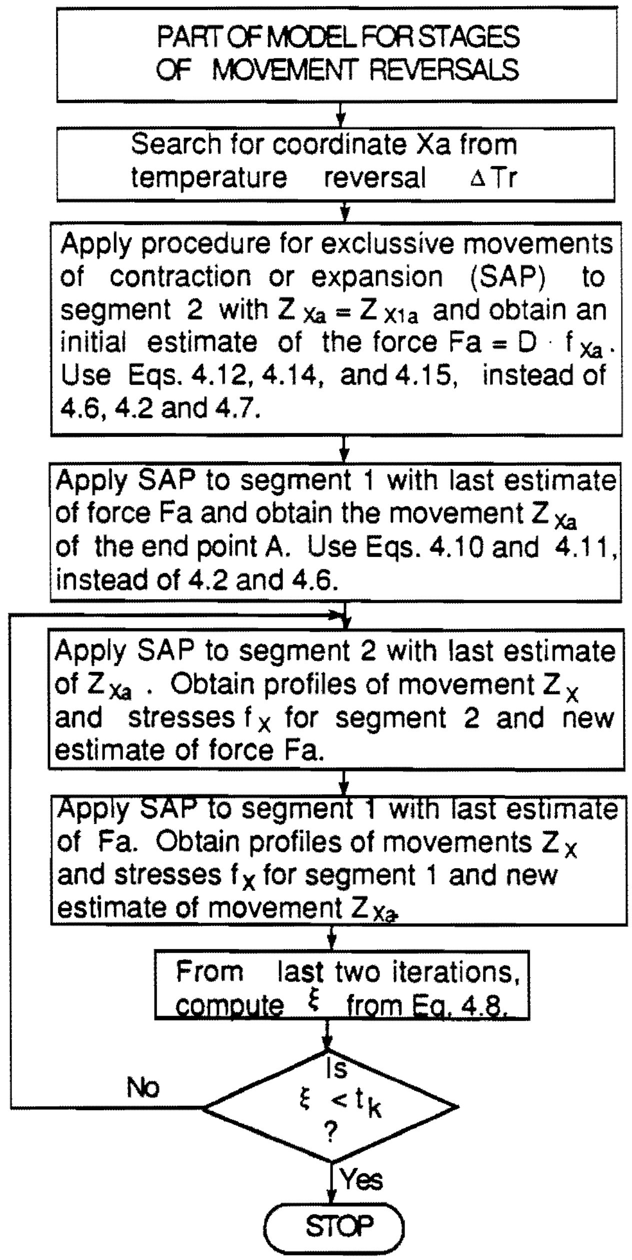
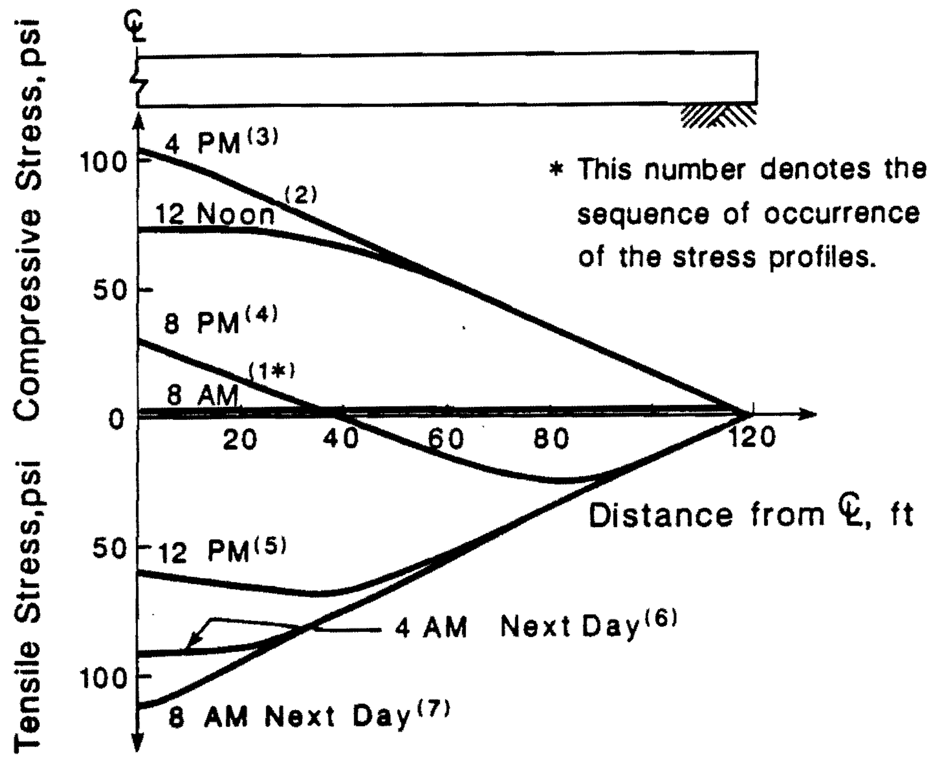
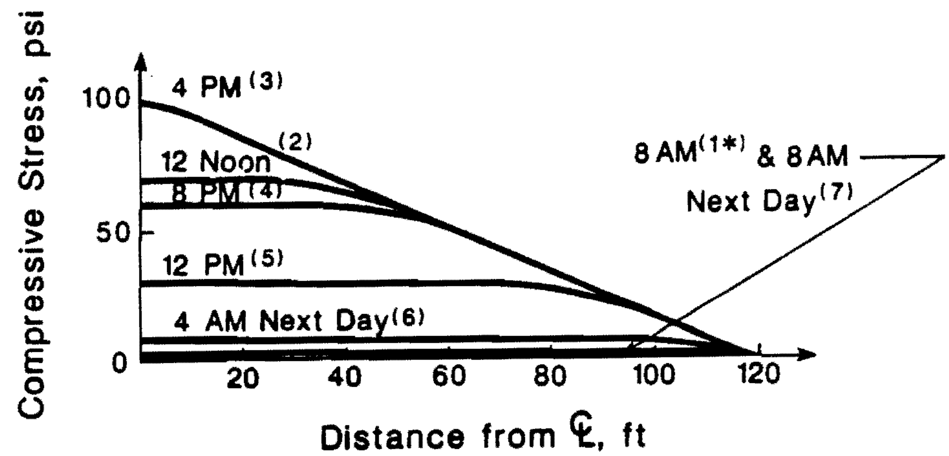


Fig 4.8. Flow chart for iterative solution at movement reversal intervals. Submodel 2 of friction model.



(a) Stress profiles for a daily temperature cycle assuming an inelastic system of friction forces.



(b) Stress profiles for a daily temperature cycle assuming an elastic system of friction forces.

Fig 4.9. Effect of elastic and inelastic friction forces on the profiles of friction restraint stresses.

and the friction coefficient versus displacement curve presented in Fig 3.4 for a single polyethylene sheeting layer.

Figure 4.9(b) illustrates the sequence of profiles that are obtained if the friction forces beneath the slab are considered elastic. These profiles were obtained from computer program JRCP3 (Ref 36). In this case, since the setting temperature is around the minimum temperature of the day and the friction forces are assumed as elastic, the pavement develops only compressive stresses during the entire cycle.

Simulation of Consecutive Cycles

The simulation of consecutive cycles can be achieved following the principles described earlier as applicable after the first temperature reversal of the first temperature cycle. The position reached by the slab elements at a specific reversal Z_{Xi} and the restrained strain of the elements f_{Xi}/E_c represents the initial condition for computation of further movements and stresses after the reversal. After reversal i, the slab has to go through a relieving process of the restrained strains first that can be modeled with submodel 2. Once this stage is completed, submodel 1 is applicable until the next reversal occurs. Then, submodel 2 can be applied again for the subsequent cycle.

As indicated in earlier sections of this chapter, the unit deformations ε_x which the slab elements tend to experience after a reversal should be determined with respect to the initial condition defined at the reversal. The unit deformations ε_{Xi} of the elements after reversal should, then, be determined as follows:

$$\varepsilon_{Xi} = \alpha \bullet \Delta T_{ri} - f_{Xi}/E_C \qquad (4.16)$$

where

ε_{Xi}	=	unit deformation an element dx located a distance X from midslab tends to develop after the reversal i,
ΔT_{ri}	=	magnitude of temperature change with respect to peak or through temperature at reversal i,
f_{Xi}	=	restrained strain of element dX reached at reversal i.

The unit deformations ε_{Xi} from Eq 4.16 are the unit deformations that should be input into submodels 2 and 1 consecutively for analyzing the cycle after reversal i. The position reached by the slab elements at the end of this cycle and the restrained strains of the elements represent the initial condition for computation of movements and stresses at the subsequent cycle, after reversal i+1.

Figure 4.10 and 4.11 show consecutive cycles of movement and stress determined from computer program PSCP1. PSCP1 works based on the principles described earlier. Both figures were developed for 440-ft. slabs placed on a single layer of polyethylene sheeting, for a 35°F daily temperature variation.

Figure 4.10 depicts the trend of movement of end and quarter points of the slab. The increase in amplitude of the cycles is a result of the increase of the concrete elastic modulus with time. PSCP1 takes into account this effect. From Eq 4.16, it is obvious that such an effect may be expected inasmuch as increments of elastic modulus result in increments of the unit deformation ε_X of the elements. Appendix A describes the procedure adopted from the literature (Ref 35) for evaluating concrete elastic modulus as a function of time.

In Fig 4.11, the effect of the increase of elastic modulus with time is apparent in the first cycle of stresses. It can also be observed that a steady state condition is reached in subsequent cycles. In Fig 4.11, the effect of the setting hour on the concrete stresses developing during the first hours is evident too. Since the slab is set at 10 AM (early morning casting), compressive stresses develop during the first hours. However, tensile stresses start building up after the reversal of the afternoon peak (4 PM).

LENGTH CHANGES DUE TO SEASONAL CYCLES AND OTHER LONG TERM EFFECTS

Length changes due to seasonal cycles, whether caused by the slow normal changes in moisture content, creep, or other sources of long term movement occur over many days with relative minute daily movements. To integrate the effect of these factors into the analytical procedure described earlier requires not only the addition of the corresponding strains taking place during the each specific time increment to the strains produced by the temperature variations ($\alpha \bullet \Delta T$ or $\alpha \bullet \Delta T_r$). The magnitude of these strains is so small in comparison with the daily contraction and expansion strains due to temperature that the cumulative length

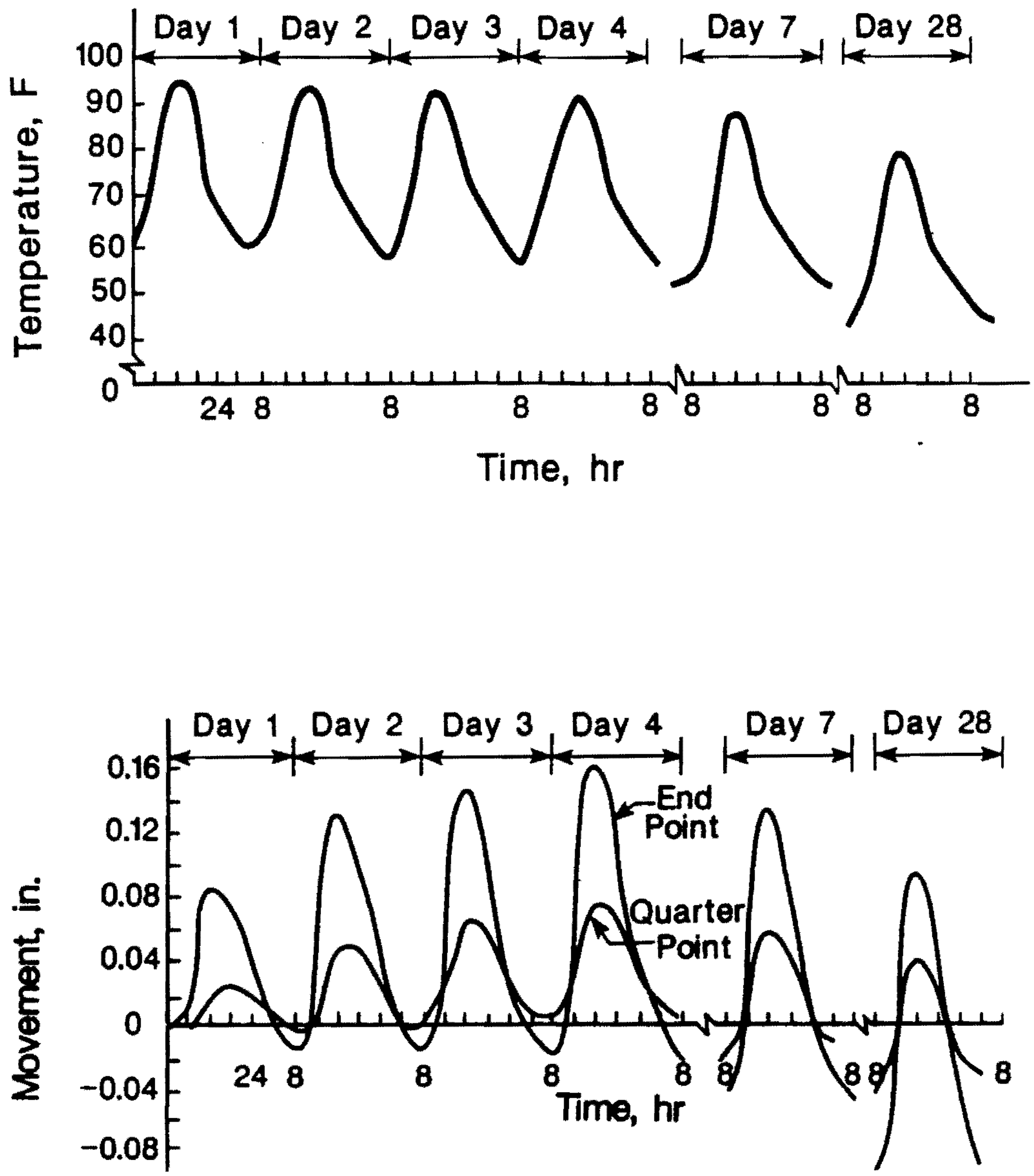
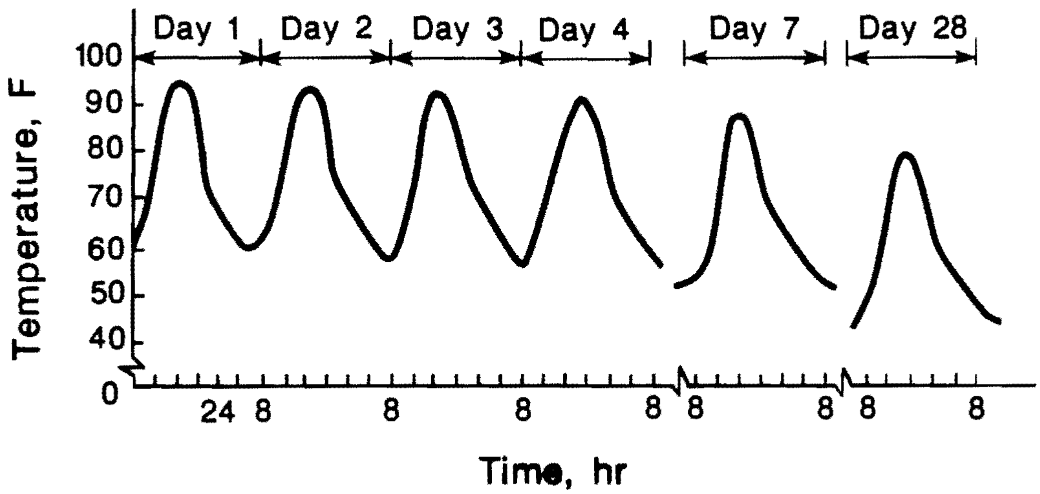


Fig 4.10. Consecutive cycles of movement for the end and quarter points of the slab, obtained from computer program PSCP1 that considers the inelastic nature of the frictional resistance.



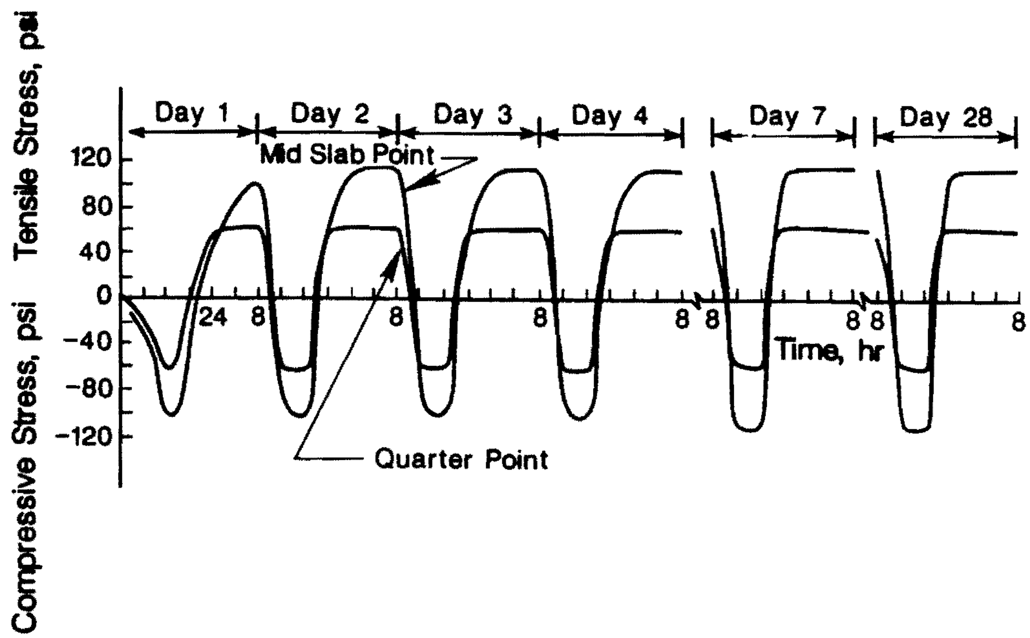


Fig 4.11. Consecutive cycles of stress for the midslab and quarter point of slab, obtained from computer program PSCP1 that assumes inelastic friction forces.

changes occur without frictional resistance in this procedure that incorporates the inelasticity of the friction forces. This may be evidenced from Figs 4.10 and 4.11. The shift of the movement cycles in Fig 4.10 for the 7^{th} and 28^{th} days toward the negative zone of the graph, which respresents contraction movements, is a result of accumulated shrinkage. However, the friction stress cycles in Fig 4.11 develop from the daily temperature changes with disregard to cumulative shrinkage and, for the most part, are practically the same from one day to another. The model used inside PSCP1 for evaluating shrinkage strains as a function of time is the one proposed by Hansen and Mattock in Ref 39. The mathematical expression is given in Appendix A. The model for creep is discussed in Chapter 5, which deals with the prestress forces related effects.

Solution for Reinforced and Cracked Pavements

Although the solution for friction stresses and restrained movements was derived for plain concrete slabs, it can also be used for uncracked pavements with conventional reinforcement. Before the slabs develop any cracking, the effect of conventional bonded reinforcement on the movements and stresses of the slab is almost negligible.

For cracked pavements, the solution for stresses is not valid because, when the pavement cracks, there is a redistribution of the friction related stresses from the concrete to the steel at the cracks. Away from the cracks, the friction stresses are restored to the concrete again through bonding forces between the concrete and the steel. However, the solution for movements is still valid if a reduced elastic modulus is introduced in the analysis to account for the effect of the transverse cracking on the pavement.

SUMMARY

The problem to be solved in this research to model the behavior of PCP slabs has been defined in this chapter. The numerical solution involves the important factors and is in a form that provides complete information, in terms of displacements and stresses, useful in the design of PCP slabs. The slab should be analyzed in, at least, three time periods:

(1) From the analysis of an initial period, the mechanism of movements and stresses during the pavement first hours can be studied, including the effect of application of prestress forces. The information generated for this period is essential for assessing time of casting and time and amount of prestress to apply at given stages to minimize problems with premature cracking of the slabs.

(2) From the second period, representing a summer day at the end of the pavement design life, the critical stress combination of friction and curling stresses can be determined. This information is necessary in the design of thickness and prestress level of the slabs.

(3) From a final period, representing a winter day at the end of the pavement design life, the maximum joint opening can be evaluated. This term is essential for designing the length of the PCP slabs.

The derivation of a model for longitudinal movements restrained by the friction, considering the inelastic nature of these forces, is also presented in this chapter.

This model is composed of two submodels:

(1) The first submodel, to simulate the contraction or expansion of the slabs away from maximum or minimum temperatures of the thermal cycle.

(2) The second submodel, to simulate the stress relief mechanism and reversal of movements of the slabs, immediately after maximum or minimum temperatures of the thermal cycle.

The friction model derived in this chapter is innovative and, at the same time, more realistic than previously developed friction models.

CHAPTER 5. MODELING THE EFFECT OF PRESTRESS FORCES

In the preceding chapter, three periods of analysis were outlined for the design of PCP slabs:

(1) An initial period for studying the stresses in the pavement during the first hours after the setting hour.

(2) A second period for obtaining the critical stress combination, required to design the thickness and prestress level of the slabs.

(3) A final period for designing maximum joint opening and minimum level of prestress.

For the first prediction period, the stress cycles developing from consecutive temperature cycles start replicating a short time after the setting hour. This fact was typified in Chapter 4 with predictions from Computer Program PSCP1. The time required for the concrete to gain substantial strength is also the time required for the stresses to reach the stability condition. This stability condition is broken when prestress forces are applied. The unsteady condition thus obtained is of a transient nature for the steady state is shortly reestablished inasmuch as slab movements continue to occur as a result of daily temperature changes regardless of the prestress force. To determine the time dependence of movements and stresses during this transient stage is the problem considered in the first part of this chapter.

For periods of prediction subsequent to the initial period, the assumption will be made that the analysis interval takes place sometime after the completion of prestressing. Since the frictional forces occur independently of the prestress, it is valid to superimpose the prestress level on the profiles of friction restraint stresses developed during the study interval. Therefore, the subject in the second part of this chapter is to quantify the losses occurring up to the beginning of the analysis period considered, and then define the remaining prestress level to superimpose throughout the period. Additional discussion will also be provided regarding computation of friction stresses and restrained movements for these periods.

MODELING THE PRESTRESS APPLICATION EFFECT AT THE INITIAL PREDICTION PERIOD

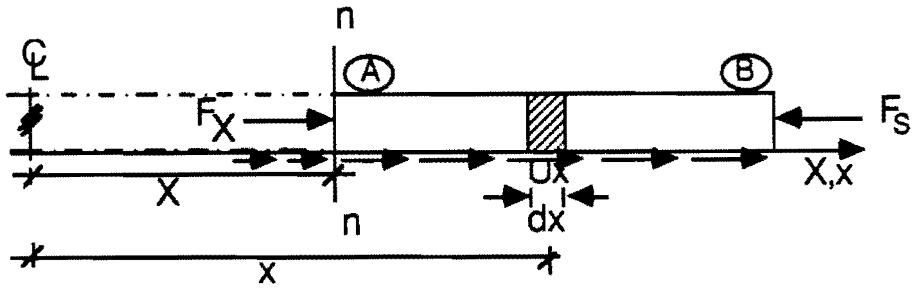
Modeling the behavior of long PCP slabs assuming inelastic friction forces has to be handled with a time incremental approach. The effect of prestress forces can be included in this approach by applying the principle of superposition. Figure 5.1(a) and (b) illustrate that if segment AB is in equilibrium, the concrete stresses should be equal to the superposition of stresses due to the two external forces: friction and prestress. Whether the stresses generated by the friction decrease or increase the precompression depends on the direction in which the friction forces develop as a result of the slab movements. This aspect is demonstrated in Fig 5.1(a) and (b). In this context, the friction forces may arise as a result of two movement types:

(1) Temperature induced movement.

(2) The contraction movement produced at prestress force applications.

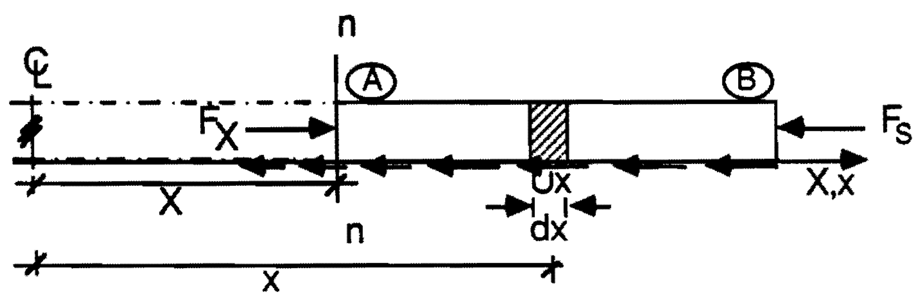
The effect of post-tensioning on PCP slabs can be modeled if, in the progression of movements and stresses due to temperature changes, the contraction produced by the prestress can be included. This contraction affects the friction forces which will react by opposing the prestress contraction movement. The final stresses in the pavement can be readily determined by superimposing the stress caused by the friction forces thus obtained on the precompression due to the prestress.

To induce in the slab elements a contraction strain $\varepsilon_X = \Delta f_c/E_c$ creates a slab contraction and corresponding friction forces (Ref 50). The term $\Delta f_c/E_c$ is composed of the concrete stress Δf_c due to the prestress in the numerator and the concrete elastic modulus E_c at the time of prestressing in the denominator. The contraction strain should be introduced at the time increment when the prestress force inducing the concrete stress change Δf_c is applied. As an example, consider the sequence of temperature shown in Fig 5.2, for the first 120 hours after setting of a 440-foot slab placed on a single polyethylene film. A concrete coefficient of contraction and expansion of 5×10^{-6} inch/inch-^oF is assumed in this example. The slab is cured at 12 AM and post-tensioned 36 hours later. A total prestress of 215 ksi is applied to 0.6-inch seven-wire strands (0.26 $inch^{2)}$ spaced 24 inches center to center. This force results in a concrete stress Δf_c of 322 psi, for a 6-inch-thick PCP slab. Assuming that the concrete elastic modulus E_c after 36 hours is 2,400,000 psi, the



$$F_X = -\int_X^{L/2} Ux \cdot \gamma \cdot D \cdot dx + Fs$$

(a) The friction forces reduce the concrete precompression when the slab contracts.



$$F_X = \int_X^{L/2} Ux \cdot \gamma \cdot D \cdot dx + Fs$$

(b) The friction forces increase the concrete precompression when the slab expands.

Fig 5.1. Superposition of stresses produced by friction and prestress.

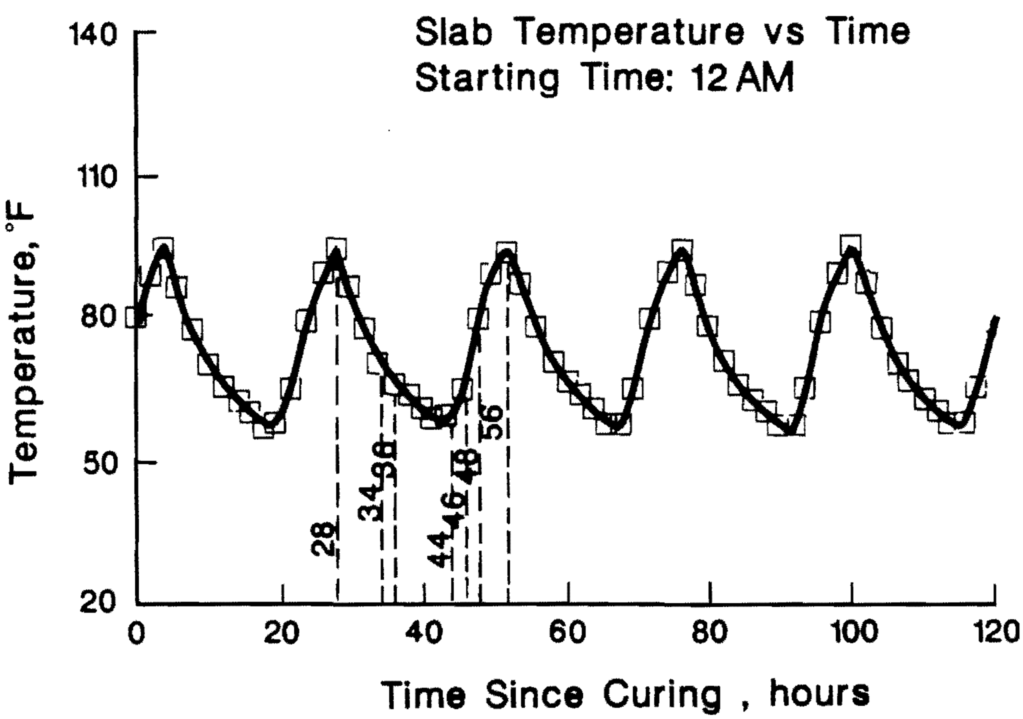


Fig 5.2. Pavement temperature sequence.

contraction strain ε_X to be induced in the slab after 36 hours is equal to $\Delta f_c/E_c$ = 0.0001323 inch/inch. The effect of the sudden contraction can be noticed on the diagram of slab and movement versus time in Fig 5.3 by a downward shift in the trend of movements. This graph was obtained with computer program PSCP1.

The time required for the movement to stabilize after the contraction is nearly 12 hours following post-tensioning, as shown in Fig 5.3. After 12 hours, the movements become the "mirror-image" of the corresponding movement in a graph in which the contraction effect is not included. Given that the magnitude of the slab movements is dependent on the concrete volumetric strains, the slab length, and the base restraining characteristics, this stabilizing time would be greater for longer slabs cast on bases offering a higher resistance to the slab's longitudinal movements. For slabs on friction reducing membranes, the stability condition is reestablished in the next temperature cycle after the prestress force is applied.

Stress Profile Diagrams

The approach adopted herein for simulating the effect of prestress application can be explained by analyzing the sequence of stress profiles along the slab between Hours 28 and 52. Fig 5.2 shows that a peak temperature is reached 28 hours after the setting hour. The stress profile obtained from the setting time up to this hour using a simulation with Computer Program PSCP1 is shown in Fig 5.4. Subsequent temperature drops after the peak values causes slabs contraction and the profiles to shift upwards, toward the tensile stress zone as shown for Hours 30, 32, and 34 in Fig 5.4. Since the entire slab is in tension by Hour 34, the friction force vectors beneath the slab should oppose the movement, i.e., that from the slab center toward the slab ends.

The contraction produced by the prestress at Hour 36 develops the maximum friction coefficients beneath the slab (0.96 for single film polyethylene according to Fig 3.4). Therefore, the maximum attainable friction forces are obtained beneath each point of the slab. Since this represents a constant force per unit length, it follows immediatelly that the stress profile due to friction must be a straight line, as shown in Fig 5.4 for Hour 36. The slope of this line is defined by the maximum friction coefficient, U_{max}, and the concrete unit weight, γ, according to the following relationship:

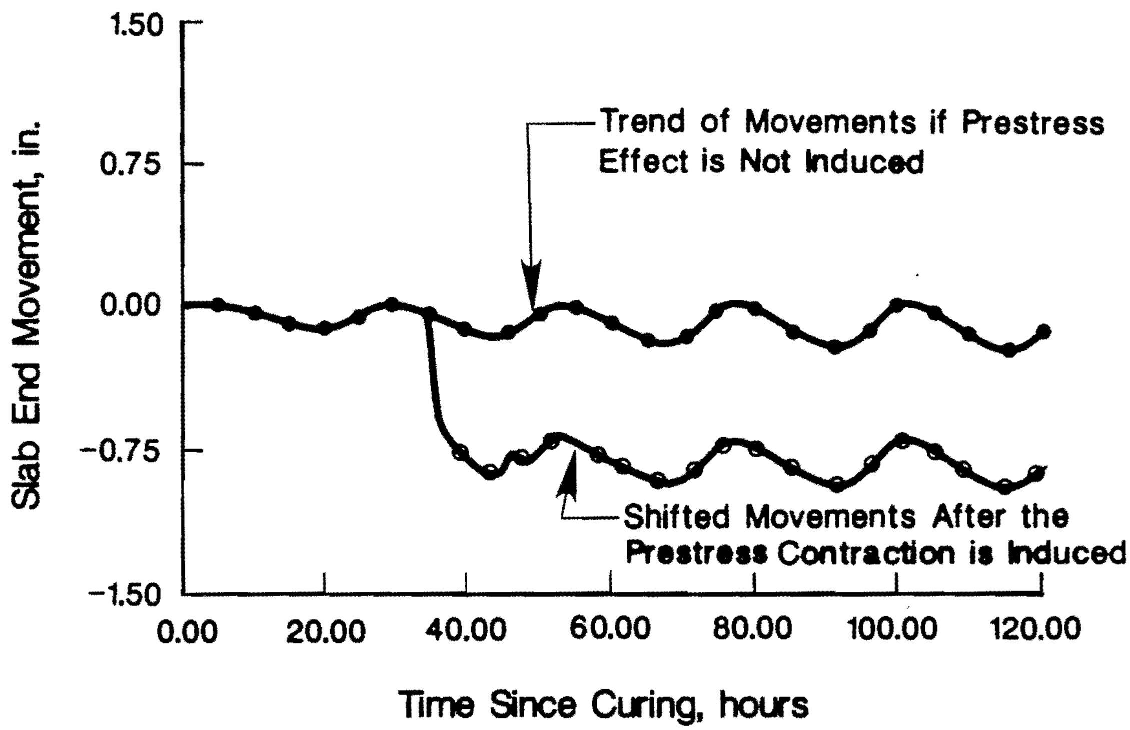


Fig 5.3. Slab end movements versus time since curing.

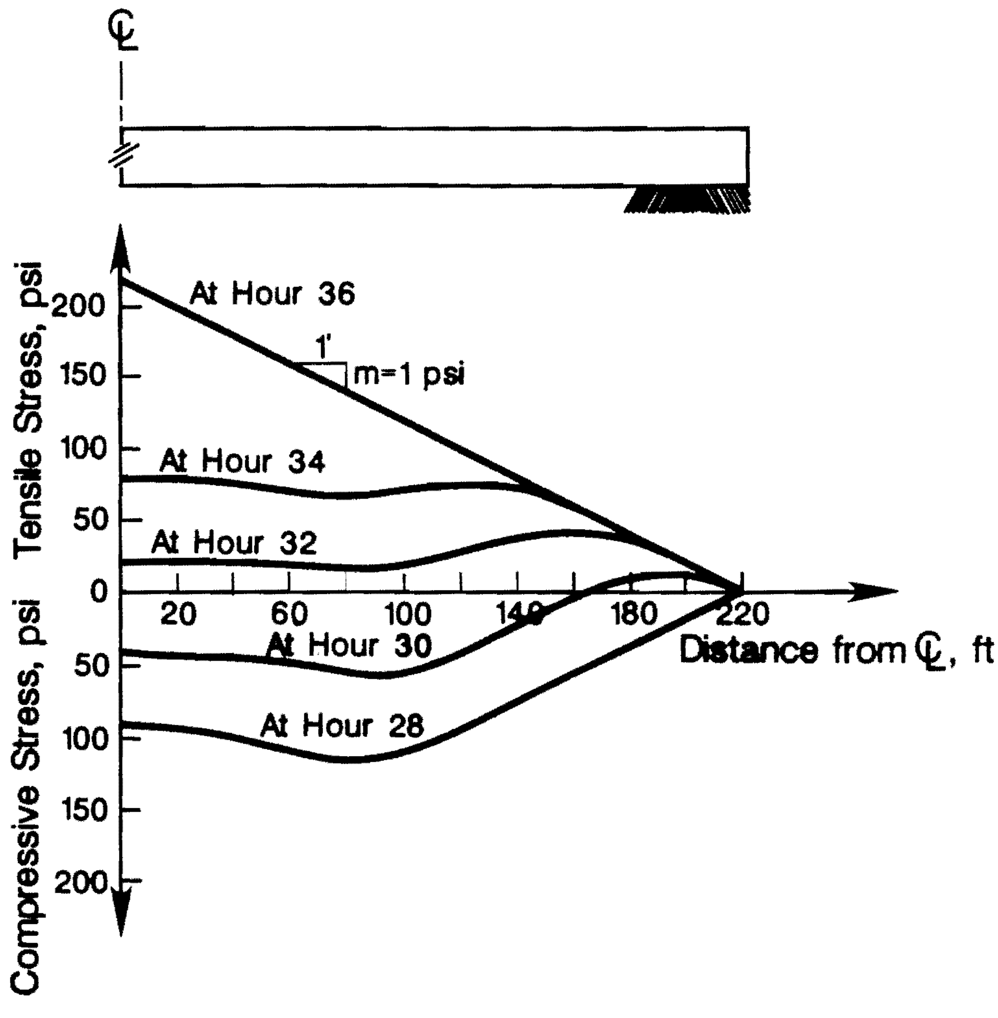


Fig 5.4. Sequence of friction stress profiles developing between Hours 28 and 36 since curing.

$$\text{slope} = U_{max} \bullet \gamma \tag{5.1}$$

For a concrete unit weight g of 150 pcf, the slope should be

$$\text{slope} = \frac{0.96 \times 150}{144} = \frac{1 \text{ psi}}{\text{ft length}}$$

which is the slope of the profile for Hour 36 in Fig 5.4. This profile represents the reduction of precompression exerted by the friction forces on any given section of the slab. The final concrete stresses can then be found by superimposing the precompression as illustrated in Fig 5.5. In this figure, the origin of ordinates has been redefined in a scale on the right side of the chart for reading final concrete stresses. For the slab quarter point, 110 feet from the slab center, the friction reduces the precompression by 110 psi as indicated on the left side scale. Therefore, the final concrete compressive stress, from the right side scale, is 212 psi. A peculiar feature to note in this example is that temperature drops occurring immediately after prestressing cause the slab to slide farther, but additional increments in frictional resistance are not obtained because the maximum friction coefficients had developed along the entire slab when the prestress was applied. This sliding is evidenced in Fig 5.3. The fact that increments of frictional resistance are not possible cause the friction profiles for Hours 36, 38, 40, 42, and 44 to remain the same as shown in Figs 5.5 and 5.6. This pattern of constant stresses several hours after Hour 36 can also be observed in Fig 5.7, which shows midslab stress versus time since the setting hour.

After Hour 44, temperature increments cause expansion movements in the slab and friction forces which develop from the slab ends toward the center, thus increasing in any given section of the slab the precompression stress produced by the prestress. This effect is evident in the profiles shown in Fig 5.6. The slab should exhibit maximum compressive stresses when the temperature reaches a maximum again, at Hour 52. From here on, the effect of the prestress on the magnitude of the friction forces will be negligible. Therefore, it is valid to superimpose the effects of friction and prestress forces if they are determined independently.

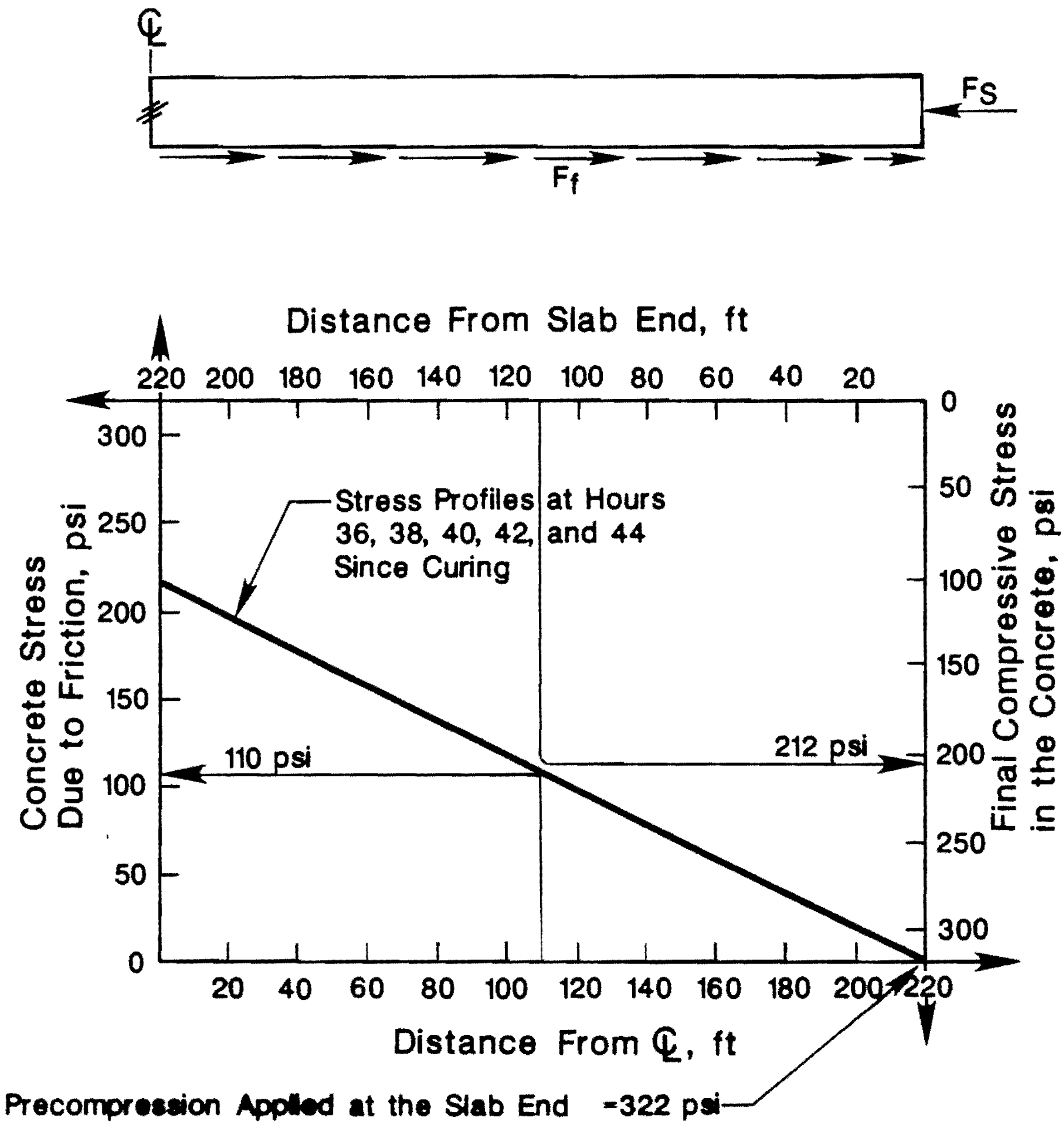


Fig 5.5. Superposition of prestressed on the stress profiles produced by friction.

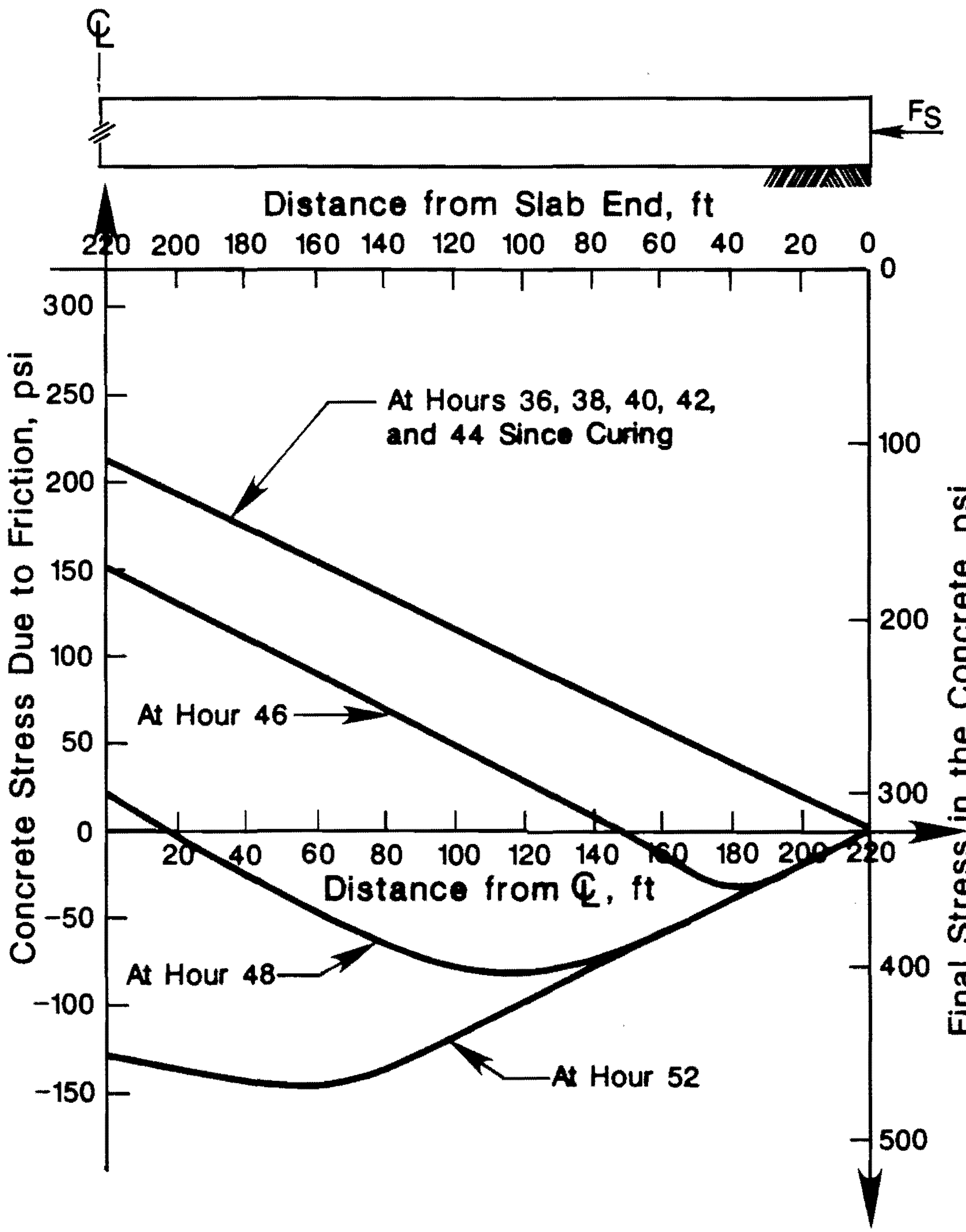


Fig 5.6. Stress profiles developing between Hours 36 and 52.

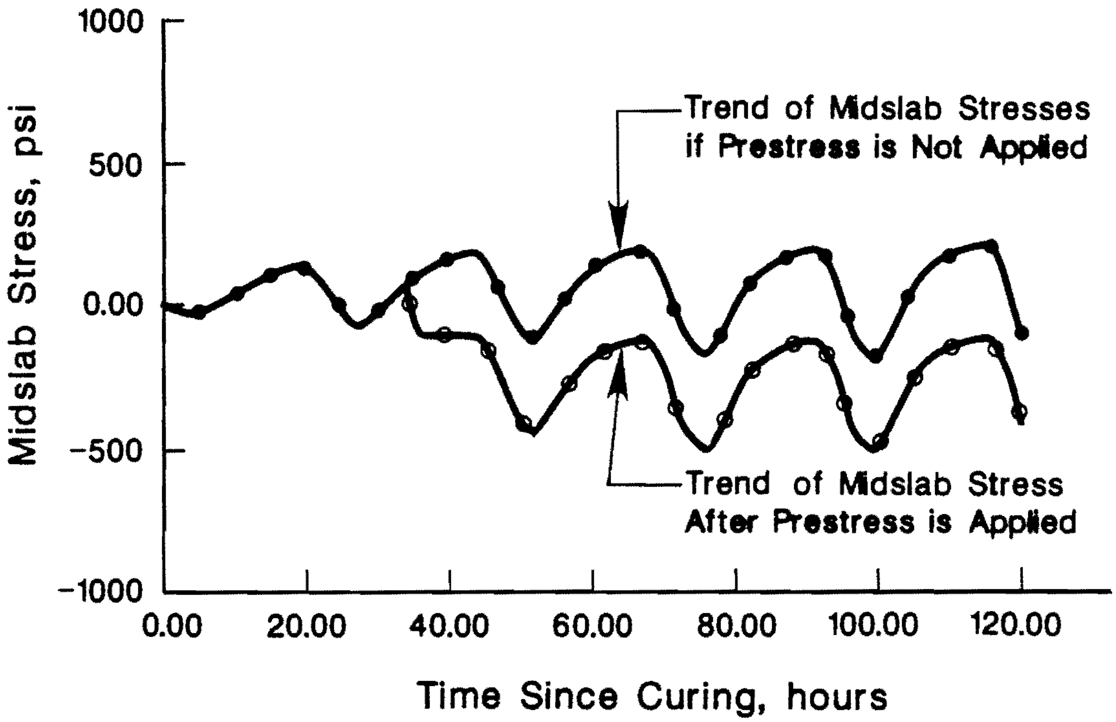


Fig 5.7. Midslab stress versus time since curing.

The effect of the prestress is to shift the friction profiles an equal amount to the precompression being applied at the slab ends. The final stresses in the concrete will be the "mirror-image" of the friction profiles. Likewise, the friction forces will develop primarily as a result of the daily temperature related movements, thus practically unrestrained by the prestressing steel. This is true because the axial stiffness of the concrete plate ($E_c \bullet A_c/L$) is normally many time greater than the axial stiffness of the strands ($E_s \bullet A_s/L$).

Behavior Assuming Elastic Friction Forces

If the friction forces were modeled elastically, the prestress force would produce a thrusting slab movement toward the center with respect to its initial position at the reference time (setting hour). Hence, most of the slab would work in the sliding range with maximum friction forces opposing the contraction movement. The daily slab expansion would not suffice to remove the slab from the sliding zone since the prestress contraction is fairly substantial, as may be evidenced in Fig 5.3 for the slab end point. During the daily cycle, most of the slab points would oscillate within the sliding zone, similarly to the response shown for point A (between positions Z_{An} and Z_{An-1}) in Fig 3.11 in Chapter 3. Since movements within this zone do not result in changes of the frictional force, the stress profile for Hour 36 in Fig 5.6 would be constantly and indefinitely predicted for all subsequent hours after post-tensioning. To design a PCP slab considering that the maximum friction forces along the entire slab always oppose the effect of the prestress is very unrealistic and may lead to very conservative designs.

Key Assumption

A major assumption in this derivation and inside the Computer Program PSCP1 is that the prestress applied at the slab ends remains constant during the periods of prediction. This assumption is valid since short-term maximum movements, as may be observed for average conditions in Fig 5.3, fall in the range of the 0.06 inches per 100 feet of slab length. Movements in this order of magnitude result in negligible variations of the strand's elongation. The long term slab end movements, on the other hand, may generate as much as 0.5 inch of contraction per 100 feet of slab length (Ref 4). The necessity to include this effect on the prestress level is then evident. This will be the matter of issue in subsequent sections of this chapter.

LONG TERM PREDICTION OF PAVEMENT RESPONSES

Unlike the initial prediction period required in the design of PCP slabs, the intermediate and final periods take place long after the setting time. The following considerations for predicting behavior during these periods arise therefrom:

(1) The compatibility relationship between concrete and steel deformations that governs the average prestress acting on the slab during the period considered should be derived. This will permit one to evaluate the prestress level after losses to the friction stresses arising during the period.

(2) The time incremental scheme adopted in this study requires that, for predicting slab responses during a time period, a simulation of the development of movements and stresses due to environmental factors, shrinkage, creep, etc. should be followed starting from the setting hour. By following this simulation, the initial condition for movements and stresses at the beginning of the period considered can be obtained. This initial condition is required to determine further movements and stresses during the period itself. However, it is not feasible to run a simulation starting from the setting hour for analysis periods occurring a long time after setting.

Both aspects will be discussed in subsequent sections consecutively.

Long Term Changes of the Prestress Level

Time dependent variations of the prestress level are produced by slab longitudinal movements due to seasonal temperature changes, concrete shrinkage and creep, plus relaxation of the prestressing steel. Evaluations of seasonal temperature related movements are not a problem per se because the concrete strains during this period are equal to the temperature change between seasons multiplied by the concrete thermal coefficient of contraction and expansion. Reference was made in Chapter 4 to the selected expression for evaluating shrinkage strains as a function of time. Still pending for discussion are creep, an expression for evaluating prestress level changes from the strains produced by the factors above mentioned, and an expression for evaluating steel relaxation. Elastic shortening is another source of prestress variation because the tendons are stressed successively. Tendons that are tensioned first suffer losses of elongation due to concrete shortening when the prestress is applied to subsequent tendons. However in PCP with long joint spacings and correspondingly long tendon elongations, these losses are insignificant and are typically ignored (Ref 44).

Concrete Creep. A significant long term loss is the creep loss of the prestress in the concrete. Creep is a property of the material that causes it to continue to deform over long time periods under a constant stress. The rate of strain is usually very rapid after initial loading and decreases with time until a nearly constant value of strain is approached. For concrete, the constant strain level is approached asymptotically after several months.

Creep strain in concrete depends on the mix proportions as well as humidity, curing conditions and age of concrete at loading. Creep strain is nearly proportional to the initial strain in the concrete upon loading. Therefore, it is possible to define a creep coefficient C_u as

$$C_u = \frac{\varepsilon_{cu}}{\varepsilon_{ci}} \qquad (5.2)$$

where ε_{ci} is the initial or elastic strain in the concrete and ε_{cu} is the additional or creep strain.

Creep at any time t in days, can be estimated as (Ref 45)

$$\varepsilon_{ct} = \frac{t^{0.60}}{10 + t^{0.60}} \bullet C_u \qquad (5.3)$$

Correspondingly, the creep strain at time t as a function of the ultimate concrete creep strain is

$$\varepsilon_{ct} = \frac{t^{0.60}}{10 + t^{0.60}} \bullet \frac{\varepsilon_{cu}}{\varepsilon_{ci}} \tag{5.4}$$

Compatibility Relationship Between Concrete and Steel Deformations

In this section, the pavement is considered as a material composed of concrete and steel whose behavior is unaffected by the friction produced by the base material. Relative movements between concrete and steel are assumed to occur freely. Therefore, the equations derived herein hold strictly true for the case of unbonded tendons. However, from a practical standpoint, the solutions are also valid for bonded tendons since the effect of bonding is insignificant before the slabs experience cracking. The initial average stress f_{ci} is considered to be applied in the concrete immediately after prestressing . This is the stress in the concrete after deduction of the losses due to friction between the tendons and their ducts, elastic shortening, and anchor set, if any. To satisfy the internal equilibrium of forces between the concrete and steel, an initial tensile stress equal to f_{si} is considered to be applied in the steel.

If the concrete experiences a unit expansion deformation equal to ε_c, the compressive stress in the concrete will increase under the restraint of the prestress force, with a corresponding increase of the steel tensile stress. If the concrete were unrestrained by the prestress force, the slab would experience the end movement Z_e:

$$Z_e = \varepsilon_c \bullet L/2 \tag{5.5}$$

where L is the slab length. This condition is illustrated in Fig 5.8(a).

In the presence of the restraining force, both materials will experience the same end movement as shown in Fig 5.8(b). Hence, the respective variations of the concrete and steel ΔF_c and ΔF_s according to the sign convention adopted in Chapter 4 are

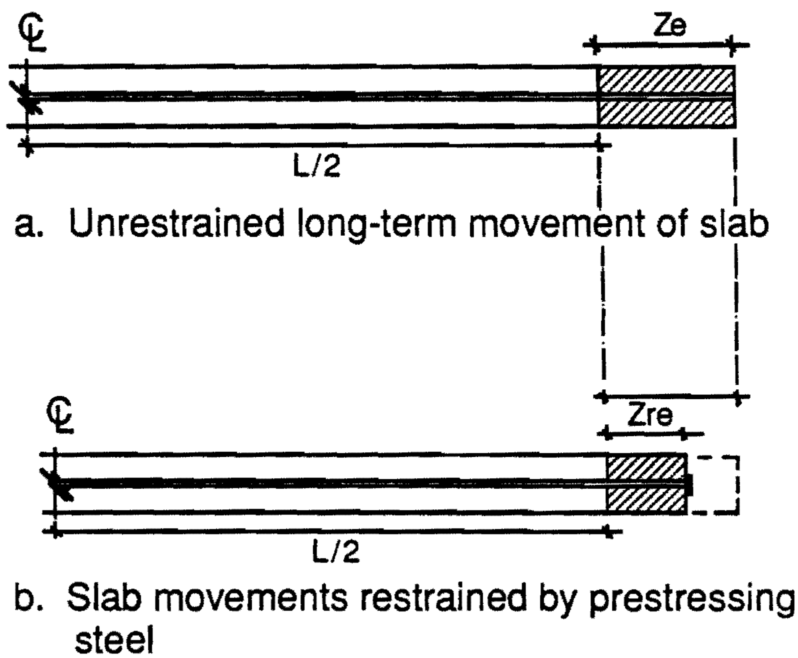


Fig 5.8. Compatibility relationship between concrete and steel deformations.

$$\Delta F_c = \frac{-E_c (Z_e - Z_{re}) A_c}{L/2} \tag{5.6}$$

and

$$\Delta F_s = \frac{E_s \bullet Z_{re} \bullet A_s}{L/2} \tag{5.7}$$

where

E_c	=	concrete modulus of elasticity,
E_s	=	steel modulus of elasticity,
Z_e	=	unrestrained end movement,
Z_{re}	=	actual end movement,
A_c	=	transverse area of concrete slab,
A_s	=	reinforcing steel area.

Equating both terms as follows,

$$\Delta F_c = -\Delta F_s \tag{5.8}$$

and substituting the end movements by the corresponding strains,

$$(\varepsilon_c - \varepsilon_{cr})/\rho = \varepsilon_{cr} \bullet n \tag{5.9}$$

where

ρ	=	reinforcement percentage,
ε_c	=	unrestrained concrete strain,

ε_{cr} = actual concrete strain,

n = ratio of steel to concrete elastic moduli.

Solving for the actual strain ε_{cr},

$$\varepsilon_{cr} = \frac{\varepsilon_c}{1 + \rho n} \tag{5.10}$$

Therefore, the movement Z_{Xr} of a point located a distance X from midslab is

$$Z_{Xr} = \frac{\varepsilon_c \bullet X}{1 + \rho n} \tag{5.11}$$

Likewise, the changes in concrete and steel stresses, Δf_c and Δf_s, with respect to the initial values f_{ci} and f_{si}, respectively, are

$$\Delta f_c = -E_c (\varepsilon_c - \varepsilon_{cr}) \tag{5.12}$$

and

$$\Delta f_s = E_s \bullet \varepsilon_{cr} \tag{5.13}$$

Substituting Eq 5.10 into relationships 5.12 and 5.13,

$$\Delta f_c = -\frac{\varepsilon_c \bullet E_c}{1 + 1/\rho n} \tag{5.14}$$

and

$$\Delta f_s = \frac{\varepsilon_c \bullet E_s}{1 + \rho n} \tag{5.15}$$

For the sake of clarification, the development shown above was presented for the generic concrete strain ε_c. In this form, the strains produced by seasonal temperature variations, shrinkage, and creep occurring from post-tensioning until the time of analysis should be included.

Steel Relaxation. A significant amount of prestress loss is due to the relaxation exhibited by the steel strands. Steel relaxation is defined as the loss in steel stress when it is held at a constant strain level. Equation 5.16 provides a reasonable estimate of the steel relaxation after t hours of stress (Ref 46):

$$f_{pt} = 1 - \frac{\log t}{10} \left(\frac{f_{pi}}{f_{yi}} - 0.55 \right) f_{pi} \tag{5.16}$$

where

f_{pt} = prestress level in the steel after t hours,
f_{pi} = initial prestress level in the steel,
t = time in hours after initial prestressing, and
f_{yi} = steel yield stress.

This equation is commonly used by designers of PCP slabs (Refs 44 and 46) and, therefore, the expression was adopted for this study.

Simulation of the Sequence of Friction Restraint Stresses for Analysis Periods Occurring a Long Time Since the Setting Time

Given the impossibility of running a simulation since the setting hour for analysis periods occurs a long time after setting, a technique to circumvent this limitation should be devised. If the period of analysis takes place several hours following the setting time when substantial shrinkage and creep have occurred and if, in addition, it occurs in a different season than when the pavement was cured, then, the volumetric strains due to these factors, to input into the incremental approach adopted in this study for the first time increment, would be fairly substantial. If the simulation is started from an initial stressless condition and this initial strain is input into the incremental procedure as the volumetric strain of the first time increment, then unrealistically high predictions of restraint stresses would be obtained for the first time increments. Likewise, the movements during these increments would be significantly restrained by the friction. For subsequent increments, the effect of this large initial volumetric strain would tend to dissipate, as illustrated in Fig 5.9 for midslab stresses and end movements of a 440-foot-long slab. These figures were derived from Computer Program PSCP1, for the friction coefficient vs. displacement curves shown in Fig 3.4 in Chapter 3, for a single polyethylene layer and an asphalt treated base. It may be observed in Fig 5.9 that if a 24-hour period, starting at 8 AM, is simulated twice, even for the case of the treated base representing very critical restraining conditions, the trends of movements and stresses stabilize for the second 24-hour round of predictions. For the second 24-hour period, shrinkage, creep and seasonal temperature changes are not affected by the frictional resistance and the friction restraint stresses develop exclusively from the daily temperature variations of the corresponding season. This is the technique used in computer program PSCP1 for determining friction stresses for 24-hour periods of analysis following the initial period. PSCP1 determines the prestress losses up to the beginning of the period considered and deducts it from the initially specified prestress level. Then, it superimposes this reduced prestress level on the cycle of friction stresses obtained as described above. This detail of the program operation is further discussed in the next chapter.

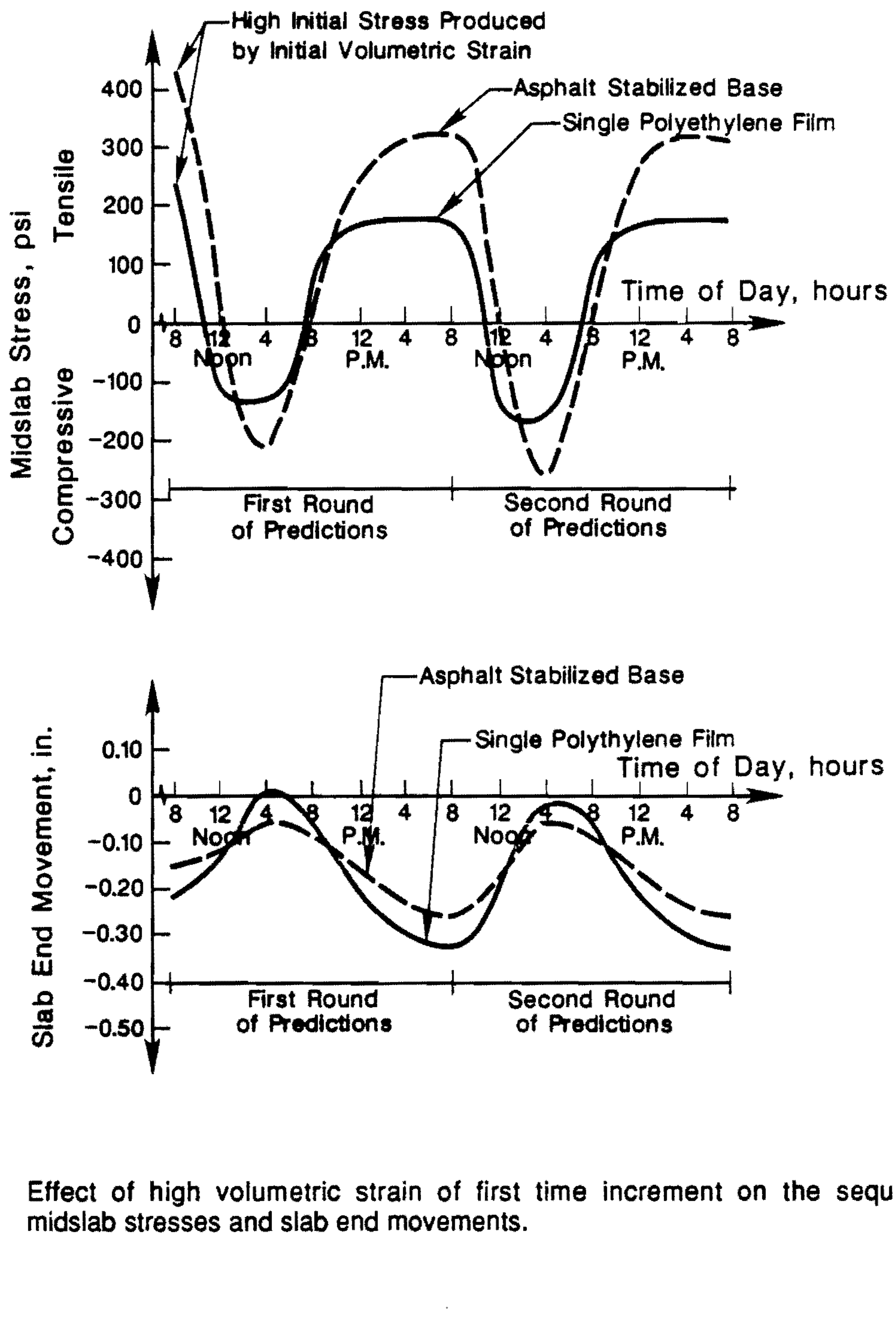


Fig 5.9. Effect of high volumetric strain of first time increment on the sequence of midslab stresses and slab end movements.

SUMMARY

In this chapter, the effect of the variables associated with the application of prestress forces has been incorporated in the modeling of PCP behavior.

For the initial period of predictions considered in this study, the effect of prestress force applications on the sequence of movements and stresses due to other factors is introduced by applying the contraction produced by the post-tensioning in the time increment when the prestress force is applied. Thus, the prestress compression is superimposed onto the friction restraint stresses due to the contraction. It has been shown that, shortly after post-tensioning, the effect of the prestress is to shift the cycle of friction stresses due to daily temperature changes an amount equal to the precompression applied at the slab ends. Such prediction of behavior could not be obtained if elastic friction forces were assumed beneath the slab.

For prediction periods after the initial period, the equations for determining the prestress losses up to the beginning of such periods have been established. The superposition of the prestress level after losses on the cycle of friction restraint stresses is valid, since the friction forces are assumed to develop independently of the prestress during these periods.

CHAPTER 6. DESCRIPTION OF COMPUTER PROGRAM PCP1

Program PCP1 is the first program developed for studying the mechanistic behavior of PCP slabs considering the inelastic nature of the slab base friction forces. This chapter is intended to provide a brief discussion on the use and operation of the program, as well as a description of the data, and input variables and an interpretation of the program output. The program is written in FORTRAN 77 so that it may be easily adapted to any computer system. The compile time for the program is less than 6 seconds. The storage requirement for the program presently is 66500 locations.

The cost per run for PCP1 depends on the characteristics of the problem analyzed, i.e., the nature of the friction versus movement relationship, the variation of concrete strength with time, the number of periods of analysis specified per run, and the number of temperatures input for the initial period at 2-hour intervals. However, the execution time depends primarily on the number of iterations to achieve convergence, for a specified tolerance level, in the loop for determining friction restraint stresses. The number of iterations is particularly dependent on the slab length and the number of elements into which the slab is divided for analysis. A typical run of 3 periods for a 240-foot divided in 50 elements would take approximately 8 seconds to run. This figure represents a very favorable indicator of the program's efficiency.

INTRODUCTION TO PCP1

The primary objective of the PCP1 Computer Program is to provide engineers with a design tool for PCP slabs. Since PCPs are designed for zero cracks, the slabs are considered by the program as solid plates without discontinuities. The capabilities of PCP1 permit analysis of the effect of time and different environmental conditions on the slab responses and the prestress magnitude.

The approach inside PCP1 consists of simulating deflections, movements, and stresses occurring in the slab during an initial analysis period at 2-hour intervals; and for two or more subsequent 24-hour periods, also in 2-hour intervals. The predictions for the initial period start from the setting hour, which is specified by the user, and continues through the number of temperatures input by the user. In addition to the setting hour, the slab middepth temperature should also be supplied by the user. Curing temperature and curing hour are used by PCP1 as reference values for computing daily and seasonal temperature variations and other time dependent variables, i.e., concrete strength, shrinkage, etc. For analysis periods different from the initial period, the prediction intervals are started at the specified number of days after curing. The analysis interval for this case extends for almost 24 hours, from 8 AM until 6 AM the next morning. The user should input temperature data consisting of slab middepth temperatures and top to bottom temperature differentials for twelve two-hour time increments.

The approach inside PCP1 of predicting slab responses at specific periods allows flexibility in the use of the program for design. The user is permitted to search for the most critical condition for the design element considered. This program's flexibility is demonstrated for the reader in a design example shown in Chapter 8.

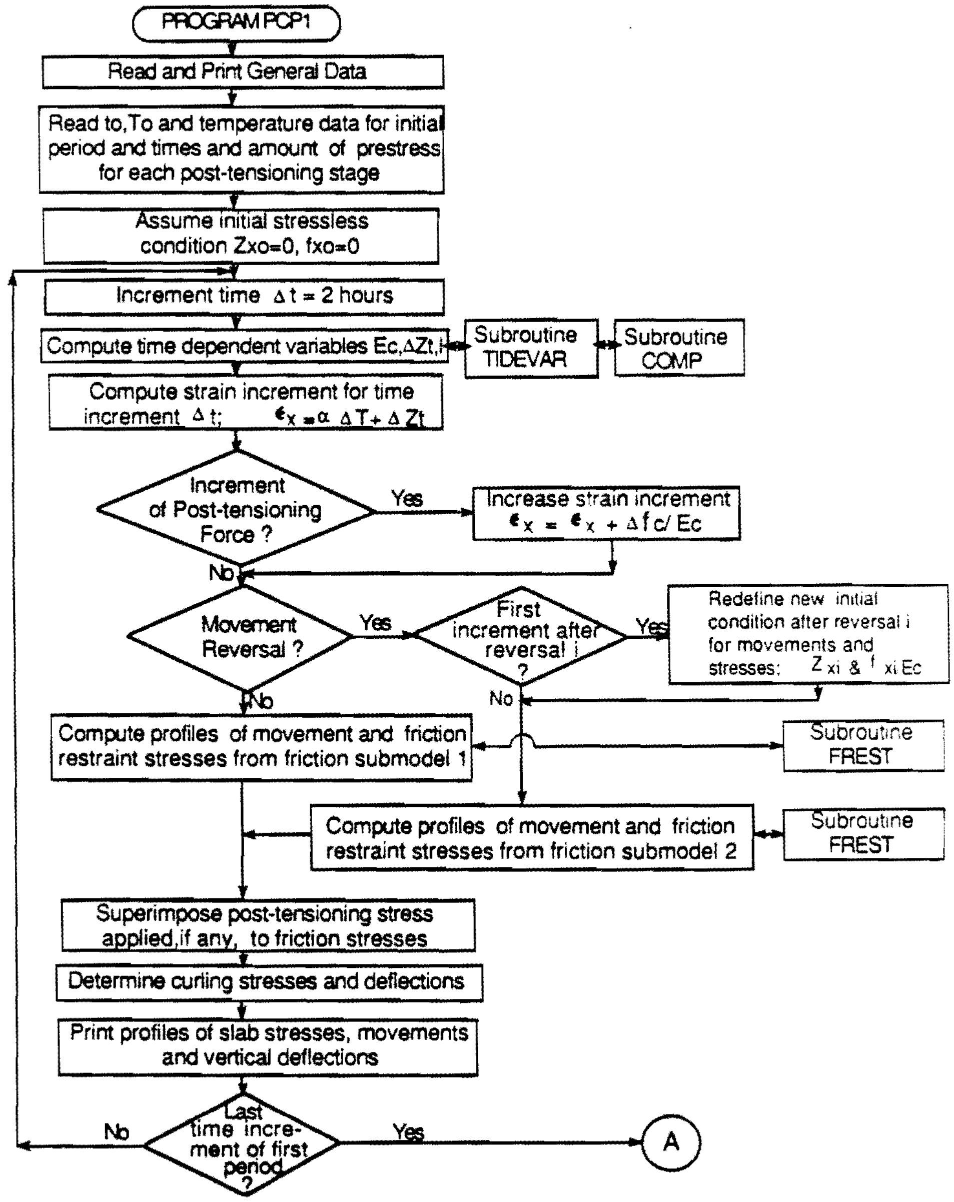
PROGRAM OPERATION

The PCP1 Computer Program contains the main program, PCP, and seven subroutine subprograms. Within PCP1, the main program is followed by the subprograms, arranged in order of execution, as follows: TITLE, FREST, ITER, TIDEVAR, FRIC, COMP, and CURL.

The main program,PCP, performs a series of tasks by organizing the operation of the subprograms according to the flow diagram shown in Fig 6.1. The different subroutines and procedures shown in this figure are subsequently explained.

First, PCP reads the problem's general data. For convenience and help in identifying input errors, the program makes an echo-print of the data at the beginning of the run. The general data are categorized in the following types: problem identification, problem definition, concrete properties, concrete compressive strength versus age relationship, friction coefficient versus displacement relationship, stiffness of the slab support, and properties of the prestressing steel.

After reading these general data, PCP reads the temperature data for the initial period. These data includes curing hour and curing temperature, the sequence of slab middepth temperatures, top to bottom temperature differentials, and time and amount of prestress applied at each post-tensioning stage. The program's input data are discussed in more detail in subsequent sections of this chapter.



(continued)

Fig 6.1. General flow diagram of computer program PCP1.

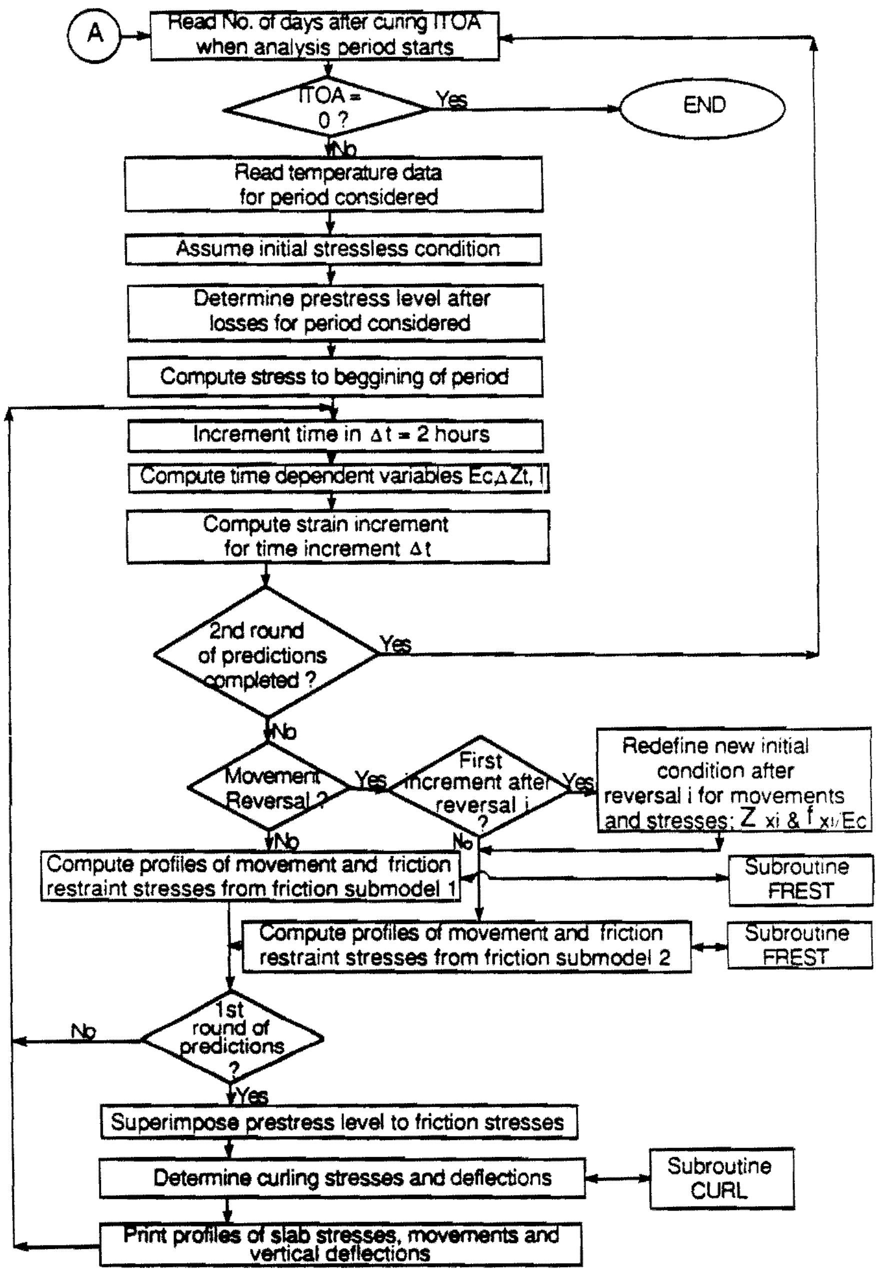


Fig 6.1. (continued)

After reading the data for the initial period, PCP proceeds to determine the sequence of pavement responses for this period, at 2-hour intervals, starting from the curing hour. For each time increment, PCP calls subroutine TIDEVAR for getting estimates of concrete elastic modulus, shrinkage, and radius of relative stiffness of the slab. TIDEVAR, in turn, makes use of subroutine COMP for obtaining estimates of concrete compressive strength as a function of time. Subsequently, PCP computes the strain increment in the longitudinal direction due to temperature, shrinkage, and prestress force application, for the time increment considered.

Then, PCP determines if the strain increment results in a reversal of movements with respect to the movements experienced by the slab in the previous time increment.

The next major step involves the estimation of the profiles of longitudinal movement and stress of the slab points, from the friction submodels described in Chapter 4. Submodel 1 is applied if the slab is contracting or expanding (away from maximum or minimum temperatures of the period) and stresses of one nature develop along the entire slab, either tensile or compressive. Submodel 2 is applied if the slab is reversing movements near maximum or minimum temperatures and tensile and compressive stresses develop at the same time in different locations along the slab length.

For estimating movement and friction stress profiles, PCP resorts to subroutines FREST and ITER to handle the iterative procedures. Once longitudinal movements and friction stresses have been estimated, if prestress forces are applied by the time of analysis, PCP superimposes the corresponding precompression to the friction stress profiles.

The PCP program then calls subroutine CURL to determine curling deflections and stresses from the temperature differential of the time increment analyzed. The expressions in subroutine CURL for estimating curling deflections and stresses are those obtained by Westergaard solving the curvature differential equation of a slab with an infinite edge and extending infinitely in the direction perpendicular to the edge (Ref 42). The differential equation and its solution are presented in Appendix A. Finally, PCP prints, for the time increment considered, the profiles of longitudinal movements, friction coefficients, concrete stresses produced by friction and prestress, and vertical curling deflections and stresses. This sequence is repeated consecutively by PCP for all time increments of the initial period.

Once the analysis of all time increments of the initial period is completed, PCP starts reading the data for the next time period. First, PCP reads the number of days since curing when this analysis period starts. Then, it reads the sequence of twelve middepth temperatures and temperature differentials for the 24 -hour period.

Immediately, for the total prestress specified in the initial period, PCP calls subroutine TIDEVAR for computing estimates of steel relaxation, concrete creep, and shrinkage occurring since the last time of prestress force was applied, until the beginning of this period. These estimates are subsequently used for computing prestress losses and the prestress level of the strands, after losses, for the period analyzed.

Next, PCP superimposes on the friction restraint stresses thus obtained the level of prestress, after losses, effective during this period. Finally, as for the initial period, PCP calls subroutine CURL for determining the curling stresses and deflections for the temperature differentials of this period. Then, the program reports sequentially, for each time increment analyzed, the profiles of longitudinal movement along the slab, friction coefficient, concrete stresses produced by friction and prestress, and curling deflections and stresses. This same procedure is repeated for all subsequent periods to be investigated. The user should input for each period the time since curing when the period starts and the sequence of temperature data. When the program attempts to read the time since curing of a new period, after solving for all the desired periods, and finds a blank card, PCP assumes that the run of all periods is complete and execution is terminated.

A complete listing of computer program PCP1 is included in Appendix D.

PROGRAM INPUT DATA

The format used for inputting data into the program is arranged as conveniently as possible. The input data may be categorized into ten different types: problem identification, problem definition, concrete properties, concrete compressive strength versus age relationship, friction coefficient versus displacement relationship, k-value of slab support, steel properties, sequence of temperature data for initial period, time and amount of prestress applied in each post-tensioning stage during the initial period, and sequence of temperature data for subsequent periods. The format for inputting data into the program is included in Appendix B. The codification of an example problem presented in Chapter 8 is included in Appendix C.

The input variables for each data category are as follows.

Problem Identification Input Variable

VECTOR1 contains alphanumeric information to identify the problem, i.e., project location, date, user's name, etc.

Problem Definition Variables

DL defines the pavement slab length in feet. This value is in the range of 10 to 40 feet for conventional jointed pavements (JCP or JRCP) and from 100 to 800 feet for prestressed concrete slabs (PCP).

D defines the thickness in inches of the concrete slab. PCP thicknesses range from 6 inches for highway pavements up to 8 inches for airport pavements. Likewise, this value is in the range of 8 to 14 inches for jointed reinforced pavements.

NILD represents the number of elements to which the slab is divided for analysis in the longitudinal direction. A relatively large number of elements should be specified so that the program algorithm may converge to a reasonable tolerance level. The integer number of 2-foot-long elements fitting into the slab length is an adequate rule of thumb for selecting the value of this parameter.

NMAX identifies the maximum number of iterations to prevent excessive computation in those problems in which the program finds difficulty in converging within the desired tolerance level. Most PCP problems should close to a reasonable tolerance within 50 iterations. However, the program efficiency permits up to 100 iterations to be specified without a significant increase in the CPU time for a given run.

TOL refers to the relative closure tolerance within consecutive iterations and should be expressed in percent. If it is unreasonably small, closure may be difficult to achieve. For most PCP slab problems, a value of one percent is satisfactory.

Concrete Properties Characteristics

ALTOT is the variable representing the concrete thermal coefficient (inch/inch-^{o}F). The value of this parameter is primarily dependent on the coarse aggregate type and moisture content of the concrete. The literature reports, for saturated concrete, minimum values for this term in the order of 3×10^{-6} inch/inch-^{o}F for limestone aggregate concrete and

6×10^{-6} inch/inch-^{o}F for silicious aggregate concrete (Ref 51). For summer dry conditions, thermal coefficients may be in the order of 4×10^{-6} inch/inch-^{o}F for limestone and 7×10^{-6} inch/inch-^{o}F for silicious aggregate concrete. The fluctuations of joint width expected between PCP slabs are governed, to a great extent, by the concrete thermal coefficient.

ZTOT defines the final or total value of concrete drying shrinkage strain. Values of final shrinkage for ordinary concretes are generally within the range of 0.0002 to 0.0007 inch/inch, depending on initial water content, ambient temperature and humidity conditions, and the nature of the aggregate (Ref 51). Highly absorptive aggregates, such as some sandstones and slates, result in shrinkage values twice those obtained with less absorptive materials such as granites and some limestones. For the purpose of design, shrinkage strain may be assumed to be about 0.0002 to 0.0004 for the concrete mixes usually used in highway and airport PCP.

G is the concrete unit weight (in pcf). Typical values of this parameter for normal weight concrete ranges between 140 and 150 pcf.

PR is the variable which defines concrete's Poisson's Ratio. For most portland cement concretes, the value of this variable normally ranges between 0.20 and 0.25 with a value of 0.20 being common. A default value of 0.20 is assumed by the program if this term is not input by the user.

CREEP represents the ultimate creep coefficient. Creep magnitude in portland cement concrete varies with gradation of concrete aggregate, particle shape, aggregate type, cement content, water-cement ratio, concrete density, curing, age at loading, load intensity, etc. An ultimate creep coefficient between 2.3 and 2.5 is suggested for computing creep associated strains of PCP slabs (Ref 51). A default value of 2.35 is assumed by the program in case this term is not provided by the user.

Age Versus Compressive Strength Relationship

KK, AGEU(I), and COMP(I) are the variables containing the age versus compressive strength relationship of concrete. KK represents the total number of points supplied for the relationship. COMP(I) is the compressive strength, in psi, of point I at the corresponding age AGEU(I).

This relationship can be determined from compressive strength tests performed on cylindrical specimens at different ages according to the procedures described in ASTM C39 or AASHTO T22, T140 (Refs 26 and 56). If the complete relationship cannot be determined from tests, PCP1 can generate it from recommendations given by the US Bureau of Reclamation. In this case, KK should be specified into PCP1 as 1, and into AGEU(I) as 28 days, and COMP(1) should contain the 28^{th} day compressive strength as obtained from the standard cylinder tests.

Slab Versus Base Friction Curve (U-Z Relationship)

M1, ZU(I), and UU(I) are the variables representing the friction coefficient versus displacement relationship. M1 represents the number of points supplied to describe the relationship, ZU(I) is the displacement in inches of the I^{th} point, and UU(I) is the corresponding friction coefficient. Three types of friction relationships can be input into the program: a straight line, an exponential curve, and a multi-linear curve. The desired relationship is specified by the control variable M1, in which, a value of one, two or greater than two, indicates that the curve is a straight line or an exponential or multi-linear relationship, respectively. In the case of a straight line, only one point is required to define the curve. This is the point where sliding occurs. In the case of an exponential curve, the program uses a function of the following form:

$$U = U_{max} (Z/a)^{\frac{1}{3}} \qquad (6.1)$$

where

U_{max}	=	maximum friction coefficient,
Z	=	movement of a given point of the slab,
U	=	friction coefficient corresponding to movement Z, and
a	=	movement at sliding point.

The maximum friction coefficient and the movement at sliding are, then, the variables to input in this case. If exponential or multi-linear curves are used, the first point to input should contain the origin: ZU(1) = 0 and UU(1) = 0. Otherwise, the program prints an error message and the execution is aborted. In case an exponential function is specified (M1=2), the first point should contain the origin and the second the movement for which sliding occurs and the maximum friction coefficient.

Finally, regardless of the curve type used for specifying the slab base friction properties, the mirror image of the curve is used for movements reversing direction, with the origin redefined where the reversing movement starts occurring. This implies that only one portion of the curve has to be supplied; the remainder is generated by the program. Figure 6.2 shows the curve types considered by PCP1.

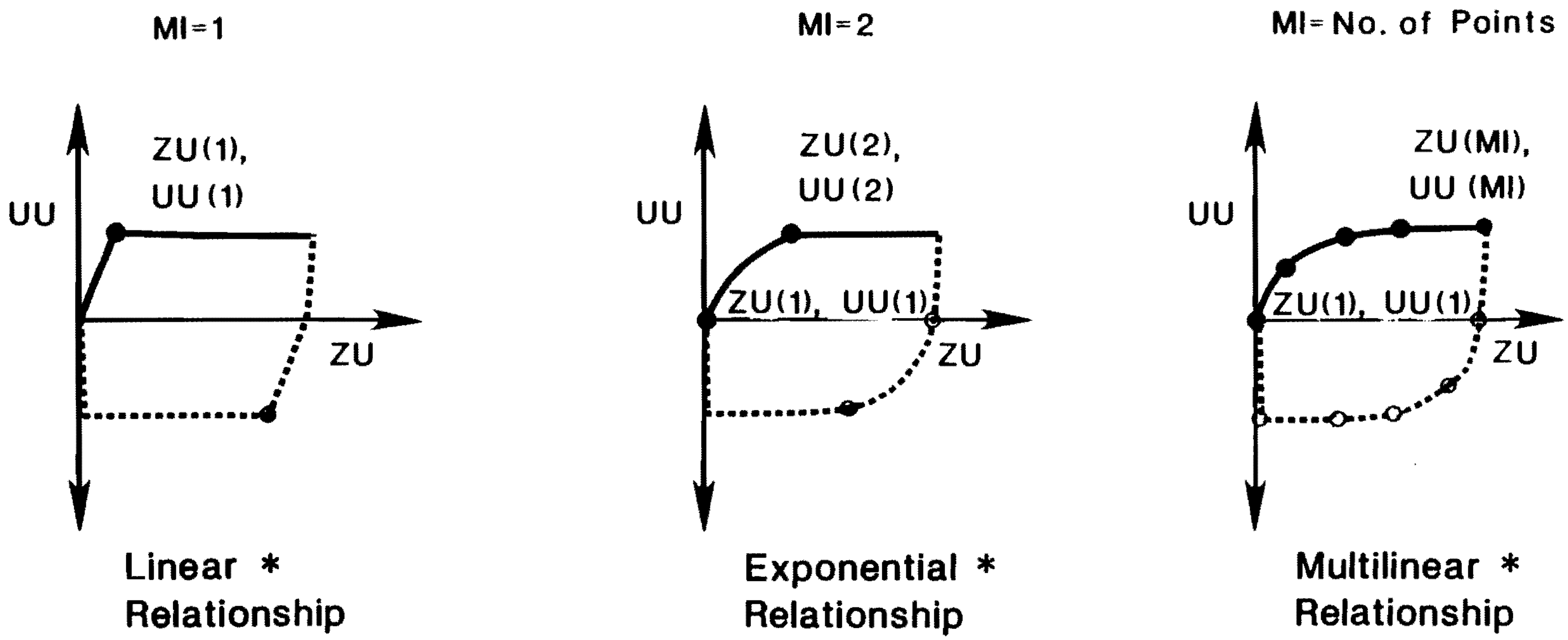
Properties of Slab Support

SK is the variable that defines the modulus of reaction on top of the supporting layer of the slab, in psi per inch of deflection (psi/inch). The determination of this variable can be done from in-place loading tests on the representative supporting layer or from correlation with other field tests or laboratory tests on the supporting base material.

Normally, rigid pavements are provided with one or two base layers of well compacted granular material between the roadbed soil and the rigid pavement. It is costly and sometimes impossible to run plate loading tests on these materials as the loads required to obtain a given deflection on the top layer may be extremely high. To circumvent this difficulty, a method for obtaining the modulus of reaction on top of the upper base layer (composite k-value) has been proposed by Elkins and McCullough (Ref 52), for the design of continuously reinforced concrete pavements (CRCP). The composite k-value can be estimated from the modulus of subgrade reaction, obtained from plate loading tests on the roadbed soil and corrected to account for the effect of as many layers as provided between the subgrade and the slab. This procedure is recommended as a practical method for defining the value of this parameter.

Steel Properties

SS defines the strand spacing in inches. If the program reads a value of zero for this variable, it assumes that steel properties are not required for the problem considered. Likewise, the program assumes that data will not be provided for the category type in which the sequence of post-tensioning applications for the initial period is specified.



* Only the thicker portion of the curve needs to be defined; the thinner portion is generated by the program.

Fig 6.2. Types of friction coefficient versus displacement curves considered by computer program PCP1.

SA represents the nominal area of the tendons in $inch^2$. The tendons commonly specified in PCP are 7-wire strands with 0.6 inch nominal diameter and a nominal area of 0.216 $inch^2$. From this value and the strand spacing, PSCP1 computes the percent reinforcement the steel represents of the pavement cross section.

FPY is the steel yield stress in ksi. A default value of 230 ksi, which is typical of high strength steel, is assumed by PSCP1 if a value for this term is not provided by the user.

ES is the steel elastic modulus in psi. Values between 25×10^6 and 28×10^6 psi are typical of high strength steel working in the elastic range. PSCP1 assumes a default value of 28×10^6 psi if a value is not supplied for this parameter.

ALS defines the steel thermal coefficient. A value of 5×10^{-6} is recommended for use in design. This value is assumed as the default by PSCP1 in case a value is not supplied for this term.

Sequence of Temperature Data for Initial Period

NPER defines the number of pairs of slab middepth temperatures and top to bottom temperature differentials provided at 2-hour intervals, for the initial period.

CURH represents the setting hour in the scale of 0 to 24 hours from which PSCP1 starts the predictions for the initial period of analysis. The program uses this variable as the reference time for evaluating time dependent parameters.

CURTEMP is the variable defining the slab mid depth temperature of the setting hour in degrees Fahrenheit. The program uses this value to determine temperature variations for the time increments of the initial and subsequent periods of analysis.

ADT(I) and TDIF(I) are the variables containing the I^{th} pair of slab middepth temperatures and top to bottom temperature differentials, in degrees Fahrenheit, occurring 2xI hours after the setting hour. Temperature differentials should be positive if the temperature is higher at the top than at the bottom of the pavement. One card should be codified per pair of temperature data.

Values for these variables can be obtained from temperature records of existing concrete pavements in the same climatic zone and with physical characteristics similar to those of the one being designed. One of the predictive models of pavement temperatures based on the theory of heat conduction through semi-infinite masses can also be used for defining these parameters. A model of such nature is presented by Uddin, Nazarian, et al in Ref 41.

Sequence of Post-tensioning Applications During Initial Period

These variables should be provided only if steel properties were specified earlier in the corresponding data category.

NS represents the number of stages in which the total post-tensioning force will be completed.

IAGE and PS(I) represent the time since setting, in hours, and the partial amount of prestress per strand PS(I), in ksi, completed at post-tensioning stage I. One card containing these variables should be codified for each stage of post-tensioning application.

Temperature Data for Subsequent Periods

ITOA is the variable indicating the number of days elapsed since setting to the beginning of the period considered. This variable is also used as a switch for the program to stop execution when PSCP1 has completed the analysis of the time increments of all desired periods of analysis. Hence, a blank card after the last temperature data input of the last period should be used to specify that the program execution is to be terminated.

ADT(I) and TDIF(I) are the variables containing the 12 pairs of middepth and top to bottom temperature differentials, in degrees Fahrenheit, for the 24-hour cycle of the given period. The program assumes that the first data pair corresponds to 8 AM, the second to 10 AM, the third to 12 AM, and so on, until 6 AM of the next morning. One card should be codified per pair of temperature data input.

PSCP1 OUTPUT DESCRIPTION

The output of the PSCP1 Computer Program basically consists of two parts: (1) an echo print of the general data and (2) a report of the profiles of longitudinal movements, friction coefficients, prestress plus friction restraint stresses, curling stresses, and deflections at the bottom of the slab, from midslab to the slab ends. This information is reported for all 2-hour increments of all periods of analysis requested by the user. A complete printout from PSCP1 corresponding to an example problem shown in Chapter 8 is presented in Appendix C. Pavement responses are generated for three periods of analysis in this example.

SUMMARY

A description of the main features of Computer Program PSCP1 has been presented in this chapter, and some of the assumptions considered inside the program have been emphasized. The cost per run of the program depends on the characteristics of the problem analyzed, i.e., the nature of the friction versus movement relationship, the variation of concrete strength with time, the number of periods of analysis specified per run and the number of temperatures input for the initial period of predictions at 2-hour intervals. However, the execution time and related cost depend primarily on the number of elements in which the slab is divided for analysis. A detailed description of the program variables, and input data and an interpretation of the output have also been presented in this chapter. A complete listing of Computer Program PSCP1 is included in Appendix D. The format for inputting data into the program is included in Appendix B. The codification and run of an example problem are shown in Appendix C.

CHAPTER 7. COMPARISON OF PREDICTIONS FROM PCP1 WITH DATA COLLECTED FROM THE McLENNAN COUNTY OVERLAY (WACO)

Equally as important as the development of a model and mathematical techniques for analyzing a problem is the comparison of predictions from the model with real world data. In the first part of this chapter, some background information on the McLennan County Project, located 15 miles north of Waco, is given as is a description of the instrumentation program for monitoring the section. In the second part of this chapter, a statistical analysis is performed on a set of joint openings recorded at different pavement ages and temperatures. Estimates are obtained from this analysis of the following concrete properties:

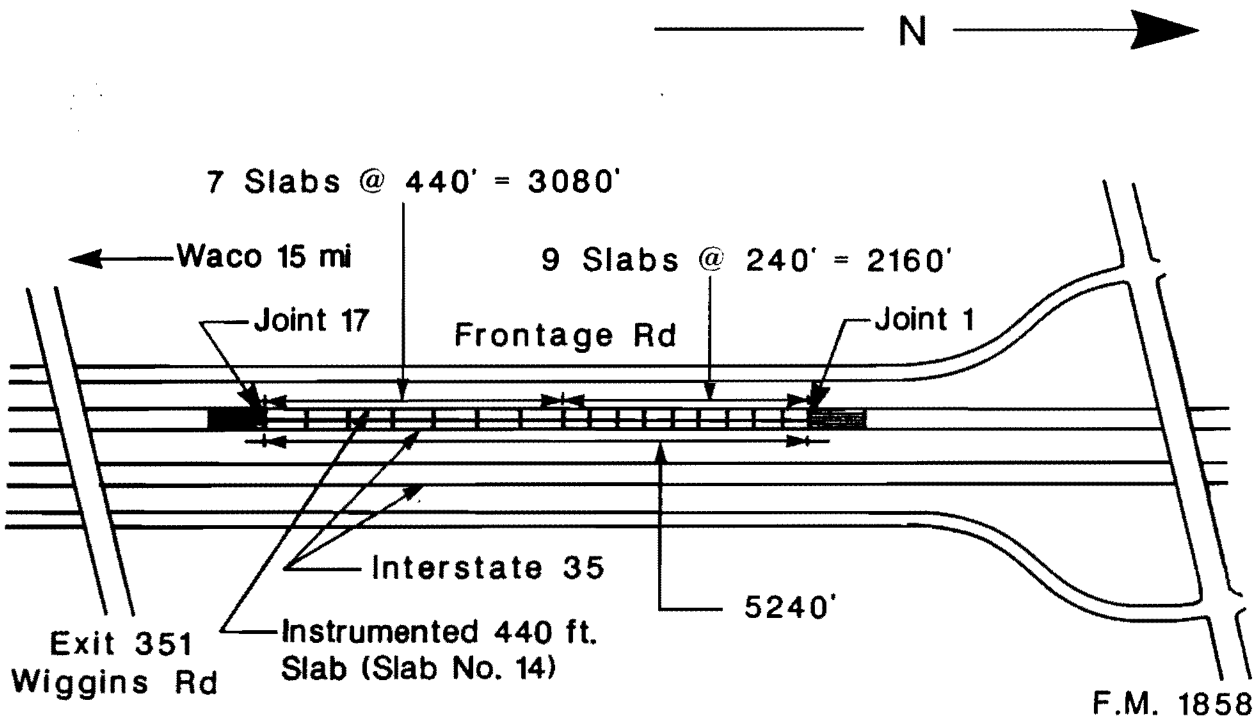
(1) thermal coefficient of contraction and expansion,
(2) ultimate shrinkage strain, and
(3) ultimate creep strain.

This analysis will permit an evaluation of the accuracy of the models inside PCP1 for predicting long term slab movements.

Since the main contribution of this study is the incorporation of the inelastic effect of the friction, the third part of this chapter is devoted to comparing measured and computed longitudinal movements during temperature cycles in which consecutive cycles of slab movements are observed. Moreover, the in-service slab base friction properties of the Waco pavement can be inferred by comparing recorded cycles of movements at Waco with predictions from Computer Program PCP1.

PROJECT BACKGROUND

The experimental prestressed concrete overlay in Waco is located on southbound IH-35 between stations 696+00 and 749+00. Between 17 September and 20 November 1985, eighteen 240-foot and fourteen 440-foot PCP slabs were cast. The arrangement of the slabs in each of the southbound lanes of IH-35 and the locations of the test sections are presented in Fig 7.1. The original pavement consisted of a 12-inch jointed concrete pavement 38 feet width. The jointed pavement was sealed and overlaid with approximately 2 inches of asphalt concrete pavement (ACP); subsequently a single polyethylene layer and 6-inch-thick PCP



Total of 32 Prestressed Pavement Slabs:

9 Prestressed Slabs 240'x21'
7 Prestressed Slabs 440'x21'
9 Prestressed Slabs 240'x17'
7 Prestressed Slabs 440'x17'

Fig 7.1. Location of prestressed slabs along southbound lanes of IH-35.

slabs were placed on top. The slabs were posttensioned by applying the prestress in pockets near midslab. This technique of central stressing was introduced for the first time with PCP in the McLennan County Project. This technique eliminated the use of gaps between adjacent prestressed slabs for the post-tensioning operations. Another innovation in PCP for highways introduced in the McLennan County overlay was the use of prestress in the transverse direction. The need of transverse prestress has been recognized in the past since commonly in-service PCP projects have developed longitudinal cracking (Refs 10 and 11). In addition, the transverse prestress in the Waco Project would keep the longitudinal joint closed as the tendons of the transverse prestress would be continuous into adjacent slabs accross the longitudinal joint. The PCP overlay in Waco was opened to traffic in December 1985. The design and construction of the overlay is reported by Mendoza, McCullough, et al in Ref 4.

Since construction of the Waco Project, the pavement has been continuously instrumented and monitored. An instrumentation plan for the pavement is presented in Ref 4, and the testing program and the set of recorded data are reported by Maffei, Burns, et al (Ref 53). In general, the instrumentation scheme implemented in Waco consisted of short term instrumentation and long term instrumentation. In turn, the short term instrumentation consisted of continuous recordings that necessitated the use of an electronic data acquisition system. Voltage signals from thermocoples and displacement transducers were recorded by the data acquisition device over several daily temperature cycles. Thermocouples were used to monitor both ambient and concrete temperatures. Slab movements were monitored using displacement transducers mounted along the pavement edge.

Most of the long term measurements consisted of mechanical measurements of joint width at all transverse joints. These measurements were taken between reference marks on each side of the joints using calipers and extensometers. A record of joint width accross all joints with time and temperature constituted the best source of information for evaluating the concrete properties relevant to this study. For this evaluation, a regression analysis was performed on the joint openings. A description of the analysis, the data setup, and the conclusions from the analysis are presented in the following section.

REGRESSION ANALYSIS OF THE JOINT WIDTH DATA

Regression analysis is a powerful statistical tool for identifying relationships among variables. The relationship is formed through an equation relating a dependent or response variable to more than one independent or explanatory variable.

The main purpose of the analysis shown herein is to determine the values of concrete thermal coefficient and ultimate shrinkage and creep strains and to evaluate the reliability of the models inside PCP1 for predicting long term movements. The data set used in this analysis corresponds to the joints of the inside lane slabs which were constructed first, in the direction north to south. The joint openings were recorded between 20 September and 10 December, 1985. Hence, inherent in the movements are shrinkage and creep deformations which for the most part occur during the first three months of the pavement for normal concrete mixes, such as the one used in Waco.

The pavement joints were numbered sequentially from 1 to 17 from north to south. Number 1 was assigned to the joint on the section north end and 17 to the section south end. The joint openings used in this analysis are reported following the nomenclature in Appendix E. As may be evidenced from Fig 7.1, the movements of Joint 1 result from the movements of one 240-foot slab. The movements of Joints 2 to 9 result from the contraction and expansion of two 240-foot slabs. The movements of Joint 10 are the result of the movements of a 240-foot slab and a 440-foot slab. Joints 11 to 16 move as a result of contraction and expansion of contiguous 440-foot slabs. Finally, the movements of Joint 17 result from the movements of one 440-foot slab.

The combined data set used in this analysis is comprised of 51 points. The data set is reported in Appendix E. Figure 7.2 shows a plot of change in joint opening from the initial width shown by the joints at a reference date, versus the temperature change from the temperature at the reference date. The date at which the first opening was taken for a given joint was defined as the reference date for the joint. Generally, the first opening reading for each joint was taken within the first 48 hours after construction of contiguous slabs when the final prestress had been applied on both slabs. In Fig 7.2, it is apparent that there is a trend to decreasing joint width with temperature increments. This tendency is obviously more significant in joints between 440-foot slabs than in joints between 240-foot slabs. The effect of time is included in this figure.

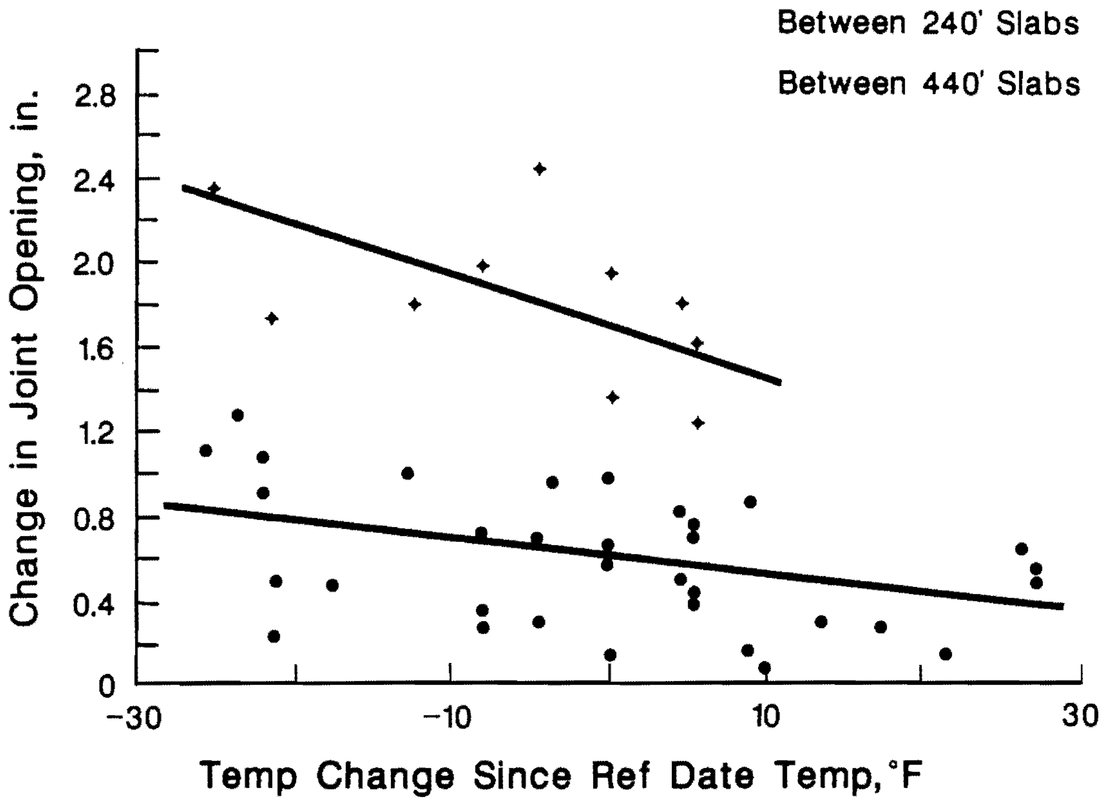


Fig 7.2. Change in joint opening versus temperature change with respect to temperature of the reference data (all joints of the Waco prestressed overlay).

Figure 7.3 shows the same data plotted, but now as a function of time. The increase of joint opening with time is evident from the chart. The rate of increase is obviously larger for joints between 440-foot slabs than for joints between 240-foot slabs. The effect of temperature variations is included in this chart.

In order to separate the effect of temperature and time in the joint openings, a model of the following form was specified in the forward regression procedure of the SPSS computer package (Ref 54):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + U \tag{7.1}$$

where

$\underline{Y}$ = vector of observed joint opening change from joint opening observed at reference date,

$\underline{X}_1$ = vector of observations on the explanatory variable associated with the temperature variation effect,

$\underline{X}_2$ = vector of observations on the explanatory variable associated with time dependent effects, i.e., shrinkage and creep,

$\underline{U}$ = vector of stochastic disturbances, and

β_0, β_1, and β_2 = parameters of the model.

Estimates of the regression coefficients β_0, β_1 and β_2 can be obtained based on the sampled values of Y and the independent variables X_1 and X_2 defined as follows. Given that the relationship between joint movement and temperature change is a linear one, the X_1 value for every observation was computed from the following transformation relationship:

$$X_1 = 12 \bullet \Delta T \bullet L \tag{7.2}$$

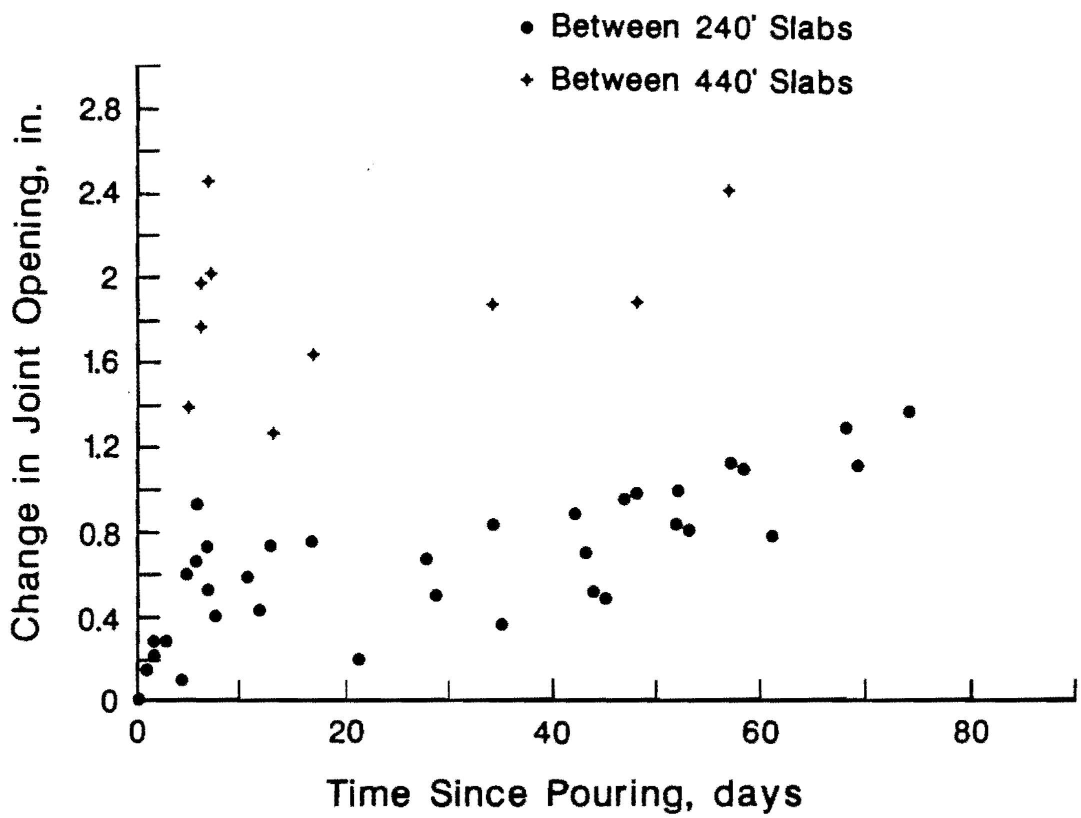


Fig 7.3. Change in joint opening versus time since pouring (all joints of the Waco overlay).

where

ΔT = temperature change, in degrees Fahrenheit, with respect to the reference temperature of the joint,

L = summation of slab halves at both sides of the joint considered, in feet.

The transformation relationship for the explanatory variable X_2, associated with time dependent effects, should have the form of the equations for evaluating creep and shrinkage, shown in Chapter 5 and Appendix A, respectively. After attempting a regression equation with a transformation function similar to the one shown for shrinkage, a better result was obtained with an expression similar to the one for creep:

$$X_2 = \frac{12 \bullet L}{\frac{10}{t^{0.60}} + 1} \qquad (7.3)$$

where

L = as defined before, and

t = time since reference date, in days.

The estimated equation using SPSS is

$$Y = 0.02355 - 4.22 \times 10^{-6} X_1 + 6.291174 \times 10^{-4} X_2 \qquad (7.4)$$

Namely,

$$Y = 0.02355 - 4.22 \times 10^{-6} \bullet (12 \bullet T \bullet L) + 6.291174 \times 10^{-4} \bullet \frac{12 \bullet L}{\frac{10}{t^{0.60}} + 1} \tag{7.5}$$

The statistical characteristics of the regression model that directly indicate the goodness of fit are summarized in Table 7.1. The coefficient of partial determination R^2, representing the proportion of sum of squares in the dependent variable Y explained by the regression equation, is relatively high ($R^2 = 0.8534$). This statistic, together with the small standard error for residuals (0.23) indicates a fairly adequate goodness of fit.

The statistical significance of the independent variables X_i can be tested using a t test. In Table 7.1, the t statistic for each estimator of the β parameters is reported. The null hypothesis Ho: $\beta_i = 0$ may be tested against the alternative hypothesis $H_1: \beta_i <> 0$. The null hypothesis for a given coefficient β_i can be accepted at the 5 percent level of significance if the absolute value of the reported t statistic in Table 7.1 lies between the confidence interval given by the positive and negative t value read from the t distribution for 48 degrees of freedom (number of observations minus number of estimated regression coefficients). The corresponding t value from a t distribution table is 2.001. Hence, the following conclusions can be reiterated from the tests:

(1) $\beta_0 = 0$ since $t_{\beta 0}$ is lower than 2.001. Such a result is obvious as the existence of a constant term β_0 would not be logical in a relationship in which Y represents change in joint width with respect to the joint width observed at the reference date.

(2) β_2 and $\beta_3 <> 0$. This result supports the statistical significance of temperature and shrinkage and creep effects in the joint movements.

The analysis shown above gives estimates of the concrete thermal coefficient of contraction and expansion and the combined ultimate strain due to shrinkage and creep. These terms are the parameters β_1 and β_2 in model 7.1, respectively. A thermal coefficient of 4.22×10^{-6} inch/inch-^{o}F is fairly normal for the limestone river gravel aggregate concrete used for the McLennan County overlay. An ultimate strain for the combined effect of shrinkage and creep of 6.2911×10^{-4} inch/inch is also very reasonable as the ultimate strain of each separated factor should be in the order of 3×10^{-4} inch/inch as indicated in the description of the PCP1 Computer Program input variables in Chapter 6.

Final observations regarding the analysis shown above are the following:

(1) It was not possible to obtain separate estimates of ultimate shrinkage and creep strains as the observations started being recorded after the total prestress had been applied. The effect of shrinkage and creep is, therefore, combined in the recorded joint widths. If some readings had been taken before prestress forces were applied in the slab, the effect of creep would not be included in some of the data. In this case, by contrasting joint widths before and after creep strains had occurred, it would have been possible to make a separate evaluation of these parameters.

(2) When regression model 7.1 was run defining the term X_2 similarly to the shrinkage model shown in Appendix A, the R^2 statistic of the regression decreased to 0.825 from the 0.8534 obtained for the term X_2 defined in a form similar to the creep equation (Eq 7.3). Likewise, the standard error of the residuals increased from 0.23 to 0.281. The term X_2 was defined in this case for each observation as follows:

$$X_2 = \frac{12 \bullet L}{\frac{26e^{0.36D}}{t} + 1} \tag{7.6}$$

where

L and t are as defined earlier, and

D = slab thickness in inches.

This shows that the creep model represents the collected data more faithfully than the shrinkage model. However, the statistics indicating goodness of fit are fairly adequate in both cases (high R^2 and low standard errors). Hence, it can be concluded that the shrinkage and creep models are fairly reliable. Graphical evidence of this is provided in Fig 7.4 in which the data points, after removing the temperature effect, are plotted together with the estimated term for $\beta_2 \bullet X_2$ in Eq 7.5. From this chart, it is evident that the creep model inside PCP1 would provide reasonable predictions of time dependent movements of the joints. The same conclusion is valid for the shrinkage model.

COMPARISON OF RECORDED CYCLES OF MOVEMENT VERSUS PREDICTED MOVEMENTS FROM COMPUTER PROGRAM PCP1

In this part of the analysis, joint movements measured over several daily temperature cycles are compared with the corresponding predictions from Computer Program PCP1. The recorded movements were obtained from 48-hour sessions of electronic instrumentation installed in a 440-foot slab at Waco. Data for the 240-foot slabs are reported by Maffei, Burns, et al (Ref 53) and their analysis may lead to conclusions very similar to those obtained herein.

The third 440-foot outside lane slab from south to north (slab No. 14 in Fig 7.1) was instrumented in February and April 1986, two and four months respectively after being constructed. During the first session of readings, thermocouples were placed in the outside lane shoulder, one embeded in the concrete at middepth and the other in the shade outside the slab. The locations of the thermocouples along the slab length are illustrated in the sketch at the top of Fig 7.5. Figure 7.5. shows plotted ambient and concrete temperatures (in °F) versus hour of the day. Slab movements were measured (at the same times as temperatures) through displacement transducers mounted along the pavement edge in two locations: the slab end and 55 feet from the end toward the center. The transducers' locations are illustrated in the diagram at the top of Fig 7.6. In this figure, the trend of recorded movements versus the time of the day is shown. Two facts are relevant from a joint analysis of Figs 7.5 and 7.6:

(1) The maximum temperature rise for the first cycle occurs between 8 AM and 4 PM. The slab middepth temperature increases from 59.5 °F up to 69.5 °F or a temperature increase of nearly 10 °F in Fig 7.5. Between these hours, the

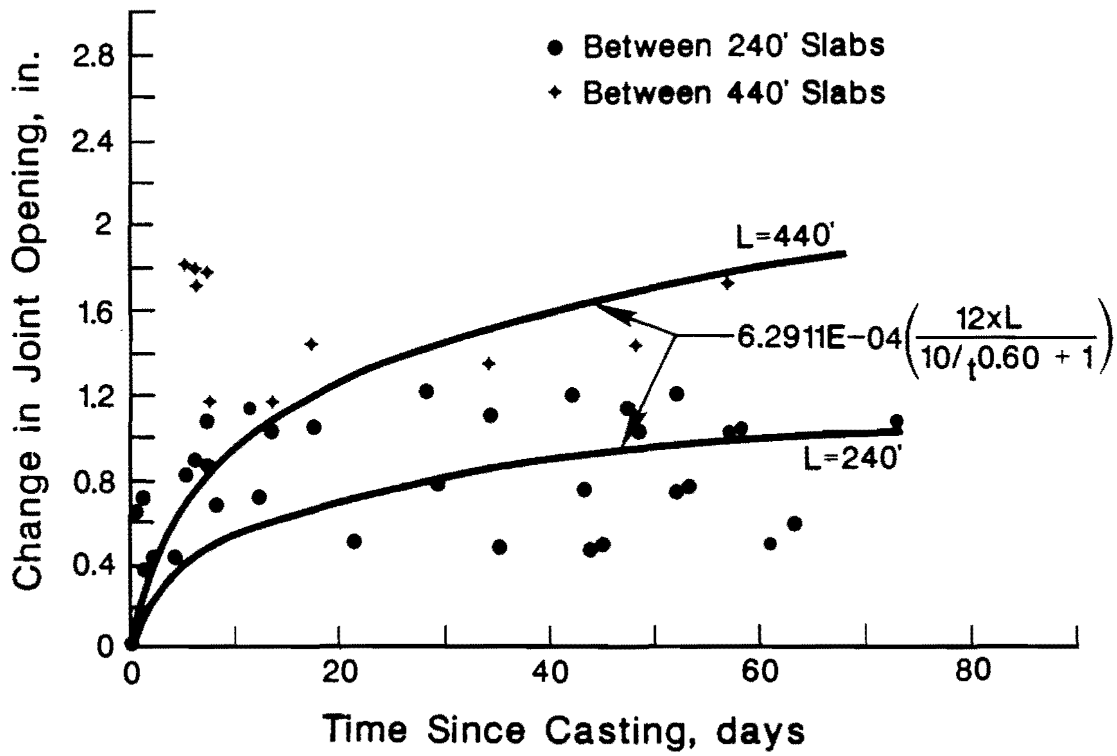


Fig 7.4. Comparison of actual and predicted change in joint opening versus time.

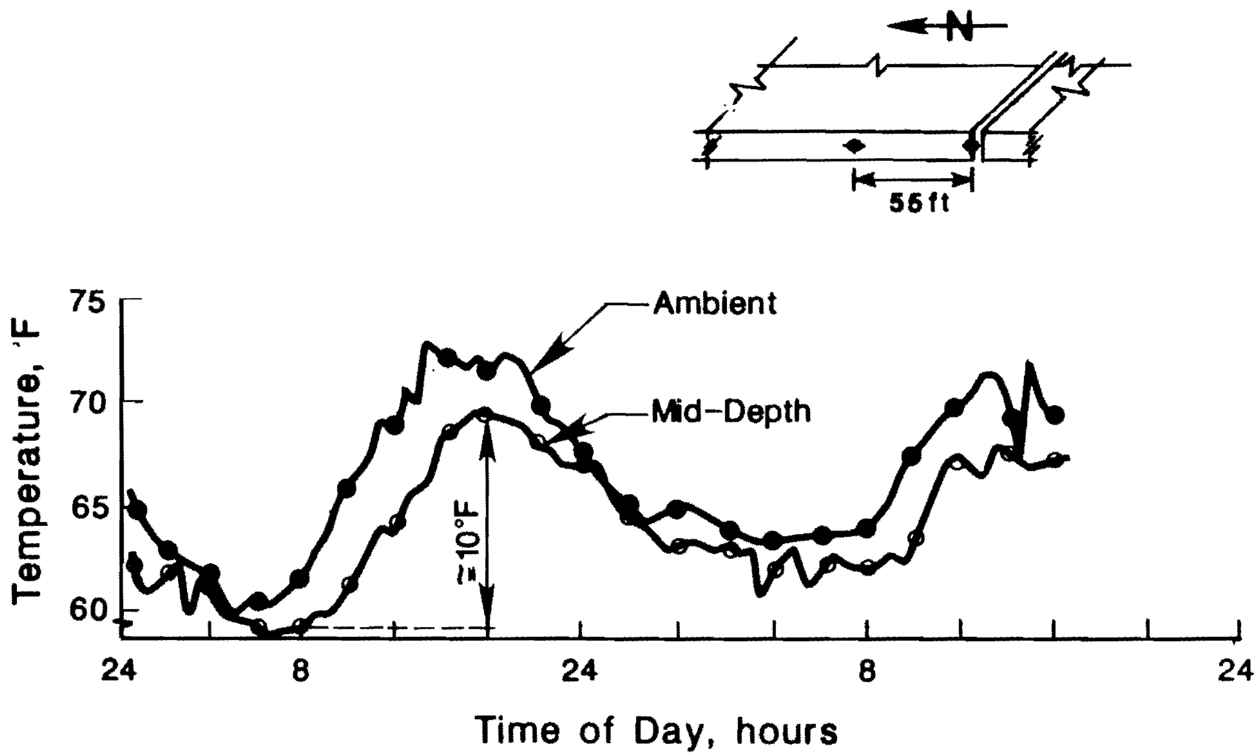


Fig 7.5. Ambient and slab temperature cycles recorded in Waco for 440-foot slab (February 1986).

recorded expansion of the slab end point is in the neighborhood of 0.10 inch, as may be observed in Fig 7.6. This expansion corresponds closely to the unrestrained movement of the slab end point, which can be determined as follows:

$$Z_e = \frac{\alpha \bullet \Delta T \bullet L}{2} \quad (7.7)$$

where

α	=	concrete thermal coefficient
	=	4.22×10^{-6} inch/inch-$^{\circ}$F as determined earlier,
ΔT	=	temperature change
	=	10 °F,
L	=	slab length
	=	440 x 12 = 5280 inches.

For these data,

$$Z_e = 0.11 \text{ inch.}$$

From these measurements, it may be observed that the slab is developing much lower friction coefficients than those assumed in the design of the slabs (Ref 4). The friction coefficient versus displacement curve used in the design is the one shown in Fig 3.4 (Chapter 3) for a single polyethylene film. If this curve is input into PCP1 together with the temperatures in Fig 7.5 and the concrete thermal coefficient and ultimate shrinkage and creep strains evaluated above, the trends of computed movements for the points being analyzed are those shown in Fig 7.7. It may be noticed that the computed movements are significantly lower than the actual movements. This provides further evidence that actual friction coefficients should be lower than those assumed in design.

Displacement vs Time

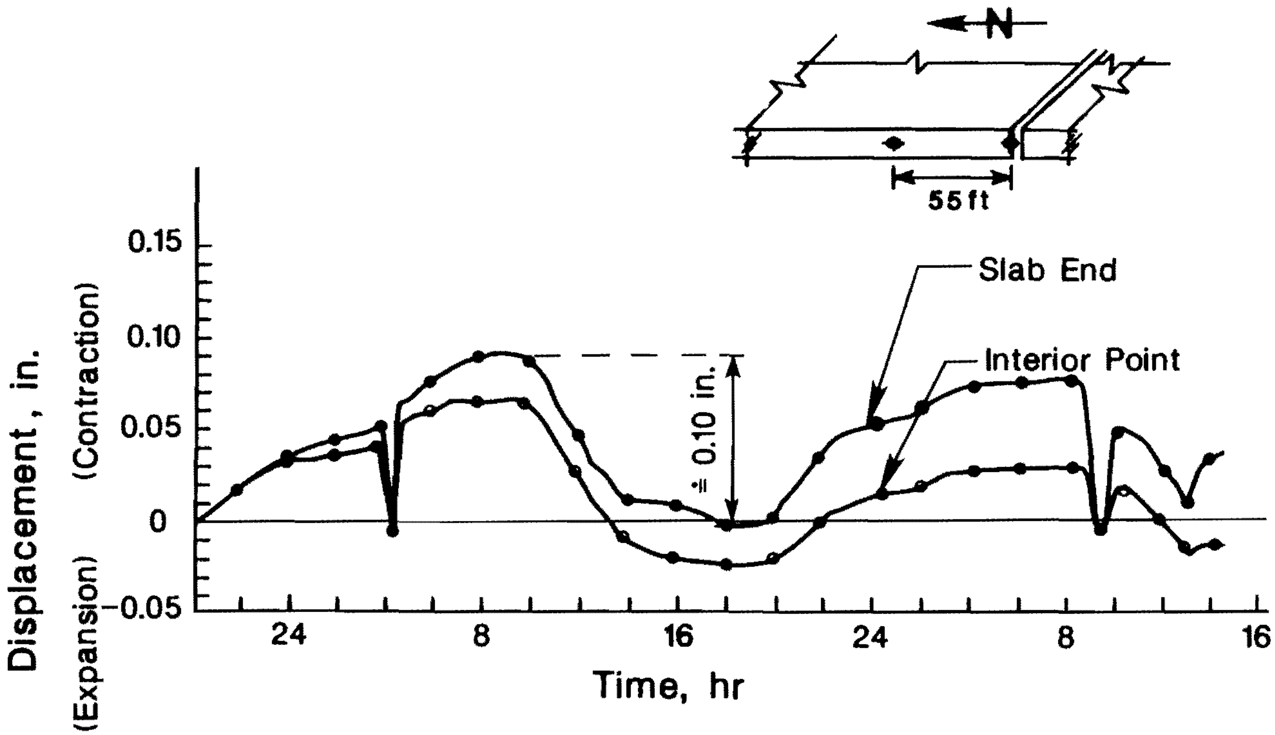


Fig 7.6. Cycle of movement for end and interior points of the slab. Slab number 14 (February 1986).

Computed Displacement vs Time

(For Single Film of Polyethylene Friction Properties)

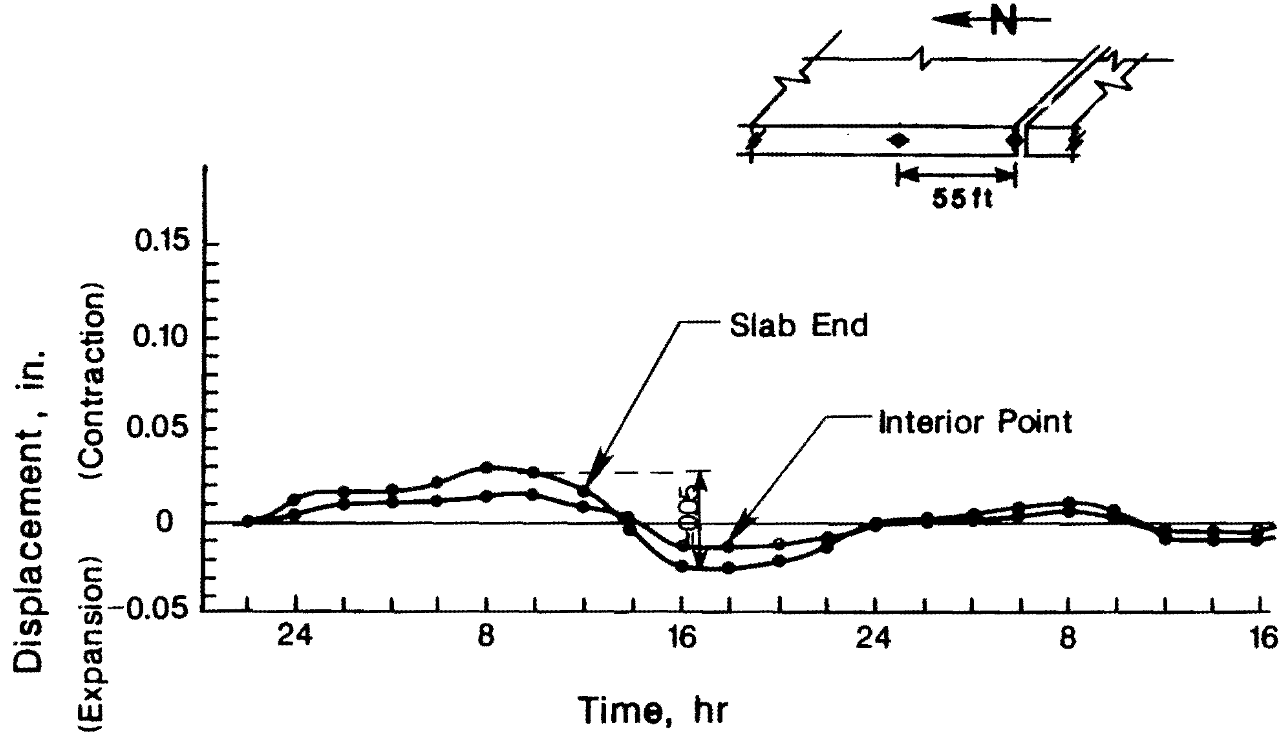


Fig 7.7. Cycle of computed movements from computer program PCP1, for the friction characteristics of a single film of polyethylene.

In an attempt to match the 0.10 inch of end expansion movement observed between 8 AM and 4 PM, the friction coefficients from Fig 3.4 had to be decreased approximately 80 percent. The maximum friction coefficient was, therefore, reduced from 0.96 to nearly 0.20. The movements computed from PCP1 for the reduced friction condition are presented in Fig 7.8. It should be noticed that the predictions of displacement of the interior point (55 feet from the end) compare reasonably well with the observed displacements for the same point in Fig 7.6. Computed and measured movements of the interior point for the same session of recordings can be better compared from the plot in Fig 7.9. Alternatively, for the slab end point, the comparison between actual and predicted movements is poor as actual movements of the slab end are significantly affected by creep and shrinkage. This may be evidenced in Fig 7.10 showing computed versus measured movements for the slab end point.

(2) The fact that the movement curve for the slab end point in Fig 7.7 separates continuously with time from the interior point movements indicates that creep and shrinkage deformations are more substantial near the slab ends, where the prestress force is exerted with more intensity. This effect is not considered by the PCP1 computer model.

SUMMARY

This chapter has presented a regression analysis on a set of joint-opening data collected in Waco since construction of the PCP experimental section. From this analysis, estimates have been obtained of the concrete thermal coefficient of contraction and expansion, and ultimate shrinkage and creep strains. Likewise, the accuracy of the models inside PCP1 for predicting long-term movements due to creep and shrinkage has been evaluated from this analysis

In a subsequent section of this chapter, measured and computed cycles of longitudinal movement have been compared. It has been observed that the movements of a 440-foot long slab have occurred scarcely restrained by the friction. A maximum friction coefficient of around 0.2 has been determined to match the cycle of predicted movements from PCP1 to the recorded movement. Maffei, Burns, et al (Ref 53) have back calculated the maximum friction

Computed Displacement vs Time
(Reduced Friction Condition)

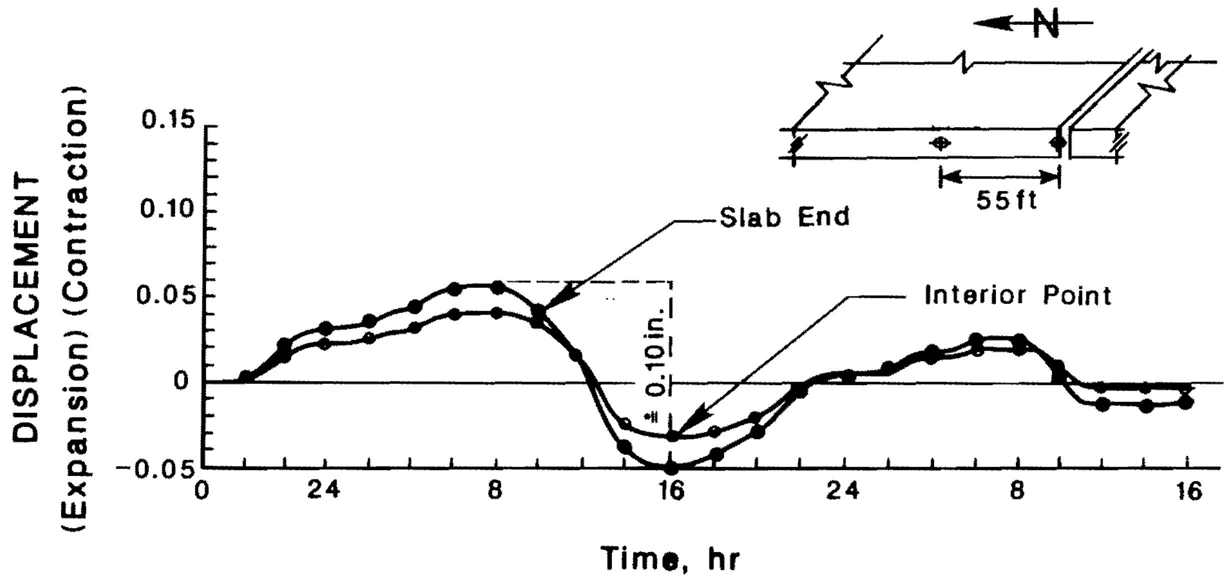


Fig 7.8. Cycle of computed movements from computer program PSCP1 after reducing the friction coeffficients for a single polyethylene sheeting in 80 percent.

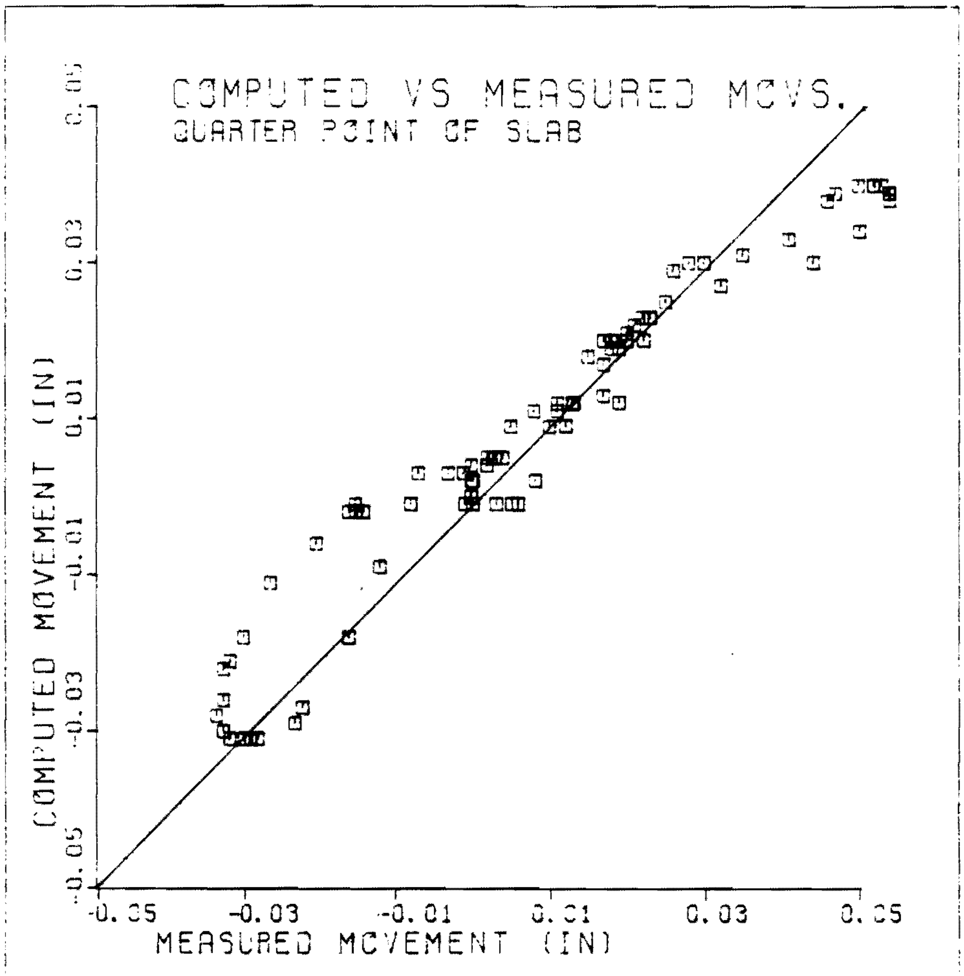


Fig 7.9. Computed movements from PSCP1 versus measured movements at Waco for Slab quarter point.

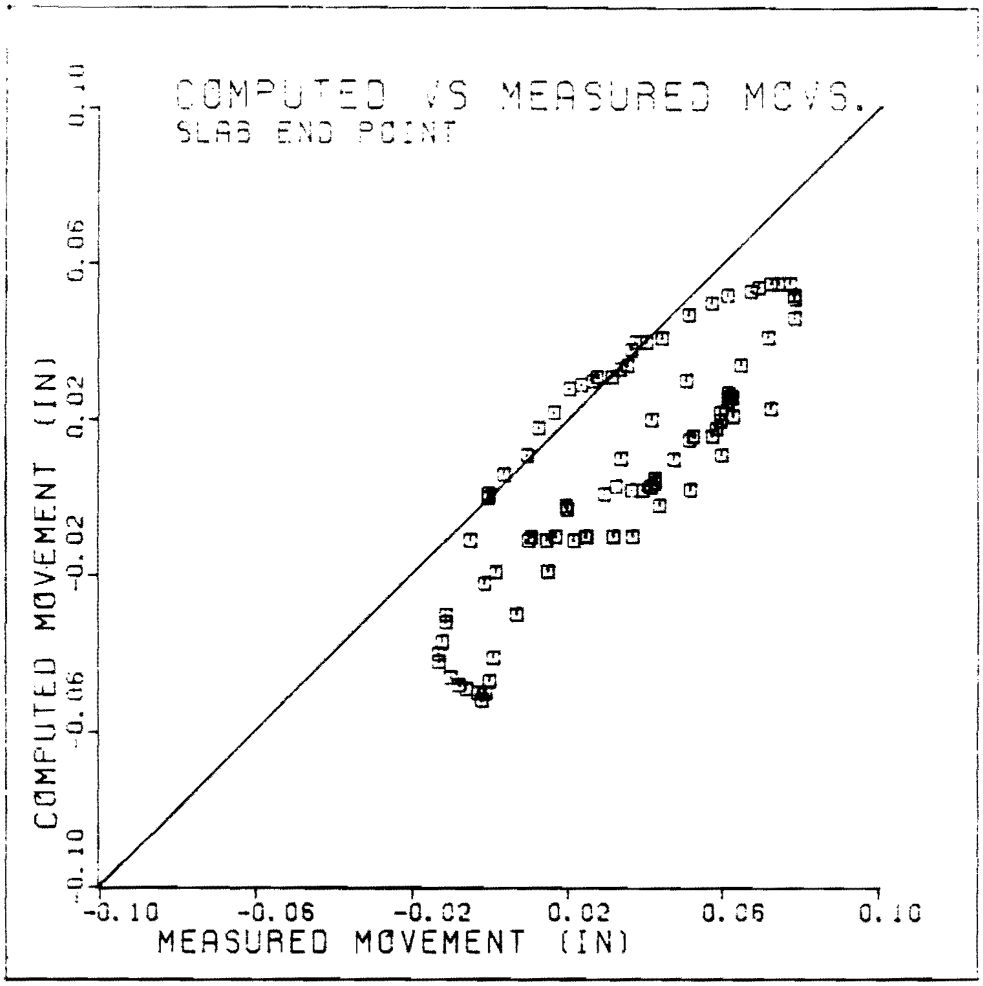


Fig 7.10. Computer movements from PSCP1 versus measured movements at Waco for slab end point.

coefficient under the slabs at Waco from a record of slab displacements taken when the slabs were post-tensioned. They derived a maximum friction coefficient of between 0.45 and 0.5. These figures indicate that, for the same base type and friction reducing membrane, the lowest friction forces develop for the cyclic movements of the daily thermal cycle. A much higher frictional resistance takes place when the slabs are post-tentioned. In both cases, the friction forces are lower than those developing under slabs tested for the first time for noncyclic movements. The experiments conducted in Gainsville, from which the curves in Fig 3.4 (Chapter 3) were obtained, were run for noncyclic movements of the test slabs. These friction coefficients are, then, higher than those under the actual PCP slabs in Waco. The design of the Waco PCP, which was based on the results from the Gainsville tests, is thus conservative.

CHAPTER 8. APPLICATION OF COMPUTER PROGRAM PSCP1 AND DESIGN METHODOLOGY

The purpose of this chapter is to discuss several of the possible applications of computer program PSCP1 in connection with the design parameters considered in this study. Hence, a scheme for a design methodology is presented in the first part of this chapter. This methodology primarily considers the design of PCP slabs for overlay applications as this is the primary objective of CTR Research Project 401. In the second part of this chapter, a complete design example is developed.

DESIGN METHODOLOGY

The design methodology proposed herein embraces two basic stages. In the first stage, the thickness, length, prestress level, amount of prestress losses, and strand spacing of PCP slabs are defined. Particularly important in this stage is the analysis of the slab stresses developing during time periods close to the end of the design life when most prestress losses have occurred and the pavement experiences minimum levels of prestress. Equally important in this stage is the prediction of total joint opening for these final time periods.

The second stage deals with the development of a rational strategy for application of the prestress level defined in the first stage. The study of the stresses occurring during an initial time period is primarily important in this stage.

Stage 1 of Design Methodology

Based on the design principles described in Chapter 2, the steps that may be used in this stage of the design methodology can be summarized as follows:

Step 1. Define an initial thickness and prestress level to cover the fatigue requirements of the section. This aspect is generally ignored by past design procedures though its importance is fundamental, as addressed in Chapter 2. The use of Figs 8.1, 8.2, 8.3, and 8.4 is proposed in this study to obtain initial estimates of these parameters. These charts are solutions for PCP overlays cast over 8 to 12 inch concrete pavements respectively (jointed or CRCP). Figures 8.1 and 8.2 consider an existing pavement with an elastic modulus of 1 million psi by the time of overlay. In Figs 8.3 and 8.4, the original pavement is considered as

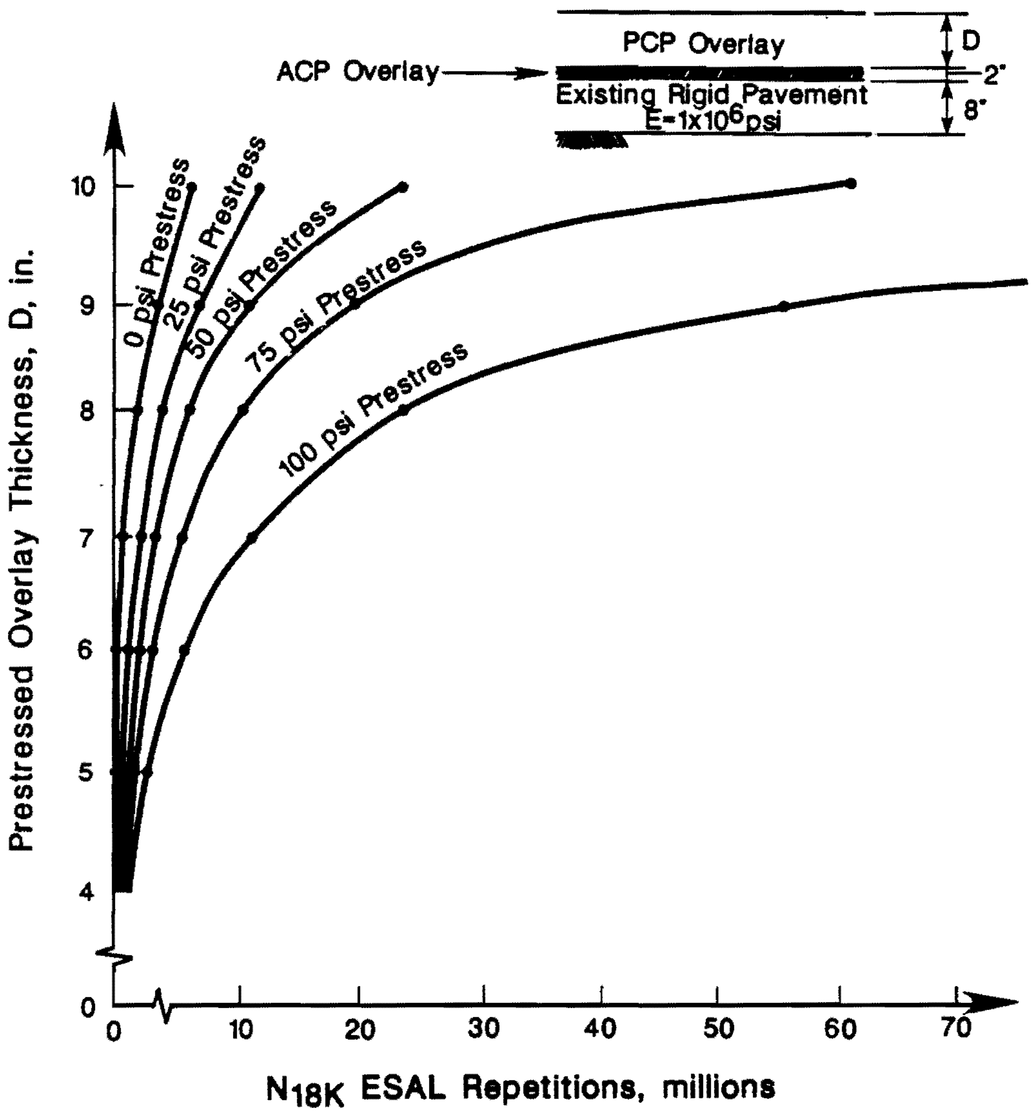


Fig 8.1. Design chart based on fatigue for PSCP overlay over 8 inch rigid pavement. Poor structural conditions of existing rigid pavement.

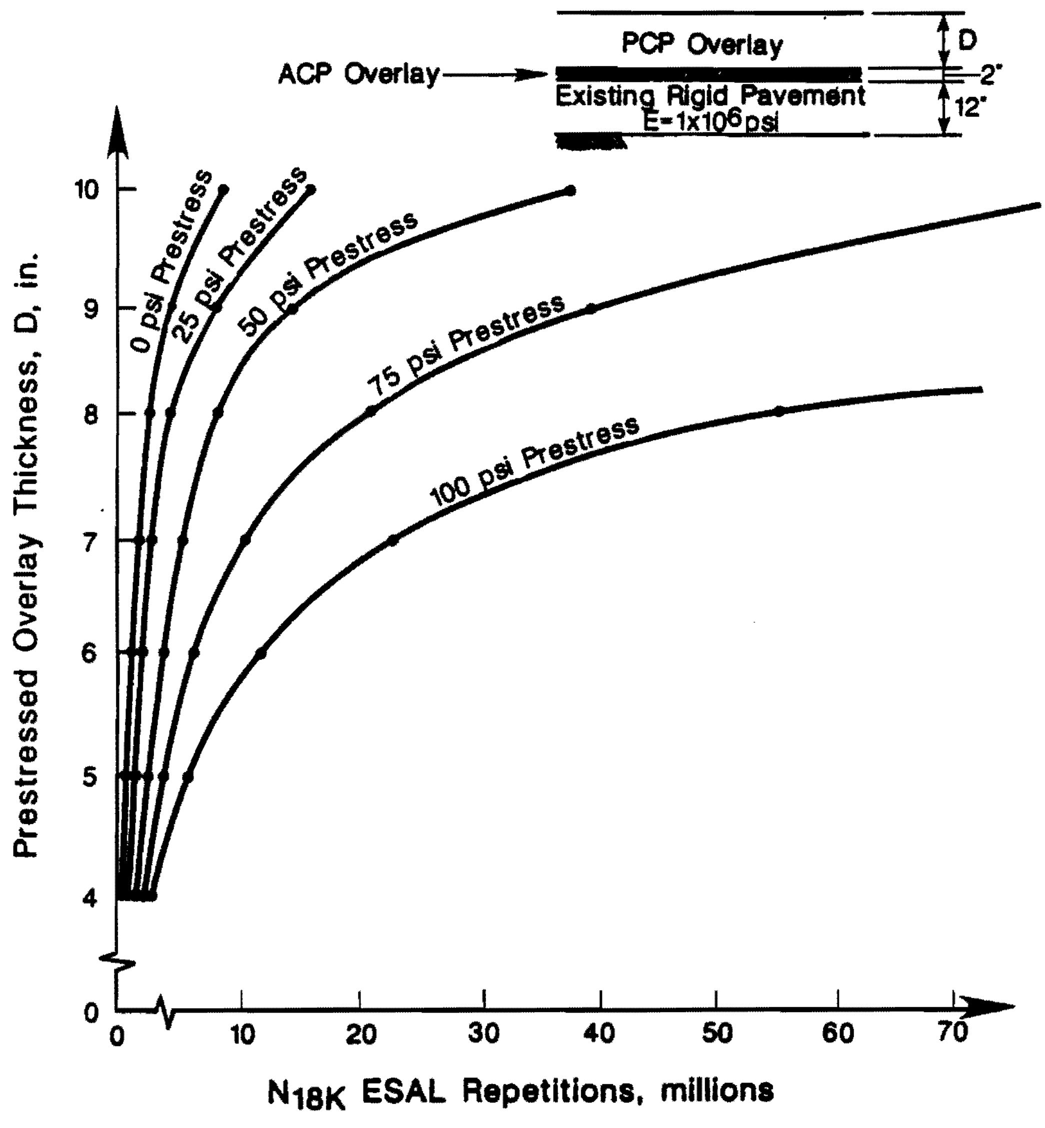


Fig 8.2. Design chart based on fatigue for PSCP overlay over 12 inch rigid pavement. Poor structural condition of existing rigid pavement.

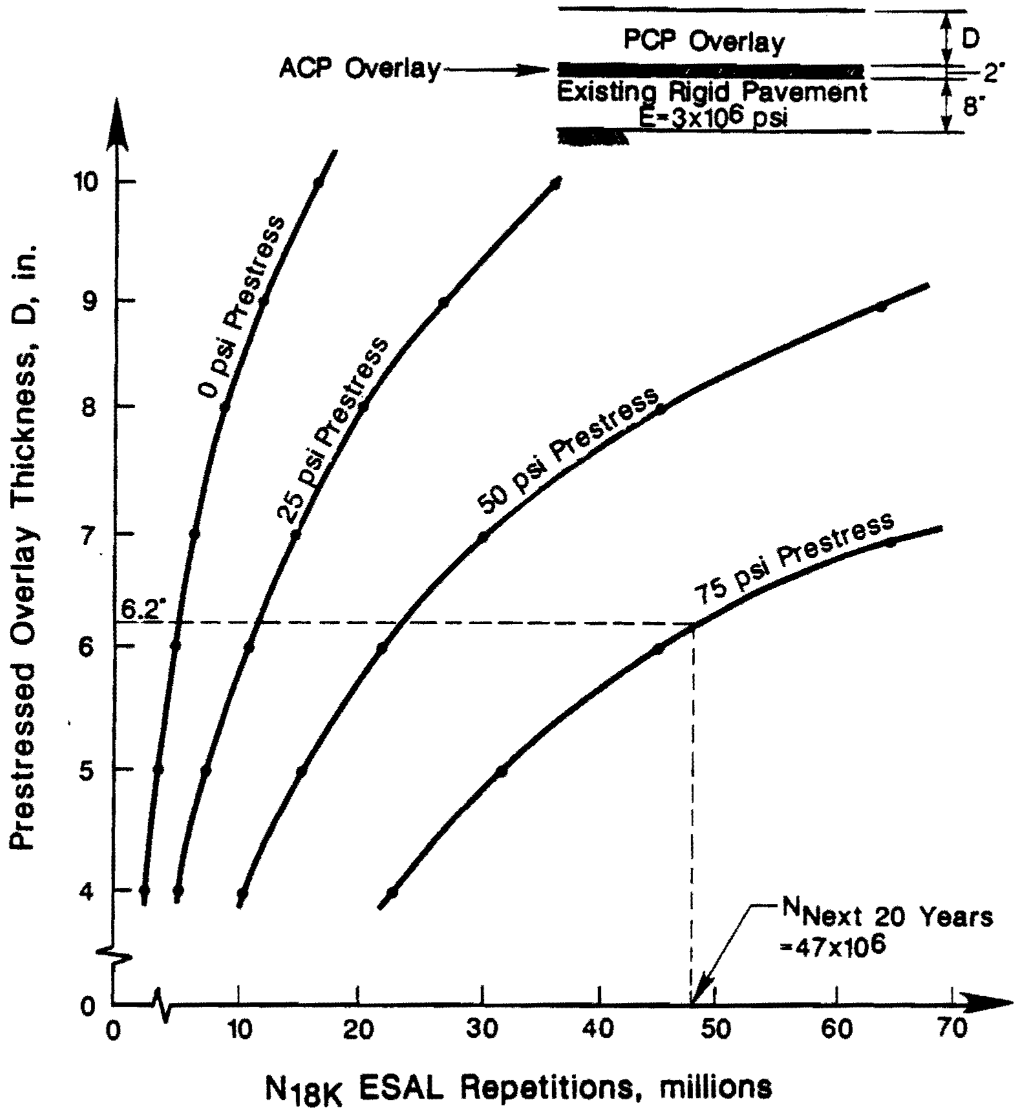


Fig 8.3 Design chart based on fatigue for PSCP overlay over 8 inch rigid pavement. Good structural condition of existing rigid pavement.

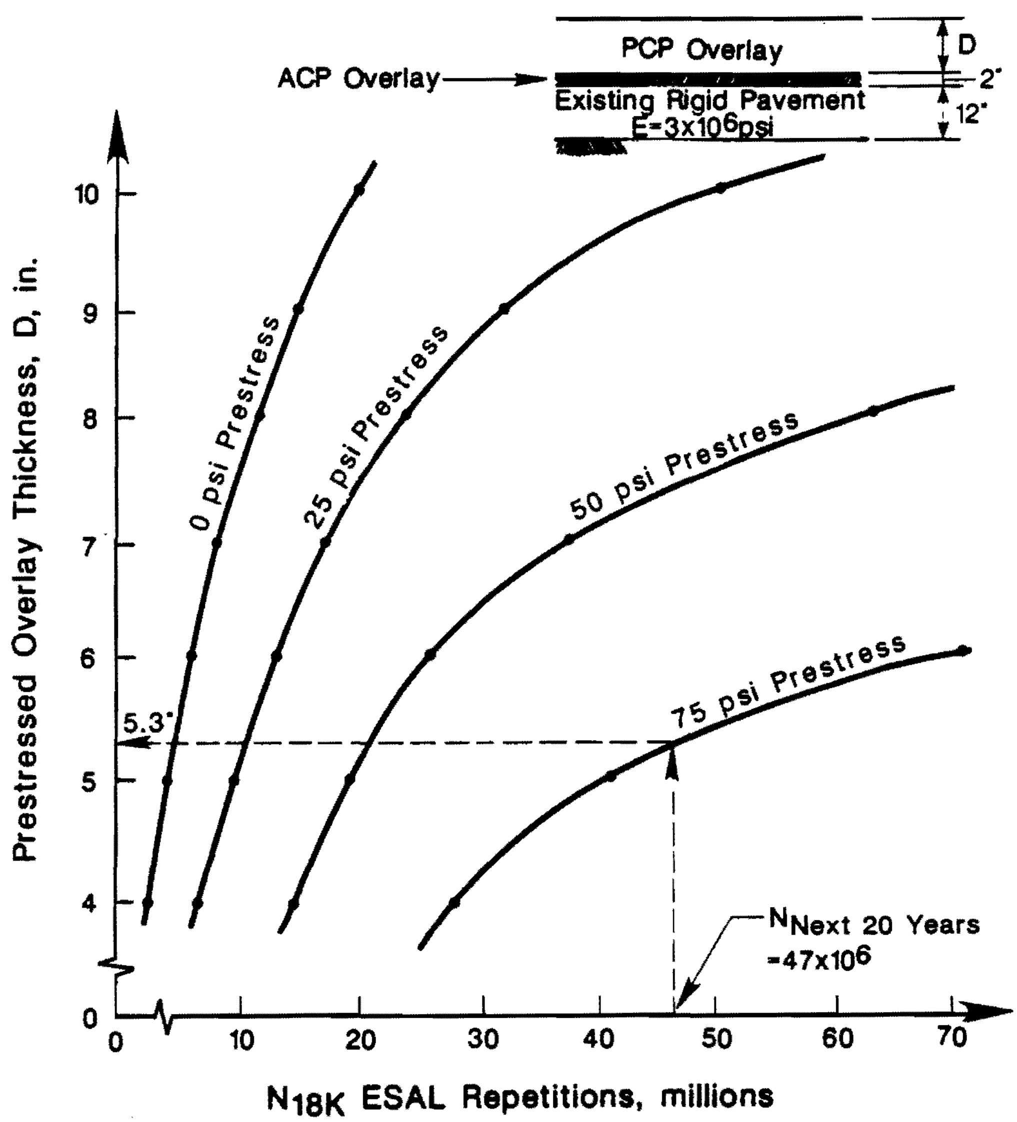


Fig 8.4 Design chart based on fatigue for PSCP overlay over 12 inch rigid pavement. Good structural condition of existing rigid pavement..

having an elastic modulus of 3 million psi. Most rigid pavements should exhibit elastic moduli within this range by the time a major rehabilitation is needed. Methods for evaluating the elastic properties of in-service rigid pavements, prior to overlaying, are discussed in Ref 4. The solutions in Figs 8.1 to 8.4 assume that a 2-inch ACP layer is provided between the old pavement and the prestressed overlay. The use of this layer is essential to patch and seal the old pavement, provide a uniform support for the overlay, and avoid the risk that cracking of the old pavement may propagate to the PCP. Full slip at the interface between the PCP and the ACP was assumed in the development of these charts for this is the effect produced by the introduction of friction relieving interlayers at the interface. These charts cover the thickness range of most existing Texas pavements. Overlays in design conditions intermediate to those considered by Figs 8.1 to 8.4 can be designed by interpolation between the results of designs from these charts.

The procedure followed to develop the design charts in Figs 8.1 to 8.4 is presented in great detail in Ref 4. It consisted of the application of multi-layered elastic theory to determine the stress levels produced by a standard 18-kip ESAL at the bottom of overlays of different thicknesses. Then, the stress levels thus obtained were reduced by imposing different slab prestress levels. These reduced stresses were subsequently input into a fatigue relationship for jointed pavements to obtain the curves in each figure.

Step 2. Assume an initial slab length which,in the designer's judgement, may result in final joint openings of less than 4 inches for the overlay site environmental conditions. Lengths commonly used vary between 200 and 500 ft. The chart in Fig 8.5 may be used to get an initial estimate of this parameter. This chart was used in the selection of the slab lengths of the McLennan County overlay. It was developed from slab end movements recorded in the Virginia, Arizona and Mississippi Projects (Refs 8, 10, and 11). The development of this chart is documented by Mendoza, McCullough, and Burns in Ref 4.

In a subsequent step in this procedure, the length assumed in this step will be checked with the more accurate predictions from computer program PSCP1.

Step 3. As mentioned in Chapter 2, the tensile stress at the bottom of the pavement due to traffic loads is an input to the elastic design of PCP slabs. To estimate this stress, Figs 8.6, 8.7, 8.8 and 8.9 can be used. These figures were obtained by running BISAR (Ref 55) on the model presented at the top of each figure. BISAR was selected for developing these charts because it allows for specifying a variable amount of slip at the interface between the PCP and the ACP. Full slip at the interface was assumed in these charts to include the effect of using

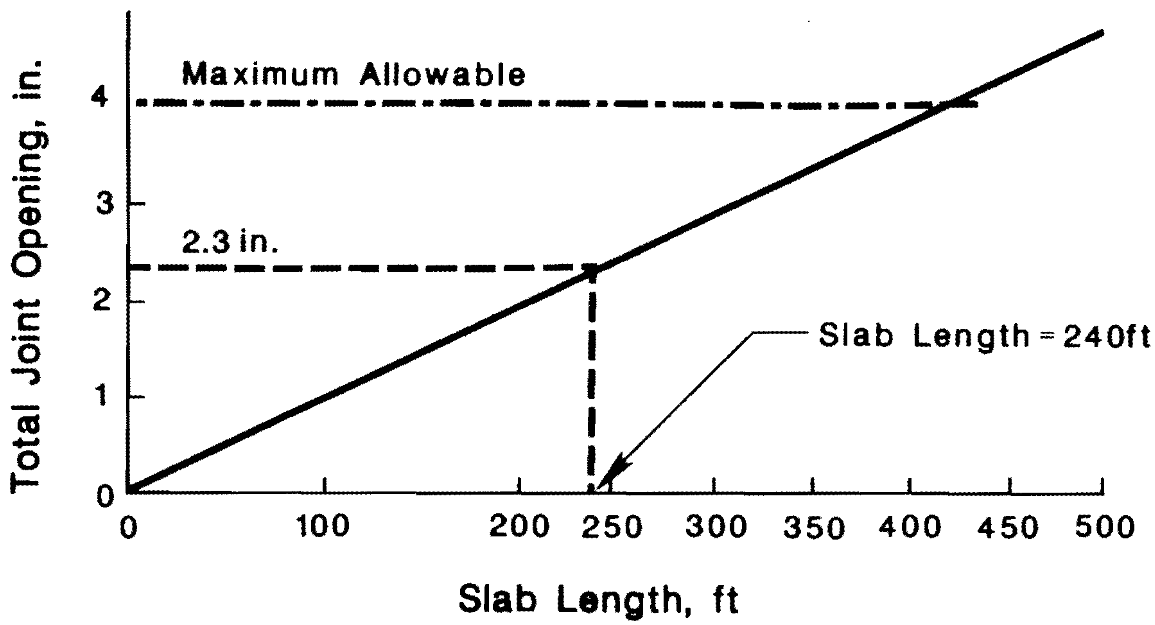


Fig 8.5. Expected joint opening versus slab length from slab end movements recorded in the Virginia, Arizona, and Mississippi projects (Refs 8, 10, and 11).

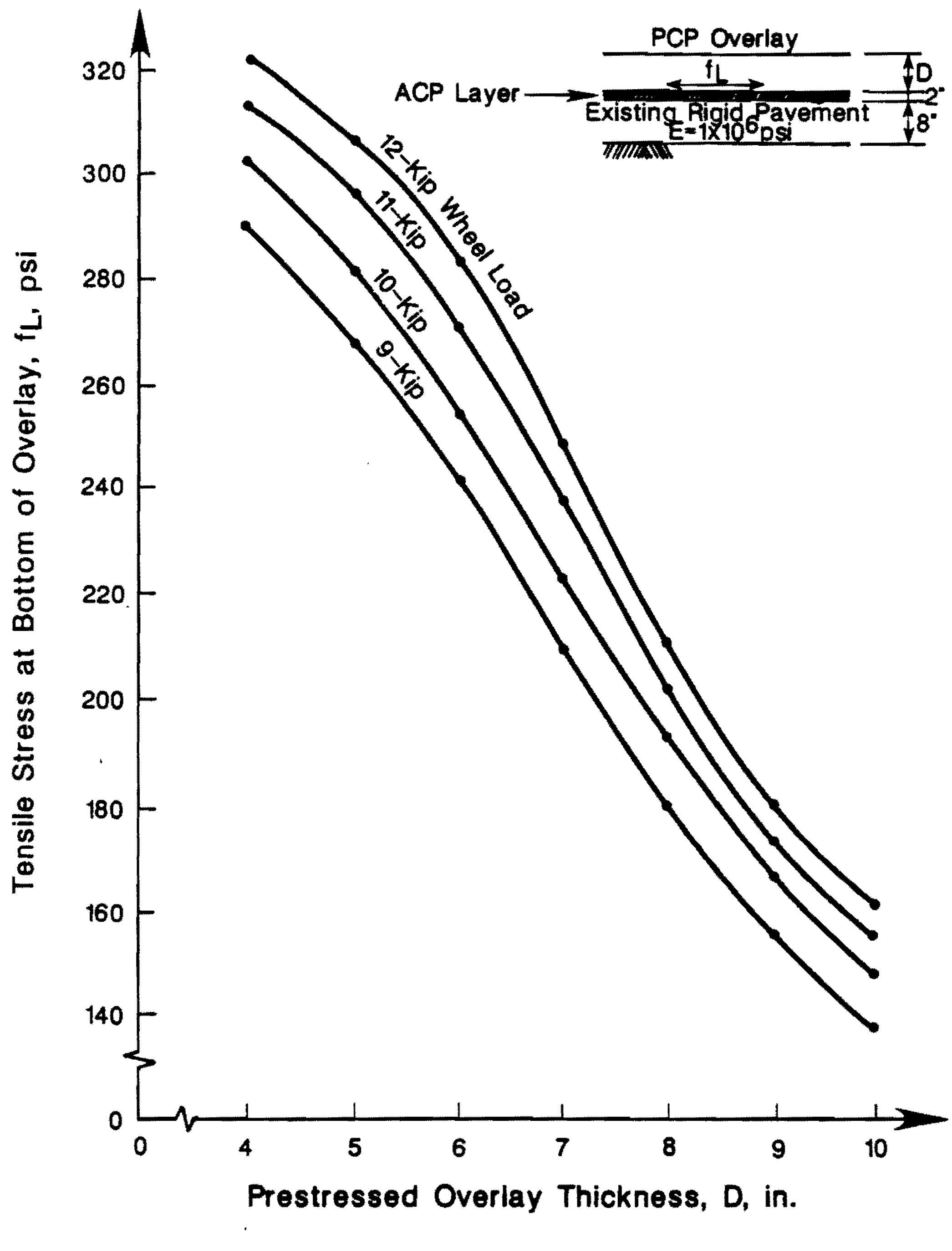


Fig 8.6 Tensile stress at the bottom of the overlay versus overlay thickness for PSCP overlay over 8 inch rigid pavement in poor structural condition by the time of overlay.

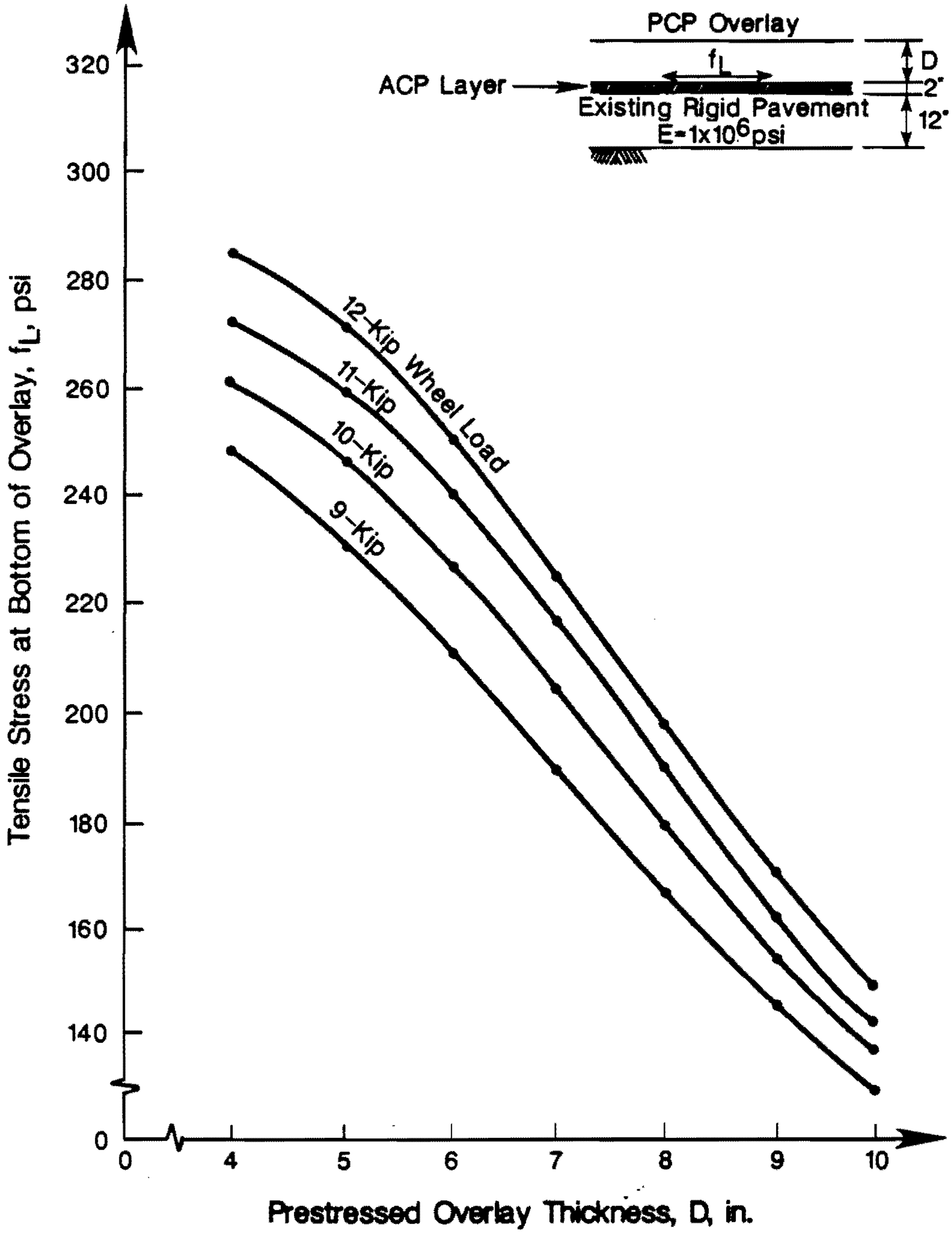


Fig 8.7. Tensile stress at the bottom of the overlay versus overlay thickness for PSCP overlay over 12 inch rigid pavement in poor structural condition by the time of overlay.

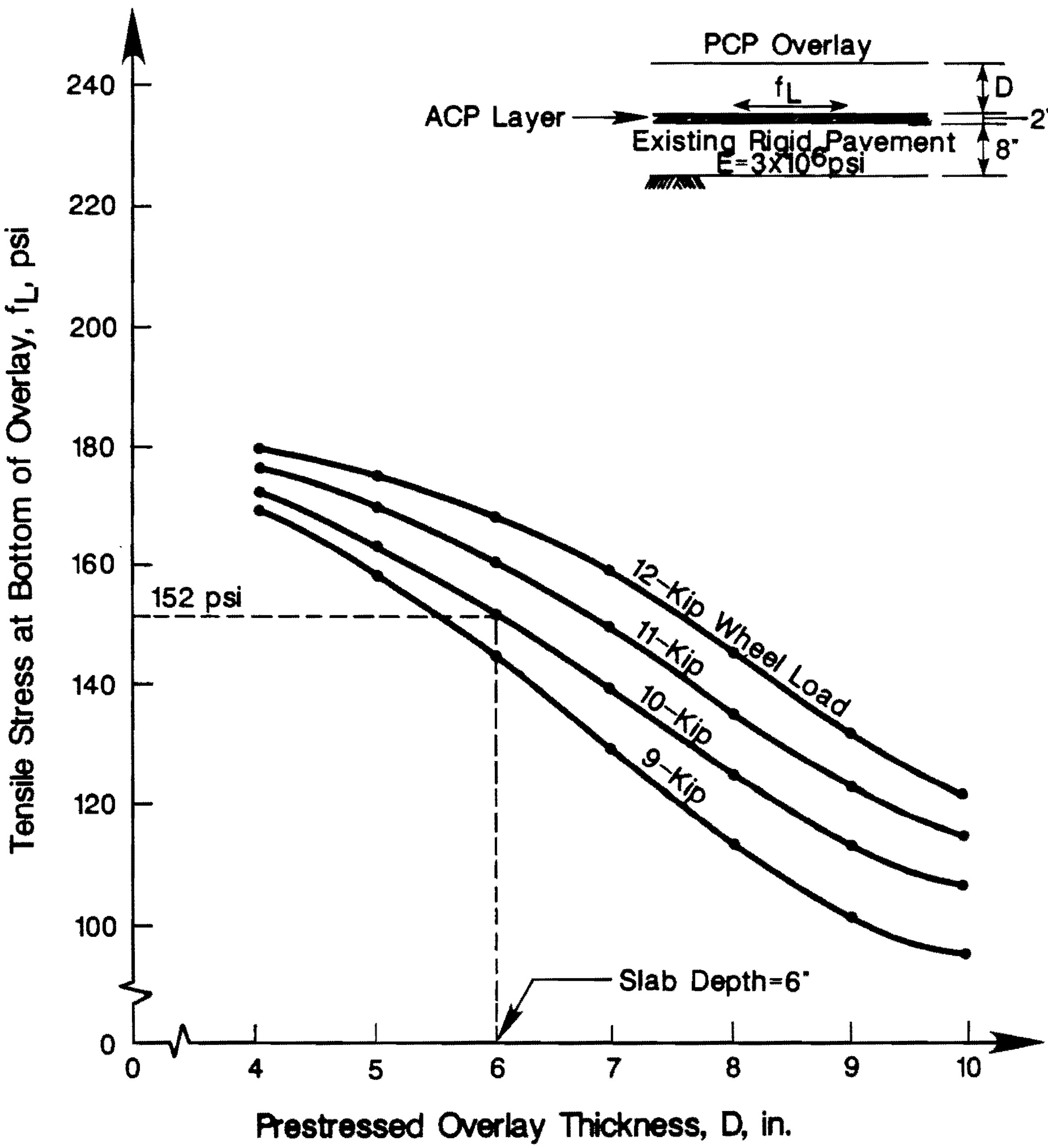


Fig 8.8. Tensile stress at the bottom of the overlay versus overlay thickness for PSCP overlay over 8 inch rigid pavement in good structural condition by the time of overlay.

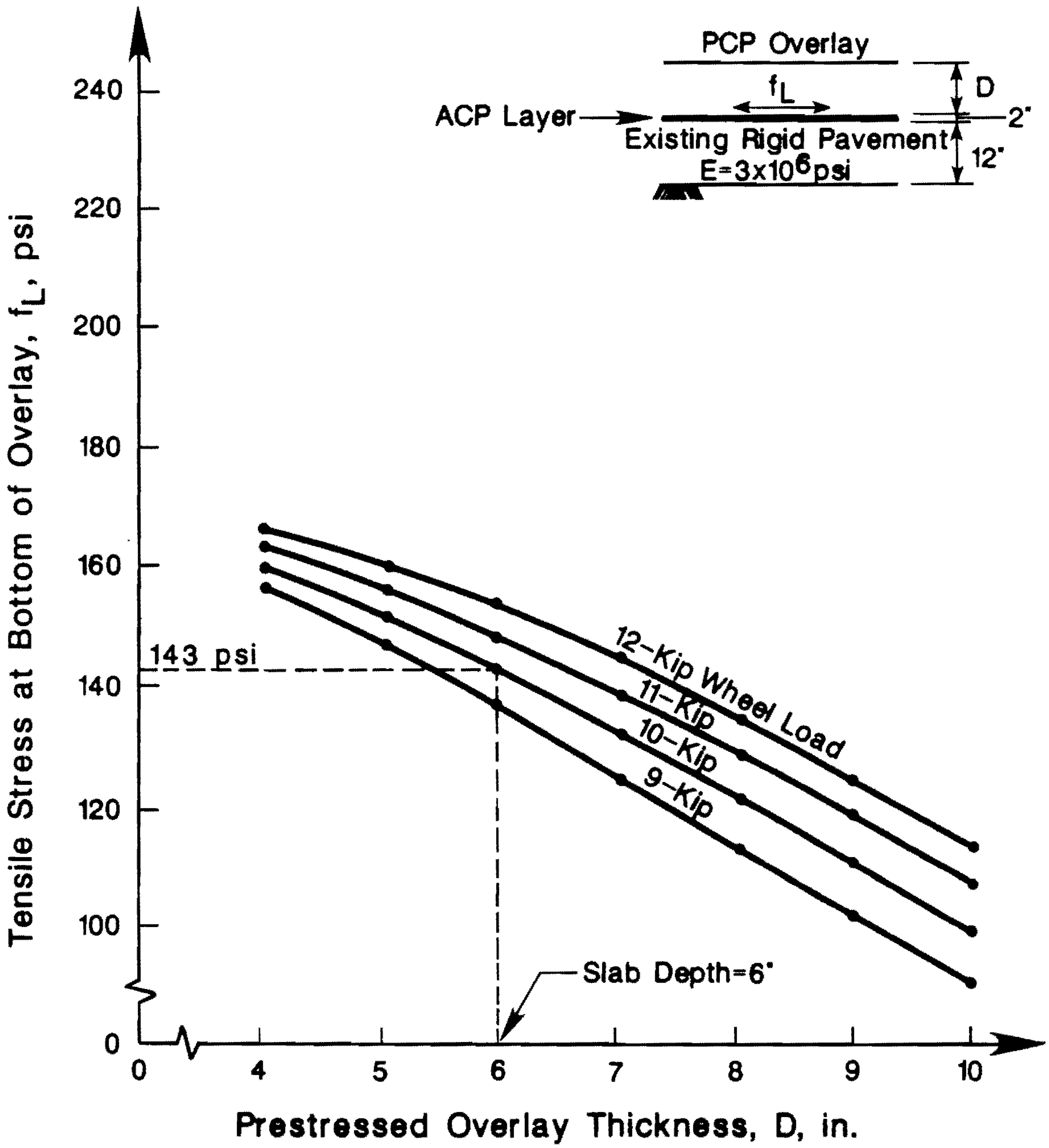


Fig 8.9. Tensile stress at the bottom of the overlay versus overlay thickness for PSCP overlay over 12 inch rigid pavement in good structural condition.

friction relieving materials at the interface. Interpolation can be used in design for conditions intermediate to those considered by these charts. For conditions outside the range of these charts, the wheel load stresses can be calculated using one of the computer codes to predict stresses from multilayered elastic theory (Refs 29 and 55), preferably BISAR (Ref 55), or any of the finite element computer programs (Ref 30).

Step 4. In this step, the allowable flexural stress, which is another input variable of the elastic design procedure for PCP slabs, should be determined from the concrete flexural strength information. First, the 28-day concrete flexural strength should be estimated. An estimate of this parameter can be obtained from numerous flexural tests on beams using third point loading, according to ASTM C78 (Ref 26). The tests should be performed on trial batches of concrete using the aggregate and cement for mix designs expected to be used in the project.

The allowable flexural stress can be determined by dividing the 28-day flexural strength by a safety factor. ACI Committee 325 (Ref 1) suggests the use of values between 1.5 and 2.0 as safety factors for secondary and primary highways, respectively.

Step 5. For the problem considered, complete the set of design inputs for computer program PSCP1, as described in Chapter 6, in the section on the description of the program input data.

A sequence of post-tensioning forces applied at certain hours after curing should be assumed initially for the initial period. Whether these forces can avoid the formation of premature cracks in the slab or whether they can be withstood by the concrete without causing anchor zone failure is the design aspect covered in stage 2 of this methodology. Temporary estimates of these parameters should be defined in this step and checked later in stage 2.

Step 6. Determine the strand spacing for which the elastic design criterion is met (Eq 2.1 in Chapter 2). The elastic design equation should be established for the stresses developing at the bottom of the slab at midlength on a summer day near the end of the overlay design life. The detrimental effect of all factors considered in this study is additive for this condition. A summer day should be analyzed because the largest environmental stresses (due to friction and curling) develop during summer days as the fluctuations of air temperatures are generally the largest of the year. Likewise, a day near the end of the overlay design life should be considered because it is when the prestress level is minimum, as almost all prestress losses have occurred.

The following substeps can be followed to define strand spacing:

(a) Assume a strand spacing and run PSCP1

(b) From the PSCP1 output, obtain the critical combination (for a summer day near the end of the overlay design life) of the following factors:

$$f_C + f_F + f_L - f_P \quad (8.1)$$

where

f_C	=	curling stress,
f_F	=	stress due to friction,
f_L	=	flexural stress due to wheel load, and
f_P	=	prestress level for strand spacing assumed.

(c) Repeat steps (a) and (b) until the strand spacing is obtained for which the following relationship holds:

$$f_C + f_F + f_L - f_P = f_t \quad (8.2)$$

where

f_C, f_F, f_L and f_P are as defined above, and f_t = allowable concrete flexural stress.

Step 7. Determine the strand spacing for which the summation of prestress plus friction (at the slab midlength for a summer day near the end of the overlay design life) exceeds the minimum prestress level from fatigue. A search technique based on consecutive runs of PSCP1 as described in Step 6 can be used in this step. The relationship in this case is

$$f_F + f_P \geq f_{fatigue} \quad (8.3)$$

where

f_F and f_P are as defined earlier, and

$f_{fatigue}$ = prestress level from fatigue.

Step 8. The design strand spacing should be the lowest between the spacings obtained in steps 6 and 7.

Step 9. For the strand spacing selected, determine from predictions of PSCP1 the minimum stress in the strands (for a winter day at the end of the overlay design life). If the opening is less than 4 inches, the slab length initially assumed is correct. Otherwise, a shorter length should be chosen and the analysis repeated starting from Step 5 to redefine strand spacing, prestress levels, etc.

Stage 2 of Design Methodology

The objective in this stage is to assess the prestress forces to apply at the slab ends, at the earliest time possible following curing, to minimize the risks of developing premature temperature cracking in the slab. Predictions of stresses are required along with knowledge of the strength gain properties of concrete at very early ages to avoid applying excessive forces which may cause concrete failure at the anchor zone.

Computer program PSCP1 permits evaluation of the effect of placing the slab at different hours of the day on the stresses arising during the first hours. Figure 8.10 was obtained from PSCP1 predictions. The dark lines represent the first-hours stresses for setting hours at 12 a.m., 5 p.m., and 8 p.m. The dashed lines represent tensile strength gain curves for good and poor quality concretes, respectively. Two facts are evident from this figure:

(1) The probability of premature cracking is substantial for slabs placed in the morning, decreasing to a minimum for slabs placed in the late afternoon and in the night.

(2) The slabs would likely crack if poor quality concrete is supplied for the project.

In this study, it will be considered that the total prestress will be completed in two stages (initial and final). Likewise, it will be considered that, independently of the setting hour, all slabs will be post-tensioned initially as soon as they get enough strength to withstand 10 kips at the anchor zone. To apply a force in the neighborhood of 10 kips at the initial stage has been common of previous US prestress projects (Ref 4). The aspects to define herein are then

(1) Time of application of initial prestress,
(2) Whether or not 10 kips of initial prestress is sufficient to avoid temperature cracking in the slab, and
(3) Time of application of final prestress.

The following steps can be used to define these aspects.

Step 1. Determine from Fig 8.11 the compressive strength required in the concrete that allows a 10-kip load at the anchor. This figure was determined from tests reported by O'Brien, Burns, and McCullough (Ref 22) on the capacity of the anchorage zone for very early post-tensioning. Given its empirical nature, the use of this chart is limited to applications similar to those of the study conducted by O'Brien, et al.

(1) Concrete compressive strengths between 0 and 2000 psi,
(2) Slab thicknesses of 6 to 8 inches,
(3) Strand spacings of 12 and 24 inches,
(4) 0.6-inch-diameter mono-strand flat anchors with 16.19 and 21 square inches in area.

Interpolation or extrapolation for conditions different than these is possible, but the designer should be careful to be sure that the tests verify adequate safety.

Step 2. Determine the compressive strength versus age relationship of concrete at very early ages. This relationship can be derived from compressive strength tests performed on cylindrical specimens at different ages according to ASTM C 39 or AASHTO T22, T140 test specifications (Refs 26 and 56). As for the flexural strength, the compressive strength should be evaluated by performing the tests on small trial batches of concrete using the aggregate and cement for mix designs anticipated to be used in the project.

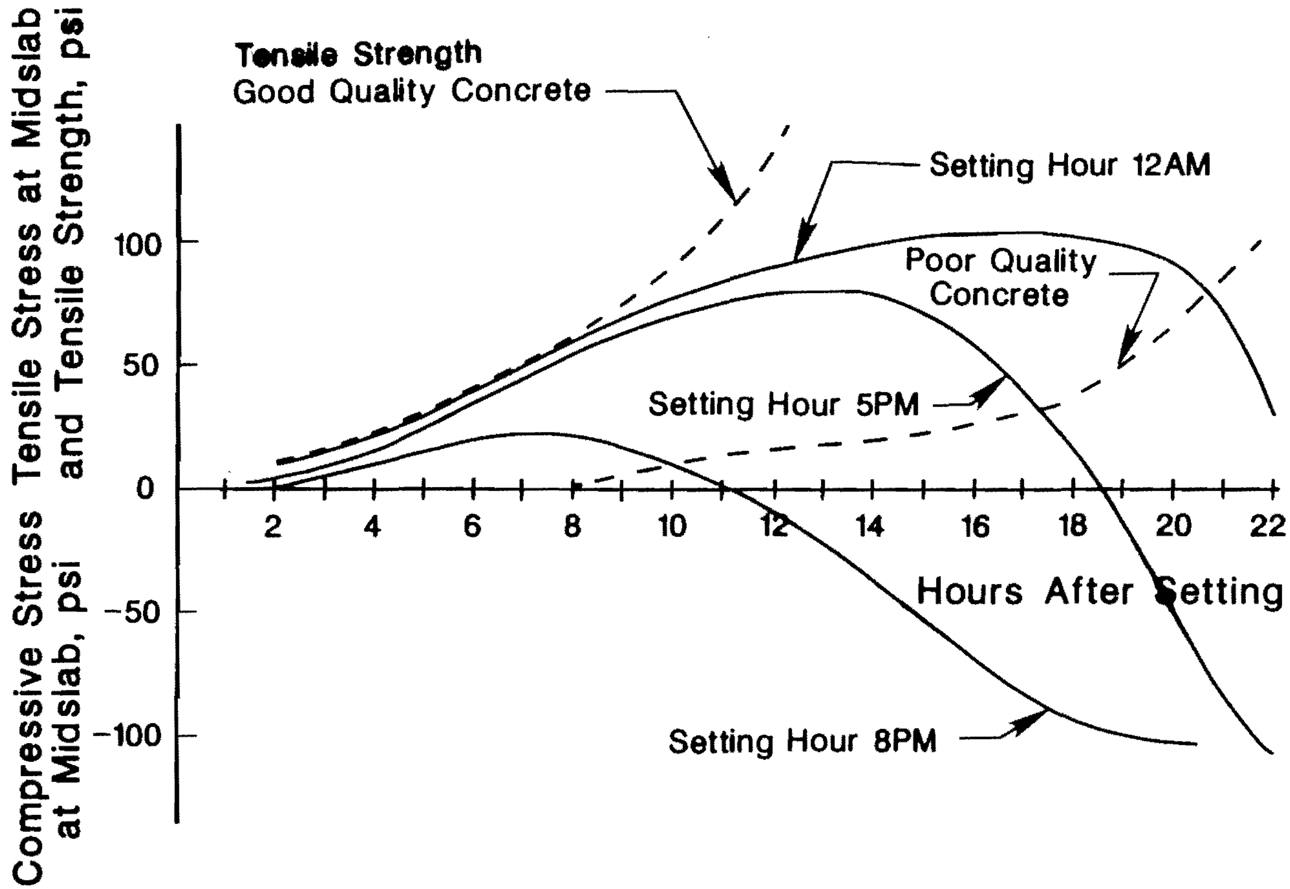


Fig 8.10. Effect of placement hour on the slab stresses arising during the first hours of placement life.

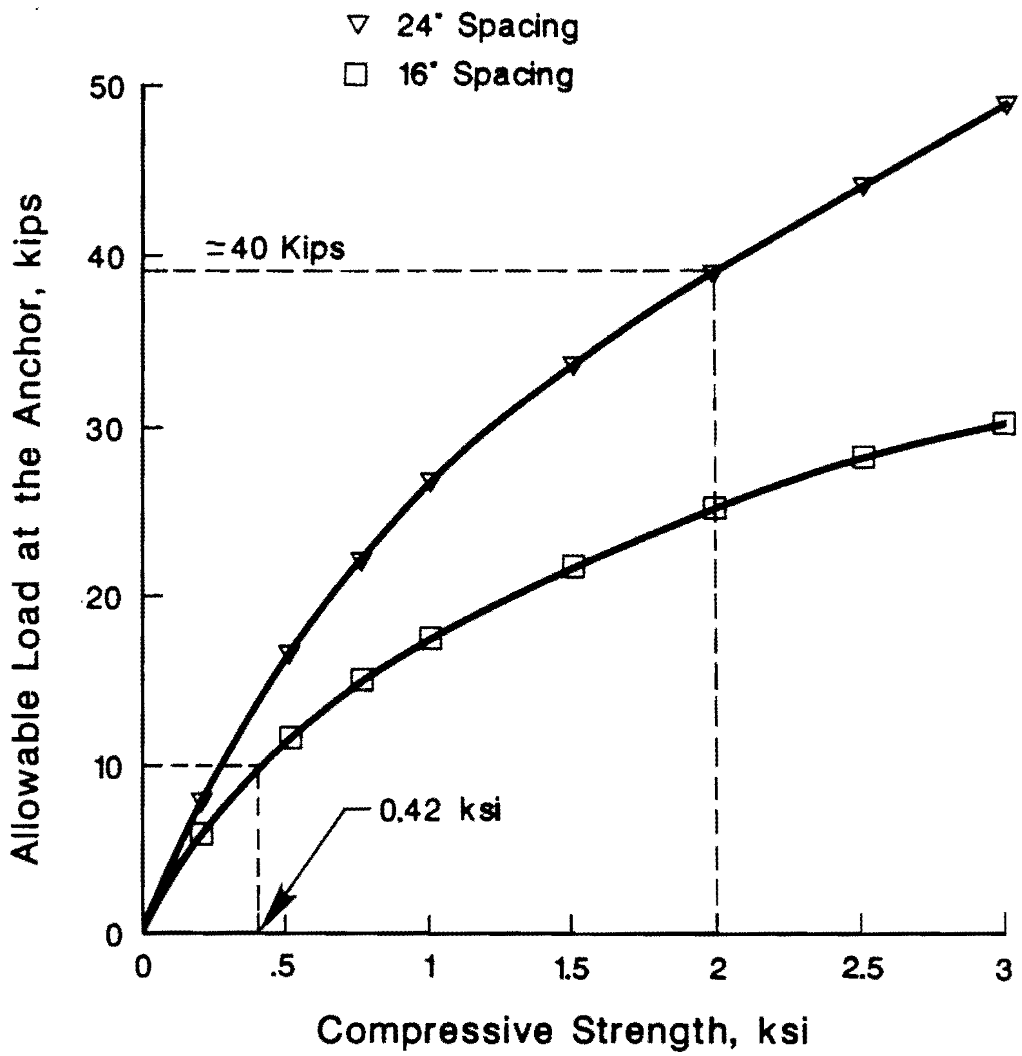


Fig 8.11. Allowable load at the anchor versus concrete compressive strength after experiments by O'Brien et al. (Ref 22).

Step 3. From the compressive strength versus age relationship obtained in Step 2, determine the age at which the concrete gains the required compressive strength for applying 10 kips at the anchor (from Step 1).

Step 4. Determine the concrete tensile strength versus age relationship form the compressive strength versus age relationship derived in Step 2. To obtain compressive strengths from tensile, the following equation from Ref 35 can be used:

$$f_t = c \bullet \frac{1000 f'_c}{4000 + f'_c} \tag{8.4}$$

where

f_c	=	concrete compressive strength, psi,
f_t	=	concrete tensile strength, psi, and
c	=	constant which depends on the coarse aggregate type of concrete (5/8, 2/3, and 3/4 for gravel, limestone, and light-weight aggregate, respectively).

Step 5. As may be evidenced from Fig 8.10, the most critical placement hour is around 9 a.m.. In this case, the concrete has to withstand the friction restraint stresses of the complete drop of the daily thermal cycle. This placement hour is, therefore, the one to be analyzed in this stage of the procedure. The recommendations developed for this case would obviously be valid for other less critical placement hours.

PSCP1 should be run, specifying for the initial period, the sequence of temperatures after a 2 p.m. curing hour and an initial prestress of 10 kips at the age obtained in Step 2. A final prestress of 80 percent of the steel ultimate strength (46.4 kips for 270-k grade, 7-wire strands with 0.6-inch nominal diameter) can be specified after 48 hour,s as the study conducted by O'Brien et al (Ref 22) demonstrated that loads in this order of magnitude can be safely applied by this age. The strand spacing to input into PSCP1 should be the one defined in stage 1 of this methodology.

Step 6. From the PSCP1 run, obtain the sequence of curling and prestress plus friction stresses and evaluate if the specified initial and final prestress forces are adequate for eliminating the chances of developing premature cracking. If not, the 10-kip initial prestress may be increased and the procedure repeated starting from Step 3 of this stage.

EXAMPLE PROBLEM

An example design problem using the concepts and procedures presented in this chapter is shown in this section.

Stage 1 of Design Methodology

Step 1. Design a PCP overlay to be placed in a two-lane rural interstate highway. The existing pavement is a 10-inch CRCP 38-feet wide. The design traffic to be carried by the facility for a design life of 20 years is 52×10^6 18-kip ESAL. The total traffic in the design lane can be obtained by modifying the design traffic of the two-lane facility with a lane distribution factor of 0.9 as recommended by Elkins and McCullough (Ref 52) for CRCP design. Namely,

$$N18\text{-k ESAL} = 52 \times 10^6 \times 0.9 = 47 \times 10^6$$

A design elastic modulus for the existing pavement was back-calculated from a set of deflection basins measured with the Dynaflect. (For details on this evaluation procedure, the reader should consult Ref 4). A concrete elastic modulus of 3×10^6 psi was obtained from this evaluation.

Interpolating between the thickness values in Figs 8.3 and 8.4 for a 75-psi prestress level:

Existing Pavement Thickness, Inches		
8	10	12
6.2	5.8	5.3

Therefore, a slab thickness of 6 inches and a midslab prestress level of 75 psi are initially assumed.

Step 2. Selecting a length of PCP slabs between expansion joints of 240-feet, an expected total joint opening of 2.3 inches is read from Fig 8.5. This opening is lower than the 4-inch maximum allowed.

Step 3. The elastic design of the slabs is to be performed for the maximum 20-kip single axle load allowed in interstate highways. The axle consists of two 10-kip loads spaced 72 inches from center to center of loads. The tensile stress at the bottom of the overlay can be obtained by interpolation between the stress values from Figs 8.8 and 8.9:

Existing Pavement Thickness, Inches		
8	10	12
152	148	143

Therefore, a wheel load stress f_L = 148 psi is obtained.

Step 4. A 28-day flexural strength of 730 psi was obtained from flexural tests on beams. For the rural facility with high traffic considered, a safety factor of 2.00 is assumed. Correspondingly, the allowable concrete flexural stress is

$$f_t = 730/2.00 = 365 \text{ psi}$$

Step 5. The information presented in Table 8.1 is available for the problem considered. The friction coefficient versus displacement curve assumed herein correspond to a single polyethylene film. A slab placed early in the morning of a summer day and cured at 2:00 p.m., approximately at the maximum temperature of the day, is to be analyzed. The curing temperature is 90°F. If prestress forces are required, the strands should be stressed initially to a stress of 46.2 psi (10 kips per strand). The codification of these data, to input into PSCP1, is given in the first part of Appendix C.

Step 6. The stresses obtained from PSCP1 for summer and winter days near the end of the pavement design life (20 years = 7300 days) are given in Table 8.2. The stresses at

TABLE 8.1. PSCP1 DESIGN INPUTS FOR PROBLEM CONSIDERED

Input Category	Factor	Value
Problem Identification		
Problem Definition	Slab Length, ft	240
	Slab Thickness, in	6
	No. of Elements	50
	No. Max. of Iterations	100
	Tolerance, percent	0.5
Concrete Properties	Thermal Coefficient, in/in-°F	$5x10^{-6}$
	Ultimate Shrinkage Strain, in/in	$3x10^{-4}$
	Unit Weight, pcf	150
	Poisson Ratio	0.15
	Creep Coefficient	2.10
Age Compressive Strength Relationship (generated by the program from 28th day compressive strength)	Age, Days	28
	Compressive Strength, psi	3000
Friction Coefficient vs. Displacement Relationship	1st Displacement, in	0.0
	Friction Coefficient	0.0
	2nd Displacement, in	0.001
	Friction Coefficient	0.25
	3rd Displacement, in	0.002
	Friction Coefficient	0.40
	4th Displacement, in	0.003
	Friction Coefficient	0.50
	5th Displacement, in	0.004
	Friction Coefficient	0.625
	6th Displacement, in	0.007
	Friction Coefficient	0.74
	7th Displacement, in	0.02
	Friction Coefficient	0.96
Stiffness of Slab Support	K-Value, psi/in	500

(continued)

TABLE 8.1. (CONTINUED)

Input Category	Factor	Value
Steel Properties	Strand Spacing, in	Variable
	Strand Nominal Area, in^2	0.216
	Yield Strength, ksi	270
	Elastic Modulus, psi	$30x10^6$
	Thermal Coefficient, in/in-^oF	$7x10^{-6}$
Temperature Data for Initial Period	No. of Temperature Data for Initial Period	18
	Curing Hour	14 (2 PM)
	Curing Temperature, ^oF	90
	(The set of 18 mid-depth temperatures and temperature differentials after the curing hour are those shown in Table 8.6)	
Sequence of Post-tensioning Applications During Initial Period	No. of Post-Tensioning Stages	2
	Time Since Curing to 1st Post-Tensioning, Hours	10
	Completed Post-Tensioning per Strand, ksi	46.4
	Time Since Curing to 2nd Post-Tensioning, Hours	24
	Completed Post-Tensioning per Strand, ksi	215
Temperature Data for Second Period of Analysis	Time of Analysis Since Curing, Days	7300
	(The set of 12 mid-depth temperatures and temperature differentials for the period are those shown in Table 8.2)	
Data for Third Period of Analysis	Time of Analysis Since Curing, Days	7300
	(The set of 12 mid-depth temperatures and temperature differentials for the period are those shown in Table 8.2)	

TABLE 8.2. TOTAL STRESSES ($f_F + f_C + f_L$) FROM PSCP1 VERSUS FLEXURAL STRESSES (f_t) FOR SUMMER AND WINTER DAYS

Period of Analysis	Col. 1 Hour	Col. 2 Mid-depth Temperature, °F	Col. 3 Temperature Differential, °F	Col. 4 Friction Stress, f_F, psi	Col. 5 Curling Stress, f_C, psi	Col. 6 Wheel Load Stress, f_L, psi	Col. 7 Total Stress, psi	Col. 8 Flexural Stress, f_T, psi
Second	8	57	-2.5	115.98	-24.42	148	240.00	365
(summer	10	65	1.8	34.76	17.58	148	200.30	365
day near	12 noon	80	17.4	-111.46	169.93	148	206.47	365
end of	2	90	20.4	-115.21	199.23	148	232.02	365
design	4	95	12.5	-115.99	122.08	148	154.09	365
life)	6	87	-0.5	34.76	-4.88	148	177.88	365
	8	78	-6.4	103.54	-62.50	148	189.08	365
	10	70	-6.4	112.71	-62.50	148	85.50	365
	12 midn.	65	-5.8	114.63	-54.64	148	205.99	365
	2	62	-5.1	115.20	-49.81	148	213.39	365
	4	60	-5.3	115.56	-51.76	148	211.80	365
	6	57	-5.1	115.98	-49.81	148	214.17	365
Third	8	49	-2.0	86.28	-19.53	148	281.50	365
(winter	10	51	1.4	52.86	13.67	148	214.53	365
day near	12 noon	56	10.1	-35.91	98.64	148	210.73	365
end of	2	60	11.6	-81.64	113.29	148	179.65	365
design	4	59	7.1	-66.13	69.34	148	151.21	365
life)	6	56	-0.3	-16.25	-2.93	148	128.82	365
	8	53	-3.8	37.20	-37.11	148	148.09	365
	10	52	-4.2	50.81	-41.02	148	157.80	365
	12 midn.	51	-4.3	63.12	-42.00	148	169.12	365
	2	50	-4.1	73.78	-40.04	148	181.74	365
	4	49	-4.3	82.55	-42.00	148	188.55	365
	6	49	-4.1	82.55	-40.04	148	190.51	365

midslab and at the bottom of the pavement are tabulated every two hours. The column of total stress (col. 7) includes the summation of the friction restraint stress (col. 4), curing stress (col. 5), and wheel load stress (col. 6). From comparison of columns 7 and 8, it can be noticed that the total tensile stress is far lower than the concrete flexural stress. Then, the elastic design criterion indicates that post-tensioning is not required. Hence, the prestress level from fatigue controls the design. This aspect brings about the importance of considering fatigue in design over the elastic design criterion which is shown to be irrelevant in this example.

In general, very small or null amounts of prestress come out from the elastic design of prestressed overlays over existing rigid pavements as the overlays experience relatively low stresses under wheel loads (148 psi in this example). This is a result of the excellent support provided by the rigid pavement. This is not the case of PCP's placed on other weaker base types, e.g., lime or asphalt stabilized granular bases.

Step 7. A trial-and-error procedure was followed to get the strand spacing resulting in compressive stresses at midslab equal or higher (at all times) than the minimum precompression required for fatigue (75 psi). After several trials, a 32-inch strand spacing was obtained. Table 8.3 shows the variation of prestress plus friction stresses at midslab obtained from PSCP1 for this strand spacing, for summer and winter days, respectively. The PSCP1 computer run from which these values were obtained is given in Appendix C. A minimum precompression of around 75 psi is obtained during the night hours (between 8 p.m. and 8 a.m.). During the day hours this precompression is far exceeded.

Steps 8 and 9. From steps 6 and 7, a strand spacing of 32 inches should be selected. For this strand spacing, Table 8.4 presents the amount of stress in the strands effective by the end of the overlay life (obtained from the run in Appendix C) and the amount of losses with respect to the 215 ksi initially applied (following second stage stressing).

Step 10. The maximum slab end contraction (for a winter day near the end of the overlay life) from PSCP1 occurs around 8 a.m. and is equal to 1.4 inches (see the computer run in Appendix C). This contraction results in a joint opening of 2.8 inches, lower than the maximum allowed, 4 inches. Therefore, the initially assumed slab length of 240 feet is satisfactory.

TABLE 8.3. PRESTRESS PLUS FRICTION STRESSES FOR SUMMER AND WINTER DAYS FROM PSCP1 COMPUTER PROGRAM

Period of Analysis	Hour	Prestress and Friction Stress, psi
SECOND	8	-73.40
(summer day near end of design life)	10	-223.90
	12 noon	-300.83
	2	-304.59
	4	-305.36
	6	-154.84
	8	-85.84
	10	-76.67
	12 midn.	-74.75
	2	-74.17
	4	-73.82
	6	-73.40
THIRD	8	-103.68
(winter day near end of design life)	10	-137.05
	12 noon	-225.82
	2	-271.55
	4	-256.04
	6	-206.16
	8	-152.71
	10	-139.10
	12 midn.	-126.79
	2	-116.13
	4	-107.36
	6	-107.36

TABLE 8.4. FINAL STRESS IN STRANDS FROM COMPUTER PROGRAM PSCP1 AND COMPUTATION OF PERCENT LOSSES WITH RESPECT TO INITIAL STRAND STRESS

Period of Analysis	Stress in Strands, ksi	Loss With Respect to Initial 215 Ksi, Ksi	Percent Losses (%)
SECOND (summer day near end of design life)	168.3	46.7	21.7
THIRD (winter day near end of design life)	168.8	46.2	21.4

Stage 2 of Design Methodology

Step 1. From Fig 8.11, a 420-psi compressive strength is required for an allowable load at the anchor of 10 kips.

Step 2. The concrete compressive strength versus age relationship in Table 8.5 is available for design.

Step 3. The age at which concrete gains a 420-psi compressive strength can be obtained interpolating between the ages for 300 psi and 580 psi in Table 8.5. The concrete gains 420 psi after approximately 10 hours.

Step 4. The tensile strength values corresponding to the compressive strength versus age relationship from Step 2 are reported in Table 8.5.

Steps 5 and 6. Table 8.6 shows the sequence of prestress plus friction and curling stresses, at midslab, obtained from PSCP1 for a setting hour at 2:00 p.m., specifying 10 kips after 10 hours and 46.4 kips after 24 hours since slab setting. These values were obtained for the initial period of the PSCP1 computer run included in Appendix C. A total of 46.4 kips was specified after 24 hours because, from Table 8.5, the concrete gains 2000 psi after 24 hours. For this strength, Fig 8.11 indicates that almost 40 kips can be allowed at the anchor for a 24-inch strand spacing. It is considered, then, that the concrete can withstand safely 46.4 kips for the 32-inch strand spacing defined in stage 1 of this example. The column of total stress in Table 8.6 corresponds to the sum of the columns of prestress plus friction stresses and the column of curling stresses.

From a comparison of the columns of total stress and tensile strength in Table 8.6, it is apparent the high chance of cracking is during the first 10 hours since curing. However, after applying the initial prestress (12:00 midnight), the tensile strength decreases far below the tensile strength. The tensile strength, on the other hand, keeps on increasing until the concrete attains strength levels at which cracking occurrence may be fairly unlikely.

An alternative that may reduce the chance of cracking during the first 10 hours would be to reduce the initial post-tensioning development force below 10 kips and apply it sooner. However, 10 kips is considered as a reasonable minimum that is desirable for a prestressing stage, given the labor time and cost involved in post-tensioning operations (Ref 4). Therefore, 10 kips at the slab ends after 10 hours and 46.4 after 24 hours is a viable post-tensioning strategy.

TABLE 8.5. COMPRESSIVE STRENGTH VERSUS AGE RELATIONSHIP FOR CONCRETE AT EARLY AGES FOR EXAMPLE CONSIDERED

Age, Hours	Compressive Strength, psi	Tensile Strength, psi
4	80	12
8	300	45
12	580	80
16	1400	160
20	1600	180
24	2000	205

TABLE 8.6. CONCRETE STRESSES FROM PSCP1 (f_p, f_F, f_C), AND TENSILE STRENGTH (f_t) DURING FIRST HOURS AFTER CURING (INITIAL PERIOD OF PREDICTIONS)

Hour	Mid-depth Temperature, °F	Temperature Differntial, °F	Prestress & Friction Stress, $f_p + f_F$, psi	Curling Stress, f_C psi	Total Stress, $f_p + f_F + f_C$, psi	Tensile Strength, f_t, psi
4	95	12.5	-9.3	13.7	4.4	6
6	87	- 0.5	11.8	-0.8	11.0	12
8	78	- 6.4	43.4	-12.1	31.3	23
10	70	- 6.4	.4	-14.0	64.4	52
12 midn.	65	- 5.8	61.1	-14.2	46.9	63
2	62	- 5.1	62.7	-13.6	49.1	85
4	60	- 5.3	63.3	-15.3	48.0	120
6	57	- 5.1	63.9	-15.8	48.1	
8	57	- 2.5	64.0	-8.2	55.8	
10	65	1.8	16.1	6.2	22.3	
12 noon	80	17.4	-91.0	63.0	-28.0	
2	90	20.4	-163.6	77.2	-86.4	
4	95	12.5	-194.8	48.8	-146.0	
6	87	- 0.5	-168.5	-2.0	-170.5	
8	78	- 6.4	-130.3	-26.4	-156.7	
10	70	- 5.8	-126.9	-27.1	-154	
12 midn	65	- 5.8	-126.0	-25.2	-151.2	
2	62	- 5.1	-125.7	-22.7	-148.4	

CHAPTER 9. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This chapter presents a summary of findings and conclusions resulting from this study of modeling the behavior of PCP slabs to incorporate the model into a design procedure. As the results presented herein are based on a small sample of data, they must not be considered as universal, but indicative of the expected behavior that must be checked for each project until enough data becomes available to verify the model. Recommendations for further research are also provided as possible extensions of the design methodology presented.

SUMMARY AND CONCLUSIONS

In Chapter 2, a detailed description of the important variables affecting PCP behavior and the design factors covered in this study are presented. These are the relevant statements in this chapter:

(1) The movements of PCP slabs can be classified as short-term and long-term movements. Short-term movements, i.e., those due to daily temperature changes occur restrained by the friction. Therefore, slab stresses due to friction develop almost exclusively as a result of these movements. Long-term movements, i.e., those produced by concrete swelling, shrinkage, creep, and seasonal temperature changes, occur unrestrained by the friction. Therefore, concrete stresses due to friction are not caused by these movements. However, since their magnitude is fairly significant in the long term, the variations of the prestress level are primarily a result of the accumulation of these movements.

Slab elastic shortening due to prestress forces occurs under frictional resistance when the prestress forces are applied. However, the effect of the friction dissipates shortly after prestressing. These movements can be considered, therefore, as temporarily restrained by the friction.

(2) An elastic design of PCP slabs is not sufficient inasmuch as this method is not sensitive to wheel load repetitions. A fatigue analysis is particularly indispensable for designing pavements of highly trafficked facilities.

In Chapter 3, there is a discussion of the nature of the friction forces developing under rigid slabs. Important conclusions derived in this chapter are the following:

(1) The friction forces under rigid pavements resemble elastic forces for small displacements (less than a maximum of 0.02 inch). However, for displacements of a higher magnitude, like those experienced by the long PCP slabs, for daily temperature cycles, the frictional resistance is substantially inelastic. In this case, the model indicates that reversals of slab movement result in reversals of the direction of the friction forces under the slab and changes in the nature of the concrete stresses (tensile to compressive or vice versa).

(2) The inelastic nature of the friction forces explains why the slab short-term movements (due to daily temperature changes) occur restrained by the friction whereas long-term movements occur unrestrained. This behavior cannot be explained if the friction forces are considered as elastic. Elastic friction forces have been assumed in the past in the design of CRCP and JRCP slabs.

In Chapter 4, the problem to be solved in this research for modeling the behavior of PCP slabs was established. The problem was stated in a form such that its solution may provide the most complete information for the design of PCP slabs. In this chapter, the derivation of a model for friction considering its inelastic nature is also presented. Such a model permits a better simulation of PCP behavior than if the friction forces were considered to be elastic, as is typically assumed in the design of JRCP and CRCP.

In Chapter 5, a series of considerations were made for incorporation in modeling PCP behavior, considering the effects of the variables associated with the application of prestress forces. Likewise, it was shown that a few hours after post-tensioning, the effect of the prestress is to shift the cycle of stresses arising from daily temperature changes an amount equal to the precompression being applied at the slab ends. The final stresses become, then, the mirror-image of the stresses that would develop if prestress forces were not applied.

A description of the main features of computer program PSCP1 and some of the assumptions considered inside the program are provided in Chapter 6. A detailed description of input variables and an interpretation of the program output is also presented.

In Chapter 7, several concrete properties (thermal coefficient of contraction and expansion, and ultimate shrinkage and creep strains) were evaluated following a regression analysis on a set of joint openings recorded since construction of the Waco prestressed overlay. The evaluation of these parameters validated the accuracy of the predictive models for creep and shrinkage inside PSCP1. The creep model was more reliable than the model for shrinkage; however, both of them showed to be fairly accurate. Subsequently in this chapter, measured and computed cycles of longitudinal displacements for a 440 foot slab were compared. The slab experienced movements scarcely restrained by the friction.

In this testing computer program PSCP1 proved to be an excellent tool for back-calculating the frictional restraining properties of existing bases under rigid pavements, from observed cycles of movement. A maximum friction coefficient of around 0.2 was determined to match the cycle of computed movements from PSCP1 to the cycle of observed movements. This value, together with the curve in Fig 3.4 for a single layer of polyethylene, and a back-calculated value between 0.45 and 0.5 obtained by Maffei, Burns, and McCullough (Ref 53) (from a record of displacements experienced by the slabs at the time of post-tensioning) justify the following conclusions:

(1) The lowest friction coefficients under rigid slabs are observed for the cyclic movements of the thermal cycle (O.2 for the base condition of the Waco overlay),

(2) Higher friction coefficients are obtained when the slabs are post-tensioned (0.45 to 0.50 for the Waco overlay), and

(3) The highest friction coefficients develop beneath slabs tested for the first time under non-cyclic conditions (0.96 for a single polyethylene layer, from the pushoff tests on small concrete slabs in Gainesville (Ref 34).

Several of the possible applications of computer program PSCP1 in connection with the design parameters considered in this study were described in Chapter 8. A scheme for a design methodology was presented in the first part of this chapter. In the first stage of this methodology, the thickness, length, prestress level, amount of prestress losses, and strand spacing of PCP slabs may be defined. The second stage is a rational strategy for applying the prestress forces so as to reduce the chance that the slabs may develop premature temperature contraction cracking. The second part of this chapter presents a complete design example. The need of performing a fatigue design for PCP slabs is apparent from this example.

RECOMMENDATIONS FOR FURTHER RESEARCH

Several recommendations for further research along with possible extensions of the concepts developed in this study are presented below:

(1) The design procedure for PCP should be improved by including the beneficial effect of certain environmental factors in resisting wheel loads, e.g., the permanent moisture differential through the slab depth. This permanent moisture differential causes the precompression due to the prestress to concentrate at the bottom of the pavement. The present state of the technology does not allow the designer to incorporate the effects of this factor in the design with sufficient reliability.

(2) A further study on the merits of different bases and interlayer materials in reducing the frictional resistance should be conducted. The variations in frictional coefficients on frozen and non-frozen bases with age and climatologic conditions should be researched.

(3) Little is known with respect to the fatigue versus stress level relationship of prestressed concrete pavements. The charts presented in Chapter 8 to account for the fatigue aspect were derived from a fatigue relationship for JRC pavements, reducing the wheel load stresses an equal amount to the precompression due to the prestress. Accordingly, the use of these charts in the design may lead to uncertainties in two aspects: (1) the failure mechanism for PCP's may be substantially different from the failure mechanism for JRCP's and (2) inputting in a fatigue relationship the wheel load stresses reduced by the precompression due to prestress implies that both of them occur dynamically. However, the prestress is a static effect rather than a repetitive stress. Extensive laboratory testing is required to clear out these dubious matters.

(4) A close monitoring of behavior of the Waco PCP joints is particularly recommended for the development of an improved and more reliable joint detail.

(5) Criteria should be developed for evaluating long-term (20 years or more) performance of in-service PCP as related to wheel load repetitions and allowable stresses to use in design.

REFERENCES

1. ACI Committee 325, "Recommended Practice for Design of Concrete Pavements Prestressed with Post-tensioned Steel Tendons," Proposed Report for Committee Consideration, October 30, 1979.
2. Friberg, B. F., "Investigation of Prestressed Concrete for Pavements," HRB Bulletin 332, Highway Research Board, 1962.
3. Netter, M., "The Prestressed Concrete Runway at Orly," Annales de l'Institut Technique du Batiment et deus Travaux Publics (Paris), No. 5, January 1948.
4. Mendoza-Diaz, A., B. F. McCullough, and Ned H. Burns, "Design of the Texas Prestressed Concrete Pavement Overlays in Cooke and McLennan County and Construction of the McLennan County Project," Research Report 556-1, Center for Transportation Research, The University of Texas at Austin, February 1986.
5. Cable, N. D., Ned H. Burns, and B. F. McCullough, "New Concepts in Prestressed Pavements," Research Report 401-2, Center for Transportation Research, The University of Texas at Austin.
6. Melville, Philip L., "Review of French and British Procedures in the Design of Prestressed Pavements," HRB Bulletin 179, Highway Research Board, May 1958.
7. ACI Committee 325, Subcommittee VI, "Prestressed Pavement. A World View of Its Status," ACI Journal, Proceedings, Vol 30, No. 8, February 1959.
8. Friberg, B. F., and T. J. Pasko, "Prestressed Concrete Highway Pavement at Dulles International Airport. Research Program Report to 100 Days," FHWA-RD/DP/17-1, August 1973.
9. Brunner, R. J., "Prestressed Pavement Demonstration Project," TRB Record 535, Transportation Research Board, 1975.
10. Albritton, G., "Prestressed Concrete Pavement Near Brookhaven, Mississippi," Mississippi Department of Transportation, 1976.
11. Morris, G. R., and H. C. Emergy, "The Design and Construction of Arizona's Prestressed Concrete Pavement," Arizona Department of Transportation, October 1977.
12. Weil, G., "Der Verschiebewiderstand von Betonfahrbahnplatten," Betonstein Jahrbuch, Bauverlag GMBH, Wiesbaden, 1960.

13. Cashell, H. D., and S. W. Benham, "Experiments with Continuous Reinforcement in Concrete Pavements," Proceedings, Highway Research Board, Vol 29, 1949.

14. ACI Committee 504, Joint Sealants, "Guide to Joint Sealants for Concrete Structures," ACI Journal, June 1977.

15. Sargious, M., and S. K. Wang, "Economical Design of Prestressed Concrete Pavements," Journal of the Prestressed Concrete Institute, Vol 16, No. 4, July/August 1971.

16. Sargious, M., and S. K. Wang, "Design of Prestressed Concrete Airfield Pavements Under Dual and Dual-Tandem Wheel Loadings, Journal of the Prestressed Concrete Institute, Vol 16, No. 6, November/December 1971.

17. "The AASHO Road Test, Report 5, Pavement Research," Special Report 61E, Highway Research Board, Washington, D. C., 1962.

18. Teller, L. W., and E. C., Sutherland, "The Structural Design of Concrete Pavements," Public Road Administration, Reprints from Public Roads; Part I, October 1935; Part II, November 1935; Part III, December 1935; Part IV, September/October 1936; Part V, April/May/June 1943.

19. Kelley, E. F., "Application of the Results of Research to the Structural Design of Concrete Pavements," Public Roads, August 1939.

20. Friberg, B. F., "Frictional Resistance Under Concrete Pavements and Restraint Stresses in Long Reinforced Slabs," Proceedings, Highway Research Board, Vol 33, 1954.

21. Stott, J. P., "Tests on Materials for Use as Sliding Layers Under Concrete Road Slabs," Civil Engineering, 56, 1961.

22. O'Brien, J. S., N. H. Burns, and B. F. McCullough, "Very Early Post-tensioning of Prestressed Concrete Pavements," Research Report 401-1, Center for Transportation Research, The University of Texas at Austin, July 1985.

23. Nussbaum, P. J., S. D. Tayabji, and A. T. Ciolko, "Prestressed Pavement Joint Designs," Transportation Research Record 888, Transportation Research Board, Washington, D. C., 1982.

24. Friberg, B. F., "Prestressed Pavements, Theory into Practice," Proceedings, International Conference on Concrete Pavement Design, Purdue University, February 15-17, 1977.

25. Sargious, M., and A. Ghali, "Stresses in Prestressed and Non-Prestressed Pavements and Slabs on Grade," ACI Journal, Proceedings, February 1986.

26. ASTM Test Procedures, 1982 Annual Book of Standards.

27. Westergaard, H. M., "Stresses in Concrete Pavements Computed by Theoretical Analysis," Public Roads, Vol 7, No. 2, April 1926.

28. Steltzer, C. Fred, Jr., and W. R. Hudson, "A Direct Computer Solution for Plates and Pavement Slabs (DSLAB5)," Research Report 56-9, Center for Highway Research, The University of Texas at Austin, October 1967.

29. Ahlborn, G., ELSYM5 3/72-3, Elastic Layered System with One to Ten Normal Identical Circular Uniform Loads," Unpublished Computer Application, Institute of Transportation and Traffic Engineering, University of California at Berkeley, 1972.

30. Wilson, E. L., "SOLID SAP, A static Analysis Program for Three Dimensional Solid Structures," Structural Engineering Laboratory, University of California at Berkeley, 1971.

31. McCullough, B. F., and A. Mendoza, "Report on a Mechanistic Analysis of the PCC Aprons at King Fahd International Airport, Kingdom of Saudi Arabia," Austin Research Engineers, October 1985.

32. Goldbeck, A. T., "Friction Tests of Concrete on Various Subbases," Public Roads 5, July 1924.

33. Timms, A. G., "Evaluating Subgrade Friction Reducing Mediums for Rigid Pavements," Highway Research Record 60, Highway Research Board, Washington, D. C., 1963.

34. Mendoza, A., "Repetition of Friction Tests on the Test Slabs Constructed Near Valley View, Texas, for the Design of the Prestressed Highway Project in Cooke County," Technical Memorandum 401-20, Center for Transportation Research, The University of Texas at Austin, 1984.

35. McCullough, B. F., A., Abou-Ayyash, W. R. Hudson, and J. P. Randall, "Design of Continuously Reinforced Concrete Pavements for Highways," NCHRP 1-15, Center for Transportation Research, The University of Texas at Austin, 1975.

36. Rivero-Vallejo, F., and B. F. McCullough, "Drying Shrinkage and Temperature Drop Stresses in Jointed Reinforced Concrete Pavements," Research Report 177-1,

Center for Transportation Research, The University of Texas at Austin, August 1975.

37. "American Concrete Institute Standards," 1966.

38. Concrete Manual, Seventh Edition, United States Department of the Interior, Bureau of Reclamation, Denver, Colorado, 1966.

39. Hansen, T. C., and A. H. Mattock, "Influence of Size and Shape of Member on the Shrinkage and Creep of Concrete," Journal of the American Concrete Institute, Proceedings, Vol 63, No. 2, February 1966.

40. Barber, E. S., "Calculation of Maximum Pavement Temperatures from Weather Reports," HRB Bulletin 168, Highway Research Board, Washington, D. C., 1957.

41. Uddin, W., S. Nazarian, W. R. Hudson, A. H. Meyer, and K. H. Stokoe II, "Investigation into Dynaflect Deflections in Relation to Location/Temperature Parameters and Insitu Material Characterization of Rigid Pavements," Research Report 256-6, Center for Transportation Research, The University of Texas at Austin, December 1983.

42. Westergaard, H. M., "Analysis of Stresses in Concrete Roads Caused by Variations of Temperature, Public Roads, May 1927.

43. ACI Committee 325, "Proposed Design for Experimental Prestressed Pavement Slab, and Restrained Temperature Movements in Long Slabs," ACI Journal, Proceedings, Vol 64, No. 4, April 1968.

44. Barenberg, E. J., "Fundamentals of Prestressed Pavement Design," paper presented at the Annual Meeting of the ACI, Chicago, Ill., October 1985.

45. "Designing for Effects of Creep, Shrinkage and Temperature in Concrete Structures," ACI Special Publication Sp-27, ACI Journal, 1971.

46. Nilson, A. H., Design of Prestressed Concrete, John Wiley & Sons, 1978.

47. "Revised AASHTO Guide for Design of Pavement Structures," prepared for National Cooperative Highway Research Program and AASHTO Joint Task Force, ARE, Inc., 1986.

48. Ware, K. R., "EPIA Friction Test Results, Arabian Bechtel Company, Ltd., January 1982," ARE, Inc., August 1984.

49. Greenberg, M. D., Foundations of Applied Mathematics, Prentice-Hall, Inc., N. J., 1978.

50. Przemieniecki, J. S., Theory of Structural Analysis, McGraw-Hill, Inc., New York, 1968.

51. Neville, A. M., Properties of Concrete, Pitman Publishing Limited, London, 1978.

52. McCullough, B. F., and G. E. Elkins, CRC Pavement Design Manual, ARE, Inc., October 1979.

53. Maffei, J., Ned H. Burns, and B. Frank McCullough, "Instrumentation for Monitoring PCP Behavior," Research Report 401-4, Center for Transportation Research, The University of Texas at Austin, September 1986.

54. Nie, H. H. C. H. Hull, J. G. Jenkins, K. Steinbrenner, and D. H. Bent, SPSS Statistical Package for the Social Sciences, McGraw-Hill, Inc., New York, 2nd Edition, 1975.

55. BISAR User's Manual, Shell Research, Koninklijke/Shell Laboratorium, Amsterdam, July 1972.

56. "Standard Specifications for Transportation Materials and Methods of Sampling and Testing," AASHTO, 12th Edition, Part II, Methods of Sampling and Testing, September 1982.

57. "Thickness Design for Concrete Highway and Street Pavements," Portland Cement Asssociation, Skokie, Illinois, 1984.

58. "Prestressed Pavement, Vol. 2, Thickness Design," FHWA/RD-82/091, Final Report; June 1983.

59. "Prestressed Pavement Performance in Four States - A Panel Report," FHWA/RD-82/169, Final Report; September 1983.

60. "Prestressed Pavement, Vol. 1, Joint Design," FHWA/RD-82/090, Final Report; June 1983.

APPENDIX A

PREDICTIVE MODELS OF CONCRETE MODULUS OF ELASTICITY AND SHRINKAGE AND ESTIMATION OF CURLING AND WARPING DEFLECTIONS AND STRESSES

APPENDIX A. PREDUCTIVE MODELS OF CONCRETE MODULUS OF ELASTICITY AND SHRINKAGE AND ESTIMATION OF CURLING AND WARPING DEFLECTIONS AND STRESSES

Estimates of concrete modulus of elastricity and shrinkage as a function of time are needed in the approach presented in this study for predicting PCP behavior. The first section of this appendix will describe the models adopted from the literature for evaluating these concrete properties. The second section will present the Westergaard solution of deflections and stresses due to temperature and moisture gradients from top to bottom of the slabs.

CONCRETE PROPERTIES

Modulus of elasticity and shrinkage are the time dependent concrete properties discussed in this section.

Modulus of Elasticity

If the compressive strength-time relationship is known, the modulus of elasticity can be computed from the following relationship specified by the ACI (Ref 37):

$$E_c = \gamma^{1.5} \sqrt[33]{f'_c} \tag{A.1}$$

where

E_C	=	modulus of elasticity of concrete, psi
γ	=	unit weight of concrete, pcf,
f'_C	=	compressive strength, psi.

If the compressive strength as a function of time is not known, the predictoin of modulus of elasticity is still possible. Figure A.1 shows approximate typical values of the percentage of the 28-day compressive strength for various intermediate ages tested by the US Bureau of Reclamation (Ref 38). The only information required in this case is the compressive strength at 28 days. Users should find a typical plot of data shown in Fig A.1 which may be representative of the material user intends to use.

Concrete Shrinkage

Hansen and Mattock (Ref 39) suggest the following expression:

$$\frac{Z_t}{Z_t^{\infty}} = \frac{t}{M+t} \tag{A.2}$$

where

M	=	$26\ e^{0.36(V/S)}$
V	=	volume of the member in inches,
S	=	exposed surface area in inches,
t	=	time in days after concrete is set,
Z_t	=	drying shrinkage strain at time t,
Z_t^{∞}	=	final value of shrinkage strain.

In the case of pavement slabs, where drying occurs from the top surface, the ratio of volume to surface area is the thickness of the concrete slab.

Therefore,

V/S = pavement thickness D in inches.

CURLING AND WARPING RESTRAINT STRESSES

Deflections and stresses for temperature and moisture gradients from top to bottom of slabs may be determined using the principles of beams on elastic foundation. Westergaard (Ref 42) presents the solution for a slab with an infinite edge and extending infinitely in the X direction, perpendicularly to its edge.

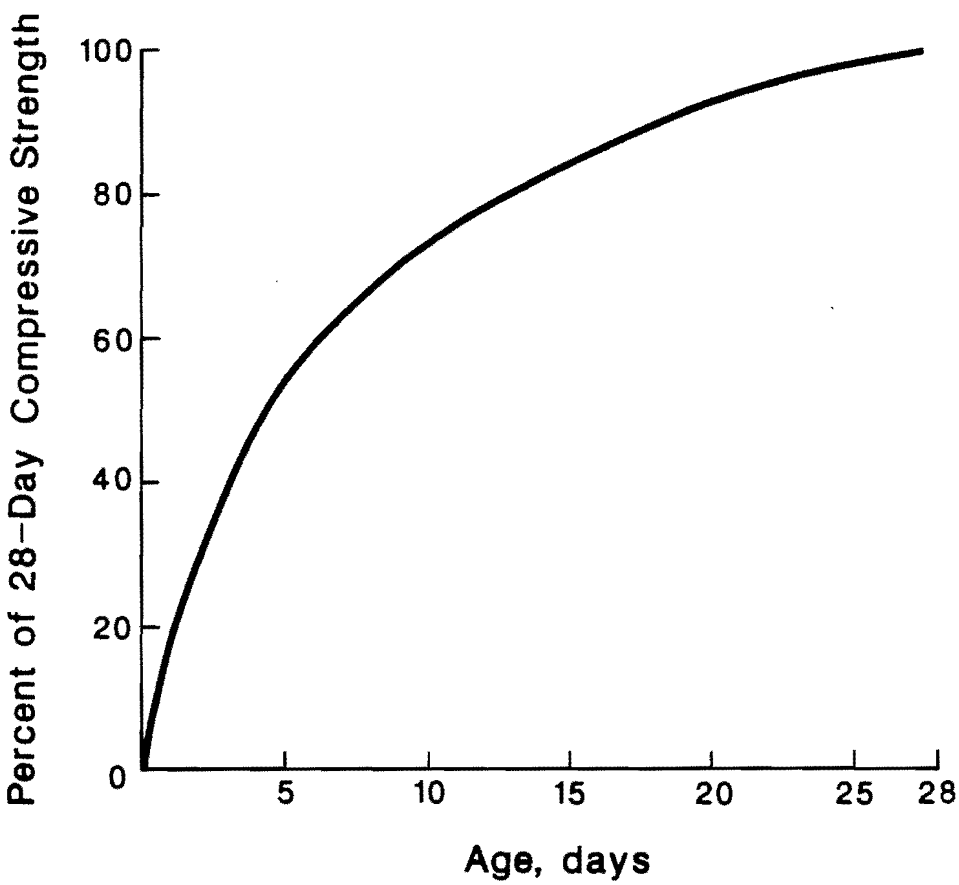


Fig A.1. Percent of the 28 day compressive strength versus concrete age after US Bureau of Reclamation (Ref 38).

Assumptions

(1) The vertical reaction to any section is directly proportional to the deflection Y, the proporionality constant k being the modulus of subgrade reaction.

(2) Zero deflection is at the position of rest on the level subgrade from the initial deflection w/k, w being the weight of the slab.

(3) Concrete is a homogeneous, linearly elastic material.

(4) Temperature or moisture differentials from top to bottom producing upward deflections are negative.

(5) Upward deflections are positive.

(6) Tensile stresses are positive.

(7) The origin of coordinates X is taken at the midslab.

General Equations

Assuming that the temperature is ΔT_D degrees higher at the top of the pavement than at the bottom, the curvature of the middle plane of the pavement in the X direction is

$$\frac{d^2Y}{DX^2} = \frac{12\,(1 - v^2)\,Mx}{E_c \bullet D^3} - \frac{(1 + v) \bullet \propto \bullet \Delta T_D}{D} \tag{A.3}$$

where

μ	=	concrete thermal coefficient of contraction and expansion,
v	=	Poisson's ratio of concrete,
M_X	=	bending moment in x direction per unit width, and
D and E_C	=	as defined above.

The equilibrium of any small element of the slab requires that,

$$\frac{d^2 Mx}{dX^2} = -K \bullet Y \tag{A.4}$$

Solutions

Combining Eqs A.3 and A.4 and introducing the radius of relative stiffness, l

$$l^4 \frac{d^4Y}{dX^4} + Y = 0 \tag{A.5}$$

where

$$l = \sqrt[4]{\frac{E_c \bullet D^3}{12\,(1 - v^2)\,k}} \tag{A6}$$

At the edge X = L/2, where L is the slab length, the bending moment M_X and the vertical shear dM_X/d_X must be 0. Therefore, the following solutions are correct for deflections:

$$Y = Y_e \sqrt{2} \bullet \cos\left(\frac{\frac{L}{2} - X}{1 \bullet \sqrt{2}} + \frac{\pi}{4}\right) e^{-\left(\frac{\frac{L}{2} - X}{l\sqrt{2}}\right)} \tag{A.7}$$

where Y_e is the deflection at the edge:

$$Y_e = \frac{(1 + v) \bullet \alpha \bullet \Delta T_D \bullet l^2}{D} \tag{A.8}$$

and by substituting these expressions in Equation A.7, the bending moment M_X is obtained. By dividing M_X by the section modulus per unit width, $D_2/6$, the tensile stress at the bottom of the slab at any location X is obtained.

$$f_{cx} = f_{co} \; 1 - \sqrt{2} \; \sin \left(\frac{\frac{L}{2} - X}{l\sqrt{2}} + \frac{\pi}{4} \right) e^{-\left(\frac{\frac{L}{2} - X}{l\sqrt{2}} \right)} \tag{A.9}$$

where f_{co} is the stress for the fully restrained curling deformation differential:

$$f_{co} = \frac{E_c \bullet \alpha \bullet \Delta T_D}{2 \, (1 - v)} \tag{A.11}$$

The same solutions can be applied to warping deflections and stresses, if the warping deformation from top to bottom w_D is introduced in the equations instead of the term ΔT_D.

APPENDIX B

USER MANUAL FOR COMPUTER PROGRAM PSCP1

APPENDIX B. USER MANUAL FOR COMPUTER PROGRAM PSCP1

This appendix provides the necessary input data instructions for operating the PSCP1 program. The user should refer to Chapter 6 for criteria on the selection of appropriate values for the data. The specification of a run should consist of one alphanumeric card with a description of the problem, followed by cards defining the problem, concrete properties, concrete compressive strength-age curve, slab-base friction relationship, k-value of slab support, steel properties, concrete temperature data for initial period, time and amount of prestress applied at each post-tensioning stage (at initial period), and temperature data for subsequent periods. The following pages provide a guide for data input. It should be noted that "real" variables can be placed anywhere in the available field but must be punched with a decimal point. Integer numbers, on the other hand, should be right justified in their field and punched without the decimal point. Alphanumeric variables allow the use of any combination of numbers and/or letters in an available field.

PCP1 - Guide for Data Input

PROBLEM IDENTIFICATION (One Card)

VECTOR1
(Alphanumeric) 20A4
1–80

PROBLEM DEFINITION (Two Cards)

Slab Length (ft) DL	Slab Depth (in) D
F10.0	F10.0
1	11–20

No. of Elements NILD	No. Max. Iterations NMAX	Tolerance (Percent) TOL
I5	I5	F10.0
1	6	11–20

CONCRETE PROPERTIES (One Card)

Thermal Coeff. (in/in-Deg.F) ALTOT	Ultimate Shrink. Strain ZTOT	Unit Weigth (pcf) G	Poisson Ratio PR	Creep Coefficient CREEP
F10.0	F10.0	F10.0	F10.0	F10.0
1	11	21	31	41–50

PCP1 - Guide for Data Input
(Continued)

AGE-COMPRESSIVE STRENGTH RELATIONSHIP

No. of Points KK		Age (Days) AGEU(1)	Strength (psi) COMP(1)				AGEU(7)	COMP(7)
I5		F5.0	F5.0	F5.0	F5.0		F5.0	F5.0
1 5		11	16	21	26	31	71	76 80

AGEU(8)	COMP(8)				AGEU(KK)	COMP(KK)
F5.0	F5.0	F5.0	F5.0		F5.0	F5.0
11	16	21	26	31	61	66 70

KK = 1, if no compressive strength data are available. The relationship will be generated by the program from the 28th day compressive strength. In this case, the 28th day should be input in COMP(1), and AGEU(1) should be equal 28.

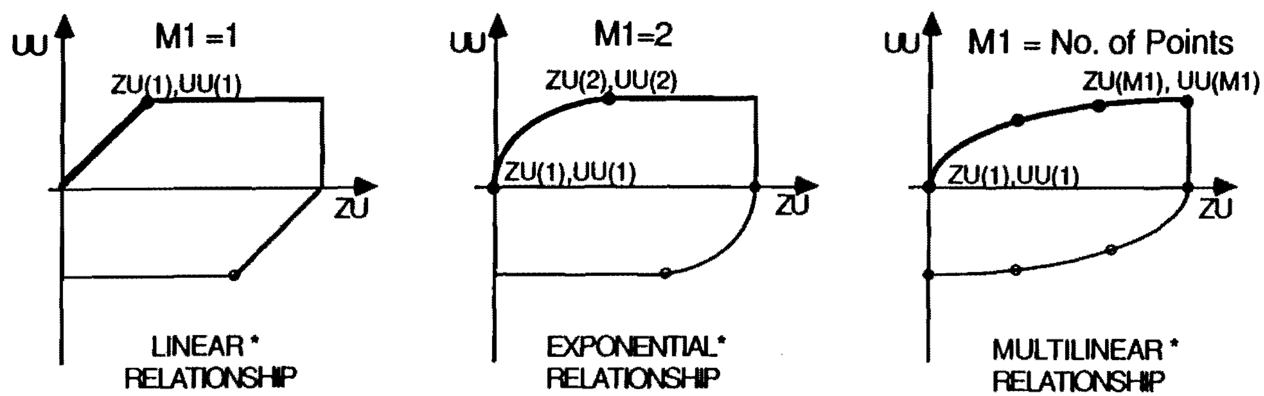
PCP1 - Guide for Data Input
(Continued)

COEFF. OF FRICTION-DISPLACEMENT RELATIONSHIP
(Z-U Relationship)

No. of Points M1
I5
1 5

Displ. (in) ZU(1)	Friction Coeff. UU(1)				ZU(7)	UU(7)
F5 .0	F5.0	F5.0	F5.0		F5.0	F5.0
11	16	21	26	31	71	76 80

ZU(8)	UU(8)				ZU(M1)	UU(M1)
F5.0	F5.0	F5.0	F5.0		F5.0	F5.0
11	16	21	26	31	61	66 70



* Only the thicker portion of the curve needs to be defined; the thinner portion is generated by the program.

PCP1 - Guide for Data Input
(Continued)

STIFFNESS OF SLAB SUPPORT (One Card)

K-Value (psi/in) SK
F10.0
1 – 10

STEEL PROPERTIES (One Card)

Strand Sp. (in) SS	Nominal Area of Strand (sq.in) SA	Yield Strength (ksi) FPY	Elastic Modulus (psi) ES	Thermal Coeff. (in/in-Deg.F) ALS
F10.0	F10.0	F10.0	F10.0	F10.0
1	11	21	31	41 – 50

SS = 0, if post-tensioning forces are not to be specified.

PCP1 - Guide for Data Input
(Continue)

TEMPERATURE DATA FOR INITIAL PERIOD

No. of Temp. Data NTEMP		Setting Hour CURH	Setting Temp. (Deg.F) CURTEMP
I5		F10.0	F10.0
1 5		11	21 30

CURH = Setting hour between 0.00 and 24.00 hours.

Mid-depth Temp. (Deg.F) ADT(1)	Top-To-Bottom Temp. Diff. (Deg.F) TDIF(1)
F10.0	F10.0
1	11 20

ADT(2)	TDIF(2)
F10.0	F10.0
1	11 20

ADT(NTEMP)	TDIF(NTEMP)
F10.0	F10.0
1	11 20

PCP1 - Guide for Data Input
(Continued)

SEQUENCE OF POST-TENSIONING APPLICATIONS DURING INITIAL PERIOD *
(* Specify only if SS = 0, and steel properties were provided)

No. of Post-Tensioning Stages
NS

I5
1 5

Time Since Setting (Hours) IAGE	Prestress Completed per Strand (Ksi) PS(1)
I5	F10.0
1 5	11 20

IAGE	PS(2)
I5	F10.0
1 5	11 20

IAGE	PS(NS)
I5	F10.0
1 5	11 20

PCP1 - Guide for Data Input
(Continued)

TEMPERATURE DATA FOR SUBSEQUENT PERIODS*

(*Repeat for as many subsequent periods as desired to analyze)

Time of Analysis Since Setting (Days) ITOA
I5
1 – 5

Mid-depth Temp. (Deg.F) ADT(1)	Top-To-Bottom Temp. Diff. (Deg.F) TDIF(1)
F10.0	F10.0
1	11 – 20

ADT(2)	TDIF(2)
F10.0	F10.0
1	11 – 20

ADT(12)	TDIF(12)
F10.0	F10.0
1	11 – 20

TERMINATION BLANK CARD...

1 – 80

APPENDIX C.

CODIFICATION OF DATA AND OUTPUT FROM COMPUTER PROGRAM PCP1 FOR THE DESIGN EXAMPLE PRESENTED IN CHAPTER 8

IDENTIFICATION EXAMPLE RUN CODED BY AHD DATE 04-16-1986 PAGE 1 OF 4

```
ANALYSIS AND DESIGN OF PRESTRESSED PAVEMENTS
200.      6.
   50  1000.5
0.000005  0.0003    150.      0.15      2.10
    1     28.  3000.
    7     0.   0.   0.0010.25 0.0020.40 0.0030.50 0.0040.6250.0070.74 0.02 0.76
500.
52.       0.216     270.      3000000.  0.000007
   18     14.       90.
95.       12.5
87.       -0.5
78.       -6.4
70.       -6.4
65.       -5.8
62.       -5.1
60.       -5.3
```

IDENTIFICATION *Example Run* CODED BY *LMC* DATE *04-16-1986* PAGE *2* OF *4*

Columns 1–10	Columns 11–20
57.	-5.1
57.	-2.5
65.	1.8
80.	17.4
90.	20.4
95.	12.5
87.	-0.5
78.	-6.4
70.	-6.4
65.	-5.8
62.	-5.1
2	
10	46.4
24	215.
7300	
57.	-2.5

IDENTIFICATION: EXAMPLE RUN CODED BY: AMC DATE: 04-16-1986 PAGE 3 OF 4

Columns 1–10	Columns 11–15
65.	1.8
80.	17.4
90.	20.4
95.	12.5
87.	-0.5
78.	-8.4
70.	-6.4
65.	-5.8
62.	-5.1
60.	-5.3
57.	-5.1
7300	
49.	-2.0
51.	1.4
56.	10.1
60.	11.8

IDENTIFICATION Example Run CODED BY AMD DATE 04-16-1986 PAGE 4 OF 4

Columns 1–10	Columns 11–15
59.	7.1
56.	-0.3
53.	-3.8
52.	-4.2
51.	-4.3
50.	-4.1
49.	-4.3
49.	-4.1

```
PPPPPP      CCCCC   PPPPPP       11
PPPPPPP    CCCCCCC  PPPPPPP     111
PP    PP  CC        PP    PP   1111
PP    PP  CC        PP    PP     11
PPPPPPP   CC        PPPPPPP      11
PPPPPP    CC        PPPPPP       11
PP         CCCCCCC  PP         11111111
PP          CCCCC   PP         11111111
```

```
***************************************************************
*                                                             *
*      ANALYSIS OF PRESTRESSED CONCRETE PAVEMENTS             *
*               CONSIDERING THE INELASTIC                     *
*       NATURE OF THE SLAB-BASE FRICTION FORCES               *
*              (VERSION 1, FEBRUARY 1986)                     *
*                                                             *
*          CENTER FOR TRANSPORTATION RESEARCH                 *
*           THE UNIVERSITY OF TEXAS AT AUSTIN                 *
*                                                             *
***************************************************************
```

```
*---*---*---*---*---*---*---*---*---*---*---*---*---*---*---*---*---*---*
*---*    ANALYSIS AND DESIGN OF PRESTRESSED PAVEMENT SLABS          *---*
*---*                 ECHO-PRINT OF GENERAL DATA                    *---*
*---*---*---*---*---*---*---*---*---*---*---*---*---*---*---*---*---*---*


          ********************************
          *     PROBLEM DEFINITION       *
          ********************************

              SLAB LENGTH (FT)          =     240.0
              SLAB THICKNESS (IN)       =       6.0
              NO.OF INCREMENTS          =        50
              MAX. NO. OF ITERATIONS    =       100
              REL. CLOSURE TOLERANCE    =        .5


          ********************************
          *     CONCRETE PROPERTIES      *
          ********************************

              THERMAL COEFFICIENT       =  .500E-05
              TOTAL SHRINKAGE           =  .300E-03
              UNIT WEIGHT (PCF)         =     150.0
              POISSON RATIO             =       .15
              CREEP COEFFICIENT         =      2.10
```

```
***********************************
*          COMPRESSIVE            *
*         STRENGTH DATA           *
***********************************

   THE FOLLOWING  STRENGTH RELATIONSHIP  WAS
DEVELOPED BASED ON THE RECOMMENDATION GIVEN
BY THE  U.S.  BUREAU OF RECLAMATION AND THE
28TH DAY COMPRES. STRENGTH PROVIDED BY USER
```

AGE (DAYS)	COMPRESSIVE STRENGTH
.0	.0
1.0	450.0
3.0	1140.0
5.0	1590.0
7.0	1890.0
14.0	2460.0
21.0	2820.0
28.0	3000.0

```
***********************************
* SLAB-BASE FRICTION PROPERTIES  *
*        Z-U RELATIONSHIP         *
***********************************

TYPE OF FRICTION CURVE IS A MULTILINEAR CURVE
```

Z(I)	U(I)
.000	.000
.001	.250
.002	.400
.003	.500
.004	.625
.007	.740
.020	.960

```
**********************************
*   STIFFNESS OF SLAB SUPPORT    *
**********************************

            K-VALUE OF SUPPORT(PCI) =    500.00


**********************************
*        STEEL PROPERTIES        *
**********************************

            PERCENT REINFORCEMENT   =      .113
            STRAND SPACING (IN)     =     32.00
            NOMINAL AREA (SQ.IN)    =      .216
            YIELD STRENGTH (KSI)    =    270.00
            ELASTIC MODULUS (PSI)   =  .300E+08
            THERMAL COEFFICIENT     =  .700E-05
```

ANALYSIS AND DESIGN OF PRESTRESSED PAVEMENT SLABS

PREDICTION OF PAVEMENT STRESSES FOR INITIAL PERIOD

CURING TEMP. (DEG.F) = 90.00

HOUR OF DAY	TEMP. AT MID-DEPTH (DEG.F)	TEMP. DIFF. (DEG.F)	PRESTRESS PER STRAND (KSI)
4 P.M.	95.0	12.5	.0
6 P.M.	87.0	-.5	.0
8 P.M.	78.0	-6.4	.0
10 P.M.	70.0	-6.4	.0
12 MIDNIGHT	65.0	-5.8	46.4
2 A.M.	62.0	-5.1	46.4
4 A.M.	60.0	-5.3	46.4
6 A.M.	57.0	-5.1	46.4
8 A.M.	57.0	-2.5	46.4
10 A.M.	65.0	1.8	46.4
12 NOON	80.0	17.4	46.4
2 P.M.	90.0	20.4	215.0
4 P.M.	95.0	12.5	215.0
6 P.M.	87.0	-.5	215.0
8 P.M.	78.0	-6.4	215.0
10 P.M.	70.0	-6.4	215.0
12 MIDNIGHT	65.0	-5.8	215.0
2 A.M.	62.0	-5.1	215.0

HOUR = 4 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-9.30	.00000	13.65
4.80	.00000	-.00071	-9.29	.00000	13.65
9.60	.00000	-.00164	-9.28	.00000	13.65
14.40	.00000	-.00185	-9.27	.00000	13.65
19.20	.00000	-.00174	-9.27	.00000	13.65
24.00	.00000	-.00152	-9.26	.00000	13.65
28.80	.00000	-.00129	-9.25	.00000	13.65
33.60	.00000	-.00112	-9.25	.00000	13.65
38.40	.00000	-.00105	-9.24	.00000	13.65
43.20	.00000	-.00111	-9.24	.00000	13.65
48.00	.00000	-.00135	-9.23	.00000	13.65
52.80	.00001	-.00183	-9.22	.00000	13.65
57.60	.00001	-.00267	-9.21	.00000	13.65
62.40	.00002	-.00405	-9.19	.00000	13.65
67.20	.00003	-.00625	-9.15	.00000	13.65
72.00	.00005	-.00972	-9.11	.00000	13.65
76.80	.00007	-.01518	-9.03	.00000	13.65
81.60	.00012	-.02373	-8.91	.00000	13.65
86.40	.00018	-.03711	-8.73	.00000	13.65
91.20	.00028	-.05806	-8.44	.00000	13.65
96.00	.00044	-.09085	-7.98	.00000	13.65
100.80	.00069	-.14215	-7.27	.00000	13.65
105.60	.00108	-.21801	-6.18	.00000	13.65
110.40	.00168	-.30711	-4.65	.00000	13.64
115.20	.00255	-.40317	-2.63	.00001	14.09
120.00	.00378	-.52588	.00	-.00140	.00

HOUR = 6 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	11.83	.00000	-.77
4.80	.00000	-.00064	11.83	.00000	-.77
9.60	.00001	-.00130	11.84	.00000	-.77
14.40	.00001	-.00105	11.84	.00000	-.77
19.20	.00001	-.00046	11.84	.00000	-.77
24.00	.00001	.00012	11.84	.00000	-.77
28.80	.00001	.00053	11.84	.00000	-.77
33.60	.00001	.00074	11.84	.00000	-.77
38.40	.00001	.00079	11.83	.00000	-.77
43.20	.00001	.00076	11.83	.00000	-.77
48.00	.00001	.00075	11.83	.00000	-.77
52.80	.00001	.00088	11.82	.00000	-.77
57.60	.00001	.00133	11.81	.00000	-.77
62.40	.00001	.00234	11.80	.00000	-.77
67.20	.00001	.00429	11.78	.00000	-.77
72.00	.00001	.00781	11.74	.00000	-.77
76.80	.00000	.01390	11.67	.00000	-.77
81.60	-.00001	.02427	11.55	.00000	-.77
86.40	-.00003	.04164	11.34	.00000	-.77
91.20	-.00007	.07047	10.99	.00000	-.77
96.00	-.00015	.11799	10.40	.00000	-.77
100.80	-.00028	.19583	9.42	.00000	-.77
105.60	-.00051	.29171	7.96	.00000	-.77
110.40	-.00087	.39701	5.98	.00000	-.77
115.20	-.00140	.53672	3.29	.00000	-.80
120.00	-.00216	.65895	.00	.00007	.00

HOUR = 8 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	HOT.CURLING STRESS(PSI)
.00	.00000	.00000	43.39	.00000	-12.10
4.80	.00001	-.00337	43.41	.00000	-12.10
9.60	.00001	-.00690	43.44	.00000	-12.10
14.40	.00001	-.00470	43.47	.00000	-12.10
19.20	.00000	.00168	43.46	.00000	-12.10
24.00	-.00002	.01063	43.41	.00000	-12.10
28.80	-.00006	.02101	43.30	.00000	-12.10
33.60	-.00011	.03239	43.14	.00000	-12.10
38.40	-.00017	.04522	42.91	.00000	-12.10
43.20	-.00025	.06085	42.61	.00000	-12.10
48.00	-.00035	.08154	42.20	.00000	-12.10
52.80	-.00049	.11040	41.65	.00000	-12.10
57.60	-.00069	.15164	40.89	.00000	-12.10
62.40	-.00097	.21077	39.84	.00000	-12.10
67.20	-.00135	.27594	38.46	.00000	-12.10
72.00	-.00187	.34673	36.72	.00000	-12.10
76.80	-.00256	.42536	34.60	.00000	-12.10
81.60	-.00346	.51799	32.01	.00000	-12.10
86.40	-.00461	.61392	28.94	.00000	-12.10
91.20	-.00604	.68472	25.51	.00000	-12.10
96.00	-.00776	.73723	21.83	.00000	-12.10
100.80	-.00980	.77978	17.93	.00000	-12.10
105.60	-.01216	.82231	13.82	.00000	-12.10
110.40	-.01483	.87314	9.45	.00000	-12.08
115.20	-.01783	.93039	4.80	-.00003	-12.62
120.00	-.02116	.96000	.00	.00094	.00

HOUR = 10 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	78.35	.00000	-13.98
4.80	-.00013	.01553	78.28	.00000	-13.98
9.60	-.00027	.04819	78.03	.00000	-13.98
14.40	-.00043	.08581	77.61	.00000	-13.98
19.20	-.00064	.13218	76.94	.00000	-13.98
24.00	-.00091	.19192	75.98	.00000	-13.98
28.80	-.00126	.25753	74.70	.00000	-13.98
33.60	-.00174	.32474	73.07	.00000	-13.98
38.40	-.00235	.39751	71.09	.00000	-13.98
43.20	-.00313	.47569	68.71	.00000	-13.98
48.00	-.00412	.57309	65.84	.00000	-13.98
52.80	-.00534	.65317	62.58	.00000	-13.98
57.60	-.00683	.70531	59.05	.00000	-13.98
62.40	-.00860	.75065	55.30	.00000	-13.98
67.20	-.01066	.78494	51.37	.00000	-13.98
72.00	-.01304	.82274	47.26	.00000	-13.98
76.80	-.01573	.86600	42.93	.00000	-13.98
81.60	-.01877	.91507	38.35	.00000	-13.98
86.40	-.02216	.95055	33.60	.00000	-13.98
91.20	-.02592	.96000	28.80	.00000	-13.98
96.00	-.03003	.96000	24.00	.00000	-13.98
100.80	-.03449	.96000	19.20	.00000	-13.98
105.60	-.03931	.96000	14.40	.00000	-13.98
110.40	-.04446	.96000	9.60	.00000	-13.95
115.20	-.04995	.96000	4.80	-.00004	-14.58
120.00	-.05576	.96000	.00	.00101	.00

HOUR = 12 MIDNIGHT

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	HOT.CURLING STRESS(PSI)
.00	.00000	.00000	61.07	.00000	-14.16
4.80	-.00346	.27855	59.68	.00000	-14.16
9.60	-.00708	.64918	56.43	.00000	-14.16
14.40	-.01095	.77398	52.56	.00000	-14.16
19.20	-.01509	.84179	48.35	.00000	-14.16
24.00	-.01954	.91456	43.78	.00000	-14.16
28.80	-.02432	.95612	39.00	.00000	-14.16
33.60	-.02943	.96000	34.20	.00000	-14.16
38.40	-.03488	.96000	29.40	.00000	-14.16
43.20	-.04065	.96000	24.60	.00000	-14.16
48.00	-.04676	.96000	19.80	.00000	-14.16
52.80	-.05321	.96000	15.00	.00000	-14.16
57.60	-.05999	.96000	10.20	.00000	-14.16
62.40	-.06711	.96000	5.40	.00000	-14.16
67.20	-.07456	.96000	.60	.00000	-14.16
72.00	-.08236	.96000	-4.20	.00000	-14.16
76.80	-.09050	.96000	-9.00	.00000	-14.16
81.60	-.09900	.96000	-13.80	.00000	-14.16
86.40	-.10785	.96000	-18.60	.00000	-14.16
91.20	-.11706	.96000	-23.40	.00000	-14.16
96.00	-.12665	.96000	-28.20	.00000	-14.16
100.80	-.13660	.96000	-33.00	.00000	-14.16
105.60	-.14694	.96000	-37.80	.00000	-14.16
110.40	-.15764	.96000	-42.60	.00000	-14.14
115.20	-.16871	.96000	-47.40	-.00005	-14.77
120.00	-.18014	.96000	-52.20	.00097	.00

HOUR = 2 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	62.66	.00000	-13.64
4.80	-.00492	.33004	61.01	.00000	-13.64
9.60	-.01000	.72541	57.38	.00000	-13.64
14.40	-.01533	.83585	53.20	.00000	-13.64
19.20	-.02094	.92048	48.60	.00000	-13.64
24.00	-.02685	.96000	43.80	.00000	-13.64
28.80	-.03306	.96000	39.00	.00000	-13.64
33.60	-.03958	.96000	34.20	.00000	-13.64
38.40	-.04640	.96000	29.40	.00000	-13.64
43.20	-.05353	.96000	24.60	.00000	-13.64
48.00	-.06096	.96000	19.80	.00000	-13.64
52.80	-.06870	.96000	15.00	.00000	-13.64
57.60	-.07675	.96000	10.20	.00000	-13.64
62.40	-.08511	.96000	5.40	.00000	-13.64
67.20	-.09378	.96000	.60	.00000	-13.64
72.00	-.10277	.96000	-4.20	.00000	-13.64
76.80	-.11209	.96000	-9.00	.00000	-13.64
81.60	-.12174	.96000	-13.80	.00000	-13.64
86.40	-.13172	.96000	-18.60	.00000	-13.64
91.20	-.14206	.96000	-23.40	.00000	-13.64
96.00	-.15275	.96000	-28.20	.00000	-13.64
100.80	-.16381	.96000	-33.00	.00000	-13.64
105.60	-.17523	.96000	-37.80	.00000	-13.64
110.40	-.18702	.96000	-42.60	.00000	-13.62
115.20	-.19916	.96000	-47.40	-.00005	-14.22
120.00	-.21165	.96000	-52.20	.00089	.00

HOUR = 4 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	HOT.CURLING STRESS(PSI)
.00	.00000	.00000	63.32	.00000	-15.31
4.80	-.00600	.35079	61.57	.00000	-15.31
9.60	-.01216	.76444	57.75	.00000	-15.31
14.40	-.01857	.88150	53.34	.00000	-15.31
19.20	-.02524	.94784	48.60	.00000	-15.31
24.00	-.03219	.96000	43.80	.00000	-15.31
28.80	-.03943	.96000	39.00	.00000	-15.31
33.60	-.04694	.96000	34.20	.00000	-15.31
38.40	-.05474	.96000	29.40	.00000	-15.31
43.20	-.06283	.96000	24.60	.00000	-15.31
48.00	-.07119	.96000	19.80	.00000	-15.31
52.80	-.07984	.96000	15.00	.00000	-15.31
57.60	-.08877	.96000	10.20	.00000	-15.31
62.40	-.09799	.96000	5.40	.00000	-15.31
67.20	-.10751	.96000	.60	.00000	-15.31
72.00	-.11731	.96000	-4.20	.00000	-15.31
76.80	-.12742	.96000	-9.00	.00000	-15.31
81.60	-.13784	.96000	-13.80	.00000	-15.31
86.40	-.14857	.96000	-18.60	.00000	-15.31
91.20	-.15962	.96000	-23.40	.00000	-15.31
96.00	-.17100	.96000	-28.20	.00000	-15.31
100.80	-.18272	.96000	-33.00	.00000	-15.31
105.60	-.19477	.96000	-37.80	.00000	-15.31
110.40	-.20715	.96000	-42.60	.00000	-15.29
115.20	-.21986	.96000	-47.40	-.00006	-15.95
120.00	-.23288	.96000	-52.20	.00097	.00

HOUR = 6 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	63.88	.00000	-15.75
4.80	-.00728	.37232	62.01	.00000	-15.75
9.60	-.01472	.80758	57.98	.00000	-15.75
14.40	-.02239	.91525	53.40	.00000	-15.75
19.20	-.03032	.96000	48.60	.00000	-15.75
24.00	-.03852	.96000	43.80	.00000	-15.75
28.80	-.04698	.96000	39.00	.00000	-15.75
33.60	-.05570	.96000	34.20	.00000	-15.75
38.40	-.06469	.96000	29.40	.00000	-15.75
43.20	-.07394	.96000	24.60	.00000	-15.75
48.00	-.08346	.96000	19.80	.00000	-15.75
52.80	-.09325	.96000	15.00	.00000	-15.75
57.60	-.10331	.96000	10.20	.00000	-15.75
62.40	-.11369	.96000	5.40	.00000	-15.75
67.20	-.12425	.96000	.60	.00000	-15.75
72.00	-.13514	.96000	-4.20	.00000	-15.75
76.80	-.14632	.96000	-9.00	.00000	-15.75
81.60	-.15781	.96000	-13.80	.00000	-15.75
86.40	-.16961	.96000	-18.60	.00000	-15.75
91.20	-.18173	.96000	-23.40	.00000	-15.75
96.00	-.19418	.96000	-28.20	.00000	-15.75
100.80	-.20697	.96000	-33.00	.00000	-15.75
105.60	-.22009	.96000	-37.80	.00000	-15.75
110.40	-.23355	.96000	-42.60	.00000	-15.73
115.20	-.24733	.96000	-47.40	-.00006	-16.39
120.00	-.26145	.96000	-52.20	.00096	.00

HOUR = 8 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	63.97	.00000	-8.19
4.80	-.00764	.37540	62.09	.00000	-8.19
9.60	-.01544	.81673	58.01	.00000	-8.19
14.40	-.02345	.92134	53.40	.00000	-8.19
19.20	-.03172	.96000	48.60	.00000	-8.19
24.00	-.04023	.96000	43.80	.00000	-8.19
28.80	-.04899	.96000	39.00	.00000	-8.19
33.60	-.05799	.96000	34.20	.00000	-8.19
38.40	-.06725	.96000	29.40	.00000	-8.19
43.20	-.07676	.96000	24.60	.00000	-8.19
48.00	-.08652	.96000	19.80	.00000	-8.19
52.80	-.09653	.96000	15.00	.00000	-8.19
57.60	-.10680	.96000	10.20	.00000	-8.19
62.40	-.11732	.96000	5.40	.00000	-8.19
67.20	-.12811	.96000	.60	.00000	-8.19
72.00	-.13916	.96000	-4.20	.00000	-8.19
76.80	-.15049	.96000	-9.00	.00000	-8.19
81.60	-.16210	.96000	-13.80	.00000	-8.19
86.40	-.17401	.96000	-18.60	.00000	-8.19
91.20	-.18622	.96000	-23.40	.00000	-8.19
96.00	-.19874	.96000	-28.20	.00000	-8.19
100.80	-.21157	.96000	-33.00	.00000	-8.19
105.60	-.22472	.96000	-37.80	.00000	-8.19
110.40	-.23819	.96000	-42.60	.00000	-8.18
115.20	-.25195	.96000	-47.40	-.00003	-8.51
120.00	-.26600	.96000	-52.20	.00049	.00

HOUR =   10 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	16.06	.00000	6.22
4.80	-.00800	.37844	14.17	.00000	6.22
9.60	-.01615	.82580	10.04	.00000	6.22
14.40	-.02451	.92736	5.40	.00000	6.22
19.20	-.03310	.96000	.60	.00000	6.22
24.00	-.04194	.96000	-4.20	.00000	6.22
28.80	-.05101	.96000	-9.00	.00000	6.22
33.60	-.06033	.96000	-13.80	.00000	6.22
38.40	-.06990	.96000	-18.60	.00000	6.22
43.20	-.07974	.96000	-23.40	.00000	6.22
48.00	-.08984	.96000	-28.20	.00000	6.22
52.80	-.10023	.96000	-33.00	.00000	6.22
57.60	-.11091	.96000	-37.80	.00000	6.22
62.40	-.12190	.96000	-42.60	.00000	6.22
67.20	-.13320	.96000	-47.40	.00000	6.22
72.00	-.14483	.96000	-52.20	.00000	6.22
76.80	-.15189	.17512	-59.34	.00000	6.22
81.60	-.16358	.21773	-60.43	.00000	6.22
86.40	-.17539	.21324	-61.49	.00000	6.22
91.20	-.18730	.16195	-62.30	.00000	6.22
96.00	-.19931	.06153	-62.61	.00000	6.22
100.80	-.21141	-.09349	-62.14	.00000	6.22
105.60	-.22354	-.27420	-60.77	.00000	6.21
110.40	-.23566	-.43659	-58.59	.00000	6.21
115.20	-.24773	-.58258	-55.68	.00003	6.45
120.00	-.25969	-.69517	-52.20	-.00036	.00

HOUR = 12 NOON

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-90.98	.00000	63.01
4.80	-.00829	.07985	-91.38	.00000	63.01
9.60	-.01663	.21754	-92.46	.00000	63.01
14.40	-.02504	.30455	-93.99	.00000	63.01
19.20	-.03355	.35257	-95.75	.00000	63.01
24.00	-.04218	.38064	-97.65	.00000	63.01
28.80	-.05092	.38969	-99.60	.00000	63.01
33.60	-.05979	.38082	-101.50	.00000	63.01
38.40	-.06878	.35097	-103.26	.00000	63.01
43.20	-.07787	.30104	-104.76	.00000	63.01
48.00	-.08705	.20598	-105.79	.00000	63.01
52.80	-.09629	.04492	-106.02	.00000	63.01
57.60	-.10554	-.16754	-105.18	.00000	63.01
62.40	-.11476	-.36869	-103.33	.00000	63.01
67.20	-.12390	-.54310	-100.62	.00000	63.01
72.00	-.13294	-.67121	-97.26	.00000	63.01
76.80	-.14192	-.73841	-93.57	.00000	63.01
81.60	-.15076	-.79026	-89.62	.00000	63.01
86.40	-.15947	-.84079	-85.42	.00000	63.01
91.20	-.16804	-.89857	-80.92	.00000	63.01
96.00	-.17647	-.94465	-76.20	.00000	63.01
100.80	-.18476	-.96000	-71.40	.00000	63.01
105.60	-.19289	-.96000	-66.60	.00000	63.01
110.40	-.20084	-.96000	-61.80	-.00002	62.99
115.20	-.20860	-.96000	-57.00	.00028	65.32
120.00	-.21619	-.96000	-52.20	-.00355	.00

HOUR = 2 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-163.58	.00000	77.16
4.80	-.00867	.04669	-163.82	.00000	77.16
9.60	-.01736	.13840	-164.51	.00000	77.16
14.40	-.02612	.22231	-165.62	.00000	77.16
19.20	-.03495	.28558	-167.05	.00000	77.16
24.00	-.04389	.33311	-168.71	.00000	77.16
28.80	-.05294	.37896	-170.61	.00000	77.16
33.60	-.06212	.41699	-172.69	.00000	77.16
38.40	-.07143	.44888	-174.94	.00000	77.16
43.20	-.08088	.48356	-177.36	.00000	77.16
48.00	-.09048	.52819	-180.00	.00000	77.16
52.80	-.10024	.58707	-182.93	.00000	77.16
57.60	-.11016	.63433	-186.10	.00000	77.16
62.40	-.12025	.66583	-189.43	.00000	77.16
67.20	-.13052	.70414	-192.95	.00000	77.16
72.00	-.14098	.74167	-196.66	.00000	77.16
76.80	-.15170	.77230	-200.52	.00000	77.16
81.60	-.16262	.80453	-204.55	.00000	77.16
86.40	-.17378	.84270	-208.76	.00000	77.16
91.20	-.18519	.88726	-213.20	.00000	77.16
96.00	-.19687	.93560	-217.88	.00000	77.16
100.80	-.20884	.96000	-222.68	.00000	77.16
105.60	-.22110	.96000	-227.48	.00000	77.15
110.40	-.23365	.96000	-232.28	-.00002	77.15
115.20	-.24649	.96000	-237.08	.00035	79.88
120.00	-.25959	.96000	-241.88	-.00425	.00

HOUR = 4 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-194.76	.00000	48.77
4.80	-.00869	.04981	-195.01	.00000	48.77
9.60	-.01742	.14812	-195.75	.00000	48.77
14.40	-.02620	.23536	-196.93	.00000	48.77
19.20	-.03507	.30137	-198.44	.00000	48.77
24.00	-.04405	.35548	-200.21	.00000	48.77
28.80	-.05315	.40324	-202.23	.00000	48.77
33.60	-.06238	.44254	-204.44	.00000	48.77
38.40	-.07175	.48025	-206.84	.00000	48.77
43.20	-.08126	.52564	-209.47	.00000	48.77
48.00	-.09092	.58129	-212.38	.00000	48.77
52.80	-.10075	.62655	-215.51	.00000	48.77
57.60	-.11070	.65568	-218.79	.00000	48.77
62.40	-.12085	.68622	-222.22	.00000	48.77
67.20	-.13113	.72320	-225.84	.00000	48.77
72.00	-.14162	.75519	-229.61	.00000	48.77
76.80	-.15236	.78227	-233.52	.00000	48.77
81.60	-.16333	.81532	-237.60	.00000	48.77
86.40	-.17454	.85491	-241.88	.00000	48.77
91.20	-.18548	.03609	-247.26	.00000	48.77
96.00	-.19711	.04712	-247.49	.00000	48.77
100.80	-.20883	.01050	-247.54	.00000	48.77
105.60	-.22063	-.07726	-247.16	.00000	48.76
110.40	-.23248	-.21009	-246.11	-.00002	48.77
115.20	-.24434	-.35365	-244.34	.00022	50.43
120.00	-.25617	-.49273	-241.88	-.00265	.00

HOUR = 6 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-168.52	.00000	-2.01
4.80	-.00997	.17579	-169.40	.00000	-2.01
9.60	-.02001	.44999	-171.65	.00000	-2.01
14.40	-.03019	.60873	-174.69	.00000	-2.01
19.20	-.04053	.70410	-178.21	.00000	-2.01
24.00	-.05105	.75543	-181.99	.00000	-2.01
28.80	-.06178	.78849	-185.93	.00000	-2.01
33.60	-.07270	.82255	-190.04	.00000	-2.01
38.40	-.08384	.85817	-194.33	.00000	-2.01
43.20	-.09520	.89555	-198.81	.00000	-2.01
48.00	-.10678	.93508	-203.49	.00000	-2.01
52.80	-.11860	.95772	-208.28	.00000	-2.01
57.60	-.13065	.96000	-213.08	.00000	-2.01
62.40	-.14294	.96000	-217.88	.00000	-2.01
67.20	-.15548	.96000	-222.68	.00000	-2.01
72.00	-.16828	.96000	-227.48	.00000	-2.01
76.80	-.18140	.96000	-232.28	.00000	-2.01
81.60	-.19481	.96000	-237.08	.00000	-2.01
86.40	-.20852	.96000	-241.88	.00000	-2.01
91.20	-.24003	.96000	-213.08	.00000	-2.01
96.00	-.25268	.96000	-217.88	.00000	-2.01
100.80	-.26582	.96000	-222.68	.00000	-2.01
105.60	-.27949	.96000	-227.48	.00000	-2.01
110.40	-.29370	.96000	-232.28	.00000	-2.01
115.20	-.30850	.96000	-237.08	-.00001	-2.07
120.00	-.32389	.96000	-241.88	.00011	.00

HOUR = 8 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-130.34	.00000	-26.43
4.80	-.01197	.23997	-131.54	.00000	-26.43
9.60	-.02301	.58418	-134.46	.00000	-26.43
14.40	-.03469	.72747	-138.10	.00000	-26.43
19.20	-.04654	.79215	-142.06	.00000	-26.43
24.00	-.05857	.84379	-146.28	.00000	-26.43
28.80	-.07081	.89694	-150.77	.00000	-26.43
33.60	-.08328	.94196	-155.48	.00000	-26.43
38.40	-.09599	.96000	-160.28	.00000	-26.43
43.20	-.10897	.96000	-165.08	.00000	-26.43
48.00	-.12224	.96000	-169.88	.00000	-26.43
52.80	-.13583	.96000	-174.68	.00000	-26.43
57.60	-.14980	.96000	-179.48	.00000	-26.43
62.40	-.16420	.96000	-184.28	.00000	-26.43
67.20	-.17908	.96000	-189.08	.00000	-26.43
72.00	-.19449	.96000	-193.88	.00000	-26.43
76.80	-.21052	.96000	-198.68	.00000	-26.43
81.60	-.22714	.96000	-203.48	.00000	-26.43
86.40	-.24439	.96000	-208.28	.00000	-26.43
91.20	-.25939	.96000	-213.08	.00000	-26.43
96.00	-.27477	.96000	-217.88	.00000	-26.43
100.80	-.29067	.96000	-222.68	.00000	-26.43
105.60	-.30711	.96000	-227.48	.00000	-26.42
110.40	-.32413	.96000	-232.28	.00001	-26.44
115.20	-.34176	.96000	-237.08	-.00012	-27.27
120.00	-.36002	.96000	-241.88	.00139	.00

HOUR = 10 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-126.94	.00000	-27.13
4.80	-.01377	.33359	-128.61	.00000	-27.13
9.60	-.02764	.73129	-132.26	.00000	-27.13
14.40	-.04166	.84001	-136.46	.00000	-27.13
19.20	-.05587	.92231	-141.08	.00000	-27.13
24.00	-.07029	.96000	-145.88	.00000	-27.13
28.80	-.08493	.96000	-150.68	.00000	-27.13
33.60	-.09980	.96000	-155.48	.00000	-27.13
38.40	-.11491	.96000	-160.28	.00000	-27.13
43.20	-.13029	.96000	-165.08	.00000	-27.13
48.00	-.14594	.96000	-169.88	.00000	-27.13
52.80	-.16192	.96000	-174.68	.00000	-27.13
57.60	-.17827	.96000	-179.48	.00000	-27.13
62.40	-.19505	.96000	-184.28	.00000	-27.13
67.20	-.21231	.96000	-189.08	.00000	-27.13
72.00	-.23010	.96000	-193.88	.00000	-27.13
76.80	-.24851	.96000	-198.68	.00000	-27.13
81.60	-.26751	.96000	-203.48	.00000	-27.13
86.40	-.28714	.96000	-208.28	.00000	-27.13
91.20	-.30454	.96000	-213.08	.00000	-27.13
96.00	-.32232	.96000	-217.88	.00000	-27.13
100.80	-.34063	.96000	-222.68	.00000	-27.13
105.60	-.35949	.96000	-227.48	.00000	-27.12
110.40	-.37895	.96000	-232.28	.00001	-27.15
115.20	-.39902	.96000	-237.08	-.00013	-27.97
120.00	-.41974	.96000	-241.88	.00141	.00

HOUR = 12 MIDNIGHT

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-126.01	.00000	-25.20
4.80	-.01529	.36281	-127.83	.00000	-25.20
9.60	-.03069	.78637	-131.76	.00000	-25.20
14.40	-.04626	.90355	-136.28	.00000	-25.20
19.20	-.06201	.96000	-141.08	.00000	-25.20
24.00	-.07797	.96000	-145.88	.00000	-25.20
28.80	-.09415	.96000	-150.68	.00000	-25.20
33.60	-.11055	.96000	-155.48	.00000	-25.20
38.40	-.12719	.96000	-160.28	.00000	-25.20
43.20	-.14409	.96000	-165.08	.00000	-25.20
48.00	-.16127	.96000	-169.88	.00000	-25.20
52.80	-.17876	.96000	-174.68	.00000	-25.20
57.60	-.19663	.96000	-179.48	.00000	-25.20
62.40	-.21492	.96000	-184.28	.00000	-25.20
67.20	-.23370	.96000	-189.08	.00000	-25.20
72.00	-.25300	.96000	-193.88	.00000	-25.20
76.80	-.27293	.96000	-198.68	.00000	-25.20
81.60	-.29345	.96000	-203.48	.00000	-25.20
86.40	-.31461	.96000	-208.28	.00000	-25.20
91.20	-.33555	.96000	-213.08	.00000	-25.20
96.00	-.35288	.96000	-217.88	.00000	-25.20
100.80	-.37275	.96000	-222.68	.00000	-25.20
105.60	-.39319	.96000	-227.48	.00000	-25.19
110.40	-.41425	.96000	-232.28	.00001	-25.23
115.20	-.43590	.96000	-237.08	-.00012	-25.96
120.00	-.45823	.96000	-241.88	.00130	.00

HOUR = 2 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-125.73	.00000	-22.69
4.80	-.01626	.37500	-127.60	.00000	-22.69
9.60	-.03262	.81490	-131.68	.00000	-22.69
14.40	-.04915	.91990	-136.28	.00000	-22.69
19.20	-.06587	.96000	-141.08	.00000	-22.69
24.00	-.08280	.96000	-145.88	.00000	-22.69
28.80	-.09993	.96080	-150.68	.00000	-22.69
33.60	-.11728	.96000	-155.48	.00000	-22.69
38.40	-.13487	.96000	-160.28	.00000	-22.69
43.20	-.15271	.96000	-165.08	.00000	-22.69
48.00	-.17083	.96000	-169.88	.00000	-22.69
52.80	-.18927	.96000	-174.68	.00000	-22.69
57.60	-.20807	.96000	-179.48	.00000	-22.69
62.40	-.22730	.96000	-184.28	.00000	-22.69
67.20	-.24702	.96000	-189.08	.00000	-22.69
72.00	-.26726	.96000	-193.88	.00000	-22.69
76.80	-.28814	.96000	-198.68	.00000	-22.69
81.60	-.30963	.96000	-203.48	.00000	-22.69
86.40	-.33176	.96000	-208.28	.00000	-22.69
91.20	-.35168	.96000	-213.08	.00000	-22.69
96.00	-.37201	.96000	-217.88	.00000	-22.69
100.80	-.39289	.96000	-222.68	.00000	-22.69
105.60	-.41435	.96000	-227.48	.00000	-22.68
110.40	-.43643	.96000	-232.28	.00001	-22.72
115.20	-.45916	.96000	-237.08	-.00011	-23.35
120.00	-.48254	.96000	-241.88	.00115	.00

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--- ANALYSIS AND DESIGN OF PRESTRESSED PAVEMENT SLABS *---*

--- PREDICTION OF PAVEMENT STRESSES FOR INTERMEDIATE/FINAL PERIOD *---*

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TIME OF ANALYSIS FROM END
OF MOIST CURING (DAYS) = 7300

HOUR OF DAY	TEMP. AT MID-DEPTH (DEG.F)	TEMP. DIFF. (DEG.F)	PRESTRESS PER STRAND (KSI)
8 A.M.	57.0	-2.5	168.3
10 A.M.	65.0	1.8	168.3
12 NOON	80.0	17.4	168.3
2 P.M.	90.0	20.4	168.3
4 P.M.	95.0	12.5	168.3
6 P.M.	87.0	-.5	168.3
8 P.M.	78.0	-6.4	168.3
10 P.M.	70.0	-6.4	168.3
12 MIDNIGHT	65.0	-5.8	168.3
2 A.M.	62.0	-5.1	168.3
4 A.M.	60.0	-5.3	168.3
6 A.M.	57.0	-5.1	168.3

HOUR = 8 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	ROT.CURLING STRESS(PSI)
.00	.00000	.00000	-73.40	.00000	-24.42
4.80	-.05192	.36909	-75.24	.00000	-24.42
9.60	-.10406	.79837	-79.23	.00000	-24.42
14.40	-.15648	.90928	-83.78	.00000	-24.42
19.20	-.20920	.96000	-88.58	.00000	-24.42
24.00	-.26222	.96000	-93.38	.00000	-24.42
28.80	-.31549	.96000	-98.18	.00000	-24.42
33.60	-.36898	.96000	-102.98	.00000	-24.42
38.40	-.42265	.96000	-107.78	.00000	-24.42
43.20	-.47647	.96000	-112.58	.00000	-24.42
48.00	-.53041	.96000	-117.38	.00000	-24.42
52.80	-.58443	.96000	-122.18	.00000	-24.42
57.60	-.63853	.96000	-126.98	.00000	-24.42
62.40	-.69268	.96000	-131.78	.00000	-24.42
67.20	-.74687	.96000	-136.58	.00000	-24.42
72.00	-.80109	.96000	-141.38	.00000	-24.42
76.80	-.85532	.96000	-146.18	.00000	-24.42
81.60	-.90958	.96000	-150.98	.00000	-24.42
86.40	-.96384	.96000	-155.78	.00000	-24.42
91.20	-1.01812	.96000	-160.58	.00000	-24.42
96.00	-1.07240	.96000	-165.38	.00000	-24.42
100.80	-1.12668	.96000	-170.18	.00000	-24.42
105.60	-1.18097	.96000	-174.98	.00000	-24.37
110.40	-1.23526	.96000	-179.78	.00001	-24.82
115.20	-1.28955	.96000	-184.58	-.00015	-23.72
120.00	-1.34384	.96000	-189.38	.00084	.00

HOUR = 10 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-223.90	.00000	17.58
4.80	-.05222	.03741	-224.09	.00000	17.58
9.60	-.10461	.10692	-224.62	.00000	17.58
14.40	-.15722	.16335	-225.44	.00000	17.58
19.20	-.21007	.20371	-226.46	.00000	17.58
24.00	-.26314	.22727	-227.60	.00000	17.58
28.80	-.31641	.23383	-228.76	.00000	17.58
33.60	-.36983	.22320	-229.88	.00000	17.58
38.40	-.42336	.19498	-230.86	.00000	17.58
43.20	-.47697	.14856	-231.60	.00000	17.58
48.00	-.53061	.08322	-232.01	.00000	17.58
52.80	-.58427	-.00200	-232.00	.00000	17.58
57.60	-.63790	-.10825	-231.46	.00000	17.58
62.40	-.69149	-.22552	-230.34	.00000	17.58
67.20	-.74501	-.33375	-228.67	.00000	17.58
72.00	-.79845	-.42426	-226.55	.00000	17.58
76.80	-.85180	-.51564	-223.97	.00000	17.58
81.60	-.90504	-.60550	-220.94	.00000	17.58
86.40	-.95816	-.66649	-217.61	.00000	17.58
91.20	-1.01116	-.71209	-214.05	.00000	17.58
96.00	-1.06403	-.74913	-210.30	.00000	17.58
100.80	-1.11675	-.77526	-206.42	.00000	17.58
105.60	-1.16932	-.80305	-202.41	.00000	17.55
110.40	-1.22172	-.83376	-198.24	.00000	17.87
115.20	-1.27396	-.86756	-193.90	.00010	17.08
120.00	-1.32600	-.90465	-189.38	-.00060	.08

HOUR = 12 NOON

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-300.83	.00000	169.93
4.80	-.04922	-.23524	-299.66	.00000	169.93
9.60	-.09856	-.57639	-296.77	.00000	169.93
14.40	-.14806	-.72314	-293.16	.00000	169.93
19.20	-.19772	-.78992	-289.21	.00000	169.93
24.00	-.24751	-.84314	-284.99	.00000	169.93
28.80	-.29740	-.89901	-280.58	.00000	169.93
33.60	-.34735	-.94381	-275.78	.00000	169.93
38.40	-.39731	-.96000	-270.98	.00000	169.93
43.20	-.44725	-.96000	-266.18	.00000	169.93
48.00	-.49714	-.96000	-261.38	.00000	169.93
52.80	-.54696	-.96000	-256.58	.00000	169.93
57.60	-.59667	-.96000	-251.78	.00000	169.93
62.40	-.64626	-.96000	-246.98	.00000	169.93
67.20	-.69572	-.96000	-242.18	.00000	169.93
72.00	-.74503	-.96000	-237.38	.00000	169.93
76.80	-.79418	-.96000	-232.58	.00000	169.93
81.60	-.84316	-.96000	-227.78	.00000	169.93
86.40	-.89196	-.96000	-222.98	.00000	169.93
91.20	-.94058	-.96000	-218.18	.00000	169.93
96.00	-.98900	-.96000	-213.38	.00000	169.94
100.80	-1.03721	-.96000	-208.58	.00000	169.94
105.60	-1.08522	-.96000	-203.78	-.00001	169.63
110.40	-1.13302	-.96000	-198.98	-.00004	172.74
115.20	-1.18059	-.96000	-194.18	.00092	165.11
120.00	-1.22795	-.96000	-189.38	-.00583	.00

HOUR = 2 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-304.59	.00000	199.23
4.80	-.04640	-.34171	-302.88	.00000	199.23
9.60	-.09291	-.74679	-299.14	.00000	199.23
14.40	-.13957	-.85895	-294.85	.00000	199.23
19.20	-.18637	-.93387	-290.18	.00000	199.23
24.00	-.23329	-.96000	-285.38	.00000	199.23
28.80	-.28030	-.96000	-280.58	.00000	199.23
33.60	-.32737	-.96000	-275.78	.00000	199.23
38.40	-.37445	-.96000	-270.98	.00000	199.23
43.20	-.42151	-.96000	-266.18	.00000	199.23
48.00	-.46851	-.96000	-261.38	.00000	199.23
52.80	-.51543	-.96000	-256.58	.00000	199.23
57.60	-.56225	-.96000	-251.78	.00000	199.23
62.40	-.60893	-.96000	-246.98	.00000	199.23
67.20	-.65547	-.96000	-242.18	.00000	199.23
72.00	-.70184	-.96000	-237.38	.00000	199.23
76.80	-.74804	-.96000	-232.58	.00000	199.23
81.60	-.79405	-.96000	-227.78	.00000	199.23
86.40	-.83986	-.96000	-222.98	.00000	199.23
91.20	-.88546	-.96000	-218.18	.00000	199.23
96.00	-.93084	-.96000	-213.38	.00000	199.24
100.80	-.97601	-.96000	-208.58	.00000	199.24
105.60	-1.02094	-.96000	-203.78	-.00001	198.88
110.40	-1.06565	-.96000	-198.98	-.00005	202.52
115.20	-1.11013	-.96000	-194.18	.00108	193.58
120.00	-1.15437	-.96000	-189.38	-.00684	.00

HOUR = 4 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-305.36	.00000	122.08
4.80	-.04497	-.36907	-303.52	.00000	122.08
9.60	-.09085	-.79834	-299.53	.00000	122.08
14.40	-.13527	-.90927	-294.98	.00000	122.08
19.20	-.18064	-.96000	-290.18	.00000	122.08
24.00	-.22612	-.96000	-285.38	.00000	122.08
28.80	-.27169	-.96000	-280.58	.00000	122.08
33.60	-.31731	-.96000	-275.78	.00000	122.08
38.40	-.36295	-.96000	-270.98	.00000	122.08
43.20	-.40856	-.96000	-266.18	.00000	122.08
48.00	-.45412	-.96000	-261.38	.00000	122.08
52.80	-.49959	-.96000	-256.58	.00000	122.08
57.60	-.54494	-.96000	-251.78	.00000	122.08
62.40	-.59016	-.96000	-246.98	.00000	122.08
67.20	-.63522	-.96000	-242.18	.00000	122.08
72.00	-.68010	-.96000	-237.38	.00000	122.08
76.80	-.72480	-.96000	-232.58	.00000	122.08
81.60	-.76930	-.96000	-227.78	.00000	122.08
86.40	-.81359	-.96000	-222.98	.00000	122.08
91.20	-.85765	-.96000	-218.18	.00000	122.08
96.00	-.90149	-.96000	-213.38	.00000	122.08
100.80	-.94510	-.96000	-208.58	.00000	122.08
105.60	-.98848	-.96000	-203.78	.00000	121.86
110.40	-1.03163	-.96000	-198.98	-.00003	124.09
115.20	-1.07454	-.96000	-194.18	.00066	118.61
120.00	-1.11723	-.96000	-189.38	-.00419	.00

HOUR = 6 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-154.84	.00000	-4.88
4.80	-.04467	-.03741	-154.66	.00000	-4.88
9.60	-.08951	-.10690	-154.12	.00000	-4.88
14.40	-.13454	-.16332	-153.31	.00000	-4.88
19.20	-.17977	-.20366	-152.29	.00000	-4.88
24.00	-.22519	-.22720	-151.15	.00000	-4.88
28.80	-.27076	-.23374	-149.98	.00000	-4.88
33.60	-.31646	-.22310	-148.87	.00000	-4.88
38.40	-.36224	-.19485	-147.89	.00000	-4.88
43.20	-.40806	-.14842	-147.15	.00000	-4.88
48.00	-.45391	-.08304	-146.74	.00000	-4.88
52.80	-.49975	.00220	-146.75	.00000	-4.88
57.60	-.54557	.10849	-147.29	.00000	-4.88
62.40	-.59135	.22573	-148.42	.00000	-4.88
67.20	-.63708	.33393	-150.09	.00000	-4.88
72.00	-.68274	.42443	-152.21	.00000	-4.88
76.80	-.72833	.51581	-154.79	.00000	-4.88
81.60	-.77384	.60564	-157.82	.00000	-4.88
86.40	-.81927	.66657	-161.15	.00000	-4.88
91.20	-.86461	.71217	-164.71	.00000	-4.88
96.00	-.90987	.74919	-168.46	.00000	-4.88
100.80	-.95504	.77530	-172.33	.00000	-4.88
105.60	-1.00014	.80310	-176.35	.00000	-4.87
110.40	-1.04517	.83381	-180.52	.00000	-4.96
115.20	-1.09014	.86762	-184.86	-.00003	-4.74
120.00	-1.13507	.90472	-189.38	.00017	.00

HOUR = 8 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-85.84	.00000	-62.50
4.80	-.04608	.13326	-86.50	.00000	-62.50
9.60	-.09235	.34784	-88.24	.00000	-62.50
14.40	-.13886	.50108	-90.75	.00000	-62.50
19.20	-.18564	.61828	-93.84	.00000	-62.50
24.00	-.23269	.69349	-97.31	.00000	-62.50
28.80	-.27996	.74250	-101.02	.00000	-62.50
33.60	-.32745	.77728	-104.91	.00000	-62.50
38.40	-.37509	.80998	-108.96	.00000	-62.50
43.20	-.42287	.84527	-113.18	.00000	-62.50
48.00	-.47075	.88322	-117.60	.00000	-62.50
52.80	-.51870	.92389	-122.22	.00000	-62.50
57.60	-.56670	.95246	-126.98	.00000	-62.50
62.40	-.61473	.96000	-131.78	.00000	-62.50
67.20	-.66278	.96000	-136.58	.00000	-62.50
72.00	-.71083	.96000	-141.38	.00000	-62.50
76.80	-.75886	.96000	-146.18	.00000	-62.50
81.60	-.80687	.96000	-150.98	.00000	-62.50
86.40	-.85485	.96000	-155.78	.00000	-62.50
91.20	-.90280	.96000	-160.58	.00000	-62.50
96.00	-.95071	.96000	-165.38	.00000	-62.51
100.80	-.99858	.96000	-170.18	.00000	-62.51
105.60	-1.04642	.96000	-174.98	.00000	-62.39
110.40	-1.09424	.96000	-179.78	.00002	-63.54
115.20	-1.14203	.96000	-184.58	-.00034	-60.73
120.00	-1.18982	.96000	-189.38	.00214	.00

HOUR = 10 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-76.67	.00000	-62.50
4.80	-.04823	.26631	-78.00	.00000	-62.50
9.60	-.09667	.62886	-81.15	.00000	-62.50
14.40	-.14537	.75875	-84.94	.00000	-62.50
19.20	-.19437	.82314	-89.05	.00000	-62.50
24.00	-.24364	.88598	-93.40	.00000	-62.50
28.80	-.29317	.93903	-98.18	.00000	-62.50
33.60	-.34291	.96000	-102.98	.00000	-62.50
38.40	-.39283	.96000	-107.78	.00000	-62.50
43.20	-.44290	.96000	-112.58	.00000	-62.50
48.00	-.49308	.96000	-117.38	.00000	-62.50
52.80	-.54334	.96000	-122.18	.00000	-62.50
57.60	-.59365	.96000	-126.98	.00000	-62.50
62.40	-.64400	.96000	-131.78	.00000	-62.50
67.20	-.69437	.96000	-136.58	.00000	-62.50
72.00	-.74474	.96000	-141.38	.00000	-62.50
76.80	-.79510	.96000	-146.18	.00000	-62.50
81.60	-.84545	.96000	-150.98	.00000	-62.50
86.40	-.89578	.96000	-155.78	.00000	-62.50
91.20	-.94609	.96000	-160.58	.00000	-62.50
96.00	-.99637	.96000	-165.38	.00000	-62.51
100.80	-1.04663	.96000	-170.18	.00000	-62.51
105.60	-1.09686	.96000	-174.98	.00000	-62.39
110.40	-1.14708	.96000	-179.78	.00002	-63.54
115.20	-1.19729	.96000	-184.58	-.00034	-60.73
120.00	-1.24749	.96000	-189.38	.00214	.00

HOUR = 12 MIDNIGHT

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-74.75	.00000	-56.64
4.80	-.04964	.32535	-76.38	.00000	-56.64
9.60	-.09949	.71596	-79.96	.00000	-56.64
14.40	-.14962	.82275	-84.07	.00000	-56.64
19.20	-.20004	.90711	-88.60	.00000	-56.64
24.00	-.25075	.95498	-93.38	.00000	-56.64
28.80	-.30172	.96000	-98.18	.00000	-56.64
33.60	-.35290	.96000	-102.98	.00000	-56.64
38.40	-.40427	.96000	-107.78	.00000	-56.64
43.20	-.45578	.96000	-112.58	.00000	-56.64
48.00	-.50741	.96000	-117.38	.00000	-56.64
52.80	-.55912	.96000	-122.18	.00000	-56.64
57.60	-.61089	.96000	-126.98	.00000	-56.64
62.40	-.66271	.96000	-131.78	.00000	-56.64
67.20	-.71456	.96000	-136.58	.00000	-56.64
72.00	-.76642	.96000	-141.38	.00000	-56.64
76.80	-.81830	.96000	-146.18	.00000	-56.64
81.60	-.87018	.96000	-150.98	.00000	-56.64
86.40	-.92206	.96000	-155.78	.00000	-56.64
91.20	-.97393	.96000	-160.58	.00000	-56.64
96.00	-1.02580	.96000	-165.38	.00000	-56.65
100.80	-1.07767	.96000	-170.18	.00000	-56.65
105.60	-1.12954	.96000	-174.98	.00000	-56.54
110.40	-1.18140	.96000	-179.78	.00001	-57.58
115.20	-1.23326	.96000	-184.58	-.00031	-55.04
120.00	-1.28513	.96000	-189.38	.00194	.00

HOUR = 2 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-74.17	.00000	-49.81
4.80	-.05049	.34173	-75.88	.00000	-49.81
9.60	-.10120	.74683	-79.62	.00000	-49.81
14.40	-.15219	.85900	-83.91	.00000	-49.81
19.20	-.20348	.93390	-88.58	.00000	-49.81
24.00	-.25505	.96000	-93.38	.00000	-49.81
28.80	-.30688	.96000	-98.18	.00000	-49.81
33.60	-.35893	.96000	-102.98	.00000	-49.81
38.40	-.41116	.96000	-107.78	.00000	-49.81
43.20	-.46354	.96000	-112.58	.00000	-49.81
48.00	-.51602	.96000	-117.38	.00000	-49.81
52.80	-.56860	.96000	-122.18	.00000	-49.81
57.60	-.62124	.96000	-126.98	.00000	-49.81
62.40	-.67392	.96000	-131.78	.00000	-49.81
67.20	-.72663	.96000	-136.58	.00000	-49.81
72.00	-.77936	.96000	-141.38	.00000	-49.81
76.80	-.83210	.96000	-146.18	.00000	-49.81
81.60	-.88485	.96000	-150.98	.00000	-49.81
86.40	-.93759	.96000	-155.78	.00000	-49.81
91.20	-.99033	.96000	-160.58	.00000	-49.81
96.00	-1.04307	.96000	-165.38	.00000	-49.81
100.80	-1.09580	.96000	-170.18	.00000	-49.81
105.60	-1.14853	.96000	-174.98	.00000	-49.72
110.40	-1.20126	.96000	-179.78	.00001	-50.63
115.20	-1.25399	.96000	-184.58	-.00027	-48.39
120.00	-1.30672	.96000	-189.38	.00171	.00

HOUR = 4 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	HOT.CURLING STRESS(PSI)
.00	.00000	.00000	-73.82	.00000	-51.76
4.80	-.05106	.35267	-75.58	.00000	-51.76
9.60	-.10234	.76745	-79.42	.00000	-51.76
14.40	-.15391	.88318	-83.84	.00000	-51.76
19.20	-.20577	.94842	-88.58	.00000	-51.76
24.00	-.25792	.96000	-93.38	.00000	-51.76
28.80	-.31032	.96000	-98.18	.00000	-51.76
33.60	-.36295	.96000	-102.98	.00000	-51.76
38.40	-.41576	.96000	-107.78	.00000	-51.76
43.20	-.46871	.96000	-112.58	.00000	-51.76
48.00	-.52177	.96000	-117.38	.00000	-51.76
52.80	-.57492	.96000	-122.18	.00000	-51.76
57.60	-.62819	.96000	-126.98	.00000	-51.76
62.40	-.68140	.96000	-131.78	.00000	-51.76
67.20	-.73469	.96000	-136.58	.00000	-51.76
72.00	-.78799	.96000	-141.38	.00000	-51.76
76.80	-.84131	.96000	-146.18	.00000	-51.76
81.60	-.89463	.96000	-150.98	.00000	-51.76
86.40	-.94795	.96000	-155.78	.00000	-51.76
91.20	-1.00127	.96000	-160.58	.00000	-51.76
96.00	-1.05458	.96000	-165.38	.00000	-51.76
100.80	-1.10789	.96000	-170.18	.00000	-51.76
105.60	-1.16120	.96000	-174.98	.00000	-51.67
110.40	-1.21450	.96000	-179.78	.00001	-52.62
115.20	-1.26781	.96000	-184.58	-.00028	-50.29
120.00	-1.32112	.96000	-189.38	.00178	.00

HOUR = 6 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-73.40	.00000	-49.81
4.80	-.05192	.36910	-75.24	.00000	-49.81
9.60	-.10406	.79840	-79.23	.00000	-49.81
14.40	-.15649	.90929	-83.78	.00000	-49.81
19.20	-.20921	.96000	-88.58	.00000	-49.81
24.00	-.26222	.96000	-93.38	.00000	-49.81
28.80	-.31549	.96000	-98.18	.00000	-49.81
33.60	-.36899	.96000	-102.98	.00000	-49.81
38.40	-.42266	.96000	-107.78	.00000	-49.81
43.20	-.47648	.96000	-112.58	.00000	-49.81
48.00	-.53042	.96000	-117.38	.00000	-49.81
52.80	-.58445	.96000	-122.18	.00000	-49.81
57.60	-.63855	.96000	-126.98	.00000	-49.81
62.40	-.69270	.96000	-131.78	.00000	-49.81
67.20	-.74689	.96000	-136.58	.00000	-49.81
72.00	-.80111	.96000	-141.38	.00000	-49.81
76.80	-.85535	.96000	-146.18	.00000	-49.81
81.60	-.90960	.96000	-150.98	.00000	-49.81
86.40	-.96387	.96000	-155.78	.00000	-49.81
91.20	-1.01815	.96000	-160.58	.00000	-49.81
96.00	-1.07243	.96000	-165.38	.00000	-49.81
100.80	-1.12671	.96000	-170.18	.00000	-49.81
105.60	-1.18100	.96000	-174.98	.00000	-49.72
110.40	-1.23529	.96000	-179.78	.00001	-50.63
115.20	-1.28958	.96000	-184.58	-.00027	-48.39
120.00	-1.34388	.96000	-189.38	.00171	.00

ANALYSIS AND DESIGN OF PRESTRESSED PAVEMENT SLABS

PREDICTION OF PAVEMENT STRESSES FOR INTERMEDIATE/FINAL PERIOD

TIME OF ANALYSIS FROM END OF MOIST CURING (DAYS) = 7300

HOUR OF DAY	TEMP. AT MID-DEPTH (DEG.F)	TEMP. DIFF. (DEG.F)	PRESTRESS PER STRAND (KSI)
8 A.M.	49.0	-2.0	168.8
10 A.M.	51.0	1.4	168.8
12 NOON	56.0	10.1	168.8
2 P.M.	60.0	11.6	168.8
4 P.M.	59.0	7.1	168.8
6 P.M.	56.0	-.3	168.8
8 P.M.	53.0	-3.8	168.8
10 P.M.	52.0	-4.2	168.8
12 MIDNIGHT	51.0	-4.3	168.8
2 A.M.	50.0	-4.1	168.8
4 A.M.	49.0	-4.3	168.8
6 A.M.	49.0	-4.1	168.8

HOUR = 8 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-103.68	.00000	-19.53
4.80	-.05535	.05450	-103.96	.00000	-19.53
9.60	-.11112	.16452	-104.78	.00000	-19.53
14.40	-.16717	.26059	-106.08	.00000	-19.53
19.20	-.22338	.33760	-107.77	.00000	-19.53
24.00	-.27969	.40441	-109.79	.00000	-19.53
28.80	-.33604	.46301	-112.11	.00000	-19.53
33.60	-.39241	.52901	-114.75	.00000	-19.53
38.40	-.44878	.60019	-117.75	.00000	-19.53
43.20	-.50514	.64844	-121.00	.00000	-19.53
48.00	-.56149	.67989	-124.40	.00000	-19.53
52.80	-.61785	.71511	-127.97	.00000	-19.53
57.60	-.67416	.74461	-131.69	.00000	-19.53
62.40	-.73047	.76570	-135.52	.00000	-19.53
67.20	-.78677	.78712	-139.46	.00000	-19.53
72.00	-.84306	.81073	-143.51	.00000	-19.53
76.80	-.89935	.83664	-147.70	.00000	-19.53
81.60	-.95561	.86498	-152.02	.00000	-19.53
86.40	-1.01187	.89587	-156.50	.00000	-19.53
91.20	-1.06814	.92947	-161.15	.00000	-19.53
96.00	-1.12441	.95348	-165.91	.00000	-19.53
100.80	-1.18068	.96000	-170.71	.00000	-19.53
105.60	-1.23695	.96000	-175.51	.00000	-19.50
110.40	-1.29325	.96000	-180.31	.00001	-19.85
115.20	-1.34955	.96000	-185.11	-.00011	-18.98
120.00	-1.40585	.96000	-189.91	.00067	.00

HOUR = 10 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-137.05	.00000	13.67
4.80	-.05534	.05487	-137.32	.00000	13.67
9.60	-.11112	.16559	-138.15	.00000	13.67
14.40	-.16718	.26190	-139.46	.00000	13.67
19.20	-.22340	.33892	-141.15	.00000	13.67
24.00	-.27970	.40562	-143.18	.00000	13.67
28.80	-.33605	.46394	-145.50	.00000	13.67
33.60	-.39242	.52978	-148.15	.00000	13.67
38.40	-.44879	.60054	-151.15	.00000	13.67
43.20	-.50515	.64833	-154.39	.00000	13.67
48.00	-.56149	.67951	-157.79	.00000	13.67
52.80	-.61783	.71449	-161.36	.00000	13.67
57.60	-.67415	.74407	-165.09	.00000	13.67
62.40	-.73046	.76538	-168.91	.00000	13.67
67.20	-.78676	.78694	-172.85	.00000	13.67
72.00	-.84306	.81089	-176.90	.00000	13.67
76.80	-.89936	.83738	-181.09	.00000	13.67
81.60	-.95567	.86659	-185.42	.00000	13.67
86.40	-1.01199	.89867	-189.91	.00000	13.67
91.20	-1.06817	.00365	-193.67	.00000	13.67
96.00	-1.12439	.00085	-193.68	.00000	13.67
100.80	-1.18052	-.02252	-193.57	.00000	13.67
105.60	-1.23656	-.06732	-193.23	.00000	13.65
110.40	-1.29255	-.13482	-192.56	.00000	13.90
115.20	-1.34844	-.22097	-191.45	.00007	13.28
120.00	-1.40422	-.30719	-189.91	-.00047	.00

HOUR = 12 NOON

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-225.82	.00000	98.64
4.80	-.05543	.01293	-225.89	.00000	98.64
9.60	-.11131	.03824	-226.08	.00000	98.64
14.40	-.16745	.06153	-226.39	.00000	98.64
19.20	-.22373	.08103	-226.79	.00000	98.64
24.00	-.28007	.09513	-227.27	.00000	98.64
28.80	-.33644	.10227	-227.78	.00000	98.64
33.60	-.39278	.10083	-228.28	.00000	98.64
38.40	-.44908	.08895	-228.73	.00000	98.64
43.20	-.50533	.06466	-229.05	.00000	98.64
48.00	-.56151	.02620	-229.18	.00000	98.64
52.80	-.61761	-.02807	-229.04	.00000	98.64
57.60	-.67362	-.09980	-228.54	.00000	98.64
62.40	-.72953	-.19075	-227.59	.00000	98.64
67.20	-.78535	-.27982	-226.19	.00000	98.64
72.00	-.84105	-.36118	-224.38	.00000	98.64
76.80	-.89664	-.43810	-222.19	.00000	98.64
81.60	-.95212	-.51800	-219.60	.00000	98.64
86.40	-1.00747	-.60228	-216.59	.00000	98.64
91.20	-1.06270	-.66036	-213.29	.00000	98.64
96.00	-1.11780	-.70203	-209.78	.00000	98.64
100.80	-1.17276	-.73950	-206.08	.00000	98.64
105.60	-1.22758	-.76707	-202.25	.00000	98.47
110.40	-1.28228	-.79281	-198.28	-.00003	100.27
115.20	-1.33682	-.82129	-194.18	.00053	95.84
120.00	-1.39120	-.85268	-189.91	-.00338	.00

HOUR = 2 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-271.55	.00000	113.29
4.80	-.05507	-.03285	-271.38	.00000	113.29
9.60	-.11057	-.10048	-270.88	.00000	113.29
14.40	-.16652	-.17389	-270.01	.00000	113.29
19.20	-.22218	-.24652	-268.78	.00000	113.29
24.00	-.27808	-.31128	-267.22	.00000	113.29
28.80	-.33395	-.37557	-265.35	.00000	113.29
33.60	-.38976	-.43689	-263.16	.00000	113.29
38.40	-.44549	-.50053	-260.66	.00000	113.29
43.20	-.50110	-.58138	-257.75	.00000	113.29
48.00	-.55660	-.64272	-254.54	.00000	113.29
52.80	-.61197	-.67765	-251.15	.00000	113.29
57.60	-.66720	-.71712	-247.56	.00000	113.29
62.40	-.72229	-.74886	-243.82	.00000	113.29
67.20	-.77724	-.77111	-239.96	.00000	113.29
72.00	-.83204	-.79506	-235.99	.00000	113.29
76.80	-.88669	-.82136	-231.88	.00000	113.29
81.60	-.94119	-.85011	-227.63	.00000	113.29
86.40	-.99553	-.88145	-223.22	.00000	113.29
91.20	-1.04971	-.91549	-218.65	.00000	113.29
96.00	-1.10373	-.94660	-213.91	.00000	113.29
100.80	-1.15756	-.96000	-209.11	.00000	113.29
105.60	-1.21122	-.96000	-204.31	.00000	113.09
110.40	-1.26472	-.96000	-199.51	-.00003	115.16
115.20	-1.31803	-.96000	-194.71	.00061	110.87
120.00	-1.37113	-.96000	-189.91	-.00389	.00

HOUR = 4 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	HOT-CURLING STRESS(PSI)
.00	.00000	.00000	-256.04	.00000	69.34
4.80	-.05509	-.03048	-255.89	.00000	69.34
9.60	-.11061	-.09335	-255.42	.00000	69.34
14.40	-.16638	-.16187	-254.61	.00000	69.34
19.20	-.22226	-.23331	-253.45	.00000	69.34
24.00	-.27818	-.29770	-251.96	.00000	69.34
28.80	-.33408	-.36073	-250.15	.00000	69.34
33.60	-.38991	-.42204	-248.04	.00000	69.34
38.40	-.44567	-.48148	-245.64	.00000	69.34
43.20	-.50131	-.55808	-242.85	.00000	69.34
48.00	-.55685	-.62601	-239.72	.00000	69.34
52.80	-.61225	-.66728	-236.38	.00000	69.34
57.60	-.66752	-.70523	-232.85	.00000	69.34
62.40	-.72265	-.73939	-229.16	.00000	69.34
67.20	-.77764	-.76448	-225.33	.00000	69.34
72.00	-.83248	-.78777	-221.40	.00000	69.34
76.80	-.88717	-.81346	-217.33	.00000	69.34
81.60	-.94170	-.84170	-213.12	.00000	69.34
86.40	-.99607	-.87266	-208.76	.00000	69.34
91.20	-1.05028	-.90647	-204.22	.00000	69.34
96.00	-1.10431	-.94205	-199.51	.00000	69.34
100.80	-1.15815	-.96000	-194.71	.00000	69.34
105.60	-1.21179	-.96000	-189.91	.00000	69.22
110.40	-1.26479	.00865	-189.30	-.00002	70.49
115.20	-1.31825	.03670	-189.48	.00038	67.37
120.00	-1.37160	.08669	-189.91	-.00238	.00

HOUR = 6 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-206.16	.00000	-2.93
4.80	-.05509	-.03042	-206.01	.00000	-2.93
9.60	-.11061	-.09291	-205.54	.00000	-2.93
14.40	-.16658	-.16049	-204.74	.00000	-2.93
19.20	-.22227	-.23120	-203.58	.00000	-2.93
24.00	-.27819	-.29490	-202.11	.00000	-2.93
28.80	-.33409	-.35696	-200.33	.00000	-2.93
33.60	-.38993	-.41856	-198.23	.00000	-2.93
38.40	-.44569	-.47896	-195.84	.00000	-2.93
43.20	-.50132	-.55733	-193.05	.00000	-2.93
48.00	-.55684	-.62730	-189.91	.00000	-2.93
52.80	-.61180	-.02172	-178.09	.00000	-2.93
57.60	-.66691	-.05795	-177.80	.00000	-2.93
62.40	-.72194	-.07968	-177.40	.00000	-2.93
67.20	-.77689	-.08669	-176.97	.00000	-2.93
72.00	-.83175	-.07870	-176.57	.00000	-2.93
76.80	-.88653	-.05522	-176.30	.00000	-2.93
81.60	-.94122	-.01547	-176.22	.00000	-2.93
86.40	-.99582	.04173	-176.43	.00000	-2.93
91.20	-1.05036	.11803	-177.02	.00000	-2.93
96.00	-1.10481	.21163	-178.08	.00000	-2.93
100.80	-1.15919	.30233	-179.59	.00000	-2.93
105.60	-1.21349	.38454	-181.51	.00000	-2.92
110.40	-1.26781	.46770	-183.85	.00000	-2.98
115.20	-1.32205	.56713	-186.68	-.00002	-2.85
120.00	-1.37624	.64606	-189.91	.00010	.00

HOUR = 8 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-152.71	.00000	-37.11
4.80	-.05501	-.00838	-152.67	.00000	-37.11
9.60	-.11045	-.02503	-152.55	.00000	-37.11
14.40	-.16614	-.04086	-152.34	.00000	-37.11
19.20	-.22195	-.05452	-152.07	.00000	-37.11
24.00	-.27782	-.06452	-151.75	.00000	-37.11
28.80	-.33369	-.06924	-151.40	.00000	-37.11
33.60	-.38952	-.06700	-151.07	.00000	-37.11
38.40	-.44530	-.05601	-150.79	.00000	-37.11
43.20	-.50102	-.03430	-150.62	.00000	-37.11
48.00	-.55668	.00035	-150.62	.00000	-37.11
52.80	-.61227	.05009	-150.87	.00000	-37.11
57.60	-.66780	.11680	-151.45	.00000	-37.11
62.40	-.72326	.20226	-152.46	.00000	-37.11
67.20	-.77867	.28492	-153.89	.00000	-37.11
72.00	-.83403	.36114	-155.69	.00000	-37.11
76.80	-.88934	.43505	-157.87	.00000	-37.11
81.60	-.94460	.51098	-160.42	.00000	-37.11
86.40	-.99982	.59538	-163.40	.00000	-37.11
91.20	-1.05501	.65548	-166.68	.00000	-37.11
96.00	-1.11016	.69583	-170.16	.00000	-37.11
100.80	-1.16527	.73424	-173.83	.00000	-37.11
105.60	-1.22033	.76312	-177.64	.00000	-37.05
110.40	-1.27544	.78856	-181.59	.00001	-37.72
115.20	-1.33051	.81707	-185.67	-.00020	-36.06
120.00	-1.38554	.84849	-189.91	.00127	.00

HOUR = 10 P.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-139.10	.00000	-41.02
4.80	-.05506	-.00149	-139.09	.00000	-41.02
9.60	-.11056	-.00392	-139.08	.00000	-41.02
14.40	-.16631	-.00448	-139.05	.00000	-41.02
19.20	-.22219	-.00153	-139.05	.00000	-41.02
24.00	-.27813	.00668	-139.08	.00000	-41.02
28.80	-.33408	.02197	-139.19	.00000	-41.02
33.60	-.39000	.04621	-139.42	.00000	-41.02
38.40	-.44589	.08137	-139.83	.00000	-41.02
43.20	-.50172	.12961	-140.47	.00000	-41.02
48.00	-.55750	.19337	-141.44	.00000	-41.02
52.80	-.61323	.26092	-142.75	.00000	-41.02
57.60	-.66891	.32594	-144.38	.00000	-41.02
62.40	-.72454	.39306	-146.34	.00000	-41.02
67.20	-.78013	.45816	-148.63	.00000	-41.02
72.00	-.83567	.53417	-151.30	.00000	-41.02
76.80	-.89118	.61082	-154.36	.00000	-41.02
81.60	-.94665	.66138	-157.66	.00000	-41.02
86.40	-1.00209	.70054	-161.17	.00000	-41.02
91.20	-1.05750	.73688	-164.85	.00000	-41.02
96.00	-1.11289	.76400	-168.67	.00000	-41.02
100.80	-1.16825	.78851	-172.61	.00000	-41.02
105.60	-1.22359	.81579	-176.69	.00000	-40.95
110.40	-1.27898	.84636	-180.92	.00001	-41.70
115.20	-1.33436	.88038	-185.33	-.00022	-39.85
120.00	-1.38975	.91773	-189.91	.00141	.00

HOUR = 12 MIDNIGHT

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-126.79	.00000	-42.00
4.80	-.05514	.00814	-126.83	.00000	-42.00
9.60	-.11071	.02530	-126.96	.00000	-42.00
14.40	-.16654	.04519	-127.18	.00000	-42.00
19.20	-.22251	.06961	-127.53	.00000	-42.00
24.00	-.27855	.10082	-128.04	.00000	-42.00
28.80	-.33460	.14091	-128.74	.00000	-42.00
33.60	-.39064	.19215	-129.70	.00000	-42.00
38.40	-.44665	.24832	-130.94	.00000	-42.00
43.20	-.50262	.30263	-132.46	.00000	-42.00
48.00	-.55856	.36225	-134.27	.00000	-42.00
52.80	-.61446	.42216	-136.38	.00000	-42.00
57.60	-.67031	.48174	-138.79	.00000	-42.00
62.40	-.72613	.55946	-141.58	.00000	-42.00
67.20	-.78192	.62773	-144.72	.00000	-42.00
72.00	-.83768	.66900	-148.07	.00000	-42.00
76.80	-.89342	.70783	-151.61	.00000	-42.00
81.60	-.94913	.74185	-155.32	.00000	-42.00
86.40	-1.00482	.76663	-159.15	.00000	-42.00
91.20	-1.06049	.79058	-163.10	.00000	-42.00
96.00	-1.11615	.81710	-167.19	.00000	-42.00
100.80	-1.17179	.84635	-171.42	.00000	-42.00
105.60	-1.22741	.87853	-175.81	.00000	-41.92
110.40	-1.28310	.91412	-180.38	.00001	-42.69
115.20	-1.33878	.94643	-185.11	-.00023	-40.80
120.00	-1.39446	.96000	-189.91	.00144	.00

HOUR = 2 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-116.13	.00000	-40.04
4.80	-.05524	.02121	-116.24	.00000	-40.04
9.60	-.11092	.06481	-116.56	.00000	-40.04
14.40	-.16687	.11199	-117.12	.00000	-40.04
19.20	-.22295	.16525	-117.95	.00000	-40.04
24.00	-.27912	.22509	-119.08	.00000	-40.04
28.80	-.33531	.28033	-120.48	.00000	-40.04
33.60	-.39150	.33261	-122.14	.00000	-40.04
38.40	-.44767	.38990	-124.09	.00000	-40.04
43.20	-.50382	.44519	-126.32	.00000	-40.04
48.00	-.55994	.50663	-128.85	.00000	-40.04
52.80	-.61603	.58433	-131.77	.00000	-40.04
57.60	-.67209	.64281	-134.99	.00000	-40.04
62.40	-.72813	.67669	-138.37	.00000	-40.04
67.20	-.78415	.71510	-141.94	.00000	-40.04
72.00	-.84014	.74680	-145.68	.00000	-40.04
76.80	-.89612	.76933	-149.53	.00000	-40.04
81.60	-.95209	.79291	-153.49	.00000	-40.04
86.40	-1.00804	.81895	-157.58	.00000	-40.04
91.20	-1.06399	.84761	-161.82	.00000	-40.04
96.00	-1.11993	.87907	-166.22	.00000	-40.04
100.80	-1.17587	.91352	-170.79	.00000	-40.04
105.60	-1.23181	.94576	-175.51	.00000	-39.97
110.40	-1.28782	.96000	-180.31	.00001	-40.78
115.20	-1.34384	.96000	-185.11	-.00022	-38.91
120.00	-1.39987	.96000	-189.91	.00137	.00

HOUR = 4 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-107.36	.00000	-42.00
4.80	-.05558	.03828	-107.55	.00000	-42.00
9.60	-.11120	.11637	-108.13	.00000	-42.00
14.40	-.16729	.19910	-109.13	.00000	-42.00
19.20	-.22353	.27219	-110.49	.00000	-42.00
24.00	-.27985	.33462	-112.16	.00000	-42.00
28.80	-.33622	.39690	-114.15	.00000	-42.00
33.60	-.39259	.45493	-116.42	.00000	-42.00
38.40	-.44895	.52083	-119.03	.00000	-42.00
43.20	-.50531	.59575	-122.00	.00000	-42.00
48.00	-.56164	.64878	-125.25	.00000	-42.00
52.80	-.61796	.68298	-128.66	.00000	-42.00
57.60	-.67426	.72101	-132.27	.00000	-42.00
62.40	-.73055	.75095	-136.02	.00000	-42.00
67.20	-.78682	.77217	-139.88	.00000	-42.00
72.00	-.84308	.79561	-143.86	.00000	-42.00
76.80	-.89932	.82157	-147.97	.00000	-42.00
81.60	-.95556	.84956	-152.22	.00000	-42.00
86.40	-1.01179	.88030	-156.62	.00000	-42.00
91.20	-1.06802	.91374	-161.19	.00000	-42.00
96.00	-1.12425	.94558	-165.91	.00000	-42.00
100.80	-1.18048	.96000	-170.71	.00000	-42.00
105.60	-1.23672	.96000	-175.51	.00000	-41.92
110.40	-1.29302	.96000	-180.31	.00001	-42.69
115.20	-1.34953	.96000	-185.11	-.00023	-40.80
120.00	-1.40563	.96000	-189.91	.00144	.00

HOUR = 6 A.M.

COORDINATES FROM MIDSLAB(FT)	MOVEMENT (IN)	COEFF OF FRICTION	PREST+FRICT STRESS (PSI)	CURLING DEFLECTION(IN)	BOT.CURLING STRESS(PSI)
.00	.00000	.00000	-107.36	.00000	-40.04
4.80	-.05558	.03829	-107.55	.00000	-40.04
9.60	-.11120	.11640	-108.13	.00000	-40.04
14.40	-.16729	.19915	-109.12	.00000	-40.04
19.20	-.22353	.27225	-110.49	.00000	-40.04
24.00	-.27986	.33468	-112.16	.00000	-40.04
28.80	-.33622	.39696	-114.14	.00000	-40.04
33.60	-.39259	.45498	-116.42	.00000	-40.04
38.40	-.44896	.52091	-119.02	.00000	-40.04
43.20	-.50531	.59580	-122.00	.00000	-40.04
48.00	-.56164	.64882	-125.25	.00000	-40.04
52.80	-.61796	.68301	-128.66	.00000	-40.04
57.60	-.67426	.72104	-132.27	.00000	-40.04
62.40	-.73055	.75097	-136.02	.00000	-40.04
67.20	-.78682	.77219	-139.88	.00000	-40.04
72.00	-.84308	.79564	-143.86	.00000	-40.04
76.80	-.89932	.82140	-147.97	.00000	-40.04
81.60	-.95556	.84959	-152.22	.00000	-40.04
86.40	-1.01179	.88033	-156.62	.00000	-40.04
91.20	-1.06802	.91377	-161.19	.00000	-40.04
96.00	-1.12425	.94559	-165.91	.00000	-40.04
100.80	-1.18049	.96000	-170.71	.00000	-40.04
105.60	-1.23672	.96000	-175.51	.00000	-39.97
110.40	-1.29303	.96000	-180.31	.00001	-40.70
115.20	-1.34933	.96000	-185.11	-.00022	-38.91
120.00	-1.40564	.96000	-189.91	.00137	.00

END OF JOB

APPENDIX D

LISTING OF COMPUTER PROGRAM PSCP1

```
      PROGRAM PCP1(INPUT,OUTPUT,PLOT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE7=PLOT
     1)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     PROGRAM PCP1 -  ANALYSIS OF PRESTRESSED CONCRETE PAVEMENTS
C     CONSIDERING THE INELASTIC NATURE OF THE SLAB-BASE FRICTION
C     FORCES, FEBRUARY 1986.
C
C          THIS PROGRAM WAS DEVELOPED BY ALBERTO MENDOZA AT THE
C     CENTER FOR TRANSPORTATION RESEARCH, THE UNIVERSITY OF TEXAS AT
C     AUSTIN, IN RESEARCH PROJECT 401, 'DESIGN AND CONSTRUCTION OF
C     PRESTRESSED CONCRETE PAVEMENTS FOR OVERLAY APPLICATIONS',
C     CONDUCTED IN COOPERATION WITH THE TEXAS STATE DEPARTMENT OF
C     HIGHWAYS AND PUBLIC TRANSPORTATION, AND THE FEDERAL HIGHWAY
C     ADMINISTRATION.  DOCUMENTATION RELATED TO THE DEVELOPMENT AND
C     APPLICATION OF THIS PROGRAM IS PRESENTED IN CTR REPORT NO. 401-7,
C     BY ALBERTO MENDOZA, B. FRANK MCCULLOUGH AND NED H. BURNS
C
C          THIS PROGRAM DOES NOT CONSTITUTE A STANDARD OR POLICY OF
C     THE TEXAS SDHPT. ANY USER SHOULD ACCEPT RESPONSIBILITY FOR THE
C     ACCURACY OF THE INPUTS AND VALIDITY OF THE RESULTS.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      DIMENSION VECTOR1(20),VECTOR2(20),ARRE(24)
      DIMENSION AGE(8),PCTC(8),PCTT(8)
      DIMENSION CURH(1),P(100)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C                        LIST OF VARIABLES
C
C     INPUT VARIABLES:
C
C     VECTOR1= ALPHANUMERIC INFORMATION TO IDENTIFY THE PROBLEM
C         DL = SLAB LENGTH (FT)
C          D = SLAB THICKNESS (IN)
C       NILD = NO. OF INCREMENTS CONSIDERED BY THE PROGRAM FOR ANALYSIS
C              OF SLAB HALF
C       NMAX = MAXIMUM NO. OF ITERATIONS
C        TOL = RELATIVE CLOSURE TOLERANCE (PERCENT)
C      ALTOT = CONCRETE THERMAL COEFFICIENT OF CONTRACTION OR EXPANSION
C              (IN/IN-DEG.F)
C       ZTOT = FINAL SHRINKAGE STRAIN (IN/IN)
C          G = CONCRETE UNIT WEIGHT (PCF)
C         PR = CONCRETE POISSON RATIO
C      CREEP = CONCRETE CREEP COEFFICIENT
C         KK = NO. OF POINTS IN COMPRESSIVE STRENGTH VS AGE
C              RELATIONSHIP PROVIDED BY USER
C     AGEU(I)= AGE IN DAYS FOR POINT I OF RELATIONSHIP
C     COMP(I)= COMPRESSIVE STRENGTH FOR POINT I OF RELATIONSHIP
```

```
C          M1 = NO OF POINTS IN THE FRICTION COEFFICIENT VS DISPLACEMENT
C               RELATIONSHIP
C       ZU(I) = DISPLACEMENT IN INCHES FOR POINT I OF RELATIONSHIP
C       UU(I) = FRICTION COEFFICIENT FOR POINT I OF RELATIONSHIP
C          SK = K-VALUE ON TOP OF SLAB SUPPORTING LAYER (PSI/IN)
C          SS = STRAND SPACING (IN)
C          SA = NOMINAL AREA OF THE STRANDS (SQ.IN)
C         FPY = STEEL YIELD STRESS (KSI)
C          ES = STEEL ELASTIC MODULUS (PSI)
C         ALS = STEEL THERMAL COEFFICIENT (PSI)
C        NPER = PAIRS OF SLAB MID-DEPTH TEMPERATURES AND TOP-TO-BOTTOM
C               TEMPERATURE DIFFERENTIALS PROVIDED AT 2-HOUR INTERVALS
C        CURH = CURING HOUR (IN THE SCALE OF 0 TO 24 HOURS)
C      CURTEMP= SLAB MID-DEPTH TEMPERATURE AT THE CURING HOUR (DEG.F)
C       ADT(I)= MID-DEPTH TEMPERATURE FOR DATA PAIR I (DEG.F)
C      TDIF(I)= TOP-TO-BOTTOM SLAB TEMPERATURE DIFFERENTIAL FOR DATA
C               PAIR I (DEG.F)
C          NS = NUMBER OF POST-TENSIONING STAGES
C        IAGE = TIME SINCE CURING TO COMPLETION OF POST-TENSIONING
C               STAGE I (HOURS)
C       PS(I) = AMOUNT OF PRESTRESS COMPLETED PER STRAND AT POST-
C               TENSIONING STAGE I (KSI)
C        ITOA = NUMBER OF DAYS SINCE CURING TO BEGINNING OF PERIOD
C               OF ANALYSIS CONSIDERED
C
C      OTHER VARIABLES:
C
C         FPA = MAXIMUM TENSILE STRESS ALLOWED BY ACI IN STEEL TENDONS
C               (KSI)
C         SFF = INCREMENT OF CONCRETE STRAIN (SINCE APPLICATION OF LAST
C               POST-TENSIONING FORCE) THAT RESULTS IN A CHANGE OF THE
C               PRESTRESS LEVEL IN THE STRANDS (IN/IN)
C       ELONG = CHANGE IN THE STRESS IN THE STRANDS DUE TO THE
C               CONCRETE STRAIN INCREMENT SFF (KSI)
C       RELAX = LOSS IN THE STRESS IN THE STRANDS DUE TO STEEL RELAXATION
C               (KSI)
C      PRFINAL= TOTAL PRESTRESS IN THE STRANDS AFTER LOSSES (KSI)
C      SFINAL = PRESTRESS LEVEL IN THE CONCRETE AFTER LOSSES (PSI)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      COMMON/BLOCK1/DT(10,25),TMID(10,25)
      COMMON/BLOCK2/KK,AGEU(20),COMP(20)
      COMMON/BLOCK3/M1,ZU(20),UU(20)
      COMMON/BLOCK4/IR,IW
      COMMON/BLOCK5/KI,CURTEMP,AG(100),ADT(100),TDIF(100),PP(100)
      COMMON/BLOCK6/G,COMPF,ALTOT,ZTOT,CREEP,PR,SK,SL
      COMMON/BLOCK7/DL,NILD,NTEMP,TOL,NMAX
      COMMON/BLOCK8/AL,EL,ZZ,SA,SS,PS(10),AGEP(10)
      COMMON/BLOCK9/M,Z(200),U(200)
      COMMON/BLOCK10/Z1(200),X(200),FX(200),STF1(200)
      COMMON/BLOCK11/C,H,R
      COMMON/BLOCK12/TOA(10)
      COMMON/BLOCK13/CPF,CPM,ZZF,RELAX,FPY
C
C      INITIALIZE VARIABLES FOR HEADINGS, COMPRESSIVE STRENGTH VS
```

```
C      AGE RELATIONSHIP AND INPUT/OUTPUT PARAMETERS
C
       DATA ARRE/24*4H*---*/
       DATA AGE/0.,1.,3.,5.,7.,14.,21.,28./
       DATA PCTC/0.,15.,38.,53.,63.,82.,94.,100./
C      ***********************************************
       IR=05
       IW=06
C      ***********************************************
C
C      PRINT TITLE
C
       CALL TITLE
C
C      INPUT AND ECHO-PRINT OF GENERAL DATA
C
C      ********************
C      *                  *
C      *  READ INPUT DATA *
C      *                  *
C      ********************
C
C      PROGRAM AND PROBLEM IDENTIFICATION
C
       READ(IR,1000)VECTOR1
 1000  FORMAT(20A4)
       WRITE(IW,1020)ARRE
 1020  FORMAT(1H1,2(/),T17,24A4)
       WRITE(IW,1030)ARRE(1),VECTOR1,ARRE(1)
 1030  FORMAT(/,T17,A4,4X,20A4,4X,A4)
       WRITE(IW,1031)ARRE(1),ARRE(1)
 1031  FORMAT(/,T17,A4,31X,'ECHO-PRINT OF GENERAL DATA',31X,A4)
       WRITE(IW,1032)ARRE
 1032  FORMAT(/,T17,24A4,///)
C
C      READ PROBLEM DEFINITION
C
       READ(IR,1040)DL,D
 1040  FORMAT(8F10.0)
       READ(IR,1050)NILD,NMAX,TOL
 1050  FORMAT(2I5,F10.0)
       WRITE(IW,1052)
 1052  FORMAT(///,1H0,33X,33(1H*))
       WRITE(IW,1060)
 1060  FORMAT(34X,'*      PROBLEM DEFINITION       *')
       WRITE(IW,1070)
 1070  FORMAT(34X,33(1H*))
       WRITE(IW,1080)DL,D
 1080  FORMAT(1H0,45X,25HSLAB LENGTH (FT)         =,F10.1/
      *          46X,25HSLAB THICKNESS (IN)      =,F10.1)
       WRITE(IW,1086)NILD,NMAX,TOL
 1086  FORMAT(46X,25HNO.OF INCREMENTS         =,I10/
      *        46X,25HMAX. NO. OF ITERATIONS  =,I10/
      *        46X,25HREL. CLOSURE TOLERANCE  =,F10.1///)
       TOL=TOL/100.
C
C      READ CONCRETE PROPERTIES
```

```
C
      READ(IR,1040)ALTOT,ZTOT,G,PR,CREEP
      IF(CREEP.EQ.0.0)CREEP=2.35
      IF(PR.EQ.0.0)PR=0.15
      WRITE(IW,1052)
      WRITE(IW,1090)
1090  FORMAT(34X,'*       CONCRETE PROPERTIES       *')
      WRITE(IW,1070)
      WRITE(IW,1110)ALTOT,ZTOT,G,PR,CREEP
1110  FORMAT(1H0,45X,25HTHERMAL COEFFICIENT      =,E10.3/
     *            46X,25HTOTAL SHRINKAGE         =,E10.3/
     *            46X,25HUNIT WEIGHT (PCF)       =,F10.1/
     *            46X,25HPOISSON RATIC           =,F10.2/
     *            46X,25HCREEP COEFFICIENT       =,F10.2///)
C
C     INPUT AGE-COMPRESSIVE STRENGTH RELATIONSHIP
C
      READ(IR,1120)KK,(AGEU(I),COMP(I),I=1,7)
1120  FORMAT(I5,5X,14F5.0)
      WRITE(IW,1121)
1121  FORMAT(1H1,6(/))
      WRITE(IW,1052)
      WRITE(IW,1122)
1122  FORMAT(33X,' *          COMPRESSIVE           *'/
     *       33X,' *         STRENGTH DATA          *')
      WRITE(IW,1070)
      IF(KK.GT.1)GO TO 1200
C
C     RELATIONSHIP IS NOT USER-SUPPLIED
C
      IF(AGEU(1).EQ.28.)GO TO 1135
      WRITE(IW,1130)
      WRITE(IW,1131)
1130  FORMAT(////,1H0,28X,'ERROR,STRENGTH VALUE PROVIDED IS NOT FOR 28TH
     * DAY')
1131  FORMAT(32X,'***            EXECUTION ABORTED            ***')
      GO TO 2000
1135  KL=8
C
C     AGE-COMPRESSIVE STRENGTH RELATIONSHIP DEVELOPED FROM
C     28TH DAY COMPRESSIVE STRENGTH SUPPLIED BY USER
C
      WRITE(IW,1144)
1144  FORMAT(1H0,38X,'THE FOLLOWING  STRENGTH RELATIONSHIP  WAS'/
     *            37X,'DEVELOPED BASED ON THE RECOMMENDATION GIVEN'/
     *            37X,'BY THE  U.S.  BUREAU OF RECLAMATION AND THE'/
     *            37X,'28TH DAY COMPRES. STRENGTH PROVIDED BY USER')
      COMP(8)=COMP(1)
      COMPF=COMP(1)
      DO 1150 I=1,8
      AGEU(I)=AGE(I)
      COMP(I)=COMP(8)*PCTC(I)/100.
1150  CONTINUE
      GO TO 1280
1200  CONTINUE
      IF((AGEU(1).EQ.0.).AND.(COMP(1).EQ.0.))GO TO 1204
      WRITE(IW,1202)
```

```
           WRITE(IW,1131)
     1202  FORMAT(////,1H0,28X,'ERROR,THE AGE-STRENGTH RELATIONSHIP DOES NOT
          +BEGIN WITH (0.0,0.0)')
           GO TO 2000
     1204  CONTINUE
           IF(KK.GT.7)READ(IR,1206)(AGEU(I),COMP(I),I=8,KK)
     1206  FORMAT((10X,14F5.0))
           KL=KK
     C
     C     RELATIONSHIP IS USER-SUPPLIED
     C     AGE-COMPRESSIVE STRENGTH RELATIONSHIP IS USER-SUPPLIED
     C
           WRITE(IW,1230)
     1230  FORMAT(1H0,38X,'THE COMPRESSIVE STRENGTH-AGE RELATIONSHIP'/
          +             39X,'AS SUPPLIED BY USER IS:')
           DO 1277 I=2,KK
           IF(AGEU(I).LT.28.)GO TO 1277
           SLOPE=(COMP(I)-COMP(I-1))/(AGEU(I)-AGEU(I-1))
           COMPF=COMP(I-1)+SLOPE*(28.-AGEU(I-1))
           GO TO 1280
     1277  CONTINUE
           COMPF=COMP(KK)
     1280  CONTINUE
           WRITE(IW,1290)(AGEU(I),COMP(I),I=1,KL)
     1290  FORMAT(1H0,46X,' AGE         COMPRESSIVE'/
          +             46X,'(DAYS)        STRENGTH'//
          +             (46X,F5.1,9X,F5.1))
     C
     C     INPUT COEFFICIENT OF FRICTION-DISPLACEMENT RELATIONSHIP
     C
           READ(IR,1120)M1,(ZU(I),UU(I),I=1,7)
           IF(M1.GT.7)READ(IR,1206)(ZU(I),UU(I),I=8,M1)
           WRITE(IW,1052)
           WRITE(IW,1294)
     1294  FORMAT(34X,'* SLAB-BASE FRICTION PROPERTIES *'/
          +        34X,'*        Z-U RELATIONSHIP         *')
           WRITE(IW,1070)
           IF(M1.EQ.1)GO TO 1300
           IF(M1.GE.2)GO TO 1320
           WRITE(IW,1296)
           WRITE(IW,1131)
     1296  FORMAT(1H0,28X,'ERROR,TYPE OF FRICTION CURVE INPUT NOT IDENTIFIED'
          +)
           GO TO 2000
     1300  CONTINUE
     C
     C     RELATIONSHIP IS LINEAR
     C
           ZU(2)=ZU(1)
           UU(2)=UU(1)
           ZU(1)=0.
           UU(1)=0.
           GO TO 1330
     1320  CONTINUE
     C
     C     RELATIONSHIP IS EXPONENTIAL OR MULTILINEAR
     C
```

```
      IF((ZU(1).EQ.0.).AND.(UU(1).EQ.0.))GO TO 1330
      WRITE(IW,1322)
      WRITE(IW,1131)
 1322 FORMAT(////,1H0,28X,'ERROR,THE Z-U RELATIONSHIP DOES NOT BEGIN WIT
     +H (0.0,0.0)')
      GO TO 2000
 1330 CONTINUE
      IF(M1.EQ.1)WRITE(IW,1340)ZU(2),UU(2)
 1340 FORMAT(1H0,36X,'TYPE OF FRICTION CURVE IS A STRAIGHT LINE'//
     +            37X,'MOVEMENT AT SLIDING    =',2X,F6.3/
     +            37X,'MAXIMUM COEFFICIENT OF FRICTION=',2X,F6.3)
      IF(M1.EQ.2)WRITE(IW,1350)ZU(2),UU(2)
 1350 FORMAT(1H0,36X,'TYPE OF FRICTION CURVE IS AN EXPONENTIAL CURVE'//
     +            37X,'MOVEMENT AT SLIDING    =',2X,F6.3/
     +            37X,'MAXIMUM COEFFICIENT OF FRICTION=',2X,F6.3)
      IF(M1.GT.2)WRITE(IW,1360)(ZU(I),UU(I),I=1,M1)
 1360 FORMAT(1H0,36X,'TYPE OF FRICTION CURVE IS A MULTILINEAR CURVE'//
     +,47X,' Z(I)            U(I)'//(46X,F6.3,8X,F6.3))
C
C     INPUT PROPERTIES OF SLAB SUPPORT
C
      WRITE(IW,1121)
      WRITE(IW,1052)
      WRITE(IW,1542)
 1542 FORMAT(33X,' *     STIFFNESS OF SLAB SUPPORT     *')
      WRITE(IW,1070)
      READ(IR,1040)SK
      WRITE(IW,1544)SK
 1544 FORMAT(1H0,45X,25HK-VALUE OF SUPPORT(PCI) =,F10.2)
C
C     READ STEEL PROPERTIES
C
      READ(IR,1040)SS,SA,FPY,ES,ALS
      IF(SS.LE.0.)GO TO 1435
      WRITE(IW,1052)
      WRITE(IW,1415)
 1415 FORMAT(33X,' *          STEEL PROPERTIES          * ')
      WRITE(IW,1070)
      SPT=SA*100./(SS*D)
      WRITE(IW,1420)SPT,SS,SA,FPY,ES,ALS
 1420 FORMAT(1H0,45X,25HPERCENT REINFORCEMENT    =,F10.3/
     +           46X,25HSTRAND SPACING (IN)      =,F10.2/
     +           46X,25HNOMINAL AREA (SQ.IN)     =,F10.3/
     +           46X,25HYIELD STRENGTH (KSI)     =,F10.2/
     +           46X,25HELASTIC MODULUS (PSI).   =,E10.3/
     +           46X,25HTHERMAL COEFFICIENT      =,E10.3/)
      FPA=0.94*FPY
 1435 CONTINUE
C
C     INPUT CONCRETE TEMPERATURES FOR FIRST PERIOD AND TIME AND AMOUNT
C     OF PRESTRESS FOR EACH POST-TENSIONING STAGE
C
      WRITE(IW,1020)ARRE
      WRITE(IW,1030)ARRE(1),VECTOR1,ARRE(1)
      WRITE(IW,1700)ARRE(1),ARRE(1)
 1700 FORMAT(/T17,A4,19X,'PREDICTION OF PAVEMENT STRESSES FOR INITIAL PE
     1RIOD',19X,A4)
```

```
      WRITE(IW,1032)ARRE
C
C     READ NO. OF TEMPERATURES FOR INITIAL PERIOD
C
      READ(IR,1367)NTEMP,CURH(1),CURTEMP
 1367 FORMAT(I5,5X,2F10.0)
      IF(NTEMP.EQ.0)GO TO 1710
      GO TO 1720
 1710 WRITE(IW,1386)CURTEMP
      WRITE(IW,1715)
 1715 FORMAT(1H0,28X,'WARNING,NO TEMPERATURE DATA WERE PROVIDED FOR'/
     129X,'INITIAL ANALYSIS PERIOD;GO TO ANALYZE NEXT PERIOD'/)
      NS=0
      GO TO 1446
 1720 CONTINUE
      IF(CURH(1).GT.6.)GO TO 1370
      K=CURH(1)+19
      GO TO 1372
 1370 K=CURH(1)-5
 1372 XK=K
      RES=XK/2.-K/2
      IF(RES.EQ.0.)GO TO 1374
      KI=K+2
      GO TO 1376
 1374 KI=K+1
 1376 CONTINUE
      DO 1378 I=1,NTEMP
      READ(IR,1040)ADT(I),TDIF(I)
 1378 CONTINUE
      IF(SS.EQ.0.)GO TO 1384
C
C     READ NO. OF POST-TENSIONING STAGES
C
      READ(IR,1050)NS
      DO 1382 I=1,NS
      READ(IR,1367)IAGE,PS(I)
      AGEP(I)=IAGE
 1382 CONTINUE
 1384 CONTINUE
C
C     PRINT SEQUENCE OF PAVEMENT TEMPERATURES AND APPLICATION OF POST-
C     TENSIONING FORCES
C
      WRITE(IW,1386)CURTEMP
 1386 FORMAT(1H0,45X,25HCURING TEMP.  (DEG.F)   =,F10.2/)
      NG38=NTEMP/39+1
      NC24=1
      EL=0.
      PANT=0.
      DO 1440 I1=1,NG38
      IF(I1.EQ.1)GO TO 1390
      WRITE(IW,1388)
 1388 FORMAT(1H1/40X,'            TEMP. AT        TEMP.       PRESTRESS'/
     1            41X,' HOUR       MID-DEPTH       DIFF.      PER STRAND'/
     2            41X,'OF DAY      (DEG.F)        (DEG.F)        (KSI)'/)
      GO TO 1394
 1390 CONTINUE
```

```
      WRITE(IW,1392)
 1392 FORMAT(41X,'             TEMP. AT        TEMP.       PRESTRESS'/
     1       41X,' HOUR        MID-DEPTH        DIFF.      PER STRAND'/
     2       41X,'OF DAY       (DEG.F)        (DEG.F)        (KSI) '/)
 1394 NTEM=38
      IF(I1.EQ.NC38)NTEM=NTEMP-38*(NC38-1)
      DO 1419 I2=1,NTEM
      NCOUNT=38*(I1-1)+I2
      P(NCOUNT)=0.
      PP(NCOUNT)=0.
      ATIM=NCOUNT*2.
      AG(NCOUNT)=ATIM/24.
      DO 1396 KP=1,NS
      NKP=NS-KP+1
      IF(ATIM.LT.AGEP(NKP))GO TO 1396
      P(NCOUNT)=PS(NKP)
      TIME=AGEP(NKP)/24.
      CALL TIDEVAR(TIME,D,0,0)
      GO TO 1400
 1396 CONTINUE
 1400 CONTINUE
      II=KI+2*NCOUNT-2-(NC24-1)*24
      IF(II.EQ.25)GO TO 1402
      GO TO 1404
 1402 NC24=NC24+1
 1404 CONTINUE
      ITIM=II+5
      IF(ITIM.GT.12)ITIM=ITIM-12
      IF(II.GT.7)GO TO 1406
      IF(II.LE.6)WRITE(IW,1408)ITIM,ADT(NCOUNT),TDIF(NCOUNT),P(NCOUNT)
 1408 FORMAT(37X,I5,' A.M.',3(3X,F10.1))
      IF(II.EQ.7)WRITE(IW,1410)ITIM,ADT(NCOUNT),TDIF(NCOUNT),P(NCOUNT)
 1410 FORMAT(37X,I5,' NOON',3(3X,F10.1))
      IF(P(NCOUNT).GT.FPA)GO TO 1445
      GO TO 1416
 1406 IF(II.LE.18)WRITE(IW,1412)ITIM,ADT(NCOUNT),TDIF(NCOUNT),P(NCOUNT)
 1412 FORMAT(37X,I5,' P.M.',3(3X,F10.1))
      IF(ITIM.GT.12)ITIM=ITIM-12
      IF(II.EQ.19)WRITE(IW,1414)ITIM,ADT(NCOUNT),TDIF(NCOUNT),P(NCOUNT)
 1414 FORMAT(37X,I5,' MIDNIGHT',1X,F8.1,2(3X,F10.1))
      IF(II.GT.19)WRITE(IW,1408)ITIM,ADT(NCOUNT),TDIF(NCOUNT),P(NCOUNT)
      IF(P(NCOUNT).GT.FPA)GO TO 1445
      GO TO 1416
 1445 WRITE(IW,1417)P(NCOUNT),FPA
 1417 FORMAT(////1H0,28X,'ERROR,STRAND TENSILE STRESS =',F7.2,' KSI'/
     1                  29X,'EXCEEDS MAXIMUM ALLOWED'/
     2                  29X,'BY  ACI   (0.94*FPY)         =',F7.2,' KSI')
      WRITE(IW,1131)
      GO TO 2000
 1416 CONTINUE
      P(NCOUNT)=1000.*P(NCOUNT)*SA/(SS*D)
      IF(EL.EQ.0.)GO TO 10
      PP(NCOUNT)=(P(NCOUNT)-PANT)/EL
      PANT=P(NCOUNT)
 10   CONTINUE
      IF(NCOUNT.GT.1)GO TO 1418
      TEMPT1=ADT(1)
```

```
      ADT(1)=ADT(1)-CURTEMP
      GO TO 1419
 1418 ADT(NCOUNT)=ADT(NCOUNT)-TEMPT1
      TEMPT1=ADT(NCOUNT)+TEMPT1
 1419 CONTINUE
 1440 CONTINUE
C
C     SOLVE FOR ALL TIME INCREMENTS
C
      CALL FRLST(1,P,D,0,0)
C
C     STARTS ANALYSIS FOR INTERMEDIATE/FINAL PERIOD IF REQUESTED
C     INITIALIZES PRESTRESS VARIABLES
C
 1446 CONTINUE
      PRFINAL=0.
      SFINAL=0.
      NTEMP=24
      DO 1450 I=1,24
      P(I)=0.
      PP(I)=0.
 1450 CONTINUE
      IF(NS.EQ.0)GO TO 1462
C
C     CONVERT TIMES OF POST-TENSIONING TO DAYS FOR COMPUTATION OF
C     PRESTRESS LOSSES FOR INTERMEDIATE/FINAL PERIOD
C
      DO 1460 I=1,NS
      AGEP(I)=AGEP(I)/24.
 1460 CONTINUE
      IP1=NS
      PRT=PS(NS)
      GO TO 1461
 1462 PRT=0.
C
C     READ TEMPERATURES FOR 24-HOUR PERIOD
C
 1461 CONTINUE
      READ(IR,1367)ITOA
      TOA(1)=ITOA
      IF(ITOA.EQ.0)GO TO 2000
      DO 1470 I=1,12
      READ(IR,1040)ADT(I),TDIF(I)
 1470 CONTINUE
      KI=3
      WRITE(IW,1020)ARRE
      WRITE(IW,1030)ARRE(1),VECTOR1,ARRE(1)
      WRITE(IW,1480)ARRE(1),ARRE(1)
 1480 FORMAT(/T17,A4,13X,'PREDICTION OF PAVEMENT STRESSES FOR INTERMEDIA
     1TE/FINAL PERIOD',14X,A4)
      WRITE(IW,1032)ARRE
      IF(PRT.EQ.0.)GO TO 1482
      TIME=TOA(1)
C
C     DETERMINE EFFECTIVE PRESTRESS LEVEL AT PERIOD CONSIDERED
C
      CALL TIDEVAR(TIME,D,NS,1)
```

```
      TEMPD=ADT(1)-CURTEMP
      SFF=(AL-ALS)*TEMPD-CPF-(ZZ-ZZF)
      ELONG=SFF*ES/(1000.*(1.+(SPT*ES)/(100.*EL)))
      PRFINAL=PRT+ELONG-RELAX
      SFINAL=1000.*PRFINAL*SA/(SS*D*EL)+CPM
 1482 CONTINUE
C
C     PRINT SEQUENCE OF PAVEMENT TEMPERATURES AND EFFECTIVE
C     PRESTRESS LEVEL FOR PERIOD CONSIDERED
C
      WRITE(IW,1484)ITOA
 1484 FORMAT(1H0,45X,25HTIME OF ANALYSIS FROM END/
     1           46X,25HOF MOIST CURING (DAYS)   =,I10/)
      IF(ITOA.GE.28)GO TO 1466
      WRITE(IW,1464)
 1464 FORMAT(1H0,28X,'WARNING,THE TIME OF ANALYSIS FOR PERIODS OTHER'
     1/29X,'THAN THE INITIAL PERIOD SHOULD BE GREATER THAN 28 DAYS'/)
 1466 CONTINUE
      WRITE(IW,1392)
      DO 1516 I1=1,12
      NCOUNT=I1
      II=K1*2+I1-2
      ITIM=II+5
      IF(ITIM.GT.12)ITIM=ITIM-12
      IF(II.GT.7)GO TO 1506
      IF(II.LE.6)WRITE(IW,1408)ITIM,ADT(NCOUNT),TDIF(NCOUNT),PRFINAL
      IF(II.EQ.7)WRITE(IW,1410)ITIM,ADT(NCOUNT),TDIF(NCOUNT),PRFINAL
      GO TO 1516
 1506 IF(II.LE.18)WRITE(IW,1412)ITIM,ADT(NCOUNT),TDIF(NCOUNT),PRFINAL
      IF(ITIM.GT.12)ITIM=ITIM-12
      IF(II.EQ.19)WRITE(IW,1414)ITIM,ADT(NCOUNT),TDIF(NCOUNT),PRFINAL
      IF(II.GT.19)WRITE(IW,1408)ITIM,ADT(NCOUNT),TDIF(NCOUNT),PRFINAL
 1516 CONTINUE
 1600 CONTINUE
      DO 1610 I=13,24
      ADT(I)=ADT(I-12)
      AG(I)=(I-12)*2+TOA(1)
 1610 CONTINUE
      DO 1620 I=1,12
      AG(I)=AG(I+12)
 1620 CONTINUE
      DO 1640 I=1,NTEMP
      IF(I.GT.1)GO TO 1630
      TEMPT1=ADT(1)
      ADT(1)=ADT(1)-CURTEMP
      GO TO 1640
 1630 ADT(I)=ADT(I)-TEMPT1
      TEMPT1=ADT(I)+TEMPT1
 1640 CONTINUE
C
C     SOLVE FOR ALL TIME INCREMENTS
C
      CALL FREST(2,P,D,SFINAL,PRFINAL)
      GO TO 1461
 2000 CONTINUE
      WRITE(IW,2020)
 2020 FORMAT(1H1,20(/),T51,'E N D     O F     J O B')
```

```
      SUBROUTINE TITLE
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     THIS SUBROUTINE PRINTS THE PROGRAM TITLE
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      COMMON/BLOCK4/IR,IW
      WRITE(IW,10)
10    FORMAT(15(/),46X,6('P'),6X,5('C'),3X,6('P'),6X,2('1')/
     1       46X,7('P'),4X,7('C'),2X,7('P'),4X,3('1')/
     2       46X,2('P'),4X,2('P'),2X,2('C'),8X,2('P'),4X,
     3       2('P'),2X,4('1')/
     4       46X,2('P'),4X,2('P'),2X,2('C'),8X,2('P'),4X,
     5       2('P'),4X,2('1')/
     6       46X,7('P'),3X,2('C'),8X,7('P'),5X,2('1')/
     7       46X,6('P'),4X,2('C'),8X,6('P'),6X,2('1')/
     8       46X,2('P'),9X,7('C'),2X,2('P'),7X,8('1')/
     9        46X,2('P'),10X,5('C'),3X,2('P'),7X,8('1'))
      WRITE(IW,20)
20    FORMAT(4(/),36X,55('*')/36X,'*',53X,'*'/36X,'*',6X,'ANALYSIS',
     1       ' OF PRESTRESSED CONCRETE PAVEMENTS',5X,'*'/36X,'*',14X,
     2       'CONSIDERING THE INELASTIC',14X,'*'/36X,'*',7X,'NATURE',
     3       ' OF THE SLAB-BASE FRICTION FORCES',7X,'*'/36X,'*',13X,
     4       '(VERSION 1, FEBRUARY 1986)',14X,'*'/36X,'*',53X,'*'/36X,
     5       '*',9X,'CENTER FOR TRANSPORTATION RESEARCH',10X,'*'/36X,
     6       '*',10X,'THE UNIVERSITY OF TEXAS AT AUSTIN',10X,'*'/36X,
     7       '*',53X,'*'/36X,55('*'))
      RETURN
      END
```

```
      SUBROUTINE FREST(KK,P,D,SFINAL,PRFINAL)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     SUBROUTINE FREST DETERMINES THE PROFILES OF FRICTION RESTRAINT
C     STRESSES AND PRESTRESS, ACCUMULATED LONGITUDINAL MOVEMENTS AND
C     CURLING STRESSES AND DEFLECTIONS, FOR ALL TIME INCREMENTS OF
C     THE PERIOD OF ANALYSIS CONSIDERED.  THE FRICTION SUBMODELS FOR
C     THE INTERVALS OF CONTRACTION/EXPANSION AND THE MOVEMENT REVERSAL
C     INTERVALS, ARE INTEGRATED IN THIS SUBROUTINE.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
C     VARIABLES:
C
C        X(I) = COORDINATE ALONG SLAB LENGTH OF POINT I (FT)
C       FX(I) = AVERAGE STRESS IN ELEMENT I (PSI)
C     STF1(I) = STRAIN THAT ELEMENT I TENDS TO DEVELOP AT TIME
C               INCREMENT CONSIDERED (IN/IN)
C     ZANT(I) = INITIAL CONDITION FOR MOVEMENTS OF POINT I, FROM WHICH
C               FURTHER MOVEMENTS OF THE POINT ARE COMPUTED (IN)
C        TIME = AGE SINCE THE CURING HOUR FOR THE TIME INCREMENT CONSIDERED
C               (HOURS)
C        DELT = TEMPERATURE CHANGE FOR TIME INCREMENT CONSIDERED (DEG.F)
C          ZZ = STRAIN INCREMENT OF SLAB ELEMENTS DUE TO SHRINKAGE FOR TIME
C               INCREMENT CONSIDERED (IN/IN)
C       PP(I) = STRAIN INCREMENT DUE TO PRESTRESS APPLICATION DURING TIME
C               INCREMENT CONSIDERED (IN/IN)
C         STF = TOTAL STRAIN INCREMENT OF SLAB ELEMENTS FOR TIME INCREMENT
C               CONSIDERED (IN/IN)
C         NEL = INITIAL ELEMENT FOR SEGMENT EXPERIENCING A REVERSAL OF
C               MOVEMENT (SEGMENT 2 IN FRICTION SUBMODEL 2)
C        Z(I) = TOTAL MOVEMENT EXPERIENCED BY POINT I AT TIME INCREMENT
C               CONSIDERED (IN)
C       RATIO = RATIO BETWEEN THE NORM OF THE CHANGE OF MOVEMENTS OF THE
C               SLAB POINTS BETWEEN SUCCESSIVE ITERATIONS, AND THE NORM OF
C               THE MOVEMENTS AT THE LAST ITERATION
C          Z0 = UNRESTRAINED MAXIMUM CURLING
C               FOR TIME INCREMENT CONSIDERED (IN)
C          S0 = FULLY RESTRAINED CURLING STRESS FOR THE TIME INCREMENT
C               CONSIDERED (PSI)
C        U(I) = AVERAGE FRICTION COEFFICIENT UNDER ELEMENT I
C          ZX = FINAL MOVEMENT OF GIVEN SLAB POINT AT TIME INCREMENT
C               CONSIDERED (IN)
C           F = AVERAGE PRESTRESS PLUS FRICTION RESTRAINT STRESS FOR GIVEN
C               SLAB ELEMENT AT TIME INCREMENT CONSIDERED (PSI)
C         ZFI = CURLING DEFLECTION OF GIVEN SLAB POINT AT TIME INCREMENT
C               CONSIDERED (IN)
C          SY = CURLING STRESS AT BOTTOM OF SLAB OF GIVEN SLAB POINT AT
C               TIME INCREMENT CONSIDERED (PSI)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
```

```
C
C
      COMMON /BLOCK3/M1,ZU(20),UU(20)
      COMMON /BLOCK4/IR,IW
      COMMON /BLOCK5/KI,CURTEMP,AG(100),ADT(100),TDIF(100),PP(100)
      COMMON /BLOCK6/G,COMPF,ALTOT,ZTOT,CREEP,PR,SK,SL
      COMMON /BLOCK7/DL,NILD,NTEMP,TOL,NMAX
      COMMON /BLOCK8/AL,EL,ZZ,SA,SS,PS(10),AGEP(10)
      COMMON /BLOCK9/M,Z(200),U(200)
      COMMON /BLOCK10/Z1(200),X(200),FX(200),STF1(200)
      COMMON /BLOCK12/TOA(10)
      COMMON /BLOCK13/CPF,CPM,ZZF,RELAX,FPY
      DIMENSION Z2(200),ZANT(200),P(100)
C
C     DEFINE LENGTH OF SLAB ELEMENTS AND INITIALIZE PARAMETERS
C
      DX=DL/NILD
      XN=NILD/2.
      IF((XN-IFIX(XN)).EQ.0.)GO TO 100
      X(2)=DX/2.
      AM=NILD/2.+1.5
      M=AM
      K1=3
      GO TO 110
100   M=NILD/2+1
      K1=2
110   CONTINUE
      M2=M-1
C
C     INITIALIZE TO ZERO THE VARIABLES FOR STRESS AND STRAIN
C     OF THE ELEMENTS (FX AND STF1)
C
      DO 120 I=1,M2
      FX(I)=0.
      STF1(I)=0.
120   CONTINUE
      FX(M)=0.
      X(1)=0.
      U(1)=0.
C
C     DEFINE COORDINATES OF NODES BOUNDING THE ELEMENTS
C
      DO 130 I=K1,M
      X(I)=X(I-1)+DX
130   CONTINUE
C
C     INITIALIZE TO ZERO THE VARIABLES REPRESENTING NEW INITIAL CONDITION
C     FOR MOVEMENTS, DEFINED AT THE LAST REVERSAL OF MOVEMENTS (ZANT)
C
      DO 132 I2=1,M
132   ZANT(I2)=0.
C
C     INITIALIZE TO ZERO VARIABLE REPRESINTING INCREMENT IN MOVEMENT OF
C     END POINT OF SEGMENT 1 (ZZ) BETWEEN SUCCESSIVE ITERATIONS AT
C     MOVEMENT REVERSAL INTERVAL
C
      ZZ=0.
```

```
      TEMPT=CURTEMP
      INDIK=0
      INDPP=0
      NC24=1
C
C     SOLVE FOR DEFORMATIONS AND STRESSES FOR ALL TEMPERATURES OF
C     THE ANALYSIS PERIOD CONSIDERED, AT 2-HOUR INTERVALS
C
      DO 140 I=1,NTEMP
      NEL=0
      INDCON=0
      ZY=ZZ
      TIME=AG(I)
      DELT=ADT(I)
      TEMPT=TEMPT+DELT
C
C     DETERMINE ELASTIC MODULUS AND SHRINKAGE STRAIN OF CONCRETE
C     FOR THE TIME INTERVAL CONSIDERED
C
      CALL TIDEVAR(TIME,0,IP1,0)
      ZZ=ZZ-ZY
      IF(KK.EQ.1)GO TO 25
      IF(I.GT.1.AND.I.LE.12)ZZ=0.
25    CONTINUE
C
C     DETERMINE STRAIN INCREMENT FOR SLAB ELEMENTS IN TIME INCREMENT
C     CONSIDERED
C
      STF=AL*DELT-ZZ-PP(I)
C
C     DETERMINE IF STRAIN INCREMENT LEADS TO A MOVEMENT REVERSAL
C     AND DEFINE STRAINS OF ELEMENTS FOR ANALYSIS
C
      DO 148 I1=1,M2
      FPROM=(FX(I1+1)+FX(I1))/2.
      IF(STF.GE.0..AND.FPROM.LE.0.)GO TO 146
      IF(STF.LE.0..AND.FPROM.GE.0.)GO TO 146
      FAUX=STF-FPROM/EL
      IF(FPROM.GT.0.)GO TO 142
      IF(FAUX.GT.0.)GO TO 146
      GO TO 144
142   CONTINUE
      IF(FAUX.LT.0.)GO TO 146
C
C     SLAB IN A MOVEMENT-REVERSAL INTERVAL
C
144   CONTINUE
      IF(NEL.NE.0)GO TO 145
C
C     DEFINE INITIAL ELEMENT OF SEGMENT 2 REVERSING MOVEMENT
C     IF IT HAS NOT BEEN DEFINED BEFORE
C
      NEL=I1
      INEL=NEL+1
      IF(NEL.EQ.1)INEL=1
C
C     DEFINE NEW INITIAL CONDITION FOR ELEMENTS REVERSING MOVEMENT
```

```
C
      DO 14 I2=INEL,M
   14 ZANT(I2)=Z2(I2)
C
C     DEFINE STRAIN OF ELEMENTS REVERSING MOVEMENT
C
  145 STF1(I1)=FAUX
      INDIK=1
      GO TO 148
C
C     DEFINE STRAIN OF ELEMENTS IN CONTRACTION/EXPANSION INTERVAL
C     OR THAT DO NOT REVERSE MOVEMENT IN MOVEMENT-REVERSAL INTERVAL
C
  146 STF1(I1)=STF1(I1)+STF
  148 CONTINUE
      IF(INDIK.EQ.1.AND.NEL.LE.1)GO TO 3
      GO TO 2
   11 INDPP=0
    3 CONTINUE
C
C     DEFINE NEW INITIAL CONDITION FOR ALL ELEMENTS
C     (MOVEMENT-REVERSAL INTERVAL COMPLETED)
C
      DO 4 I2=1,M
    4 ZANT(I2)=Z2(I2)
      INDIK=0
    2 CONTINUE
      IF(NEL.LE.1)GO TO 190
C
C     SOLVE FOR SLAB IN MOVEMENT-REVERSAL INTERVAL
C
      NN=0
      ZI=0.
      ZULT=Z(NEL)
  150 SII=S1
      SUM1=0.
      SUM2=0.
C
C     SOLVE FOR SEGMENT 2
C
      CALL ITER(ZI,SII,NEL,M,D,INDCON)
      SII=FX(NEL)
C
C     SOLVE FOR SEGMENT 1
C
      CALL ITER(0.,SII,1,NEL,D,INDCON)
C
C     COMPUTE RATIO FOR SUCCESSIVE ITERATIONS
C
      DO 180 I1=2,M
      ZM=Z(I1)
      IF(I1.GT.NEL)GO TO 160
      Z(I1)=Z1(I1)+ZANT(I1)
      GO TO 170
  160 Z(I1)=Z1(I1)+ZANT(I1)+ZI
  170 SUM1=SUM1+(ZM-Z(I1))*(ZM-Z(I1))
  180 SUM2=SUM2+Z(I1)*Z(I1)
```

```
      RATIO=SQRT(SUM1/SUM2)
      IF(RATIO.LT.TOL)GO TO 200
      ZI=0.10*(Z(NEL)-ZULT)+0.90*ZI
      NN=NN+1
      IF(NN.LE.NMAX)GO TO 150
      INDCON=1
      GO TO 200
C
C     SLAB IN CONTRACTION/EXPANSION INTERVAL
C
190   CONTINUE
      CALL ITER(0.,SI,1,M,D,INDCON)
C
C     DEFINE MOVEMENT OF NODES
C
      DO 195 I1=1,M
195   Z(I1)=Z1(I1)+ZANT(I1)
200   CONTINUE
      IF(NEL.LE.1)GO TO 202
      IF(PP(I).NE.0.)GO TO 201
      GO TO 212
201   INDPP=1
202   CONTINUE
C
C     PREPARE VARIABLES FOR COMPUTATION OF NEXT TIME INCREMENT
C
      DO 210 I2=1,M
210   Z2(I2)=Z(I2)
212   CONTINUE
      ZZ=ZZ+ZY
      ITEMP=I
      IF(I.LE.12.AND.KK.NE.1)GO TO 140
C
C     PRINT HEADINGS AND RESULTS
C
      IF(KK.EQ.1)GO TO 214
      ITEMP=ITEMP-12
      II=KI+2*I-26
      GO TO 216
214   II=KI+2*I-2-(NC24-1)*24
      IF(II.EQ.25)GO TO 215
      GO TO 216
215   NC24=NC24+1
216   ZO=(1.+PR)*ALTOT*TDIF(ITEMP)*(SL**2.0)/D
      SO=(EL*ALTOT*TDIF(ITEMP)/(2.*(1.-PR)))
      ITIM=II+5
      IF(ITIM.GT.12)ITIM=ITIM-12
      IF(II.GT.7)GO TO 10
      IF(II.LE.6)WRITE(IW,5)ITIM
5     FORMAT(1H1,24X,7HHOUR = ,I5,' A.M.'/)
      IF(II.EQ.7)WRITE(IW,6)ITIM
6     FORMAT(1H1,24X,7HHOUR = ,I5,' NOON'/)
      GO TO 50
10    IF(II.LE.18)WRITE(IW,7)ITIM
7     FORMAT(1H1,24X,7HHOUR = ,I5,' P.M.'/)
      IF(ITIM.GT.12)ITIM=ITIM-12
      IF(II.EQ.19)WRITE(IW,8)ITIM
```

```
      8    FORMAT(1H1,24X,7HHOUR = ,I5,' MIDNIGHT'/)
           IF(II.GT.19)WRITE(IW,5)ITIM
      50   CONTINUE
           NG55=M/56+1
           DO 310 I1=1,NG55
           IF(I1.EQ.1)GO TO 51
      1000 WRITE(IW,302)
      302  FORMAT(1H1/23X,' COORDINATES       MOVEMENT  COEFF OF FRICTION  PRE
          1ST+FRICT        CURLING     BOT.CURLING'/23X,'FROM MIDSLAB(FT)      (
          2IN)                        STRESS (PSI)  DEFLECTION(IN)  STRESS(PSI)'
          3/)
           GO TO 304
      51   CONTINUE
           WRITE(IW,314)
      314  FORMAT(24X,' COORDINATES       MOVEMENT  COEFF OF FRICTION  PREST+F
          +RICT        CURLING    BOT.CURLING'/23X,'FROM MIDSLAB(FT)      (IN)
          +                        STRESS (PSI)  DEFLECTION(IN) STRESS(PSI)'/)
      304  NELE=55
           IF(I1.EQ.NG55)NELE=M-55*(NG55-1)
           DO 310 I2=1,NELE
           NCOUNT=55*(I1-1)+I2
      C
      C    COMPUTE CURLING STRESSES
      C
           ZK=0.
           SK0=0.
           TDF=TDIF(ITEMP)
           XNC=X(NCOUNT)
           CALL CURL(TDF,XNC,ZK,SK0)
           ZFI=Z0+ZK
           SY=S0+SK0
           IF(PRFINAL.EQ.0.)GO TO 309
           ZX=Z(NCOUNT)-SFINAL*X(NCOUNT)*12.
           F=FX(NCOUNT)-1000.*PRFINAL*SA/(SS*D)
           GO TO 311
      309  ZX=Z(NCOUNT)
           F=FX(NCOUNT)-P(I)
      311  IF(NCOUNT.EQ.1)FPLOT=F
      310  WRITE(IW,320)X(NCOUNT),ZX,U(NCOUNT),F,ZFI,SY
      320  FORMAT(20X,F15.2,2F15.5,F15.2,F15.5,F15.2)
           IF(INDCON.EQ.1)GO TO 330
           GO TO 140
      C
      C    PRINT MESSAGE AT END OF ITERATIONS
      C
      330  WRITE(IW,350)
      350  FORMAT(///1H0,28X,'CONVERGENCE NOT ACHIEVED; ALGORITHM'/
          1              29X,'STOPPED FOR MAXIMUM NO. OF ITERATIONS')
      140  WRITE(07,*)ZX,FPLOT
           RETURN
           END
```

```
      K=MT-I+NEL
      U(K+1)=(U(K+1)+U(K))/2.
      FX(K)=FX(K+1)+U(K+1)*6*(X(K+1)-X(K))/144.
30    CONTINUE
C
C     DETERMINE RESTRAINED MOVEMENTS OF NODES AND COMPUTE
C     RATIO FOR SUCCESSIVE ITERATIONS
C
      DO 40 I=IN,MT
      ZM=Z1(I)
      FPROM=(FX(I)+FX(I-1))/2.
      DMOV=STF1(I-1)*FPROM/EL
      Z1(I)=0.65*(Z1(I-1)+DMOV*(X(I)-X(I-1))*12.)+0.35*Z1(I)
      SUM1=SUM1+(ZM-Z1(I))*(ZM-Z1(I))
      SUM2=SUM2+Z1(I)*Z1(I)
40    CONTINUE
      RATIO=SQRT(SUM1/SUM2)
      IF(RATIO.LT.TOL)GO TO 50
      NN=NN+1
      IF(NN.LE.NMAX)GO TO 20
      MM=NILD/2+1
      IF(NEL.EQ.1.AND.MT.EQ.MM)GO TO 42
      GO TO 50
42    CONTINUE
C
C     MAKE SWITCH VARIABLE INDCON=1 IF SLAB IS IN
C     CONTRACTION/EXPANSION INTERVAL
C
      INDCON=1
50    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TIDEVAR(TIME,D,IPI,INDICA)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     SUBROUTINE TIDEVAR DETERMINES ESTIMATES OF CONCRETE ELASTIC
C     MODULUS, RADIUS OF RELATIVE STIFFNESS OF THE SLAB, SHRINKAGE,
C     CREEP AND RELAXATION OF THE STEEL STRANDS.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     VARIABLES:
C
C         TIME = TIME OF EVALUATION SINCE CURING (DAYS)
C       COMSTR = CONCRETE COMPRESSIVE STRENGTH AT TIME
C                OF EVALUATION (PSI)
C           EL = CONCRETE ELASTIC MODULUS AT TIME OF EVALUATION (PSI)
C           SL = RADIUS OF RELATIVE STIFFNESS (IN)
C           ZZ = SHRINKAGE STRAIN AT TIME OF EVALUATION (IN/IN)
C          CPF = CREEP STRAIN (FOR EVALUATION OF PRESTRESS LOSSES)
C                BY THE TIME OF EVALUATION, SINCE APPLICATION OF
C                LAST PRESTRESS FORCE (IN/IN)
C          CPM = TOTAL CREEP STRAIN BY THE TIME OF EVALUATION, SINCE
C                APPLICATION OF FIRST PRESTRESS FORCE (IN/IN)
C        RELAX = TOTAL STEEL RELAXATION BY THE TIME OF EVALUATION
C                (PERCENT)
C          ZZF = SHRINKAGE STRAIN (FOR EVALUATION OF PRESTRESS LOSSES)
C                BY THE TIME OF EVALUATION, SINCE APPLICATION OF
C                LAST PRESTRESS FORCE (IN/IN)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      DIMENSION CREP(10,10)
      COMMON/BLOCK6/G,COMPF,ALTOT,ZTOT,CREEP,PR,SK,SL
      COMMON/BLOCK8/AL,EL,ZZ,SA,SS,PS(10),AGLP(10)
      COMMON/BLOCK13/CPF,CPM,ZZF,RELAX,FPY
C
C     DEFINE CONCRETE PROPERTIES INDEPENDENT OF PRESTRESS FORCE
C
      CALL COMPSTR(TIME,COMSTR)
      EL=33.*(G**1.5)*SQRT(COMSTR)
      SL=((EL*D**3.0)/(12.*(1-PR**2.0)*SK))**0.25
      IF(TIME.LT.1./3000.)GO TO 70
      AL=ALTOT
      GO TO 80
70    AL=(1.-9.*(1./3.-TIME)**2.)*ALTOT
80    SHRN=26.*EXP(0.36*D)
      ZZ=(TIME/(SHRN+TIME))*ZTOT
      IF(INDICA.EQ.0)GO TO 200
C
C     DEFINE PARAMETERS DEPENDENT ON AMOUNT OF PRESTRESS FORCE
C
      CPM=0.
      PANT=0.
```

```
      DO 120 I1=1,IP1
      DP=PS(I1)-PANT
      TIMP=AGEP(I1)
      CALL COMPSTR(TIMP,COM)
      EP=33.*(G**1.5)*SQRT(COM)
      STI=1000.*DP*SA/(SS*D*EP)
      CRA=0.
      DO 115 I2=I1,IP1
      IF(I2.EQ.IP1)GO TO 112
      TIM=AGEP(I2+1)-AGEP(I1)
      GO TO 113
112   TIM=TIME-AGEP(I1)
113   CONTINUE
      CRAUX=TIM**0.6
      CR=(CRAUX*CREEP*STI)/(10.+CRAUX)
      CREP(I2,I1)=CR-CRA
      CPM=CPM+CREP(I2,I1)
      CRA=CR
115   CONTINUE
120   PANT=PS(I1)
      CPF=0.
      DO 125 I1=1,IP1
      CPF=CPF+CREP(IP1,I1)
125   CONTINUE
C
C     DEFINE AMOUNTS OF SHRINKAGE AT THE TIME OF STRESSING
C     AND STRAND RELAXATION
C
      TIM=(TIME-AGEP(IP1))*24.
      RAUX=PS(IP1)/FPY-0.55
      IF(RAUX.LT.0.)RAUX=0.
      RELAX=((ALOG10(TIM)/10.)*RAUX)*PS(IP1)
      ZZF=(AGEP(IP1)/(SHRN+AGEP(IP1)))*ZTOT
200   CONTINUE
      RETURN
      END
```

```
      SUBROUTINE FRIC(NEL,MT,Z1)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     SUBROUTINE FRIC COMPUTES FRICTION COEFFICIENTS FROM THE
C     MOVEMENTS OF THE SLAB NODES.  INFORMATION FROM THIS SUB-
C     ROUTINE IS USED IN SUBROUTINE ITER TO DETERMINE THE
C     PROFILES OF FRICTION RESTRAINT STRESSES.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     VARIABLES:
C
C        M1 = NO. OF POINTS IN THE SUPPLIED FRICTION COEFFICIENT
C             VS. DISPLACEMENT RELATIONSHIP. MOREOVER, M1 IS A CONTROL
C             VARIABLE INDICATING THE TYPE OF RELATIONSHIP:
C             IF M1=1, THE RELATIONSHIP IS A STRAIGTH LINE,
C             IF M1=2, THE RELATIONSHIP IS AN EXPONENTIAL RELATIONSHIP,
C             IF M1>2, THE RELATIONSHIP IS A MULTILINEAR CURVE.
C     ZAUX = ABSOLUTE VALUE OF THE DISPLACEMENT Z1(I) OF POINT I (IN)
C     U(I) = FRICTION COEFFICIENT UNDER POINT I
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      DIMENSION Z1(200)
      COMMON /BLOCK3/M1,ZU(20),UU(20)
      COMMON /BLOCK9/M,Z(200),U(200)
      IF(M1.EQ.1)GO TO 10
      IF(M1.EQ.2)GO TO 80
      IF(M1.GT.2)GO TO 20
10    CONTINUE
      M2=2
      GO TO 30
20    CONTINUE
      M2=M1
30    CONTINUE
C
C     COMPUTE FRICTION COEFFICIENTS FROM STRAIGTH LINE OR FROM MULTILINEAR
C     CURVE
C
      DO 40 I1=NEL,MT
      ZAUX=ABS(Z1(I1))
      DO 50 J=2,M2
      J1=J
      IF(ZAUX.LT.ZU(J))GO TO 60
50    CONTINUE
      U(I1)=UU(M2)
      GO TO 70
60    SLOPE=(UU(J1)-UU(J1-1))/(ZU(J1)-ZU(J1-1))
      U(I1)=UU(J1-1)+SLOPE*(ZAUX-ZU(J1-1))
70    CONTINUE
      IF(Z1(I1).GT.0.)U(I1)=-U(I1)
40    CONTINUE
```

```
      GO TO 110
80    CONTINUE
C
C     COMPUTE FRICTION COEFFICIENTS FROM EXPONENTIAL RELATIONSHIP
C
      DO 95 I1=NEL,MT
      ZAUX=ABS(Z1(I1))
      IF(ZAUX.LT.ZU(2))GO TO 100
      U(I1)=UU(2)
      GO TO 90
100   PAUX=(ZAUX/ZU(2))**0.3333
      U(I1)=PAUX*UU(2)
90    IF(Z1(I1).GT.0.)U(I1)=-U(I1)
95    CONTINUE
110   RETURN
      END
```

```
      SUBROUTINE COMPSTR(TIME,CONSTR)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     SUBROUTINE COMP COMPUTES COMPRESSIVE STRENGTH OF CONCRETE
C     AT SPECIFIED TIMES
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     VARIABLES:
C
C          TIME = TIME OF EVALUATION SINCE CURING (DAYS)
C         COMPF = FINAL COMPRESSIVE STRENGTH (PSI)
C        PERCOM = PERCENT OF THE FINAL COMPRESSIVE STRENGTH
C        CONSTR = COMPRESSIVE STRENGTH EVALUATED (PSI)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      DIMENSION PERCENT(8),AGE(8)
      COMMON/BLOCK2/KK,AGEU(20),COMP(20)
      COMMON/BLOCK6/G,COMPF,ALTOT,ZTOT,CREEP,PR,SK,SL
      DATA AGE/0.,1.,3.,5.,7.,14.,21.,28./
      DATA PERCENT/0.,15.,38.,53.,63.,82.,94.,100./
      IF(KK.GT.0)GO TO 30
C
C     COMPUTE COMPRESSIVE STRENGTH IF
C     THERE IS NO USER-SUPPLIED RELATIONSHIP
C
      DO 10 I=1,8
      J=I
      IF(TIME.LE.AGE(I))GO TO 20
   10 CONTINUE
      CONSTR=COMPF
      GO TO 60
   20 PERCOM=(PERCENT(J)-PERCENT(J-1))/(AGE(J)-AGE(J-1))
      PERCOM=PERCENT(J-1)+PERCOM*(TIME-AGE(J-1))
      CONSTR=PERCOM*COMPF/100.
      GO TO 60
C
C     COMPUTE COMPRESSIVE STRENGTH IF
C     THERE IS A USER-SUPPLIED RELATIONSHIP
C
   30 CONTINUE
      DO 40 I=1,KK
      J=I
      IF(TIME.LE.AGEU(I))GO TO 50
   40 CONTINUE
      CONSTR=COMPF
      GO TO 60
   50 SLOPE=(COMP(J)-COMP(J-1))/(AGEU(J)-AGEU(J-1))
      CONSTR=COMP(J-1)+SLOPE*(TIME-AGEU(J-1))
   60 CONTINUE
      RETURN
```

```
      SUBROUTINE CURL(TD,X,ZK,SKO)
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     SUBROUTINE CURL COMPUTES CURLING STRESSES AND
C     DEFLECTIONS
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     VARIABLES:
C
C          Y = COORDINATE MEASURED FROM THE SLAB END, OF NODE LOCATED
C              AT COORDINATE X FROM THE MID-SLAB (IN)
C         ZK = PERCENT DEFLECTION FOR NODE LOCATED A DISTANCE X FROM
C              MID-SLAB, WITH RESPECT TO THE MAXIMUM DEFLECTION AT THE
C              SLAB END
C        SKO = PERCENT STRESS FOR NODE LOCATED A DISTANCE X FROM MID-SLAB,
C              WITH RESPECT TO THE MAXIMUM STRESS AT MIDSLAB
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      COMMON /BLOCK6/G,FPC,ALTOT,ZTOT,STRNMUL,PR,SK,SL
      COMMON /BLOCK7/DL,NILD,NTEMP,TCL,NMAX
      Y=(DL/2.-X)*12.
      YAUX=(Y/(1.4142*SL))
      EX=EXP(-YAUX)
C
C     DETERMINES DEFLECTION AND STRESS PERCENTAGES WITH RESPECT
C     TO MAXIMUM VALUES AT THE EDGE AND MIDSLAB RESPECTIVELY FOR
C     ALL COORDINATES CONSIDERED
C
      ZK=-1.4142*COS(YAUX+0.7854)*EX
      SKO=(1.-1.4142*SIN(YAUX+0.7854)*EX)
      RETURN
      END
```

APPENDIX E

JOINT OPENING DATA USED IN THE REGRESSION ANALYSIS IN CHAPTER 7 FOR EVALUATING CONCRETE THERMAL COEFFICIENT AND ULTIMATE CREEP AND SHRINKAGE STRAINS

Temperature (Deg. C)	Age (Days)	Movements Joints 2-9 (in.)	Movements Joints 11-16 (in.)
27.0	0	0.000000	
27.0	5	0.600000	
15.0	6	0.917500	
27.0	6	0.655000	
22.5	7	0.725000	
24.5	7	0.700000	
30.0	13	0.735000	
30.0	17	0.757500	
29.5	34	0.820000	
20.0	48	0.967500	
13.0	57	1.107500	
15.0	58	1.075000	
2.0	74	1.347500	
15.0	1	0.225000	
27.0	1	0.135000	
22.5	2	0.278333	
24.5	2	0.270000	
30.0	8	0.396666	
30.0	12	0.425000	
29.5	29	0.498333	
20.0	43	0.683333	
13.0	52	0.826666	
15.0	53	0.800000	
2.0	69	1.083333	
27.0	0	0.155000	
22.5	1	0.297500	
24.5	1	0.297500	
30.0	7	0.520000	
30.0	11	0.577500	
29.5	28	0.670000	
20.0	42	0.862500	
13.0	47	0.955000	
15.0	52	0.980000	
2.0	68	1.275000	
30.0	4	0.090000	
29.5	21	0.170000	
20.0	35	0.355000	
13.0	44	0.495000	
15.0	45	0.475000	
2.0	61	0.760000	
30.0	4		0.946666
29.5	21		1.368333
20.0	35		1.740000

Temperature (Deg. C)	Age (Days)	Movements Joints 2-9 (in.)	Movements Joints 11-16 (in.)
13.0	44		1.948333
15.0	45		1.986666
2.0	61		2.436666
29.5	17		1.238333
20.0	31		1.615000
13.0	40		1.806666
15.0	41		1.806666
2.0	57		2.331666